MARTIN MARIETTA

KAPL, INC

KNOLLS ATOMIC POWER LABORATORY
POST OFFICE BOX 1072
SCHENECTADY, NEW YORK 12301-1072
TELEPHONE (518) 395-4000
FAX (518) 395-4422

MDO 724-5942
August 15, 1994

The Manager
Schenectady Naval Reactors Office
U. S. Department of Energy
Schenectady, New York 12301

SUBJECT: Transmittal of KAPL Topical Report on J-Integral Characterization of Nozzle Steels, For Information

ATTACHMENT: KAPL-4744, "J-Integral Characterization of the Nozzle Steels from Intermediate Test Vessels IV-5 and IV-9", TA Auten, BD Macdonald, DW Scavone, D. Bozik.

Dear Sir:

This letter transmits a topical report describing J-integral tests performed on two nozzle steels from the Heavy Section Steel Technology Program run for the US Nuclear Regulatory Commission by the Oak Ridge National Laboratory in the 1970's. The nozzles had six inch thick walls and had fatigue-sharpened defects at inner radius positions. The vessels were tested to failure, providing cases that could be analyzed by modern elastic-plastic J-integral design procedures.

The US NRC agreed to supply the remnant nozzle materials to KAPL to run J-integral tests, which are reported here. This work was reported at the 25th National Symposium on Fracture Mechanics on June 30, 1993, at Lehigh University, Bethlehem, Pennsylvania. The proceedings will be published as ASTM Special Technical Publication No. 1220. The accompanying topical report, KAPL-4744, is essentially identical to that presented at the symposium; however, the raw data for the J-integral tests have been appended. Also, the Charpy impact data and the tensile data have been included.

Naval Reactors action required: None. This report is for information only.

Very truly yours,

T. A. Auten, Senior Engineer
Structural Materials Unit
MDO/Structural Materials Engineering

cc:			
DI Curtis (3)	NR FOR INFORMATION	CA Grove	MAO
TF Kennedy	NR	AC Davis	Bettis
DB Pye	NR	GL Wire	Bettis
GM Millis	SNR	Bettis Library	
FE Brosnihan/DR Clapper	SNR	WR Kennedy	WPAD
		R. Spada	WPAD

OPERATED FOR THE U.S. DEPARTMENT OF ENERGY BY KAPL, INC., A SUBSIDIARY OF THE MARTIN MARIETTA CORPORATION

sg393

bcc:	TA Auten (5)	A1 117
	D. Bozik (5)	A3 219
	GT Embley	D1 101
	DA Ferrill	A3 219
	JN Ferrucci	A1 214
	SZ Hayden	A1 117
	BD Macdonald (5)	D1 101
	DL McCullough	D2 124
	PM Rosecrans	A3 200
	TG Sauer	A3 204
	DW Scavone (5)	A3 219
	Technical Publications (3)	A1 34
	Document Library (3)	A1 112
	NRIC	C3 125
	File (2)	A1 117

sg393

STRUCTURAL MATERIALS ENGINEERING - DESIGN CHECK SHEET

FOR: MDO 724-5942, TA Auten, BD Macdonald, DW Scavone, and D. Bozik
(DOCUMENT LETTER NUMBER/AUTHOR)

A. CONTENTS: INFORMATION CONSIDERED AS A BASIS FOR DESIGN ____ PRELIMINARY RESULTS ____
FINAL RESULTS ____ FOR INFORMATION ____ FOR NR APPROVAL ✓
FOR PRIME CONTRACTOR CONCURRENCE ____ FOR SNR APPROVAL ✓

B. CONCURRENCE REQUIREMENTS: REVIEWED BY: [signature] 12/15/93
MANAGER, STRUCTURAL MATERIALS ENGINEERING DATE

SIGNATURES REQUIRED ON "bcc" INDICATED BELOW:

MDO COMPONENT	CONCURRENCE REQUESTED (YES/NO*)	BASIS (SEE "D") BELOW
MAT'LS DEVELOPMENT OPERATION, MGR.	NO	
STRUCTURAL MAT'LS ENGINEERING, MGR.	Yes	8
Pressurizer Materials Unit	No	
Structural Materials Unit	↓	
Welding Engineering	↓	
Metallurgical Fabrication Facility	↓	
PLANT MATERIALS DEVELOPMENT	↓	
ALLOY 600 PROGRAM	↓	
CORE MATERIALS ENGINEERING	↓	
MATERIALS ENGINEERING LABORATORY	↓	
STEAM GENERATORS	↓	
MDO FINANCIAL REPRESENTATIVE	↓	

KAPL PROJECTS/OPERATIONS	CONCURRENCE REQUESTED YES/NO*)	BASIS (SEE "D") BELOW
REACTOR ENGINEERING OPERATION	No	
ENGINEERING DESIGN OPERATION	↓	
NEW CONCEPT STEAM GENERATOR	↓	
ADVANCED REACTOR PROJECT	↓	
PROCUREMENT OPERATION	↓	
QUALITY ASSURANCE OPERATION	↓	
LABORATORY SUPPORT SERVICES	↓	
PROTOTYPE SUPPORT OPERATION	↓	
FLEET SUPPORT OPERATION	↓	
ROSC/RDSC/FHSCC CHAIRMAN	↓	
OTHER: ____		

* SIGNATURES NOT REQUIRED AND WHY: ____

C. CHECKING OF ENGINEERING WORK:
PRELIMINARY CHECK BY: Previously Performed. ORGANIZATION: ____ DATE: ____
BASIS (SEE "D" BELOW): ____
COMMENTS (REFERENCES TO SUPPORTING DOCUMENTS, FILE IDENTIFICATION): ____

D. BASIS FOR CONCURRENCE AND/OR CHECKING:

1. ADEQUACY OF STATEMENTS ON IMPACT ON DESIGNS OR OPERATING OF REACTORS.
2. SPOT CHECK REPEAT OF SOME CALCULATIONS AND/OR RESULTS.
3. COMPARISON WITH PRIOR TESTS OR CALCULATIONS.
4. SIMPLIFIED HAND CALCULATION.
5. CHECK AGAINST AVAILABLE SPECIFICATIONS.
6. REASONABLENESS OF RESULTS.
7. COMPARISON WITH EXPERIMENT AND TEST RESULTS.
8. CHECKED FOR CONCEPTUAL ERRORS.
9. CHECKED FOR LIKELIHOOD OF ACHIEVING STATED GOALS.
10. WALK THROUGH OF PROCEDURES UNDER REALISTIC CONDITIONS.
11. ADEQUACY OF COST ESTIMATE.
12. AVAILABILITY OF FUNDING.
13. REASONABLENESS OF SCHEDULE.
14. ACCEPTABILITY OF IMPACT.
15. REASONABLENESS OF ASSUMPTIONS.
16. AGREE WITH RECOMMENDATIONS AS RELATED TO AREA OF COGNIZANCE.
17. REVIEW OF COMPUTER INPUT/OUTPUT.
18. INCLUSION OF IMPACT OF UNCERTAINTIES AND SELF CHECKS.
19. ACCEPTABILITY OF QUALITY ASSURANCE ASPECTS.
20. INDEPENDENT REVIEW OF ALL OR SELECTED DERIVATIONAL DETAILS.
21. CONCURRENCE WITH REQUESTED SIGN-OFFS.
22. REVIEW OF METHODS USED.
23. CONCURRENCE THAT DESIGN REVIEW COMMENTS HAVE BEEN ADDRESSED ADEQUATELY ENOUGH TO ISSUE DOCUMENT. FULL RESOLUTION OF COMMENTS MAY REQUIRE ADDITIONAL DOCUMENTATION, WHICH IS THE AUTHOR'S RESPONSIBILITY.

E. ADMINISTRATIVE CHECK:

	YES	NO
SECURITY CLASSIFICATION REVIEWED	✓	
THIS LETTER ESTABLISHES AN NR COMMITMENT (DUE DATE: ____)		✓
THIS LETTER COMPLETES AN NR COMMITMENT (No. 724- ____)		✓
THIS LETTER RECOMMENDS A MANUAL CHANGE		✓
POSSIBLE CHANGE TO UTRS DOCUMENTS		✓
CONCURRENCE STATEMENT		✓

NRIC DISTRIBUTION: WITH 1722 FORM ____ SECRETARIAL LOG ____

MANAGERIAL CHECK BY: [signature] CHECKING METHOD(S) USED: Agree with release of this information.

REVISED: 5/93

LFK434

KAPL-4744
UC-504, Materials
(DOE/TIC-4500-R74)

J-INTEGRAL CHARACTERIZATION OF THE NOZZLE STEELS FROM INTERMEDIATE TEST VESSELS IV-5 AND IV-9

by

T.A. Auten, B.D. Macdonald, D.W. Scavone, and D. Bozik

Prepared for
The United States Department of Energy
Assistant Secretary for Nuclear Energy
Deputy Assistant Secretary for Naval Reactors

Prepared by the
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York

Contract No. DE-AC12-76-SN-00052

DISCLAIMER

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

ABSTRACT

Reported here are the results of elastic-plastic fracture toughness tests performed on low alloy steels from the nozzles of the intermediate test vessels IV-5 and IV-9 from the Heavy Steel Section Technology Program at Oak Ridge National Laboratory. These vessels had been given prototypic nozzle corner flaw tests prior to the development of the ASTM E-813 standard test procedure for J-integral testing. The objective of this work is to provide J-integral material test support for future elastic-plastic fracture mechanics analysis of the nozzles. J-integral tests at 88°C (190°F) of the IV-5 nozzle material produced stable ductile tearing. The tearing resistance data are expected to support analysis of the observed similar stable tearing response of the nozzle corner flaw. J-integral tests at 24°C (75°F) of the IV-9 nozzle produced elastic-plastic fracture instability preceded by stable tearing. A similar response was observed in the IV-9 nozzle corner flaw test. It will be a major and important challenge to develop a fracture mechanics rationale that reconciles these small specimen and nozzle corner flaw test results. These test results are being made available to allow their use by a wide variety of organizations in developing such a rationale, which would be a significant contribution to quantifying the flaw tolerance of reactor pressure vessels.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the helpful efforts of the following KAPL personnel: R. Brownell, L. Callahan, L. DiCerbo, D. Ferrill, B. Furbeck, R. Glowacki, S. Gwiazdowski, P. Harris, S. Hayden, T. Hennessy, and G. Neugebauer.

J-INTEGRAL CHARACTERIZATION OF THE NOZZLE STEELS FROM INTERMEDIATE TEST VESSELS IV-5 AND IV-9

T.A. Auten, B.D. Macdonald, D.W. Scavone, and D. Bozik

INTRODUCTION

The analysis of postulated accidents involving nuclear reactor pressure vessels has focused on the inlet and outlet nozzles because of the high local stresses. As part of the Heavy Section Steel Technology (HSST) Program performed at the Oak Ridge National Laboratory, large-scale experiments involving nozzle geometries were performed to support the development of analysis procedures back in the 1970's *[1]*[2].Since the capability to analyze elastic-plastic flaws in arbitrary geometries did not exist at the time of those experiments, there was no need to perform J-integral characterization of the nozzle materials. The objective of this work is to characterize the elastic-plastic fracture properties of the nozzles from two of the large-scale tests that involved ductile tearing.

The HSST program comprised a series of prototypic nozzle corner flaw tests in 39 inch outside diameter vessels *[1]*. The nozzles had been machined from A508-Class 2 steel forgings and welded into the test vessels. Notches were then machined into the inner radii of the nozzles and were sharpened by fatigue in the location shown in Figure 1. Test vessel number IV-5 was then pressurized at 88°C (190°F), leading to the initiation of ductile tearing at the notch, followed by stable tearing until a through-wall leak occurred. The second vessel considered here, No. IV-9, was pressurized at 24°C (75°F) and failed by fast fracture instability, preceded by a small amount of ductile tearing. Indeed, the nozzle of this vessel fragmented, forming missiles *[1]*.

The analysis of the IV-5 failure would be appropriate for the beginning of a postulated over-cooling transient scenario for a reactor vessel when cold

---

[2]The Italic numbers in brackets refer to the list of references appended to this paper.

fill water subjects the inner wall of the nozzle to tension prior to cooling of the material at the crack front. The objective of such analysis would be to demonstrate the safety margin on ductile tearing penetration of the pressure boundary. The analysis of the IV-9 failure would apply to the same type of transient, but at a somewhat later time when the cold fill water has cooled the material somewhat at the postulated crack front. This threat may be of somewhat greater concern, since cooler temperatures tend to provide more devastating consequences due to decreased fracture toughness and enhanced probability of sudden and complete fracture instability.

Both analyses require the J-integral characterization of the nozzle materials. Toward that end, remnant pieces from the nozzles were shipped for the present tests to the Knolls Atomic Power Laboratory. J-integral tests were performed on specimens from both IV-5 and IV-9, together with supplementary tensile, Charpy, and dynamic modulus tests.

EXPERIMENTAL PROCEDURES

The nozzles for both IV-5 and IV-9 were forged from A508-Class 2 steel with the major forging axis (axis of extension during forging) oriented parallel to the axis of the nozzle. The nozzle was welded into the vessel according to the configuration given in Figure 1. The chemical analysis results shown in Table 1 were obtained on drillings taken at the Knolls Atomic Power Laboratory.

Compact tension specimens were machined from the nozzle material in the C-R orientation, Figure 2, according to ASTM Standard Terminology relating to Fracture Testing (E 616). This orientation supported characterization of the radial path of fracture resistance for the nozzle corner flaws in the IV-5 and -9 tests. Charpy and tensile specimens were similarly oriented.

The fracture toughness tests were conducted on 2T-C(T) specimens whose dimensions confromed with ASTM E 813. The specimens were precracked to a normalized crack length, a/W, of approximately 0.6. One precompression load application was used to facilitate initiation and precrack front straightness. The load level for precompression was selected to produce a specimen strength ratio of -0.65, based upon prior satisfactory experience with similar materials. The maximum precrack loads during precracking were maintained well below 0.4 P_L as defined in section 7.6.1 of ASTM E 813-89. Following precracking, the specimens were sidegrooved 20%, with a sidegroove angle and root radius in conformance with ASTM E 813-89. A strain-gaged clip gage, calibrated at each temperature of interest, was used for all precrack and test operations. These were mounted to give displacement measurements at the specimen load line.

Charpy V-notch, tensile, and dynamic modulus tests were performed on material machined from the IV-5 and IV-9 nozzles. A full set of 24 Charpy V-notch tests were performed on each nozzle to establish the transition temperatures and upped shelf energies in the vicinity of the nozzle inner radii. The Charpy V-notch tests were performed to the ASTM Test Methods for Notched Bar Impact Testing of Metallic Materials (E 23-86). The test temperatures were varied between-73 and +149°C (-100 and +300°F) for the IV-5 nozzle and between -73 and +260°C (-100 and +500°F) for the IV-9 nozzle. The tensile tests were performed on 0.357 inch diameter specimens according to ASTM Practice for Elevated Temperature Tension Tests of Metallic Materials (E 21). The test temperatures were 88°C (190°F) for IV-5 and 24°C (75°F) for IV-9. Dynamic modulus tests were performed on a 5/16 inch diameter x 5 inch long rod machined from the IV-5 nozzle. The tests were performed over a temperature range of 21 to 371°C (70 to 700°F) according to the technique of Spinner and Teft *[2]*.

The test procedure for upper shelf J-integral testing was in accordance with the ASTM E 813-89 single specimen technique for J_{Ic} tests with the exception that, when possible, testing was continued to crack extensions well beyond that required for J_{Ic} determination. This was done to develop J-resistance curve information per ASTM Test Method for Determining J-R Curves (E1152). Where possible, testing was continued until the estimated crack length reached the limit based on minimum remaining ligament as defined in E 1152-89, Section 9.3.2. This practice tended to produce E 813-89 Section 9.4.1.7 validity failures, as the allowable error is based on a percentage of Δa_{pmax}, while the definition of Δa_{pmax} in E 813-89 is smaller than the same quantity in E 1152-89.

The J-integral testing was performed on a closed-loop servo-hydraulic load frame. The test specimen, fixtures, and clip gage were all maintained at test temperature within a forced air oven. Specimen loading control, data acquisition, and data analysis were performed by a Fracture Technologies Associates (FTA) materials test computer system. Periodic unloadings approaching the lesser of 0.2 P_L or 50% of current load were performed at 0.25 mm (0.010 inch) increments of a/W increase. This increment, as will be discussed in following sections, proved to be too large and resulted in invalid J-resistance curve data spacing. Once this problem was identified, the increment was changed to a successful 0.050 mm (0.002 inches).

After testing, the specimens were heat tinted at 425°C to mark the crack fronts, chilled in liquid nitrogen, and rapidly loaded to complete fracture. Measurements of the fatigue precrack and ductile tearing crack lengths were then made using a traveling microscope.

RESULTS AND DISCUSSION

Supplemental Tests

The Charpy V-notch data[2] for the IV-5 nozzle are plotted in Figure 3, along with a hyperbolic tangent curve fit to the data through a program called IMPFIT. No HSST data were available for comparison. The upper shelf energy was 121J (88.7 ft-lb), and the 41J (30 ft-lb) transition temperature was 1°C (34°F). Charpy data for the IV-9 vessel are shown in Figure 4. HSST data were comparable to those obtained currently, including a 146J (107 ft-lb) upper shelf and a 41J (30 ft-lb) transition temperature of 0°C (31°F). The present tensile test results are shown in Table 2[2]. The dynamic modulus data yielded the equation shown in Table 3 by least squares fit.

[2] The data for the individual specimens are tabulated in Appendix I.

J-Integral Results for IV-5 Specimens

Specimens CA1-U7 and CA1-U8 produced valid tearing onset or J_{IC} data (Figures 5 and 6). Valid J_{IC} results of 124 kJ/m^2 (706 in-lb/in^2) and 160 kJ/m^2 (914 in-lb/in^2) were obtained in these two tests of the IV-5 nozzle steel.

The tearing resistance or J-R curves represent the material's resistance to ductile tearing over relatively longer crack extensions[2]. The tests are conducted to the requirements of E 1152, and the curves can be used to predict the conditions required for stable and unstable tearing. The E 1152 standard requires that the specimen thickness, B, and the remaining ligament, b, meet the following size requirement:

$$J < (B, b) \times (\text{flow stress}/20)$$

Failure to satisfy this rule indicates that plane strain conditions are not met. All of the J-Δa data points in these tests satisfied this requirement.

The J-Δa curves for the IV-5 nozzle forging at 88°C (190°F) are plotted together in Figure 6. This figure also shows a "best-fit" curve that was established by combining the data from the four tests, resulting in the expression shown in Table 4.

J-Integral Tests at 75°F for IV-9 Specimens

In the J-integral test of Specimen CA1-P8, the specimen failed by elastic-plastic fracture instability prior to reaching the 0.008 inch Δa_p line (Figure 7). As a result, the procedure for transition regime testing based on Section 9.7 of the ASTM E 24.08 Draft 7-5 Test Method for J-Integral Characterization of Fracture Toughness was adopted for two additional tests. In this procedure, specimen preparation and loading conditions are the same as for the upper shelf J-integral test, with the exception that no unloadings are performed. The specimens were loaded under constant displacement rate until failure. A single valued toughness, called J_{QC} is obtained as the fracture instability value of J. This procedure also required that the amount of crack extension be less than 0.2 mm (0.008 inches), and

---

[2]The data for the individual specimens are tabulated in Appendix I.

that plane strain conditions were satisfied. Data for crack extensions greater than 0.2 mm are called J_u values; these may be sensitive to specimen size and configuration.

The result from the three IV-9 samples were designated as J_U values, as summarized in Table 5. None of the tests met the plane strain requirements. Consequently, they are of questionable value in analyzing the failure of IV-9 in the HSST pressurization test.

Fracture Appearance and Microstructure

The ductile tearing surfaces of the J-integral test specimens from IV-5 were rough, as shown by the photographs in Figure 8. This photo, which was taken at a magnification of ≈ 1X, reveals that a very rough surface extends > 25 mm beyond the fatigue precrack. This is consistent with the large extent of ductile tearing in the tests in Figure 6. Surface roughness of this type is frequently caused by the wandering of the crack plane from one sulfide (or group of sulfides) to another.

The rough nature of the ductile tearing crack planes of the IV-5 specimens tested at 88°C was confirmed in Figure 9, a metallographic section through one of the fractures. This montage at a magnification of ≈ 50X, shows the transition from the fatigue precrack to the ductile tearing crack. The fatigue crack is flat, while the ductile tear wanders up and down. This view also shows apparent inclusions near the crack plane.

The existence of sulfides was confirmed through scanning electron microscopy (SEM) of the fracture surface. Figure 10 shows the transition from the fatigue precrack to the ductile surface at the mid-thickness of the specimen. The ductile tearing surface does appear to be formed predominantly by void coalescence with some deep pockets (the dark regions) and some high points (the brighter regions). There are also numerous narrow troughs, which appear to be shaped by the presence of sulfides, scattered evenly over the surface. Some of these troughs suggest triple-point shapes - points where three grains come together. The concentrated nature of the distribution of sulfides over the tearing surface is shown in Figure 11.

Comparisons with Original Fracture Toughness Data

The fracture toughness data obtained in the original HSST program were interpreted in terms of equivalent energy *[1]* which purported to provide a lower bound value, K_{Icd}, associated with the maximum load. For IV-5 at 90°C (200°F), the average value of K_{Icd} was 216 MPa$\sqrt{m}$ (196 ksi$\sqrt{in}$) with a standard error of 0.18 for two 2T-C(T) and three 0.85T-C(T) radially oriented specimens. For comparison, the average of two $\sqrt{(EJ_{IC})}$ values at 88°C (190°F) for the current data was 171 MPa$\sqrt{m}$ (156 ksi$\sqrt{in}$) with a standard error of 0.09 for two 2T-C(T) specimens described earlier. Although both the original and current data came from specimens that gave ductile tearing responses, the current values correspond to tearing onset, which occurred prior to the attainment of maximum load. The maximum load points used in the earlier tests were undoubtedly beyond the point of tearing onset. Consequently, the higher toughness numbers for these tests are to be expected.

For IV-9 at 24°C (75°F), the average value of K_{Icd} was 214 MPa$\sqrt{m}$ (194 ksi$\sqrt{in}$) with a standard error of 0.21 for two 2T-C(T), two 1.5T-C(T) and four 0.85T-C(T) surface and center region specimens. For comparison, the average of three $\sqrt{(EJ_u)}$ values at 24°F (75°F) for the current data was 208 MPa$\sqrt{m}$ (189 ksi$\sqrt{in}$) with a standard error of 0.21.

Effect of Current Data on Original Failure Pressure Estimates

A variety of failure pressure estimating techniques was used in the original report on IV's 5 and 9 *[1]*. Those that used fracture mechanics based methods tended to under-predict the failure pressure. (Recall that the capability to analyze elastic-plastic flaws in arbitrary geometries did not exist at the time of the original studies.) Since the single point value of fracture toughness for the current IV-5 data corresponds to tearing onset rather than failure, the current data cannot be readily applied to the originial prediction methods, all of which used the maximum observed value of K_{Icd}, 265 MPa$\sqrt{m}$ (241 ksi$\sqrt{in}$).

Given that the initial flaws for IV-5 and IV-9 had about the same dimensions, the failure estimate for IV-9 using a lower bound K_{Icd} fracture toughness within a few percent of the average $\sqrt{}$ (EJ) value for IV-5 was found to correspond closely to the tearing onset pressure for IV-5. The original analysis method for IV-5 was called linear elastic fracture mechanics based on strain *[1]*. A failure pressure of 128 MPa (18.6 ksi) was reported for an assumed lower bound K value of 165 MPa$\sqrt{m}$ (150 Ksi$\sqrt{in}$). The average $\sqrt{(EJ)}$ value was 171 MPa$\sqrt{m}$ (156 ksi$\sqrt{in}$) which, using the original analysis method, would correspond to about the same pressure, 128 MPa, due to the non-linear relationship between nozzle corner strain and pressure. The experimental value of pressure at tearing onset for IV-5 was 124 MPa (18 ksi). Therefore, this analysis technique appears to have been appropriate for a tearing onset pressure estimate for IV-5.

Since the average values of the K_{Icd} from the HSST program and $\sqrt{(EJ_u)}$ values from the present work for IV-9 were about the same, using either data set in the original calculations would yield the same estimates of failure pressure, which were conservative.

CONCLUSIONS

1. The J-integral specimens from the IV-5 nozzle tested at 88°C (190°F) failed by ductile initiation and tearing, which is consistent with the failure of the IV-5 nozzle itself in the original HSST pressurization test.

2. Valid J_{IC} results of 124 kJ/m^2 (706 in-lb/in^2) and 160 kJ/m^2 (914 in-lb/in^2) were obtained at 88°C (190°F) for the IV-5 nozzle steel.

3. Charpy tests of the remnant IV-5 nozzle material near the J-integral specimens yielded a 41J (30 ft-lb) transition temperature, NDT_{30}, of 36°F and an upper shelf energy of 121J (88.7 ft-lb). This transition temperature indicates that the 88°C (190°F) temperature of the ORNL pressurization test was marginally close to being in the transition regime.

4. The J-integral tests of the IV-9 nozzle steel specimens did not produce valid J_{IC} data at 24°C (75°F) since they failed by elastic-plastic fracture instability. This is consistent with the failure of the IV-9 nozzle by sudden, catastrophic fracture instability after about 12 mm of stable tearing crack extension.

5. The Charpy tests of the IV-9 nozzle material yielded a 41J (30 ft-lb) transition temperature of 31°F and an upper shelf energy of 146J (108 ft-lb). This indicates that the 24°C (75°F) temperature of the HSST pressurization test was clearly in the midst of the transition regime, consistent with the lack of sufficient ductility to support valid J-integral tests.

6. J-integral tests of the IV-9 nozzle steel produced J_u results and at 24°C (75°F). However, these tests did not satisfy the plane strain requirements of the ASTM E 24.08 Draft 7-5 Test Method for J-Integral Characterization of Fracture Toughness.

REFERENCES:

1. JG Merkle, PP Holz, GC Robinson, and JE Smith, "Test of 6-inch Thick Pressure Vessels. Series 4: Intermediate Test Vessels V-5 and V-9 with Inside Nozzle Corner Cracks", HSST-TR-43, ORNL/NUREG-7, August, 1977.

2. S. Spinner and WE Teft, "A Method for Determining Mechanical Resonance Frequencies and Calculating Elastic Moduli from these Frequencies", ASTM Proceedings, Vol. 61, 1961, pp. 1221-1238.

3. RH Bryan, et al, "Test of 6-in. Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-8A, Tearing Behavior of Low-Upper-Shelf Material", NUREG/CR-4760, ORNL-6187, May 1987.

4 WG Reuter, JC Newman, Jr., BD Macdonald, and SR Powell, "Fracture Criteria for Surface Cracks in Brittle Materials", 24th ASTM Fracture Symposium, Gatlinburg, TN, June 1992.

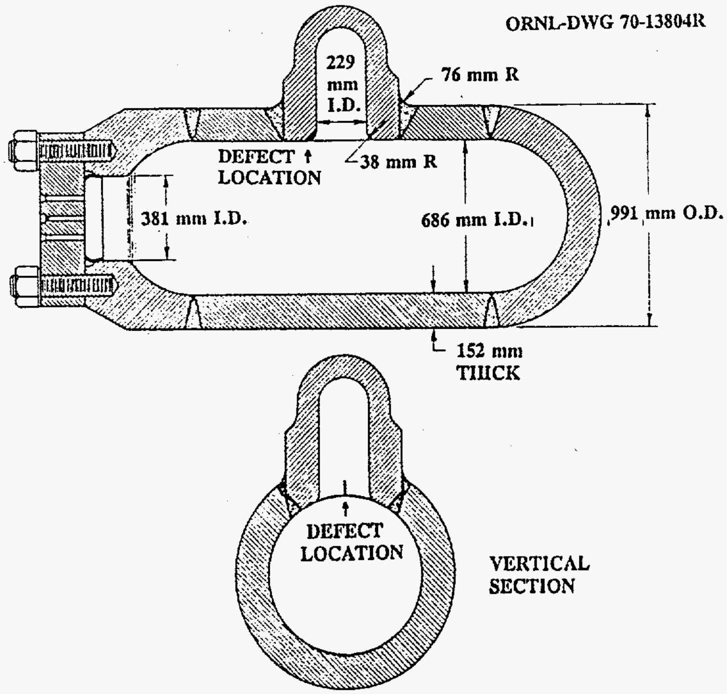

Figure 1--Longitudinal and transverse cross-sections through an intermediate test vessel with a 229 mm (9 inch) inside diameter nozzle (taken from Reference 1).

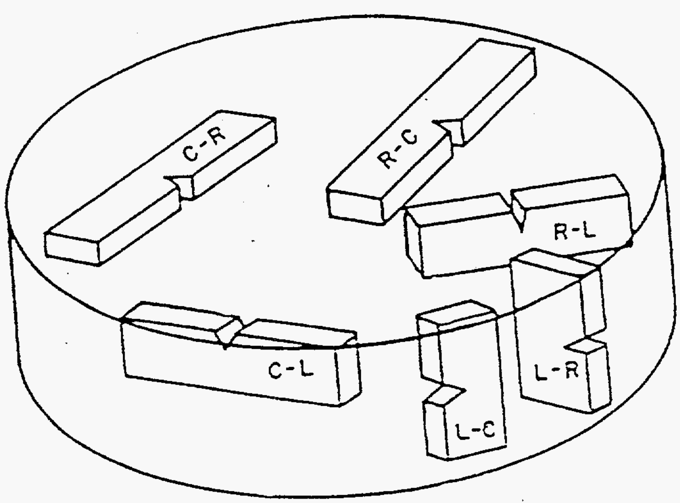

Figure 2--Crack plane orientation code for bar and hollow cylinders.

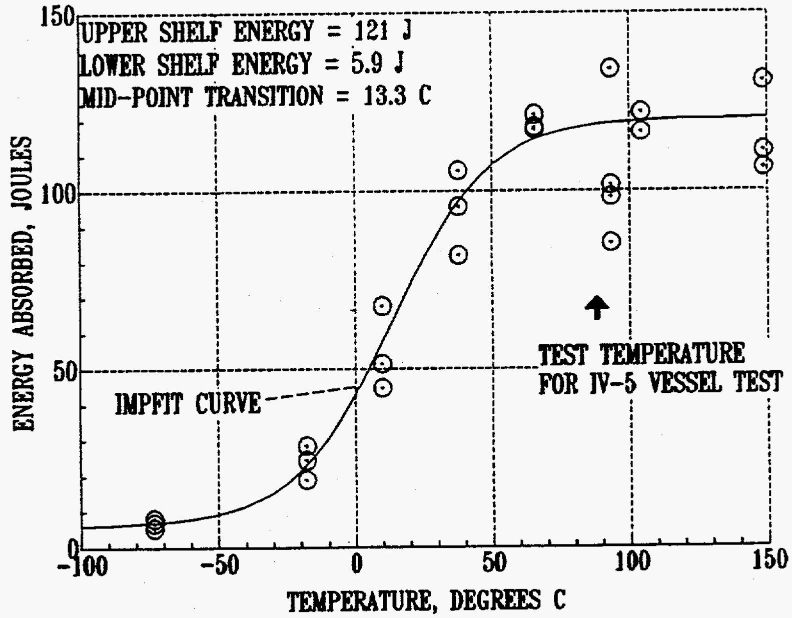

Figure 3--Charpy data for the IV-5 nozzle material shown with the IMPFIT transition curve.

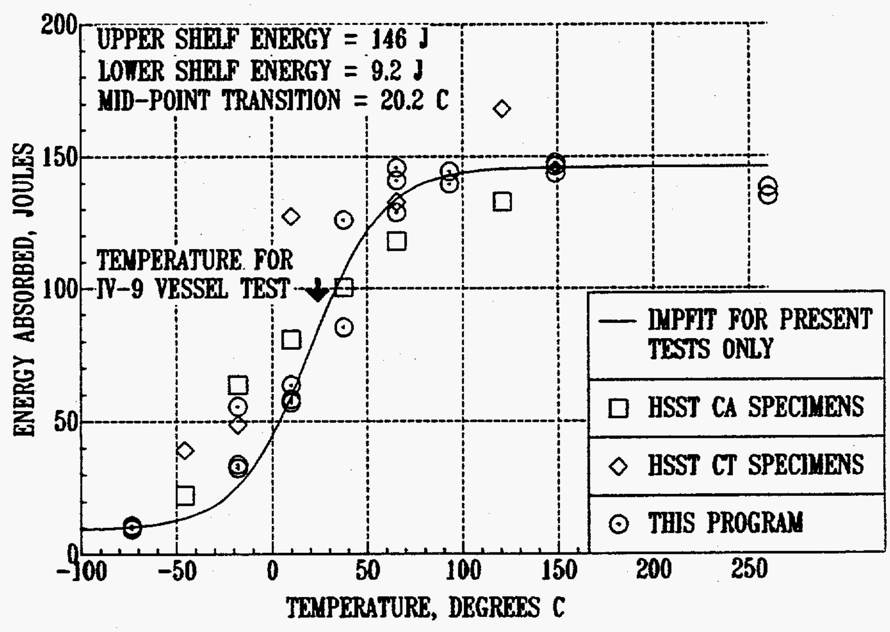

Figure 4--Charpy impact test results for the IV-9 nozzle material from the present study shown with the curve generated by the IMPFIT program. Also shown (as circles and diamonds) are the results from the prolongation of this forging as given in Table 2.4 of Reference 1.

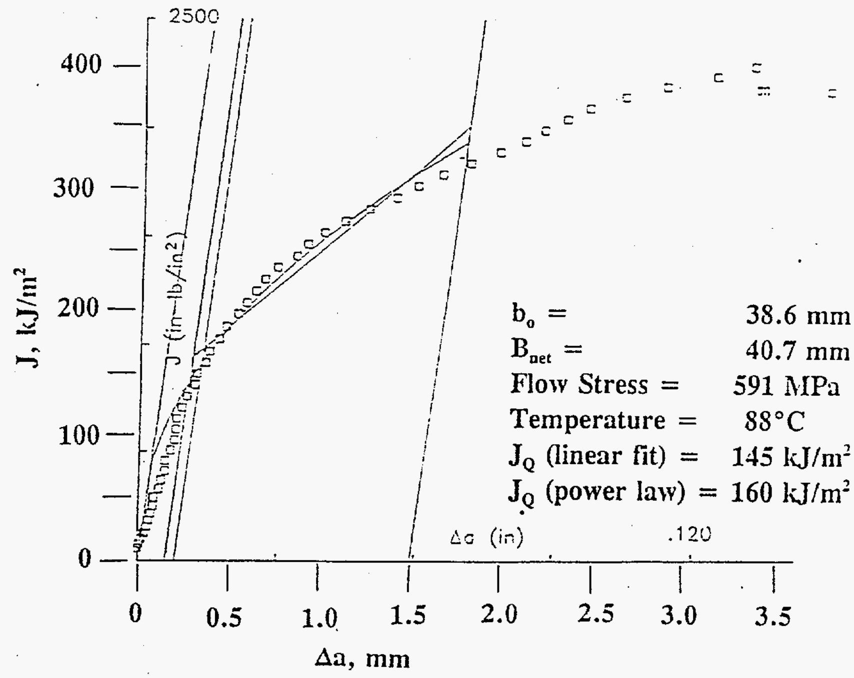

Figure 5--J-R curve at 88°C (190°F) for Specimen CA1-U7, showing exclusion lines.

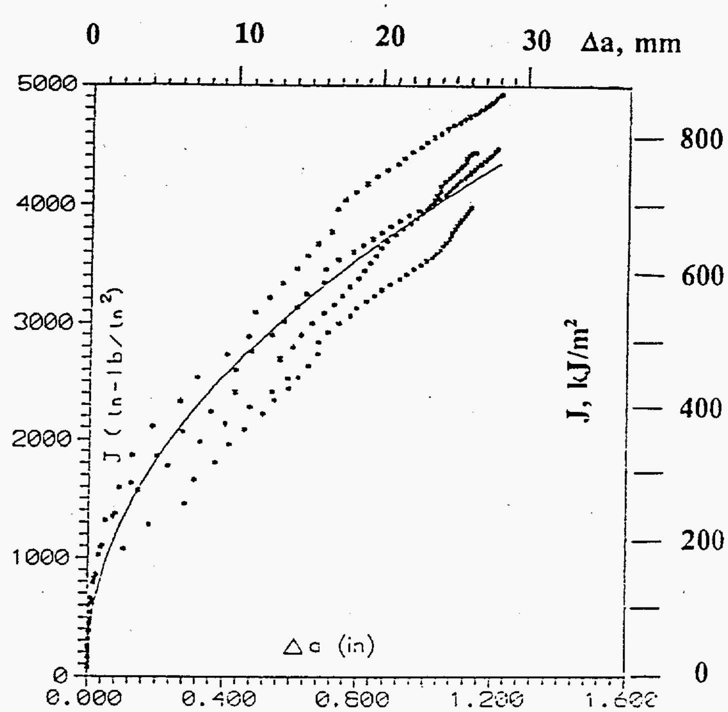

Figure 6--The best-fit J-resistance curve plotted against the data for Specimens CA1-N7, CA1-N8, CA1-P3, and CA1-P4 from the nozzle of IV-5 tested at 88°C (190°F).

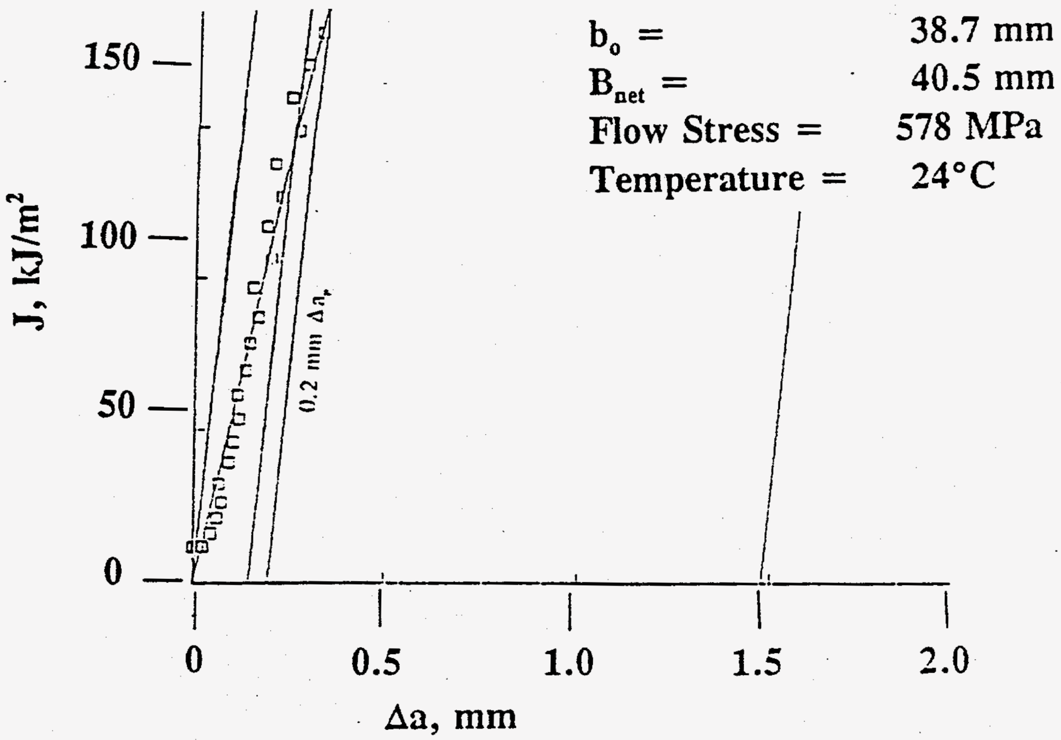

Figure 7--J-R curve at 75°F for Specimen CA1-P8 from the nozzle of IV-9 from the Oak Ridge National Laboratory. No valid J_{IC} results were obtained since the distribution of the data did not meet the ASTM E 813 requirements.

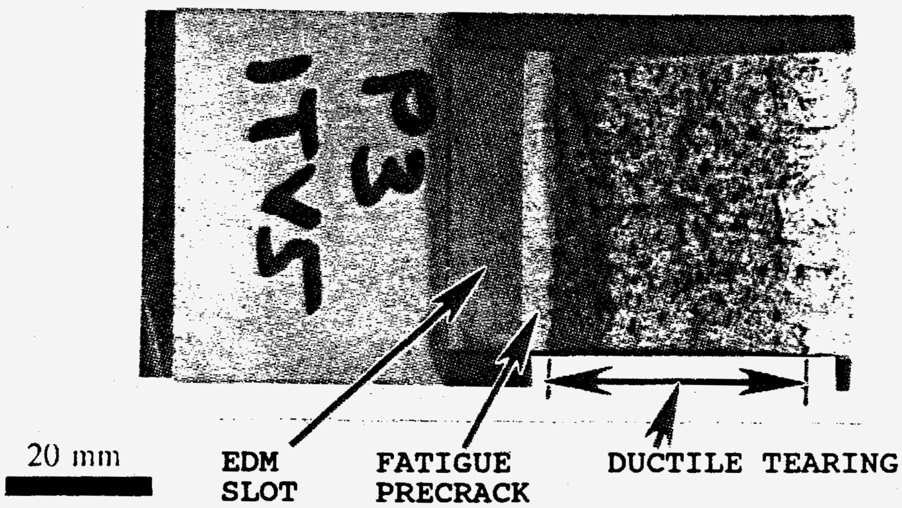

Figure 8--Macrophotograph of the fracture surface of Specimen CA1-P3 from the IV-5 nozzle. CA1-P3 had about 25 mm inch of ductile tearing crack extension, which was typical of the four tests that supported the J-resistance curve plots in Figure 6.

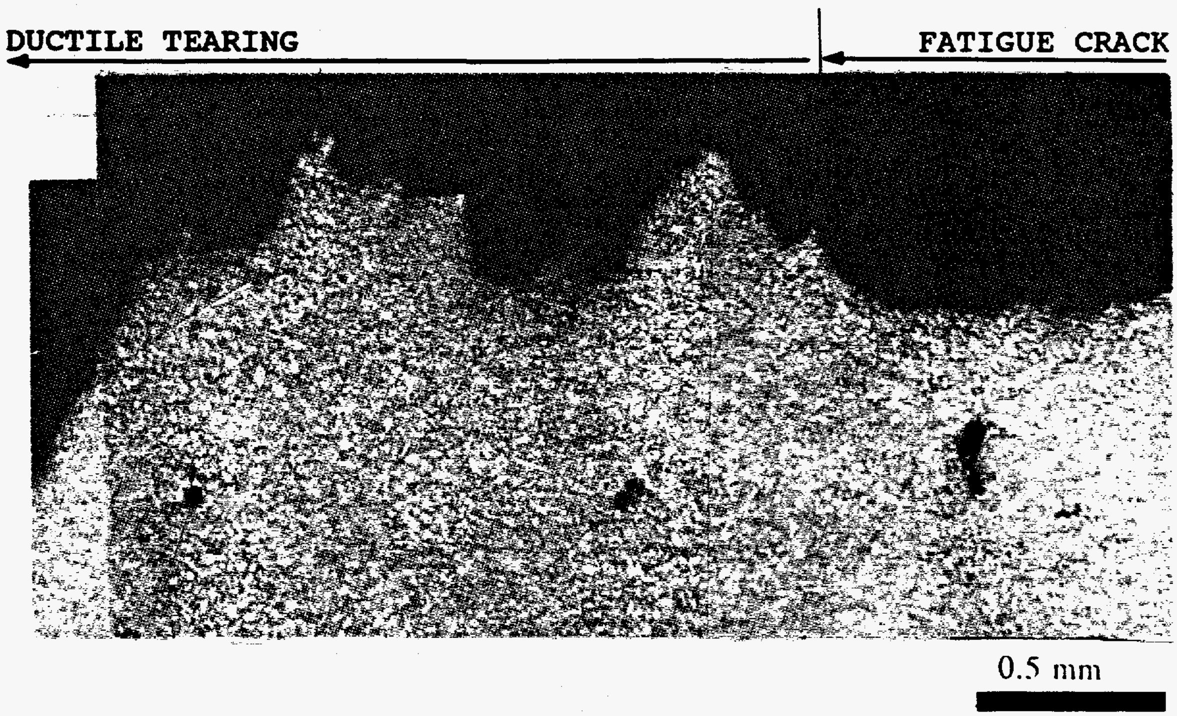

Figure 9--Optical micrograph of the metallographic section through the fatigue precrack and the initial ductile tearing section of the fracture of specimen CA1-N7 of the nozzle of vessel IV-5. Note the presence of some large inclusions and the articulated nature of the ductile tearing region. 5% Nital etch.

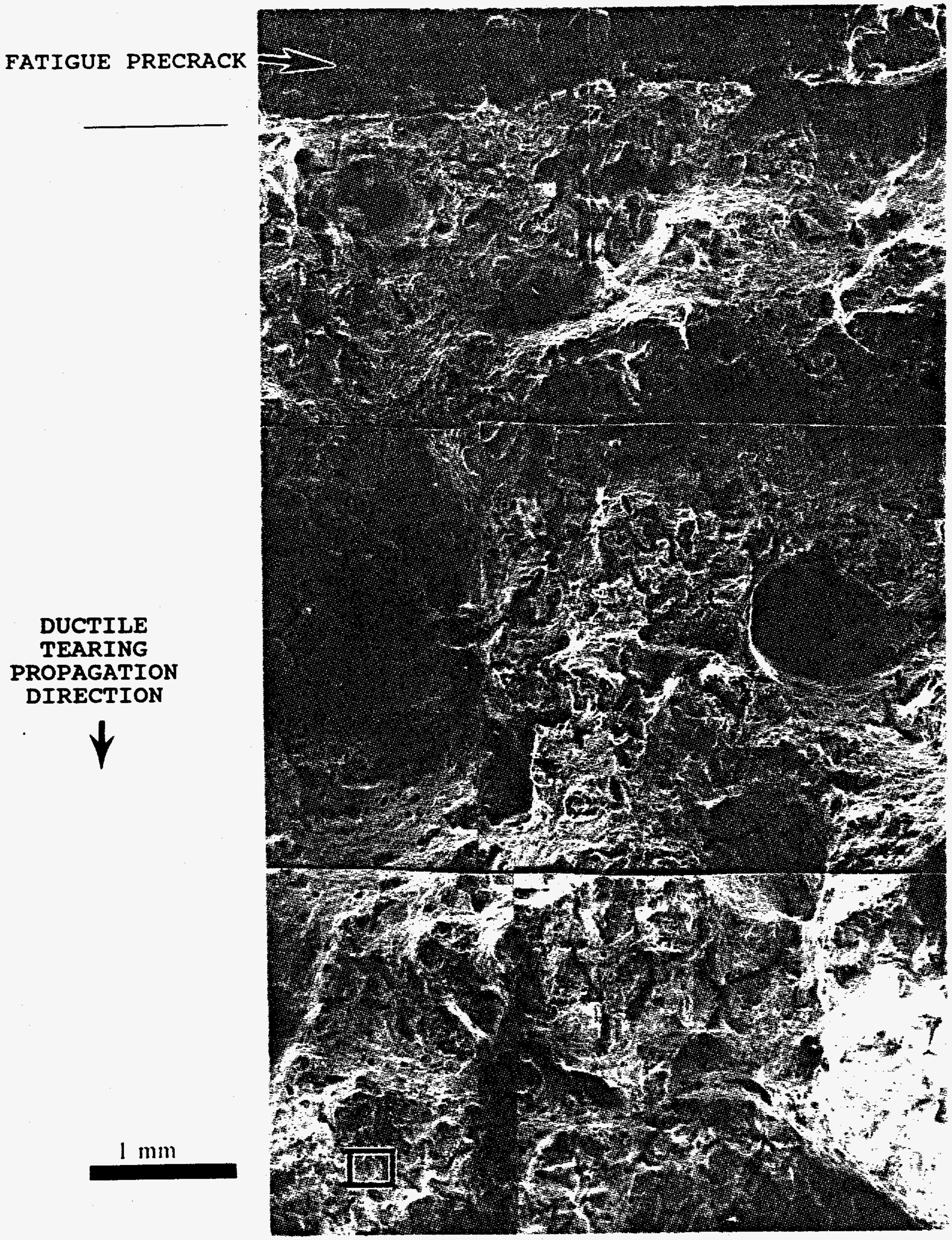

Figure 10--Scanning electron micrograph (SEM) of the mid-thickness region of the fracture surface of specimen CA1-P3 from the IV-5 nozzle.

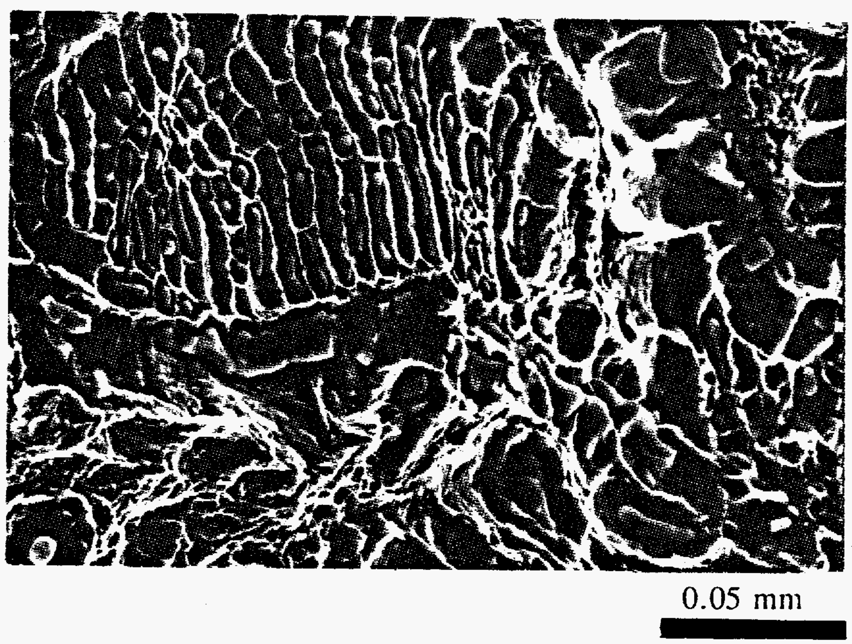

Figure 11--SEM of the region outlined in Figure 10, revealing numerous MnS inclusions.

TABLE 1--Chemical check analysis and the ASTM A508-2 specification limits.

Nozzle	C	Mn	P	S	Si	Ni
IV-5	0.208	0.72	0.012	0.0165	0.24	0.85
IV-9	0.191	0.70	0.014	0.0080	0.21	0.79
A508-2	0.27 max.	0.50 to 1.00	0.025 max.	0.025 max.	0.15 to 0.40	0.50 to 1.00

Nozzle	Mo	Cr	Cu	Co	V
IV-5	0.68	0.27	0.89	0.013	0.054
IV-9	0.65	0.34	0.121	0.009	0.013
A508-2	0.55 to 0.70	0.25 to 0.45	--	--	0.05 max.

TABLE 2--Tensile test results for the nozzle material from the Oak Ridge National Laboratory intermediate test vessels IV-5 and IV-9. The test temperatures were those used for the vessel tests, and the specimens had circumferential orientations.

Nozzle	Test Temperature °C	0.2% Yield Strength, MPa	Tensile Strength MPa	Reduction in Area, %
IV-5	88	516	632	40.4
	88	551	664	33.8
IV-9	24	512	627	60.9
	24	542	631	59.4

TABLE 3--Least squares fit lines for dynamic modulus test data for the ASTM A508-Class 2 nozzle from IV-5.

$$E = m \times T + b$$

PARAMETER	E	m	T	b
Metric	GPa	-7.03 E-2	°C	214
English	ksi	-5.66	°F	31,200

TABLE 4--Best fit J-R curve expression for IV-5 data tested at 88°C (190°F)

$$J = C\,(\Delta a/k)^m$$

PARAMETER	J	C	Δa	k	m
Metric	kJ/m^2	690.7	mm	25.4	0.473
English	$in\text{-}lb/in^2$	3944	inches	1.0	0.473

TABLE 5--J_u (Fracture Instability) Test Data from the Nozzle of IV-9 Tested at 24°C (75°F). All specimens had CR orientations shown in Figure 2. Plane strain requirements were not satisfied.

SPECIMEN NUMBER	SIZE	J_u $in\text{-}lbs/in^2$	J_u kJ/m^2
CA1-P6	2T	981	172
CA1-P7	2T	1760	309
CA1-P8	2T	827	145

APPENDIX I

Data Reports for individual specimens for the J-Integral and supporting mechanical tests. The compliance-adjusted data in Tables VIIb, VIIIb, IXb and Xb were determined based on procedures presented in Appendix II.

TABLE I. Tensile Test Results for the Nozzle Material from the Oak Ridge National Laboratory Intermediate Test Vessels IV-5 and IV-9. The test temperatures were those used for the vessel tests, and the specimens had circumferential orientations.

VESSEL	Specimen Number	Test Temp. °F	0.2% Yield Strength, ksi	Tensile Strength ksi	Reduction in Area, %
IV-5	CA1-I4 CA1-I5	190 190	74.9 79.9	91.6 96.3	40.4 33.8
IV-9	CA1-I8 CA1-I9	75 75	74.2 78.6	90.9 91.5	60.9 59.4

TABLE II. Least Squares Fit Lines for Dynamic Modulus Test Data for the ASTM A508-Class 2 Nozzle from IV-5.

MATERIAL	SPECIMEN NUMBER	MODULUS EQUATION* m b
ORNL Test Vessel 5	IV-5B	-5.663E-3(T) + 31.1480

* Where E = m x (T) + b, in units of mega-psi.

T = temperature in degrees F

TABLE III. Charpy Impact Test Results for Specimens from the Nozzle of IV-5. The specimens had "CT" orientations as shown in Figure 5.

SPECIMEN NO.	TEST TEMPERATURE °F	ENERGY ABSORBED, ft-lb	% SHEAR	LATERAL EXPANSION (MILS)
CA1-A1	-100	6	0	4.0
CA1-A2	-100	4	0	3.0
CA1-A3	-100	5	0	2.0
CA1-79	0	18	18	17.0
CA1-80	0	14	18	13.0
CA1-81	0	21	13	19.0
CA1-82	50	50	54	40.5
CA1-83	50	33	45	31.0
CA1-84	50	38	40	35.0
CA1-85	100	78	77	57.0
CA1-86	100	70.5	68	54.0
CA1-87	100	60.5	68	48.5
CA1-88	150	89.5	100	63.0
CA1-89	150	86.5	100	63.5
CA1-90	150	87	100	61.0
CA1-91	200	75	100	61.0
CA1-92	200	72.5	100	62.5
CA1-93	200	99	100	72.5
CA1-94	300	96.5	100	69.0
CA1-95	300	78.5	100	60.5
CA1-96	300	82	100	67.0
CA1-97	200	63	100	53.5
CA1-98	220	86	100	69.0
CA1-99	220	90	100	69.5

IMPFIT Results: NDT_{30} = 36°F
RTT = 96°F
Upper Shelf Energy = 88.7 ft-lb

TABLE IV. Charpy Impact Test Results for Specimens from the Nozzle of IV-9. All specimens had "CT" orientations as shown in Figure 5.

SPECIMEN NO.	TEST TEMPERATURE °F	ENERGY ABSORBED, ft-lb	% SHEAR	LATERAL EXPANSION (MILS)
CA1-F7	-100	7.5	9	6.0
CA1-F8	-100	7	9	7.0
CA1-F9	-100	8	9	6.5
CA1-G1	0	25	10	21.0
CA1-G2	0	24	10	20.0
CA1-G3	0	41	14	32.0
CA1-S7	50	47	27	39.0
CA1-S8	50	43	25	36.0
CA1-S9	50	42	27	35.0
CA1-T1	100	93	86	71.0
CA1-T2	100	63	59	50.0
CA1-T3	100	63	69	50.0
CA1-T4	150	95	92	66.0
CA1-T5	150	107.5	100	73.0
CA1-T6	150	104	100	70.0
CA1-T7	200	106.5	100	64.0
CA1-T8	200	103	100	72.5
CA1-T9	200	106.5	100	74.0
CA1-U1	300	108	100	67.0
CA1-U2	300	106	100	71.0
CA1-U3	300	109	100	72.0
CA1-U4	200	102	100	59.0
CA1-U5	220	102	100	61.0
CA1-U6	220	99.5	100	61.0

IMPFIT Results: NDT_{30} = 31°F
RTT = 91°F
Upper Shelf Energy = 107.6 ft-lb

TABLE V. J_{IC} (Tearing Onset) Data from the Nozzle of IV-5. All specimens had orientations analogous to the "CT" orienation shown in Figure 5. Note that Excess Temperature = T - (NDT_{30} + 60°F)

SPECIMEN NUMBER / SIZE	TEMPERATURE, °F ACTUAL	EXCESS	UNADJUSTED J_{IC} lbs/in	J_{IC}^* lbs/in	$K(J_{IC})^@$ ksi√inch
CA1-N7 / 2T	190	94	0★	-	-
CA1-N8 / 2T	190	94	0★	-	-
CA1-P3 / 2T	190	94	0⊠	-	-
CA1-P4 / 2T	190	94	0★	-	-
CA1-U7 / 2T	190	94	914	(914)	174
	190	94	706	(706)	152
CA1-U8 / 2T					

* J_{IC}^* results were determined with compliance-adjusted J-Δa data, except for those values given in brackets. The values in brackets were not adjusted; however, since there was no positive or negative offset of the displacement at the start of the test, the procedure would not change the result.

@ $K(J_{IC}) = (E' \times J_{IC}^*)^{0.5}$ in ksi√inch, where $E' = E/(1 - \nu^2)$.
E = Young's Modulus and ν = Poisson's Ratio

★ Invalid per ASTM E 813; Insufficient data points between exclusion lines.

⊠ Error in the estimate of Δa from compliance was too large.

TABLE VI. J_{IC} (Tearing Onset) Test Data from the Nozzle of IV-9. All specimens had orientations analogous to the "CT" orienation for Charpy bars shown in Figure 5. Note that Excess Temperature = T - (NDT_{30} + 60°F)

SPECIMEN NUMBER / SIZE	TEMPERATURE, °F ACTUAL	EXCESS	UNADJUSTED J_{IC} lbs/in	J_{IC}^{*} lbs/in	$K(J_q)^{@}$ ksi√inch
CA1-P6 / 2T	75	-16	-	-	182†♦
CA1-P7 / 2T	75	-16	-	-	244†♦
CA1-P8 / 2T	75	-16	-	-	167†♦

* J_{IC}^{*} results were determined with compliance-adjusted J-Δa data.

@ $K(J_{IC}) = (E' \times J_{IC}^{*})^{0.5}$ in ksi√inch, where $E' = E/(1 - \nu^2)$.

E = Young's Modulus and ν = Poisson's Ratio

† RTT test result based on Annex B3 in ASTM Standard E-813-91.

♦ Does NOT Satisfy B_{GROSS}, $b_o > 200 \cdot J_c/\sigma_o$.

Table VIIa. The raw load-displacement for the J-integral test of specimen CA1-N7, showing each unloading step. See the "Comments" in Table VIIc on the missing unloadings (Nos. 33 through 47).

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000		0	0	0	0
1	13068	0.0149	0.0000	0.0006	1.111989E-06	87	84	84	84
2	13117	0.0149	0.0040	0.0006	1.118655E-06	87	84	84	84
3	12946	0.0147	0.0012	0.0006	1.113987E-06	84	82	82	82
4	12750	0.0147	-.0006	0.0006	1.111076E-06	84	82	82	82
5	13019	0.0147	-.0023	0.0006	1.108168E-06	85	82	82	82
6	13214	0.0151	0.0030	0.0006	1.116961E-06	89	86	86	86
7	13361	0.0151	0.0017	0.0006	1.114751E-06	89	86	86	86
8	13459	0.0154	-.0002	0.0007	1.111658E-06	93	90	90	90
9	13630	0.0156	0.0029	0.0007	1.116796E-06	95	92	92	92
10	15608	0.0181	0.0032	0.0009	1.117055E-06	128	123	124	124
11	17611	0.0205	0.0007	0.0012	1.112732E-06	163	158	159	158
12	19565	0.0232	0.0055	0.0015	1.120458E-06	207	200	201	201
13	21568	0.0264	0.0019	0.0020	1.114088E-06	267	259	260	260
14	23547	0.0298	0.0033	0.0026	1.116171E-06	335	325	326	326
15	25525	0.0335	0.0041	0.0032	1.117206E-06	416	404	405	406
16	27455	0.0379	0.0099	0.0040	1.126555E-06	518	502	505	506
17	29384	0.0435	0.0151	0.0052	1.1349E-06	658	638	644	645
18	31339	0.0511	0.0185	0.0067	1.140043E-06	864	838	847	849
19	32438	0.0611	0.0379	0.0089	1.173183E-06	1135	1103	1115	1126
20	31900	0.0711	0.0717	0.0112	1.235E-06	1393	1360	1370	1402
21	29091	0.0811	0.1434	0.0135	1.383037E-06	1581	1582	1556	1651
22	26014	0.0918	0.2319	0.0162	1.602687E-06	1728	1791	1702	1895
23	21593	0.1026	0.3281	0.0190	1.901006E-06	1819	1993	1795	2117
24	19394	0.1126	0.4032	0.0215	2.190948E-06	1897	2147	1873	2309
25	17025	0.1226	0.4742	0.0240	2.526637E-06	1956	2295	1933	2491
26	15486	0.1329	0.5397	0.0265	2.904152E-06	2010	2422	1987	2668
27	14533	0.1429	0.5878	0.0289	3.234708E-06	2087	2537	2064	2840
28	13483	0.1529	0.5625	0.0313	3.05203E-06	2345	2703	2326	3049
29	12726	0.1629	0.6000	0.0336	3.323164E-06	2411	2807	2392	3210
30	11993	0.1727	0.6257	0.0360	3.529503E-06	2501	2911	2482	3369
31	11187	0.1827	0.6584	0.0383	3.819474E-06	2559	3008	2540	3521
32	10552	0.1927	0.6931	0.0407	4.166557E-06	2599	3094	2579	3667
48	9648	0.2005	0.7246	0.0426	4.522539E-06	2606	3165	2586	3775
49	9306	0.2106	0.7492	0.0449	4.830049E-06	2666	3240	2646	3916
50	8818	0.2206	0.7713	0.0472	5.132072E-06	2728	3317	2707	4054
51	8305	0.2306	0.7979	0.0495	5.534768E-06	2762	3387	2741	4186
52	8012	0.2404	0.8153	0.0518	5.821606E-06	2826	3452	2805	4317
53	7670	0.2504	0.8331	0.0541	6.138319E-06	2886	3518	2864	4447
54	7401	0.2604	0.8502	0.0564	6.465208E-06	2944	3579	2921	4576
55	7010	0.2704	0.8655	0.0587	6.778501E-06	3004	3642	2981	4703
56	6619	0.2804	0.8820	0.0610	7.142722E-06	3050	3702	3028	4824
57	6204	0.2904	0.9063	0.0633	7.736137E-06	3046	3755	3024	4937
58	5813	0.3002	0.9271	0.0655	8.30002E-06	3052	3805	3029	5045
59	5447	0.3102	0.9506	0.0679	9.012657E-06	3037	3850	3014	5151
60	5227	0.3202	0.9674	0.0701	9.577227E-06	3055	3892	3032	5256

Table VIIa. (Continued) Raw load-displacement data for specimen CA1-N7.

Specimen Id. CA1N7

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
61	4983	0.3302	0.9841	0.0724	1.018694E-05	3070	3933	3046	5360
62	4812	0.3403	0.9971	0.0747	1.070193E-05	3103	3973	3079	5466
63	4641	0.3503	1.0100	0.0770	1.12506E-05	3132	4011	3107	5568
64	4519	0.3603	1.0206	0.0792	1.172991E-05	3173	4047	3147	5671
65	4421	0.3703	1.0280	0.0815	1.207967E-05	3232	4084	3206	5774
66	4250	0.3803	1.0388	0.0837	1.261814E-05	3265	4120	3239	5875
67	4152	0.3901	1.0391	0.0859	1.262966E-05	3365	4158	3340	5978
68	3933	0.3999	1.0519	0.0882	1.331794E-05	3372	4192	3346	6070
69	3786	0.4099	1.0639	0.0904	1.401852E-05	3381	4223	3355	6162
70	3615	0.4196	1.0745	0.0926	1.4679E-05	3395	4253	3369	6250
71	3444	0.4294	1.0873	0.0949	1.554398E-05	3387	4281	3361	6336
72	3346	0.4394	1.0971	0.0971	1.625369E-05	3402	4307	3376	6423
73	3224	0.4492	1.1050	0.0993	1.685617E-05	3428	4334	3402	6509
74	3127	0.4590	1.1144	0.1015	1.762081E-05	3438	4359	3412	6592
75	3004	0.4692	1.1172	0.1038	1.784686E-05	3506	4388	3480	6682
76	2907	0.4792	1.1246	0.1061	1.849459E-05	3527	4413	3501	6764
77	2785	0.4890	1.1335	0.1083	1.932154E-05	3531	4436	3505	6843
78	2223	0.4812	1.1443	0.1067	2.041995E-05	3374	4436	3351	6780

Table VIIb. Calculated data for the J-integral test of specimen CA1-N7 based on compliance-adjusted load-displacement data.

Specimen Id.	(C)CA1N7	Geometry	CT
Contract #	MCL 1559	Orientation	NA
Material	A508	Flow stress (ksi)	84.4
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.397

Specimen Dimensions (in)

Thickness	2.007	Notch depth	2.256
Net thickness	1.583	Gage length	0.249
Width	4.000	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.582 1.567 1.560 1.551 1.559 1.552 1.561 1.558 1.581

Final Ligament(s) (in)

0.381 0.332 0.400 0.434 0.419 0.429 0.428 0.411 0.387

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.407	Kmax (ksi sqr[in])	40.65

Test Parameters

Initial ligament (in)	1.561	J15limit	(in-lb/in^2)	8790
Final ligament	'' 0.404	J20limit	''	6592
Delta a (actual)	'' 1.157	J25limit	''	5274
Delta a (EvB/P)	'' 1.145	*JQ (813-81)	''	395
% of DAmax Obtained 395	1664.4	*JQ (813-81)(NV)	''	
Delta a error (%)	-1.0	*JQ (813-87)	''	0
Delta amax error (%)	-16.7	*JQ (813-87)(NV)	''	554
Compliance Adjustment	1.042			
CTODi (in)	0.0031	Tearing modulus		86.4

Comments * Computed from E813-87 form for J

Test Date - 10/2/90 - Operator DB / First with capacitors on FTA interf ace panel
Clip Gage - MTS S/N 540 .500 travel .25 GL Range 2
Fixtures - 0.25W 17-4 PH pinhole 0.1875W Vascomax pin
Unloadings 33-47 do not exist (unexplained apparent unloadings occured)
Validity Requirements Failures:
Improper data group for JIc (Sec 9.2.2)
Final delta a error > 15% of DAmax (Sec 9.4.1.7)

Table VIIIa. The raw load-displacement for the J-integral test of specimen CA1-N8, showing each unloading step.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	12897	0.0149	0.0000	0.0006	1.109797E-06	84	82	82	82
2	12872	0.0149	0.0009	0.0007	1.111369E-06	84	82	82	82
3	12848	0.0151	0.0010	0.0007	1.11149E-06	87	84	84	84
4	12995	0.0151	0.0010	0.0007	1.111383E-06	87	84	84	84
5	14973	0.0176	0.0016	0.0009	1.112268E-06	117	113	114	114
6	16976	0.0203	0.0068	0.0012	1.120622E-06	155	149	150	150
7	18979	0.0227	0.0041	0.0015	1.115875E-06	193	186	187	187
8	20958	0.0256	0.0029	0.0019	1.113646E-06	244	236	237	237
9	22887	0.0286	0.0036	0.0024	1.114505E-06	302	292	293	293
10	24866	0.0320	0.0074	0.0029	1.120617E-06	372	360	362	362
11	26844	0.0357	0.0065	0.0036	1.118796E-06	457	442	445	445
12	28798	0.0401	0.0108	0.0044	1.125618E-06	563	544	549	550
13	30728	0.0467	0.0173	0.0058	1.136066E-06	733	709	717	719
14	32364	0.0567	0.0371	0.0079	1.169837E-06	999	966	979	987
15	29116	0.0667	0.1159	0.0103	1.321856E-06	1199	1183	1177	1228
16	26698	0.0767	0.1891	0.0127	1.488651E-06	1375	1384	1351	1458
17	22765	0.0870	0.2927	0.0154	1.7801E-06	1479	1565	1456	1664
18	20225	0.0970	0.3199	0.0179	1.869068E-06	1665	1765	1644	1884
19	18857	0.1070	0.3833	0.0203	2.103379E-06	1763	1908	1741	2070
20	17391	0.1170	0.4230	0.0227	2.271714E-06	1892	2060	1871	2261
21	16439	0.1268	0.4679	0.0251	2.486219E-06	1990	2188	1968	2437
22	14362	0.1368	0.5204	0.0276	2.775427E-06	2055	2324	2034	2606
23	13483	0.1470	0.5536	0.0300	2.983278E-06	2154	2442	2132	2775
24	12750	0.1571	0.5971	0.0324	3.291933E-06	2210	2541	2189	2931
25	12189	0.1668	0.6248	0.0347	3.512037E-06	2298	2638	2276	3085
26	11529	0.1768	0.6549	0.0370	3.775393E-06	2374	2735	2352	3239
27	10625	0.1869	0.6832	0.0394	4.049285E-06	2446	2834	2424	3391
28	9868	0.1969	0.6835	0.0418	4.050246E-06	2598	2939	2578	3546
29	9135	0.2069	0.7122	0.0442	4.358839E-06	2638	3020	2617	3678
30	8354	0.2169	0.7457	0.0466	4.763342E-06	2647	3094	2627	3802
31	7743	0.2269	0.7796	0.0489	5.231164E-06	2643	3159	2623	3920
32	7303	0.2367	0.7968	0.0512	5.493298E-06	2697	3222	2677	4037
33	6742	0.2465	0.8262	0.0535	5.986886E-06	2691	3279	2671	4145
34	6522	0.2562	0.8500	0.0557	6.43542E-06	2702	3326	2682	4250
35	6229	0.2662	0.8712	0.0580	6.876511E-06	2724	3376	2703	4358
36	5862	0.2763	0.8963	0.0603	7.455709E-06	2722	3423	2701	4463
37	5398	0.2863	0.9238	0.0626	8.176055E-06	2699	3469	2679	4562
38	5129	0.2963	0.9433	0.0649	8.74562E-06	2711	3511	2690	4661
39	4787	0.3063	0.9638	0.0672	9.413723E-06	2710	3552	2689	4757
40	4543	0.3163	0.9845	0.0695	1.016009E-05	2703	3587	2681	4849
41	4372	0.3263	1.0010	0.0718	1.081617E-05	2714	3621	2692	4941
42	4201	0.3363	1.0185	0.0741	1.158341E-05	2716	3652	2693	5031
43	4079	0.3464	1.0298	0.0763	1.211729E-05	2751	3685	2728	5124
44	3981	0.3564	1.0421	0.0786	1.274484E-05	2776	3714	2753	5215
45	3884	0.3664	1.0489	0.0809	1.310325E-05	2833	3747	2810	5309

Table VIIIa. (Continued) Raw load-displacement data for specimen CA1-N8.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
46	3762	0.3766	1.0596	0.0832	1.37099E-05	2864	3777	2841	5401
47	3639	0.3869	1.0689	0.0855	1.426715E-05	2902	3808	2878	5494
48	3566	0.3967	1.0748	0.0877	1.463344E-05	2956	3837	2932	5582
49	3517	0.4067	1.0782	0.0899	1.484769E-05	3026	3866	3002	5674
50	3371	0.4167	1.0861	0.0922	1.537752E-05	3062	3895	3038	5761
51	3298	0.4267	1.0926	0.0944	1.582688E-05	3106	3922	3082	5847
52	3200	0.4367	1.1001	0.0967	1.637504E-05	3140	3948	3116	5932
53	3151	0.4468	1.1072	0.0990	1.692304E-05	3175	3972	3151	6017
54	3053	0.4568	1.1155	0.1012	1.759261E-05	3199	3997	3174	6100
55	3004	0.4668	1.1202	0.1035	1.798612E-05	3249	4021	3224	6184
56	2931	0.4766	1.1246	0.1057	1.83679E-05	3297	4046	3272	6266
57	2858	0.4868	1.1302	0.1080	1.886782E-05	3337	4070	3312	6349
58	2614	0.4844	1.1339	0.1075	1.922652E-05	3286	4072	3263	6329

Table VIIIb. Calculated data for the J-integral test of specimen CA1-N8 based on compliance-adjusted load-displacement data.

Specimen Id.	(C)CA1N8	Geometry	CT
Contract #	MCL 1559	Orientation	NA
Material	A508	Flow stress (ksi)	84.4
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.543

Specimen Dimensions (in)

Thickness	2.007	Notch depth	2.256
Net thickness	1.607	Gage length	0.249
Width	3.999	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.576 1.563 1.559 1.558 1.555 1.556 1.560 1.569 1.585

Final Ligament(s) (in)

0.370 0.406 0.449 0.466 0.469 0.431 0.402 0.378 0.388

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.425	Kmax (ksi sqr[in])	40.58

Test Parameters

Initial ligament (in)	1.563	J15limit	(in-lb/in^2)	8798
Final ligament ´´	0.422	J20limit	´´	6598
Delta a (actual) ´´	1.140	J25limit	´´	5279
Delta a (EvB/P) ´´	1.133	*JQ (813-81)	´´	0
% of DAmax Obtained	1932.6	*JQ (813-81)(NV)		
0				
Delta a error (%)	-0.6	*JQ (813-87)	´´	0
Delta amax error (%)	-12.4	*JQ (813-87)(NV)	´´	0
Compliance Adjustment	0.952			
CTODi (in)	0.0000	Tearing modulus		0.0

Comments * Computed from E813-87 form for J

Test Date - 10/3/90 - Operator DB
Clip Gage - MTS S/N 540 .500 travel .25 GL Range 2
Fixtures - 0.25W 17-4 PH pinhole 0.1875W Vascomax pin
Capacitors on FTA interface panel
Validity Requirements Failures:
Improper data group for JIc (Sec 9.2.2)
Less than 4 data pts for JIc fit (Sec 9.3.2)
Crk ext edge to ctr > 2% of W (sec 9.4.1.6)
Curve fit with less than two points

Table IXa. The raw load-displacement for the J-integral test of specimen CA1-P3, showing each unloading step.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	12970	0.0142	0.0000	0.0006	1.070495E-06	80	78	78	78
2	12799	0.0142	-.0034	0.0006	1.065134E-06	80	78	78	78
3	12702	0.0139	-.0004	0.0006	1.069918E-06	77	75	75	75
4	12775	0.0142	-.0001	0.0006	1.070269E-06	80	78	78	78
5	14753	0.0164	-.0002	0.0008	1.07001E-06	106	103	103	103
6	16756	0.0186	0.0004	0.0010	1.070781E-06	136	133	133	133
7	18686	0.0210	-.0010	0.0013	1.068365E-06	173	169	169	169
8	20664	0.0234	0.0014	0.0016	1.071949E-06	214	208	208	208
9	22643	0.0261	0.0005	0.0020	1.070189E-06	265	258	258	258
10	24573	0.0288	0.0015	0.0024	1.071628E-06	320	312	312	312
11	26502	0.0315	0.0025	0.0028	1.072987E-06	380	370	370	370
12	28481	0.0347	0.0027	0.0034	1.07302E-06	456	444	445	445
13	30484	0.0386	0.0078	0.0042	1.08078E-06	554	539	541	542
14	32462	0.0427	0.0110	0.0050	1.085608E-06	665	647	650	651
15	34367	0.0479	0.0142	0.0061	1.090231E-06	815	792	798	800
16	36297	0.0562	0.0279	0.0079	1.112138E-06	1062	1030	1041	1047
17	37152	0.0660	0.0471	0.0101	1.143834E-06	1361	1320	1337	1352
18	35613	0.0760	0.0869	0.0125	1.214787E-06	1636	1598	1609	1653
19	34441	0.0860	0.1241	0.0148	1.286672E-06	1900	1867	1870	1950
20	31803	0.0962	0.1826	0.0172	1.412737E-06	2110	2115	2078	2231
21	28065	0.1065	0.2652	0.0198	1.622427E-06	2237	2334	2205	2482
22	26160	0.1165	0.3156	0.0222	1.772334E-06	2401	2540	2368	2730
23	21837	0.1265	0.4040	0.0249	2.086639E-06	2429	2731	2399	2937
24	20127	0.1368	0.4671	0.0275	2.361161E-06	2504	2887	2473	3147
25	17220	0.1468	0.4867	0.0301	2.455951E-06	2673	3090	2646	3366
26	16146	0.1568	0.5280	0.0326	2.675819E-06	2748	3219	2721	3550
27	15169	0.1668	0.5670	0.0350	2.910201E-06	2818	3341	2790	3730
28	13947	0.1771	0.6114	0.0375	3.214692E-06	2859	3460	2832	3905
29	13141	0.1871	0.6426	0.0399	3.455864E-06	2930	3569	2903	4075
30	12286	0.1971	0.6743	0.0423	3.728815E-06	2987	3673	2960	4238
31	11187	0.2071	0.7132	0.0448	4.10744E-06	3000	3770	2974	4390
32	9648	0.2262	0.7322	0.0494	4.309607E-06	3222	3964	3198	4687
33	9038	0.2362	0.7558	0.0518	4.584462E-06	3259	4042	3235	4822
34	8622	0.2462	0.7864	0.0542	4.980951E-06	3254	4106	3230	4950
35	8012	0.2562	0.8194	0.0566	5.466054E-06	3229	4170	3205	5073
36	7450	0.2665	0.8496	0.0590	5.973119E-06	3213	4232	3188	5197
37	7035	0.2765	0.8809	0.0614	6.570754E-06	3179	4283	3154	5311
38	6497	0.2865	0.9113	0.0638	7.239753E-06	3141	4336	3116	5422
39	6204	0.2965	0.9312	0.0661	7.729596E-06	3155	4384	3130	5536
40	5691	0.3065	0.9535	0.0685	8.3375E-06	3148	4435	3123	5644

Table IXa. (Continued) Raw load-displacement data for specimen CA1-P3.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
41	5374	0.3166	0.9777	0.0709	9.078404E-06	3122	4476	3097	5747
42	5105	0.3266	0.9954	0.0732	9.679633E-06	3130	4517	3104	5850
43	4665	0.3366	1.0171	0.0756	1.049888E-05	3104	4558	3079	5947
44	4372	0.3466	1.0383	0.0779	1.140206E-05	3073	4592	3048	6039
45	3981	0.3566	1.0586	0.0803	1.237194E-05	3041	4628	3017	6128
46	3737	0.3666	1.0763	0.0826	1.331606E-05	3020	4658	2995	6214
47	3542	0.3766	1.0937	0.0849	1.435682E-05	2994	4684	2969	6298
48	3371	0.3864	1.1085	0.0872	1.532723E-05	2981	4709	2956	6379
49	3249	0.3964	1.1229	0.0895	1.636452E-05	2969	4731	2944	6460
50	3078	0.4064	1.1390	0.0918	1.765648E-05	2940	4754	2915	6539
51	3004	0.4165	1.1508	0.0941	1.869562E-05	2942	4774	2916	6619
52	2931	0.4265	1.1632	0.0964	1.988594E-05	2936	4794	2909	6699
53	2833	0.4365	1.1732	0.0987	2.092614E-05	2946	4815	2919	6779
54	2711	0.4465	1.1846	0.1010	2.22105E-05	2942	4835	2914	6857
55	2614	0.4565	1.1941	0.1033	2.335964E-05	2950	4855	2922	6936
56	2540	0.4665	1.2012	0.1056	2.427305E-05	2976	4875	2948	7015
57	2467	0.4766	1.2069	0.1080	2.504663E-05	3012	4895	2984	7095
58	2345	0.4866	1.2159	0.1103	2.63586E-05	3014	4914	2986	7170
59	2076	0.4831	1.2199	0.1095	2.698305E-05	2952	4918	2927	7143

Table IXb. Calculated data for the J-integral test of specimen CA1-P3 based on compliance-adjusted load-displacement data.

Specimen Id.	(C)CA1P3	Geometry	CT
Contract #	MCL 1559	Orientation	NA
Material	A508	Flow stress (ksi)	84.4
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.402

Specimen Dimensions (in)

Thickness	2.006	Notch depth	2.255
Net thickness	1.602	Gage length	0.249
Width	3.999	Alpha ratio	1.000
Pin spacing	3.001		

Initial Ligament(s) (in)

1.616	1.586	1.578	1.578	1.568	1.581	1.587	1.596	1.609

Final Ligament(s) (in)

0.187	0.341	0.355	0.352	0.415	0.334	0.322	0.363	0.437

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.423	Kmax (ksi sqr[in])	39.68

Test Parameters

Initial ligament (in)	1.586	J15limit (in-lb/in^2)	8928
Final ligament ʺ	0.349	J20limit ʺ	6696
Delta a (actual) ʺ	1.237	J25limit ʺ	5357
Delta a (EvB/P) ʺ	1.221	*JQ (813-81) ʺ	466
% of DAmax Obtained 466	1785.1	*JQ (813-81)(NV) ʺ	
Delta a error (%)	-1.2	*JQ (813-87) ʺ	611
Delta amax error (%)	-22.3	*JQ (813-87)(NV) ʺ	611
Compliance Adjustment	1.044		
CTODi (in)	0.0035	Tearing modulus	80.3

Comments * Computed from E813-87 form for J

Test Date - 10/4/90 - Operator DB
Clip Gage - MTS S/N 540 .500 travel .25 GL Range 2
Fixtures - 0.25W 17-4 PH pinhole 0.1875W Vascomax pin
Capacitors on FTA interface panel / Post Test crack length meas. on SEM
Validity Requirements Failures:
Crk ext edge to ctr > 2% of W (sec 9.4.1.6)
Final delta a error > 15% of DAmax (Sec 9.4.1.7)

Table Xa. The raw load-displacement for the J-integral test of specimen CA1-P4, showing each unloading step.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87	J1152	Jmod
							(in-lb/in^2)		
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	12750	0.0142	0.0000	0.0006	1.08655E-06	79	77	77	77
2	12555	0.0139	0.0033	0.0005	1.091975E-06	75	73	73	73
3	12457	0.0139	-.0009	0.0006	1.085116E-06	76	74	74	74
4	12384	0.0139	0.0027	0.0006	1.090928E-06	75	73	73	73
5	14338	0.0161	0.0006	0.0007	1.087276E-06	101	99	99	99
6	16194	0.0186	0.0021	0.0010	1.089512E-06	134	131	131	131
7	18124	0.0210	0.0034	0.0013	1.091469E-06	170	166	166	166
8	20029	0.0237	0.0030	0.0017	1.090567E-06	215	209	210	210
9	21959	0.0264	0.0031	0.0020	1.090506E-06	265	258	259	259
10	23840	0.0291	0.0042	0.0025	1.092058E-06	319	310	311	311
11	25769	0.0325	0.0067	0.0030	1.095899E-06	392	381	383	383
12	27675	0.0357	0.0075	0.0036	1.096938E-06	466	453	456	456
13	29604	0.0396	0.0096	0.0044	1.099892E-06	563	547	551	552
14	31534	0.0442	0.0080	0.0053	1.096889E-06	688	669	674	674
15	33439	0.0503	0.0184	0.0066	1.113639E-06	855	831	839	841
16	34880	0.0603	0.0390	0.0088	1.147869E-06	1140	1106	1120	1130
17	34685	0.0703	0.0769	0.0110	1.215583E-06	1410	1372	1387	1419
18	33195	0.0806	0.1230	0.0134	1.305679E-06	1668	1635	1642	1711
19	29482	0.0906	0.1994	0.0159	1.477783E-06	1839	1859	1811	1963
20	26136	0.1006	0.2731	0.0184	1.675634E-06	1977	2066	1949	2198
21	22912	0.1106	0.3588	0.0209	1.955435E-06	2053	2244	2026	2407
22	20689	0.1207	0.4295	0.0234	2.238693E-06	2137	2407	2110	2612
23	19272	0.1307	0.4316	0.0259	2.246968E-06	2366	2603	2341	2847
24	17660	0.1407	0.4761	0.0283	2.455956E-06	2463	2755	2439	3043
25	15413	0.1510	0.5372	0.0310	2.792165E-06	2493	2898	2469	3223
26	14680	0.1610	0.5726	0.0334	3.017334E-06	2579	3014	2555	3400
27	13385	0.1710	0.6124	0.0358	3.302803E-06	2636	3133	2613	3568
28	12408	0.1808	0.6405	0.0382	3.527462E-06	2715	3243	2692	3730
29	10870	0.1908	0.6926	0.0407	4.008781E-06	2690	3343	2667	3872
30	9795	0.2008	0.6981	0.0432	4.062337E-06	2824	3453	2804	4026
31	8745	0.2106	0.7359	0.0456	4.479235E-06	2812	3532	2792	4151
32	7767	0.2206	0.7811	0.0480	5.063657E-06	2755	3599	2736	4265
33	7401	0.2308	0.8096	0.0504	5.490293E-06	2764	3656	2744	4383
34	7059	0.2408	0.8386	0.0527	5.977556E-06	2762	3709	2742	4496
35	6717	0.2509	0.8661	0.0550	6.49906E-06	2763	3760	2743	4608
36	6326	0.2609	0.8916	0.0574	7.044398E-06	2765	3810	2745	4717
37	5862	0.2706	0.9179	0.0597	7.677477E-06	2752	3857	2732	4819
38	5447	0.2807	0.9447	0.0620	8.408811E-06	2733	3902	2712	4921
39	4910	0.2907	0.9753	0.0644	9.374625E-06	2683	3944	2663	5014
40	4690	0.3007	1.0014	0.0667	1.032962E-05	2650	3975	2629	5106

Table Xa. (Continued) Raw load-displacement data for specimen CA1-P4.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87	J1152	Jmod
							(in-lb/in^2)		
41	4519	0.3107	1.0195	0.0690	1.1072E-05	2658	4008	2637	5200
42	4250	0.3207	1.0370	0.0713	1.186796E-05	2664	4044	2642	5294
43	4079	0.3305	1.0536	0.0736	1.270134E-05	2668	4073	2646	5382
44	3933	0.3403	1.0644	0.0758	1.328135E-05	2703	4105	2681	5474
45	3786	0.3500	1.0745	0.0780	1.386396E-05	2738	4135	2715	5563
46	3664	0.3600	1.0861	0.0803	1.458188E-05	2762	4163	2738	5652
47	3517	0.3701	1.0975	0.0826	1.53363E-05	2785	4191	2762	5741
48	3322	0.3798	1.1118	0.0848	1.637013E-05	2780	4218	2757	5822
49	3224	0.3898	1.1230	0.0871	1.725146E-05	2796	4242	2772	5906
50	3151	0.3999	1.1316	0.0894	1.796948E-05	2828	4266	2804	5992
51	3029	0.4099	1.1425	0.0917	1.895075E-05	2840	4289	2815	6074
52	2931	0.4199	1.1509	0.0940	1.975288E-05	2867	4313	2842	6157
53	2809	0.4299	1.1617	0.0962	2.086511E-05	2873	4335	2848	6237
54	2711	0.4399	1.1714	0.0985	2.195007E-05	2884	4356	2858	6316
55	2614	0.4497	1.1796	0.1008	2.292602E-05	2902	4376	2876	6393
56	2540	0.4597	1.1881	0.1030	2.399581E-05	2917	4395	2891	6470
57	2467	0.4695	1.1952	0.1052	2.495315E-05	2939	4414	2913	6546
58	2418	0.4795	1.1999	0.1075	2.561431E-05	2981	4434	2955	6625
59	2320	0.4895	1.2061	0.1098	2.652218E-05	3008	4454	2982	6702
60	2076	0.4858	1.2095	0.1090	2.706055E-05	2950	4457	2926	6673

Table Xb. Calculated data for the J-integral test of specimen CA1-P4 based on compliance-adjusted load-displacement data.

Specimen Id.	(C)CA1P4	Geometry	CT
Contract #	MCL 1559	Orientation	NA
Material	A508	Flow stress (ksi)	84.4
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.405

Specimen Dimensions (in)

Thickness	2.006	Notch depth	2.257
Net thickness	1.605	Gage length	0.250
Width	4.000	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.582	1.574	1.568	1.569	1.568	1.570	1.576	1.581	1.597

Final Ligament(s) (in)

0.332	0.367	0.348	0.359	0.335	0.405	0.341	0.357	0.323

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.440	Kmax (ksi sqr[in])	40.14

Test Parameters

Initial Ligament (in)	1.575	J15limit (in-lb/in^2)	8865
Final ligament ʼʼ	0.355	J20limit ʼʼ	6649
Delta a (actual) ʼʼ	1.220	J25limit ʼʼ	5319
Delta a (EvB/P) ʼʼ	1.210	*JQ (813-81) ʼʼ	0
% of DAmax Obtained 382	1763.8	*JQ (813-81)(NV)	
Delta a error (%)	-0.8	*JQ (813-87) ʼʼ	0
Delta amax error (%)	-13.9	*JQ (813-87)(NV) ʼʼ	546
Compliance Adjustment	1.045		
CTODi (in)	0.0030	Tearing modulus	83.9

Comments * Computed from E813-87 form for J

Test Date - 10/8/90 - Operator DB/DWS
Clip Gage - MTS S/N 540 .500 travel .25 GL Range 1
Fixtures - 0.25W 17-4 PH pinhole 0.1875W Vascomax pin
Capacitors on FTA interface panel
Validity Requirements Failures:
Improper data group for JIc (Sec 9.2.2)

Table XIa. The raw load-displacement for the J-integral test of specimen CA1-U7, showing each unloading step. The compliance adjustment procedure was used to determine that all of the unloadings contributed to crack tip extension.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	11016	0.0126	0.0000	0.0004	1.130197E-06	61	58	58	58
2	10967	0.0126	-.0001	0.0004	1.130091E-06	61	58	58	58
3	11065	0.0127	-.0002	0.0004	1.129799E-06	62	59	59	59
4	11065	0.0127	-.0003	0.0004	1.129597E-06	62	59	59	59
5	12677	0.0147	0.0003	0.0006	1.13055E-06	83	79	79	79
6	14192	0.0167	0.0008	0.0008	1.131145E-06	107	102	102	102
7	15730	0.0188	0.0013	0.0010	1.13185E-06	134	129	129	129
8	17220	0.0209	0.0018	0.0012	1.132597E-06	165	158	158	158
9	18564	0.0228	0.0023	0.0015	1.13323E-06	195	187	187	187
10	19834	0.0249	0.0027	0.0018	1.133682E-06	230	221	221	221
11	21080	0.0269	0.0030	0.0020	1.134119E-06	266	256	256	256
12	22277	0.0289	0.0032	0.0024	1.134206E-06	304	292	293	293
13	23376	0.0309	0.0043	0.0027	1.135929E-06	344	331	332	332
14	24377	0.0329	0.0047	0.0030	1.136421E-06	386	372	373	373
15	25330	0.0350	0.0056	0.0034	1.13784E-06	432	416	418	418
16	26185	0.0370	0.0056	0.0038	1.137668E-06	478	460	462	462
17	26991	0.0391	0.0067	0.0041	1.139348E-06	526	507	510	510
18	27675	0.0411	0.0076	0.0045	1.140645E-06	574	554	557	558
19	28261	0.0431	0.0078	0.0049	1.140865E-06	624	602	606	606
20	28896	0.0451	0.0080	0.0053	1.141039E-06	674	651	655	656
21	29409	0.0472	0.0091	0.0058	1.14265E-06	728	704	708	709
22	29849	0.0493	0.0102	0.0062	1.144374E-06	782	757	762	763
23	30264	0.0514	0.0118	0.0066	1.14697E-06	837	811	816	817
24	30581	0.0534	0.0123	0.0071	1.147705E-06	891	863	869	871
25	30899	0.0554	0.0141	0.0075	1.150643E-06	944	915	921	924
26	31119	0.0574	0.0149	0.0079	1.151788E-06	998	969	976	978
27	31387	0.0595	0.0169	0.0084	1.155085E-06	1055	1025	1031	1035
28	31583	0.0616	0.0183	0.0088	1.157458E-06	1112	1081	1089	1093
29	31705	0.0637	0.0209	0.0093	1.161718E-06	1169	1137	1145	1150
30	31827	0.0657	0.0227	0.0097	1.164728E-06	1224	1191	1199	1206
31	31900	0.0677	0.0246	0.0102	1.167982E-06	1279	1246	1254	1262
32	31998	0.0697	0.0266	0.0106	1.17124E-06	1334	1300	1308	1317
33	32022	0.0718	0.0293	0.0111	1.175855E-06	1391	1357	1365	1376
34	31949	0.0738	0.0334	0.0115	1.183183E-06	1443	1409	1417	1431
35	31998	0.0759	0.0358	0.0120	1.187178E-06	1500	1466	1474	1490
36	31974	0.0779	0.0393	0.0124	1.193469E-06	1553	1519	1526	1545
37	31900	0.0799	0.0438	0.0129	1.201466E-06	1605	1572	1578	1600
38	31681	0.0820	0.0490	0.0134	1.210926E-06	1658	1627	1630	1658
39	31583	0.0841	0.0547	0.0138	1.221489E-06	1710	1680	1682	1715
40	31510	0.0862	0.0594	0.0143	1.230103E-06	1764	1734	1735	1773
41	31339	0.0883	0.0648	0.0148	1.240341E-06	1815	1788	1786	1830
42	31143	0.0903	0.0709	0.0152	1.251965E-06	1863	1838	1833	1884
43	30899	0.0924	0.0773	0.0157	1.264318E-06	1912	1891	1882	1940
44	30679	0.0944	0.0825	0.0162	1.274476E-06	1961	1941	1930	1994
45	30630	0.0964	0.0867	0.0166	1.282708E-06	2010	1991	1979	2049
46	30532	0.0985	0.0916	0.0171	1.292386E-06	2061	2043	2030	2106
47	30435	0.1006	0.0964	0.0176	1.302048E-06	2112	2095	2080	2162
48	30166	0.1027	0.1042	0.0181	1.318058E-06	2157	2145	2125	2217
49	29800	0.1048	0.1132	0.0186	1.336807E-06	2198	2194	2166	2272

Table XIb. Calculated data for the J-integral test of specimen CA1-U7. No compliance adjustment was necessary.

Specimen Id.	CA1U7	Geometry	CT
Contract #	1559K	Orientation	NA
Material	A508	Flow stress (ksi)	85.7
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.451

Specimen Dimensions (in)

Thickness	2.002	Notch depth	2.251
Net thickness	1.604	Gage length	0.107
Width	4.000	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.575	1.565	1.556	1.553	1.552	1.553	1.559	1.567	1.584

Final Ligament(s) (in)

1.430	1.466	1.453	1.460	1.442	1.347	1.411	1.383	1.355

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.455	Kmax (ksi sqr[in])	40.78

Test Parameters

Initial ligament (in)	1.561	J15limit	(in-lb/in^2)	8917
Final ligament ´´	1.419	J20limit	´´	6687
Delta a (actual) ´´	0.141	J25limit	´´	5350
Delta a (EvB/P) ´´	0.149	*JQ (813-81)	´´	826
% of DAmax Obtained	199.9	*JQ (813-81)(NV)	´´	826
Delta a error (%)	5.3	*JQ (813-87)	´´	914
Delta amax error (%)	10.6	*JQ (813-87)(NV)	´´	914
Compliance Adjustment	1.029			
CTODi (in)	0.0060	Tearing modulus		73.3

Comments * Computed from E813-87 form for J

Tested 04/02/91 by DB
Transducer: S/N 542 MODEL 632.03B-33 0.1GL 0-.125 INCHES FS
Fixtures: 0.25W pinhole 0.1875W pin Specimen: .188W pinhole
Crk ext edge to ctr > 2% of W (sec 9.4.1.6)

Table XIIa. The raw load-displacement for the J-integral test of specimen CA1-U8, showing each unloading step. The compliance adjustment procedure was used to determine that all of the unloadings contributed to crack tip extension.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87	J1152 (in-lb/in^2)	Jmod
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	11163	0.0129	0.0000	0.0004	1.134283E-06	63	60	60	60
2	11114	0.0129	-.0002	0.0004	1.133907E-06	63	60	60	60
3	11260	0.0132	-.0002	0.0005	1.133883E-06	66	63	63	63
4	11334	0.0133	0.0002	0.0005	1.134559E-06	67	64	64	64
5	12848	0.0153	0.0010	0.0007	1.135694E-06	88	84	84	84
6	14314	0.0173	0.0016	0.0009	1.136572E-06	112	107	107	107
7	15657	0.0192	0.0010	0.0011	1.135427E-06	137	131	131	131
8	16927	0.0213	0.0012	0.0013	1.135609E-06	168	160	160	160
9	18149	0.0233	0.0017	0.0016	1.136187E-06	198	189	189	189
10	19345	0.0253	0.0026	0.0019	1.137567E-06	231	221	221	221
11	20445	0.0274	0.0029	0.0022	1.137959E-06	268	256	257	257
12	21446	0.0294	0.0036	0.0025	1.138899E-06	305	291	292	292
13	22423	0.0313	0.0043	0.0028	1.139923E-06	341	327	327	328
14	23278	0.0333	0.0048	0.0032	1.140646E-06	381	365	367	367
15	24108	0.0354	0.0054	0.0036	1.141582E-06	425	408	409	409
16	24939	0.0374	0.0060	0.0039	1.142414E-06	468	449	451	451
17	25647	0.0394	0.0071	0.0043	1.144154E-06	512	492	494	495
18	26331	0.0415	0.0087	0.0047	1.146682E-06	560	538	540	541
19	26893	0.0435	0.0094	0.0051	1.147715E-06	606	583	586	587
20	27528	0.0456	0.0107	0.0055	1.149662E-06	656	632	635	636
21	27992	0.0475	0.0121	0.0059	1.151943E-06	702	676	680	682
22	28456	0.0495	0.0134	0.0063	1.154014E-06	751	724	728	730
23	28945	0.0515	0.0135	0.0067	1.15412E-06	802	773	778	780
24	29360	0.0536	0.0165	0.0072	1.159127E-06	854	824	830	833
25	29702	0.0556	0.0175	0.0076	1.160617E-06	906	875	881	884
26	30020	0.0576	0.0192	0.0080	1.163478E-06	958	925	932	936
27	30215	0.0597	0.0217	0.0085	1.167646E-06	1012	978	985	990
28	30435	0.0617	0.0243	0.0089	1.17206E-06	1064	1029	1036	1043
29	30606	0.0637	0.0274	0.0093	1.177472E-06	1115	1080	1087	1095
30	30777	0.0658	0.0319	0.0098	1.185253E-06	1169	1132	1140	1150
31	30948	0.0678	0.0345	0.0102	1.18982E-06	1221	1184	1192	1204
32	31021	0.0699	0.0374	0.0107	1.19485E-06	1277	1238	1247	1260
33	31192	0.0720	0.0405	0.0111	1.200379E-06	1332	1293	1301	1317
34	31241	0.0740	0.0431	0.0116	1.204919E-06	1385	1345	1354	1372
35	31314	0.0760	0.0473	0.0120	1.212525E-06	1437	1396	1405	1425
36	31314	0.0782	0.0517	0.0125	1.220571E-06	1494	1453	1461	1485
37	31241	0.0802	0.0567	0.0130	1.229686E-06	1544	1503	1511	1539
38	31143	0.0823	0.0620	0.0135	1.239572E-06	1596	1557	1563	1596
39	30997	0.0842	0.0682	0.0139	1.251395E-06	1642	1603	1607	1646
40	30777	0.0862	0.0742	0.0144	1.262894E-06	1690	1653	1655	1700
41	30337	0.0884	0.0853	0.0149	1.284805E-06	1735	1705	1700	1756
42	29897	0.0906	0.0976	0.0154	1.30975E-06	1777	1754	1742	1810
43	29507	0.0926	0.1086	0.0159	1.332581E-06	1816	1799	1779	1860
44	29213	0.0948	0.1188	0.0164	1.354146E-06	1860	1848	1823	1915
45	28823	0.0968	0.1282	0.0169	1.374483E-06	1899	1893	1862	1965
46	22692	0.0907	0.1507	0.0161	1.426059E-06	1712	1784	1685	1816
47	23058	0.0907	0.1335	0.0161	1.38704E-06	1738	1792	1712	1823
48	23131	0.0908	0.1342	0.0161	1.388566E-06	1739	1793	1713	1824

Table XIIb. Calculated data for the J-integral test of specimen CA1-U8. No compliance adjustment was necessary.

Specimen Id.	CA1U8	Geometry	CT
Contract #	1559K	Orientation	NA
Material	A508	Flow stress (ksi)	85.7
Temperature (F)	190	Modulus (ksi-1E6)	30.0
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.464

Specimen Dimensions (in)

Thickness	2.001	Notch depth	2.249
Net thickness	1.601	Gage length	0.105
Width	4.000	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.589 1.570 1.562 1.563 1.557 1.560 1.561 1.567 1.579

Final Ligament(s) (in)

1.447 1.368 1.329 1.453 1.419 1.444 1.466 1.490 1.412

Precrack Parameters

Pmax (lbs)	11500.0	Stress ratio (R)	0.10
Final a (in)	2.448	Kmax (ksi sqr[in])	40.60

Test Parameters

Initial ligament (in)	1.566	J15limit (in-lb/in^2)	8944
Final ligament ''	1.425	J20limit ''	6708
Delta a (actual) ''	0.141	J25limit ''	5367
Delta a (EvB/P) ''	0.151	*JQ (813-81) ''	623
% of DAmax Obtained	203.6	*JQ (813-81)(NV) ''	601
Delta a error (%)	7.1	*JQ (813-87) ''	706
Delta amax error (%)	14.4	*JQ (813-87)(NV) ''	697
Compliance Adjustment	1.018		
CTODi (in)	0.0047	Tearing modulus	71.1

Comments * Computed from E813-87 form for J

Tested 04/03/91 by DB
Transducer: S/N 542 MODEL 632.03B-33 0.1GL 0-.125 INCHES FS
Fixtures: 0.25W pinhole 0.1875W pin Specimen: .188W pinhole

Table XIIIa. Load vs. displacement data for specimen CA1-P8. The compliance adjustment procedure was used to determine that all of the unloadings contributed to crack tip extension.

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	Compliance (in/lb)	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0 0.0	0	0	0	0
1	11163	0.0126	0.0000	0.0003	1.183178E-06	64	60	60	60
2	11212	0.0126	0.0004	0.0003	1.183918E-06	64	60	60	60
3	11187	0.0126	0.0006	0.0003	1.184258E-06	64	60	60	60
4	11187	0.0126	0.0010	0.0003	1.185055E-06	64	60	60	60
5	11187	0.0127	0.0009	0.0003	1.184788E-06	65	61	61	61
6	11163	0.0126	0.0005	0.0003	1.184112E-06	64	60	60	60
7	12799	0.0147	0.0018	0.0004	1.186173E-06	86	81	81	81
8	14387	0.0168	0.0024	0.0006	1.187173E-06	112	105	106	106
9	15926	0.0189	0.0029	0.0008	1.187825E-06	141	133	133	133
10	17416	0.0210	0.0026	0.0011	1.187124E-06	173	163	163	163
11	18832	0.0232	0.0037	0.0014	1.188902E-06	209	197	198	198
12	20200	0.0252	0.0041	0.0016	1.189488E-06	244	230	231	231
13	21470	0.0273	0.0047	0.0019	1.190371E-06	283	268	269	269
14	22692	0.0294	0.0045	0.0022	1.189877E-06	326	308	309	310
15	23815	0.0314	0.0053	0.0026	1.191133E-06	368	348	350	350
16	24915	0.0335	0.0057	0.0029	1.191738E-06	414	392	394	394
17	25892	0.0355	0.0066	0.0033	1.193147E-06	460	436	439	439
18	26795	0.0376	0.0060	0.0036	1.19186E-06	510	484	488	488
19	27724	0.0397	0.0079	0.0040	1.195174E-06	561	533	537	537
20	28530	0.0418	0.0074	0.0044	1.194051E-06	615	585	589	590
21	29262	0.0438	0.0090	0.0048	1.19677E-06	667	635	640	640
22	29971	0.0459	0.0083	0.0052	1.1953E-06	724	690	695	696
23	30655	0.0480	0.0108	0.0056	1.199654E-06	780	744	750	751
24	31241	0.0500	0.0098	0.0060	1.197781E-06	837	799	806	807
25	31778	0.0521	0.0115	0.0064	1.200654E-06	896	856	864	865
26	32267	0.0541	0.0130	0.0069	1.203187E-06	953	912	920	921

Table XIIIb. Calculated data for the J-integral test of specimen CA1-P8 from IV-9.

Specimen Id.	CA1P8	Geometry	CT
Contract #	1559H	Orientation	NA
Material	ITV9	Flow stress (ksi)	83.8
Temperature (F)	75	Modulus (ksi-1E6)	30.7
Environment	AIR	Stroke rate (in/min)	0.010
		Loading rate (min)	1.403

Specimen Dimensions (in)

Thickness	2.005	Notch depth	2.256
Net thickness	1.596	Gage length	0.100
Width	4.002	Alpha ratio	1.000
Pin spacing	3.000		

Initial Ligament(s) (in)

1.568 1.545 1.518 1.508 1.509 1.514 1.510 1.520 1.541

Final Ligament(s) (in)

1.511 1.511 1.511 1.511 1.511 1.511 1.511 1.511 1.511

Precrack Parameters

Fmax (lbs)	11560.0	Stress ratio (R)	0.10
Final a (in)	2.425	Kmax (ksi sqr[in])	42.57

Test Parameters

Initial ligament (in)	1.523	J15limit (in-lb/in^2)	8506
Final ligament ''	1.511	J20limit ''	6380
Delta a (actual) ''	0.011	J25limit ''	5104
Delta a (EvB/P) ''	0.013	*JQ (813-81) ''	0
% of DAmax Obtained	11.2	*JQ (813-81)(NV) ''	16
Delta a error (%)	13.7	*JQ (813-87) ''	0
Delta amax error (%)	1.5	*JQ (813-87)(NV) ''	984
Compliance Adjustment	1.018		
CTODi (in)	-.0001	Tearing modulus	308.1

Comments * Computed from E813-87 form for J

Note:Could not identify Jic crack on fracture surface of specimen.
Used final compliant delta a to process curves and summary.
Transducer: S/N 278 Model 632.03B-33 0.1GL 0-.150 Inches FS
Fixtures: 0.25W pinhole 0.1875W pin Specimen: .187W pinhole
Less than 4 data pts for JIc fit (Sec 9.3.2)

Table XIV. KAPL/MCL Test No. 1559. Fracture toughness at 75°F of the Nozzle Material from Vessel IV-9.

SPECIMEN NUMBER	MODULUS MPSI	THICKNESS (IN.)		WIDTH (IN.)	CRACK LENGTH aO (IN)	LIGAMENT b (IN)	PRECRACK Kf-MAX (PSI√IN)	MAXIMUM LOAD (LB)	MAXIMUM DEFLECT (IN)	AREA (IN-LB) (NOTE 1)	Kc(J) (KSI√IN) (NOTE 2)	CRACK GROWTH AVG (IN)	APPROXIMATE RAMP RATE* (KSI√IN/MIN)
		B-GROSS	B-NET										
CA1-P6	30.70	2.002	1.5975	4.000	2.388	1.6105	38955	32800	.0564	1145.66	182.38	.0103	9.8
CA1-P7	30.70	2.001	1.6083	3.999	2.393	1.6055	38915	34760	.0842	2067.91	244.55	.0411	9.6

NOTES:

1. Area measured using Tamaya Planix Model 7 digital planimeter - Serial #014353.

2. $Kc(J) = \sqrt{((JcE)/(1-v^2))}$ where E is Young's modulus, v is Poisson's ratio and $Jc = (1 + \alpha)2A/(1 + \alpha^2)Bb$ where $a = \sqrt{((2a0/b)^2 + 2(2a0/b) + 2)} - (2a0/b + 1)$, A is the area under load versus displacement record, B is the specimen net thickness and b is the initial uncracked ligament (W - a0). Formulas from ASTM STP 803.

3. MTS extensometer #632.03B-33 (Serial #278) calibrated on Range 1 from 0 - .150 inches was used on the 55 KIP MTS machine to perform these tests.

* Load rate = (stroke rate)(1/(specimen compliance + fixture compliance)) where the specimen compliance is taken from the load/COD chart and the fixture compliance calculated from a similar test program (MCL #1635). Stress intensification rate = (load rate/specimen thickness*σspecimen width)) function a/W.

Table XV.

Table A.1. Fracture toughness (K_{Icd}) of nozzle prolongation of vessel V-5 from slow-bend (0.100 in./min) tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lb_f = 4.4482 N
1 ft-lb = 1.3558 J 1 lb_f/in. = 0.17513 N/mm
1 ksi$\sqrt{in.}$ = 1.0988 MN·$m^{-3/2}$

Specimen No.	Depth[a]	Specimen orientation	Test temperature [°C (°F)]	Average crack data[b]				Load (lb)			Deflection (in.)		Energy (ft-lb)		Slope of linear load-displacement curve (10^4 lb/in.)	Lateral expansion (mils)	K_{Icd} (ksi $\sqrt{in.}$)	
				a (in.)	w-a (in.)	$\frac{a}{w}$	$f(\frac{a}{w})$	Maximum	Start of fracture	Fracture arrest	Maximum load	Start of fracture	Maximum load	Start of fracture			From crosshead motion	From specimen deflection
5V-003	0.68	CT	93.3 (200)	0.2183	0.1757	0.554	3.20	1210			0.080		6.7		8.28	33	188	216
5V-005	0.49	CT	93.3 (200)	0.1984	0.1955	0.504	2.69	1385			0.074		4.9		9.54	29	145	165
5V-007	0.96	CT	0 (32)	0.2011	0.1930	0.510	2.75	1375			0.070		6.6		9.39	34	171	196
5V-012	0.49	CT	54.4 (130)	0.1825	0.2114	0.463	2.37	1505			0.057		5.8		10.26	30	145	165
5V-013	0.39	CT	−45.6 (−50)	0.1884	0.2056	0.478	2.48	1690	1560	150	0.077	0.127	8.9		9.60	27	181	208
5V-015	0.21	CT	−73.3(−100)	0.1915	0.2024	0.486	2.55		1420	175		0.028		2.4	9.60	10	97	108
5V-016	0.86	CT	−17.8 (0)	0.1359	0.2581	0.345	1.71	2370			0.081		12.7		11.34	43	163	186
5V-018	0.58	CT	23.9 (75)	0.2000	0.1950	0.506	2.71	1285			0.070		6.2		8.13	34	151	172
5V-009	0.77	CT	22.8 (73)	0.2103	0.1837	0.534	2.98	1210			0.072		6.1		8.61	30	171	196
5V-021	0.96	CT	−73.3(−100)	0.2076	0.1864	0.527	2.91		1050	230		0.020		1.2	8.70	5	75	82
5V-023	0.77	CT	−17.8 (0)	0.2016	0.1924	0.512	2.77	1370			0.067		6.2		9.00	35	164	188
5V-025	0.58	CT	93.3 (200)	0.2159	0.1781	0.548	3.13	1095			0.067		5.2		8.73	27	167	191
5V-026	0.49	CT	−73.3(−100)	0.2081	0.1858	0.528	2.92		1275	135		0.037		2.9	8.40	3	114	128
5V-027	0.86	CT	93.3 (200)	0.2157	0.1783	0.547	3.11	1135			0.076		6.0		8.88	29	180	207
5V-002	0.77	CA	93.3 (200)	0.1945	0.2005	0.492	2.60	1435			0.093		9.5		9.99	31	201	232
5V-004	0.58	CA	93.3 (200)	0.2017	0.1933	0.511	2.76	1225			0.076		6.8		8.70	33	167	191
5V-006	0.39	CA	−45.6 (−50)	0.1928	0.2022	0.488	2.56	1580	1270	210	0.076	0.170	8.4		9.24	30	178	204
5V-008	0.86	CA	0 (32)	0.2001	0.1948	0.507	2.72	1390			0.082		8.0		9.00	38	182	209
5V-011	0.58	CA	54.4 (130)	0.1989	0.1956	0.504	2.69	1350			0.066		6.1		8.99	37	157	179
5V-014	0.30	CA	−73.3(−100)	0.1517	0.2428	0.385	1.90		1910	100		0.030	3.2		8.22	11	77	84
5V-017	0.77	CA	−17.8 (0)	0.1878	0.2063	0.477	2.48	1570			0.091		10.2		9.90	41	197	227
5V-019	0.49	CA	23.9 (75)	0.1986	0.1959	0.503	2.68	1355			0.090		8.7		10.41	37	202	233
5V-001	0.86	CA	−73.3(−100)	0.2018	0.1932	0.511	2.76		1210	220		0.023		1.6	8.46	10	80	88
5V-010	0.68	CA	22.8 (73)	0.1995	0.1947	0.506	2.71	1290			0.056		4.9		8.61	34	139	158
5V-020	0.30	CA	−17.8 (0)	0.2006	0.1926	0.510	2.75	1295			0.060		5.4		8.58	33	149	170
5V-022	0.86	CA	−73.3(−100)	0.1959	0.1989	0.496	2.63		1130	200		0.015		0.8	9.18	4	56	59
5V-024	0.68	CA	93.3 (200)	0.2006	0.1944	0.508	2.73	850			0.065		5.6		9.00	29	153	175
5V-028	0.77	CA	93.3 (200)	0.2003	0.1947	0.507	2.76	1355			0.082		7.9		8.46	34	176	202

[a] Fraction of wall thickness (6 in.) from outside.
[b] Dimension a is the average of six measurements.

Table XVI.

Table A.2. Fracture toughness (K_{Icd}) of nozzle prolongation of vessel V-9 from slow-bend (0.100 in./min) tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lb_f = 4.4482 N
1 ft-lb = 1.3558 J 1 lb_f/in. = 0.17513 N/mm
1 ksi$\sqrt{in.}$ = 1.0988 MN·$m^{-3/2}$

Specimen No.	Depth[a]	Specimen orientation	Test temperature [°C (°F)]	Average crack data[b]: a (in.)	w-a (in.)	$\frac{a}{w}$	$f(\frac{a}{w})$	Load (lb): Maximum	Load (lb): Start of fracture	Load (lb): Fracture arrest	Deflection (in.): Maximum load	Deflection (in.): Start of fracture	Energy (ft-lb): Maximum load	Energy (ft-lb): Start of fracture	Slope of linear load-displacement curve (10^4 lb/in.)	Lateral expansion (mils)	K_{Icd} (ksi $\sqrt{in.}$): From crosshead motion	K_{Icd} (ksi $\sqrt{in.}$): From specimen deflection
9V-056	0.04	CA	20.0 (68)	0.2295	0.1655	0.581	3.69	1050			0.058		4.1		7.20		159	182
9V-070	0.125	CT	20.0 (68)	0.2082	0.1851	0.529	3.10	1260			0.070		6.1		8.49		177	203
9V-071	0.21	CA	20.0 (68)	0.2167	0.1782	0.549	3.30	1195			0.066		5.2		7.92		167	191
9V-072	0.29	CT	20.0 (68)	0.3127	0.0807	0.795	10.76	270			0.058		1.08		2.76		147	167
9V-073	0.37	CA	20.0 (68)	0.2117	0.1833	0.536	3.16	1255			0.069		5.9		7.86		170	195
9V-074	0.46	CT	20.0 (68)	0.2041	0.1897	0.518	2.99	1320			0.067		5.9		8.70		169	194
9V-075	0.62	CA	20.0 (68)	0.2275	0.1676	0.576	3.62	1070			0.073		5.3		7.20	Not recorded	176	202
9V-076	0.71	CT	20.0 (68)	0.2052	0.1887	0.521	3.02	1320			0.068		6.1		8.22		169	194
9V-077	0.79	CA	20.0 (68)	0.2178	0.1772	0.551	3.33	1160	655	395	0.062		4.8		8.04		163	186
9V-078	0.87	CT	20.0 (68)	0.2071	0.1868	0.526	3.06		1295	805		0.064		5.5	8.40		164	188
9V-079	0.96	CA	20.0 (68)	0.2220	0.1730	0.562	3.45	1130	610	390	0.067		5.0		7.86		171	196
9V-042	0.04	CT	37.8 (100)	0.2037	0.1908	0.516	2.97	1355			0.063		5.9		8.85		169	194
9V-053	0.04	CT	7.2 (45)	0.2099	0.1837	0.533	3.14	1305			0.066		5.9		8.70		178	204
9V-020	0.04	CT	−6.7 (20)	0.2069	0.1879	0.524	3.05	1380			0.065		6.0		8.46		171	196

[a]Fraction of wall thickness (6 in.) from outside.
[b]Dimension a is the average of six measurements.

Table XVII.

Table A.3. Fracture toughness (K_{Idd}) of nozzle prolongation of vessel V-9 from dynamic-bend tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lbf = 4.4482 N
1 ft-lb = 1.3558 J 1 lbf/in. = 0.17513 N/mm
1 ksi$\sqrt{\text{in.}}$ = 1.0988 MN·m$^{-3/2}$

Specimen No.	Depth[a]	Specimen orientation	Test temperature [°C (°F)]	Average crack data[b]				Energy (ft-lb)		Slope of linear load-displacement curve (10^4 lb/in.)	Lateral expansion (mils)	K_{Idd} (ksi$\sqrt{\text{in.}}$)	
				a (in.)	w-a (in.)	$\frac{a}{w}$	$f(\frac{a}{w})$	Maximum load	Start of fracture			From crosshead motion	From specimen deflection
9V-017	0.79	CA	93.3(200)	0.2015	0.1941	0.509	2.91	6.6		49.5	Not recorded	Not determined	415
9V-029	0.79	CA	−17.2 (0)	0.2120	0.1836	0.536	3.16		0.66	49.5			142
9V-039	0.79	CA	37.8(100)	0.2148	0.1808	0.543	3.24	8.9		34.4			446
9V-051	0.79	CA	10 (50)	0.2056	0.1895	0.520	3.01		0.33	37.7			84
9V-059	0.79	CA	23.9 (75)	0.2035	0.1913	0.515	2.96		1.80	39.1			196
9V-019	0.96	CT	10 (50)	0.2020	0.1919	0.512	2.93		0.14	24.7			43
9V-041	0.96	CT	37.8(100)	0.1994	0.1954	0.505	2.87		3.50				191
9V-065	0.46	CT	37.8(100)	0.2213	0.1730	0.561	3.44	4.2		19.4			275
9V-085	0.46	CT	55.6(150)	0.2129	0.1821	0.539	3.19	6.9		23.5			320
9V-047	0.46	CT	10 (50)	0.2258	0.1692	0.572	3.57		0.43	18.9			80
9V-013	0.46	CT	21.1 (70)	0.2064	0.1868	0.525	3.05	7.6		24.8			332
9V-004	0.46	CT	121.1(250)	0.2216	0.1720	0.563	3.46	5.9		20.1			298
9V-025	0.46	CT	15.6 (60)	0.2139	0.1816	0.541	3.21		0.43	26.5			85
9V-026	0.54	CA	10 (50)	0.2180	0.1770	0.552	3.33		1.70	24.6			169
9V-036	0.54	CA	55.6(150)	0.2120	0.1834	0.536	3.17	6.8		27.3			340
9V-014	0.54	CA	121.1(250)	0.2179	0.1776	0.551	3.32	6.8		23.0			319
9V-048	0.54	CA	21.1 (70)	0.2116	0.1835	0.536	3.16		4.10	20.2			226
9V-012	0.37	CT	21.1 (70)	0.2180	0.1752	0.554	3.36	6.5		25.1			340
9V-034	0.37	CT	15.6 (60)	0.2149	0.1801	0.554	3.25	7.9		25.4			363
9V-057	0.37	CT	−17.8 (0)	0.2154	0.1786	0.547	3.28		0.12	25.8			46
9V-003	0.37	CA	26.7 (80)	0.2065	0.1891	0.522	3.03	7.5		23.0			313
9V-024	0.37	CA	37.8(100)	0.2145	0.1809	0.542	3.23	7.7		25.1			353
9V-046	0.37	CA	−17.8 (0)	0.2121	0.1829	0.537	3.17		0.12	29.9			47

[a] Fraction of wall thickness (6 in.) from outside.
[b] Dimension a is the average of six measurements.

APPENDIX II

Proposal to the ASTM E24.08.03/04 Working Group for a J_{IC} Initializaton Procedure

JIc Initialization Procedure

The three parameter power law (3PPL) method of adjusting the beginning J-R curve was presented for examination in a letter from Prof. Joyce to ASTM Working Group E24.08.03/04 on JIc initialization dated 1/11/91. While the procedure is painstaking and thorough, it places high credence on compliance data gathered during crack blunting. These data, which tend to be notoriously inaccurate (being in the noise range of the measurements) and erratic, are weighted heavily in the determination of the adjustment of the J-R curve. Therefore, this "instrument noise" data has a significant effect on JQ, in general. The following method makes correction for the noise.

Tearing is indicated by compliance increasing at an increasing rate. Prior to the occurrence of this response, blunting occurs. Hence, if one had a procedure by which the tearing onset point was identified, then the demarcation from blunting to tearing would be in hand. Since this onset point is the last observation of blunting, it belongs on the construction line (blunting line) of the current procedure which emanates from the origin and has a slope of twice the flow stress. Data taken prior to the onset point should be ignored since they are replaced by the construction line. Crack extension data taken after the onset point should be adjusted to reflect the difference in crack extension of the onset point between its construction line value and its compliance value.

The noise associated with compliance (Cn) measurements makes the onset point difficult to identify. The cumulative average compliance, CAC(n) = (sum Cn)/n, smooths the compliance data and increases at an increasing rate with crack extension, Figure 1. Using the finite difference equation for the second derivative, CAC(n) is judged to increase at an increasing rate when a positive value is obtained for the quantity D2(n) = CAC (n+1) - 2 CAC(n) + CAC (n-1) > 0. When D2 becomes positive, let n = N. The first derivative is D1(n) = CAC (n+1) - CAC(n). If D1 (N-1) is positive then N-1 is defined as the onset point. If D1 (N-1) is negative then N is defined as the onset point.

This procedure was applied to the data attached to Prof. Joyce's letter. The beginning compliance data of specimen FYBA2 are shown in Figure 2, and the N-1 point is identified. D1 (N-1) is positive so this point is placed on the construction line in Figure 3. The beginning J-R data for FYBA2 are shown in Figure 3. The JQ value, 602 lb/in, is about the same as that from the 3PPL procedure. The beginning compliance data of specimen FYBA1 are shown in Figure 4 and the N-1 point is identified. D1 (N-1) is positive so this point is placed on the construction line in Figure 5. The beginning J-R data for FYBA1 are shown in Figure 5.

The JQ value, 529, is about the same as that from the 3PPL procedure. These data indicate that continuity of data within the exclusion lines should perhaps be required, i.e., neither the fourth (included) nor the fifth (excluded) points appear to be part of the regression data if the fifth point must be excluded.

The CAC procedure is a bit easier to apply than the 3PPL procedure and appears to yield about the same results.

FIGURE I-1

Figure 1. C(T) Dimensionless Load–line Compliance
$0.50 \leq a/W \leq 0.70$, Newman + Saxena & Hudak, ASTM E813,A2.5.4

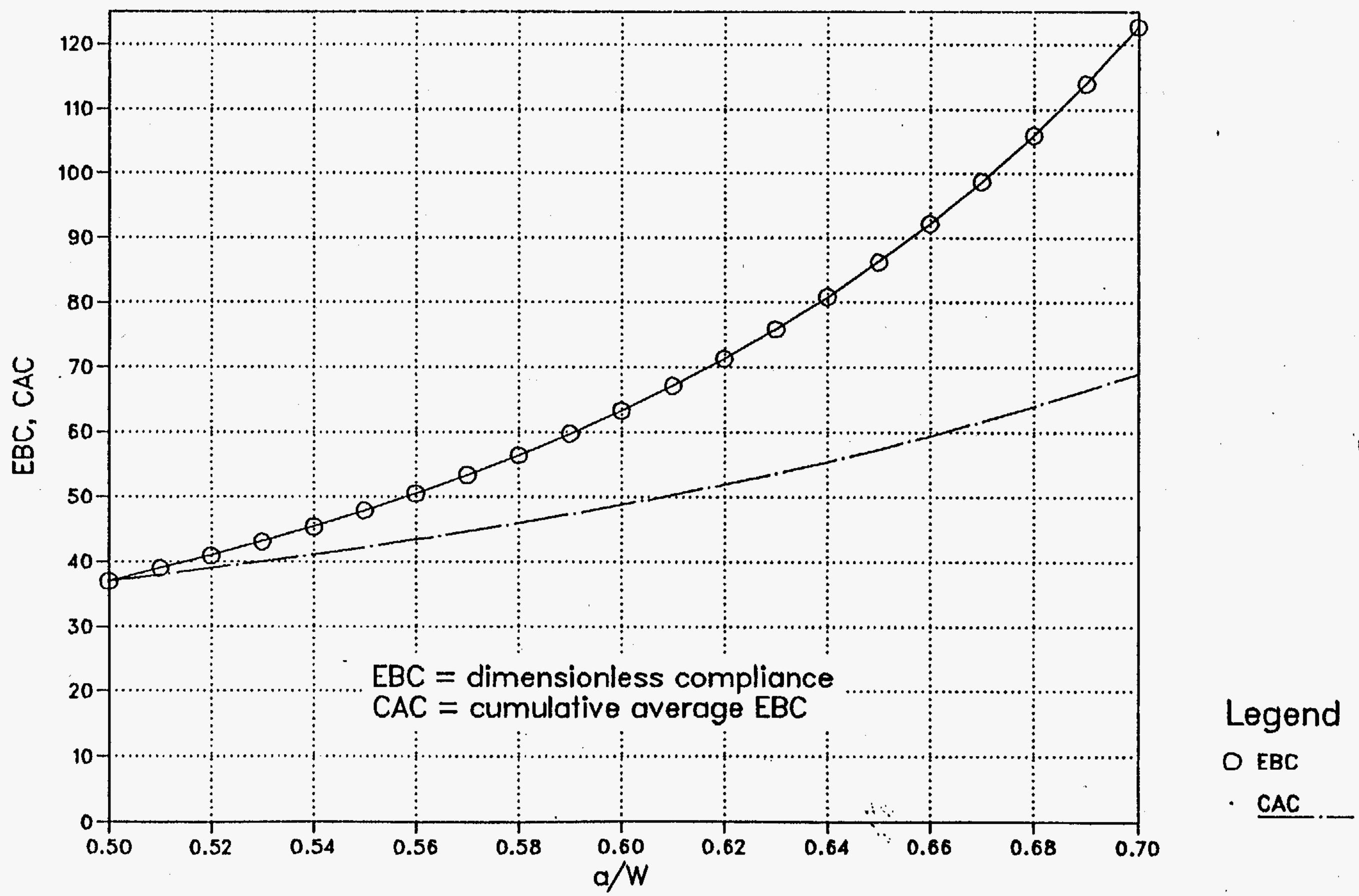

FIGURE I-2

FYBA1 Beginning Compliance

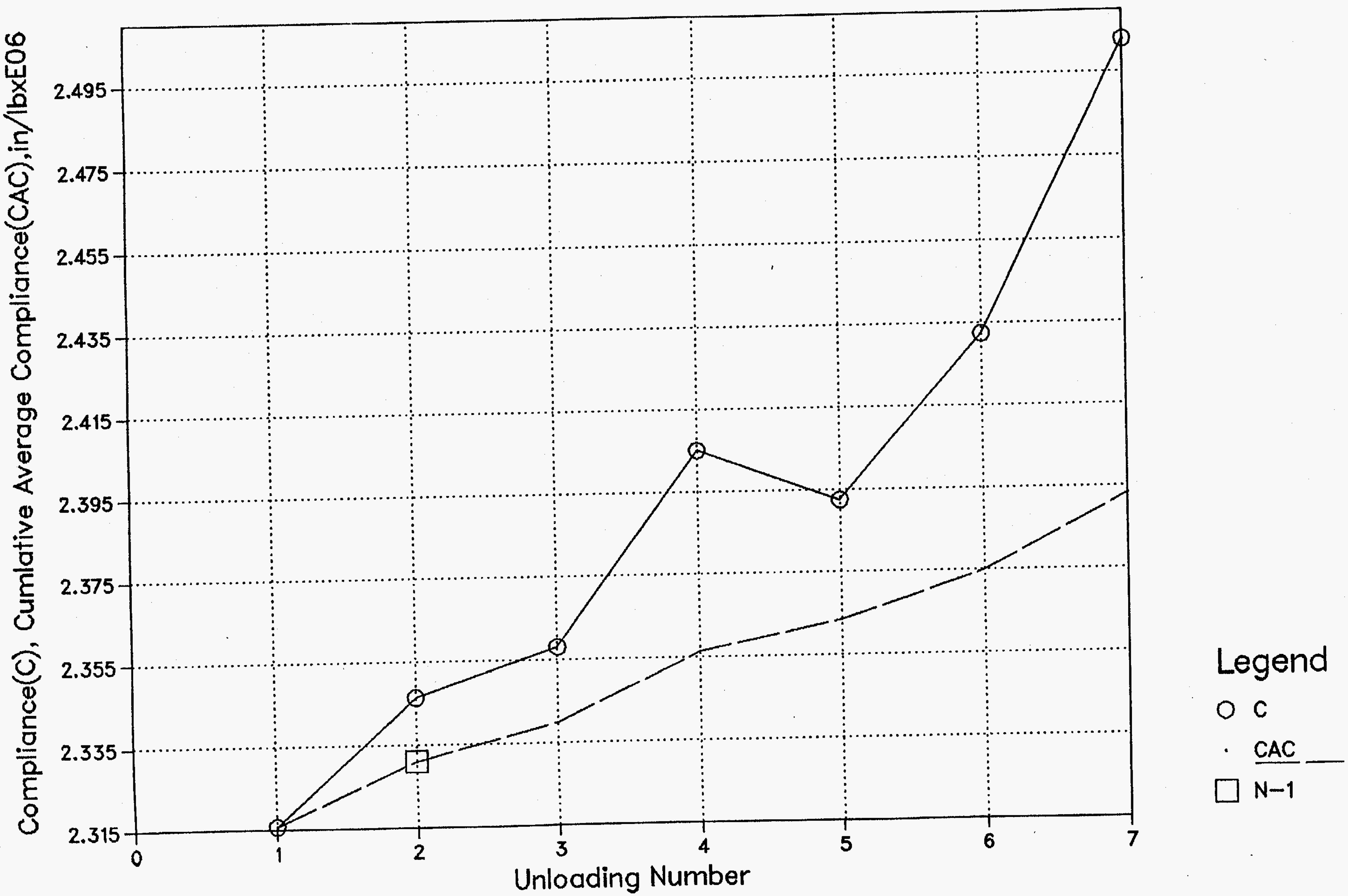

FIGURE I-3

FYBA1 Beginning J–R Curve

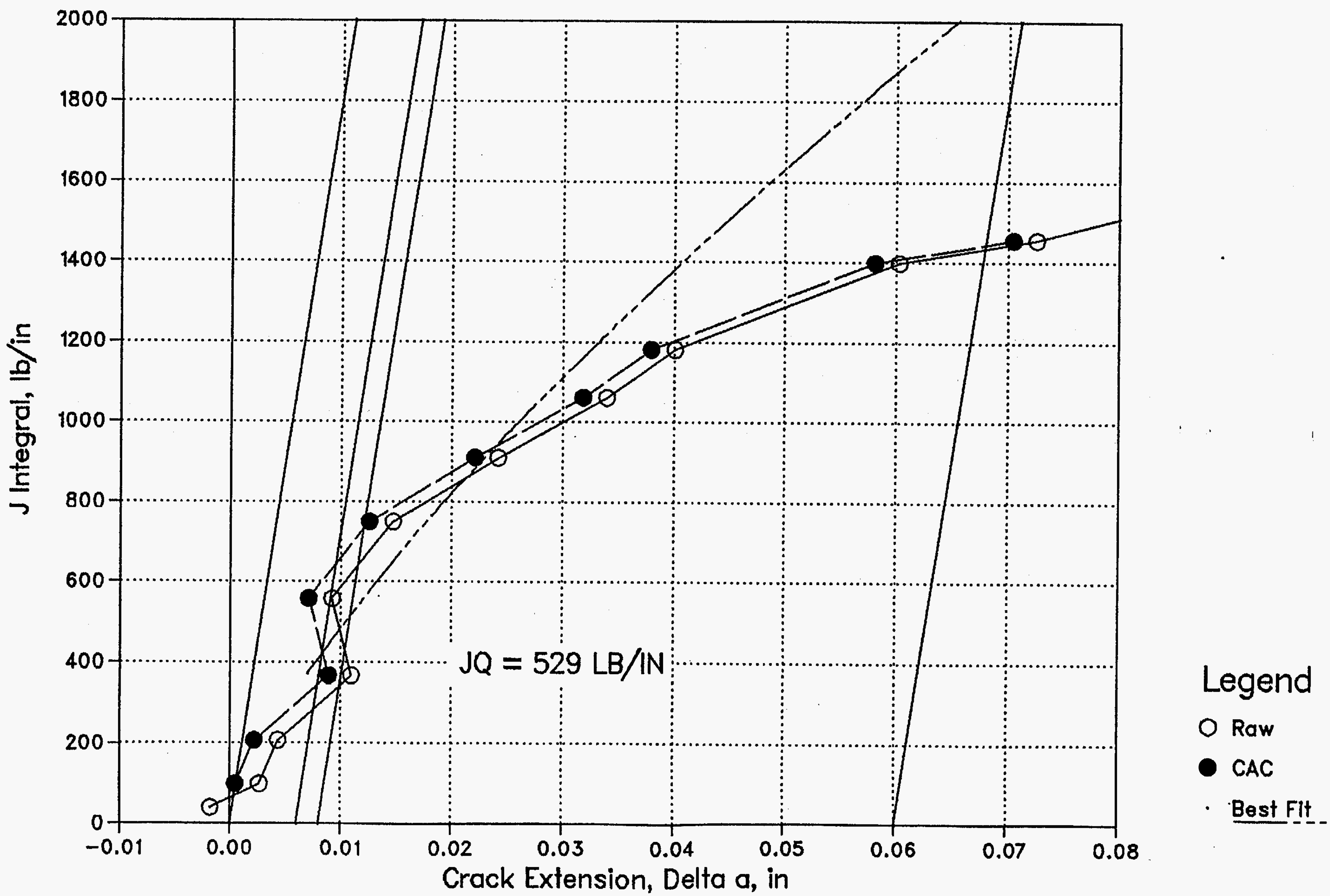

FIGURE I-4

FYBA2 Beginning Compliance

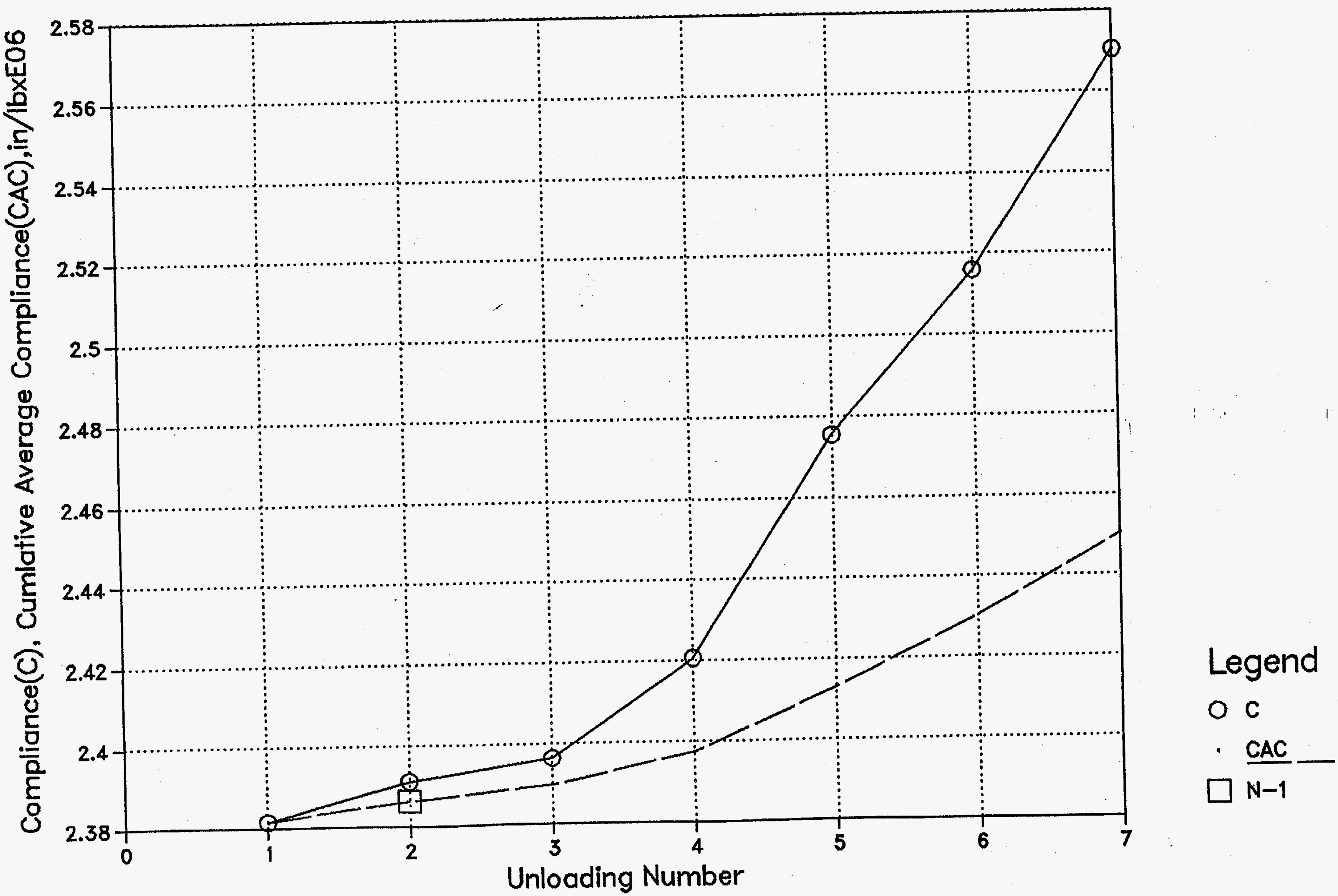

FIGURE I-5

FYBA2 Beginning J-R Curve