ornl

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

NUREG/CR-3771
ORNL/Sub/82-52845/1

Vessel V-7 and V-8 Repair and Characterization of Insert Material

FINAL REPORT

H. A. Domian

Work Performed for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75
NRC FIN No. B0119

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

Available from

GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NUREG/CR-3771
ORNL/Sub/82-52845/1
Dist. Category AN

VESSEL V-7 AND V-8 REPAIR AND CHARACTERIZATION OF INSERT MATERIAL

Final Report

H. A. Domian

Manuscript Completed — January 1984
Date Published — May 1984

Report prepared by
THE BABCOCK & WILCOX COMPANY
Research and Development Division
Alliance Research Center
1562 Beeson Street
Alliance, Ohio 44601
under
UCC-ND Subcontract No. 76Y-52845V
B&W Contract No. CRD-1107

Work performed for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
under
Interagency Agreements 40-551-75 and 40-552-75
NRC FIN No. B0119

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

LEGAL NOTICE

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Con't)

TABLES

SUMMARY

Pieces of Type SA508-2 steel, specially tempered to produce a high-impact-transition temperature, were welded in the side walls of Intermediate Test Vessels V-7 and V-8. These vessels are to be tested by the Oak Ridge National Laboratory (ORNL) in the Pressurized-Thermal-Shock (PTS) Project of the Heavy-Section Steel Technology (HSST) Program.

A comparable piece of forging taken from the same source and heat treated with the vessels was characterized for its mechanical properties to provide data for use in the PTS tests.

1. INTRODUCTION

Intermediate Test Vessels (ITV) V-7 and V-8 (Figure 1) were pressure tested by the Oak Ridge National Laboratory (ORNL) as part of the Heavy-Section Steel Technology (HSST) Program. Each vessel contained specially sharpened flaws to generate data needed to validate fracture mechanics analysis. Through the application of hydrostatic pressure, these flaws propagated to satisfy the requirements of their respective tests. This report describes the work done to:

- Repair these vessels with special steel inserts welded into the vessel walls where the flaws had been.
- Characterize the mechanical properties of the insert material.

After welding in the inserts made from a forging of SA508-2 steel composition, but which had received a nonstandard heat treatment, the vessels were returned to ORNL for testing again as part of the pressurized-thermal-shock experiments (PTSE).

To provide data for predicting the results of the PTS, material from the forging that was treated identically to the vessel inserts was characterized with the following tests:

- Chemical composition
- Macrostructure and hardness
- Tension tests
- Charpy V-notch impact tests
- Drop weight tests
- Plane strain fracture toughness tests
- J-integral tests

A companion piece of the forging was provided to Battelle Columbus Laboratories for crack-arrest testing and will be reported separately by that organization.

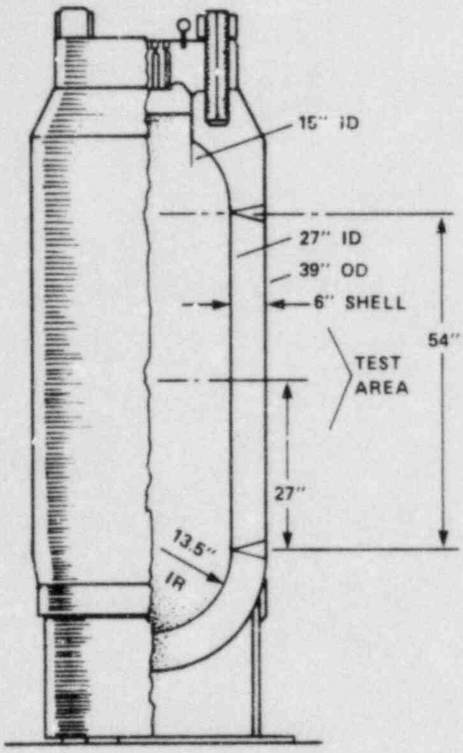


Figure 1. Intermediate Test Vessels V-7 and V-8.

2. REPAIR OF VESSELS V-7 AND V-8

The following work was performed by the Nuclear Equipment Division (NED) of The Babcock & Wilcox Company (B&W) at Barberton, Ohio, with standard practices used to generally meet the requirements of Section III of the American Society of Mechanical Engineers' Boiler and Pressure Vessel Code (ASME BPVC). The exceptions are noted. The following abbreviated process outline was used for both vessels:

1. Receive and inspect Vessels V-7 and V-8 and existing cavity in each vessel.
2. Layout to machine weld preparations to drawing requirements for cavities. Extend layout to ends for later reference.
3. Machine weld preparation for each vessel.
4. Dye penetrant test (PT) weld preparations. Magnetic particle testing (MT) was attempted, but because of high residual magnetism, PT was used.
5. Temper SA508-2 forging of Thermal Shock Cylinder-6 (TSC-6) and layout to flame cut plugs to fit vessel cavities.
6. Flame cut and machine plugs to fit cavities. Semi-finish machine plugs to 6-1/2 inches thick.
7. Magnetic particle test the machined weld preparations on the plugs. (High residual magnetism was reduced by degaussing in a coil.)
8. Fit plugs and backing straps in the two vessels.
9. Manual metal arc weld plugs into the vessels.
10. Remove backing straps by grinding from the inside diameters of the two vessels.
11. Grind the welds on the two vessels for nondestructive examination (NDE).
12. Measure outer diameter (OD) of vessels to determine if vessel will finish machine to 38.625 inches.
13. Preliminary MT the welds on the inner and outer diameter. Weld repair if required.

14. Preliminary radiographic test (RT) the welds. Weld repair if required.

15. Fit and weld temporary blocks to closure cover end of vessels for machining purposes.

16. Weld buildup repair two small machined flat spots on the OD of the vessels and MT. Repair if required.

17. Post-weld heat treat (PWHT) both vessels together with remainder of TSC-6 cylinder.

18. Flame cut characterization test pieces and ship to B&W's Alliance (Ohio) Research Center (ARC). Flame cut 12-inch length of segment and ship to Union Carbide Corporation - Nuclear Division (UCC-ND) for flawing practice.

19. Layout for RT and layout to determine location of plugs. Use previous reference lines.

20. MT plug welds on the ID and OD.

21. Final RT of plug welds.

22. Set up and machine OD of vessel to 38.625 inches (±0.010 inch). Verify vessel ID of 27 inches (±0.25 inch) and machine if required.

23. Locate centerlines of the insert by punch marks on the ID and OD of the vessels.

24. Remove temporary blocks from closure cover end and grind to blend.

25. Assemble closure head and seals.

26. Helium leak test vessel head seals.

27. Apply light preservative oil to vessels and cover ends.

28. Ship vessels and remainder of TSC-6 cylinder to UCC - ND.

2.1 VESSELS AS-RECEIVED

Inspecting the vessels upon their receipt showed the dimensions illustrated in Figure 2.

2.2 PREPARATION OF CAVITIES

The weld preparations in the vessels for the plug welds were machined to the configuration shown in Figure 3.

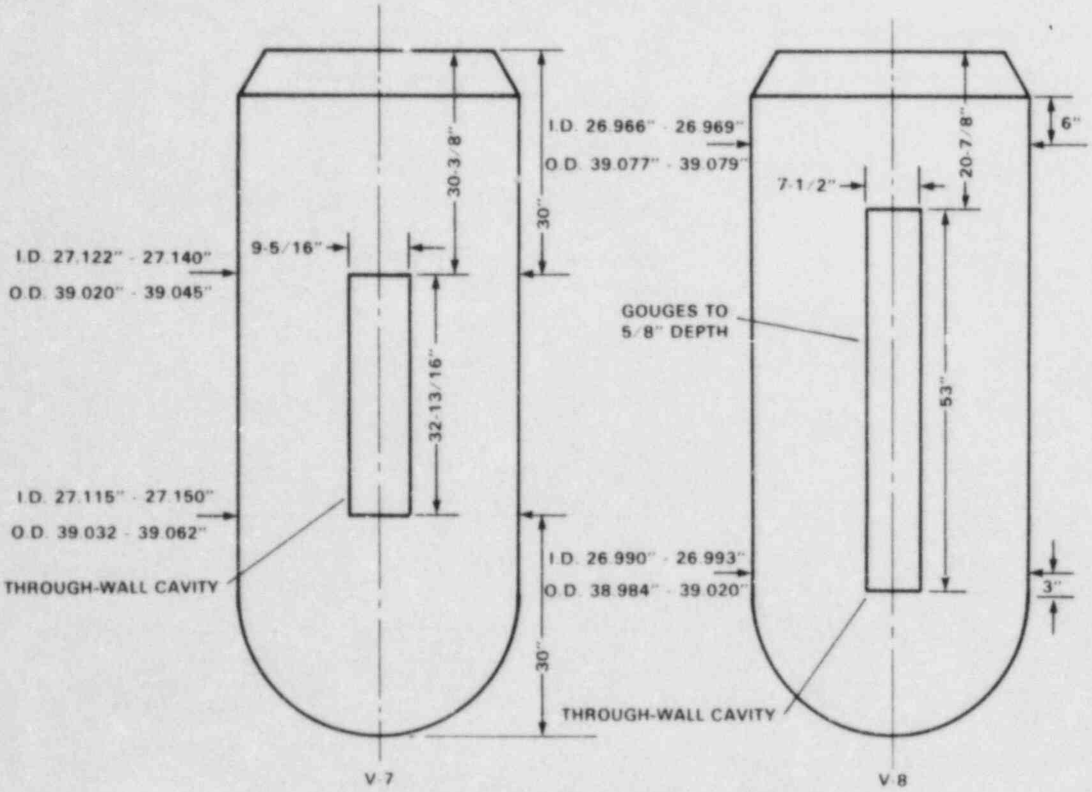


Figure 2. Dimensional inspection results for Vessels V-7 and V-8 as received.

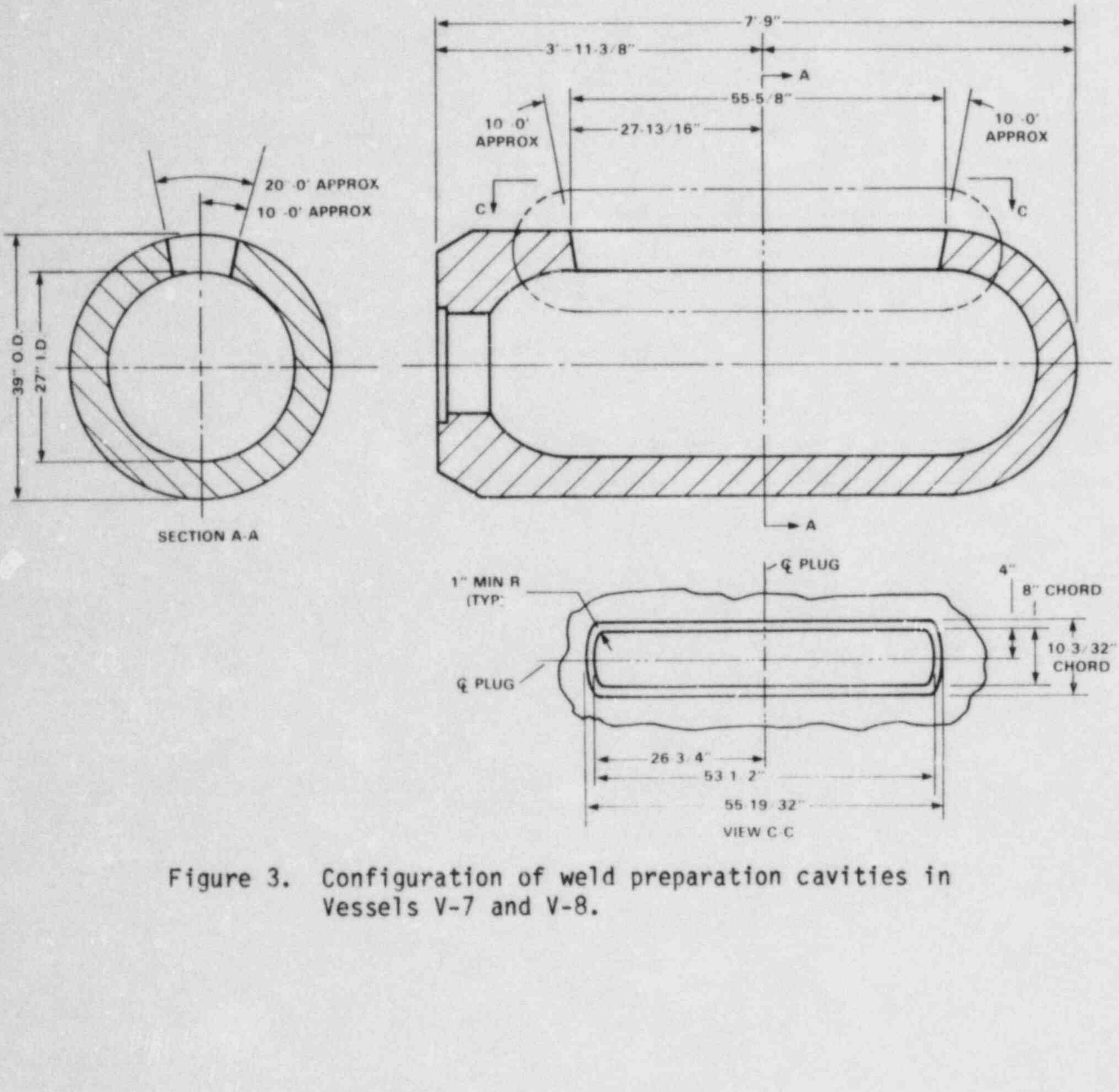


Figure 3. Configuration of weld preparation cavities in Vessels V-7 and V-8.

Magnetic particle testing of the surfaces to be welded was attempted; however, the residual magnetism was too high for meaningful inspection results. Measurements made at the machined surfaces with a gaussmeter produced readings as high as 13 gauss for Vessel V-7 and 27 gauss for Vessel V-8. Instead of magnetic particle testing, dye penetrant testing was used to detect surface flaws. None were detected. Since high magnetic fields could produce "arc-blow" in welding, there was concern that problems in welding would be encountered; however, this was not the case.

The deep gouges on the cavity in Vessel V-8 due to flame cutting were not removed in machining but were weld repaired and ground flush with the machined surface.

2.3 PREPARATION OF VESSEL INSERTS

Repairing Vessels V-7 and V-8 was accomplished by welding inserts into the enlarged cavities resulting from the previous tests of the vessels. These inserts were made from SA508-2 material, except that a high ductile-brittle transition temperature was required by UCC - ND for the PTSE.

The test material was provided by UCC - ND as a hollow cylinder (25 inches ID x 41 inches OD x 54-inches long) of SA508-2 steel in the quenched condition and identified as Thermal Shock Cylinder-6 (TSC-6). The cylinder was made by Bethlehem Steel Corp. according to Specification No. M-11587-RS-001-S-0, Revision 2, HSST Thermal Shock Test Cylinders, issued by ORNL. The data shown in Table 1 was extracted from the test report on the cylinder.

To reduce the possibility of heat-affected-zone (HAZ) cracking during welding, the as-quenched cylinder was given a low-temperature temper of 973°F for 9.5 hours. The thermal cycle achieved is shown in Figure 4 as the average of eight thermocouple readings attached to the cylinder. During the hold at 950° to 1000°F, the standard deviation of the eight thermocouple readings was less than 10°F.

The plug inserts for vessels were flame cut from TSC-6 and machined, as shown in Figures 5 and 6.

Table 1

TEST REPORT DATA ON TSC-6*

Heat No.: 121S163

Chemical Composition:

.21 C, .69 Mn, .015 P, .013 S, .17 Si, .81 Ni, .38 Cr, .01 V, .64 Mo

Heat Treatment:

Normalize -- Heated to 1640°F; held 13 hours; air cooled

Austinitize -- Heated to 1575°F; held 8-3/4 hours; water quenched

Test Results on Quenched and Tempered Prolongation:

Temper: Heated to 1240°F; held 9 hours; furnace cooled; grain size 100% 6-7

Mechanical Properties:

Yield Strength -- 70.5 ksi

Ultimate Tensile Strength -- 93.5 ksi

Elongation -- 25%

Reduction of Area -- 67%

Charpy V-Notch Impact at 40°F, Average of 6 Specimens -- 75.5 Ft. Lbs.
36.3% Fibrosity

NDT -- +20°F

---

*Report No. 342 - Part 1, 9/2-82; Bethlehem Plant.

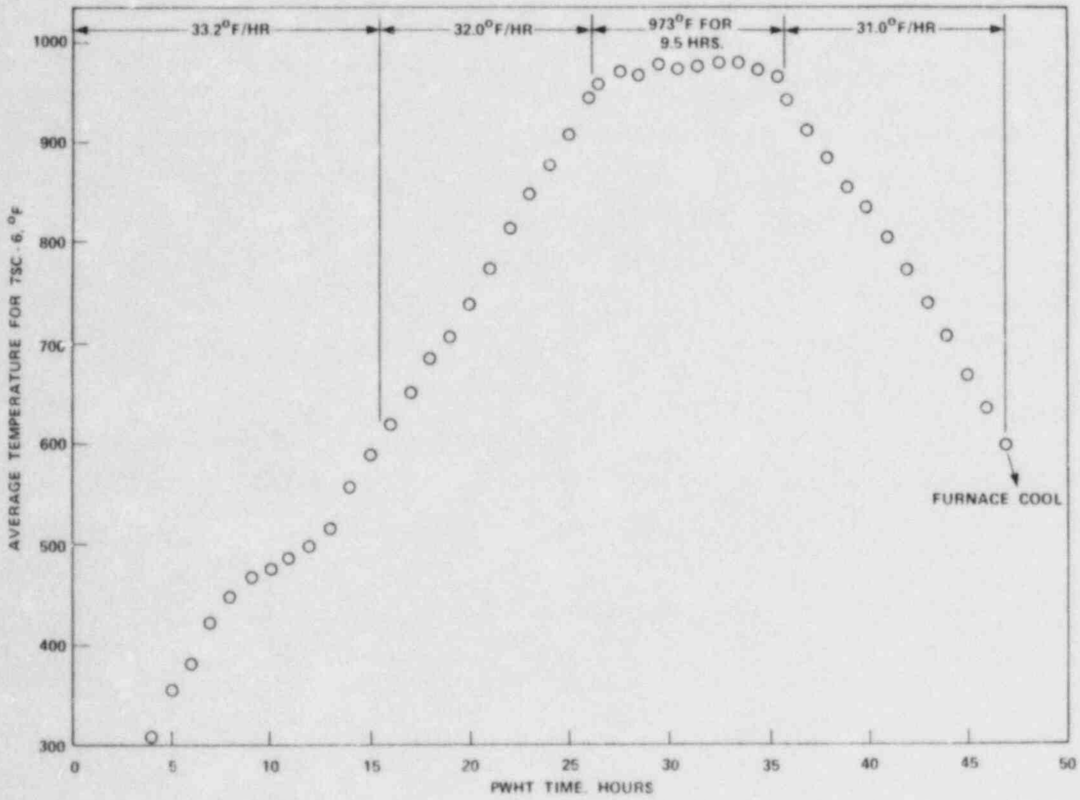


Figure 4. Average temperature of eight thermocouple locations on TSC-6 as a function of tempering time.

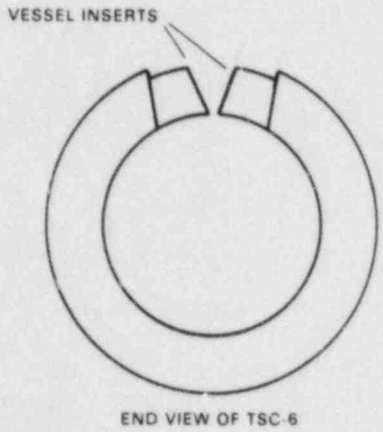


Figure 5. Position of vessel inserts removed from TSC-6 after low-temperature temper.

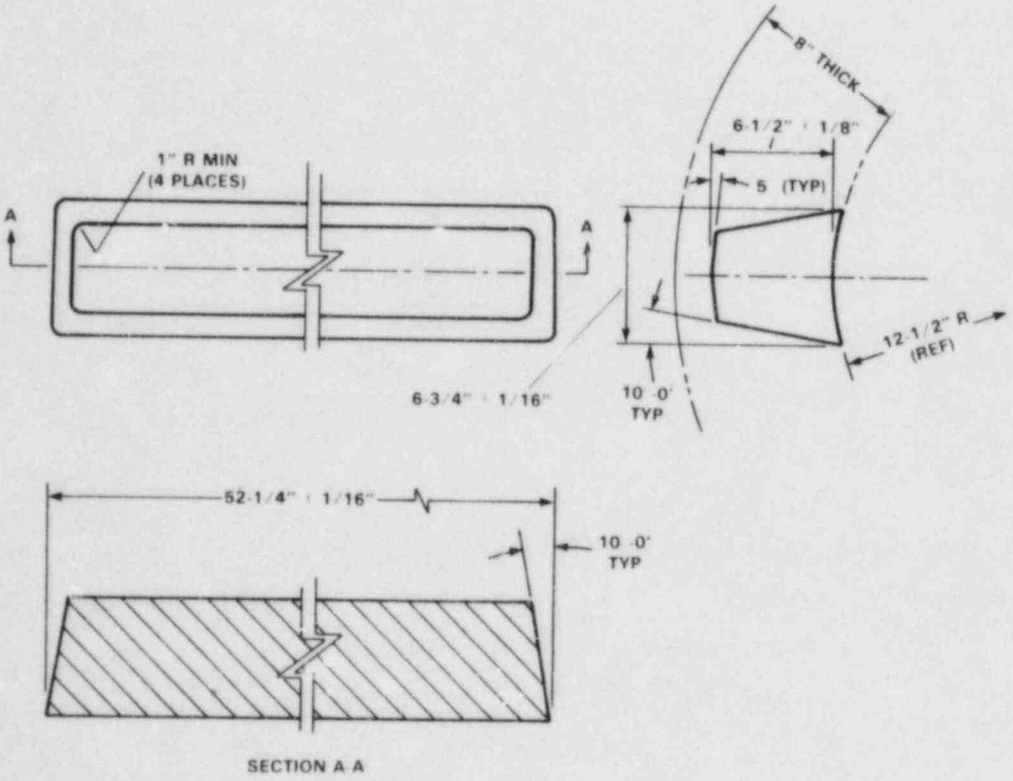


Figure 6. Nominal dimensions of plug inserts made from TSC-6 for Vessels V-7 and V-8.

Following machining, magnetic particle testing was attempted, but the residual magnetism was too high. Degaussing was accomplished by passing the pieces through a solenoid and the magnetic particle test was then accomplished with no significant flaw indications reported.

2.4 WELDING INSERTS INTO VESSELS

The plug inserts were welded into the vessel, as shown in Figure 7. Table 2 lists the welding parameters and consumables that were used to make these manual metal arc (MMA) welds:

2.5 POST-WELD HEAT TREATMENT

To provide material for characterization testing and spare material representing the plug insert material, the remainder of TSC-6 was given the same post-weld heat treatment as Vessels V-7 and V-8. The three pieces were arranged as shown in Figure 8 in a long-car-bottom, gas-fired furnace. Twenty-four thermocouples, or eight per piece, were attached to the surfaces of the pieces at the locations indicated in Figure 8.

The leads of the 24 thermocouples were attached to a multipoint strip-chart recorder. Readings were taken off the chart at hourly intervals and are reported in Tables 3 and 4. Since the temperature differences between the three pieces were small, the average temperature of the 24 thermocouple positions is given in Figure 9 as a function of the PWHT time. The thermal histories of the three pieces are considered to be very similar. Therefore, it is expected that the characterization test material and the remainder of TSC-6 is representative of the inserts in Vessels V-7 and V-8.

2.6 INSPECTION RESULTS

Not all of the inspection results are reported here. Only those considered significant for the purposes of the test vessels are given. These are: nondestructive test results after the final PWHT, OD dimensions after machining; and the leak test results of the closure head seal.

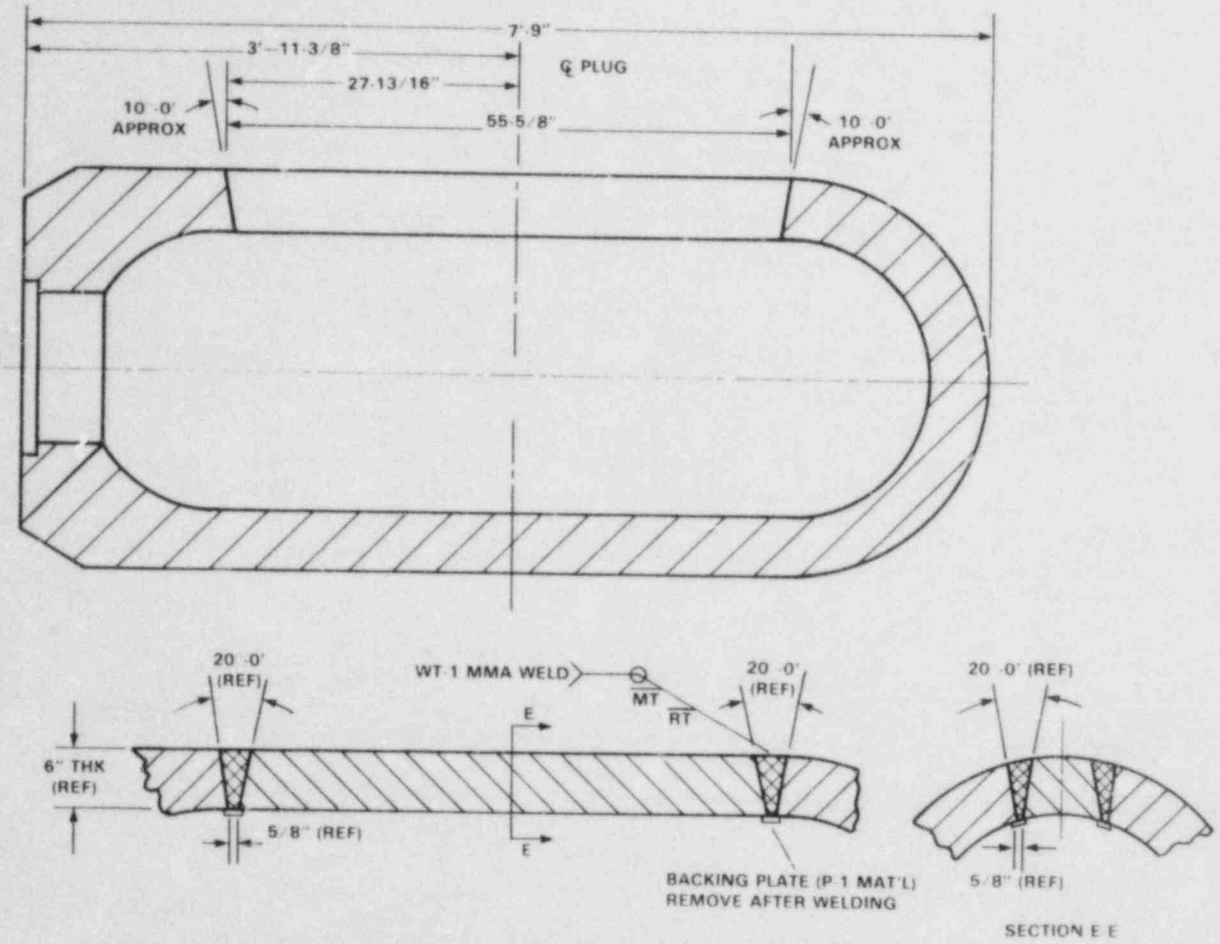


Figure 7. Plug insert welds in Vessels V-7 and V-8.

Table 2

WELDING PARAMETERS AND CONSUMABLES USED TO MAKE PLUG WELDS

Preheat Temperature: 300°F Min.

Interpass Temperature: 500°F Max.

Post Heat Temperature: 400 - 600°F/4 hours

Welding Current:

1/8-inch-diameter electrode -- 120 - 155 Amp DCRP
5/32-inch-diameter electrode -- 160 - 210 Amp DCRP
1/4-inch diameter electrode -- 325 - 425 Amp DCRP

Electrode: SFA 5.5 E 8018 C3

Electrode Diameter	Heat or Lot No.
1/8	0498314
1/8	3042A146144
5/32	0498314
5/32	0498315
1/4	1034A146188

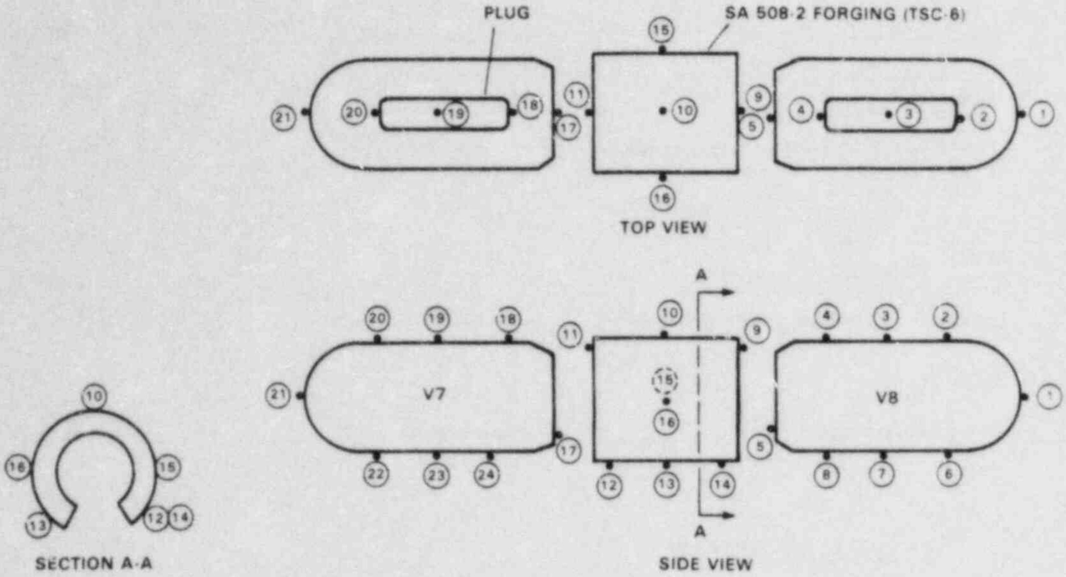


Figure 8. Thermocouple locations for final post-weld heat treatment of Vessels V-7 and V-8 and TSC-6 cylinder.

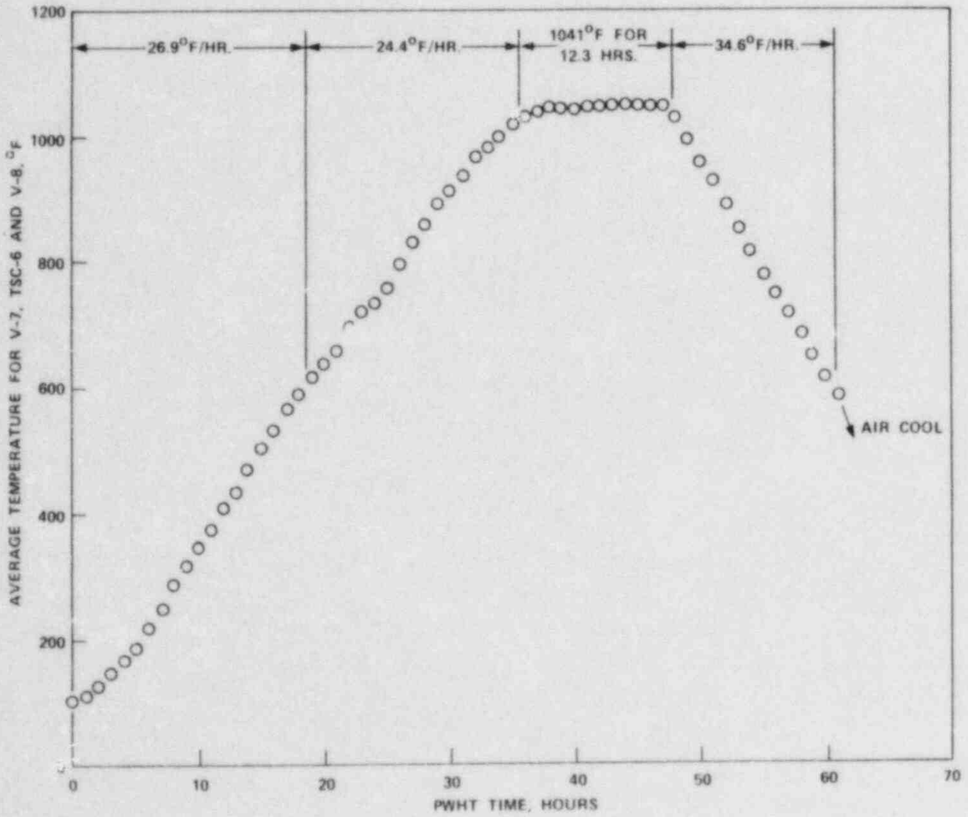


Figure 9. Average PWHT temperature of Vessels V-7 and V-8 and TSC-6 as a function of time.

Table 3

PWHT TEMPERATURES FOR V-7, V-8, AND TSC-6 (°F)

	V-7		TSC-6		V-8		
Time (hrs)	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg. for V-7, V-8 and TSC-6
0	145	27	81	7	89	4	105
1	146	22	94	9	97	5	112
2	153	21	112	17	111	10	125
3	169	19	143	11	134	13	149
4	182	21	166	9	156	16	168
5	201	22	194	11	180	18	192
6	223	22	226	12	211	19	220
7	252	24	261	14	243	24	252
8	293	21	299	16	278	24	290
9	322	22	329	14	308	23	320
10	346	22	356	14	332	22	345
11	378	21	389	14	367	20	378
12	405	23	416	17	400	20	407
13	438	24	448	16	429	20	438
14	470	23	483	13	464	18	472
15	501	21	514	14	490	18	502
16	534	20	545	14	520	19	533
17	559	21	572	12	554	16	562
18	583	19	598	12	589	16	590
19	604	19	619	13	616	20	613
20	623	20	641	10	643	20	636
21	647	16	661	11	665	19	658
22	688	12	688	11	689	17	688
23	725	14	716	12	716	15	719
24	732	11	729	9	731	16	731
25	759	9	757	11	759	9	758
26	793	10	796	11	794	9	794
27	829	7	831	11	833	11	831
28	860	5	859	12	859	12	859
29	888	5	887	13	884	12	886
30	914	6	914	13	908	14	912
31	936	7	939	11	929	16	935
32	960	5	964	7	961	16	962
33	976	7	983	8	982	13	980
34	993	7	999	9	1001	9	998
35	1011	7	1015	10	1021	9	1016
36	1024	9	1028	11	1033	10	1028
37	1034	8	1039	9	1042	9	1038
38	1039	8	1042	8	1044	8	1042
39	1039	8	1041	7	1044	6	1041
40	1039	8	1039	9	1043	7	1040
41	1042	9	1044	8	1044	7	1043
42	1042	9	1046	8	1045	8	1044
43	1044	9	1047	10	1046	8	1046
44	1044	9	1042	6	1044	7	1043
45	1045	9	1042	7	1044	7	1044
46	1045	9	1042	5	1044	7	1044
47	1045	9	1042	5	1044	7	1044
48	1028	5	1024	6	1028	5	1027
49	991	2	989	4	995	5	992
50	954	7	955	6	963	5	957
51	918	8	920	6	927	6	922
52	879	8	882	8	889	9	883
53	842	8	846	7	854	9	847
54	806	10	811	7	820	9	812
55	773	10	776	8	785	9	778
56	741	11	743	9	752	10	745
57	711	10	715	10	723	10	716
58	678	9	676	11	688	8	681
59	642	10	639	10	654	9	645
60	608	9	606	10	620	9	611
61	582	9	575	11	590	10	582

Table 4

COMPARISONS AMONG V-7, V-8, AND TSC-6

	Avg. Temperature (°F)			
Time (hrs)	V-7	TSC-6	V-8	V-7, V-8 and TSC-6
0	145	81	89	105
18	583	598	589	590
19	604	619	616	613
Time to Reach 600°F in Heating, hrs	18.8	18.1	18.4	18.4
Avg. Heating Rate to 600°F, °F/hr	24.4	29.7	28.6	26.9
Max. Heating Rate to 600°F, °F/hr	41	35	35	38
35	1011	1015	1021	1016
36	1024	1028	1033	1028
37	1034	1039	1042	1038
Time to Reach 1025°F in Heating, hrs	36.1	35.8	35.3	35.8
Avg. Heating Rate 600-1025°F, °F/hr	24.6	24.0	25.1	24.4
Max. Heating Rate 600-1025°F, °F/hr	41	39	39	37
47	1045	1042	1044	1044
48	1028	1024	1028	1027
49	991	989	995	992
Time to Reach 1025°F After Holding, hrs	48.1	47.9	48.1	48.1
Avg. Hold Time, hrs	12.0	12.1	12.8	12.3
Avg. Hold Temperature Greater Than 1025°F, °F	1041	1041	1041	1041
Tempering Parameter* for Hold X 10^{-3}	31.6	31.6	31.7	31.6
60	608	606	620	611
61	582	575	590	582
Time to Reach 600°F in Cooling, hrs	60.3	60.2	60.7	60.4
Avg. Cooling Rate 1025-600°F, °F/hr	34.8	34.6	33.7	34.6
Max. Cooling Rate 1025-600°F, °F/hr	39	38	36	39

---

*TP = T°R (20 + log t) when t = time in hours

Magnetic particle tests were performed after final machining of the vessels. Vessel V-8 was acceptable, while Vessel V-7 had some small indications on the OD of the weld that were accepted by UCC - ND. A radiographic flaw indication that was twice the size of that allowed by the ASME BPVC, in accordance with UCC - ND's contract specifications, was detected before and after PWHT of Vessel V-8. This indication, which was accepted by UCC - ND, was classified as a slag-type defect located about 2-1/2 inches away from the ID in a position illustrated in Figure 10. There was apparently no change in the size of the indication resulting from the PWHT.

OD dimensions of the vessels after final machining are shown in Figure 11.

Helium leak tests were performed on both vessels with a closure head and seal in place. No leaks were detected with a Veeco Leak Detector. The sensitivity of the probe was demonstrated and verified by sniffing and observing a calibrated standard helium leak of 1.4 x 10^{-6} standard cc/sec.

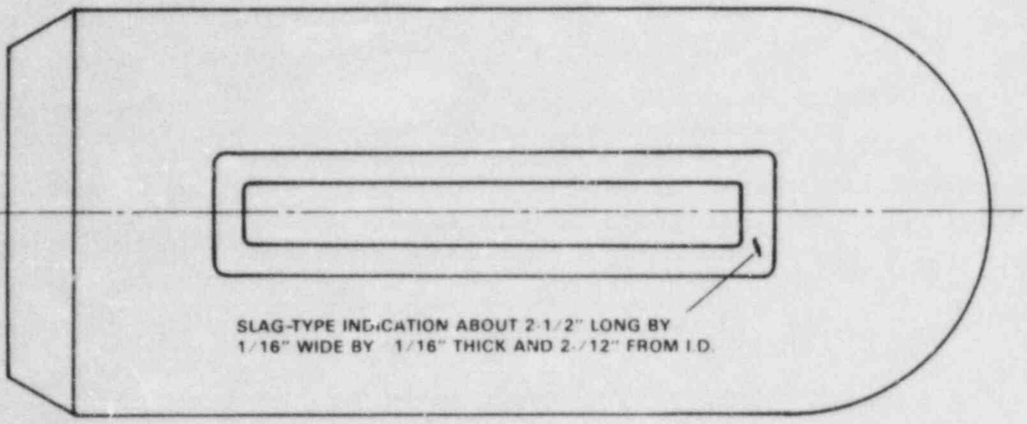


Figure 10. Location of slag-type indication in Vessel V-8 located by radiographic testing before and after PWHT.

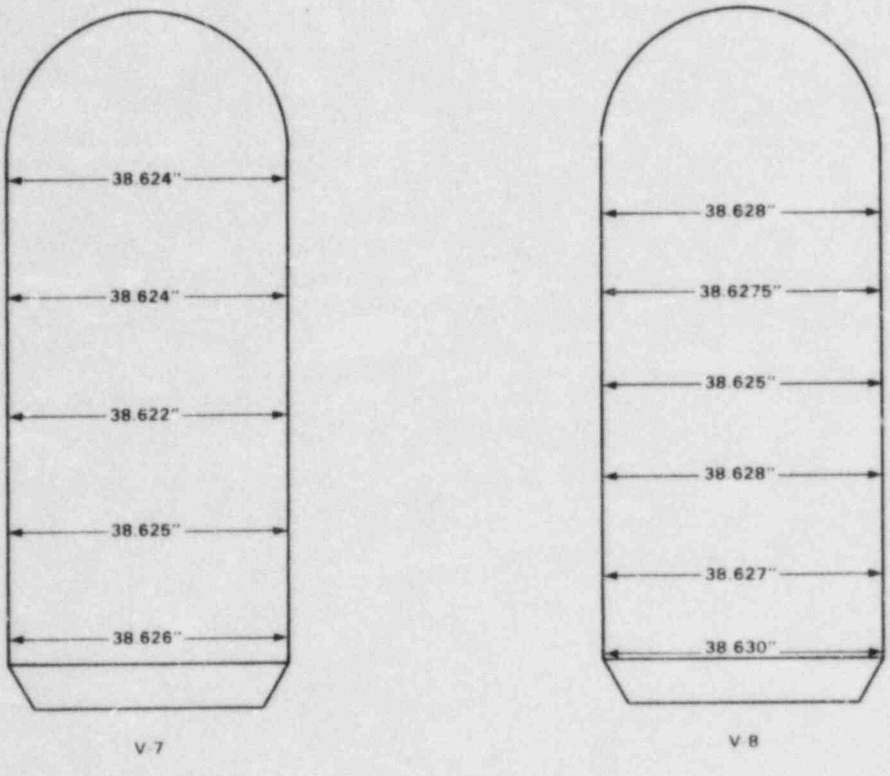


Figure 11. OD dimensions of machined vessels.

3. CHARACTERIZATION TESTING

The following test results were obtained from a piece taken from TSC-6 after heat treatment with Vessels V-7 and V-8 and represent the properties of the inserts placed in both vessels.

3.1 LOCATION OF SAMPLES

Two segments were cut from TSC-6 after the PWHT with Vessels V-7 and V-8. One segment designated V71 was used for the testing as described in this report. The other segment, V72, was shipped to Battelle Columbus Laboratories for crack-arrest testing. The location of these segments with respect to the vessel inserts is shown in Figure 12.

3.1.1 Test Matrix

The allocation of 15 tensile, 60 Charpy V-notch, 60 plane strain, and 25 J-integral test specimens according to their depth in test piece V71 and test temperatures is shown in Table 5. Their location relative to each other is shown in Figure 13.

In those cases where specimens were scrapped, others were made with the same relative location with respect to the ID of V71. All replacements occurred for 1-inch-thick compact tension (1TCT) plane strain fracture toughness specimens designated as "K-type." The following substitutions were made:

- V71K3 -- replaced by V71S11
- K9-12 -- replaced by V71K41-44
- K13 -- replaced by another location within the same block (No. 13)
- K14 -- replaced by another location within Block No. 14
- K2 and K6 -- a mixup in stamping these specimens was not resolved and one was stamped K61 and the other K62. They were not remade.

Specimens marked S9, S10, and S11 were also used for plane strain fracture toughness tests

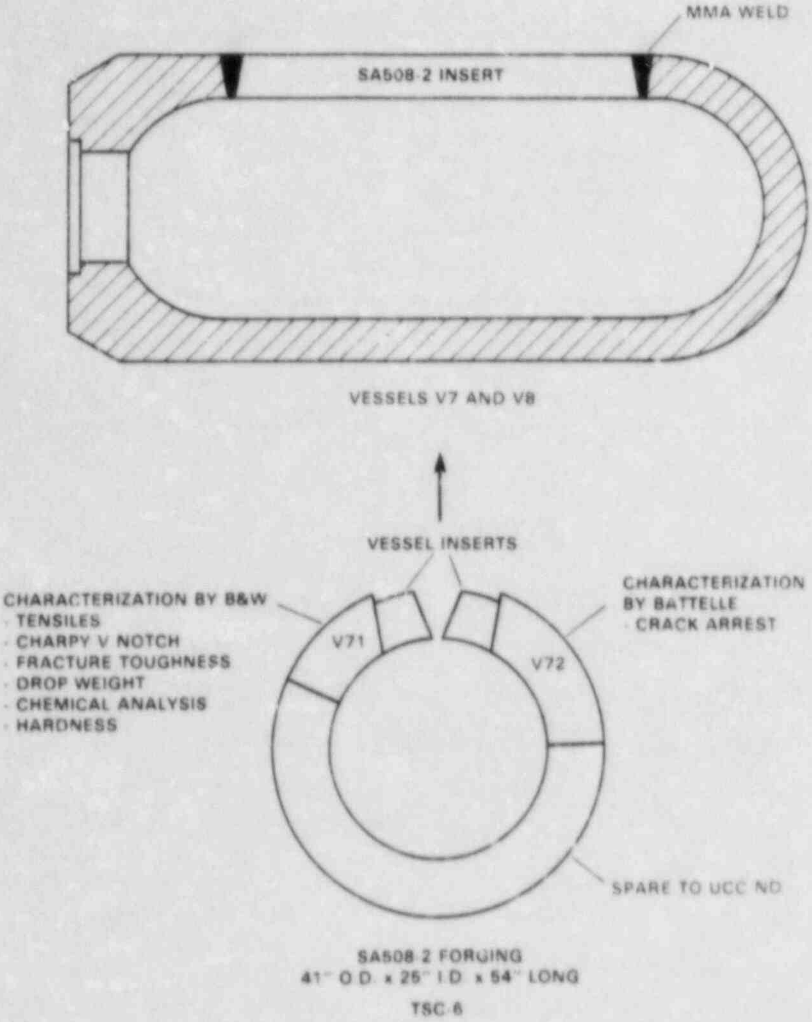
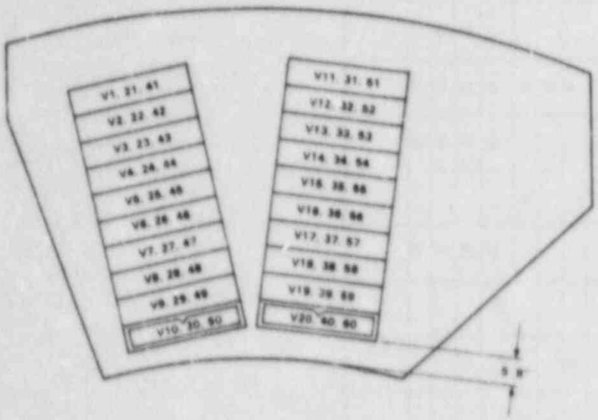
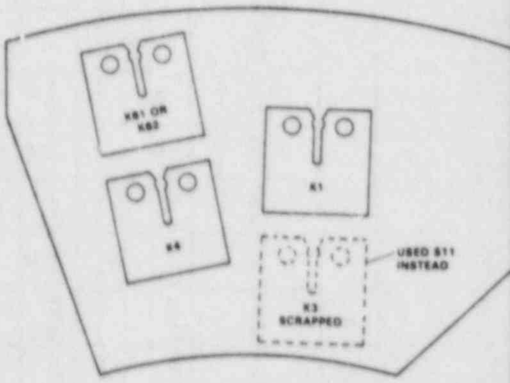


Figure 12. Location of vessel inserts and characterization test pieces.

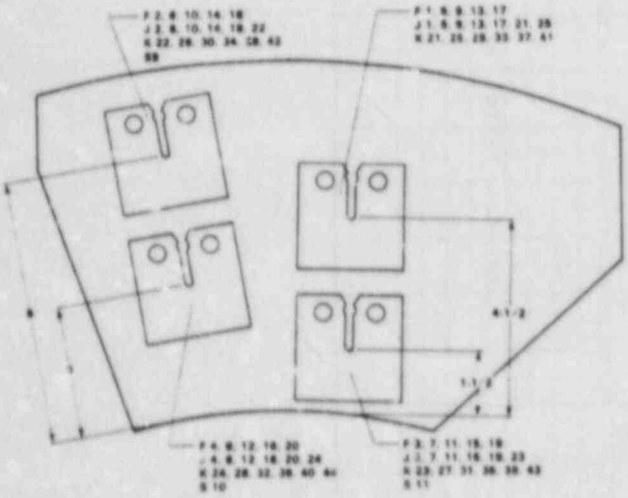
BLOCKS 3, 16, 31



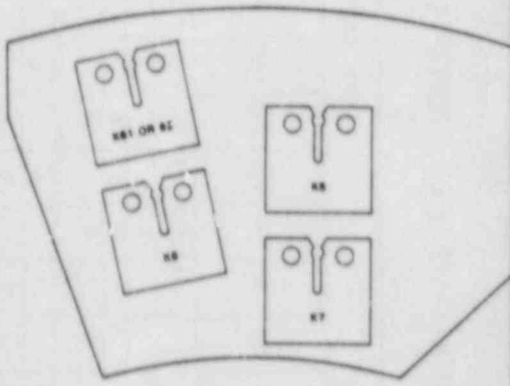
BLOCK 6

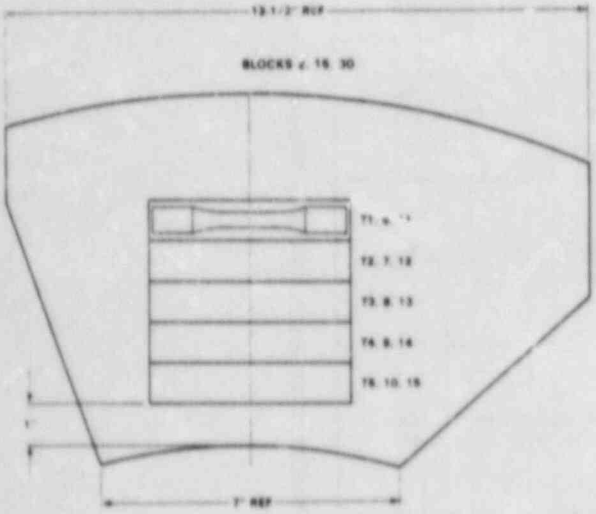


BLOCKS 4, 5, 7, 8, 10, 11, 19-28, 32

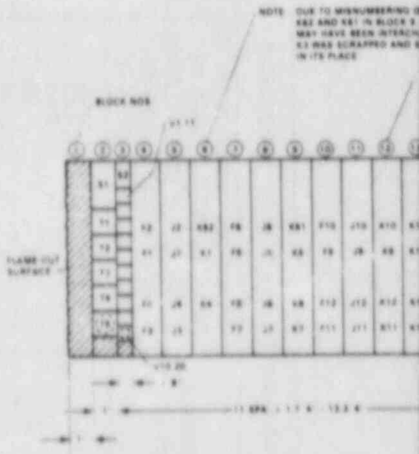


BLOCK 9





BLOCKS 2, 15, 30



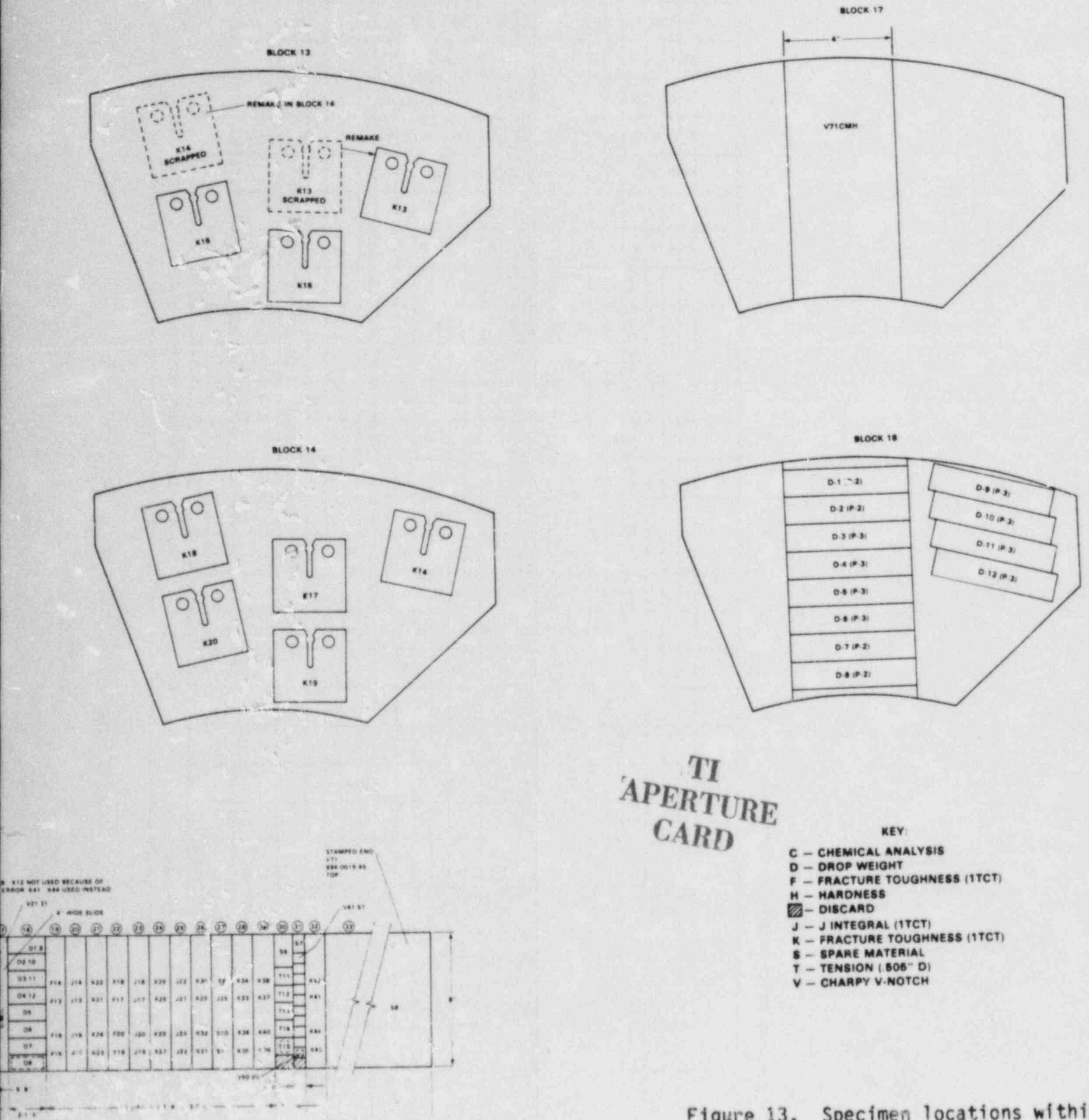


Figure 13. Specimen locations within characterization test segment V71.

Also Available On Aperture Card

8407020266-01

Table 5

TEST MATRIX-SPECIMEN IDENTIFICATION

APPROXIMATE LOCATION OF SPECIMENS			TEST TEMPERATURE, NEAREST 5°F																					
DISTANCE FROM ID, IN	FRACTION OF WALL IN TSC-6, ID = 0t OD = 1t	FRACTION OF WALL IN TEST VESSEL, ID = 0t OD = 1t	-50	-10	0	25	50	75	100	125	150	160	175	200	215	225	240	250	260	275	300	350	425	500
TENSION TESTS — .505" DIAMETER — TANGENTIAL DIRECTION																								
1.5	0.19	0.25																		●	●			●
2.5	0.31	0.42						●						●								●		
3.5	0.44	0.58						●		●								●						
4.5	0.56	0.75		●				●		●														
5.5	0.69	0.92	2	●																				
CHARPY V-NOTCH — NOTCH IN RADIAL DIRECTION																								
0.9	0.12	0.15							●		●							●		●	●			●
1.5	0.19	0.26					●		●	●				●						●	●			
2.2	0.27	0.36				●		●		●			●					●			●			
2.8	0.35	0.46			●			●	●		●					●				●				
3.4	0.42	0.56					●		●	●				●							●			●
4.0	0.50	0.67				●		●	●	●			●							●				
4.7	0.58	0.77			●			●	●		●							●			●			
5.3	0.65	0.87					●		●	●						●				●				●
5.9	0.73	0.97				●		●		●				●				●			●			
6.5	0.81	1.08			●			●	●				●			●				●				
PLANE STRAIN FRACTURE TOUGHNESS TESTS — NOTCH IN RADIAL DIRECTION																								
1.5	0.19	0.25						2		2	●		3		5				●		●			
3.0	0.38	0.50						2		2			3		5	●					2			
4.5	0.56	0.75						2		3		●	4		2				2		●			
6.0	0.75	1.00						2		3			5		3				●		●			
J-INTEGRAL TESTS — NOTCH IN RADIAL DIRECTION																								
1.5	0.19	0.25																●		●	●	●		2
3.0	0.38	0.50																●		●	●	2		●
4.5	0.56	0.75																2		●	●	●	●	●
6.0	0.75	1.00																●		●	●	●	●	●

SINGLE SPECIMENS UNLESS OTHERWISE INDICATED.

3.2 TEST PROCEDURES

The following test results were obtained with R&DD Project Technical Plan and Quality Assurance Plan No. 82C27 approved by UCC - ND. The following ASTM test specifications, unless otherwise noted, were used for characterization testing performed by the B&W Research and Development Division:

- Tension -- E-8-81 or E-21-79
- Charpy V-Notch -- E-23-82
- Plane Strain Fracture Toughness -- E-399-81
- J-Integral -- E-813-81 and ARC TP-367
- Macrostructure -- E-340-68
- Hardness -- E-18-79

The following tests were provided by B&W's Nuclear Equipment Division to meet these specifications:

- Drop Weight -- ASTM E-208-81
- Chemical Analyses -- NB2432, Section III, ASME BPVC, 1974 Edition with Summer 1977 Agenda

3.3 CHEMICAL COMPOSITION

Seven areas located at 1-inch intervals along a radial line of specimen V71CMH starting 1 inch from the ID were analyzed for chemical composition using a spectrographic technique. The results are shown in Table 6. These analyses agree well with the test report data given in Table 1.

3.4 MACROSTRUCTURE AND HARDNESS TESTS

The macrostructure of a transverse section designated V71CMH is shown in Figure 14. A short radial section of Block 18 is shown in Figure 15.

Hardness tests were also performed on specimen V71CMH. This was done by laying out 10 radial lines about 0.2 inch apart and measuring the hardness on 0.2-inch centers along the lines, starting at 0.1 and 0.2 inch from the ID for Rockwell A and G tests, respectively. The averages of the 10 isoradius measurements are plotted in Figure 16.

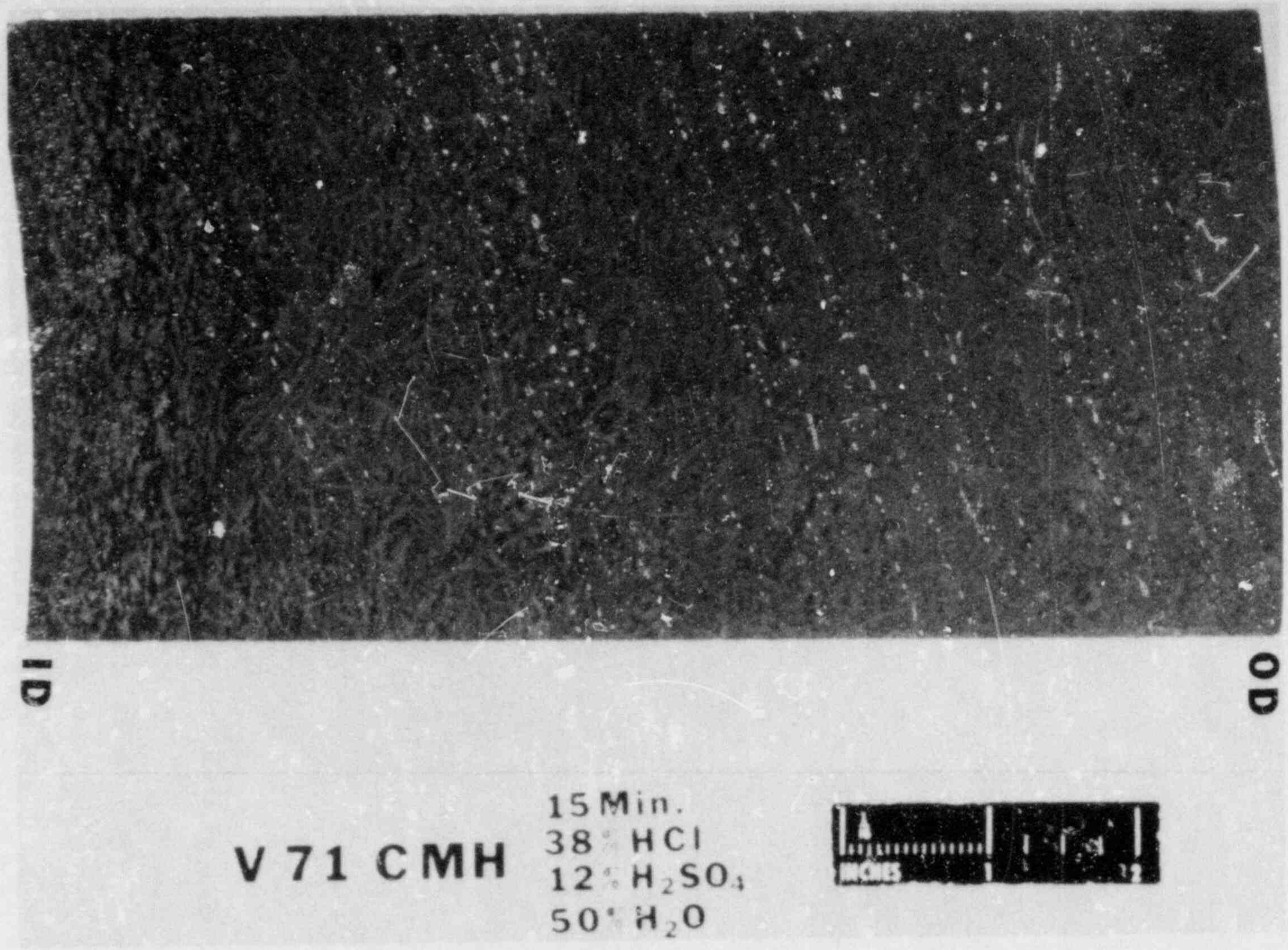


Figure 14. Photomacrograph of transverse section of Specimen V71CMH.

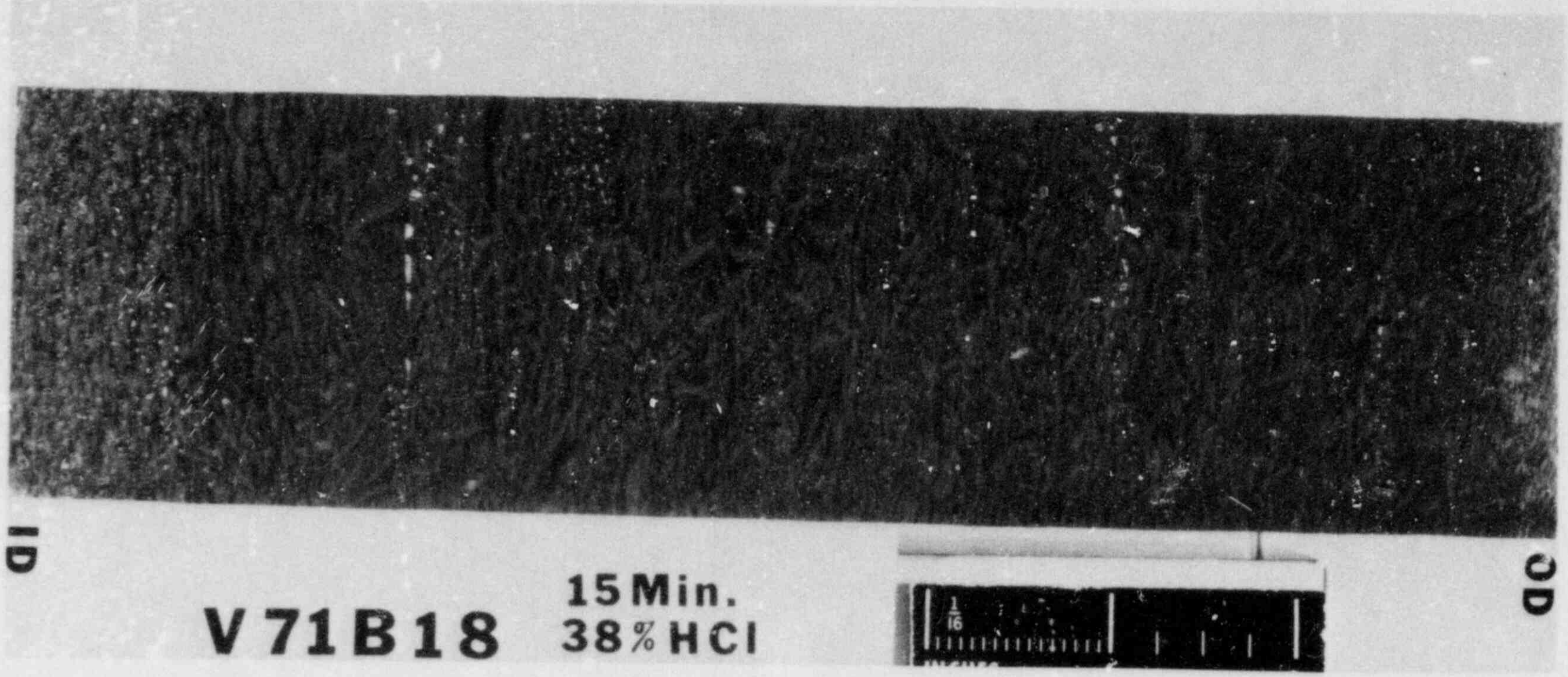


Figure 15. Photomacrograph of radial section of Specimen V71B18.

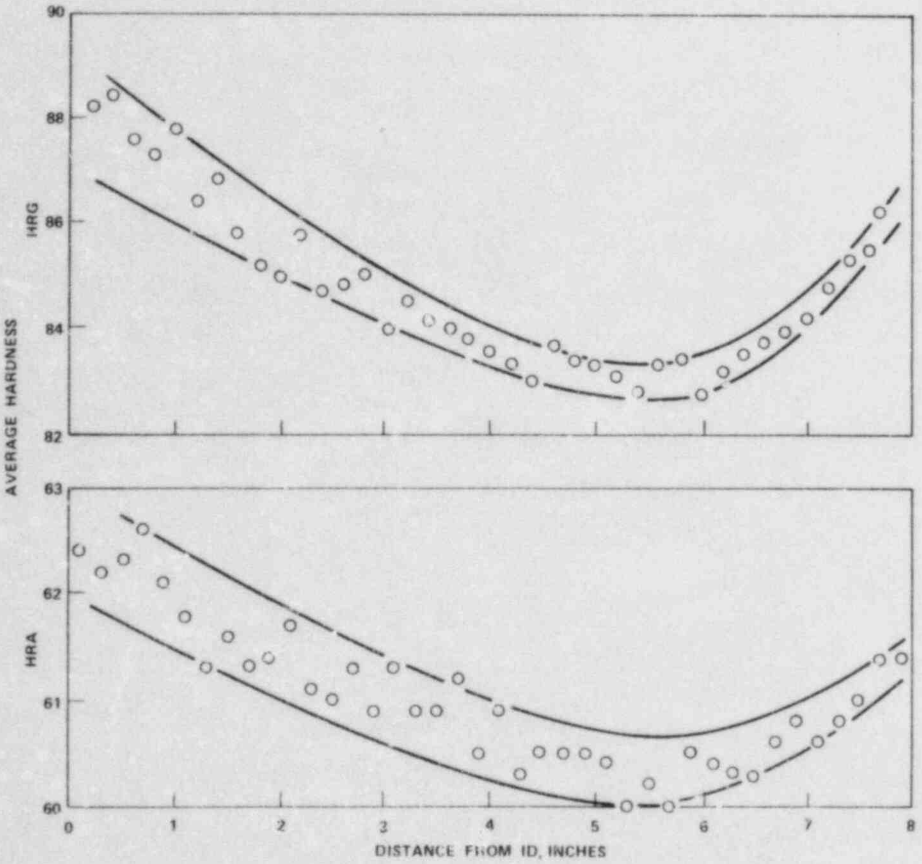


Figure 16. Hardness as a function of distance from ID of V71CMH.

Table 6

CHEMICAL ANALYSES RESULTS FOR SPECIMEN V71CMH
(Weight %)

Approximate Distance from ID (in)	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Sn	V
1	.20	.68	.017	.016	.18	.38	.78	.68	.09	.003	.008
2	.21	.68	.017	.014	.19	.36	.78	.68	.09	.003	.008
3	.20	.66	.016	.013	.18	.36	.78	.68	.09	.003	.007
4	.20	.67	.016	.014	.19	.36	.78	.68	.09	.003	.008
5	.20	.67	.016	.013	.18	.36	.78	.67	.09	.003	.007
6	.19	.67	.016	.013	.18	.37	.78	.67	.09	.004	.007
7	.19	.66	.016	.014	.18	.37	.78	.67	.09	.003	.007

These results are similar to those obtained for a piece removed from TSC-6 after the first temper of 973°F for 9.5 hours (Figure 17).

3.5 TENSION TESTS

Fifteen tension tests of 0.505-inch-diameter by 2-inch gauge length specimens taken from various locations of test piece V71 were performed at temperatures ranging from -50° to 500°F. These results are provided in Table 7.

3.6 CHARPY V-NOTCH IMPACT TESTS

Sixty Charpy V-notch impact tests taken from various locations of test piece V71 were performed at temperatures ranging from 0° to 500°F. The results are presented in Table 8 and plotted in Figure 18.

3.7 DROP WEIGHT TESTS

Twelve tests were performed; however, the results obtained did not produce a clearly defined nil-ductility transition temperature. Initial tests were performed on 3/4-inch-thick P-2 specimens, and later tests were performed on 5/8-inch-thick P-3 specimens. The results shown in Table 9 are in order of testing.

3.8 PLANE STRAIN FRACTURE TOUGHNESS TESTS

These tests, reported in Table 10, were performed in accordance with ASTM E-399-81 except that:

- The extensometer used for plane strain tests did not meet the requirements of Paragraph 6.3.1 of ASTM E-399-81 in that the maximum difference between the actual and calculated displacement was 0.00023 inch and this was greater than the 0.0001 inch allowed. Since the determination of K_{Ic} is done with a load determination which has a limit of ±1% accuracy or about six times the largest deviation of the extensometer used, this deviation from ASTM E-399-81 requirements is not considered to be significant in the test results.
- Specimens V71F10 and F11, V71F13 through F20, and V71S9 were intentionally tested with 20% deep side grooves (10% per side) and a specially written computer program that controlled the specimen loading by strain control in an attempt to obtain crack-arrest stress intensities. No crack arrests were detected; however, the plane strain test results are also reported in Table 10.

Photographs of the fractured surfaces are presented in Appendix A.

3.9 J-INTEGRAL TEST RESULTS

These were performed as single specimen computer controlled J-tests on 1TCT test specimens having 20% side grooves (10% per side). The test results are summarized in Table 11. The individual test results of load versus displacement, J versus Δa, and fracture surface photographs are contained in Appendix B.

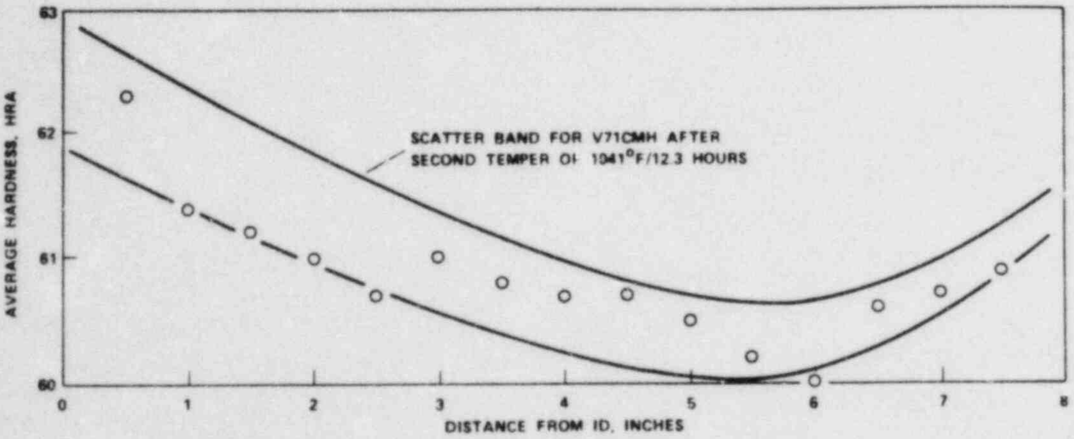


Figure 17. Hardness as a function of distance from ID for TSC-6 after first temper of 973°F for 9.5 hours.

Table 7

TENSILE TEST RESULTS FOR V71

Specimen Identification	Distance from ID (in)	Test Temp (°F)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)
V71T1	5.5	-10	91.558	115.600	21.5	57.1
2	4.5	70	89.921	112.494	20.5	59.1
3	3.5	125	89.440	111.862	20.5	59.2
4	2.5	200	87.052	108.753	20.0	59.4
5	1.5	300	86.949	108.624	19.5	57.1
6	5.5	-50	93.482	117.792	21.0	55.4
7	4.5	-10	91.916	116.585	21.0	56.4
8	3.5	75	90.117	113.332	20.0	59.2
9	2.5	75	91.558	114.354	20.0	56.2
10	1.5	500	89.973	111.276	18.5	57.3
11	5.5	-50	92.296	117.059	21.5	58.0
12	4.5	125	86.815	109.300	21.0	61.4
13	3.5	250	84.975	105.594	19.0	60.3
14	2.5	350	85.306	105.635	18.5	56.7
15	1.5	275	89.688	111.423	17.5	56.6

Table 8

CHARPY V-NOTCH TEST RESULTS

Specimen Identification	Approximate Distance from ID (in)	Test Temp. (°F)	Absorbed Energy (ft-Lbs)	Lateral Expansion (Mils)	Shear (%)
V71V1	6.5	0	3.9	2	0
V2	5.9	25	18.1	15	10
V3	5.3	50	4.0	1	0
V4	4.7	0	3.1	1	0
V5	4.0	25	6.5	7	0
V6	3.4	50	5.6	5	0
V7	2.8	0	18.8	14	10
V8	2.2	25	4.8	2	0
V9	1.5	50	27.1	19	10
V10	.9	100	20.8	12	10
V11	6.5	75	25.4	20	15
V12	5.9	75	14.6	9	1
V13	5.3	100	26.0	17	10
V14	4.7	75	14.9	11	0
V15	4.0	75	10.0	8	0
V16	3.4	100	25.7	18	1
V17	2.8	75	7.8	3	0
V18	2.2	75	20.0	14	10
V19	1.5	100	23.2	15	10
V20	.9	150	25.3	15	15
V21	6.5	100	34.1	25	25
V22	5.9	125	19.9	15	10
V23	5.3	125	28.0	20	15
V24	4.7	100	33.2	24	10
V25	4.0	100	22.1	16	10
V26	3.4	125	13.9	10	10
V27	2.8	100	24.8	16	15
V28	2.2	125	20.0	13	10
V29	1.5	125	26.8	19	15
V30	.9	250	44.0	35	35
V31	6.5	175	42.2	34	30
V32	5.9	200	49.8	38	40
V33	5.3	225	70.2	56	80
V34	4.7	150	35.3	27	20
V35	4.0	125	37.2	24	20
V36	3.4	200	45.0	35	40
V37	2.8	150	50.8	37	40
V38	2.2	175	39.0	32	30
V39	1.5	200	37.6	28	30
V40	.9	275	67.5	51	90
V41	6.5	225	80.0	57	90
V42	5.9	250	79.9	57	90
V43	5.3	275	82.0	62	100
V44	4.7	250	66.5	50	80
V45	4.0	175	37.0	27	30
V46	3.4	300	85.3	69	100
V47	2.8	225	32.8	30	40
V48	2.2	250	70.4	54	90
V49	1.5	275	68.3	54	90
V50	.9	300	86.2	60	100
V51	6.5	275	91.2	66	100
V52	5.9	300	92.3	70	100
V53	5.3	500	83.6	64	100
V54	4.7	300	85.0	61	100
V55	4.0	275	8[illegible].2	63	100
V56	3.4	500	80.6	66	100
V57	2.8	275	75.9	63	95
V58	2.2	300	83.6	62	100
V59	1.5	300	[illegible]4.0	54	95
V60	.9	500	79.0	58	100

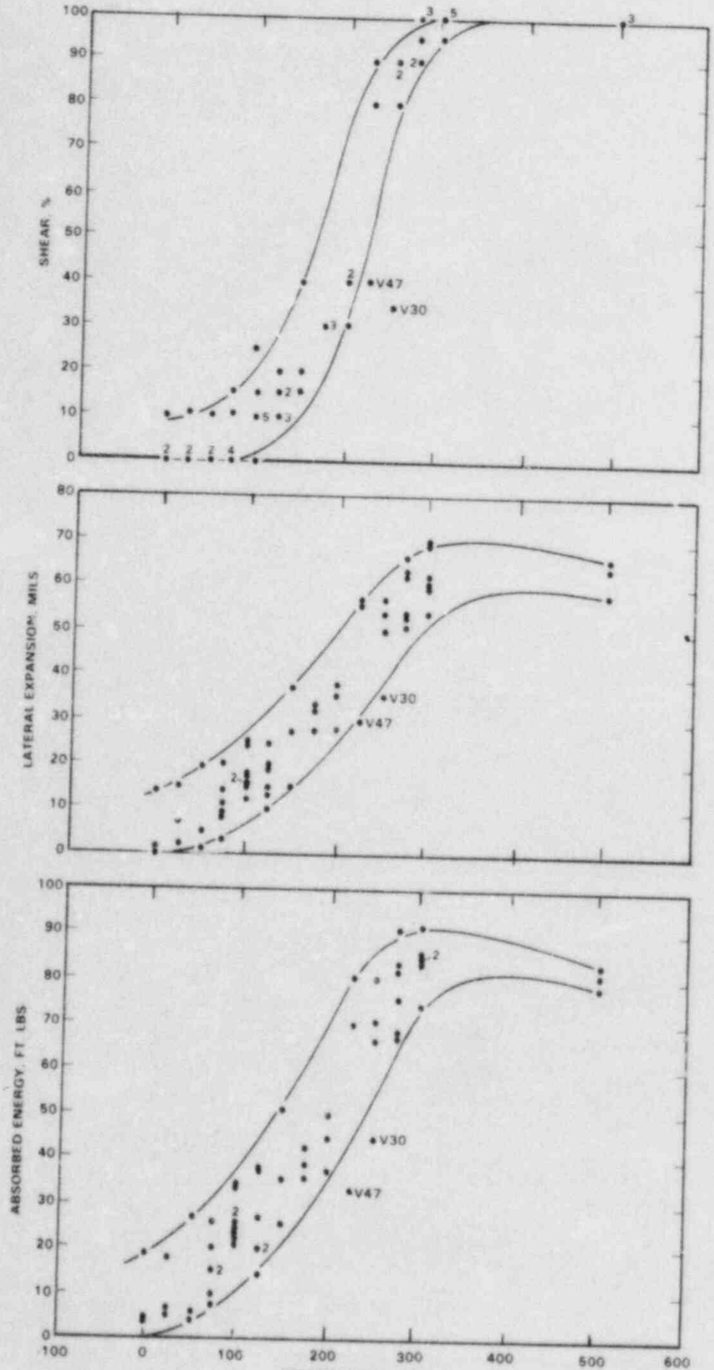


Figure 18. Charpy V-notch impact properties as a function of test temperature.

Table 9

DROP WEIGHT TEST RESULTS
(Impact load = 350 ft-lbs)

Specimen Identification	Specimen Type	Test Temp. (°F)	Result
V71 D1	P2	+100	No test*
D8	P2	+60	No test*
D2	P2	+20	No test*
D2	P2	-20	No test*
D6	P3	+170	No break
D3	P3	+160	No break
D4	P3	+160	No break
D5	P3	+150	Break
D12	P3	+150	No break
D11	P3	+130	No break
D10	P3	+90	No break
D9	P3	+50	Break

---

* Heat affected zone stoppage of the crack.

Table 10

PLANE STRAIN FRACTURE TOUGH

Fatigue Precracking Last 2.5% of "A"

$K_{max}^{(2)}$ = 15.0 ksi$\sqrt{in}$; $\Delta K^{(2)}$ = 13.5 ksi$\sqrt{in}$

Spec. Ident.	Distance of Machined Notch to ID (in)	Test Temp. (°F)	Thickness B (in)	Width, w[3] (in)	Fatigue Precracking Last 2.5% of "A", x 10-3 Cycles	Crack Length, In.			
						Left Surface	Left of Center	Center	Right of Center
V71K1	4.5	124	1.000	1.998	230	1.001	1.039	1.050	1.035
4	3.0	76	1.000	1.998	223	.993	1.032	1.031	1.018
5	4.5	126	1.000	1.998	210	.993	1.034	1.040	1.028
7	1.5	76	1.000	1.998	305	.975	1.031	1.044	1.024
8	3.0	75	1.000	2.000	415	.978	1.024	1.026	1.021
13	4.5	75	1.002	1.999	274	.981	1.021	1.034	1.036
14	6.0	76	1.003	2.000	300	1.006	1.037	1.035	1.022
15	1.5	126	1.004	1.998	210	.995	1.038	1.046	1.034
16	3.0	125	1.003	1.997	220	.994	1.033	1.046	1.037
17	4.5	75	1.004	1.998	310	.985	1.020	1.034	1.030
18	6.0	75	1.000	1.999	318	.987	1.010	1.015	1.012
19	1.5	171	1.000	1.998	290	.987	1.020	1.032	1.023
20	3.0	171	1.000	1.999	385	.988	1.006	1.008	1.011
21	4.5	125	1.003	1.998	270	.991	1.030	1.046	1.040
22	6.0	125	1.004	1.998	345	.980	1.027	1.042	1.036
23	1.5	171	1.000	1.998	247	.985	1.006	1.001	0.999
24	3.0	171	1.004	1.998	230	1.000	1.023	1.031	1.023
25	4.5	170	1.000	1.998	249	.992	1.031	1.046	1.044
26	6.0	171	1.000	1.998	286	1.001	1.018	1.032	1.020
27	1.5	215	1.000	1.998	241	.972	1.010	1.030	1.030
28	3.0	(7)	---	1.998	378	---	---	---	---
29	4.5	170	1.003	1.998	276	.982	1.018	1.019	1.008
30	6.0	171	1.003	1.998	371	.983	1.028	1.033	1.026
31	1.5	215	1.000	1.998	214	.982	1.004	1.012	1.006
32	3.0	216	1.000	1.998	150	.993	1.018	1.021	1.016
33	4.5	171	1.002	1.998	221	.988	1.024	1.036	1.036
34	6.0	171	1.000	1.998	381	.984	1.019	1.019	1.006
35	1.5	214	1.000	1.997	350	1.000	1.031	1.042	1.031
36	3.0	215	1.003	1.998	272	1.008	1.036	1.046	1.039
37	4.5	216	1.000	1.998	272	1.000	1.029	1.040	1.037
38	6.0	171	1.000	1.998	480	.981	1.020	1.028	1.011
39	1.5	215	1.003	1.997	300	1.010	1.036	1.040	1.037

---

* P. Oblique = Partially Oblique

(1) Nominal value calculated for a/w = 0.5 using requested loading rate.
(2) Nominal value calculated for a/w = 0.5 using actual precrack loads.
(3) Average of two measurements made from centerline of crack loading pin to back surface of specimen.

(4) Ambient value; not measured insi
(5) Entire load displacement curve w
space for the displacement axis.
displacement are greater than th
(6) Recorded slope of load displacem
(7) No test.
(8) Strain control.

ESS TEST RESULTS

Relative Humidity$^{(4)}$: 60%, Loading Rate $(K/t)^{(1)}$ = 1.16 ksi $\sqrt{in}$/sec

Right Surface	Fracture Appearance*	Yield Strength, (ksi)	P_{max}/P_Q	(K_{Ic}) or K_Q (ksi$\sqrt{in}$)	Validity I-Invalid V-Valid	R_{SC}	$2.5\ (K_Q/\sigma_y)^2$	J_{max} In-Lb/In^2	K_J max ksi$\sqrt{in}$
.990	Oblique	87.7	1.45	76.7	I	1.91	---	514	123
.989	P. Oblique	90.8	1.28	77.8	I	1.64	---	347	102
.988	Oblique	87.7	1.42	76.7	I	1.86	---	462	117
.980	Oblique	91.7	1.21	89.3	I	1.76	---	428	113
.982	Oblique	90.8	1.31	88.6	I	1.90	---	550	128
.996	Oblique	89.9	1.30	84.1	I	1.83	---	470	119
.980	Oblique	89.0	1.32	81.4	I	1.81	---	439	115
.995	Oblique	89.6	2.42	43.2	I	1.75	---	446	116
.998	Oblique	88.7	1.70	84.1	I	2.44	---	1380	202
.989	Oblique	89.9	1.37	76.5	I	1.75	---	415	112
.981	P. Oblique	89.0	1.12	71.2	I	1.33	1.62	223	81.8
.995	P. Oblique	88.4	1.22	77.2	I	1.59	---	311	95.7
.999	Oblique	87.5	2.05	68.3	I	2.35	---	1670	222
.987	Oblique	87.8	1.67	79.9	I	2.29	---	1060	177
.986	Oblique	86.9	1.74	78.2	I	2.35	---	1200	189
.979	Oblique	88.4	1.81	80.2	I	2.41	---	1260	192
.985	Oblique	87.5	2.11	66.3	I	2.38	---	>1310$^{(5)}$	>196$^{(5)}$
1.025	Oblique	86.7	1.88	73.0	I	2.38	---	2340	262
.986	Oblique	85.8	1.88	73.4	I	2.40	---	1580	215
.939	Oblique	87.2	1.40	78.8	I	1.89	---	1302	195$^{(6)}$
---	---	---	---	---	---	---	---	---	---
.970	Oblique	86.7	1.97	71.2	I	2.39	---	2560	274
.991	Oblique	85.8	1.85	75.4	I	2.43	---	2220	256
.964	Oblique	87.2	1.49	69.5	I	1.74	---	408	109
.980	Oblique	86.3	1.69	67.4	I	1.96	---	573	129
1.005	Oblique	86.7	1.74	78.3	I	2.38	---	1730	226
.989	Oblique	85.8	1.64	83.2	I	2.35	---	2190	254
1.008	Oblique	87.2	2.27	60.4	I	2.37	---	1260	192
1.002	Oblique	86.3	1.97	69.3	I	2.38	---	2175	252
.996	Oblique	85.5	1.99	66.7	I	2.33	---	2120	249
.972	Oblique	85.8	2.38	55.4	I	2.28	---	1070	177
.996	Oblique	87.2	2.13	67.0	I	2.47	---	1490	208

test chamber at temperature.
not recorded because of lack of chart
alue reported assumes that final load and
recorded.
does not meet ASTM E-399-81 criterion.

8407020266-02

Tab

PLANE STRAIN FRACT

Fatigue Precracking Last 2.5% of "A"

$K_{max}^{(2)} = 15.0\ \mathrm{ksi}\sqrt{\mathrm{in}}$; $\Delta K^{(2)} = 13.5\ \mathrm{ksi}\sqrt{\mathrm{in}}$

Spec. Ident.	Distance of Machined Notch to ID (in)	Test Temp. (°F)	Thickness B (in)	Width, w(3) (in)	Fatigue Precracking Last 2.5% of "A", x 10^{-3} Cycles	Crack Length		
						Left Surface	Left of Center	Center
V71K40	3.0	215	1.003	1.998	247	.997	1.027	1.038
41	4.5	215	1.002	2.000	200	1.007	1.036	1.048
42	6.0	215	1.002	2.000	223	1.003	1.036	1.046
43	1.5	125	1.003	1.998	223	.986	1.034	1.038
44	3.0	126	1.003	1.999	212	1.000	1.039	1.046
61	6.0	125	1.001	1.998	449	.985	1.026	1.027
62	6.0	125	1.000	1.999	368	1.003	1.050	1.071
V71S10	3.0	215	1.003	1.998	260	.998	1.028	1.042
S11	1.5	75	1.004	1.998	311	1.006	1.037	1.046
V71F1	4.5	303	1.000	1.998	318	.986	1.018	1.024
F2	6.0	300	1.002	1.998	275	.992	1.034	1.047
F3	1.5	302	1.000	1.997	290	.989	1.024	1.030
F4	3.0	300	1.002	1.998	323	.996	1.042	1.044
F5(8)	4.5	258	1.000	1.998	380	.999	1.024	1.030
F6(8)	6.0	258	1.003	1.998	406	1.009	1.040	1.041
F7(8)	1.5	257	1.000	1.998	313	.096	1.025	1.029
F8	3.0	300	1.002	1.996	319	.987	1.024	1.034
F9(8)	4.5	257	1.000	1.998	335	1.005	1.031	1.042
F12	3.0	~222	1.003	1.998	318	1.003	1.035	1.045
Following specimens side grooved (10% per side):								
V71F10(8)	6.0	172	1.002	1.998	255	1.018	1.044	1.045
F11(8)	1.5	147	1.003	1.998	310	1.005	1.014	1.020
F13(8)	4.5	160	1.000	1.998	375	1.024	1.059	1.074
F14	6.0	(7)	---	---	---	---	---	---
F15(8)	1.5	172	1.000	1.997	290	1.010	1.028	1.035
F16(8)	3.0	173	1.000	1.998	331	1.033	1.045	1.046
F17(8)	4.5	171	1.000	1.998	353	1.016	1.034	1.036
F18(8)	6.0	215	1.000	1.998	420	1.018	1.034	1.030
F19(8)	1.5	215	1.000	1.998	295	1.017	1.034	1.036
F20(8)	3.0	215	1.001	1.998	310	1.008	1.026	1.025
V71S9(8)	6.0	215	1.002	1.999	312	1.004	1.027	1.037

---

* P. Oblique = Partially Oblique

(1) Nominal value calculated for a/w = 0.5 using requested loading rate.
(2) Nominal value calculated for a/w = 0.5 using actual precrack loads.
(3) Average of two measurements made from centerline of crack loading pin to back surface of specimen.

(4) Ambient value; not meas
(5) Entire load displacemen space for the displacem displacement are greate
(6) Recorded slope of load
(7) No test.
(8) Strain control.

e 10 (Con't)

URE TOUGHNESS TEST RESULTS

Relative Humidity$^{(4)}$: 60%, Loading Rate (K/t)$^{(1)}$ = 1.16 ksi$\sqrt{in}$/sec

, In.

Right of Center	Right Surface	Fracture Appearance*	Yield Strength, (ksi)	P_{max}/P_Q	(K_{Ic}) or K_Q (ksi$\sqrt{in}$)	Validity I-Invalid V-Valid	R_{SC}	$2.5 (K_Q/\sigma_y)^2$	J_{max} In-Lb/In^2	K_J max ksi$\sqrt{in}$
1.029	.996	Oblique	86.3	1.94	74.6	I	2.47	---	1979	240
1.028	.986	Oblique	85.5	1.26	72.6	I	1.60	---	306	94.5
1.041	.996	Oblique	84.6	1.77	76.3	I	2.41	---	1880	235
1.028	.989	Oblique	89.6	1.80	78.5	I	2.37	---	>1680$^{(5)}$	>223$^{(5)}$
1.033	.988	Oblique	88.7	1.92	71.9	I	2.35	---	>1630$^{(5)}$	>220$^{(5)}$
1.022	.987	Oblique	86.9	1.10	72.3	I	1.40	1.73	228	82.2
1.057	1.004	Oblique	86.9	1.62	82.3	I	2.32	---	1000	172
1.029	.994	Oblique	86.3	1.63	67.6	I	1.90	---	491	120
1.040	1.002	Flat	91.7	1.00	(57.4)	V	---	.98	101	55.0
1.011	.978	Oblique	85.2	2.01	66.0	I	2.31	---	1720	223
1.032	.994	Oblique	84.4	1.91	70.4	I	2.39	---	1760	225
1.022	1.000	Oblique	86.9	1.82	76.9	I	2.41	---	1480	207
1.022	.984	Oblique	86.1	1.79	75.8	I	2.37	---	1570	212
1.023	.992	Oblique	84.5	1.93	70.8	I	2.36	---	1410	202
1.033	1.004	Oblique	83.7	1.94	70.3	I	2.45	---	1740	224
1.023	.992	Oblique	86.2	1.90	75.8	I	2.47	---	1770	226
1.024	.998	Oblique	86.1	1.88	71.8	I	2.34	---	1550	211
1.039	1.014	Oblique	84.5	1.83	75.0	I	2.44	---	1520	210
1.040	1.010	Oblique	87.0	1.83	77.5	I	2.45	---	1610	217
1.031	1.012	Oblique	85.8	1.83	84.8	I	2.72	---	1790	230
1.018	1.003	Oblique	85.0	1.70	74.9	I	2.22	---	517	124
1.094	1.071	Oblique	86.9	1.58	80.6	I	2.24	---	595	132
---	---	---	---	---	---	---	---	---	---	---
1.030	1.016	Flat	88.4	1.00	72.1	I	1.21	1.66	144	65.1
1.036	1.021	Oblique	87.5	1.92	82.0	I	2.71	---	1300	195
1.034	1.021	Oblique	86.7	1.77	88.1	I	2.70	---	1590	216
1.020	1.007	Oblique	84.6	1.68	84.6	I	2.06	---	404	109
1.033	1.018	Oblique	87.2	1.81	81.2	I	2.55	---	819	155
1.022	1.006	Oblique	86.3	1.92	80.5	I	2.67	---	1720	224
1.035	1.014	Oblique	84.6	1.79	86.3	I	2.74	---	1920	237

red inside test chamber at temperature.
curve was not recorded because of lack of chart
nt axis. Value reported assumes that final load and
than that recorded.
isplacement does not meet ASTM E-399-81 criterion.

8407020266-03

Table 11

J-INTEGRAL TEST RESULTS

Load Rate: 0.0002 in/sec Load Line Displacement
Maximum Precracking Load: 2200 lbs
Maximum Precracking ΔK: 13.5 ksi $\sqrt{in}$

Specimen Identification	Distance of Machined Notch from ID (in)	Test Temp. (°F)	Specimen Thickness, B (in)	Net Thickness (in)	Specimen Depth, W (in)	Initial Crack Length, A_o (in)	Max. Deviation From Avg., A_o (in)	Initial Ligament $W-A_o$ (in)	Corrected Modulus ($\times 10^{-6}$ psi)	J_{Ic} (Kip/in)	Notes
V71J1	4.5	353	.999	.802	1.998	1.035	-.021	.963	28.539	.641	---
2	6.0	349	.999	.800	1.997	1.014	-.016	.983	28.446	.765	---
3	1.5	350	.999	.802	1.998	1.019	-.018	.979	28.750	.766	---
4	3.0	350	.999	.798	1.997	1.018	-.017	.979	28.757	.752	---
5	4.5	252	.999	.802	1.998	1.021	-.014	.977	29.077	.653	1
6	6.0	252	.999	.800	1.996	1.026	-.017	.970	29.262	.570	1
7	1.5	251	.998	.802	1.997	1.032	-.016	.965	29.096	.062	1, 2
8	3.0	350	1.000	.798	1.998	1.026	-.015	.972	28.933	.728	---
9	4.5	250	1.003	.804	1.997	1.041	-.011	.956	29.651	.743	1
10	6.0	500	1.003	.803	1.997	1.048	-.018	.949	28.650	.821	4
11	1.5	500	1.003	.804	1.996	1.045	-.016	.951	28.262	.863	4
12	3.0	250	1.002	.807	1.997	1.030	-.011	.967	29.497	.717	1, 3
13	4.5	500	1.004	.807	1.997	1.042	-.016	.955	28.326	.705	4
14	6.0	300	1.003	.805	1.996	1.031	-.012	.965	29,804	.836	---
15	1.5	500	1.003	.805	1.995	1.041	-.016	.954	28,633	.754	4
16	3.0	500	1.004	.803	1.997	1.038	-.013	.959	28.433	.773	4
17	4.5	300	1.004	.805	1.997	1.029	-.016	.968	29.189	.656	---
18	6.0	275	1.004	.803	1.996	1.027	-.013	.969	29.528	.755	---
19	1.5	300	1.002	.807	1.996	1.033	-.013	.963	29.572	.892	1
20	3.0	300	1.002	.812	1.995	1.027	-.015	.968	29.524	.775	---
21	4.5	275	1.002	.803	1.996	1.020	-.010	.976	29.452	.836	---
22	6.0	425	1.003	.811	1.996	1.034	-.014	.962	28.404	.857	---
23	1.5	275	1.002	.807	1.996	1.017	-.012	.979	29.303	.232	1
24	3.0	275	1.004	.806	1.997	1.034	-.015	.963	30.442	.530	---
25	4.5	425	1.003	.805	1.996	1.018	-.013	.978	28.648	.755	---

Notes:

1 - Failed by cleavage after ductile initiation.

2 - Violates ASTM E-399-81 spacing criterion. Failed at Δa = .022 inch.

3 - $J_{Ic} = J_{max}$ - Some crack extension occurred.

4 - Multiple (stable) pop-in occurred throughout tests.

4. DISCUSSION OF RESULTS

4.1 VESSEL REPAIR

Repairing and inserting the test segments into the vessels was straightforward; only two difficulties were encountered. One was the high residual magnetism in the vessels which prevented use of magnetic particle testing of the weld joint cavities for surface defects. Dye penetrant testing was used instead. No difficulties were encountered in welding. The second difficulty was a slag-type radiographic indication within the weld made on Vessel V-8 that was accepted by UCC - ND, although it was slightly larger than allowed by specifications for this contract. The defect was considered to be innocuous. The procedures employed were successful in producing welded test piece insertions into the vessels and appear to be a good way of reusing the vessels.

4.2 CHARACTERIZATION TESTING

It was noted that there were small gradients in the mechanical properties in the thickness (radial) direction of the characterization test piece (V71) that was taken from the hollow A508-2 steel forging (TSC-6). The following discussion centers on this, because it could have a small influence on the pressurized thermal shock experiments of the insert material represented by the characterization test piece.

4.2.1 Chemical Composition

The results of the analysis presented in Table 6 indicate a shallow gradient in some of the elements, with the ID being slightly richer than the OD. This would lead to a gradient in hardness and strength, increasing from OD to ID. On the other hand, the hardness and strength would decrease from both the ID and OD surfaces because of decreasing heat transfer during quenching, resulting in higher-temperature transformation products.

Figure 19 illustrates schematically the effect of these two variables on the resulting hardness and strength as a function of radial position within the wall of the original cylinder.

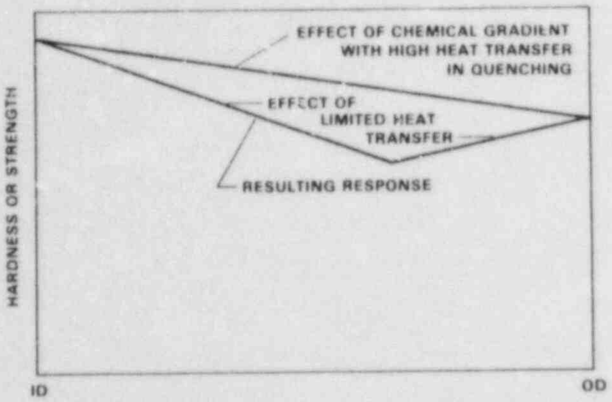


Figure 19. Schematic of effects of chemical composition and heat transfer gradients on hardness and strength of original cylinder.

The resulting hardness and strength would be a minimum located nearer the OD. This agrees with the observed values in hardness, as shown in Figure 16 and 17, where the minimum occurs at about 5-1/2 inches from the ID.

4.2.2 Tension Tests

Examining the tensile data in Table 7 shows that when specimens were tested at the same temperature but from different thickness locations, there was an increase in yield and ultimate strengths as the ID was approached. This is consistent with the hardness results. Figure 20 shows this as a plot of normalized yield and ultimate tensile strength using the values interpolated to a position 3 inches from the ID. The least-squares fit of the data obtained with a desk calculator predicts about a 2% increase in strength in going from the d = 3 inches position to ID and a 2% decrease in going to the OD, or a 6% change overall for a distance of 6 inches from the ID. This distance is about equivalent to the wall thicknesses of Vessels V-7 and V-8.

Using the equations shown in Figure 20, multiplying factors were derived to be able to predict the yield and ultimate tensile strengths from measured values by either extrapolation or interpolation. These multiplying factors are given in Table 12.

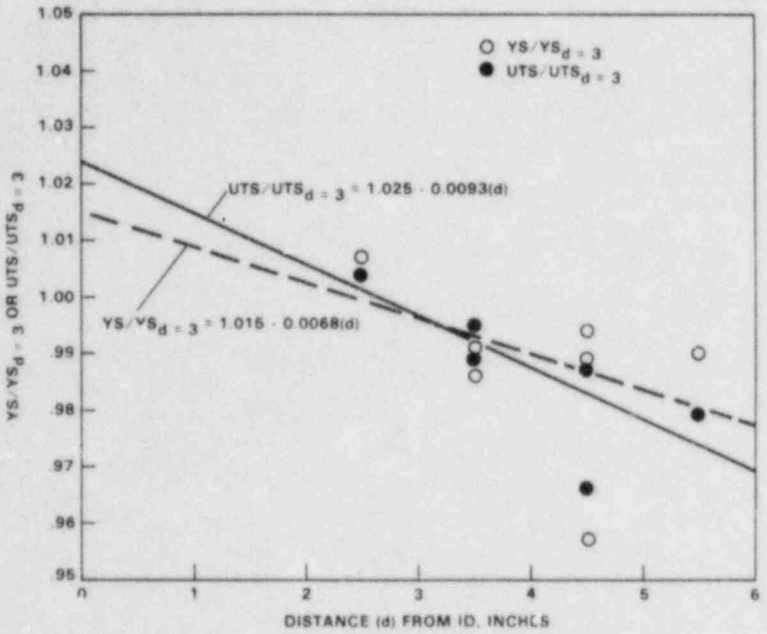


Figure 20. Normalized strengths YS/YS$_{d = 3}$ and UTS/UTS$_{d = 3}$ as a function of distance (d) from ID.

Using the multiplying factors in Table 12 and adjusting the yield and ultimate strengths to a thickness position at 3 inches, we obtain the predicted yield and tensile strengths shown in Table 13.

The values at a position of d = 3 inches are plotted as a function of temperature in Figure 21(a). Also shown are the average values of 5 heats of SA508-2 steel.*

The ultimate tensile strength response of V71 is seen to be similar to SA508-2 steel given a standard-tempering heat treatment. However. the yield strength at 500°F for V71 characterization material appears to parallel the ultimate strength rather than decrease, as shown for SA508-2 steel with standard heat treatment. The strength values obtained for specimen V71T15 appear to be too high with respect to the other results.

---

* W. L. Server and W. Oldfield, "Nuclear Pressure Vessel Steel Base," Electric Power Research Institute Report NP-933, Palo Alto, CA; December 1978.

Table 12

MULTIPLYING FACTORS FOR ESTIMATING STRENGTH AT ONE THICKNESS LOCATION FROM TEST RESULTS AT ANOTHER LOCATION

	Distance from ID (in)			
	Predicted Values			
Measured Values at:	1.5	3.0	4.5	6.0
	Yield Strength			
1.5 (T5, 10, 15)	1.000	.990	.980	.970
2.5 (T4, 9, 14)	1.007	.997	.986	.976
3.5 (T3, 8, 13)	1.014	1.003	.993	.983
4.5 (T2, 7, 12)	1.021	1.010	1.000	.990
5.5 (T1, 6, 11)	1.028	1.017	1.007	.997
	Ultimate Tensile Strength			
1.5 (T5, 10, 15)	1.000	.986	.973	.959
2.5 (T4, 9, 14)	1.009	.995	.982	.968
3.5 (T3, 8, 13)	1.019	1.005	.991	.977
4.5 (T2, 7, 12)	1.028	1.014	1.000	.986
5.5 (T1, 6, 11)	1.038	1.024	1.010	.995

Table 13

ADJUSTED STRENGTH VALUES TO A POSITION 3 INCHES FROM ID

			Yield Strength (ksi)		Ultimate Tensile Strength (ksi)	
Specimen Identification	Distance From ID (in)	Test Temp. (°F)	Actual	At d = 3"	Actual	At d = 3"
V71T1	5.5	-10	91.558	93.114	115.600	118.374
2	4.5	70	89.921	90.820	112.494	114.069
3	3.5	125	89.440	89.708	111.862	112.421
4	2.5	200	87.052	86.791	108.753	108.209
5	1.5	300	86.949	86.080	108.624	107.103
6	5.5	-50	93.482	95.071	117.792	120.619
7	4.5	-10	91.916	92.835	116.585	118.217
8	3.5	75	90.117	90.387	113.332	113.899
9	2.5	75	91.558	91.283	114.354	113.782
10	1.5	500	89.973	89.073	111.276	109.718
11	5.5	-50	92.296	93.865	117.059	119.868
12	4.5	125	86.815	87.683	109.300	110.830
13	3.5	250	64.975	85.230	105.594	106.122
14	2.5	350	85.306	85.050	105.635	105.107
15	1.5	275	89.688	88.771	111.423	[illegible].863

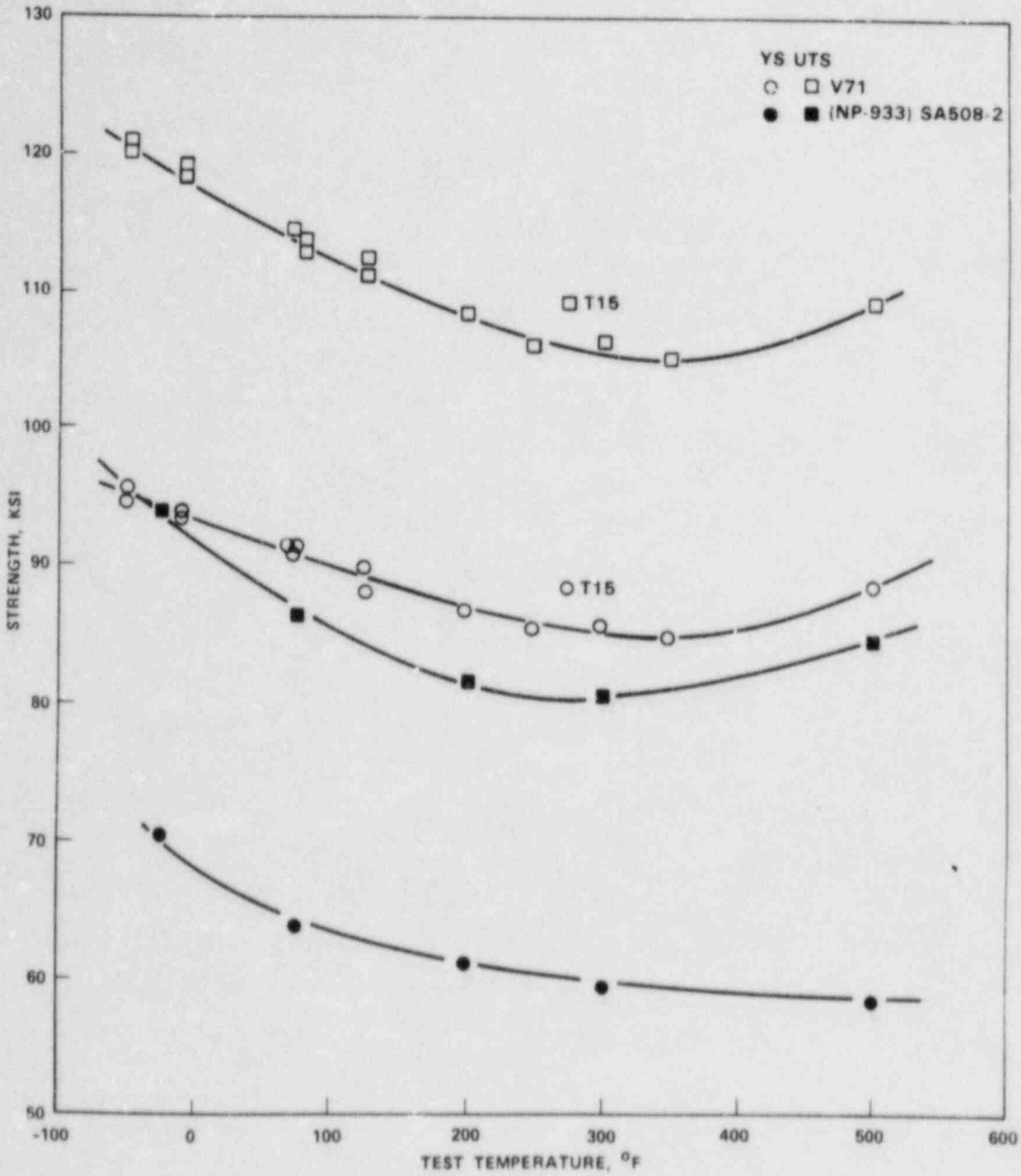


Figure 21(a). Yield and ultimate tensile strengths estimated for d = 3 as a function of temperature for V71 and for the average of five heats of SA508-2 (from EPRI Report NP-933).

Using the average values obtained for d = 3 inches from Table 14 and multiplying factors for other thickness locations, Table 15 is generated to give the estimated strengths at d ≈ 1.5, 3.0, 4.5 and 6.0 inches for temperatures where tensile data is available. This does not include a test at 275°F obtained with specimen V71T15, which appears to be high with respect to the other results.

Table 14

STRENGTH VALUES FOR d = 3 INCHES

	Test Temperature (°F)									
	-50	-10	75	125	200	250	275	300	350	500
					Yield Strength, ksi					
	95.071	93.114	90.820	89.708	86.791	85.230	88.771	86.080	85.050	89.073
	93.865	92.835	90.387	87.683						
			91.283							
Avg.	94.468	92.975	90.830	88.696	86.791	85.230	88.771	86.080	85.050	89.073
					Ultimate Tensile Strength, ksi					
	120.619	118.374	114.069	112.421	108.209	106.122	109.863	107.103	105.107	109.718
	119.868	118.217	113.899	111.830						
			113.782							
Avg.	120.244	118.296	113.917	112.126	108.209	106.122	109.863	107.103	105.107	109.718

Table 15

ESTIMATED STRENGTHS FOR V71 AT VARIOUS SPECIMEN DEPTHS AND TEST TEMPERATURES

	Test Temperature, °F								
Distance From ID (in)	-50	-10	75	125	200	250	300	350	500
				Yield Strength, ksi					
1.5	95.4	93.8	91.8	89.6	87.7	86.8	86.9	85.9	90.0
3.0	94.5	93.0	90.8	88.7	86.8	85.2	86.1	85.1	89.1
4.5	93.5	92.2	89.9	87.8	85.9	84.5	85.3	84.2	88.6
6.0	92.4	91.1	89.0	86.9	85.0	83.5	84.3	83.3	87.2
				Ultimate Tensile Strength, ksi					
1.5	122.0	120.1	115.6	113.3	109.8	107.7	108.7	106.7	111.4
3.0	120.2	118.3	113.9	111.6	108.2	106.1	107.1	105.1	109.7
4.5	118.7	116.8	112.4	110.2	106.8	104.7	105.7	103.7	108.3
6.0	117.0	115.1	110.8	108.6	105.3	103.3	104.2	102.3	106.8

Using the data in Table 7, a regression analysis was performed with BMDP Program P9R (All Possible Subsets Regression) to obtain the following equations:

$$\text{YS (ksi)} = 98.91 - 1.527D - 0.0507T + 0.000073T^2$$
$$SE = 0.92;\ R^2 = 0.90$$

$$\text{UTS (ksi)} = 124.45 - 1.862D - 0.0699T + 0.0000958T^2$$
$$SE = 1.03;\ R^2 = 0.95$$

where:

D = Distance from ID, inches

T = Test Temperature, °F

The fit of these equations is compared in Figure 21(b) to the previous interpolation for d = 3.

4.2.3 Charpy V-Notch Impact Tests

The scatter of test results appears to be quite large. But when compared to results obtained by others for the same kind of steel heat treated normally, the scatter is about typical for this kind of product. This is illustrated in Figure 22 with data taken from Derby, et al.*

To determine if there was an effect of specimen location with thickness the Charpy V-notch impact data was fitted with an expression** used for such purposes. Figure 23 shows the result of 75 iterations made with the B&W computer program "Pattern Search" to obtain a near-optimum fit for all of the 60 test results for absorbed energy without regard to its thickness position.

---

* R. W. Derby, et al., "Test of 6-Inch-Thick Pressure Vessels. Series 1: Intermediate Test Vessels V-1 and V2," Oak Ridge National Laboratory Report ORNL-4895, Oak Ridge, TN; February 1974.

** Server and Oldfield, op. cit.

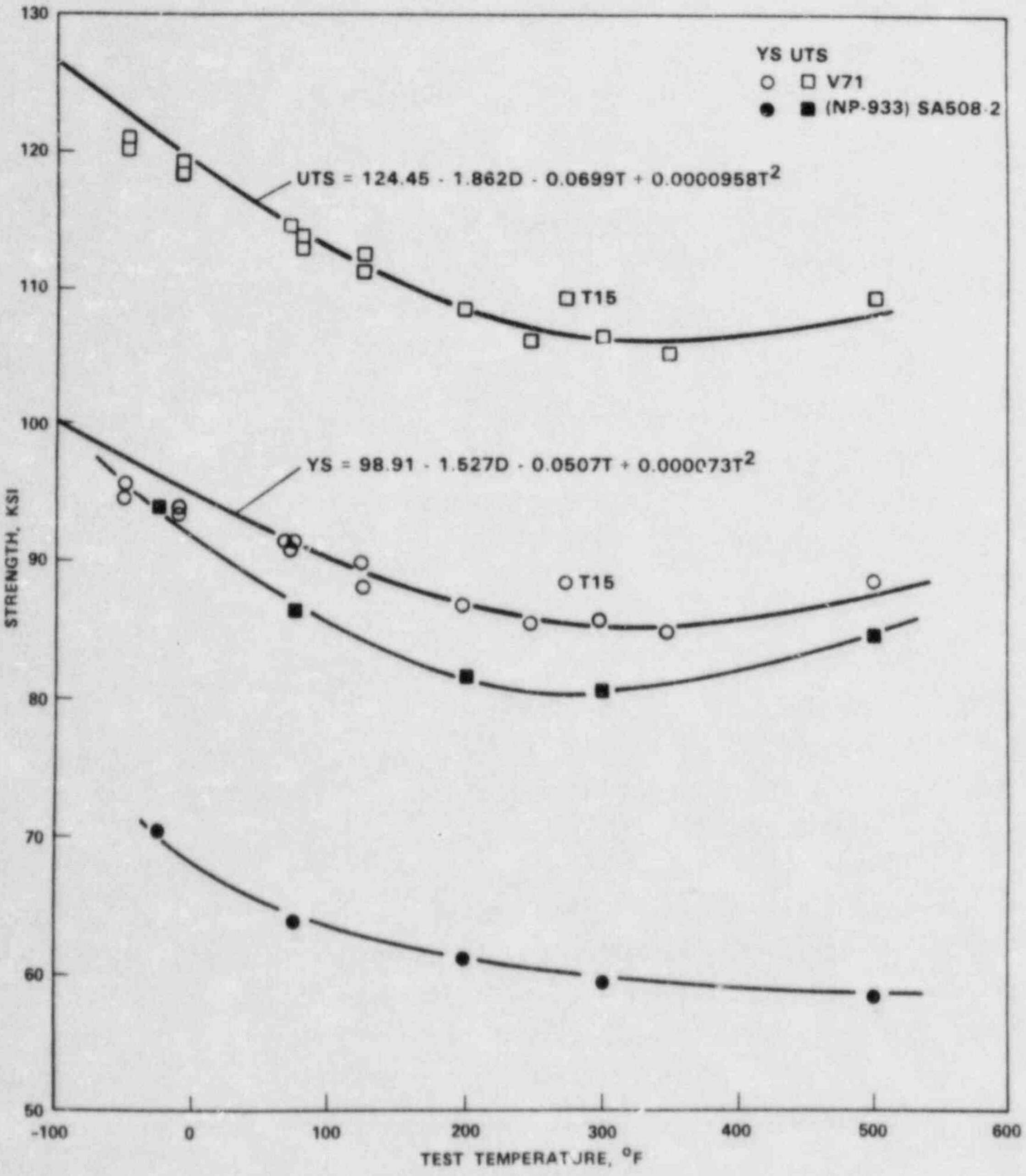


Figure 21(b). Same yield and ultimate tensile strengths as shown in Figure 21(a) except that the fit of regression analyses results with interpolated values is illustrated.

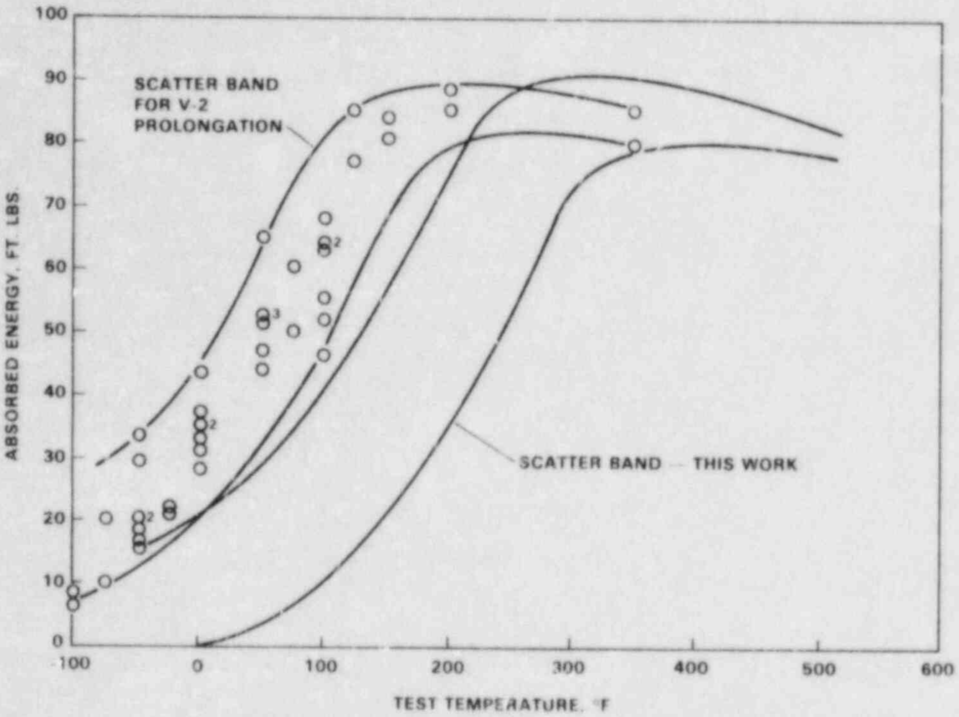


Figure 22. Comparison of scatter bands for Charpy V-notch test results of SA508-2 with standard heat treatment and this work.

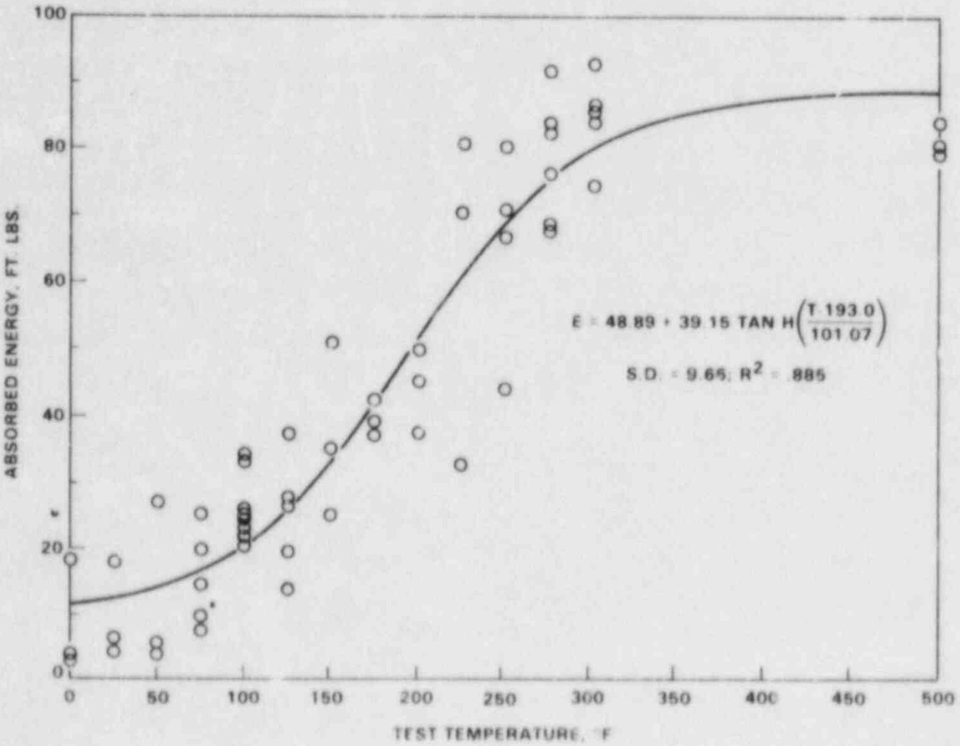


Figure 23. Fit of Charpy V-notch impact test absorbed energy.

When the location of the specimens with respect to thickness is taken into account, the fit of the equation is improved. This indicates that there is a gradient in absorbed energy, decreasing as the ID is approached (see Figure 24). Similar responses were found for lateral expansion and percent shear values.

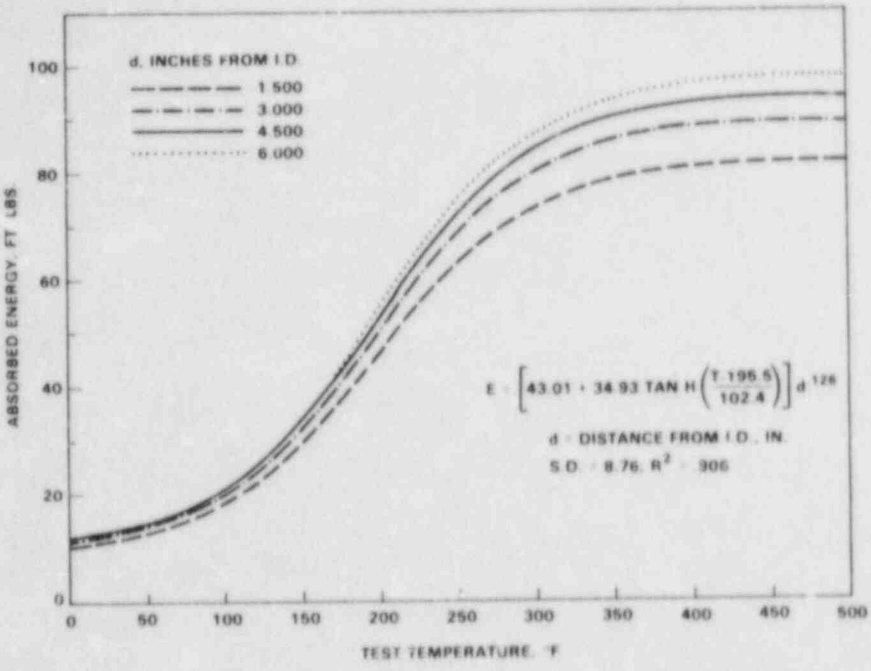


Figure 24. Effect of thickness location (inches from ID) on the Charpy V-notch impact absorbed energy transition curves.

Assuming that there is a linear relationship between absorbed energy and lateral expansion in the impact transition region, a least-squares fit of lateral expansion as a function of absorbed energy obtained with a desk calculator produced the following relationship for values between 15 and 45 ft-lbs (Table 8):

$$\text{LE (mils)} = -3.63 + 0.858\ \text{E (ft-lbs)}$$

The fit of this equation is illustrated in Figure 25. For a 30-ft-lb transition, an equivalent transition of 22.1 mils is obtained.

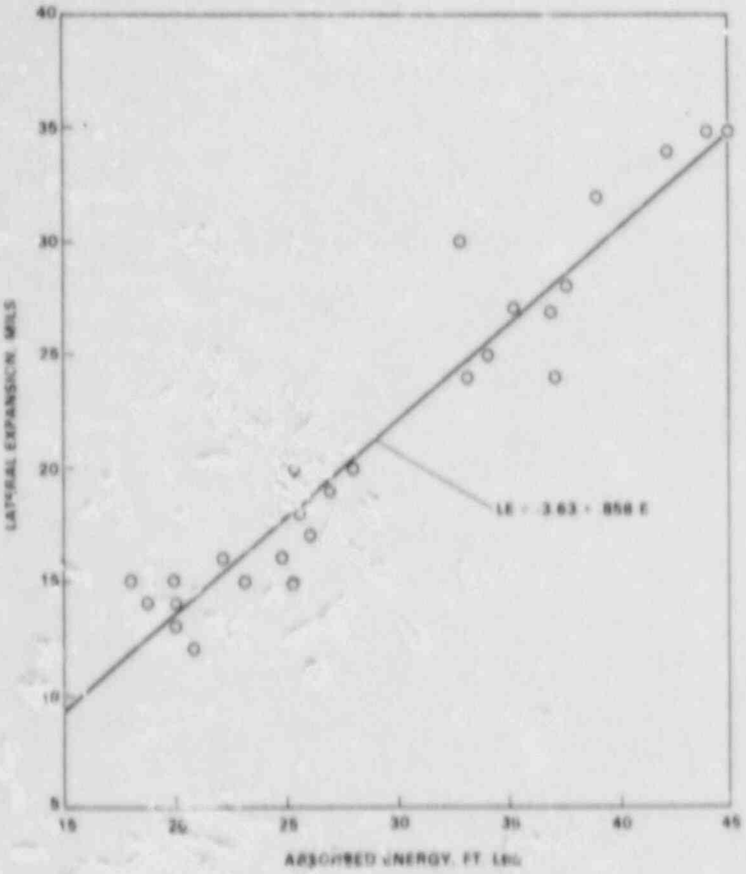


Figure 25. Plot of lateral expansion as a function of absorbed energy over the range of 15 to 45 ft-lbs.

Using the following equations derived by fitting the Charpy V-notch impact results:

$$E\ (\text{ft-lbs}) = \left[43.01 + 34.93 \tan H\left(\frac{T - 195.5}{102.4}\right)\right] d^{.126} ,$$

$$LE\ (\text{mils}) = \left[31.70 + 26.51 \tan H\left(\frac{T - 195.5}{101.80}\right)\right] d^{.126} ,$$

$$S\ (\%) = \left[49.79 + 45.32 \tan H\left(\frac{T - 214.1}{68.14}\right)\right] d^{.101} ,$$

the calculated 30 ft-lbs, 22.1 mils, and 50% shear transition temperatures as a function of distance from the ID are illustrated in Figure 26.

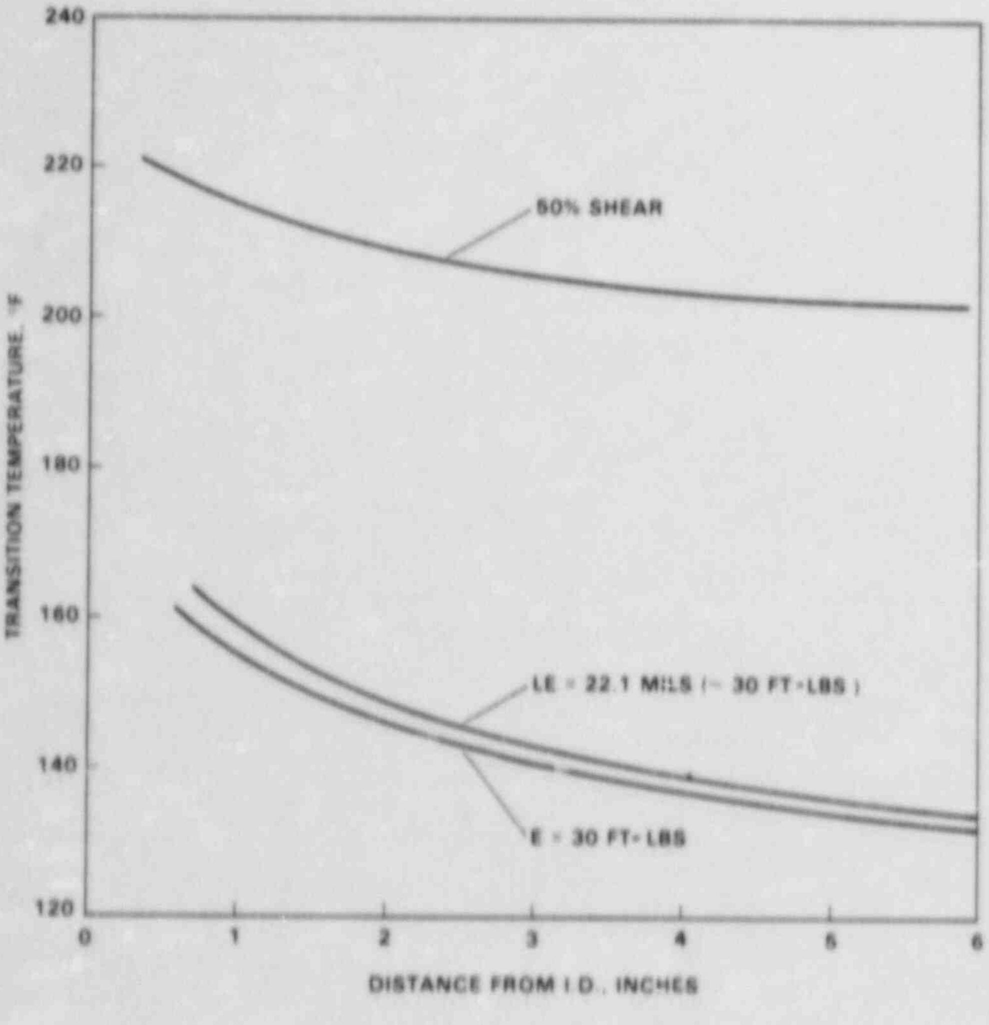


Figure 26. Calculated transition temperatures as a function of distance from ID.

4.2.4 Plane Strain Fracture Toughness Test Results

Figure 27 shows these test results as a function of test temperature for the normal and side-grooved specimens. Only one test result obtained for Specimen V71S11 tested at 75°F gave a valid K_{1c} result of 57.4 ksi$\sqrt{\text{in.}}$ The amount of scatter is similar to test results obtained on similar materials.

A regression analysis was performed with the BMDP Program P9R (All Possible Subsets Regression) on the test results to determine if the specimen depth location had an effect. A computer fit produced the following result:

$$K_{Jmax}\ (\text{ksi}\sqrt{\text{in.}}) = -18.547 + 7.146D + 1.569T - 0.0030T^2$$
$$SE = 49.60;\ R^2 = 0.336$$

where:

D = Distance from ID, inches
T = Test temperature, °F

The fit of the data with this equation is not very good, but if it were more statistically significant, it would indicate a gradient of K_{Jmax} exists across the wall of the inserts in Vessels V-7 and V-8 that could amount to 42.9 (6 x 7.146) ksi$\sqrt{\text{in.}}$, which is much greater than that derived from correlation of C_v energy with fracture toughness. This equation also indicates a maximum in K_{Jmax} values at about 265°F, which is greater than the fracture data indicate. Other regression analyses involving second powers of D and T and their cross-terms did not produce any significantly better fits than the above equation.

4.2.5 J-Integral Tests

Figure 28 shows that there is little or no effect of test temperature on J_{1c}. In an attempt to separate the effects of specimen depth, location, and temperature, regression analyses performed with the BMDP Program P9R were applied to these results. Using only linear terms, the following equation was obtained:

$$J_{1c}\ (\text{kip/in.}) = 0.639 - 0.0034D + 0.00034T$$
$$SE = 0.089;\ R^2 = 0.131$$

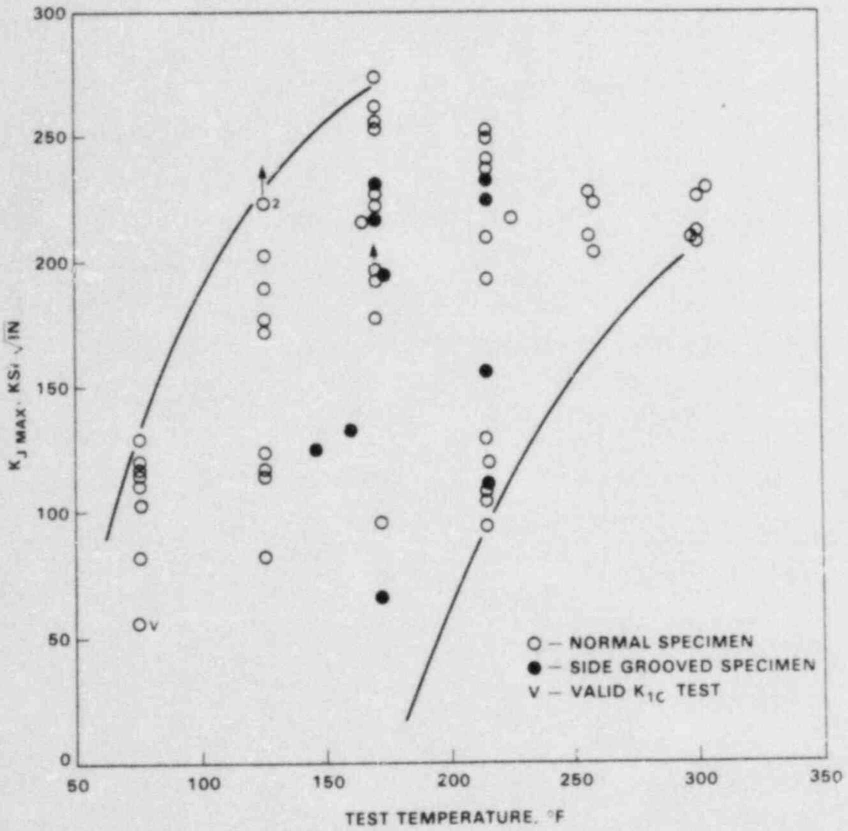


Figure 27 Plot of K_{Jmax} as a function of test temperature for plane strain fracture toughness tests.

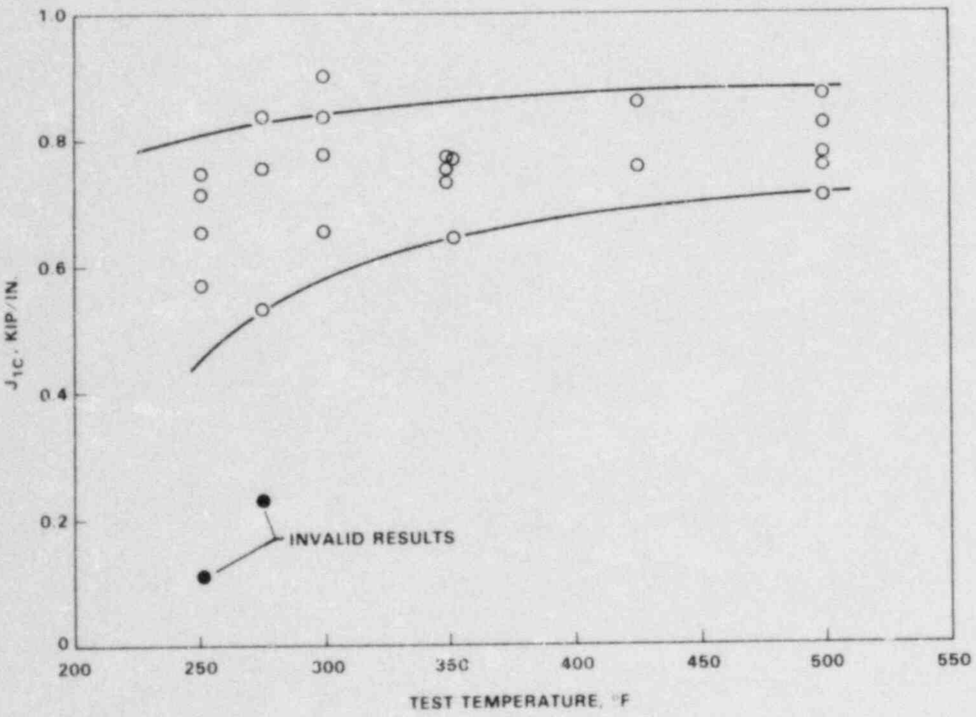


Figure 28. Plot of J_{1c} as a function of test temperature.

Using higher-order terms, the best fit of the data was obtained with the following equation:

$$J_{1c}\ (\text{kip/in}) = 0.746 + 3.978D + 353.5T + 18.29D^2 + 133{,}219T^2 + 1380.6DT$$

$$SE = 0.085;\ R^2 = 0.569$$

There could be an effect of specimen depth and temperature on J_{1c}, but this is not supported by statistical means.

5. CONCLUSIONS

- Inserting a test piece by welding into the walls of intermediate test vessels can be accomplished without difficulty.
- If these or other vessels are to be used again for such purposes, consideration should be given to degaussing the vessels to remove residual magnetism that could be present.
- There was a small gradient in mechanical properties in the characterization test piece that probably exists in the vessel inserts. It could be due to the chemical segregation in the original steel ingot used for the forging TSC-6 and its effect on hardenability. Contributing to the gradient is the decreasing heat transfer as a function of thickness, resulting in higher temperature transformation products below the surface.

6. RECOMMENDATION

If these or similar vessels are to be used again for these purposes and the residual magnetism is high, degaussing should be employed prior to welding.

7. QUALITY ASSURANCE

This work was performed at two locations with shared responsibility for quality assurance by B&W's Nuclear Equipment Division (NED) and Research and Development Division (R&DD). The work accomplished by NED is recorded within the files of that organization.

The work performed by the R&DD was performed in accordance with Quality Assurance Plan No. 82027, with the following exceptions:

- Specimens V71F10 and F11, F13 through F20, and V71S9 were tested according to ASTM E-399-81, except that the specimens were side grooved 10% on each side.
- The extensometer used for plane strain tests did not meet the requirements of Paragraph 6.3.1 of ASTM E-399-81 in that the maximum difference between the actual and calculated displacement was 0.00023 inch and this was greater than the 0.0001 inch allowed. Since the determination of K_{Ic} is done with a load determination which has a limit of ±1% accuracy or about six times the largest deviation of the extensometer used, this deviation from ASTM E-399-81 requirements is not considered to be significant in the test results.
- A post test calibration check performed on the extensometer (B&W No. 810421) used for the J-integral tests showed the following maximum differences in output of the extensometer:

Temperature, °F	% Difference
89	2.8
250	3.2
530	3.2

These values are greater than 1% allowed by ARC TP-267, Revision 2, and which were achieved prior to testing the specimens in the program. Previous work* indicates that the reproducibility of J_{Ic} is dependent on the test operator and may amount to about 4%, which is greater than these extensometer deviations. These calibration differences are about equal to a 2.5% drift experienced for some previous test results.

---

* H. A. Domian, "Vessel V-8 Repair and Preparation of Low Upper-Shelf Weldment," NUREG/CR-2676, ORNL/Sub/81-85813/1; June 1982.

To the best of my knowledge and belief and noting the preceding exceptions, the work described in Section 3 of this report was completed in accordance with Quality Assurance Plan No. 82027, Revision 0, dated December 24, 1982.

3-30-84

G. W. Roberts
Quality Assurance Manager,
Alliance Research Center

8. ACKNOWLEDGMENTS

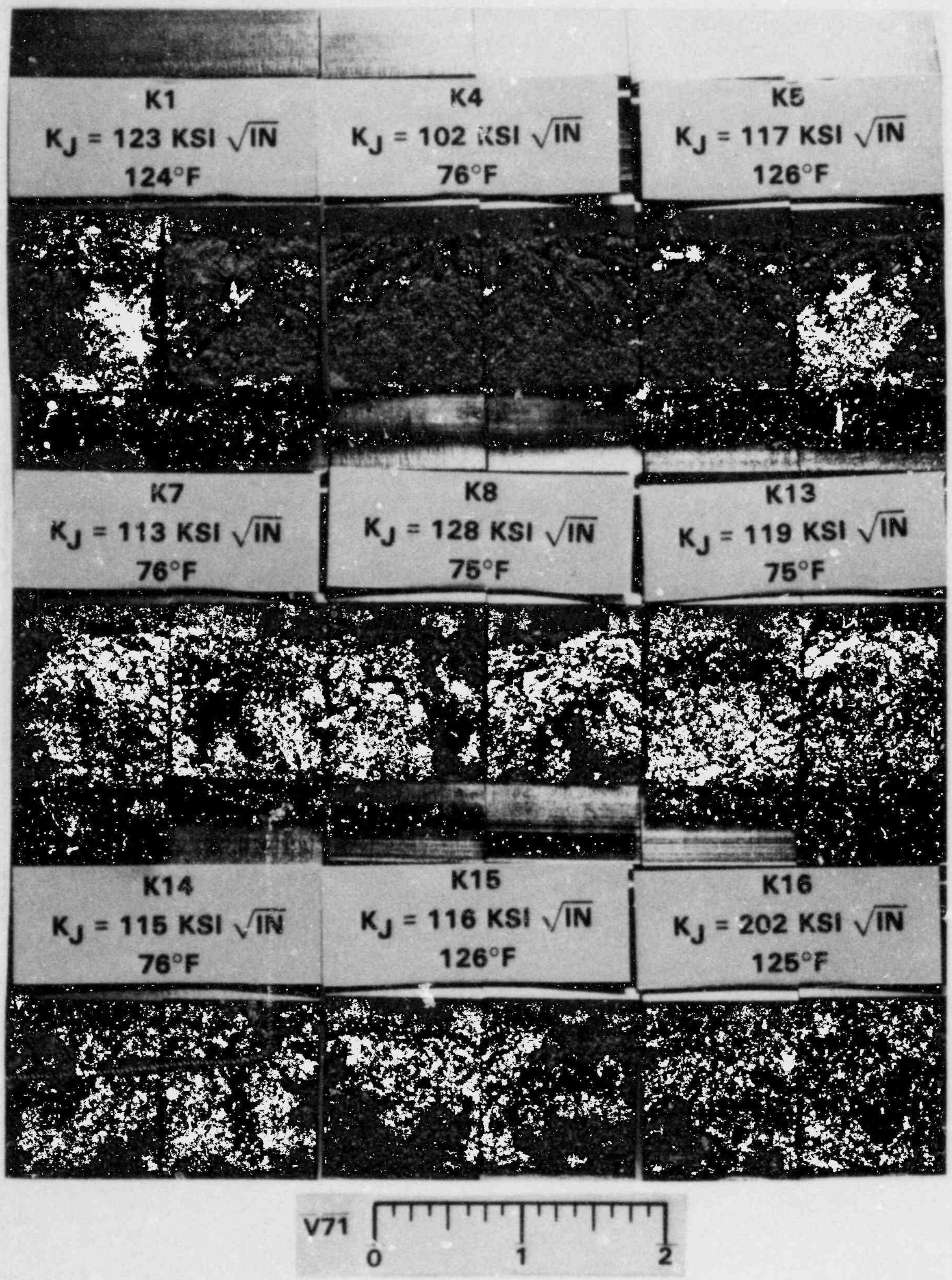
This project was accomplished with the assistance of the following persons at The Babcock & Wilcox Company:

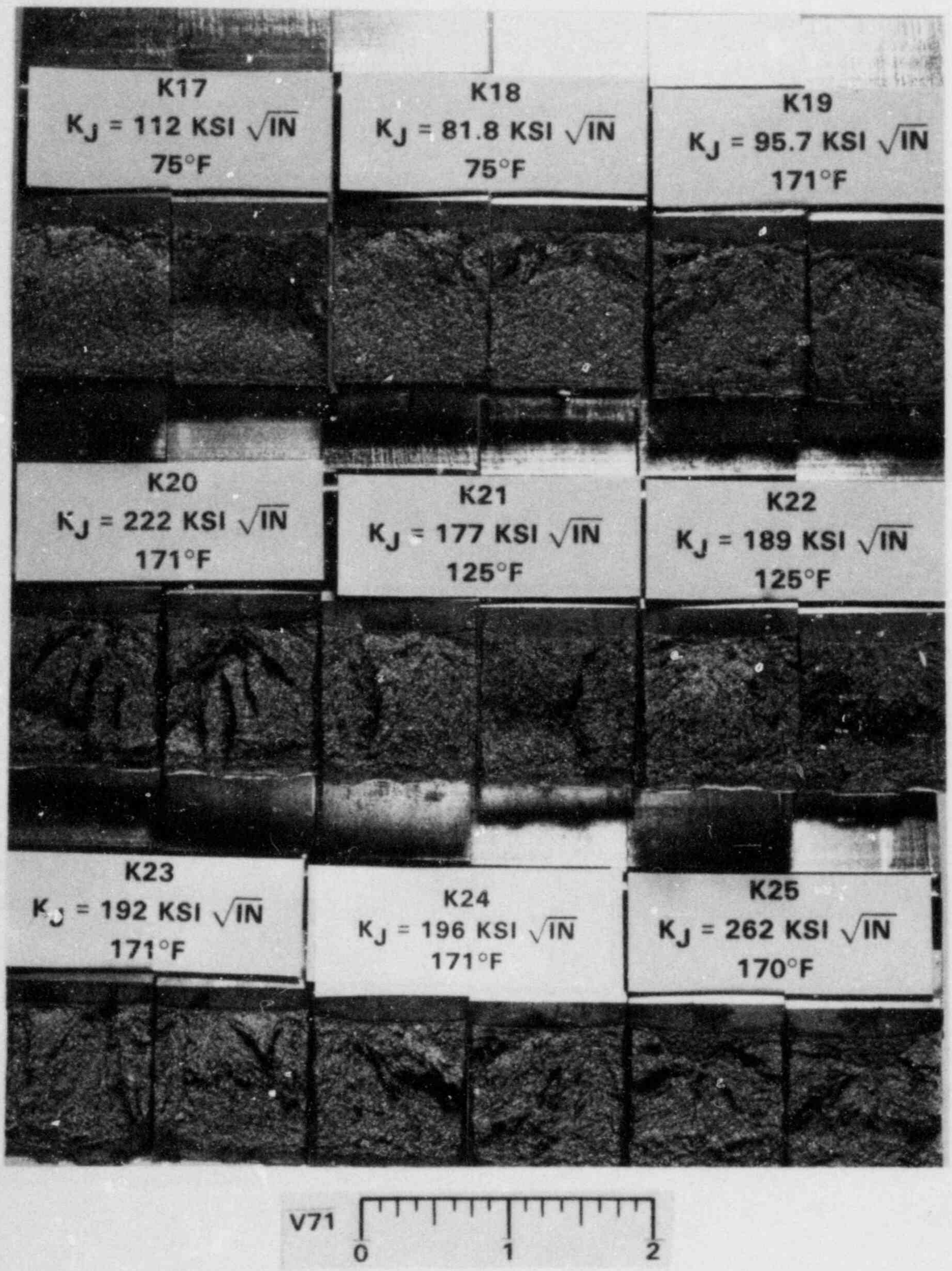
D. J. Aleman - Contract management, Contract Research Division
P. S. Ayres - Project management
C. M. Coleman - Contract administration, Barberton
R. J. Futato - Mechanical testing, Alliance
V. J. Hudacko - Mechanical testing and chemical analyses, Barberton
S. L. Molnar - Quality assurance, Alliance
D. E. Waskey - Welding, Barberton
D. E. Young - PWHT of vessels; characterization material, Barberton
W. A. Van Der Sluys - Mechanical testing, Alliance

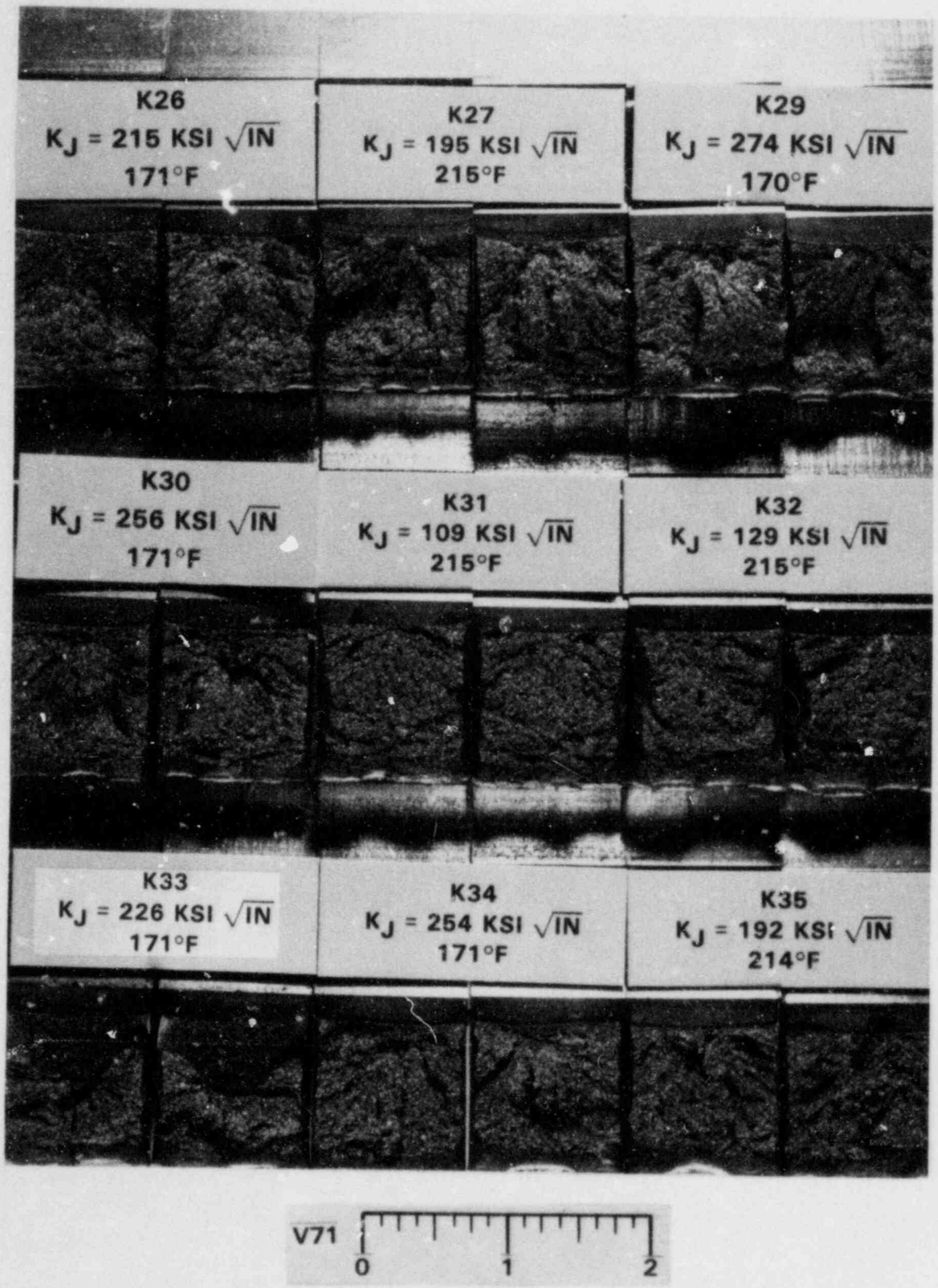
The cooperation and assistance of Union Carbide Corporation - Nuclear Division (UCC - ND) through the efforts of R. H. Bryan, R. J. Lynn and K. R. Thoms are greatly appreciated.

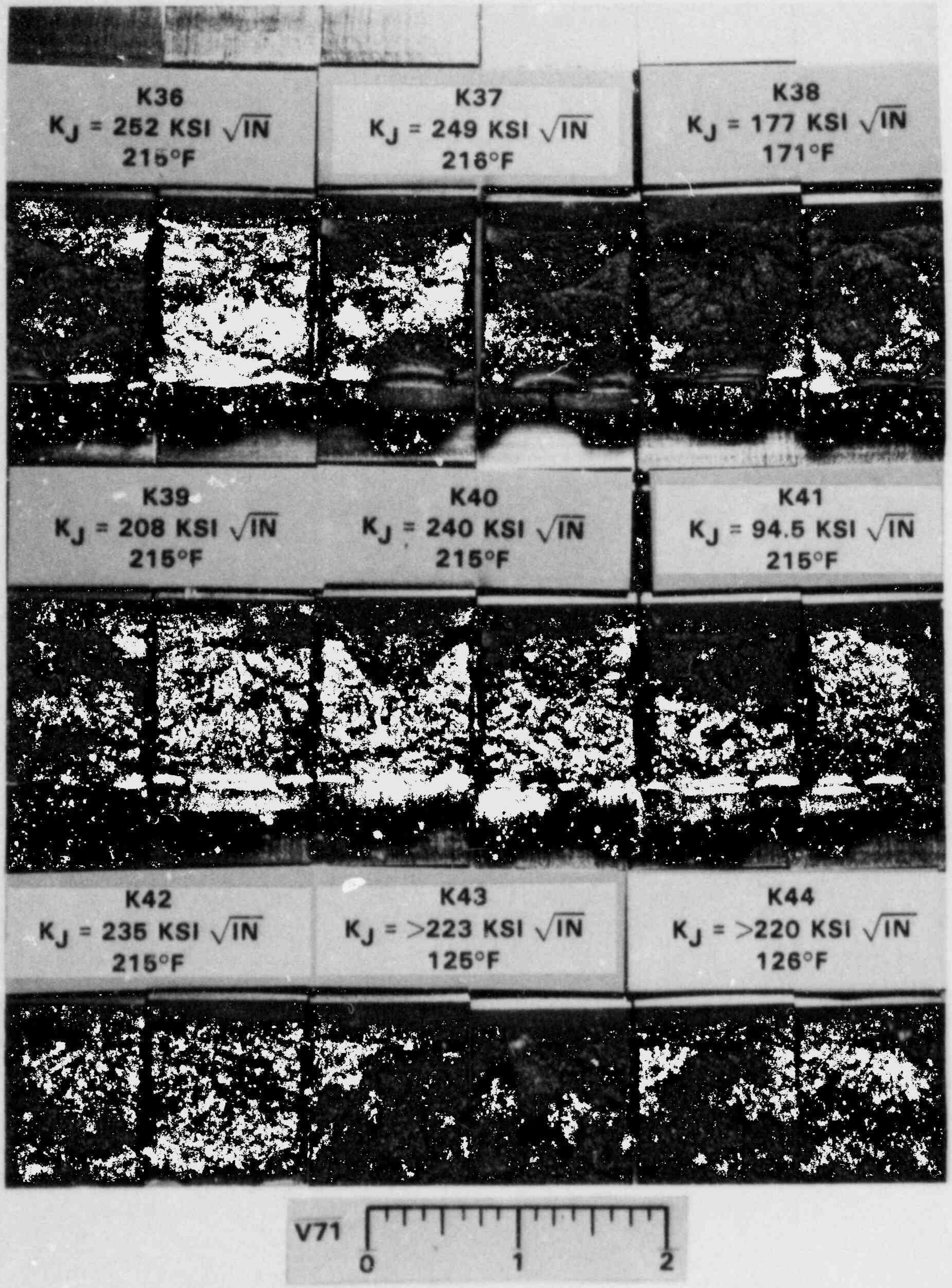
Appendix A

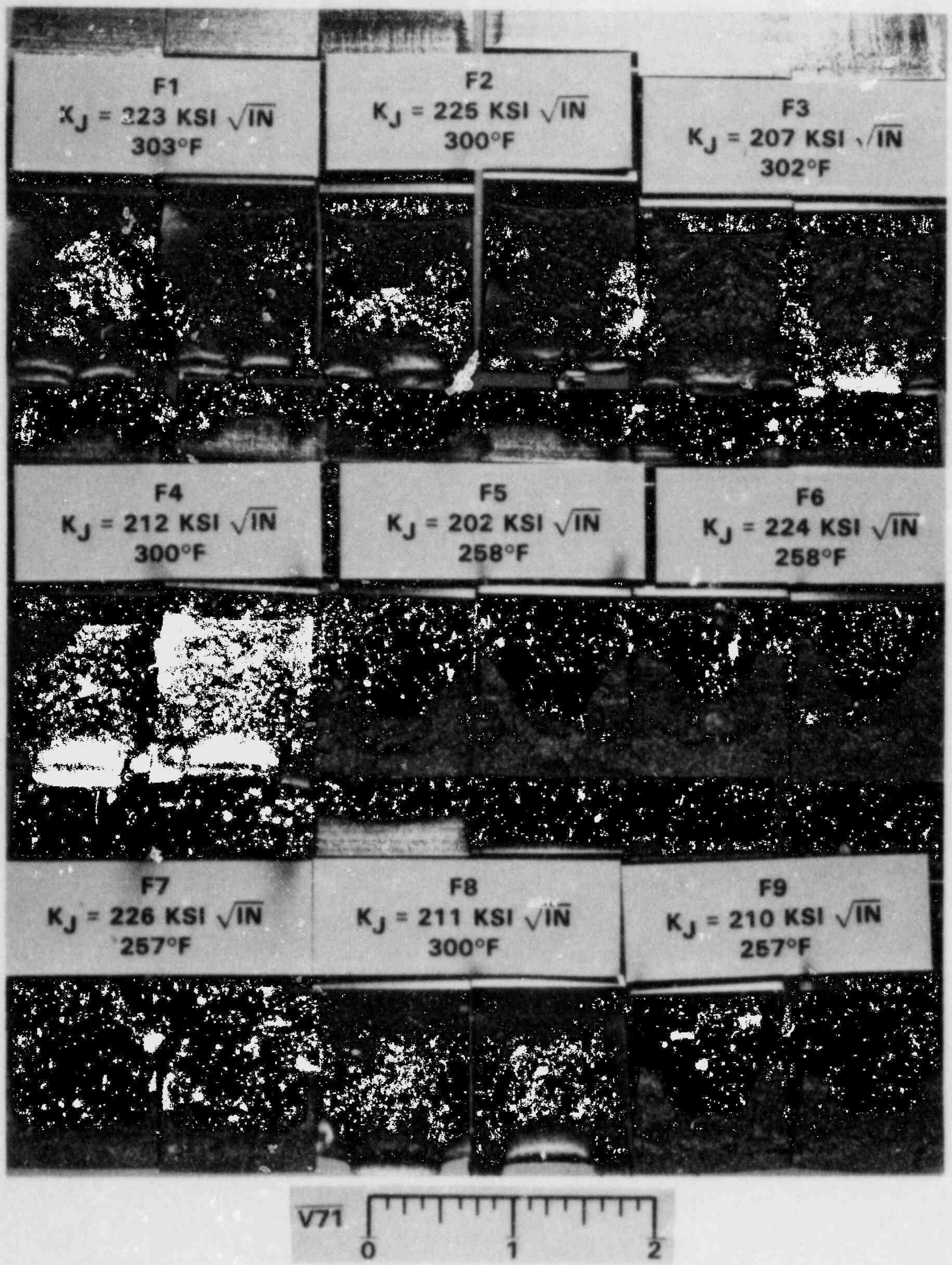
PHOTOGRAPHS OF PLANE STRAIN FRACTURE TOUGHNESS TEST SPECIMEN SURFACES

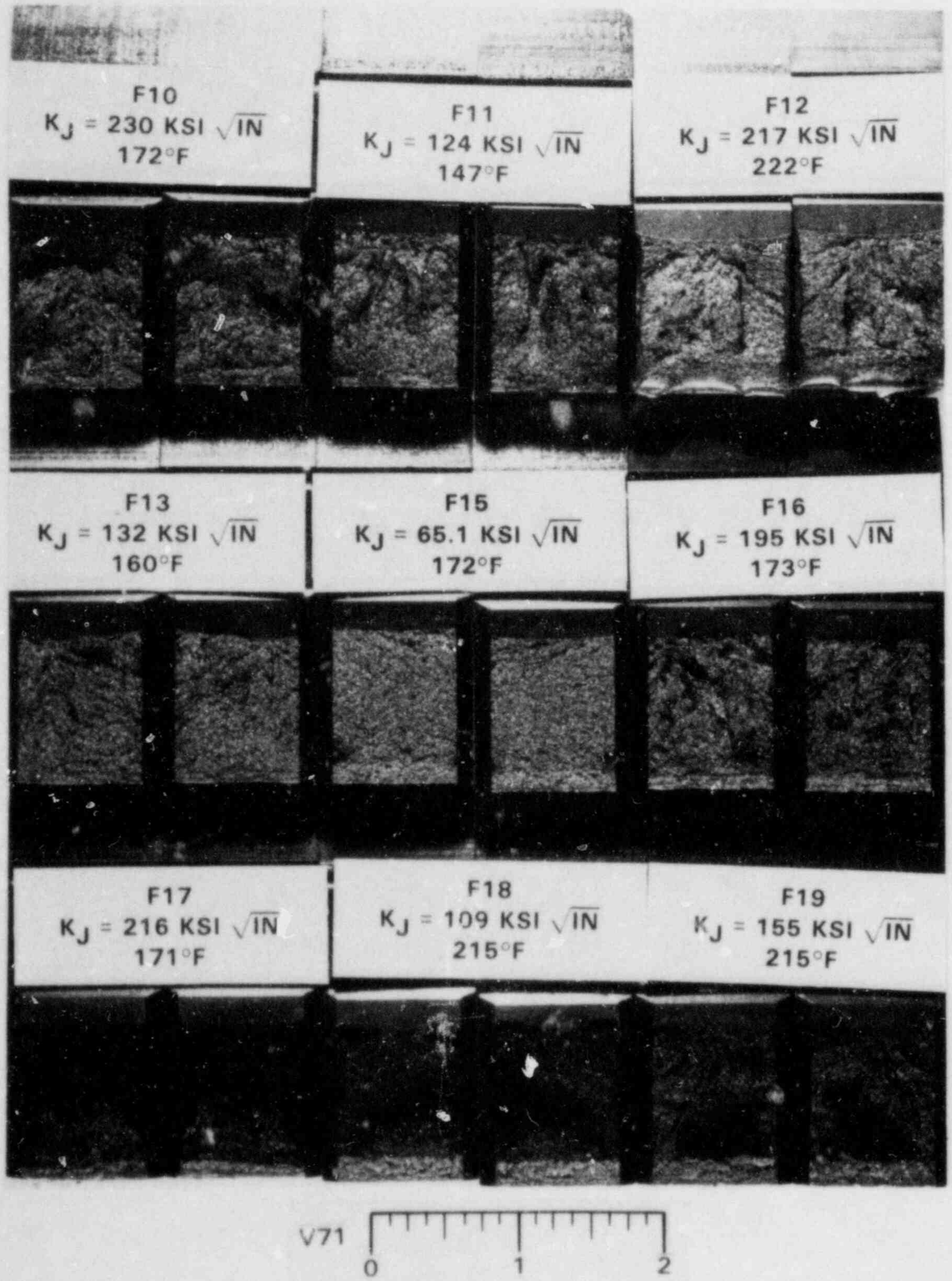

K1
K$_J$ = 123 KSI √IN
124°F
K4
K$_J$ = 102 KSI √IN
76°F
K5
K$_J$ = 117 KSI √IN
126°F
K7
K$_J$ = 113 KSI √IN
76°F
K8
K$_J$ = 128 KSI √IN
75°F
K13
K$_J$ = 119 KSI √IN
75°F
K14
K$_J$ = 115 KSI √IN
76°F
K15
K$_J$ = 116 KSI √IN
126°F
K16
K$_J$ = 202 KSI √IN
125°F
V71
0
1
2

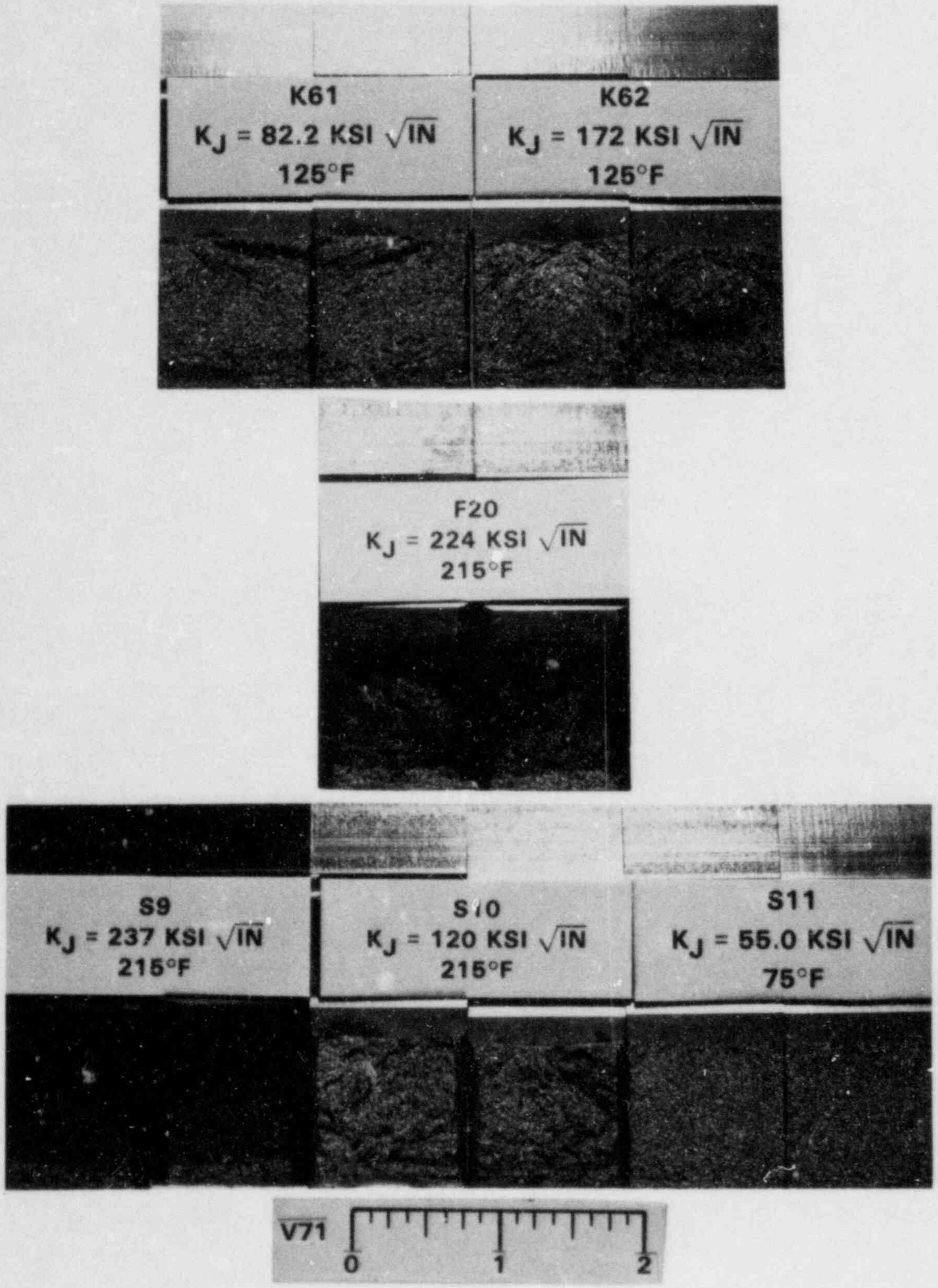

K17
K_J = 112 KSI √IN
75°F
K18
K_J = 81.8 KSI √IN
75°F
K19
K_J = 95.7 KSI √IN
171°F
K20
K_J = 222 KSI √IN
171°F
K21
K_J = 177 KSI √IN
125°F
K22
K_J = 189 KSI √IN
125°F
K23
K_J = 192 KSI √IN
171°F
K24
K_J = 196 KSI √IN
171°F
K25
K_J = 262 KSI √IN
170°F
V71
0
1
2


K26
K_J = 215 KSI $\sqrt{IN}$
171°F
K27
K_J = 195 KSI $\sqrt{IN}$
215°F
K29
K_J = 274 KSI $\sqrt{IN}$
170°F
K30
K_J = 256 KSI $\sqrt{IN}$
171°F
K31
K_J = 109 KSI $\sqrt{IN}$
215°F
K32
K_J = 129 KSI $\sqrt{IN}$
215°F
K33
K_J = 226 KSI $\sqrt{IN}$
171°F
K34
K_J = 254 KSI $\sqrt{IN}$
171°F
K35
K_J = 192 KSI $\sqrt{IN}$
214°F
V71
0
1
2


K36
$K_J = 252$ KSI $\sqrt{IN}$
215°F
K37
$K_J = 249$ KSI $\sqrt{IN}$
216°F
K38
$K_J = 177$ KSI $\sqrt{IN}$
171°F
K39
$K_J = 208$ KSI $\sqrt{IN}$
215°F
K40
$K_J = 240$ KSI $\sqrt{IN}$
215°F
K41
$K_J = 94.5$ KSI $\sqrt{IN}$
215°F
K42
$K_J = 235$ KSI $\sqrt{IN}$
215°F
K43
$K_J = >223$ KSI $\sqrt{IN}$
125°F
K44
$K_J = >220$ KSI $\sqrt{IN}$
126°F
V71
0
1
2


F1
K_J = 223 KSI √IN
303°F
F2
K_J = 225 KSI √IN
300°F
F3
K_J = 207 KSI √IN
302°F
F4
K_J = 212 KSI √IN
300°F
F5
K_J = 202 KSI √IN
258°F
F6
K_J = 224 KSI √IN
258°F
F7
K_J = 226 KSI √IN
257°F
F8
K_J = 211 KSI √IN
300°F
F9
K_J = 210 KSI √IN
257°F
V71
0
1
2


F10
K_J = 230 KSI √IN
172°F
F11
K_J = 124 KSI √IN
147°F
F12
K_J = 217 KSI √IN
222°F
F13
K_J = 132 KSI √IN
160°F
F15
K_J = 65.1 KSI √IN
172°F
F16
K_J = 195 KSI √IN
173°F
F17
K_J = 216 KSI √IN
171°F
F18
K_J = 109 KSI √IN
215°F
F19
K_J = 155 KSI √IN
215°F
V71
0
1
2


K61
K_J = 82.2 KSI $\sqrt{IN}$
125°F
K62
K_J = 172 KSI $\sqrt{IN}$
125°F
F20
K_J = 224 KSI $\sqrt{IN}$
215°F
S9
K_J = 237 KSI $\sqrt{IN}$
215°F
S10
K_J = 120 KSI $\sqrt{IN}$
215°F
S11
K_J = 55.0 KSI $\sqrt{IN}$
75°F
V71
0
1
2

Appendix B

J-TEST RESULTS
AND
PHOTOGRAPHS OF SPECIMEN FRACTURED SURFACES

Appendix B

J-TEST RESULTS

The following J-R curves were obtained with these three corrections.

1. Unloading compliance was corrected by adjusting the elastic modulus to give agreement between the measured initial length and experimental derived values using a modulus expected for the material and its test temperature in the following expression:

$$E_{expected} = (E_{assumed}) \times \frac{C_{Calculated}}{C_{measured}}$$

where:

$E_{assumed}$ = modulus value used during test

$C_{calculated}$ = specimen compliance calculated from measured initial crack length

$C_{measured}$ = specimen compliance measured at start of test

2. J-expression, moving-crack correction:

$$J_{i+1} = \left\{ Ji + \frac{\eta}{b}\Big|_i \frac{Ai,\ i+1}{Bn} \right\} \left\{ 1 - \frac{\gamma}{b}\Big|_i (a_{i+1} - a) \right\}$$

where:

Ai, i + 1 = incremental area between lines of constant displacement at points i and i + 1

$\eta = 2 + 0.522\ b/w$

$\gamma = 1 + 0.76\ b/w$

$b = w - a$

Bn = net specimen thickness

a = crack length

3. Rotation correction:

$$C\Big|_{corrected} = \frac{C\Big|_{measured}}{\left\{\frac{H}{R}\sin(\theta) - \cos(\theta)\right\} \left\{\frac{D}{R}\sin(\theta) - \cos(\theta)\right\}}$$

where:

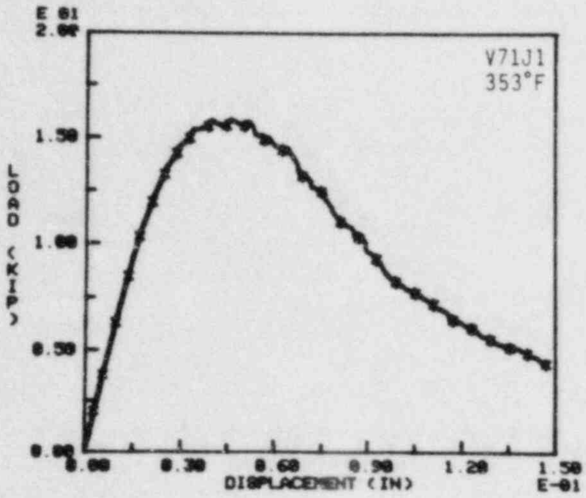
H = half span of loading points

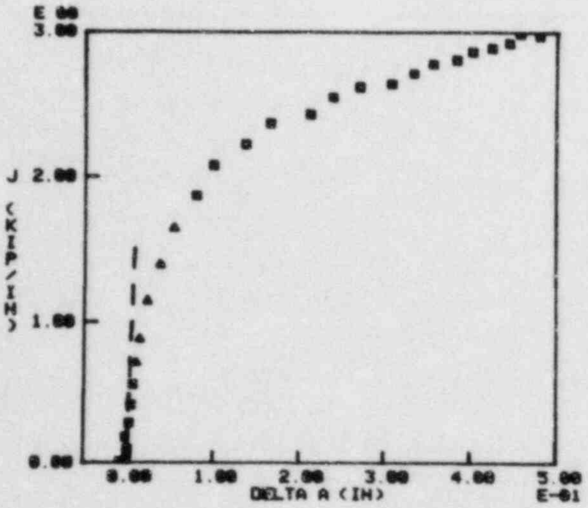
$R = \frac{W + a}{2}$ = radius of rotation

D = distance from crack plane to knife edge at zero load

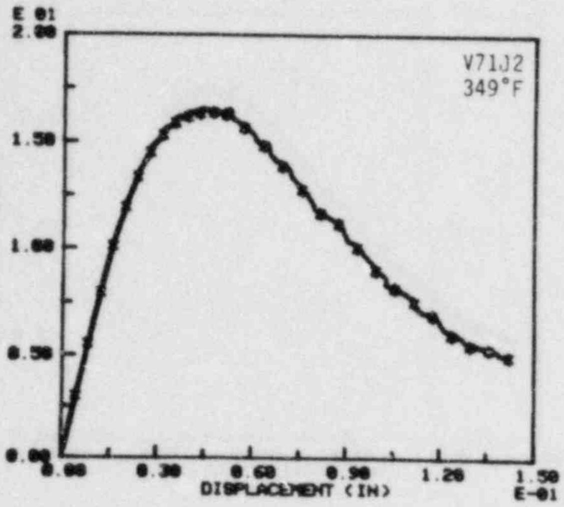
$$\theta = \sin^{-1}\left\{\frac{\delta m + D}{(D^{2d} + R^2)^{1/2}}\right\} - \tan^{-1}\left(\frac{D}{R}\right)$$

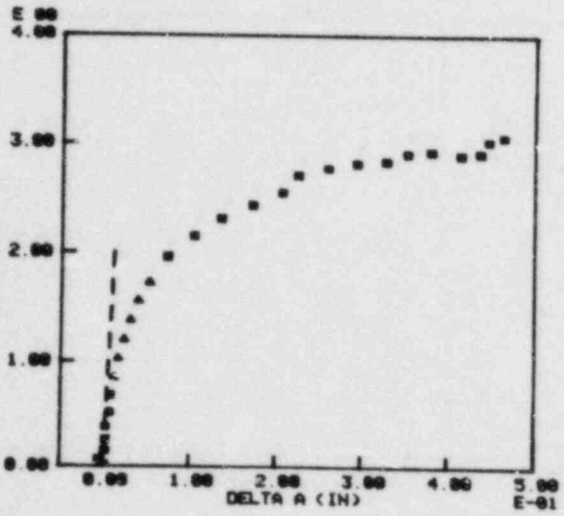
δm = measured load-line displacement



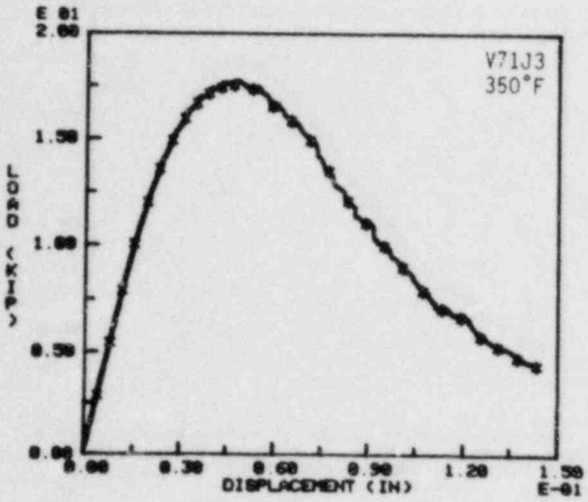


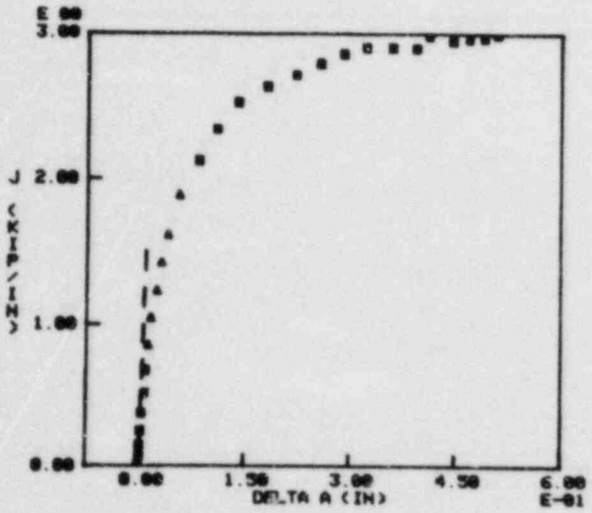
```
             J                    CRACK EXTENSION
          KIP/IN                        IN

 1 .    .0111902                 -7.29068E-03
 2 .    .0350563                 -1.20648E-04
 3 .    .0975449                  7.58648E-04
 4 .    .185133                  -1.45519E-03
 5 .    .286322                   2.99004E-03
 6 .    .41049                    4.36711E-03
 7 .    .563477                   6.06622E-03
 8 .    .722043 *+                .0109537
 9 .    .880622 *+                .0149393
10 .   1.15870 *+                 .0232017
11 .   1.4083 *+                  .0374601
12 .   1.64953 *+                 .0538002
13 .   1.86945                    .0706826
14 .   2.07832                    .0989077
15 .   2.22345                    .13736
16 .   2.36869                    .166066
17 .   2.43228                    .211367
18 .   2.54697                    .23868
19 .   2.61852                    .270827
20 .   2.64117                    .307941
21 .   2.71253                    .333140
22 .   2.78063                    .355276
23 .   2.80718                    .382868
24 .   2.86693                    .40169
25 .   2.88984                    .424755
26 .   2.92722                    .444327
27 .   2.99206                    .457561
28 .   2.9763                     .480632

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```



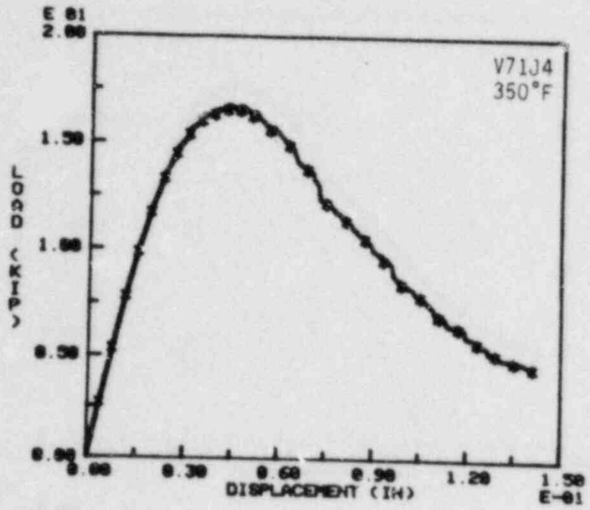


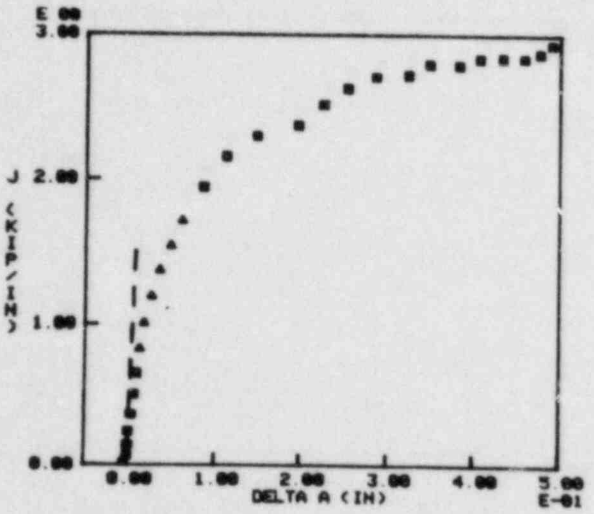
```
                J                    CRACK EXTENSION
             KIP/IN                        IN

 1 .       .0220599                  8.93593E-04
 2 .       .0730029                 -5.33891E-03
 3 .       .150134                   2.02894E-03
 4 .       .25298                    2.24745E-03
 5 .       .379999                   2.40278E-03
 6 .       .518979                   6.69742E-03
 7 .       .684942                   7.69615E-03
 8 .       .858721 *+                .0117731
 9 .      1.03537 *+                 .0167011
10 .      1.21086 *+                 .0227708
11 .      1.38903 *+                 .0301831
12 .      1.5676 *+                  .0395832
13 .      1.73678 *+                 .0519456
14 .      1.96569                    .0731739
15 .      2.15633                    .104181
16 .      2.31498                    .135754
17 .      2.44229                    .171048
18 .      2.55632                    .205915
19 .      2.71602                    .223049
20 .      2.78100                    .259062
21 .      2.82805                    .293325
22 .      2.84975                    .327255
23 .      2.91493                    .35166
24 .      2.93936                    .379262
25 .      2.90132                    .414143
26 .      2.92437                    .437121
27 .      3.03038                    .446739
28 .      3.07241                    .464267

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```



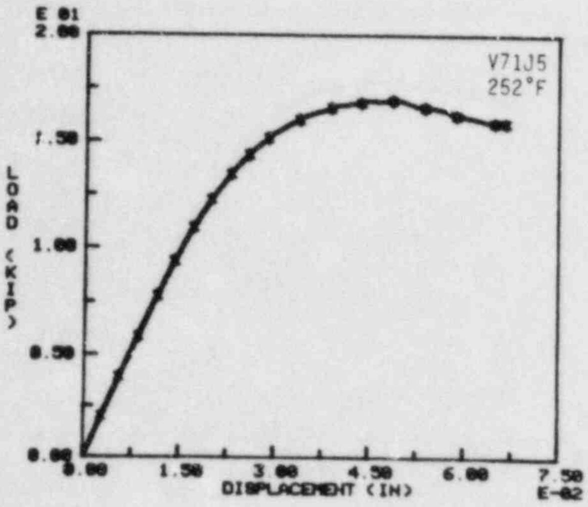


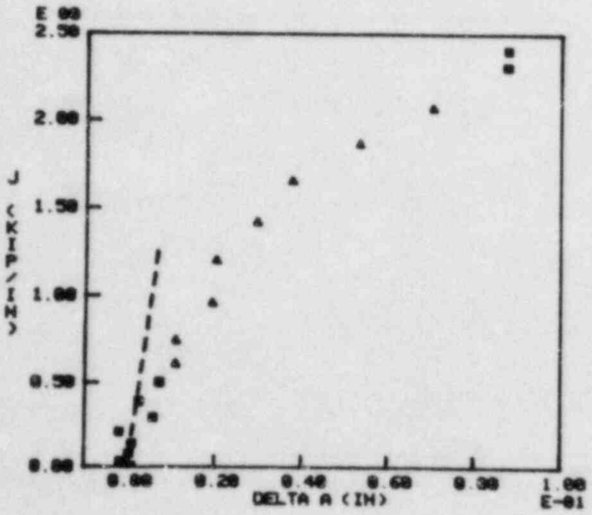
```
                 J                      CRACK EXTENSION
              KIP/IN                          IN

  1  .    .0213600                    -1.22670E-03
  2  .    .0712253                     2.53001E-04
  3  .    .140633                      3.24249E-04
  4  .    .248373                      1.70062E-03
  5  .    .370135                      2.72910E-03
  6  .    .5203                        6.61421E-03
  7  .    .683422                      8.22282E-03
  8  .    .860598  *+                   .0119717
  9  .   1.04062   *+                   .0150796
  10  .  1.23308   *+                   .0235617
  11  .  1.42727   *+                   .0290442
  12  .  1.61619   *+                   .0380089
  13  .  1.88959   *+                   .0552345
  14  .  2.12717                        .0834165
  15  .  2.34003                        .109105
  16  .  2.52273                        .139578
  17  .  2.6316                         .180714
  18  .  2.71252                        .221475
  19  .  2.7942                         .255664
  20  .  2.85953                        .285982
  21  .  2.90727                        .322543
  22  .  2.90514                        .360512
  23  .  2.90899                        .394016
  24  .  2.90913                        .411479
  25  .  2.95281                        .445169
  26  .  2.96744                        .467011
  27  .  2.97576                        .490152
  28  .  2.99664                        .500490

*-DENOTES POINTR USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```





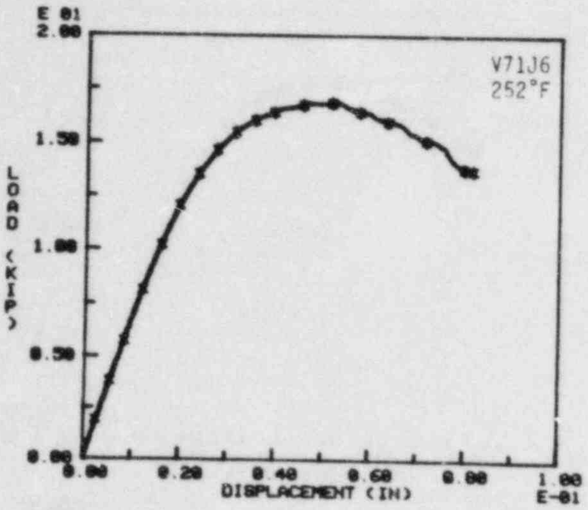
```
                  J                      CRACK EXTENSION
               KIP/IN                          IN

  1  .     .0185000                     -3.39341E-03
  2  .     .0660471                     -2.92340E-04
  3  .     .14404                        4.29034E-04
  4  .     .240604                       7.75456E-04
  5  .     .364152                       4.07255E-03
  6  .     .509063                       7.23015E-03
  7  .     .662013                       9.92668E-03
  8  .     .837493 *+                     .0139024
  9  .    1.01435  *+                     .017964
 10  .    1.19989  *+                     .0263058
 11  .    1.37462  *+                     .0356581
 12  .    1.54642  *+                     .048229
 13  .    1.71801  *+                     .0615633
 14  .    1.94366                         .0853519
 15  .    2.15737                         .111535
 16  .    2.2990                          .14772
 17  .    2.37442                         .195842
 18  .    2.51582                         .224318
 19  .    2.62706                         .252151
 20  .    2.70721                         .284009
 21  .    2.72166                         .32314
 22  .    2.75429                         .340079
 23  .    2.79400                         .382121
 24  .    2.8404                          .405969
 25  .    2.84445                         .433511
 26  .    2.84101                         .459033
 27  .    2.87633                         .477583
 28  .    2.93704                         .49104

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```

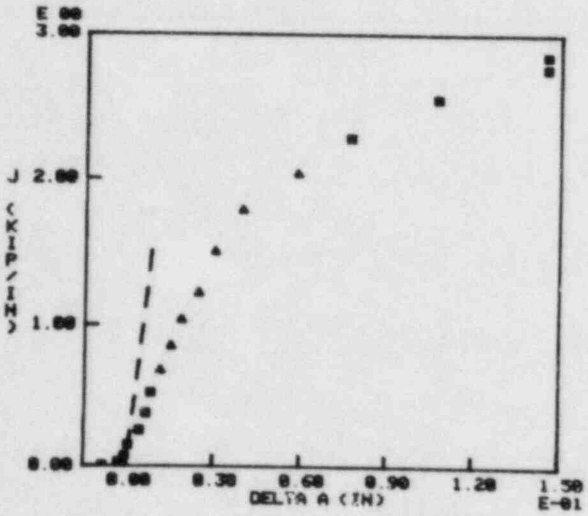




```
                J                   CRACK EXTENSION
             KIP/IN                       IN

  1  .    9.64324E-03              8.02636E-04
  2  .    .0351152                -1.66371E-03
  3  .    .0793818                 3.56674E-04
  4  .    .138981                  1.06207E-03
  5  .    .208201                 -1.93655E-03
  6  .    .294957                  5.70631E-03
  7  .    .391675                  2.71109E-03
  8  .    .504939                  7.14445E-03
  9  .    .618559  *+              .0100567
  10 .    .749452  *+              .010855
  11 .    .964899  *+              .019309
  12 .    1.20637  *+              .0201731
  13 .    1.42829  *+              .0295492
  14 .    1.66238  *+              .0375782

  15 .    1.87659  *+              .053267
  16 .    2.07674  *+              .0702327
  17 .    2.31346                  .0874306
  18 .    2.40616                  .0875661
```

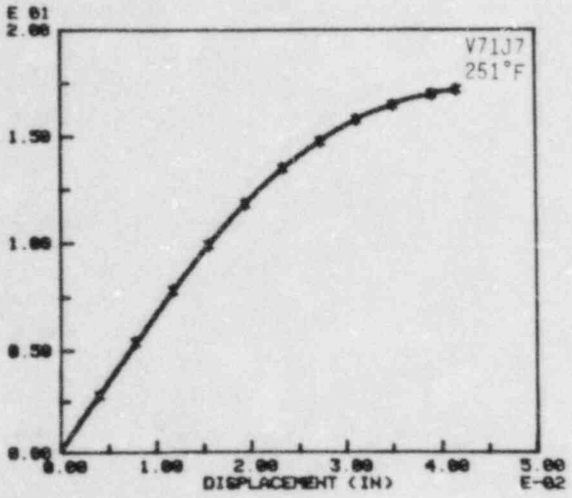
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

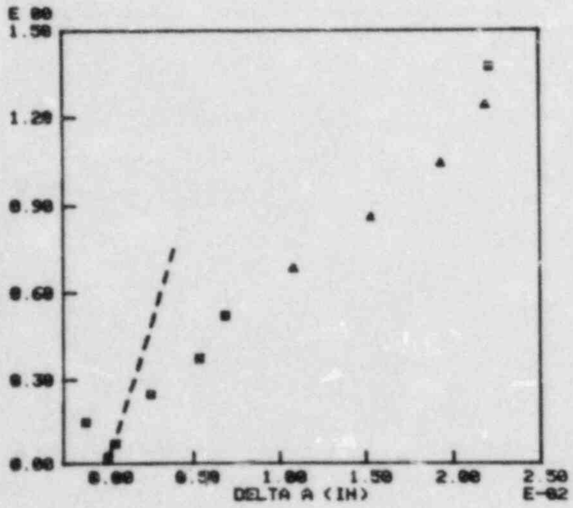




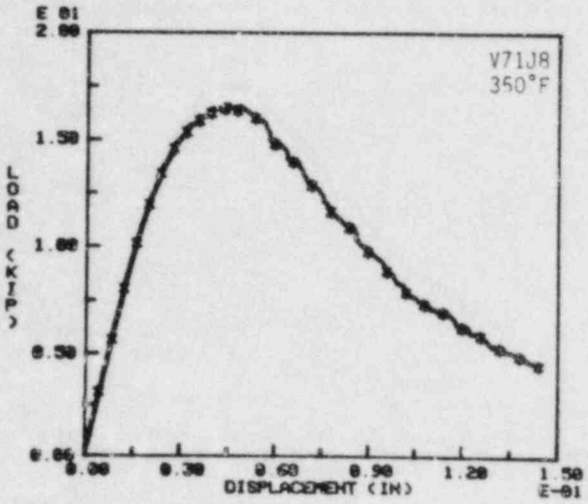
	J KIP/IN	CRACK EXTENSION IN
1 .	8.62531E-03	-8.39245E-03
2 .	.0333874	-2.79406E-03
3 .	.0755050	-4.60744E-04
4 .	.155305	4.38571E-04
5 .	.259094	4.37868E-03
6 .	.382007	6.71530E-03
7 .	.530644	8.27849E-03
8 .	.691300 *+	.0116322
9 .	.862892 *+	.0150403
10 .	1.04538 *+	.0186063
11 .	1.22008 *+	.0245477
12 .	1.5119 *+	.0303253
13 .	1.79535 *+	.039943
14 .	2.04348 *+	.0505873
15 .	2.28204	.0770267
16 .	2.55224	.107119
17 .	2.76748	.145363
18 .	2.85350	.145400

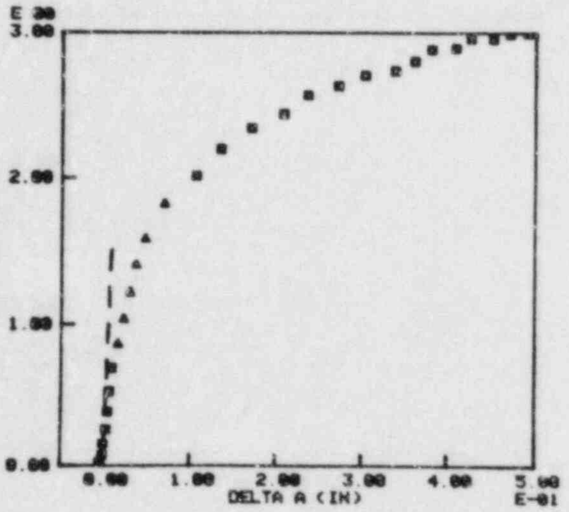
*—DENOTES POINTS USED FOR JIC DETERMINATION
+—DENOTES POINTS USED IN TEARING MODULUS CALCULATION



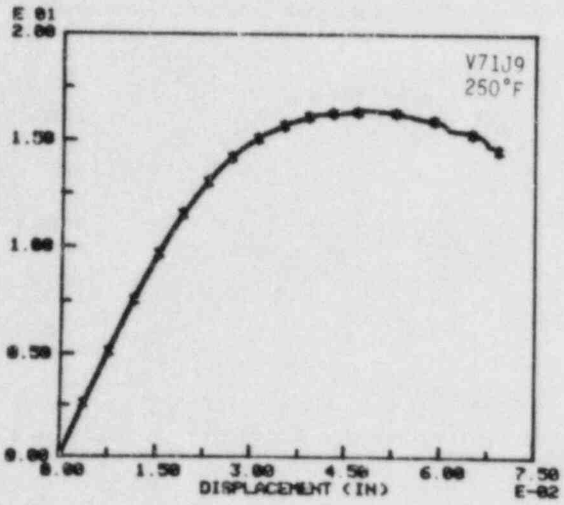


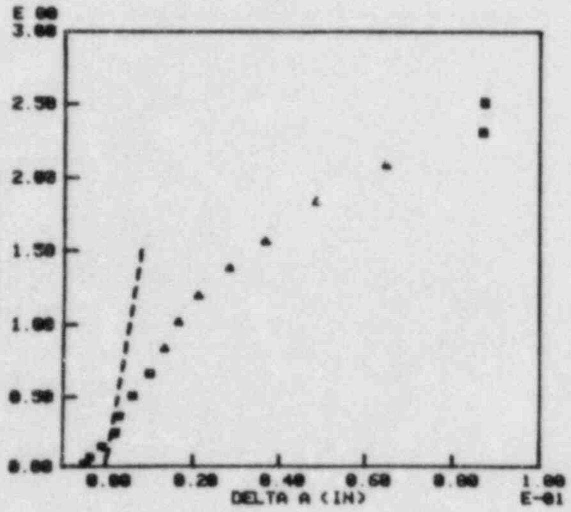
```
                 J              CRACK EXTENSION
              KIP/IN                  IN

   1 .   .0212207              4.20009E-05
   2 .   .0699653              4.56214E-04
   3 .   .149071              -1.20211E-03
   4 .   .248354               2.51158E-03
   5 .   .3753                 5.34407E-03
   6 .   .523439               6.85275E-03
   7 .   .685894  *+            .0107661
   8 .   .868583  *+            .0153298
   9 .  1.04528   *+            .0193169
   10 . 1.24383   *+            .0219551
   11 . 1.3739                  .0221497

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```



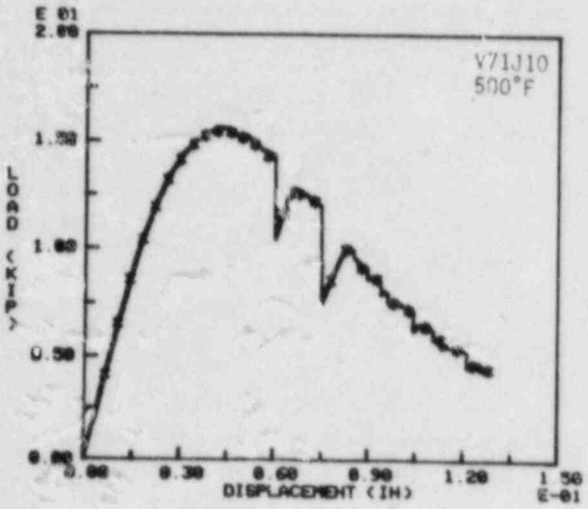


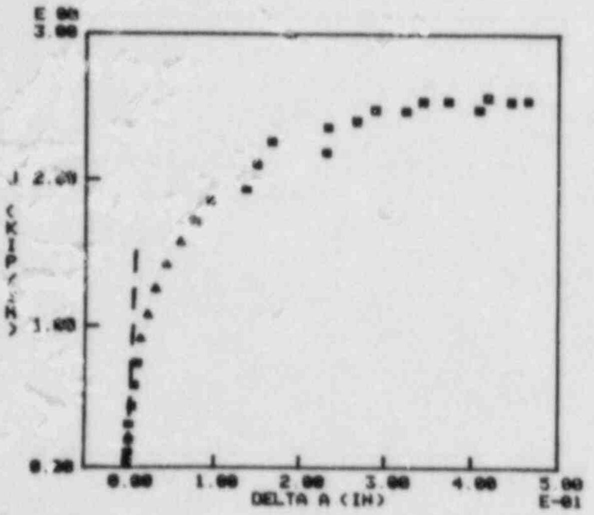
```
              J                   CRACK EXTENSION
           KIP/IN                       IN

  1 .    .0249407                 -4.38404E-03
  2 .    .0769035                 -1.23799E-03
  3 .    .158035                  -2.16603E-04
  4 .    .259363                   2.89790E-03
  5 .    .380018                   4.19509E-03
  6 .    .534075                   6.68907E-03
  7 .    .697004                   9.51123E-03
  8 .    .871234 *+                .0164372
  9 .   1.04133 *+                 .023093
 10 .   1.22269 *+                 .0290316
 11 .   1.41122 *+                 .0365438
 12 .   1.58909 *+                 .0479445
 13 .   1.82007 *+                 .0697509
 14 .   2.01404                    .106513
 15 .   2.19099                    .134424
 16 .   2.3419                     .170097
 17 .   2.43591                    .200301
 18 .   2.56856                    .235971
 19 .   2.63404                    .271475
 20 .   2.7064                     .302898
 21 .   2.7376                     .337045
 22 .   2.80417                    .361218
 23 .   2.80483                    .380501
 24 .   2.8958                     .400411
 25 .   2.96435                    .426375
 26 .   2.95764                    .452143
 27 .   2.99244                    .471052
 28 .   2.99823                    .491547

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```



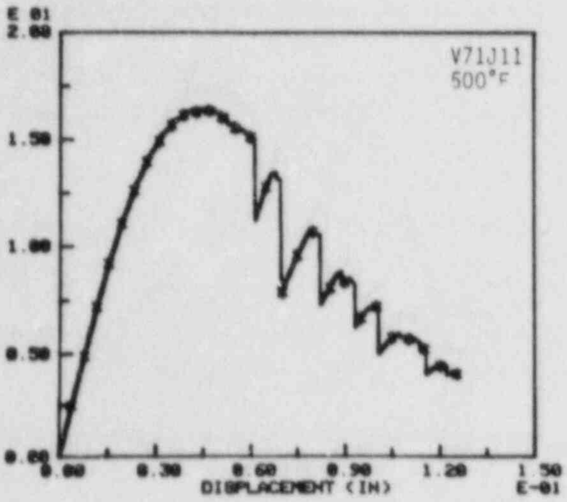


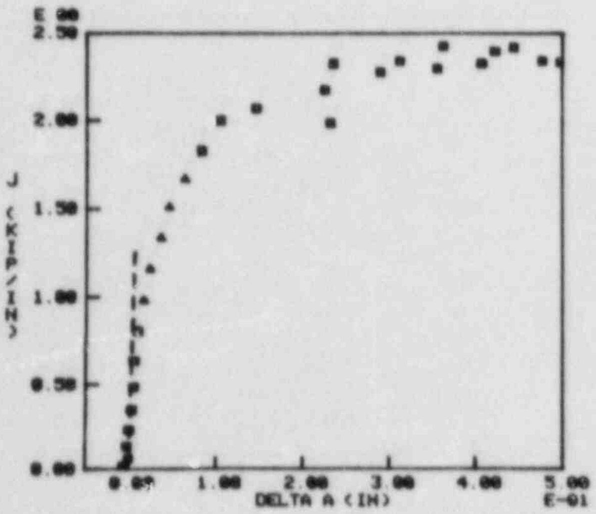
```
                J              CRACK EXTENSION
             KIP/IN                  IN

    1 .    .0176464            -4.77098E-03
    2 .    .0656017            -3.63374E-03
    3 .    .142075             -8.39114E-04
    4 .    .240319              2.06052E-03
    5 .    .361436              3.07572E-03
    6 .    .500071              6.00265E-03
    7 .    .663190               .0100135
    8 .    .84034  *+            .0133383
    9 .   1.02263  *+            .0164527
    10 .  1.20428  *+            .0210731
    11 .  1.38740  *+            .0283005
    12 .  1.56009  *+            .0366559
    13 .  1.84101  *+            .0483400
    14 .  2.08039  *+            .0645651

    15 .  2.31004                .0868181
    16 .  2.51187                .0871151

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```





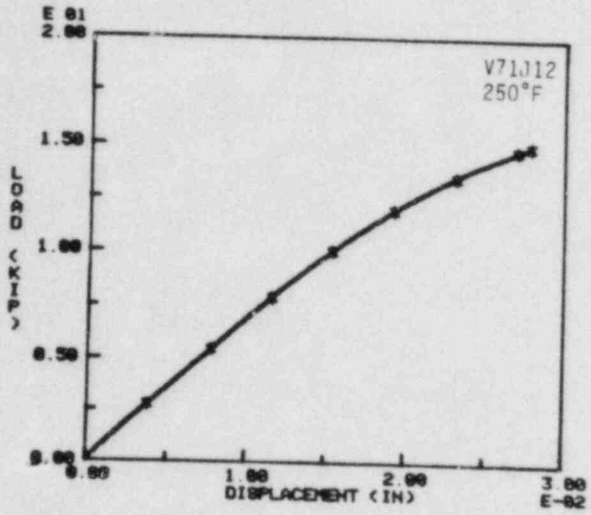
```
              J                    CRACK EXTENSION
           KIP/IN                        IN

  1  .   .0462261               -1.06204E-03
  2  .   .111398                -2.90619E-04
  3  .   .196313                 1.06061E-03
  4  .   .318008                 1.13297E-03
  5  .   .438682                 4.04918E-03
  6  .   .589383                 6.94919E-03
  7  .   .746223                 9.06507E-03
  8  .   .917531 *+              .0140055
  9  .  1.00128  *+              .0223269
 10  .  1.25797  *+              .0311741
 11  .  1.42465  *+              .0433387
 12  .  1.5769  *+               .0598969
 13  .  1.72857                  .0753146
 14  .  1.87921                  .0942791
 15  .  1.94062                  .137443
 16  .  2.19798                  .149902
 17  .  2.26129                  .166599
 18  .  2.18703                  .229705
 19  .  2.35769                  .23149
 20  .  2.40191                  .265791
 21  .  2.47961                  .287068
 22  .  2.47339                  .323618
 23  .  2.53794                  .342002
 24  .  2.53976                  .371966
 25  .  2.48177                  .400087
 26  .  2.56302                  .417902
 27  .  2.5365                   .445815
 28  .  2.54351                  .46434

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```

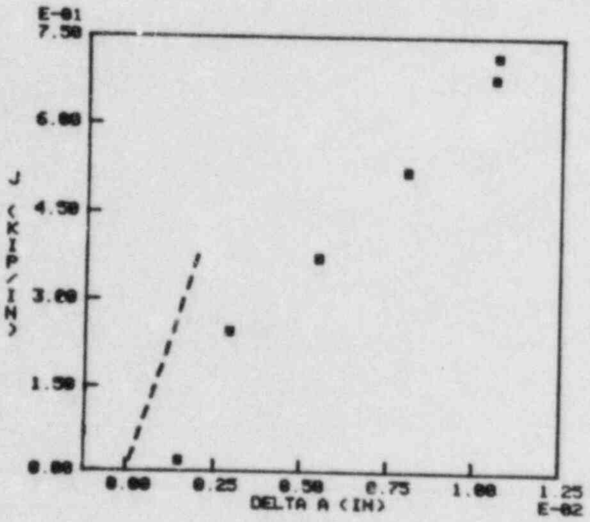




	J KIP/IN	CRACK EXTENSION IN
1 .	.0177093	-6.40400E-03
2 .	.0622406	-4.14491E-04
3 .	.135070	-1.62399E-03
4 .	.22961	4.50730E-04
5 .	.349176	3.20613E-03
6 .	.485921	5.33426E-03
7 .	.640163	5.92995E-03
8 .	.810703	9.56297E-03
9 .	.986794 #+	.0164647
10 .	1.16563 #+	.0230700
11 .	1.33982 #+	.0356973
12 .	1.51829 #+	.0445350
13 .	1.6786 #+	.0629083
14 .	1.83203	.0826815
15 .	2.00468	.104834
16 .	2.07019	.145836
17 .	1.90075	.230085
18 .	2.17485	.224479
19 .	2.32831	.234703
20 .	2.27707	.288596
21 .	2.34194	.311255
22 .	2.29896	.355620
23 .	2.4296	.362674
24 .	2.33049	.406568
25 .	2.3976	.422063
26 .	2.42211	.443323
27 .	2.34262	.477687
28 .	2.33434	.499125

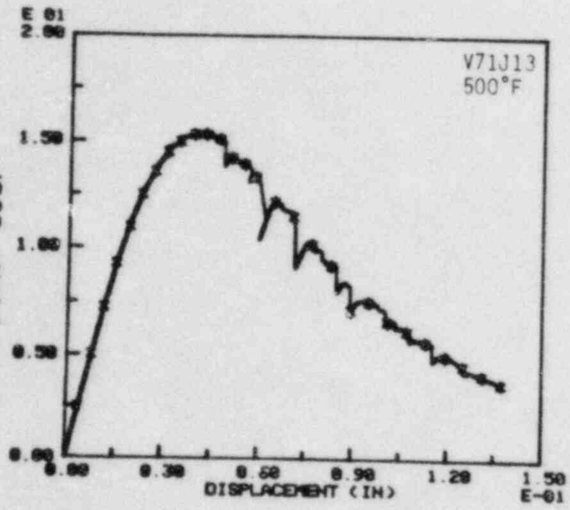
#-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

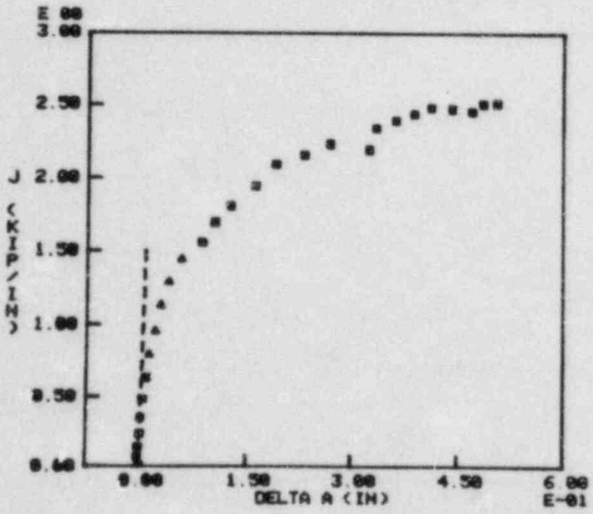




	J KIP/IN	CRACK EXTENSION IN
1 .	.0192581	1.40610E-03
2 .	.0700159	-2.04289E-03
3 .	.147402	-1.55556E-03
4 .	.247200	2.91502E-03
5 .	.372425	5.40700E-03
6 .	.519634	8.04055E-03
7 .	.679496	.010558
8 .	.716089	.0106231

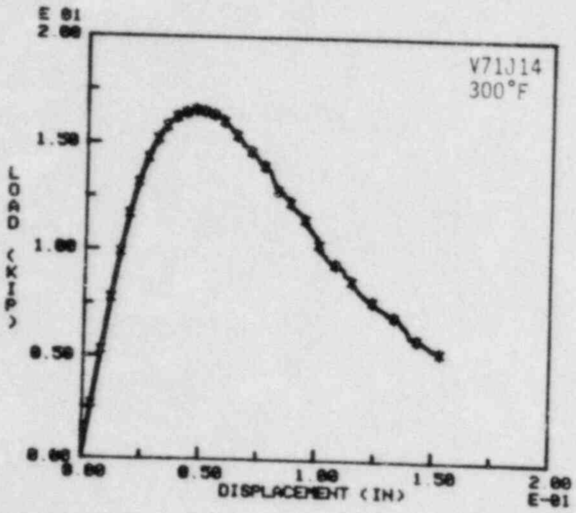
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

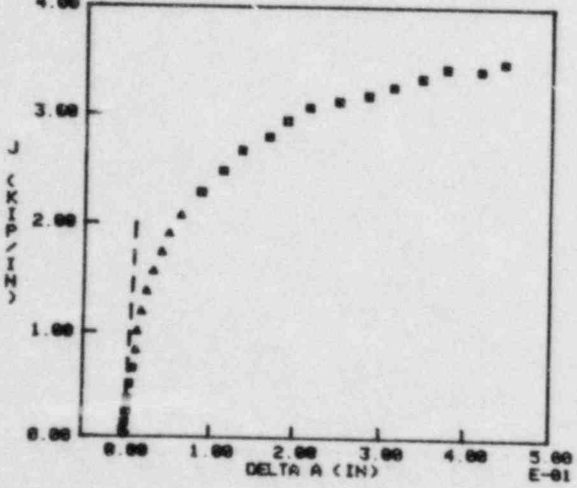




	J KIP/IN	CRACK EXTENSION IN
1 .	.0170104	1.01682E-03
2 .	.0646476	-2.11358E-03
3 .	.13642	-4.50738E-04
4 .	.230854	1.04258E-03
5 .	.317004	1.94715E-03
6 .	.401833	4.60016E-03
7 .	.634307	9.47475E-03
8 .	.798981 *+	.0130683
9 .	.959247 *+	.0210713
10 .	1.13792 *+	.0290774
11 .	1.2967 *+	.0412713
12 .	1.44946 *+	.0592618
13 .	1.56225	.087978
14 .	1.69075	.105377
15 .	1.81309	.126847
16 .	1.95004	.160900
17 .	2.09987	.190009
18 .	2.16105	.231055
19 .	2.23721	.267427
20 .	2.20097	.323764
21 .	2.34796	.333996
22 .	2.40118	.362124
23 .	2.44569	.38781
24 .	2.48752	.411658
25 .	2.48054	.440791
26 .	2.46115	.469344
27 .	2.51332	.485106
28 .	2.51696	.505411

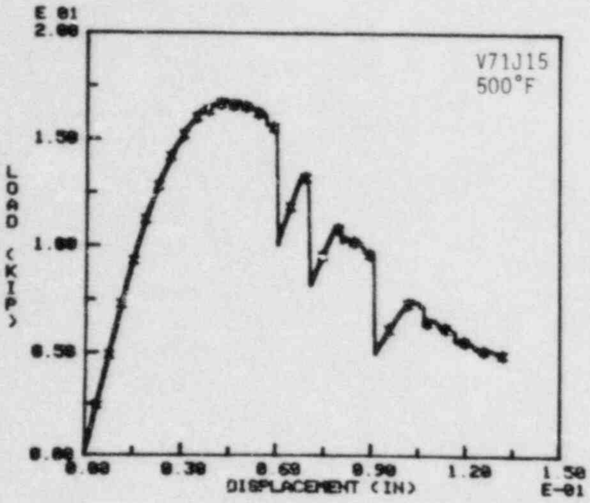
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

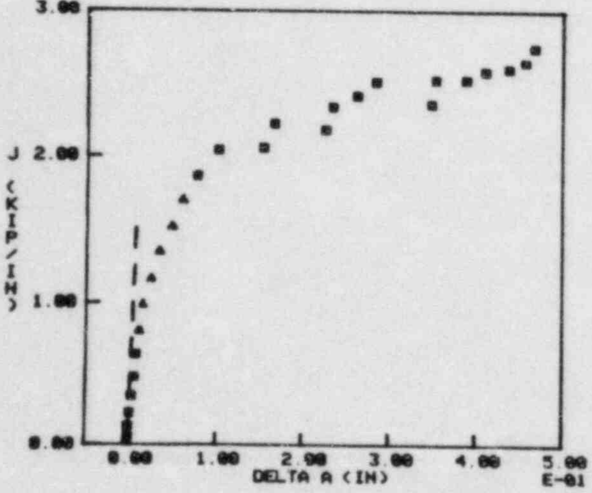




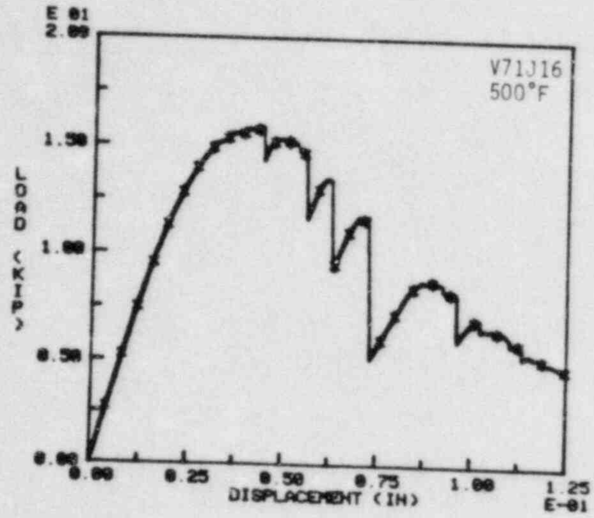
	J KIP/IN		CRACK EXTENSION IN
1 .	.0100569		9.31970E-04
2 .	.0656944		-1.15991E-03
3 .	.143555		2.22206E-04
4 .	.241653		1.54263E-03
5 .	.36313		3.46829E-03
6 .	.500332		4.92096E-03
7 .	.660737		8.93152E-03
8 .	.834395	*+	.0120453
9 .	1.01514	*+	.013665
10 .	1.19958	*+	.0185374
11 .	1.38587	*+	.0242046
12 .	1.56929	*+	.0317267
13 .	1.74348	*+	.0413889
14 .	1.91415	*+	.0532000
15 .	2.08144	*+	.0639287
16 .	2.29404		.0869635
17 .	2.49072		.11182
18 .	2.6794		.134303
19 .	2.80627		.166853
20 .	2.95367		.180067
21 .	3.0747		.21515
22 .	3.13417		.240565
23 .	3.1912		.28292
24 .	3.26894		.31226
25 .	3.34992		.346603
26 .	3.43692		.375839
27 .	3.42083		.416773
28 .	3.49021		.444226

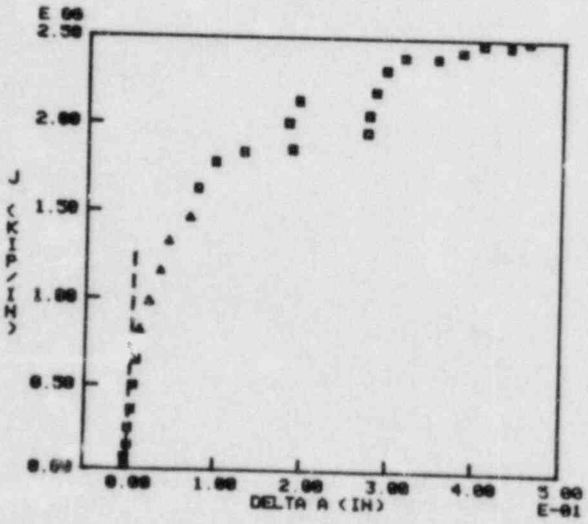
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION



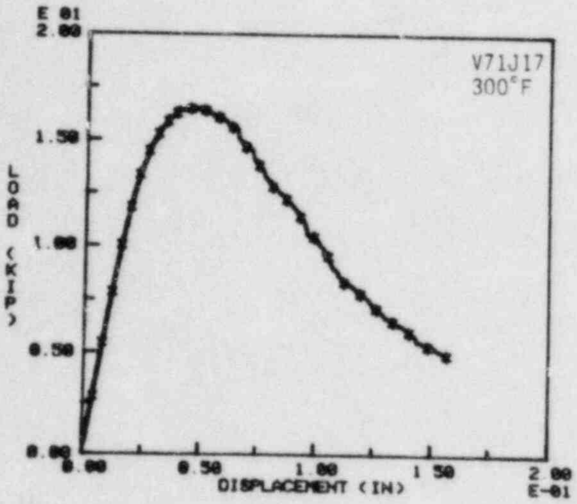


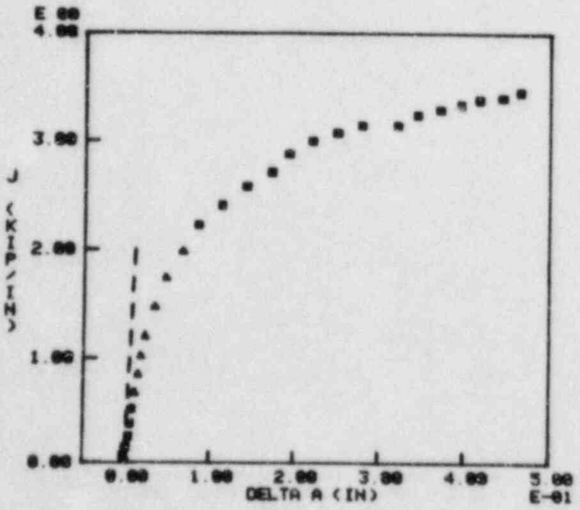
```
                J                  CRACK EXTENSION
             KIP/IN                      IN

 1  .     .0174964               -1.14310E-03
 2  .     .0620527                1.36256E-04
 3  .     .13438                  1.38283E-05
 4  .     .227052                 1.27065E-03
 5  .     .347632                 3.66378E-03
 6  .     .485412                 6.46234E-03
 7  .     .643058                 8.76272E-03
 8  .     .810169  *+            .0118163
 9  .     .992948  *+            .0161232
10  .    1.17076   *+            .0251747
11  .    1.35426   *+            .0346299
12  .    1.52475   *+            .048396
13  .    1.70501   *+            .0606163
14  .    1.86761                 .0763892
15  .    2.04568                 .100826
16  .    2.06835                 .154023
17  .    2.22824                 .166474
18  .    2.18389                 .224288
19  .    2.34047                 .233825
20  .    2.42045                 .26899
21  .    2.50953                 .28326
22  .    2.36266                 .347798
23  .    2.52427                 .352495
24  .    2.52566                 .387966
25  .    2.58578                 .409859
26  .    2.60189                 .437125
27  .    2.64834                 .456696
28  .    2.74855                 .467393

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```



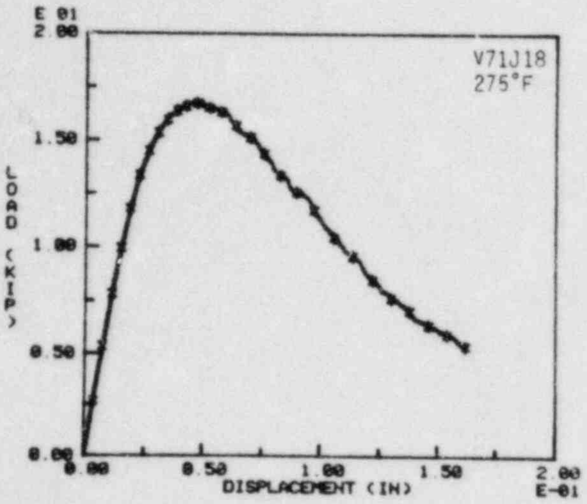


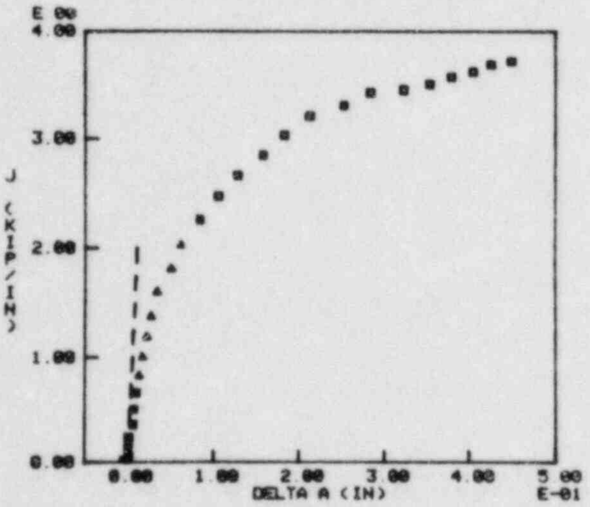
```
            J                 CRACK EXTENSION
          KIP/IN                     IN

 1 .    .0199290               -1.58441E-03
 2 .    .0721451               -1.06039E-03
 3 .    .14401                  1.07368E-03
 4 .    .245636                 1.26255E-03
 5 .    .3381                   4.01556E-03
 6 .    .501897                 6.38903E-03
 7 .    .631028                 9.32670E-03
 8 .    .82482 *+               .0125699
 9 .    .989366 *+              .0226805
10 .   1.16418 *+               .0353295
11 .   1.33212 *+               .0446062
12 .   1.47829 *+               .0687605
13 .   1.63505                  .0775682
14 .   1.78345                  .0976568
15 .   1.84626                  .138596
16 .   1.8689                   .185836
17 .   2.01387                  .181644
18 .   2.1394                   .193062
19 .   1.96851                  .272996
20 .   2.05908                  .275197
21 .   2.19161                  .282476
22 .   2.31862                  .294168
23 .   2.3947                   .315309
24 .   2.39004                  .354445
25 .   2.42825                  .382904
26 .   2.47489                  .407078
27 .   2.46685                  .438475
28 .   2.49544                  .46823

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```





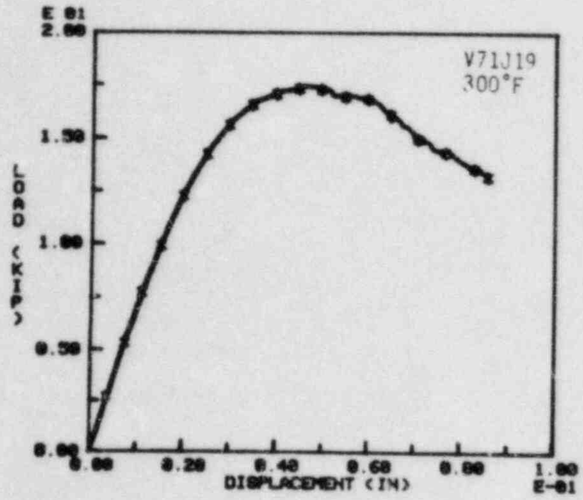
```
              J                  CRACK EXTENSION
            KIP/IN                     IN

 1 .     .0210048             -1.18971E-04
 2 .     .0705579             -1.91067E-03
 3 .     .140122               7.40277E-04
 4 .     .25295                4.26126E-03
 5 .     .376526               5.01253E-03
 6 .     .520075               7.59200E-03
 7 .     .604502 *+            .0100855
 8 .     .854094 *+            .0151048
 9 .    1.03823  *+            .0186481
10 .    1.21253  *+            .0232057
11 .    1.40574  *+            .0348269
12 .    1.75402  *+            .0479475
13 .    1.99619  *+            .0670047
14 .    2.23592                .0857127
15 .    2.41726                .113225
16 .    2.58572                .142003
17 .    2.7218                 .172511
18 .    2.8912                 .192600
19 .    3.00692                .220513
20 .    3.06224                .250405
21 .    3.15152                .279192
22 .    3.15003                .320501
23 .    3.24915                .343201
24 .    3.29740                .370077
25 .    3.34033                .395401
26 .    3.39131                .417325
27 .    3.40534                .444353
28 .    3.45929                .465024

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```

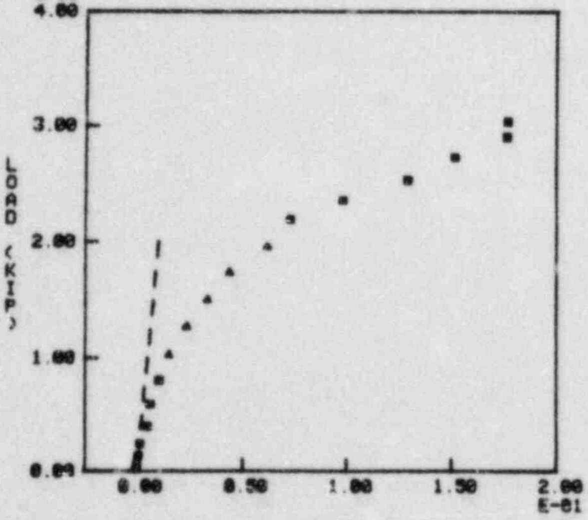




	J KIP/IN	CRACK EXTENSION IN
1 .	.0169716	-4.04100E-03
2 .	.0635879	1.44196E-03
3 .	.139607	5.62429E-04
4 .	.239257	8.62122E-04
5 .	.358451	6.04796E-03
6 .	.504557	6.93202E-03
7 .	.66453	9.39003E-03
8 .	.83465 *+	.012917
9 .	1.01259 *+	.0166359
10 .	1.19687 *+	.0219684
11 .	1.38559 *+	.0267403
12 .	1.61296 *+	.0339463
13 .	1.82137 *+	.0503441
14 .	2.03975 *+	.0618305
15 .	2.2683	.0836395
16 .	2.47742	.105374
17 .	2.6733	.127414
18 .	2.85680	.157263
19 .	3.03975	.182353
20 .	3.2181	.212501
21 .	3.31315	.252407
22 .	3.42923	.283235
23 .	3.45524	.322666
24 .	3.50939	.353700
25 .	3.57901	.379376
26 .	3.62685	.404983
27 .	3.69047	.426177
28 .	3.71774	.449915

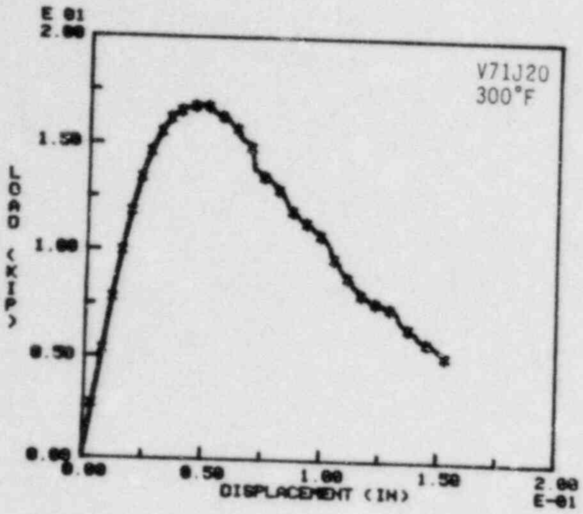
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

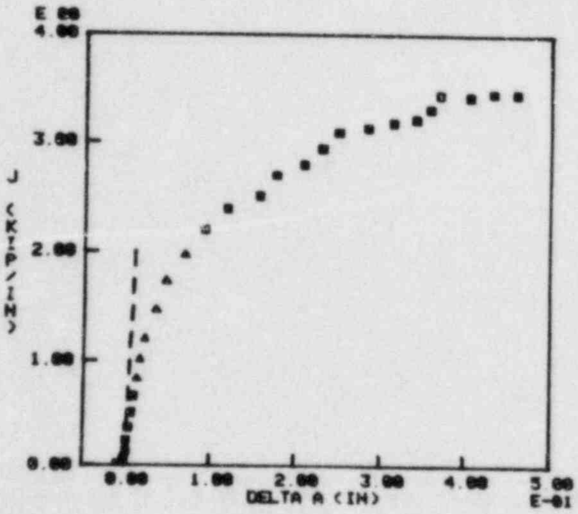




	J KIP/IN		CRACK EXTENSION IN
1 .	.010096		-3.42400E-04
2 .	.0675304		-1.06205E-04
3 .	.142602		7.44939E-04
4 .	.24527		1.45364E-03
5 .	.400578		4.03799E-03
6 .	.595767		6.39761E-03
7 .	.800363		.0105037
8 .	1.03643	*+	.014964
9 .	1.27042	*+	.023556
10 .	1.51452	*+	.0333444
11 .	1.74619	*+	.0437425
12 .	1.96512	*+	.0620383
13 .	2.19725		.0725298
14 .	2.36129		.0903586
15 .	2.5371		.129253
16 .	2.73517		.151593
17 .	2.91023		.176234
18 .	3.10197		.192579

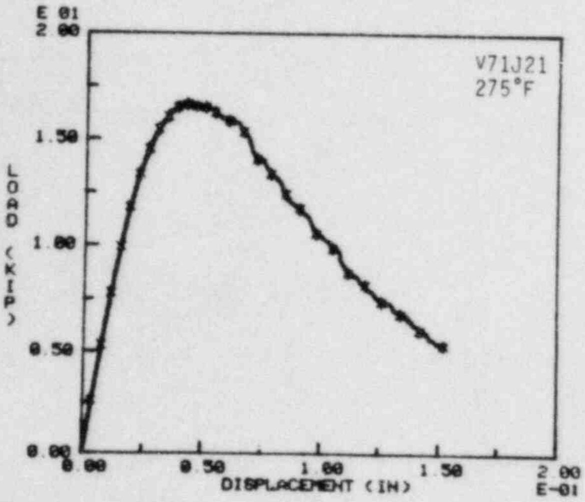
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

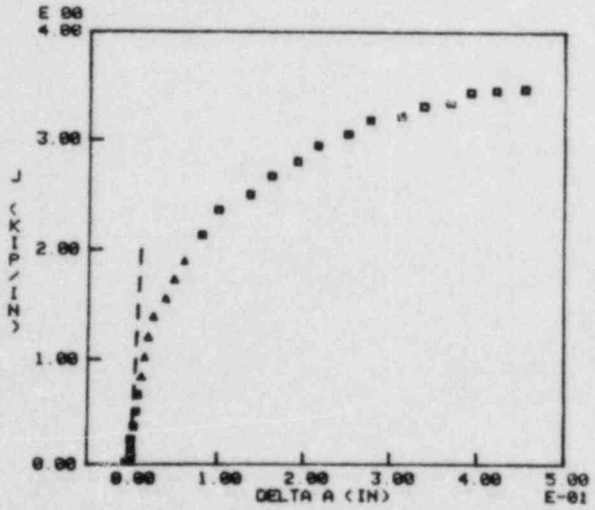




	J KIP/IN	CRACK EXTENSION IN
1 .	.0179526	-8.28028E-03
2 .	.0632333	-1.13986E-03
3 .	.14139	1.12736E-03
4 .	.241982	1.54077E-03
5 .	.361113	3.50300E-03
6 .	.586146	6.65164E-03
7 .	.664126	9.52172E-03
8 .	.830669 *+	.0130627
9 .	1.01995 *+	.0169716
10 .	1.20973 *+	.0224701
11 .	1.47703 *+	.0355643
12 .	1.74549 *+	.0474
13 .	1.9821 *+	.0697153
14 .	2.21107	.0920818
15 .	2.40429	.110629
16 .	2.52041	.156164
17 .	2.70942	.175956
18 .	2.81093	.200639
19 .	2.95501	.230183
20 .	3.10204	.249164
21 .	3.14232	.283653
22 .	3.19003	.312001
23 .	3.22538	.340224
24 .	3.31700	.357503
25 .	3.4456	.368875
26 .	3.43168	.404646
27 .	3.46139	.43218
28 .	3.46000	.459626

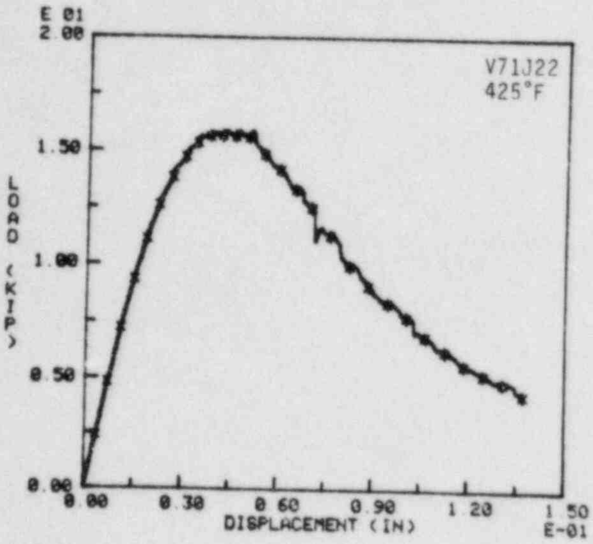
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

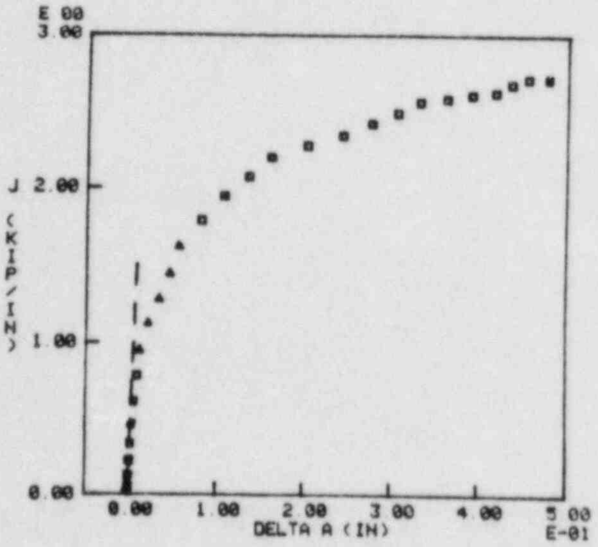




	J KIP/IN		CRACK EXTENSION IN
1	.0164479		-5.96929E-03
2	.0637585		8.15034E-04
3	.139993		3.11375E-04
4	.237788		5.40818E-05
5	.360486		3.01754E-03
6	.50486		6.01268E-03
7	.666123		7.59506E-03
8	.835759	*+	.0119849
9	1.01895	*+	.0152334
10	1.20654	*+	.0193411
11	1.39413	*+	.0251814
12	1.55773	*+	.0397184
13	1.73047	*+	.0490116
14	1.90101	*+	.0611546
15	2.13678		.0808734
16	2.36407		.0998164
17	2.50597		.135046
18	2.67539		.161153
19	2.81069		.191184
20	2.95054		.214899
21	3.05514		.249191
22	3.18745		.27548
23	3.22179		.312824
24	3.31256		.337446
25	3.34368		.367586
26	3.43779		.391393
27	3.45434		.421724
28	3.47295		.454729

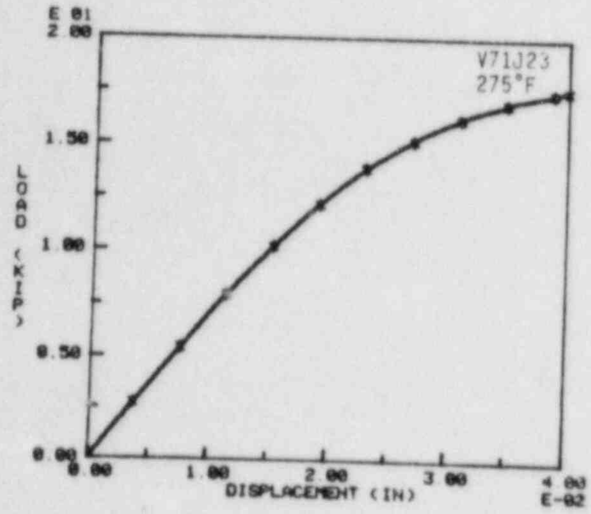
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

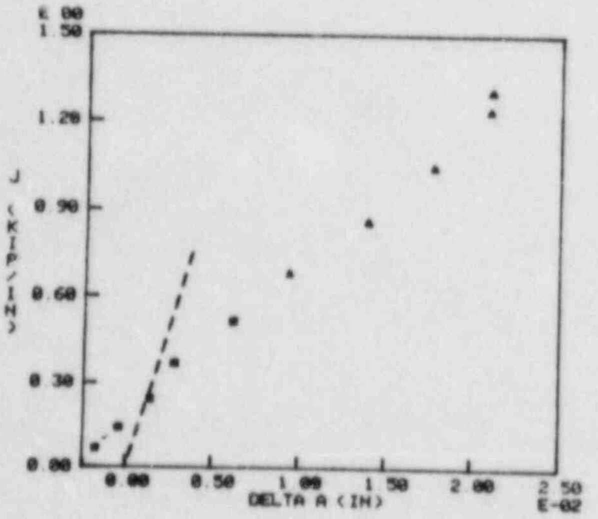




	J KIP/IN		CRACK EXTENSION IN
1	.014930		-9.31263E-04
2	.0556027		2.47836E-04
3	.127315		-3.03830E-04
4	.223083		1.12069E-03
5	.330755		2.31123E-03
6	.469915		3.11899E-03
7	.620076		5.94974E-03
8	.780652		8.92150E-03
9	.950876	*+	.0119662
10	1.13072	*+	.0215461
11	1.28980	*+	.0341876
12	1.45502	*+	.0454756
13	1.62848	*+	.0558335
14	1.79375		.0817455
15	1.94992		.106933
16	2.07596		.13587
17	2.20361		.161592
18	2.27851		.202816
19	2.34515		.243635
20	2.42193		.276518
21	2.49156		.305996
22	2.56423		.331724
23	2.58478		.363124
24	2.60981		.391377
25	2.62567		.417705
26	2.68132		.435948
27	2.71861		.454368
28	2.71697		.478036

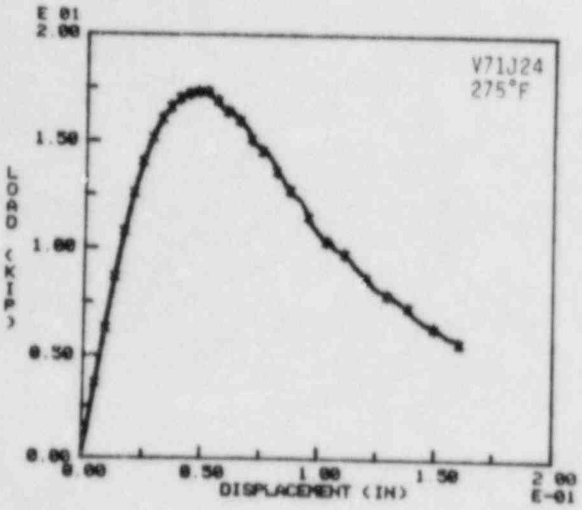
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

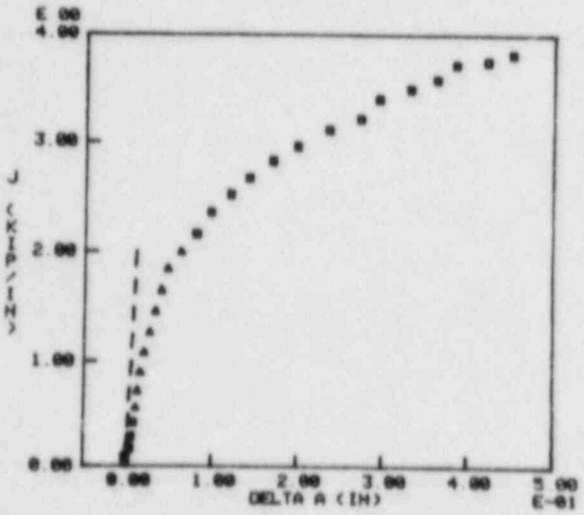




	J KIP/IN	CRACK EXTENSION IN
1 .	.0181664	-3.91150E-03
2 .	.0671069	-1.74570E-03
3 .	.142503	-4.17471E-04
4 .	.2454	1.37106E-03
5 .	.372032	2.75624E-03
6 .	.517160	6.16340E-03
7 .	.682059 *+	9.34529E-03
8 .	.861000 *+	.0139012
9 .	1.04063 *+	.0176626
10 .	1.243 *+	.0209353
11 .	1.30694 *+	.0210311

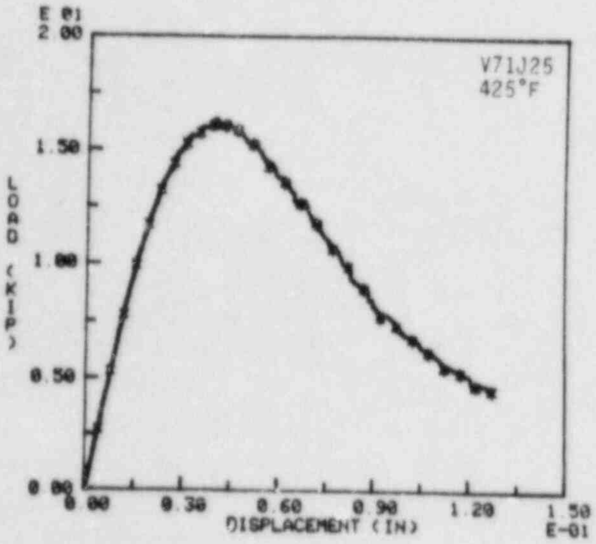
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

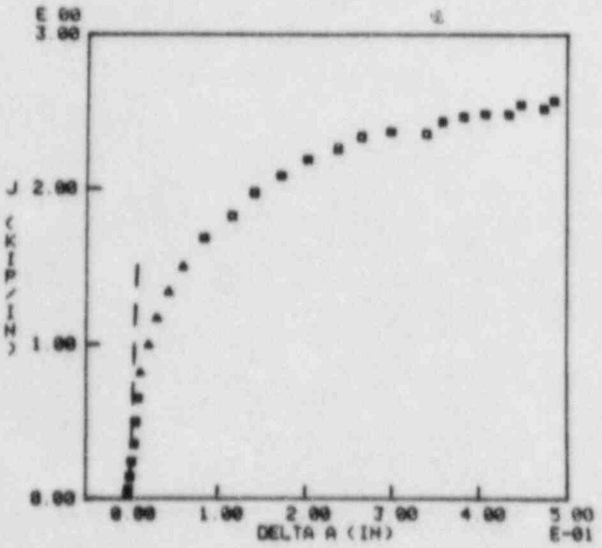




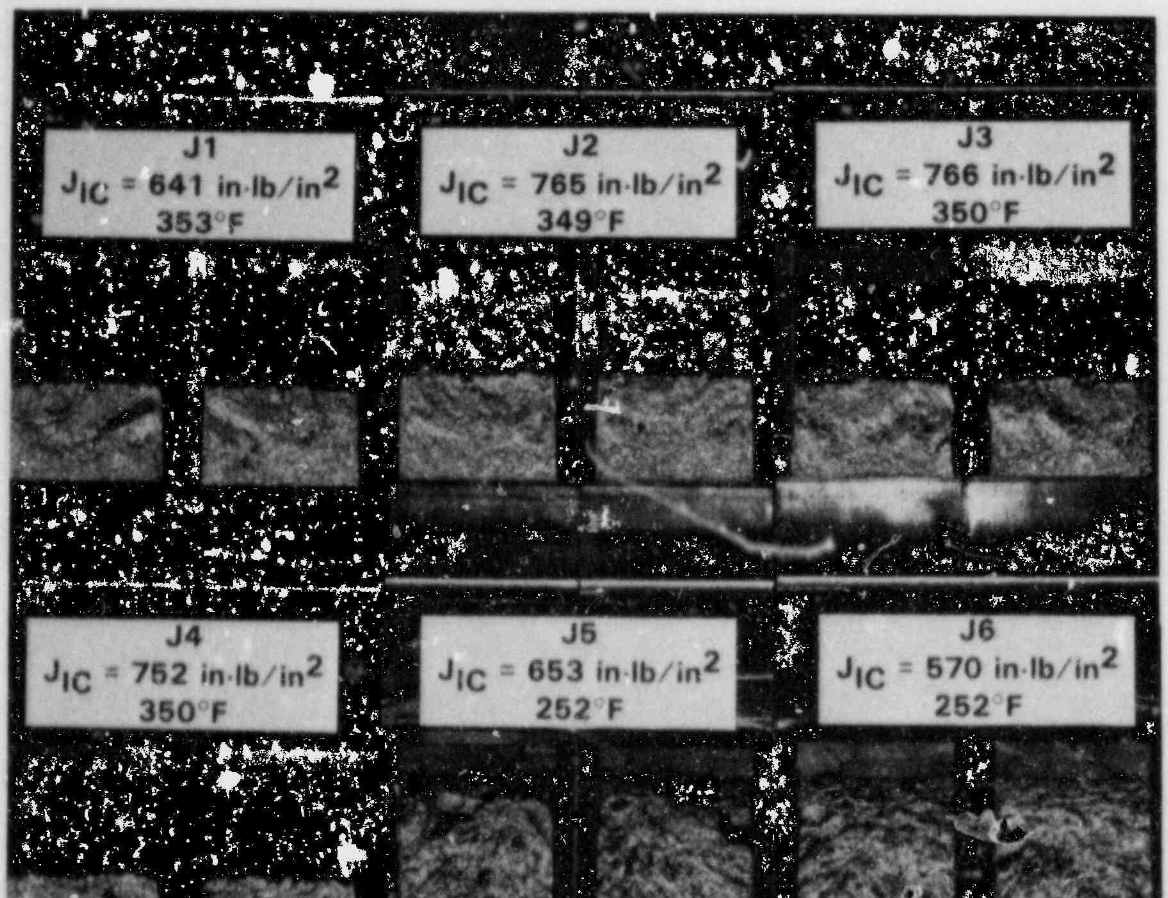
	J KIP/IN		CRACK EXTENSION IN
1	.0296367		-2.74650E-04
2	.090001		-8.91009E-04
3	.171621		3.50726E-03
4	.282641		5.16212E-03
5	.415197		7.47024E-03
6	.564955	*+	.0107675
7	.727429	*+	.0124049
8	.905918	*+	.015702
9	1.0900	*+	.0200323
10	1.27732	*+	.0262500
11	1.47039	*+	.0326017
12	1.65907	*+	.0397790
13	1.85573	*+	.0468527
14	2.01389	*+	.0626266
15	2.17001		.0806820
16	2.36694		.097525
17	2.5313		.120742
18	2.68013		.141519
19	2.84244		.169348
20	2.97753		.198637
21	3.12617		.235569
22	3.23323		.27249
23	3.40038		.294829
24	3.50114		.331568
25	3.59104		.362209
26	3.72606		.385494
27	3.75007		.422429
28	3.82195		.452379

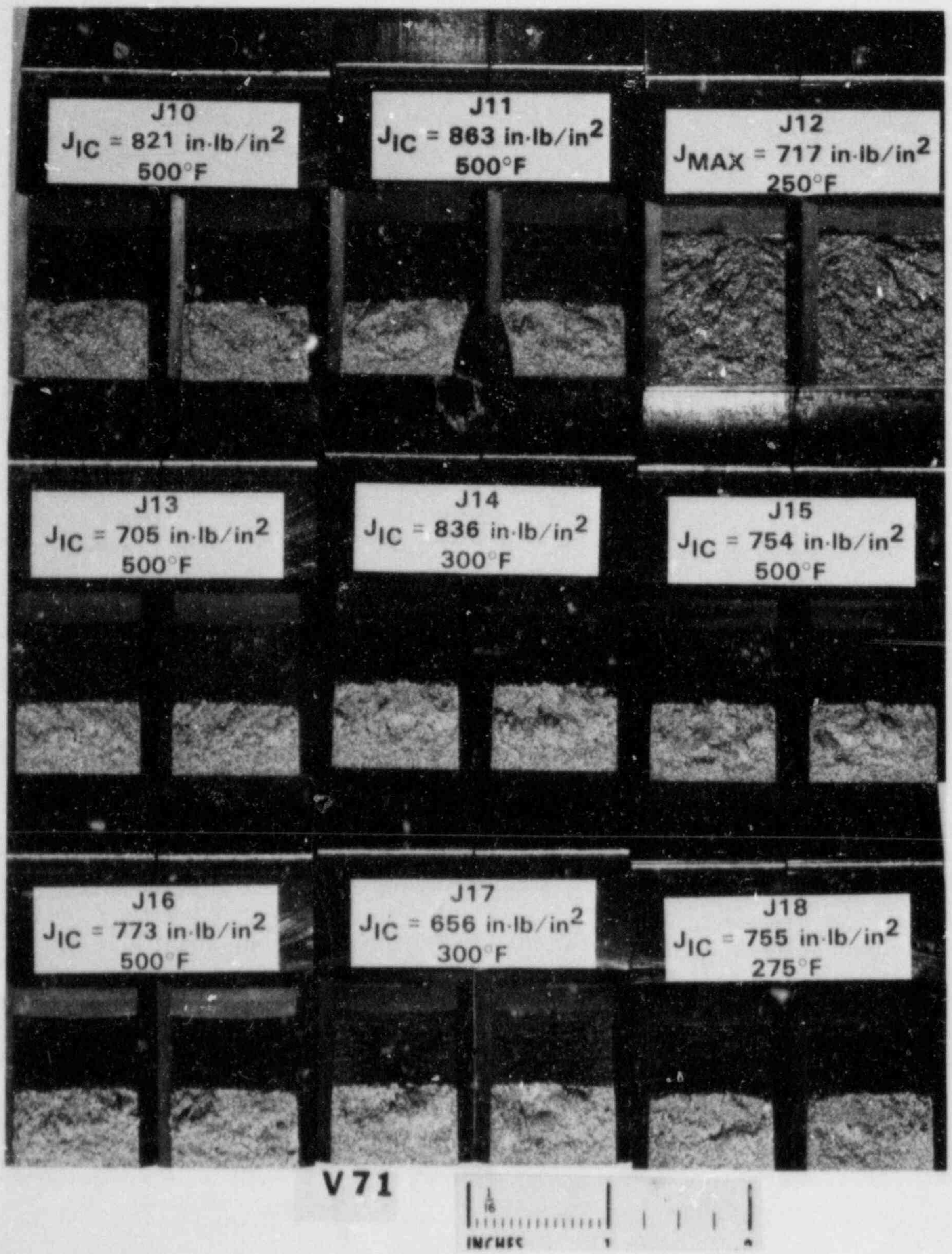
*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION

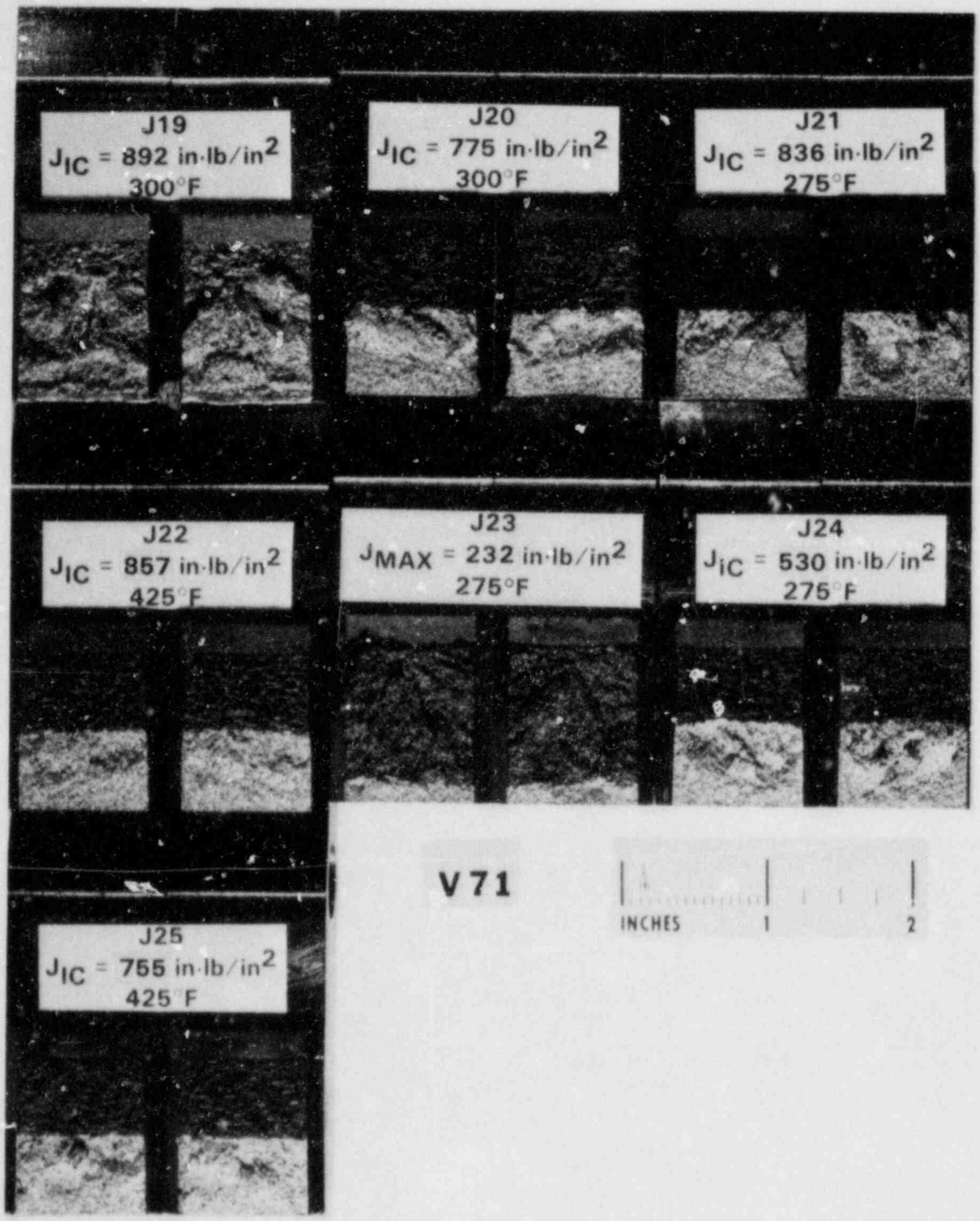




```
                J                    CRACK EXTENSION
             KIP/IN                        IN

      1 .   .0186507                 -2.76303E-03
      2 .   .0671448                 -1.82100E-03
      3 .   .141909                   6.90222E-05
      4 .   .241914                   1.44450E-03
      5 .   .359937                   5.00023E-03
      6 .   .503179                   6.13764E-03
      7 .   .656839                   8.92615E-03
      8 .   .824393 *+                .0121107
      9 .  1.00159 *+                 .0209526
     10 .  1.1707 *+                  .0304616
     11 .  1.34075 *+                 .0436562
     12 .  1.5007 *+                  .060143
     13 .  1.68100                    .084090
     14 .  1.82424                    .116022
     15 .  1.97346                    .141914
     16 .  2.08394                    .172575
     17 .  2.18718                    .202251
     18 .  2.25685                    .237119
     19 .  2.33641                    .264972
     20 .  2.36775                    .299055
     21 .  2.35638                    .339214
     22 .  2.43448                    .357933
     23 .  2.46048                    .381073
     24 .  2.48290                    .407326
     25 .  2.48396                    .43319
     26 .  2.54460                    .447573
     27 .  2.5189                     .473520
     28 .  2.57207                    .485046

*-DENOTES POINTS USED FOR JIC DETERMINATION
+-DENOTES POINTS USED IN TEARING MODULUS CALCULATION
```


J1
J_{IC} = 641 in·lb/in^2
353°F
J2
J_{IC} = 765 in·lb/in^2
349°F
J3
J_{IC} = 766 in·lb/in^2
350°F
J4
J_{IC} = 752 in·lb/in^2
350°F
J5
J_{IC} = 653 in·lb/in^2
252°F
J6
J_{IC} = 570 in·lb/in^2
252°F
J7
J_{IC} = 62 in·lb/in^2
251°F
J8
J_{IC} = 728 in·lb/in^2
350°F
J9
J_{IC} = 743 in·lb/in^2
250°F
V71
INCHES
1
2


J10
J_{IC} = 821 in·lb/in^2
500°F
J11
J_{IC} = 863 in·lb/in^2
500°F
J12
J_{MAX} = 717 in·lb/in^2
250°F
J13
J_{IC} = 705 in·lb/in^2
500°F
J14
J_{IC} = 836 in·lb/in^2
300°F
J15
J_{IC} = 754 in·lb/in^2
500°F
J16
J_{IC} = 773 in·lb/in^2
500°F
J17
J_{IC} = 656 in·lb/in^2
300°F
J18
J_{IC} = 755 in·lb/in^2
275°F
V71
1/16
INCHES
1
2


J19
J_{IC} = 892 in·lb/in^2
300°F
J20
J_{IC} = 775 in·lb/in^2
300°F
J21
J_{IC} = 836 in·lb/in^2
275°F
J22
J_{IC} = 857 in·lb/in^2
425°F
J23
J_{MAX} = 232 in·lb/in^2
275°F
J24
J_{IC} = 530 in·lb/in^2
275°F
J25
J_{IC} = 755 in·lb/in^2
425°F
V71
INCHES
1
2

NUREG/CR-3771
ORNL/Sub/82-52845/1
RDD:84:4085-02-01:01
Dist. Category AN

Internal Distribution

1. B. R. Bass
2. R. G. Berggren
3. S. E. Bolt
4–8. R. H. Bryan
9. J. W. Bryson
10. R. D. Cheverton
11. J. M. Corum
12. W. R. Corwin
13. D. P. Edmonds
14. D. S. Griffith
15. A. P. Malinauskas
16. J. J. McGowan
17. J. G. Merkle
18. R. K. Nanstad
19. C. E. Pugh
20. G. C. Robinson
21. K. R. Thoms
22. H. E. Trammell
23–27. G. D. Whitman
28. Patent Office
29. Central Research Library
30. Document Reference Section
31–32. Laboratory Records Department
33. Laboratory Records (RC)

External Distribuiton

34. C. Z. Serpan, Division of Engineering Technology, Nuclear Regulatory Commission, Washington, DC 20555
35. M. Vagins, Division of Engineering Technology, Nuclear Regulatory Commission, Washington, DC 20555
36. Office of Assistant Manager for Energy Research and Development, DOE, ORO, Oak Ridge, Tennessee 37831
37–46. H. A. Domian, Research and Development Division, Babcock & Wilcox Company, Alliance Research Center, Alliance, Ohio 44601
47–48. A. R. Rosenfield, Battelle Columbus Laboratories, 505 King Ave., Columbus, Ohio 43201
49–50. Technical Information Center, DOE Oak Ridge, Tennessee 37831
51–150. Given distribution as shown in Category AN (NTIS - 10)

☆U.S. GOVERNMENT PRINTING OFFICE: 1983-746-081/4025

NRC FORM 335
(11-81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-
ORNL/Sub/82-52845/1

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Vessel V-7 and V-8 Repair and Characterization of Insert Material

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
H. A. Domian

5. DATE REPORT COMPLETED

MONTH	YEAR
January	1984

DATE REPORT ISSUED

MONTH	YEAR

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

The Babcock & Wilcox Company
Research and Development Division
Alliance Research Center
Alliance, Ohio 44601

Work performed
under UCC-ND
Subcontract
76Y-52845V

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
B0119

13. TYPE OF REPORT
Subcontract

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

Pieces of Type SA508-2 steel, specially tempered to produce a high-impact-transition temperature, were welded in the side walls of Intermediate Test Vessels V-7 and V-8. These vessels are to be tested by the Oak Ridge National Laboratory (ORNL) in the Pressurized-Thermal-Shock (PTS) Project of the Heavy-Section Steel Technology (HSST) Program.

A comparable piece of forging taken from the same source and heat treated with the vessels was characterized for its mechanical properties to provide data for use in the PTS tests.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (11-81)