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Experimental Assessments of Gundremmingen RPV Archive Material for Fluence Rate Effects Studies

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ABSTRACT

The 250-MW boiling water Gundremmingen reactor, KRB-A, in the Federal Republic of Germany (FRG) has been decommissioned by the utility owners. A joint USA/FRG/UK study, conceived by the U. S. Nuclear Regulatory Commission (NRC), is underway to evaluate material removed from the vessel by trepanning for a critical assessment of power reactor vs. test reactor environment effects. MEA, Staatliche MaterialPruefungsanstalt (MPA), and UKAEA-Harwell are responsible for the experimental phases of the joint program. The reactor vessel operated at ~ 288°C; the inner wall fluence estimate at the time of decommissioning was about 1×10^{19} n/cm^2, E > 1 MeV.

This report describes irradiation assessments of a welded forging segment believed to be archive material from the KRB-A vessel fabrication. Preirradiation verification tests of the material are also summarized. Charpy-V (C_V), compact tension (CT) and tension test specimens were irradiated in the 2-MW light water-cooled test reactor located at the Buffalo Materials Research Center. Five as-irradiated conditions and two postirradiation annealed conditions were evaluated. With 288°C irradiations, the elevation in 100 MPa$\sqrt{m}$ temperature from fracture mechanics tests was found to match the elevation in 41-J temperature from C_V tests within 12°C. The latter elevation was predicted well by NRC's Regulatory Guide 1.99.

The L-C orientation data for the archive material vs. the vessel trepans suggest a fluence-rate effect. The C-L orientation data, however, do not. A test orientation dependence of radiation embrittlement sensitivity, described by the trepan material but not the archive material, is responsible and is anomalous.

CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

FOREWORD

The work reported here was performed at Materials Engineering Associates (MEA) under the program, Structural Integrity of Water Reactor Pressure Boundary Components, F. J. Loss, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is Alfred Taboada.

Prior reports under the current contract are listed below:

1. J. R. Hawthorne, "Significance of Nickel and Copper to Radiation Sensitivity and Postirradiation Heat Treatment Recovery of Reactor Vessel Steels," USNRC Report NUREG/CR-2948, Nov. 1982.

2. "Structural Integrity of Water Reactor Pressure Boundary Components, Annual Report for 1982," F. J. Loss, Ed., USNRC Report NUREG/CR-3228, Vol. 1, Apr. 1983.

3. J. R. Hawthorne, "Exploratory Assessment of Postirradiation Heat Treatment Variables in Notch Ductility Recovery of A 533-B Steel," USNRC Report NUREG/CR-3229, Apr. 1983.

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The authors thank the many persons in the MEA organization who made personal contributions to the experimental phases.

1. INTRODUCTION

The 250-MW boiling water Gundremmingen Reactor, KRB-A, located in the Federal Republic of Germany (FRG) was decommissioned by the utility owners in 1977. Prior to its decommissioning, the reactor vessel operated at a nominal temperature of 288°C and had an estimated inner wall fluence of 1×10^{19} n/cm^2, E > 1 MeV. In 1984, a remnant of a forging believed to be from the vessel construction was located by the U. S. Nuclear Regulatory Commission (NRC). The availability of this "archive" material and the service-degraded vessel material presented a unique opportunity for qualifying the effects of long-term irradiation on a prototypic reactor pressure vessel (RPV) steel. Specifically, the materials permitted verification tests of present prediction methods for radiation-induced embrittlement and the attenuation of radiation effects through the vessel thickness. Also, the materials allowed direct tests of the effect of fluence rate on the correlation of fracture toughness test methods with other mechanical test methods, such as the Charpy-V (C_v) test method. Recognizing these possibilities, the NRC put in place a joint USA/FRG/UK program to investigate the vessel properties in both the as-irradiated and postirradiation annealed conditions and to conduct accelerated irradiation tests of the archive material for power vs. test reactor comparisons. Materials Engineering Associates (MEA), Material-Pruefungsanstalt (MPA), and UKAEA-Harwell are the lead laboratories for the three respective countries.

MEA's tasks include the development of mechanical properties data for the unirradiated (preservice) vessel condition using the archive material and the determination of fracture resistance changes produced by a light-water test reactor environment. MPA's responsibilities include vessel trepanning and the determination of postservice vessel properties and fluences. The Institut fur Kerntechnik und Energiewandlung E. V. (IKE) is providing dosimetry support to MPA. UKAEA-Harwell is conducting irradiation tests of the archive material, using a heavy water test reactor. Through a coupling of the UKAEA-Harwell and MEA results, the program will qualify the effects on embrittlement sensitivity of large neutron spectrum differences.

This report documents MEA studies to date on the archive material and through-vessel-wall fluence determinations made by EG&G Idaho, Inc. under MEA sponsorship. In addition, MEA results for the archive material are compared to mechanical properties data for trepanned material developed by MPA. Detailed findings of the MPA tests are given in References 1-3. Results of Harwell studies on archive material supplied by MEA are not yet published although preliminary (tentative) results were described at the 1986 Workshop on the KRB-A vessel material (Ref. 4). Irradiations by Harwell primarily were in a heavy-water reactor environment; whereas the KRB-A and the test reactor used by MEA are light-water reactors.

The MEA and MPA studies jointly have produced a set of anomalous results. The anomaly pertains to one test orientation of the vessel material only and may be indicative of a unique irradiation fluence-rate effect. Resolution of the anomaly is viewed as highly important because of the potential impact on the applicability of NRC's Regulatory Guide 1.99 to long-term irradiation service at elevated temperature (Ref. 5). The studies are continuing.

2. MEA INVESTIGATIONS

MEA investigations have progressed through three phases. Phase 1 involved experimental testing of the archive material to verify that it was a remnant of the KRB-A vessel's ring forging No. 7.1 as suggested by vendor records (Refs. 6 and 7) and other information available. Phase 2 developed through-thickness mechanical properties of the archive material, for use in indexing the irradiation effects to the vessel. Phase 3 produced notch ductility, fracture toughness, and tensile strength data for irradiated and postirradiation annealed conditions. Additionally, tests of through-wall fluences were made using a portion of the material trepanned from the vessel belt-line region. The irradiation matrix that evolved since undertaking the program is summarized in Table 1. The philosophy behind each matrix point is discussed in Section 7.

Table 1 Irradiation Experiment Matrix (ASTM L-C Orientation Specimens)

Experiment		Irradiation Temperature	Fluence Target	Postirradiation[a] Test Conditions	Specimen Types	Specimen Complement		
						C_v	CT	Tensile
No.	Code[b]	(°C)	(n/cm^2, E > 1 MeV)					
1	UBR-68	288	8×10^{18}	I, IA[c], IA_{399}, IA_{454}	C_v, 0.5T-CT[d], Tensile[e]	47	24	8
[illegible]	UBR-78[f]	288	2.7×10^{18}	I, IA_{399}, IA_{454}	C_v, 0.5T-CT, Tensile	20 + 8[g]	24	2 + 2[g]
[illegible]	UBR-79A[f]	275	8×10^{18}	I	C_v, 0.5T-CT, Tensile	13 + 5[g]	6	2
[illegible]	UBR-80A[f]	288	2.3×10^{19}	I	C_v, Tensile	15 + 3[g]	0	4

[a] I = as-irradiated; IA_{399} = irradiated + 399°C-168 h annealed; IA_{454} = irradiated + 454°C-168 h annealed

[b] MEA assembly number

[c] Unspecified anneal condition

[d] 12.7-mm (0.5-in.) thick compact tension specimen

[e] 5.74-mm (0.226-in.) gage diameter

[f] Some C-L orientation C_v, tensile specimens included

[g] ASTM C-L orientation (C_v) or CMFL orientation (tensile)

3. KRB-A REACTOR VESSEL AND MATERIALS

The KRB-A reactor was placed in service in 1966. It represents an early prototype to boiling water reactors (BWR's) built by the General Electric Company. The belt-line region of the primary pressure vessel was constructed of several forged steel rings joined by circumferential submerged-arc (S/A) welding. Forging ring No. 7.1 was located at the elevation of the reactor fuel core (belt-line region). This ring has a thickness of 119 mm (4.7 in.) and is stainless steel clad on its inner surface. The steel type is 20NiMoCr26 which is similar to ASTM A 336 steel.

A reactor vessel surveillance program was implemented prior to commissioning (Refs. 7 and 8); some surveillance specimen capsules were later removed and tested (Ref. 9). In 1984, MEA obtained a few unirradiated (unused) surveillance specimens from the reactor facility, Kerkraftwerke Gundremmingen, which is owned by Rheinisch - Westfalisches Electrizitatswerk AG (RWE) and Bayernwerk AG (BAG). The specimen materials were of significant value to archive material verification.

Initially, a total of 15 trepans were removed from the vessel belt-line region. Twelve of the 100-mm diameter trepans were taken from forging ring No. 7.1; three were taken from an adjoining forging (see References 1 and 3). In addition, 3 trepans were removed from a forging in the vessel's steam drum region (essentially a nil fluence exposure region). Trepan "G", from forging ring No. 7.1, contained the material analyzed for through-wall fluence levels.

4. ARCHIVE MATERIAL

The archive material was obtained from the General Electric Company's Vallecitos site. The material was in the form of two welded ring segments. The segments did not have a stainless steel weld overlay but did have the appearance of previous machining on the I.D. and O.D. surfaces (using a large turret milling machine) to remove out-of-roundness and/or to bring the material to the design-specified thickness. The inner diameter of the vessel at the belt line is about 3.7 m (12.1 ft). In this report, the as-forged (original) I.D. surface of the material is taken as the reference surface for indexing 1/8T, 1/4T, and other thickness locations. The visual appearances of the base metals suggest that they were a prolongation of a much larger ring forging. The circumferential weld is suspected of being a portion of the weld made for surveillance program material (Ref. 7).

One ring segment, approximately 119-mm thick and weighing about 1450 kg, was given the identification code GEB by MEA. The base metals on either side of the weld deposit were coded GEB-1 and GEB-2. The other ring segment weighed about 990 kg; its base metal portions were coded GEA-1 and GEA-2. To date the MEA and Harwell irradiation programs have used the base metal, GEB-2, exclusively. The test specimens for irradiation were removed from the 1/8T-thickness location. This sampling location does not conform to ASTM Standard Practice E 185 but was chosen for specific reasons stated in Section 6.

5. VERIFICATION TESTS (PHASE 1)

Objectives of the verification tests were the experimental determination of chemical composition, hardness, tensile properties, and notch ductility properties of each of the four base metals contained in the welded ring segments. Microstructures were also characterized. The findings are documented in detail in MEA Report No. MEA-2095 (see Appendix A). In brief, the individual and combined observations for the base metals are in good agreement with existing documentation for vessel forging ring No. 7.1.

Table 2 lists the chemical compositions of the four archive base metals and the chemical compositions of the base metal portions of the three, unused surveillance specimens tested. The composition of the forging as given by KRB-A vessel documentation and the composition of the trepanned material as determined by MPA are also given. From the similarity of values for the archive materials, it is reasonable to conclude that they are all from the same steel melt. More importantly, the archive material composition matches well the composition of forging ring No. 7.1 (trepans) as determined by MPA.

The microstructures of the four archive materials were found to be tempered upper bainite or tempered upper bainite in combination with free ferrite, depending on the distance from the as-forged surface (see Appendix A). The GEB-1 and GEB-2 materials have comparable Rockwell-B hardness levels and profiles. A small hardness difference in the center region (only) was found between the GEA-1 vs. GEA-2 materials. The Rockwell-B hardness values were comparable to those of the surveillance specimens.

The newly developed C_v notch ductility data for the archive materials (1/4T location) and data for the forging ring No. 7.1 (ASTM C-L test orientation) generated in the mid-1960's (Refs. 6-8) are illustrated in Fig. 1. Note the agreement. The C-L test orientation proved to be the "strong" orientation; the C_v upper shelf energy level of this orientation is about 155 J (114 ft-lb) compared to 103 J (76 ft-lb) for the L-C orientation.

Based on the evidence (old and new), MEA and MPA concluded that a high probability exists that the four base metals and the vessel forging No. 7.1 are from the same steel melt and that the base materials are representative of this vessel forging as first placed in service.

Table 2 Chemical Compositions of Archival Materials, Surveillance Specimen Base Metal and KRB-A Trepan G

Material	Chemical Composition (wt-%)													
	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	As	Sn	Sb	V	Al
GEA-1	0.23	0.70	0.23	0.017	0.013	0.77	0.37	0.66	0.15	0.021	0.021	0.007	0.031	——
GEA-2	0.24	0.71	0.21	0.014	0.018	0.77	0.36	0.66	0.15	0.023	0.021	0.007	0.030	——
GEB-1	0.23	0.71	0.21	0.017	0.019	0.78	0.36	0.66	0.16	0.023	0.021	0.007	0.031	——
GEB-2	0.24	0.71	0.21	0.015	0.018	0.79	0.37	0.67	0.15	0.021	0.021	0.008	0.031	——
(Average)[a]	0.24	0.71	0.22	0.016	0.017	0.78	0.37	0.66	0.15	0.022	0.021	0.007	0.031	——
KRB-A Vessel[b]	0.22	0.78	0.24	0.019	0.017	0.82	0.38	0.62	——[c]	——	——	——	——	——
KRB-A Vessel[d]	0.22	0.71	0.22	0.013	0.012	0.75	0.38	0.62	0.16	0.02	0.03	<0.01	0.04	0.04
GEB-1[d]	0.23	0.71	0.23	0.013	0.012	0.75	0.38	0.65	0.16	0.02	0.03	<0.01	0.04	0.02
D7M[e]	0.23	0.71	0.26	0.022	0.015	0.86	0.38	0.64	0.16	——	——	——	——	——
D6E[e]	0.23	0.71	0.25	0.026	0.019	0.84	0.36	0.63	0.15	——	——	——	——	——
D7Y[e]	0.24	0.71	0.25	0.022	0.015	0.85	0.37	0.65	0.16	——	——	——	——	——
(Average)[d]	0.23	0.71	0.25	0.023	0.016	0.85	0.37	0.64	0.16	——	——	——	——	——

[a] Average of GEA and GEB materials

[b] From Ref. 6

[c] Not reported

[d] MPA composition determination by Quantovac Spectroscopy

[e] Surveillance specimens

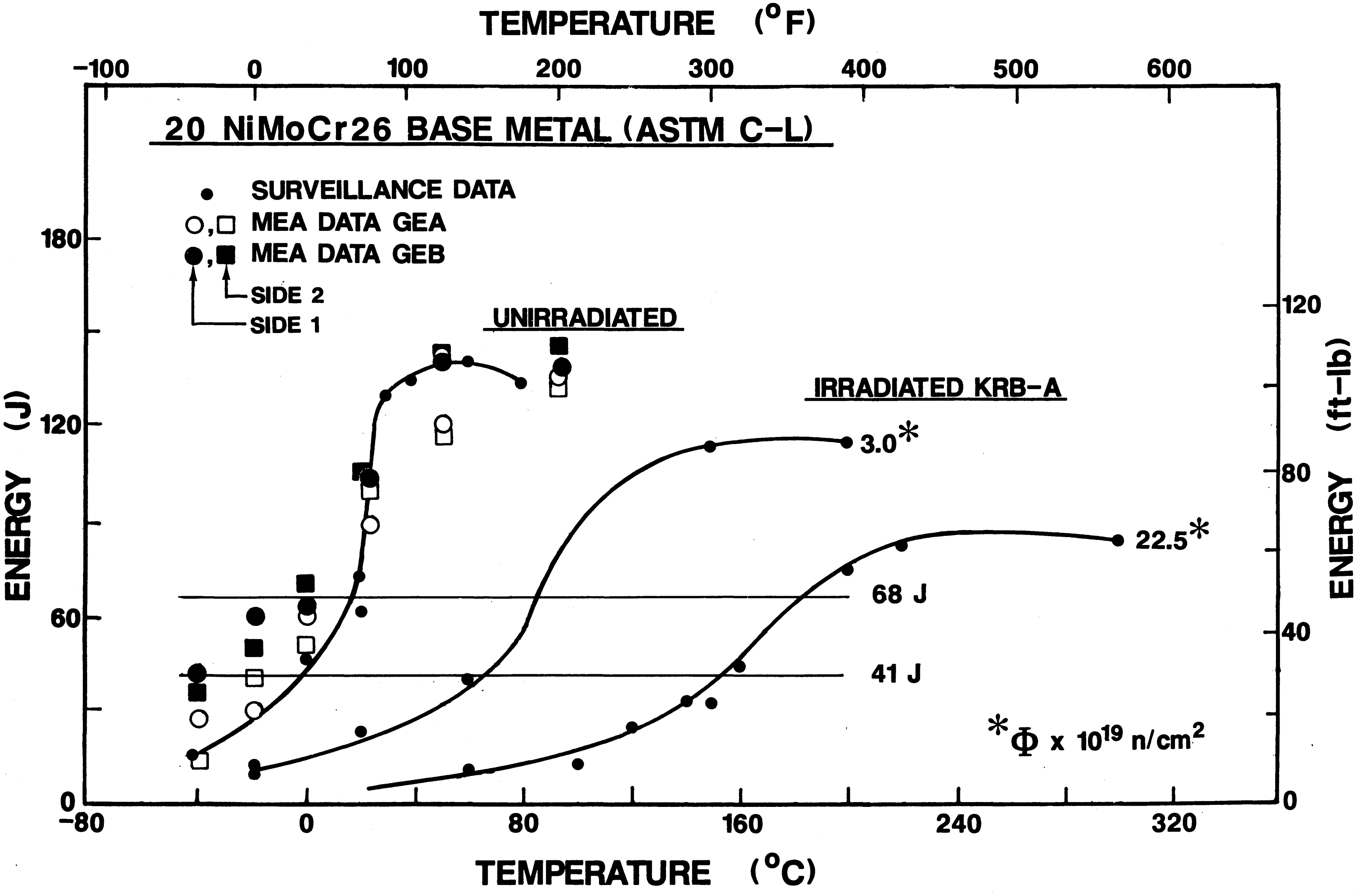


Fig. 1 Charpy-V notch ductility data for the archive base metals vs. data from the KRB-A reactor surveillance program for the same test orientation (ASTM C-L). Surveillance data for two fluence conditions are also shown.

6. THROUGH-THICKNESS PROPERTIES CHARACTERIZATION (PHASE 2)

The base metal GEB-2 was selected for the continuing program. This NRC/MEA decision, in part, reflected the large amount of material available. Also, it was decided that L-C orientation specimens (only) would be used for the balance of the program, including irradiation tests, to minimize cost.

Through-thickness properties of the GEB-2 base material were determined to establish baseline (reference) properties. (Note: The Phase 1 verification tests employed specimens from the 1/4T-thickness location only.) This information helped guide the choice of best forging sampling location for test reactor irradiation experiments. The properties investigated were notch ductility, tensile strength, and static fracture toughness, including J-R curve properties. Tests were in conformance with ASTM Standard Methods E 8, E 23, E 399, E 813, and E 1152 as applicable to the individual test methods and conditions. Procedures for testing the compact tension specimens (in this case, 12.7-mm thick 0.5T-CT specimens) are outlined in Reference 11. Appendix B provides diagrams used for the cutting of specimen blanks for the Phase 2 investigations and for the Phase 3 irradiation studies discussed below.

MEA Report No. 2159-A (see Appendix C) documents the primary MEA findings on through-thickness properties. The determinations made with full-size C_v specimens (ASTM Type A), 5.74-mm diameter tensile specimens and 12.7-mm thick CT specimens (0.5T-CT) show a good uniformity of properties through the material. Table 3 summarizes the tensile test results. Yield strength differences are less than 21 MPa (3 ksi). Figures 2 through 5 illustrate the experimental C_v and CT test data. Differences in brittle-ductile transition temperature indexed to the C_v 41-J energy level are on the order of 11°C and are on the order of 17°C for transitions indexed to the CT K_J 100 $\text{MPa}\sqrt{\text{m}}$ toughness level. C_v upper shelf levels for the 1/8T-, 1/4T-, and 7/8T-thickness locations were the same but were somewhat higher than that of the 1/2T-thickness location (103 J vs. 90 J). No significant difference in upper shelf toughness due to thickness location was observed in CT specimen tests.

Based on the through-thickness properties uniformity, the 1/8T-thickness position was selected over the 1/4T-thickness position for the irradiation investigations. For the vessel itself, it was reasoned that the 1/8T layer, having received the greater fluence in-service, would offer a high level of embrittlement for making comparisons for the fluence rate effects. Secondly, this layer better represents material associated with the small flaw case in Pressurized Thermal Shock (PTS) scenarios.

Table 3 Tensile Properties of Code GEB-2, Axial Specimen Orientation (5.74-mm diameter, 12.7-mm gage length)

Thickness Location	Specimen Number	Tensile Strength		Yield Strength (0.2% Offset)		Elongation	Reduction of Area
		(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
1/8T	GEB-T9	633	91.8	488	70.8	38.4	61.1
	GEB-T10	633	91.8	488	70.8	39.6	65.4
1/4T	GEB-T1	618	89.6	467	67.8	42.6	65.3
	GEB-T4	621	90.0	471	68.3	38.4	66.8
1/2T	GEB-T11	621	90.0	472	68.4	23.4[a]	57.3
	GEB-T12	621	90.0	467	67.8	40.6	61.6
7/8T	GEB-T13	629	91.3	488	70.8	40.8	65.9
	GEB-T14	631	91.6	488	70.8	40.0	66.4

[a] Failed at gage mark

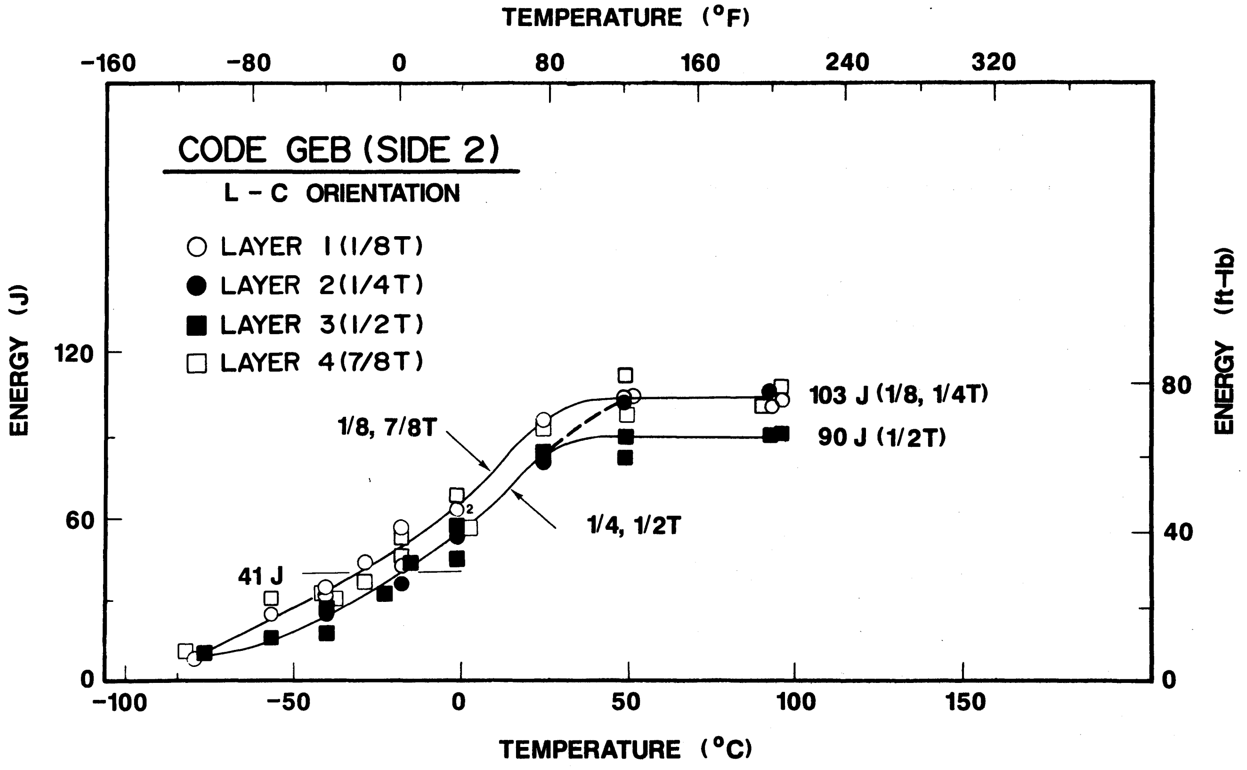


Fig. 2 Charpy-V notch ductility of Code GEB-2 material at four locations through the thickness.

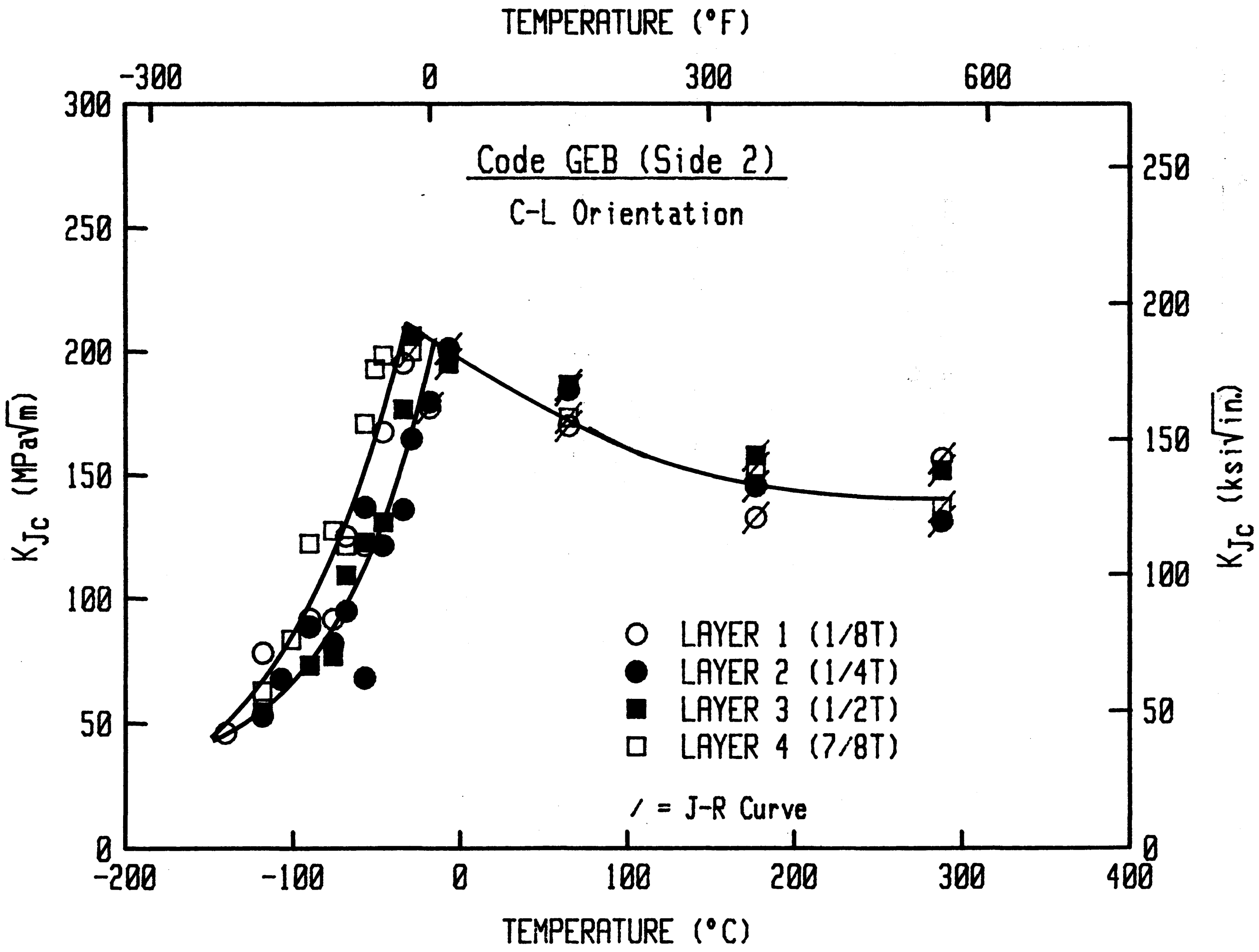


Fig. 3 Fracture toughness of Code GEB-2 material at four thickness locations. Notice the similarity in toughness vs. temperature trends. Tests producing a J-R curve are indicated by a slash (/) through the data point.

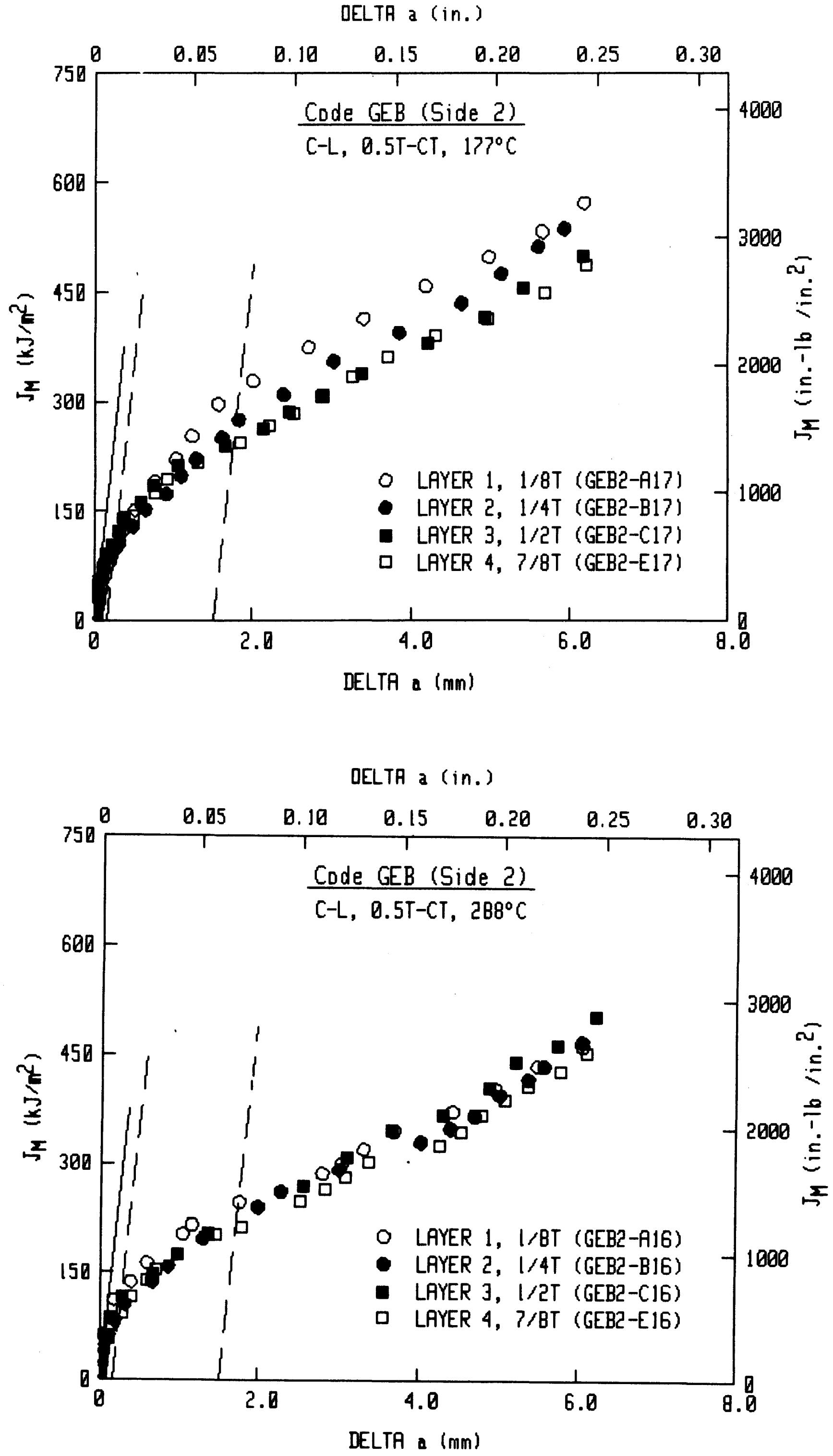


Fig. 4 J-R curves for four thickness locations in the Code GEB-2 material at 177°C and at 288°C.

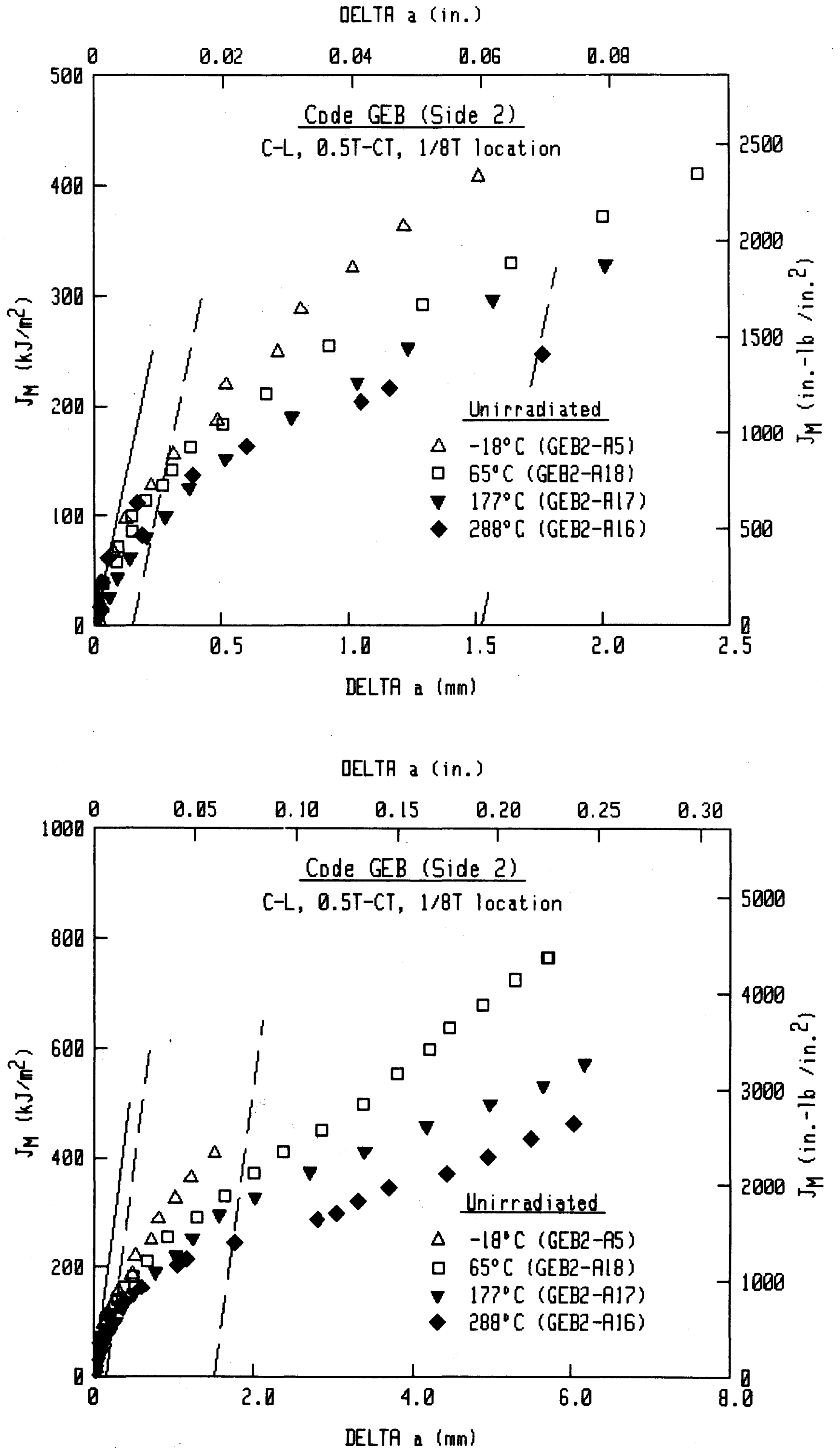
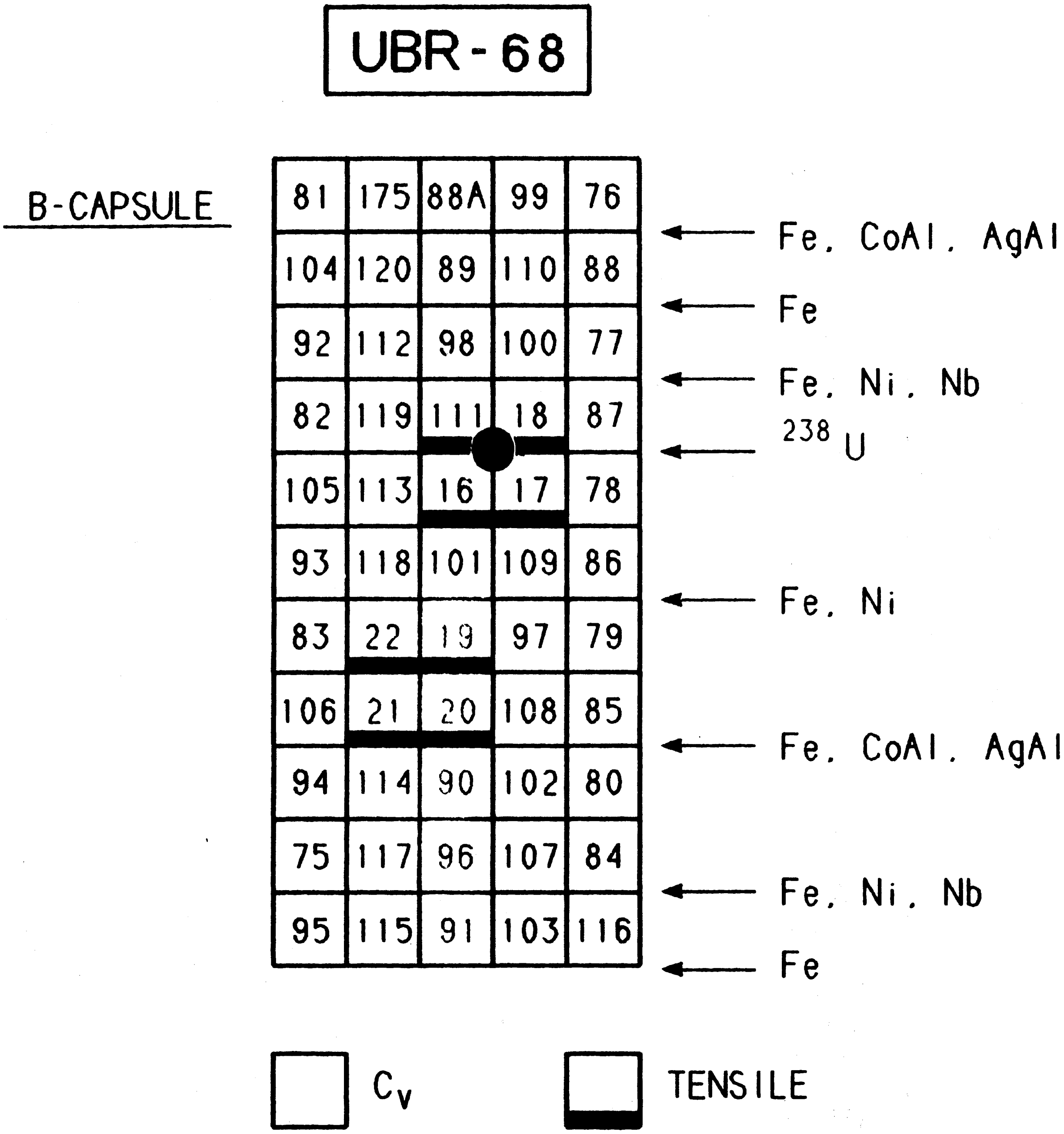


Fig. 5 J-R curves for the Code GEB-2 material showing the dependence of J-R curve level on test temperature. The J-R curve for -18°C (highest level curve) was terminated by cleavage fracture.



81	175	88A	99	76
104	120	89	110	88
92	112	98	100	77
82	119	111	18	87
105	113	16	17	78
93	118	101	109	86
83	22	19	97	79
106	21	20	108	85
94	114	90	102	80
75	117	96	107	84
95	115	91	103	116

Fig. 6b Placement of Charpy-V, tensile and 0.5T-CT specimens in Experiment UBR-68 (Capsule B; elevation view).

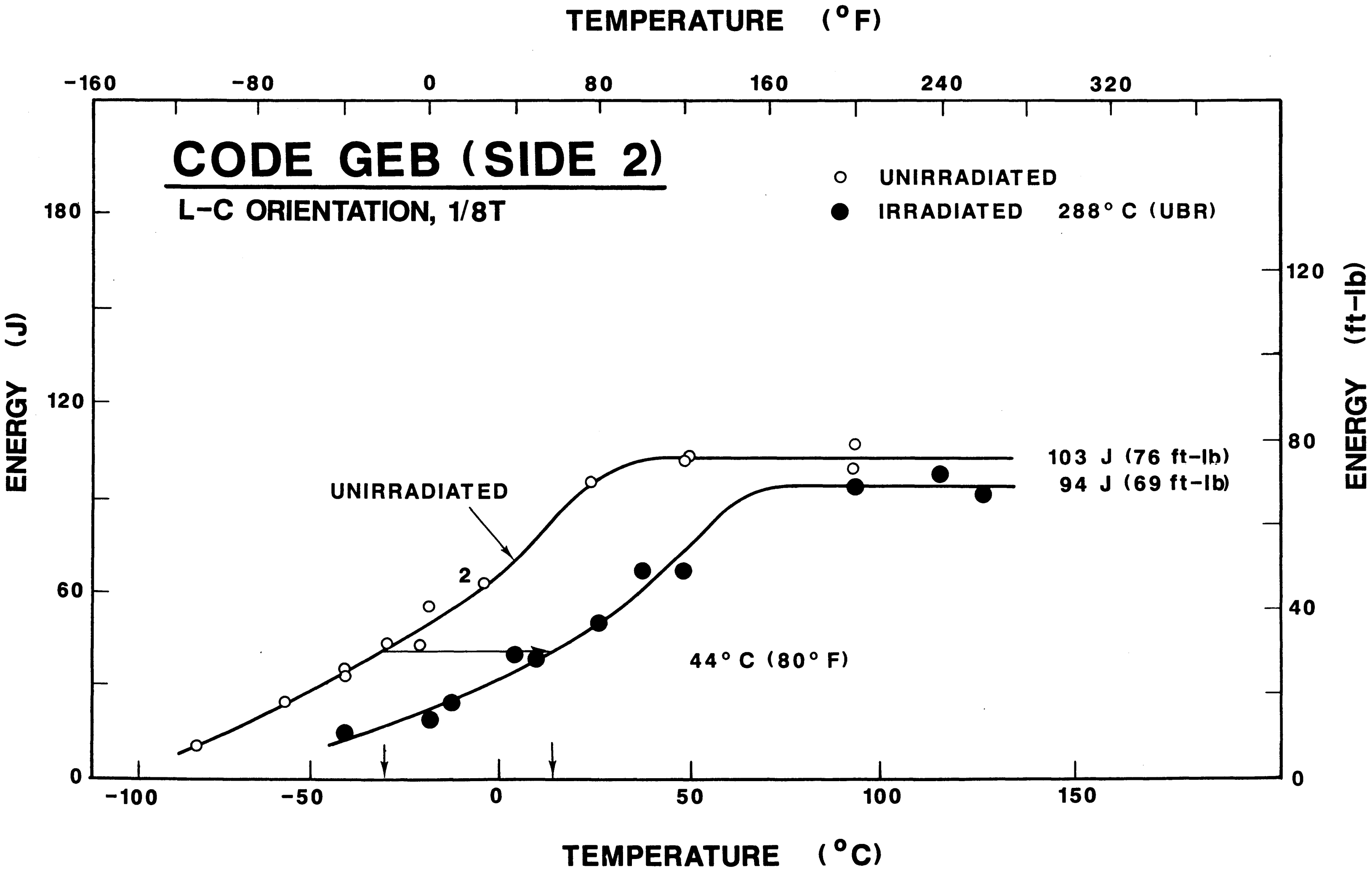


Fig. 7 Charpy-V notch ductility of Code GEB-2 material before and after irradiation at 288°C to 8.8×10^{18} n/cm^2, E > 1 MeV. The irradiation was conducted in the light-water-cooled and moderated UBR test reactor (Experiment UBR-68).

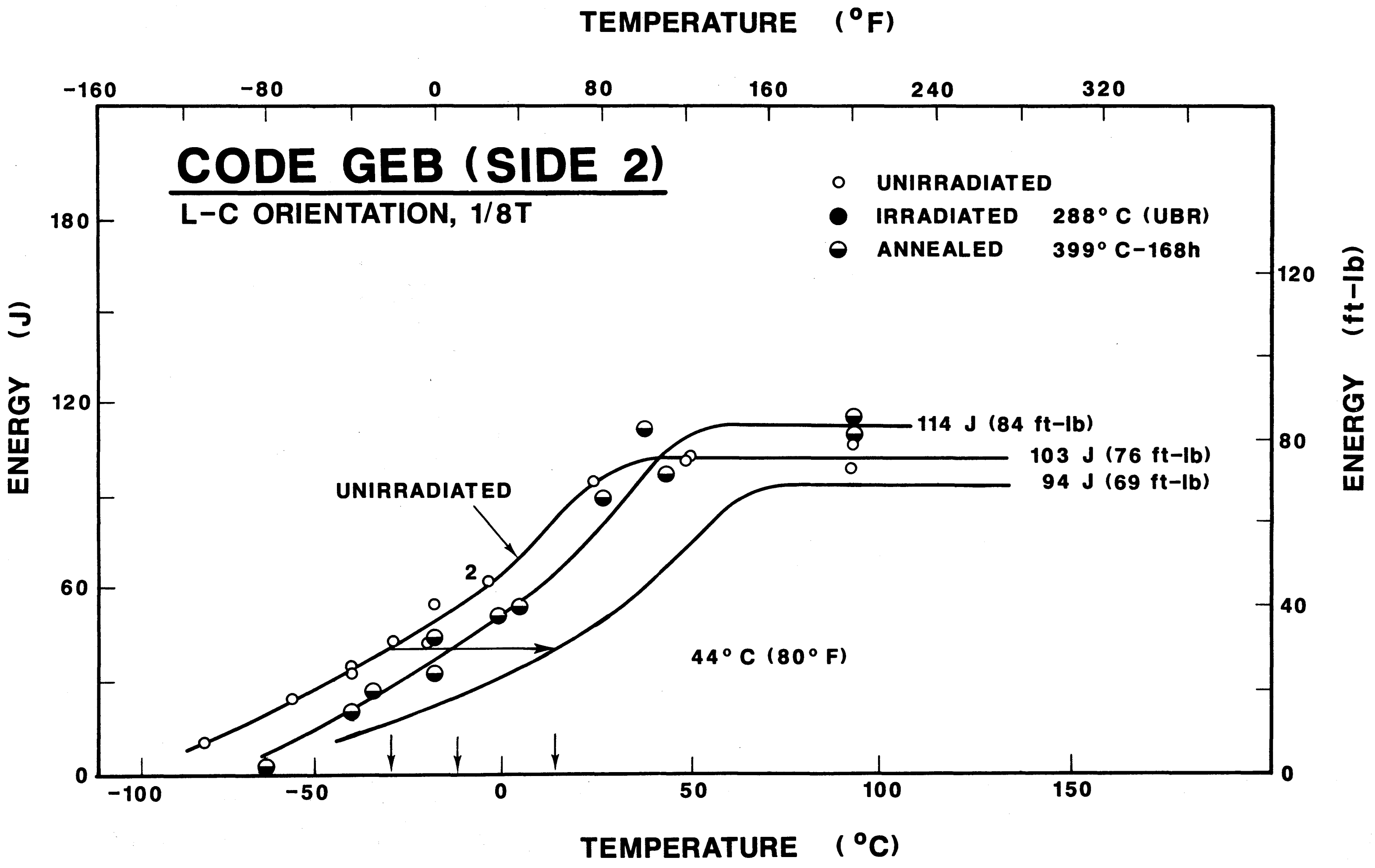


Fig. 8 Charpy-V notch ductility of Code GEB-2 material before and after postirradiation annealing at 399°C for 168 h (Experiment UBR-68).

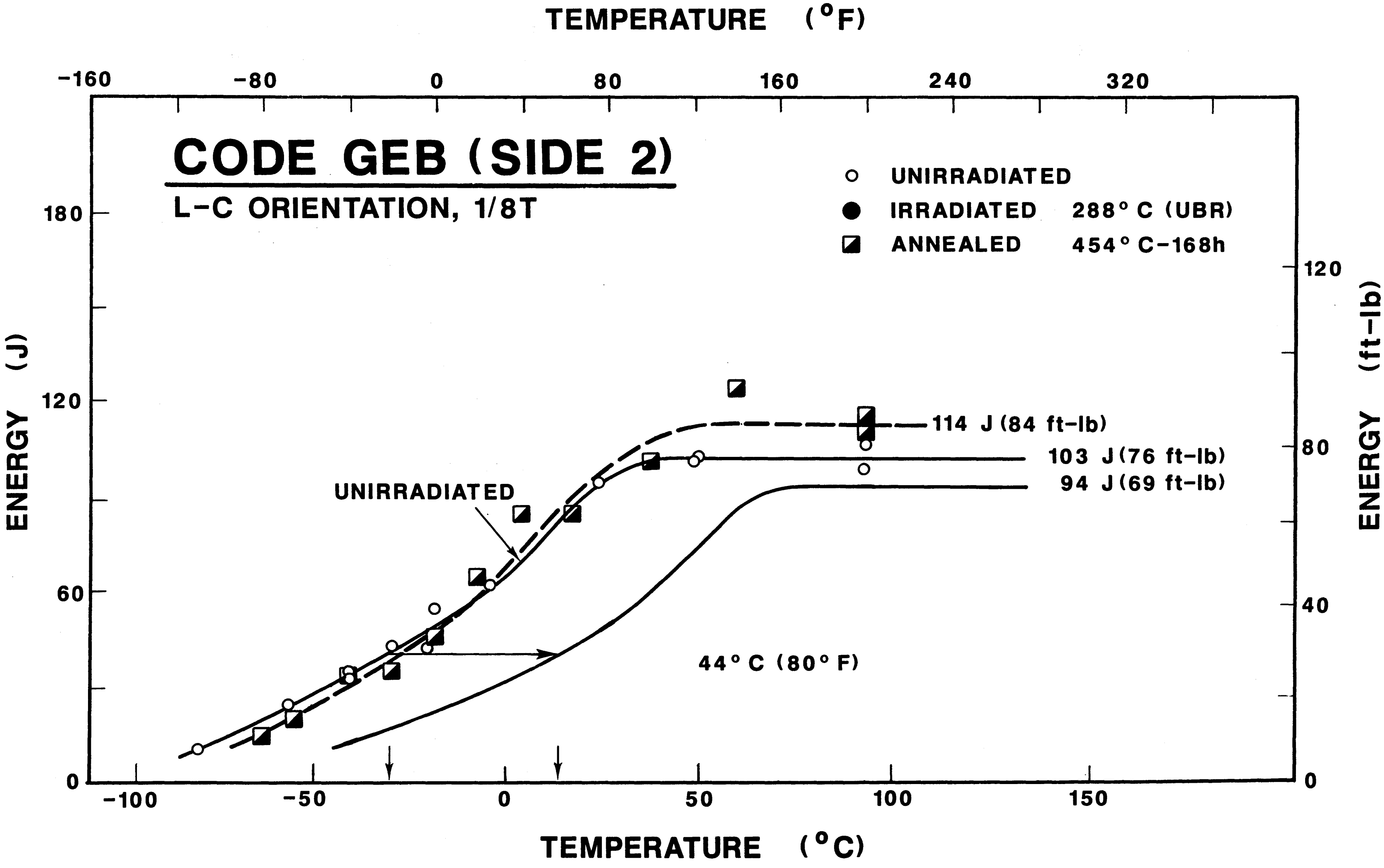


Fig. 9 Charpy-V notch ductility of Code GEB-2 material before and after postirradiation annealing at 454°C for 168 h (Experiment UBR-68).

Table 4 Summary of Postirradiation Notch Ductility Determinations (UBR Experiments)

Irradiation Assembly	Temperature (°C)	Fluence x 10^{18} n/cm^2 (E > 1 MeV)	Specimen Orientation (ASTM)	C_v 41-J Temperature Initial (°C)	C_v 41-J Temperature Initial (°F)	C_v 41-J Temperature Change[a] (Δ°C)	C_v 41-J Temperature Change[a] (Δ°F)	C_v Upper Shelf Energy Initial (J)	C_v Upper Shelf Energy Initial (ft-lb)	C_v Upper Shelf Energy Change[a] (ΔJ)	C_v Upper Shelf Energy Change[a] (Δft-lb)
Unirradiated (Set A)	—	—	L-C	-29	-20	—	—	103	76	—	—
UBR-68	288	8.76	L-C	-29	-20	44	80	103	76	9	7
(399°C Anneal)				16	60	28	50	94	69	20	15
(454°C Anneal)				16	60	43	75	94	69	20	15
Unirradiated (Set B)	—	—	L-C	-26	-15	—	—	107	79	—	—
			C-L	-40	-40	—	—	155	114	—	—
UBR-78	288	2.7	L-C[b]	-26	-15	17	30	67	79	4	3
			C-L	-40	-40	19	35	155	114	4	3
UBR-79A	275	8.5	L-C	-26	-15	47	85	107	79	9	7
			C-L	-40	-40	—[c]	—[c]	155	114	~31	~22
	260	8.8	L-C	-26	-15	56	100	107	79	17	13
			C-L	-40	-40	~53	~95	155	114	22	16
UBR-80A	288	23.0	L-C	-26	-15	64	115	107	79	19	14
			C-L	-40	-40	—[c]	—[c]	155	114	36	26

[a] Change over previous condition (unirradiated or irradiated)

[b] Untested irradiated condition specimens still available

[c] Not determined

in K_{Jc} 100 MPa$\sqrt{m}$ temperature was found with the 0.5T-CT specimen tests (Fig. 10). Both determinations show the NRC's Regulatory Guide 1.99 Rev. 1 and Rev. 2 to be conservative. Specifically, Rev. 1 and Rev. 2 project transition temperature elevations of 67°C and 59°C, respectively, for this 0.15% Cu, 0.015% P, 0.79% Ni steel.

Referring to upper shelf toughness, only a small reduction in J level at 177°C was apparent after irradiation (Fig. 11). At 288°C, the data for the unirradiated and irradiated conditions are colinear (Fig. 12). Together, the J-R curves for the irradiated condition at 177°C and at 288°C describe only a small toughness reduction with an increase in temperature in this range (Fig. 13).

Postirradiation heat treatment at 399°C for 168 h resulted in full C_v upper shelf recovery but only partial 41-J transition temperature recovery (Fig. 8). The 454°C-168 h anneal, in contrast, produced full upper shelf recovery and essentially, full 41-J recovery (Fig. 9). The C_v upper shelf energy level of the annealed material is higher than that of the unirradiated material (114 J vs. 103 J, respectively). Whether or not this was due to the prior neutron exposure or just the duplex thermal treatment of 288°C-249 h + 399°C-168 h (or alternatively 454°C-168 h) has not been established. The unirradiated and irradiated condition tests were performed on the same impact test machine; accordingly, the difference is not experimental procedure related. MEA tests of unirradiated, thermally-conditioned A 302-B and A 533-B pressure vessel steels have indicated a similar effect of duplex heat treatments on upper shelf level (Ref. 11).

The 0.5T-CT specimen data for unirradiated, irradiated, and annealed conditions are compiled in Appendix G. Specimens that were postirradiation heat treated showed an inconsistent recovery in the transition regime. For the 399°C-168 h heat treated condition (Fig. 14), two specimens showed essentially no recovery when referenced to the mean curve for the irradiated condition but four others receiving this heat treatment indicated up to 80% recovery in transition temperature at the 100 MPa$\sqrt{m}$ level. For the 454°C-168 h heat treated condition (Fig. 15), two specimens tested in the transition regime indicated essentially 100% recovery unlike three others which depicted < 50% recovery. The reason(s) for the inconsistent response to the annealing treatments has not been determined. In contrast, relatively low data scatter in the transition regime was found for both the unirradiated and the as-irradiated material conditions (see Fig. 10). Both annealing heat treatments resulted in some recovery in J-R curve level at 177°C (Fig. 16). Consistent with C_v upper shelf trends, the anneal at 399°C for 168 h produced a higher toughness than that found for the unirradiated condition. On the other hand, the higher anneal temperature 454°C, did not provide complete recovery in the J-R curve level in contrast to the > 100% upper shelf recovery demonstrated by the C_v tests. Overall, the differences in the J-R curve levels among the four conditions are not large; possibly multiple tests at each condition would have yielded overlapping trend bands.

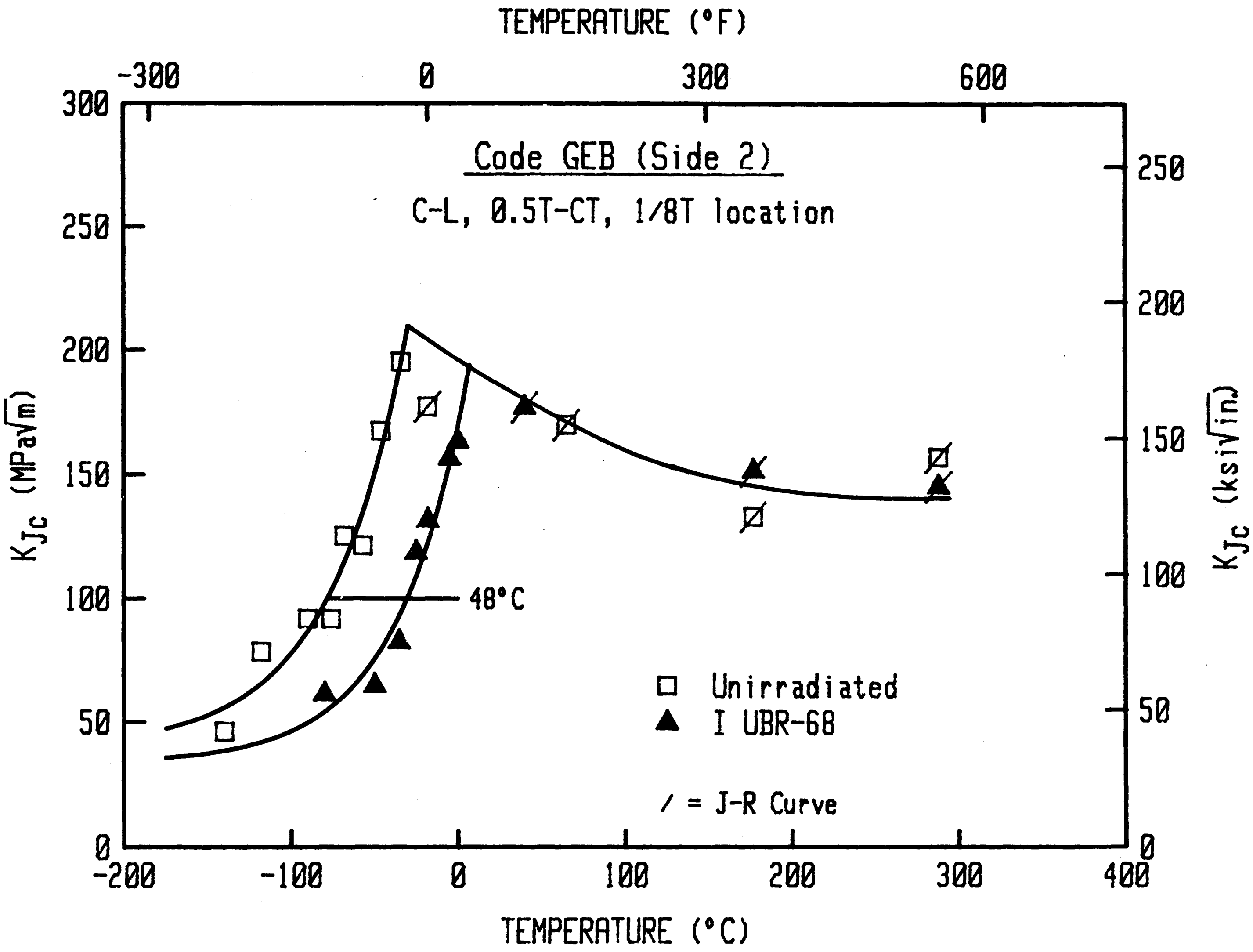
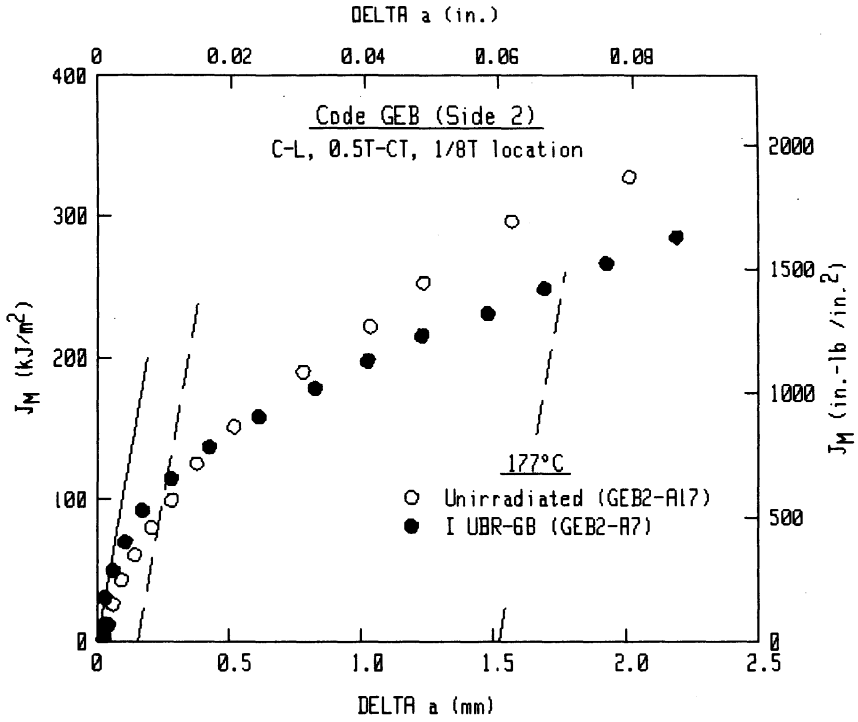


Fig. 10 Fracture toughness of Code GEB-2 material before and after irradiation at 288°C to 8.6×10^{18} n/cm^2 (Experiment UBR-68).



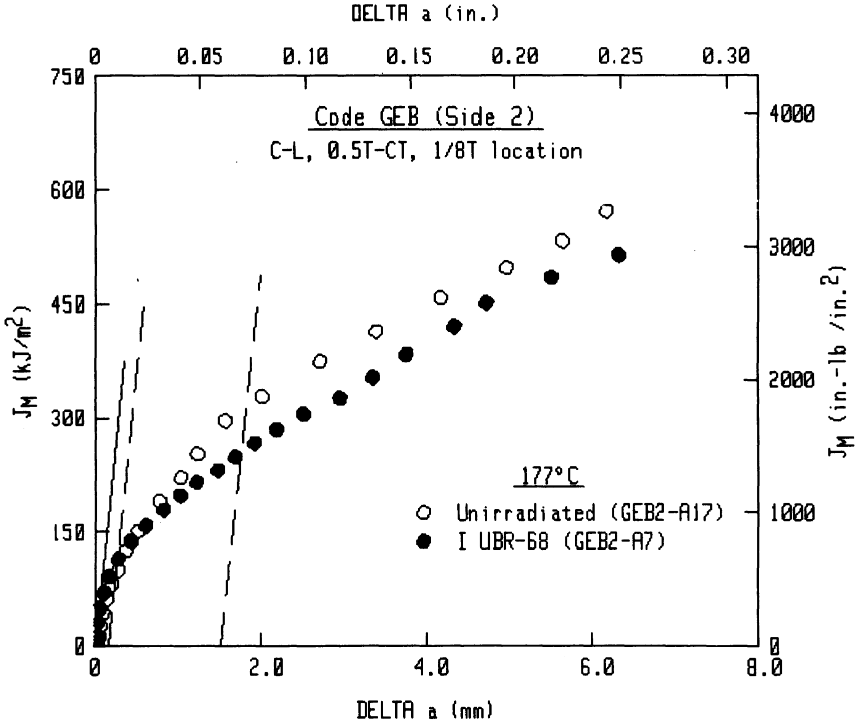


Fig. 11 J-R curves for unirradiated vs. UBR-68 irradiated conditions at 177°C. The irradiated condition test shows a slightly lower J-R curve level.

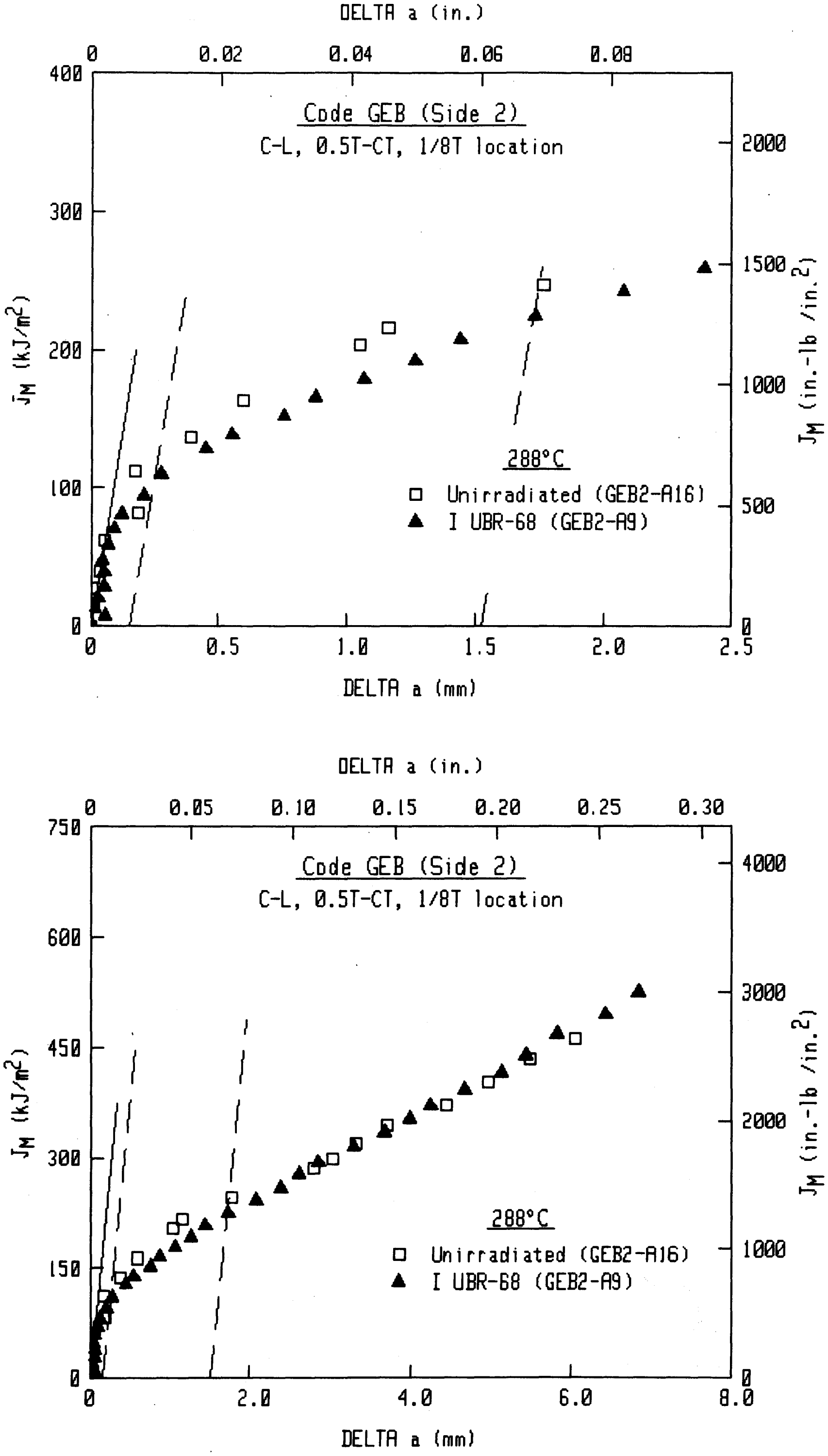


Fig. 12 J-R curves for unirradiated vs. UBR-68 irradiated conditions at 288°C. The curves are essentially colinear.

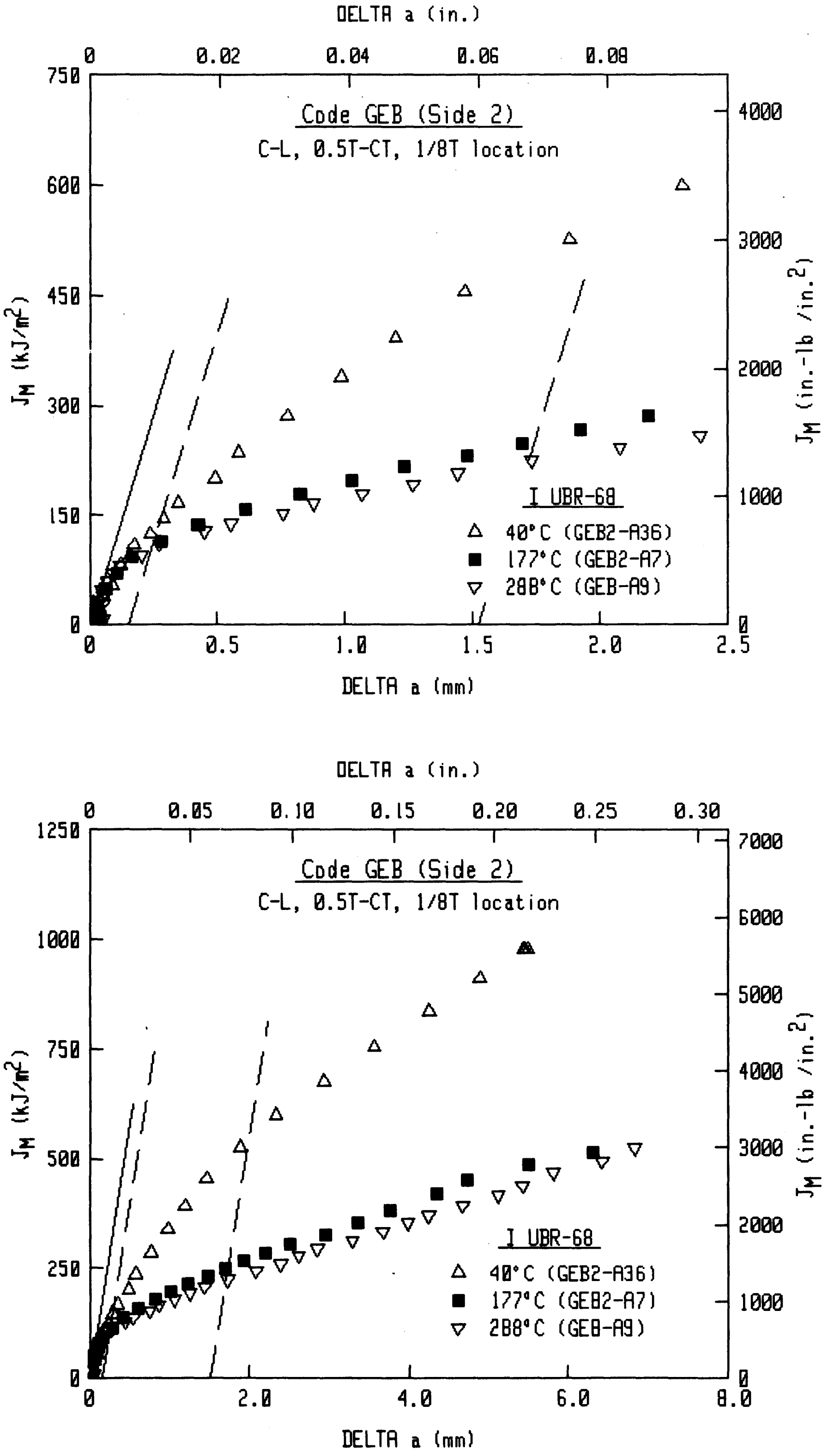


Fig. 13 J-R curves for the UBR-68 irradiated condition at 177°C and 288°C, showing a similarity in toughness level.

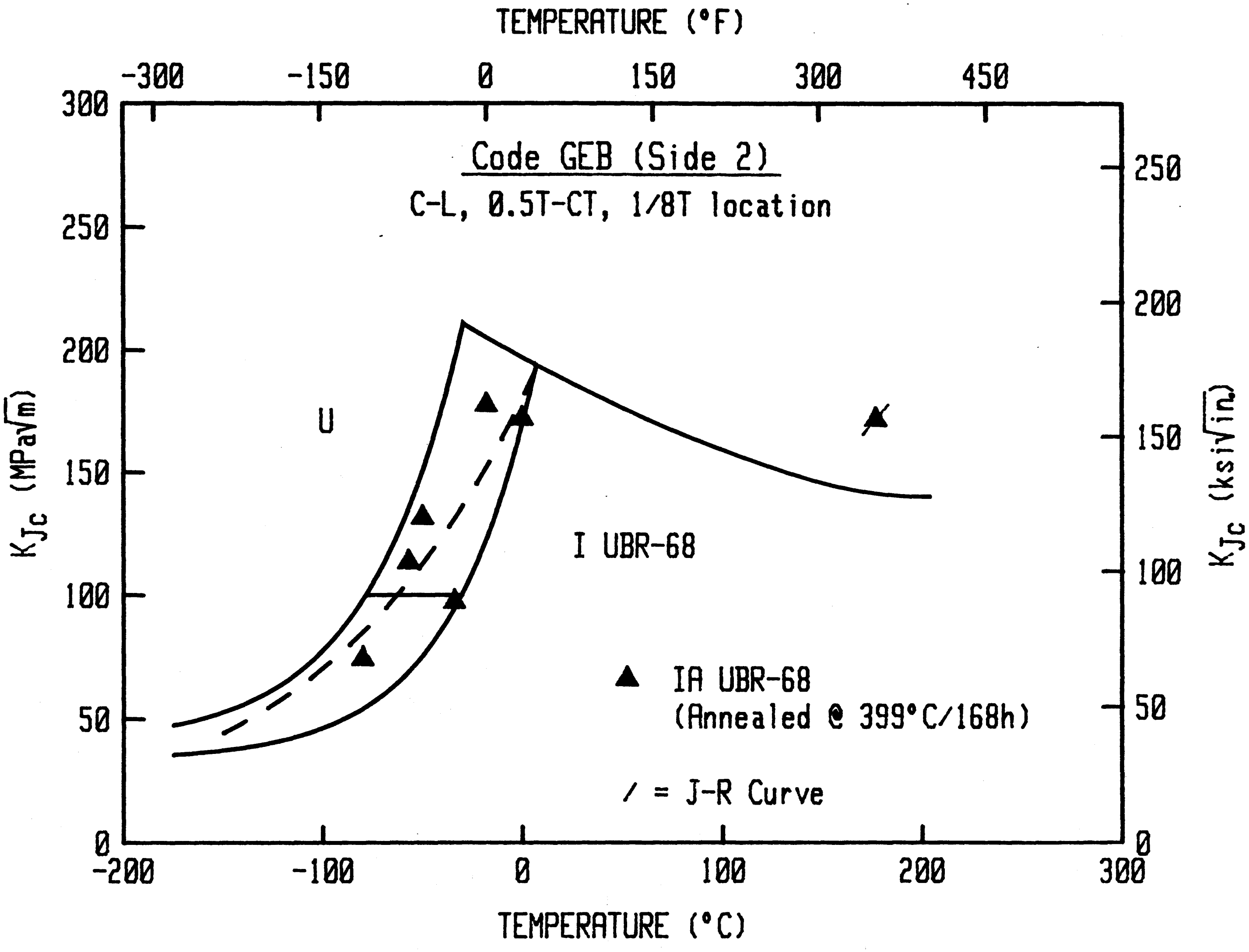


Fig. 14 Fracture toughness of Code GEB-2 material before and after postirradiation annealing at 399°C for 168 h. Individual data points show a variation in transition temperature ranging from 0% to 80% (Experiment UBR-68).

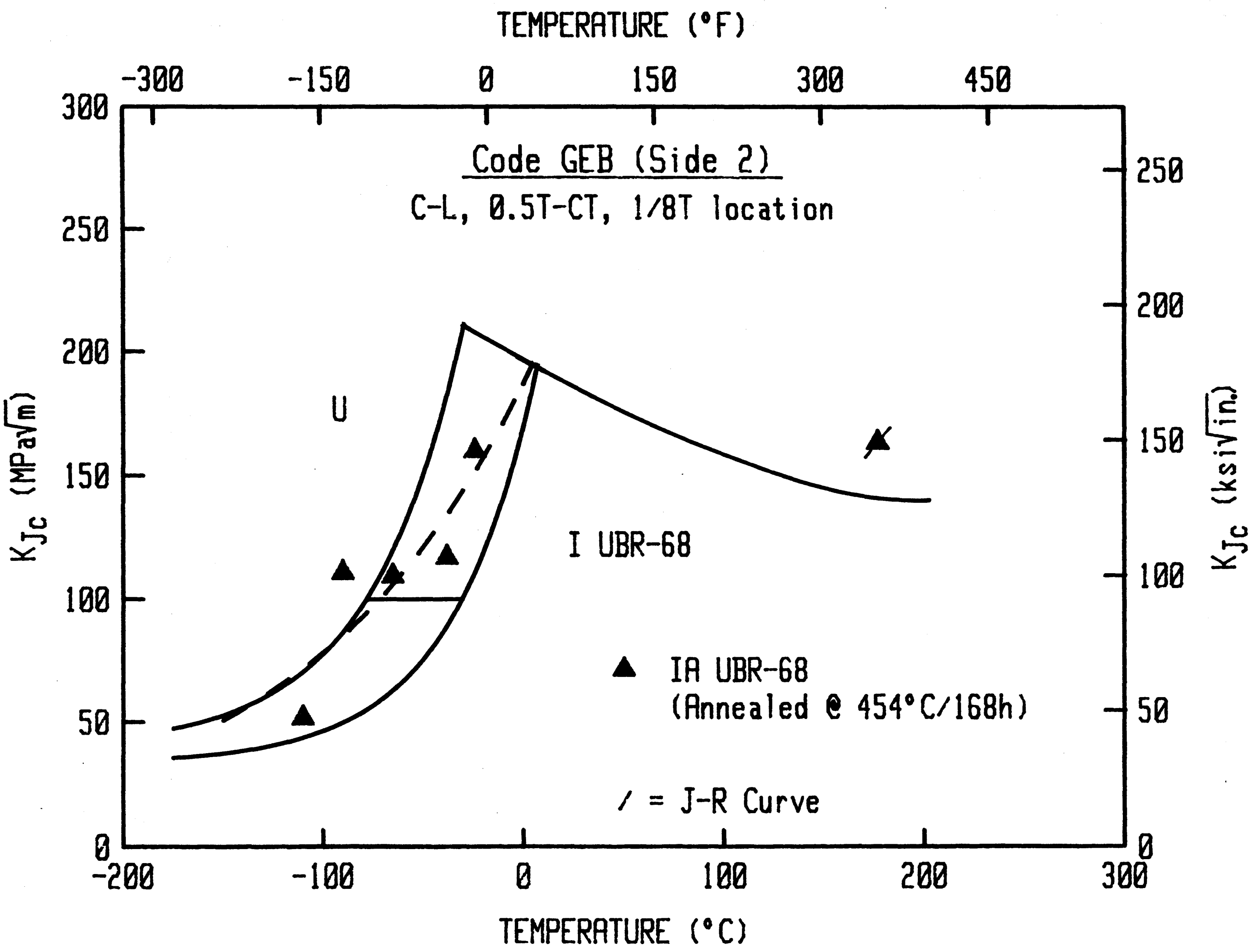


Fig. 15 Fracture toughness of Code GEB-2 material before and after postirradiation annealing at 454°C for 168 h. The wide variation in transition temperature recovery is not understood (Experiment UBR-68).

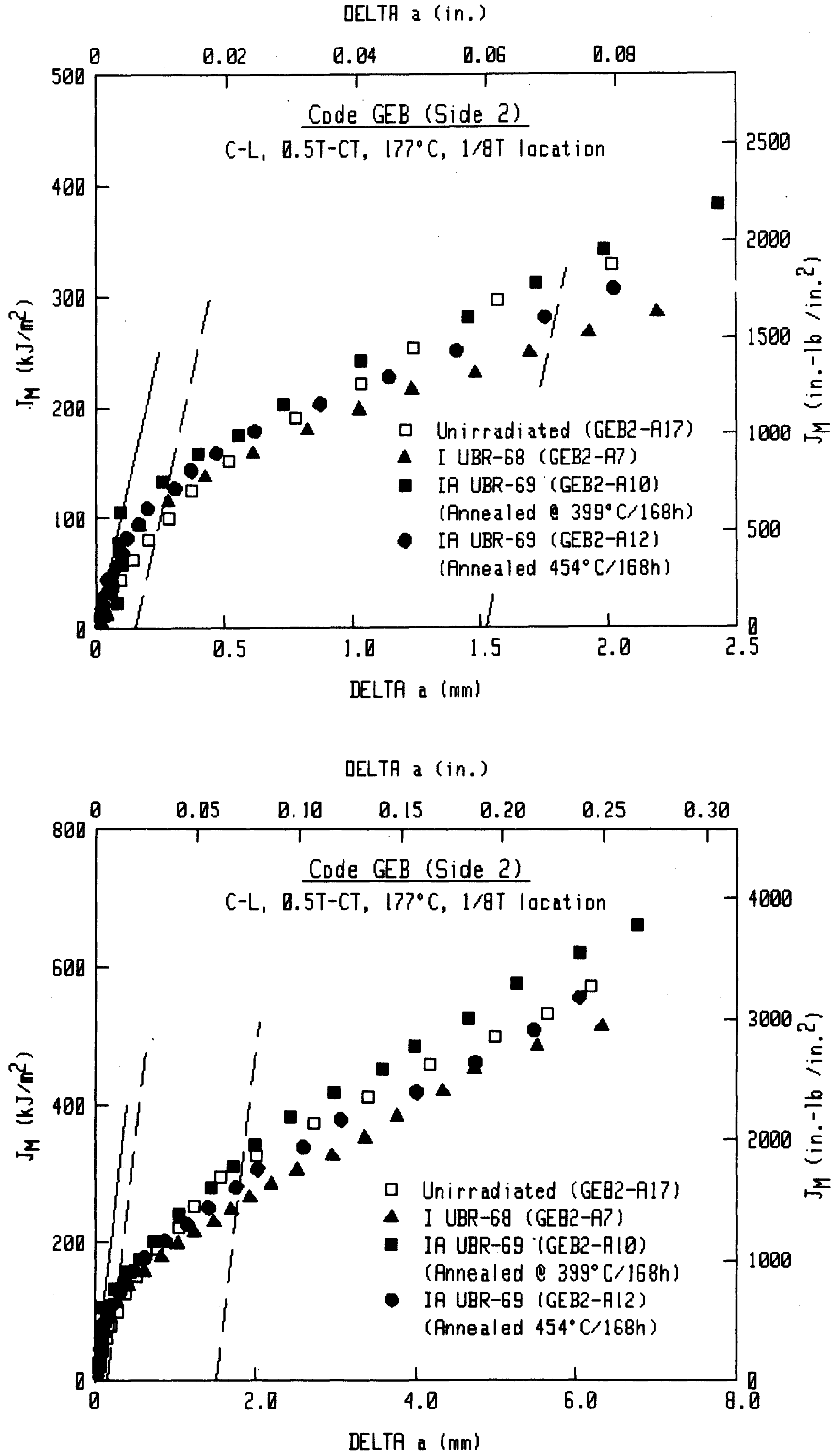


Fig. 16 J-R curves for unirradiated, UBR-68 irradiated and two postirradiated heat treated conditions at 177°C. The tests show similar J-R curve levels; the lowest curve is for the as-irradiated condition.

Tensile test results are summarized in Table 5. A 76-MPa elevation in ambient temperature yield strength and a 59-MPa elevation in ultimate strength were produced by the irradiation. Tests at 288°C showed a 23-MPa elevation in yield strength and a 16-MPa elevation in ultimate strength. The 399°C-168 h and the 454°C-168 h postirradiation heat treatments achieved 70% and 100% recovery in yield strength, respectively. Accordingly, yield strength changes follow well the concomitant C_v 41-J transition temperature changes.

7.2 Through-Wall Fluence Determination

The fluence determinations made at various depths through the vessel wall, using a slice from Trepan G, are listed in Table 6 and are illustrated in Fig. 17. The determinations were made by EG&G Idaho, Inc. (J. W. Rogers) for MEA under subcontract. Details of the fluence determination procedures are given in Reference 12 (Appendix H).

Important to the thrust of the USA/FRG/UK program, the fluence to the inner-wall surface was much less than the original fluence estimate of 1×10^{19} n/cm^2, E $\geq$ 1 MeV, made at the time of vessel decommissioning and the 8.8×10^{18} n/cm^2 fluence received by the UBR-68 irradiation experiment In turn, the planned 1:1 comparison of embrittlement for a fluence-rate-effects determination could not be made. (Note: Material for the through-wall fluence determination unfortunately was not available at the time of the UBR-68 irradiation test.)

Table 6 includes through-wall fluence projections (i.e., attenuated fluence values) by Revision 2 of Regulatory Guide 1.99. Figure 18 compares the projections against measurements. The projections of in-wall fluences appear much higher than the measurements indexed to an assumed fission spectrum but are within 5 percent of adjusted measurement values indexed to the calculated spectrum. A best-fit equation for the fission spectrum based data has an exponent value of 0.41.

7.3 UBR Test Reactor vs. Service-Irradiation Embrittlement

C_v data developed by MPA with Trepan C and G samples having the L-C and C-L orientation are illustrated in Fig. 19. The samples were from trepan specimen layer No. 2 which corresponds approximately to the 1/8T-thickness location. The data trend for the archive material from the UBR-68 experiment is also shown for comparison. The fluence to the trepan specimens (MPA determination) was approximately 2.4×10^{18} n/cm^2 or about one-third that received by the archive material. Nonetheless, the trepan L-C orientation tests describe a 60°C increase in 41-J temperature and a 50-J decrease in C_v upper shelf energy (referenced to the preirradiation properties of the archive material). Accordingly, the service-induced embrittlement is shown to be much greater than the accelerated (test reactor) irradiation-induced embrittlement. A second observation is that the trepan C-L orientation data describe only a 30°C increase in C_v 41-J transition temperature and a < 10-J decrease in upper shelf energy

Table 5 Average Tensile Data for KRB-A Archive Material (1/8T Layer)

Experiment	Fluence	Orient.[a]	Test Temp.	Yield Strength			Tensile Strength		
	([b])		(°C)	(MPa)	(ksi)	(ΔMPa)[c]	(MPa)	(ksi)	(ΔMPa)[c]
Unirradiated	—	Axial	24 to 32	489.6	71.0	—	633.1	91.8	—
			288	439.5	63.7	—	633.1	91.8	—
			-129	684.8	99.3	—	826.1	119.8	—
	—	CMFL	24 to 32	492.6	71.4	—	634.5	92.0	—
UBR-78 (288°C) As-Irradiated	2.7	Axial	31[d]	516.3	74.9	26.7	652.8	94.7	19.7
		CMFL	31[d]	529.7	76.8	37.1	656.6	95.2	22.1
UBR-68 (288°C) As-Irradiated	8.7	Axial	23[d]	564.1	81.8	74.5	691.5	100.3	58.4
			288[d]	462.6	67.1	23.1	648.8	94.1	15.7
Annealed (399°C-168 h)		Axial	22[d]	511.2	74.1	22.6	647.0	93.8	13.9
			288[d]	448.0	65.0	8.5	625.9	90.8	-7.2
Annealed (454°C-168 h)		Axial	23[d]	484.1	70.2	-5.5	631.2	91.5	-1.9
			288[d]	429.5	62.3	-10.0	614.2	89.1	-18.9
Annealed (399°C-48 h)		Axial	288[d]	464.4	67.4	24.9	650.4	94.3	17.3
UBR-79 As-Irradiated (275°C)	8.5	Axial	31[d]	565.3	82.0	75.7	703.1	102.0	70.0
As-Irradiated (260°C)	8.8	Axial	31[d]	585.4	84.9	95.8	705.5	102.3	72.4
UBR-80 (288°C) As-Irradiated	23.0	Axial	31	602.6	87.4	112.6	731.5	106.1	98.4

[a] Per ASTM E 399, Axial = Longitudinal; CMFL = Circumferential

[b] x 10^{19} n/cm^2 (E > 1 MeV)

[c] Elevation relative to unirradiated condition data, same test orientation and temperature

[d] Single values only

Table 6 Gundremmingen Vessel KRB-A, Trepan G Dosimetry

Sample ID[a]	Mass (g)	^{54}Mn Bq/g (1/13/77) (x 10^5)	> 1 MeV Neutron Fluence Rate[b] (x 10^9)	>1 MeV Neutron Fluence[c] (x 10^{18})	RG 1.99 Rev 2 > 1 MeV Fluence Projection[d] (x 10^{18})	> 1 MeV Neutron Fluence[e] (x 10^{18})	> 0.1 MeV Neutron Fluence[e] (x 10^{18})	^{60}Co Bq/g (1/13/77) (x 10^5)	Thermal Neutron Fluence Rate[b] (x 10^9)	Thermal Neutron Fluence[c] (x 10^{18})
0.02T	1.8162	7.19 ± 0.49	14.60 ± 0.12	3.34 ± 0.28	3.34[f]	2.59 ± 0.22	5.16 ± 0.43	6.00 ± 0.31	14.50 ± 0.08	3.23 ± 0.18
0.15T	1.7793	5.84 ± 0.36	11.80 ± 0.10	2.71 ± 0.22	2.92	2.38 ± 0.19	5.56 ± 0.45	2.89 ± 0.15	6.99 ± 0.36	1.60 ± 0.08
0.27T	2.8309	4.57 ± 0.28	9.29 ± 0.75	2.11 ± 0.17	2.57	2.05 ± 0.17	5.33 ± 0.43	1.62 ± 0.08	3.92 ± 0.20	0.90 ± 0.46
0.47T	1.1943	3.19 ± 0.20	6.28 ± 0.51	1.47 ± 0.12	2.09	1.59 ± 0.13	5.02 ± 0.41	0.87 ± 0.44	2.10 ± 0.11	0.48 ± 0.24
0.74T	1.7710	1.98 ± 0.13	4.02 ± 0.33	0.91 ± 0.75	1.58	1.18 ± 0.10	4.51 ± 0.37	0.56 ± 0.29	1.35 ± 0.07	0.31 ± 0.16
0.98T	1.6817	1.28 ± 0.08	2.59 ± 0.21	0.59 ± 0.48	1.23	0.80 ± 0.07	3.50 ± 0.29	0.61 ± 0.31	1.48 ± 0.08	0.34 ± 0.17

[a] Within the 1-mm (4.35-in.) thick slice sent to EG&G Idaho [vessel thickness = 119 mm (4.7 in.)]

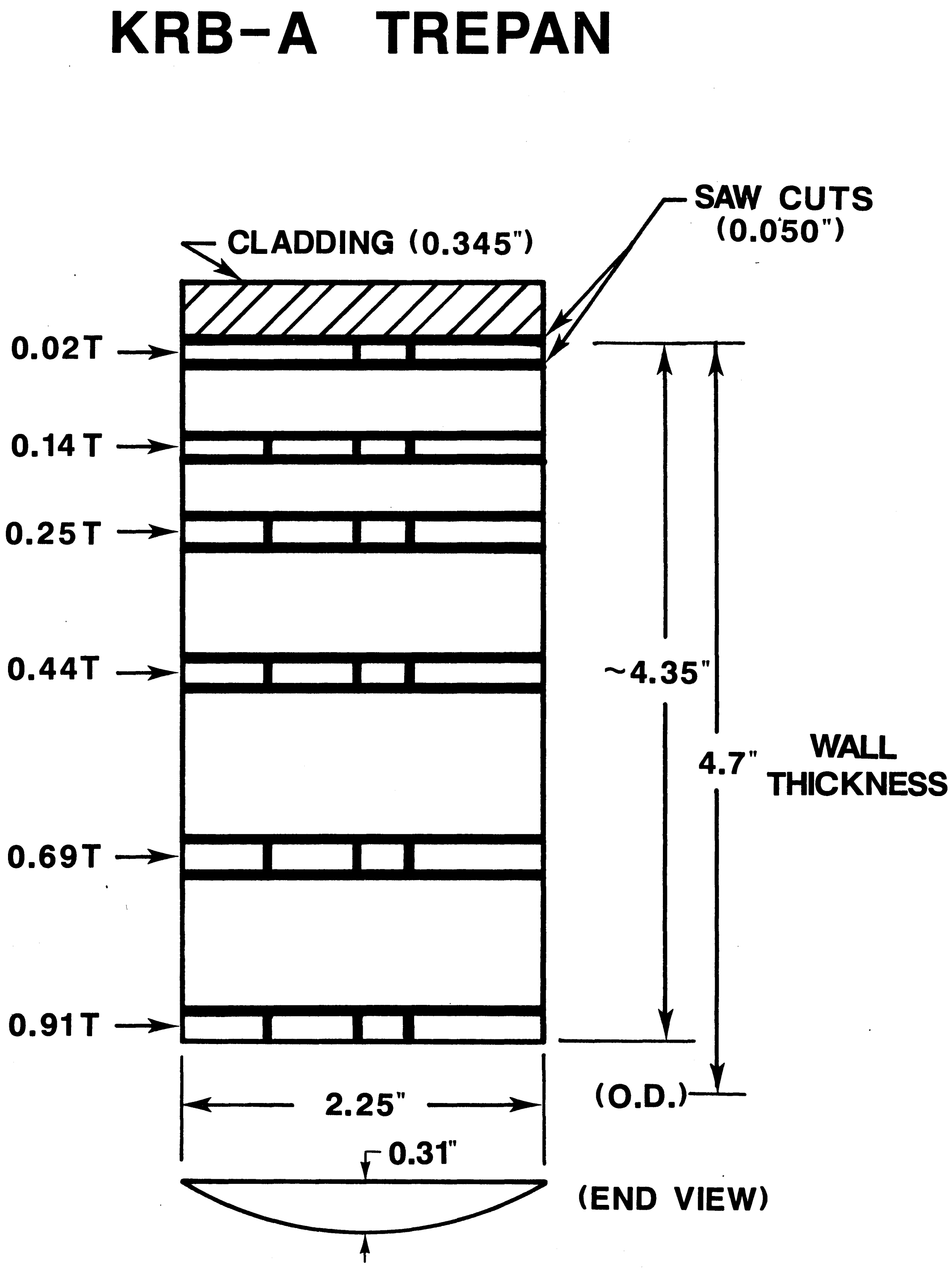
[b] n/cm^2-s^{-1} (fission spectrum assumption)

[c] n/cm^2 (fission spectrum assumption)

[d] n/cm^2

[e] n/cm^2 (calculated spectrum)

[f] Referenced to the 0.02T position



KRB-A TREPAN

Fig. 17 Sampling locations in Trepan G for fluence determinations.

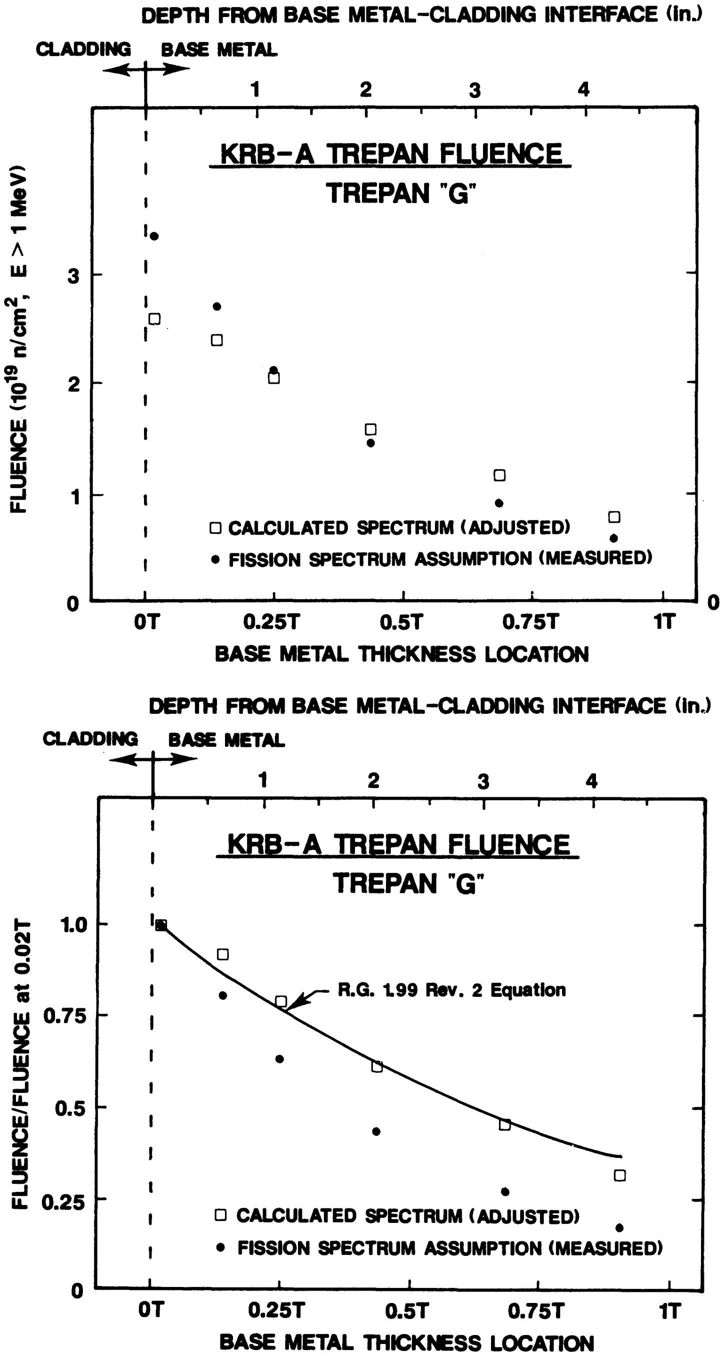


Fig. 18 EG&G Idaho, Inc. fluence measurements for through-thickness positions in Trepan G. The upper graph compares the calculated spectrum vs. assumed fission spectrum determinations; the lower graph shows measured vs. projected through-thickness fluence attenuation. (Note: 1 in. - 25.4 mm)

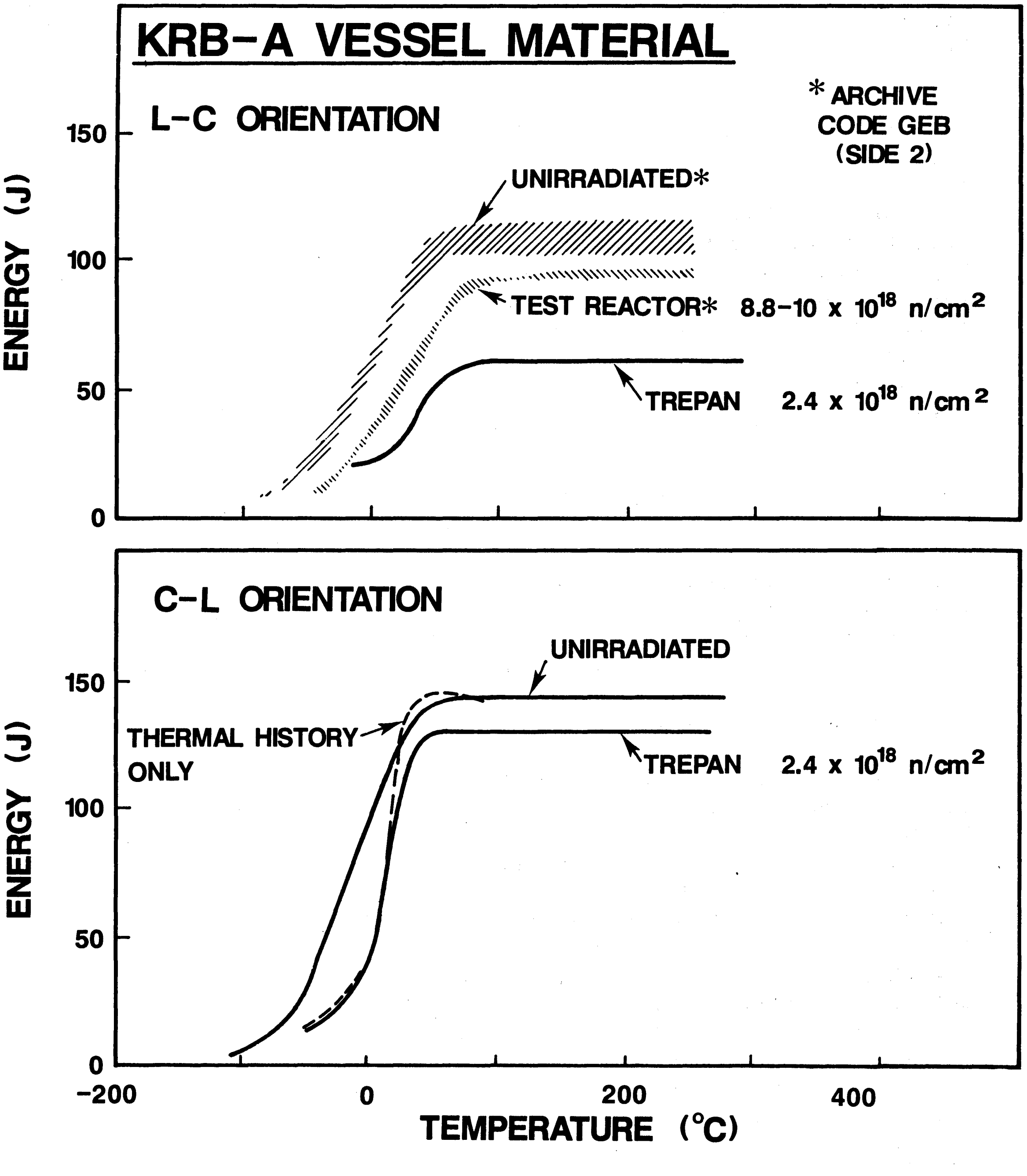


Fig. 19 Charpy-V notch ductility of KRB-A vessel material before and after irradiation service. The dashed line in the lower graph shows the effects of long-term (years) thermal conditioning without irradiation; the upper graph includes postirradiation data from accelerated (test reactor) exposures of the KRB-A archive Code GEB-2 material by MEA and Harwell (Ref. 2).

(Ref. 1). As noted in Fig. 19, a portion of the transition temperature elevation for the trepan material can be ascribed to a time-at-temperature effect without neutrons present. The above L-C vs. C-L data comparison together with the relative embrittlement sensitivity found in the UBR-68 experiment constitute the anomalous behavior referred to at the beginning of this report.

Prior experience in test reactor irradiation studies and the few comparisons of C-L vs. L-C orientation data available from power reactor surveillance programs have led investigators to expect roughly comparable elevations in 41-J transition temperature for L-C vs. C-L test orientations. A companion expectation is a greater "absolute" reduction in upper shelf level for that test orientation having the higher preirradiation C_v upper shelf energy, that is, the "strong" test orientation, for cases where the preirradiation difference is quite pronounced. This expectation is one reason that the projection of upper shelf reduction by the NRC Regulatory Guide 1.99 is given in terms of percent decrease rather than an absolute value for a given fluence.

7.4 Follow-On Irradiation Experiment Matrix (UBR-78, UBR-79, UBR-80)

To verify the anomalous behavior, and separately, to obtain a critical test of neutron spectra effects on irradiation embrittlement sensitivity, a set of three additional experiments was undertaken for the archive material. Irradiation parameters and specimen complements are indicated in Table 1. The specimen loadings of the three experiments are indicated in Figs. 20 to 22; daily operating temperature records are included in Appendix D.

The thrust of one new experiment, UBR-78, was the development of a set of data for a fluence closely matching that actually received by the 1/8T-thickness location of the vessel (Trepan C and G). As with experiment UBR-68, Capsule A contained C_v and tensile specimens and Capsule B contained 0.5T-CT specimens. The second experiment, UBR-79A, addressed the question of the effect of irradiation temperature on material irradiation sensitivity. Here, a reanalysis of the probable vessel wall operating temperature by the utility indicated a service temperature of 279°C for the vessel belt-line region, rather than 288°C. This best estimate was derived mainly from downcomer water temperature information. To test the irradiation temperature effect more critically, the target temperature for UBR-79A was 275°C, rather than 279°C. The target fluence was the same as that for the original 288°C experiment, UBR-68. In actuality, the C_v specimens in UBR-79A were irradiated at 260°C (Group 1) and 275°C (Group 2). The temperature difference resulted from the "piggybacking" of the six 0.5T-CT specimens in with the C_v specimen array. The development of two temperature zones, however, proved fortuitous.

The third experiment, UBR-80, was undertaken to obtain high fluence, 288°C irradiation data for a light-water environment, for comparison with data being developed by Harwell for a heavy-water environment. The target fluence was 2.3×10^{19} n/cm^2. In the interest of a

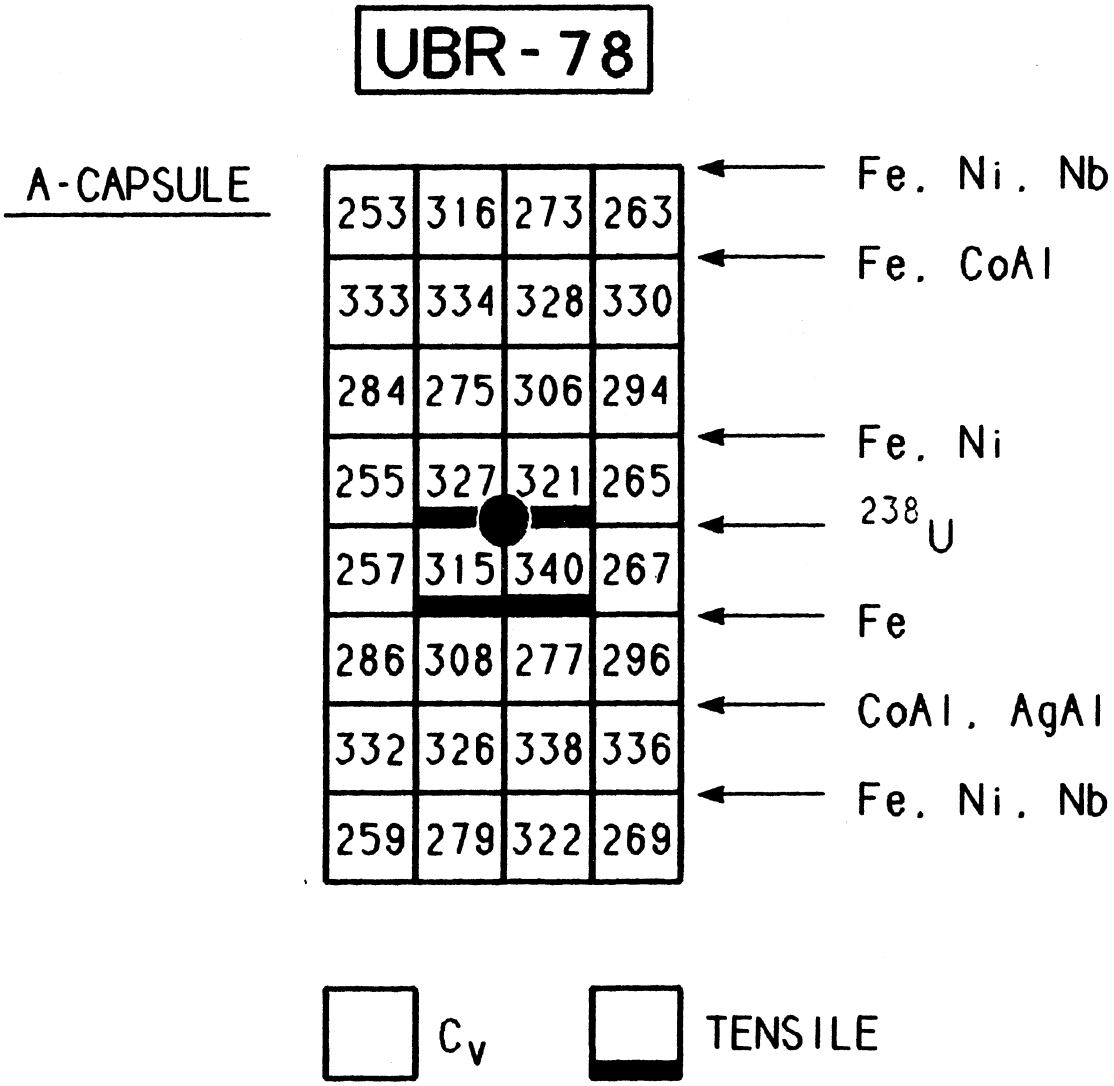


Fig. 20a Placement of Charpy-V, tensile and 0.5T-CT specimens in Experiment UBR-78 (Capsule A; elevation view).

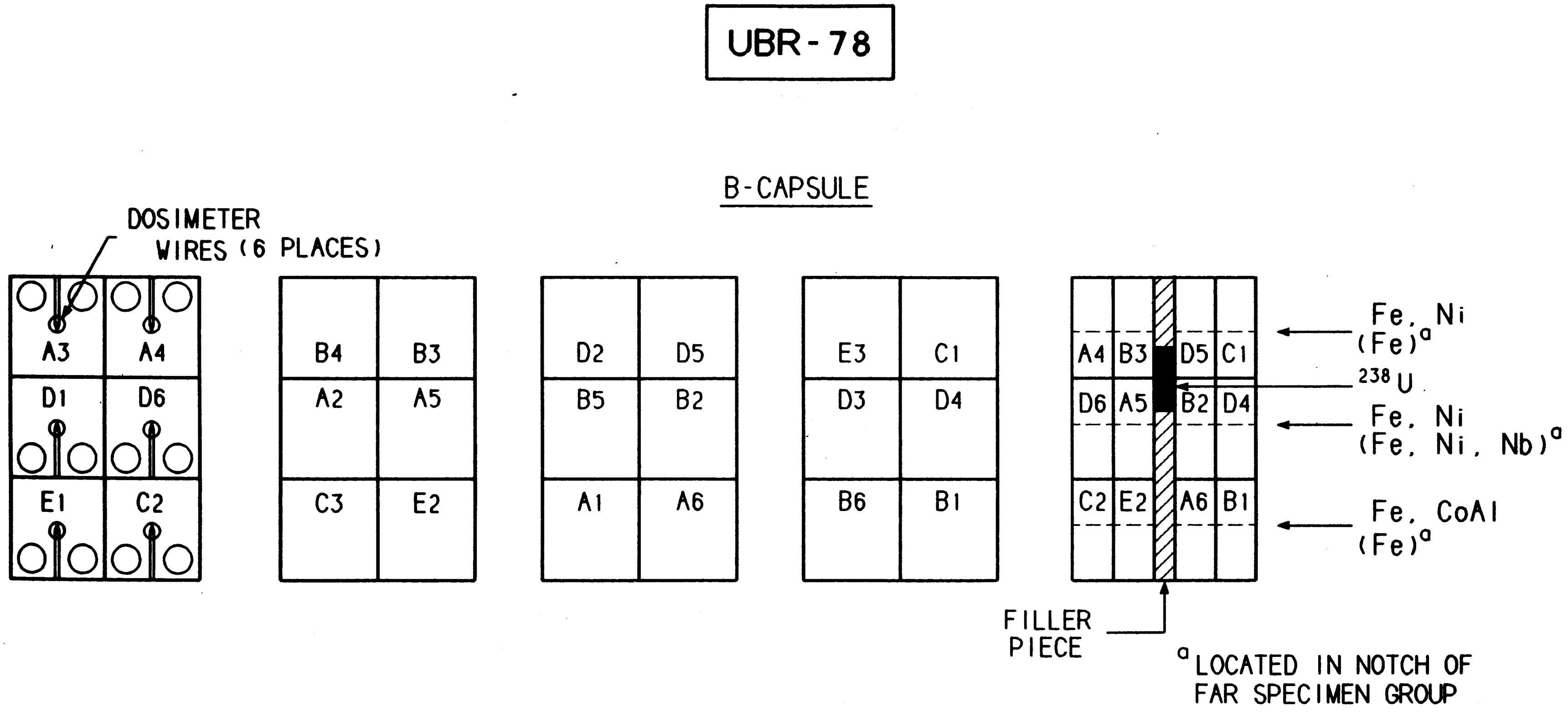


Fig. 20b Placement of Charpy-V, tensile and 0.5T-CT specimens in Experiment UBR-78 (Capsule B; elevation view).

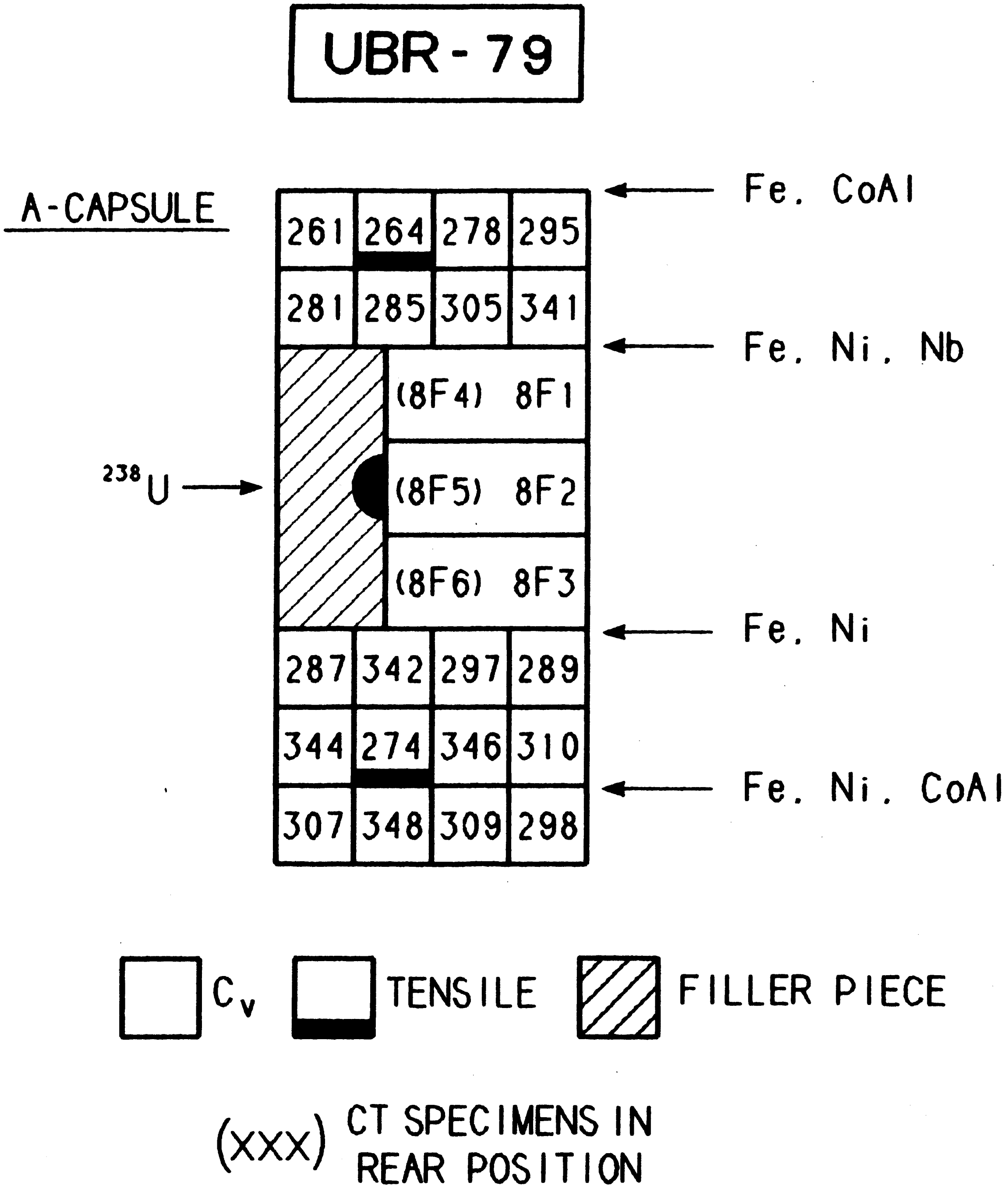


Fig. 21 Placement of Charpy-V, tensile, and 0.5T-CT specimens in Capsule A of Experiment UBR-79 (elevation view).

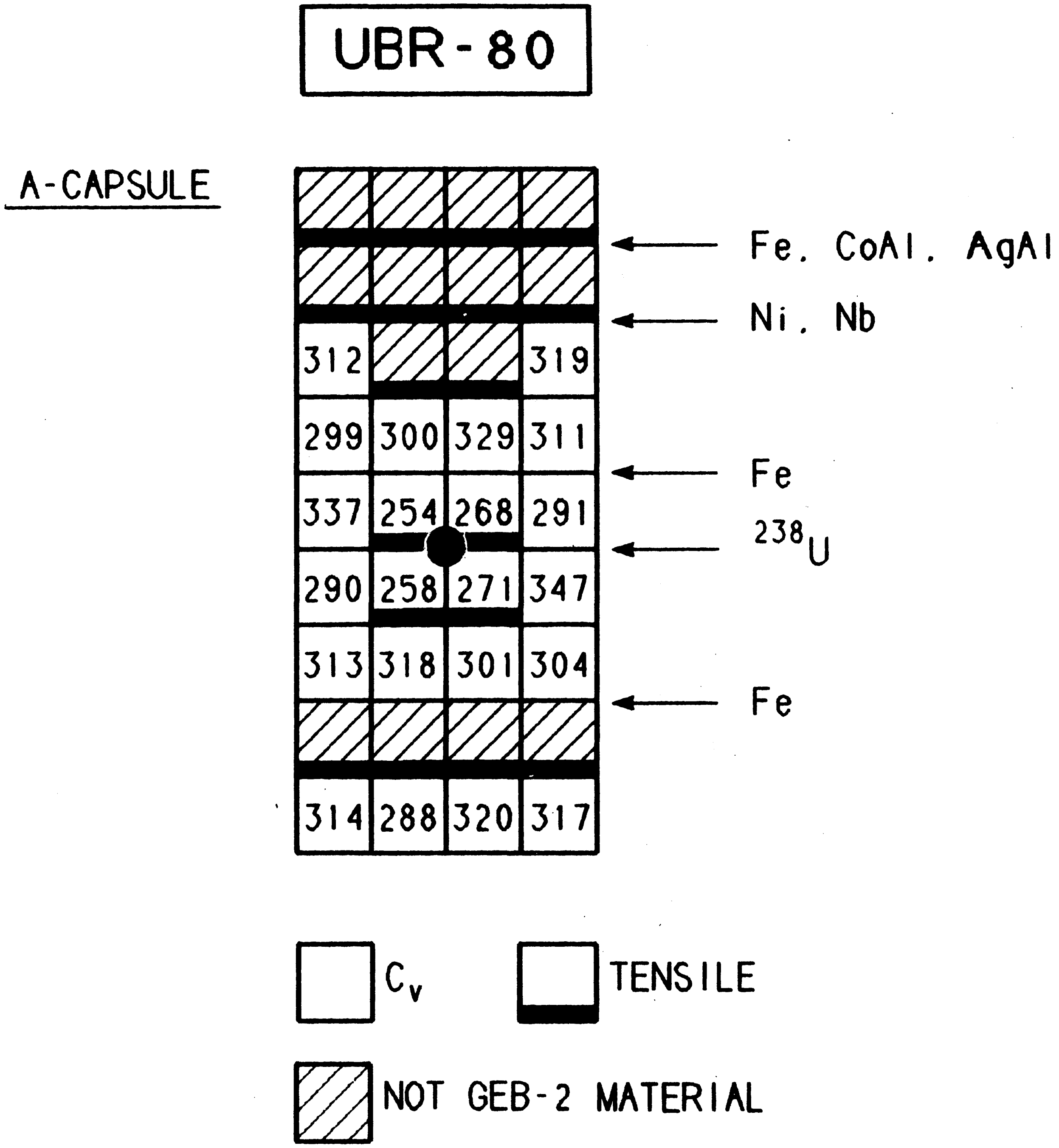


Fig. 22 Placement of Charpy-V and tensile specimens in Capsule A of Experiment UBR-80 (elevation view). Blank spaces were occupied by specimens for another MEA study for the NRC.

complete summation of MEA investigations on the archive material, data from the UBR-80 irradiation test are provided below. Data from the cited Harwell investigations are not expected until late 1989.

The C-L and L-C test orientations were included in all three irradiation assemblies (UBR-78, -79A, and -80A) to qualify the orientation-dependence of radiation sensitivity for the reactor vessel material.

The specimens for the irradiation assemblies were removed from the code GEB-2 ring forging at locations adjoining but somewhat displaced from that supplying the unirradiated condition test specimens. As a precaution against possible property differences around the forging circumference, a number of extra specimens were cut along with the specimen complement for irradiation, for check-tests of unirradiated condition properties. Results from the CT check-test specimens are illustrated in Figs. 23 and 24. Good consistency of the data in terms of transition regime trends and J-R curve trends is observed. A similar consistency was observed for the C_v specimen data sets.

7.5 Irradiation Experiment UBR-78

C_v data for the L-C orientation and the C-L (strong) orientation are presented in Fig. 25 and are tabulated in Appendix F. Appendix F also includes computer curve-fits of these data and curve-fits for the data from experiments 79A and 80A. The average fluences received by the UBR-78 experiment specimens, 2.7×10^{18} n/cm^2 (C_v, tensile) and 2.6×10^{18} n/cm^2 (0.5T-CT), essentially match 1:1 the fluences received by the Trepans C and G at their 1/8T-thickness location. Average fluence rate values determined from individual neutron dosimeters in irradiation experiments UBR-78, UBR-79A, and UBR-80 are included in Appendix E.

Unlike the trepan test results, the data from this experiment do show about equal C_v 41-J transition temperature elevations and about equal upper shelf energy reductions for the L-C and C-L test orientations. The reductions in upper shelf energy were small, that is, nominally 5 J or less. The elevations in 41-J transition temperature were also small, about 18°C.

A comparison of the C-L orientation results for the trepan vs. the archive material indicates a reasonably good agreement (Fig. 19) The transition temperature elevations are within 10°C; the upper shelf reductions are both less than 10 J. The data sets for the L-C orientation, on the other hand, reinforce the original anomalous indications for the trepan.

Data from the 0.5T-CT specimens irradiated in experiment UBR-78 are given in Appendix G. The 100 MPa$\sqrt{m}$ temperature elevation is somewhat higher than the C_v 41-J temperature elevation. In the transition regime, the data lie between that from experiment UBR-68 and that for the unirradiated condition (Fig. 26). The 100 MPa$\sqrt{m}$ transition temperature elevation is about 60% of the 100 MPa$\sqrt{m}$ temperature elevation observed with experiment UBR-68. The J-R curves for 177°C

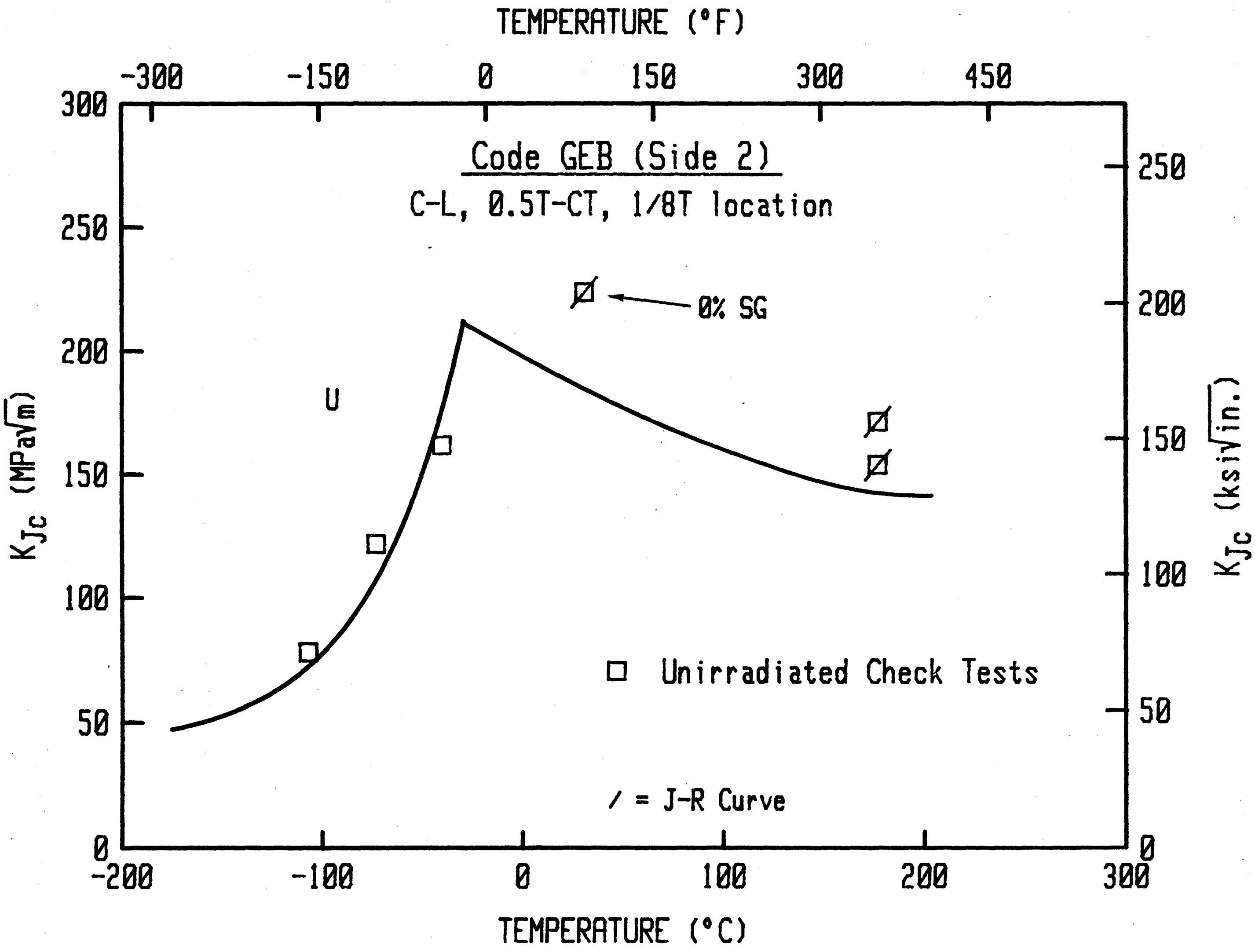


Fig. 23 Check tests of unirradiated condition, fracture toughness properties. The data match well the initial data for the transition region.

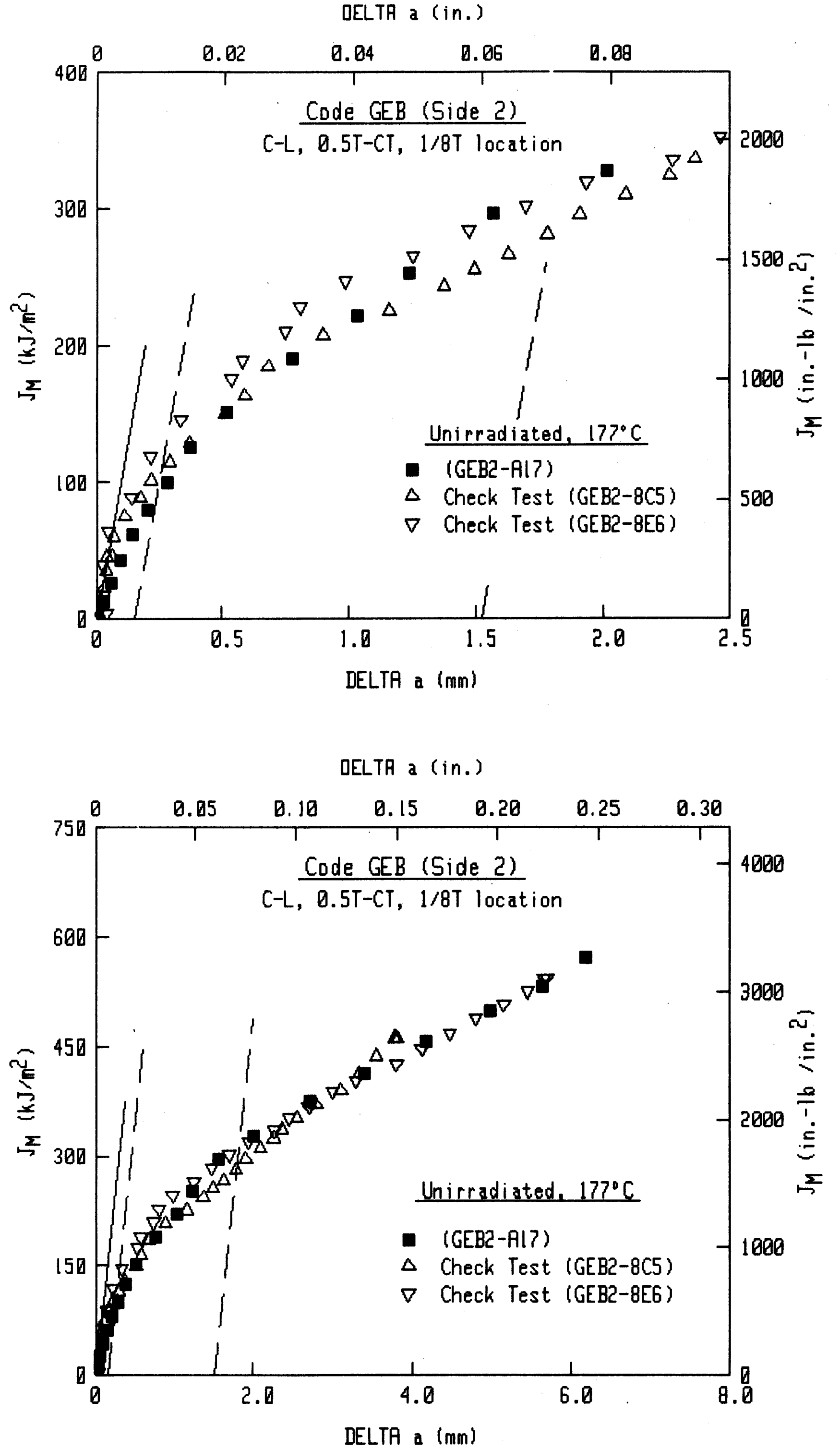


Fig. 24 J-R curves from check tests at 177°C. The new data match the prior data well although at Δa values less than 1 mm, the J levels for the check tests are slightly higher.

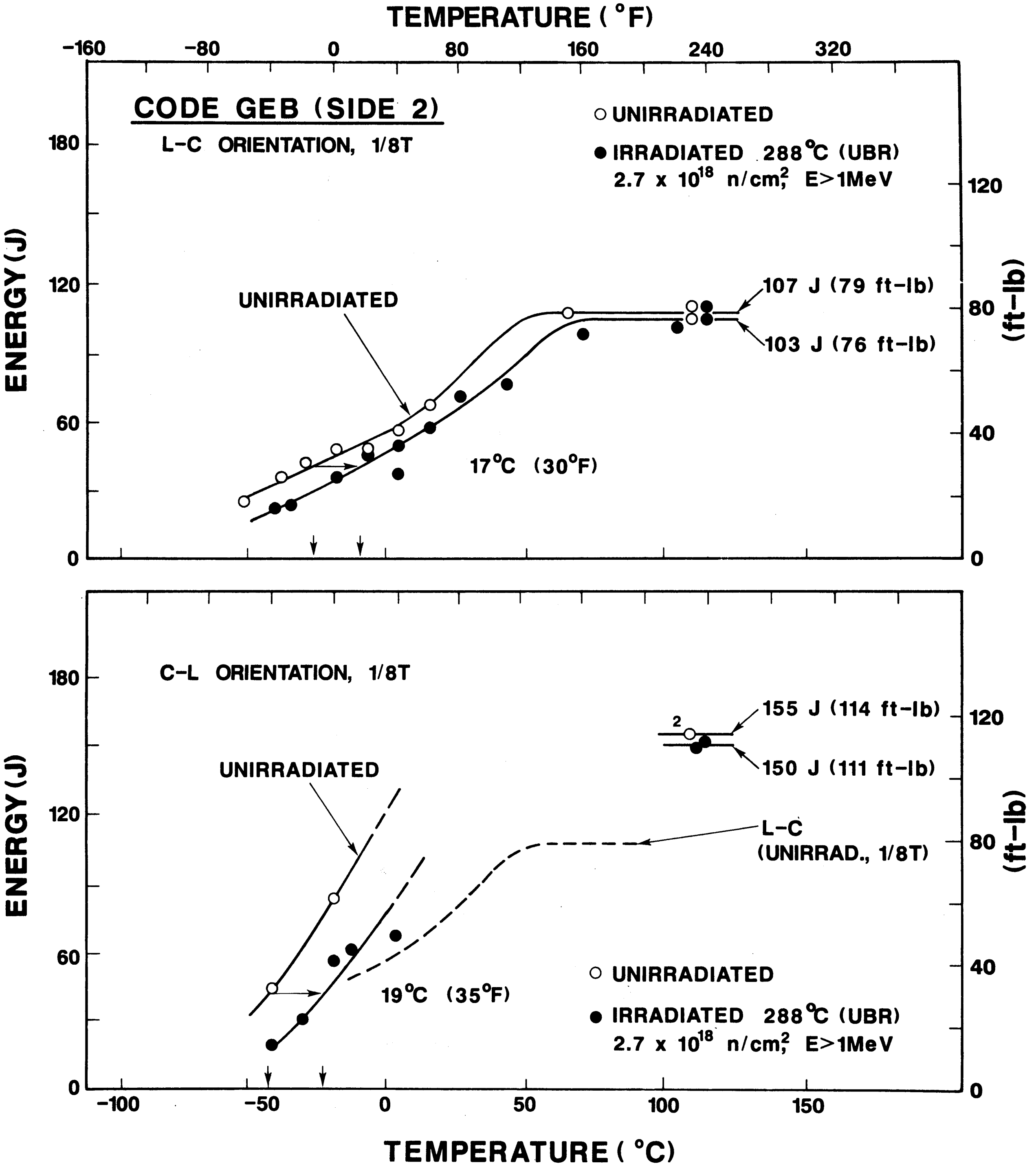


Fig. 25 Embrittlement of the Code GEB-2 archive material by a fluence matching that received by the KRB-A reactor vessel in service (Experiment UBR-78). Notice that the radiation-induced notch ductility changes for the weak orientation (upper graph) and the strong orientation (lower graph) are about equal, unlike observations for the vessel proper.

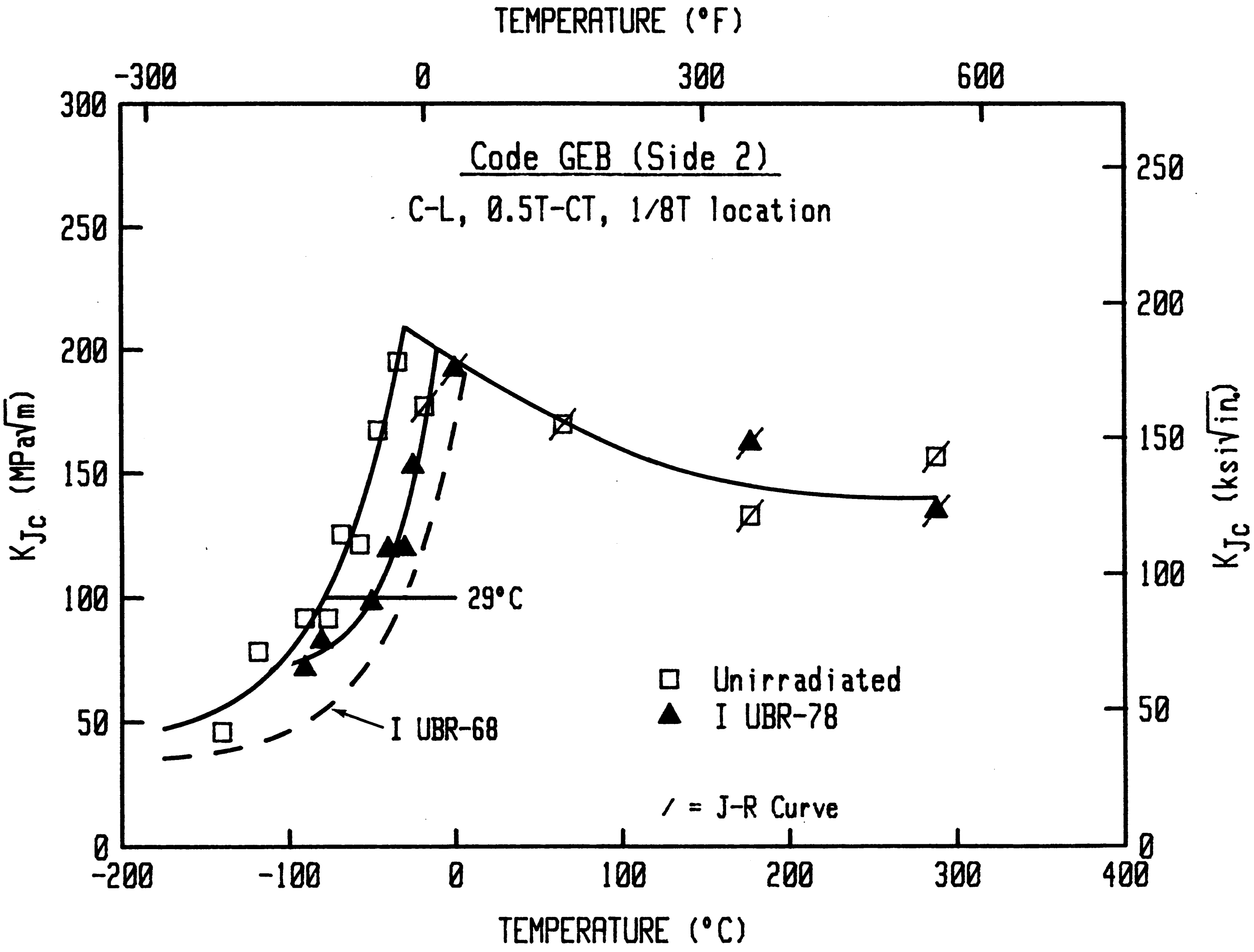


Fig. 26 Fracture toughness of the Code GEB-2 material before and after irradiation at 288°C to 2.6 x 10^{18} n/cm^2 (Experiment UBR-78) The trend for a 288°C irradiation to 8.6 x 10^{18} n/cm^2 is also indicated (see dashed curve).

describe a higher J level than the J-R curves for the unirradiated condition at this temperature for Δa values up to 0.5 mm (Fig. 27); at higher Δa values, the J level for the irradiated condition is lower than that for the reference condition. For the 288°C test condition, the J-R curves tend to be lower than those for the unirradiated condition (Fig. 28). [Note: A number of 0.5T-CT specimens from UBR-78 remain untested. Because of the low embrittlement, the planned assessments of annealing response (see Table 1) will not be made.]

The data obtained from tensile specimens are included in Table 5 and are discussed in conjunction with the UBR-79A and UBR-80A test results in a later section.

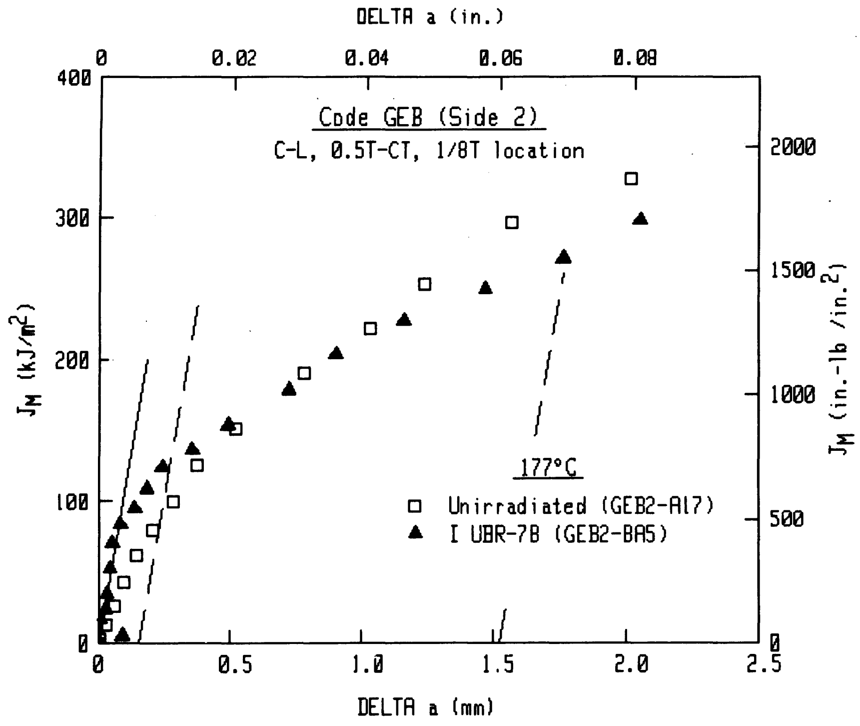
7.6 Irradiation Experiment UBR-79A

The C_v data from this experiment are illustrated in Fig. 29. The C_v specimens in this assembly were irradiated at either 260°C (Group 1) or 275°C (Group 2), as stated in paragraph 7.4. The average fluences received were 8.5×10^{18} n/cm^2 and 8.8×10^{18} n/cm^2, respectively, and closely match the fluence (8.8×10^{18} n/cm^2) of UBR-68. Accordingly, the data can be compared directly for an irradiation temperature effects determination.

The results show only a small influence of irradiation temperature on the change in notch ductility properties. Transition temperature elevations were, in order of increasing irradiation temperature: 56°C, 47°C, and 44°C. The comparison of 275°C vs. 288°C irradiation temperature effects is of particular interest to the KRB-A analysis since the various estimates of vessel in-wall temperatures at the belt line are within this temperature range. The data from experiments UBR-79A and UBR-68 indicate that the uncertainity in the irradiation service temperature is not of practical significance. In turn, it can be concluded that the currently estimated vessel service temperature at the belt line, 279°C, does not have a bearing on the anomalous C_v data for the trepan L-C vs. C-L orientation. This is supported by the few C_v data developed for the C-L test orientation in this experiment.

The tensile test results are given in Table 5. The elevations in yield strength and tensile strength compare well with those observed in the 288°C irradiation experiment.

The fracture toughness data are tabulated in Appendix G and are illustrated in Fig. 30. From the very limited data the transition temperature increase at the 100 MPa$\sqrt{m}$ level would appear to exceed that found with the UBR-68 irradiation which had a comparable fluence (ΔT 68°C vs. ΔT 48°C) and implies a somewhat higher material sensitivity to irradiation at 275°C, unlike the C_v or tensile specimen data. A relatively large decrease in J-R curve level due to irradiation is apparent at a test temperature of 31°C (Fig. 31), in contrast to the small decrease found for experiment UBR-68.



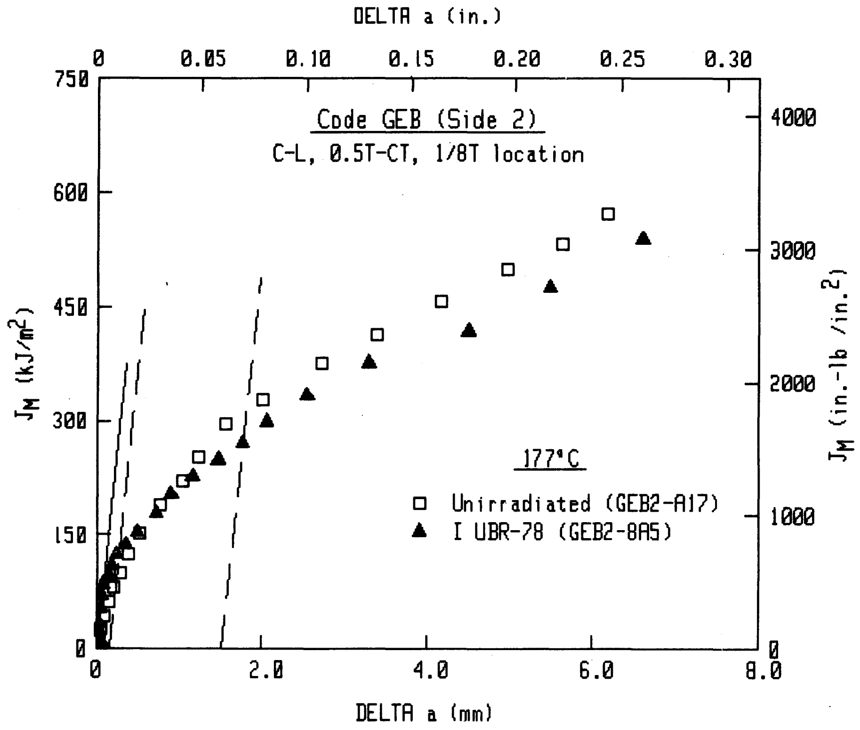


Fig. 27 J-R curve for the UBR-78 irradiated condition at 177°C. The J-R curve level is similar to that for the unirradiated condition.

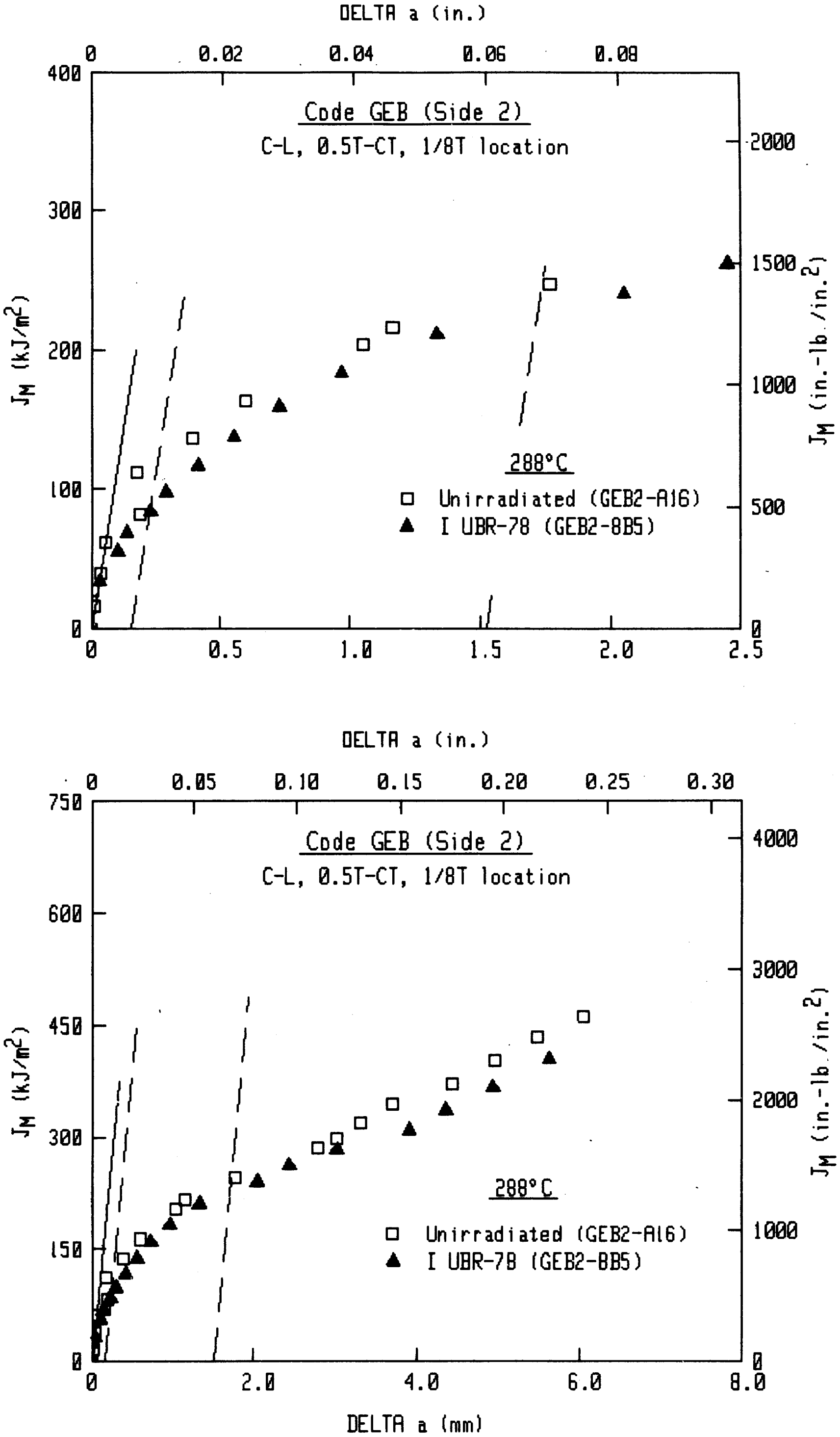


Fig. 28 J-R curve for the UBR-78 irradiated condition at 288°C. The J-R curve level here is slightly lower than that for the unirradiated condition.

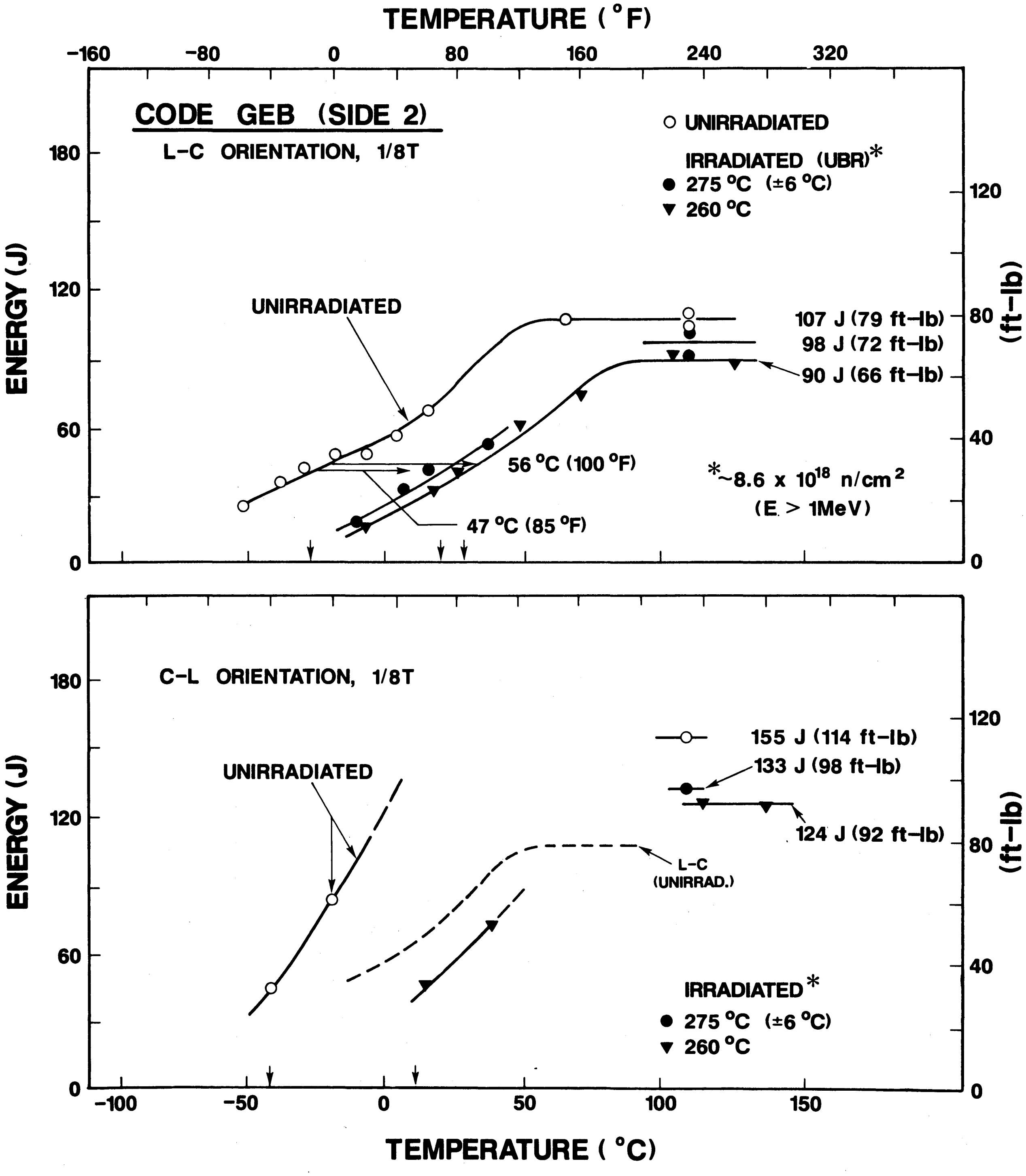


Fig. 29 Embrittlement of the Code GEB-2 material by irradiation at 260°C vs. 275°C to ~ 8.6 x 10^{18} n/cm^2. The upper and lower graphs present L-C orientation and C-L orientation data, respectively.

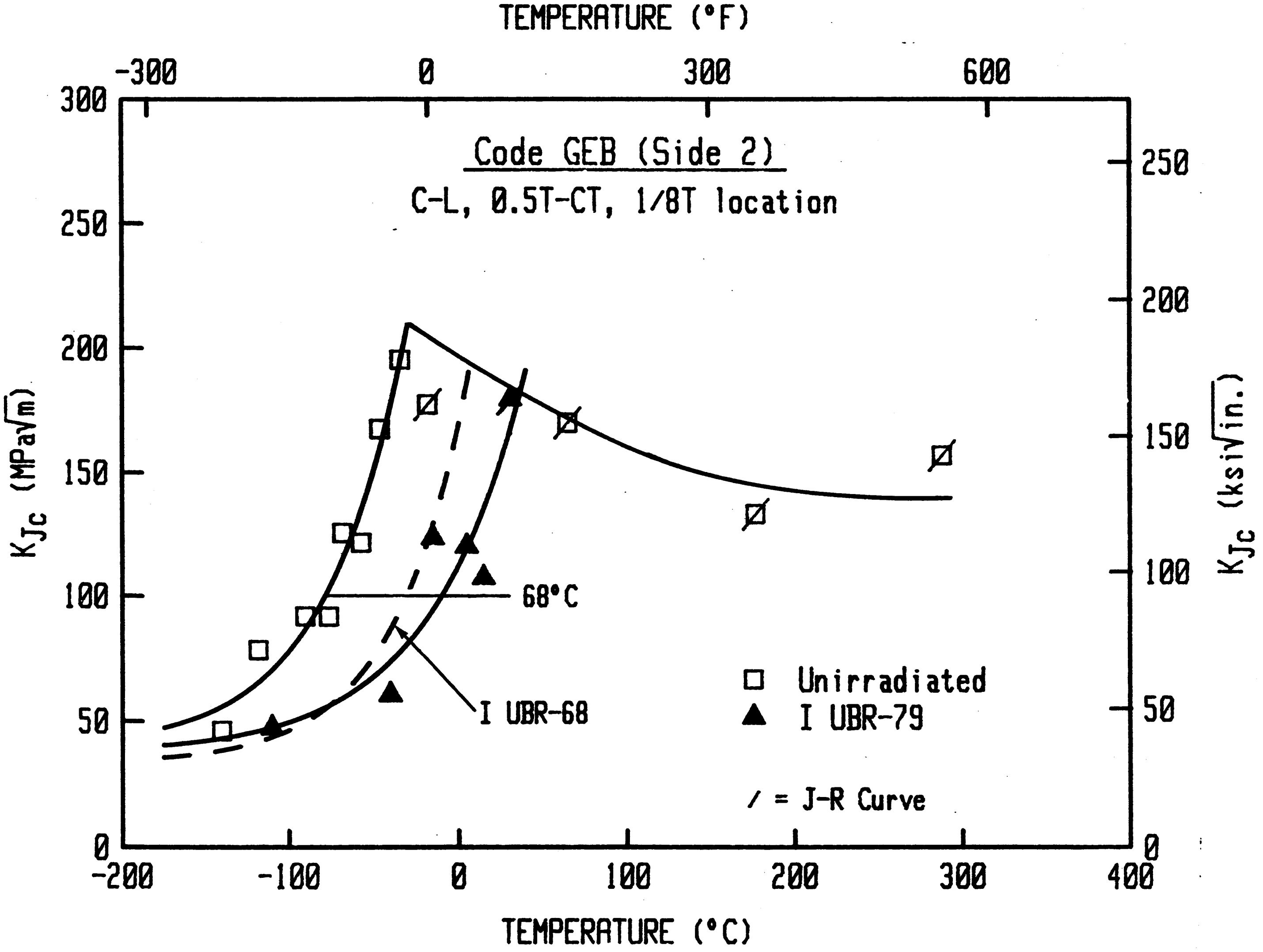


Fig. 30 Fracture toughness of the Code GEB-2 material before and after irradiation at $275^{\circ}C$ to ~ 8.6×10^{18} n/cm^2 (Experiment UBR-79)

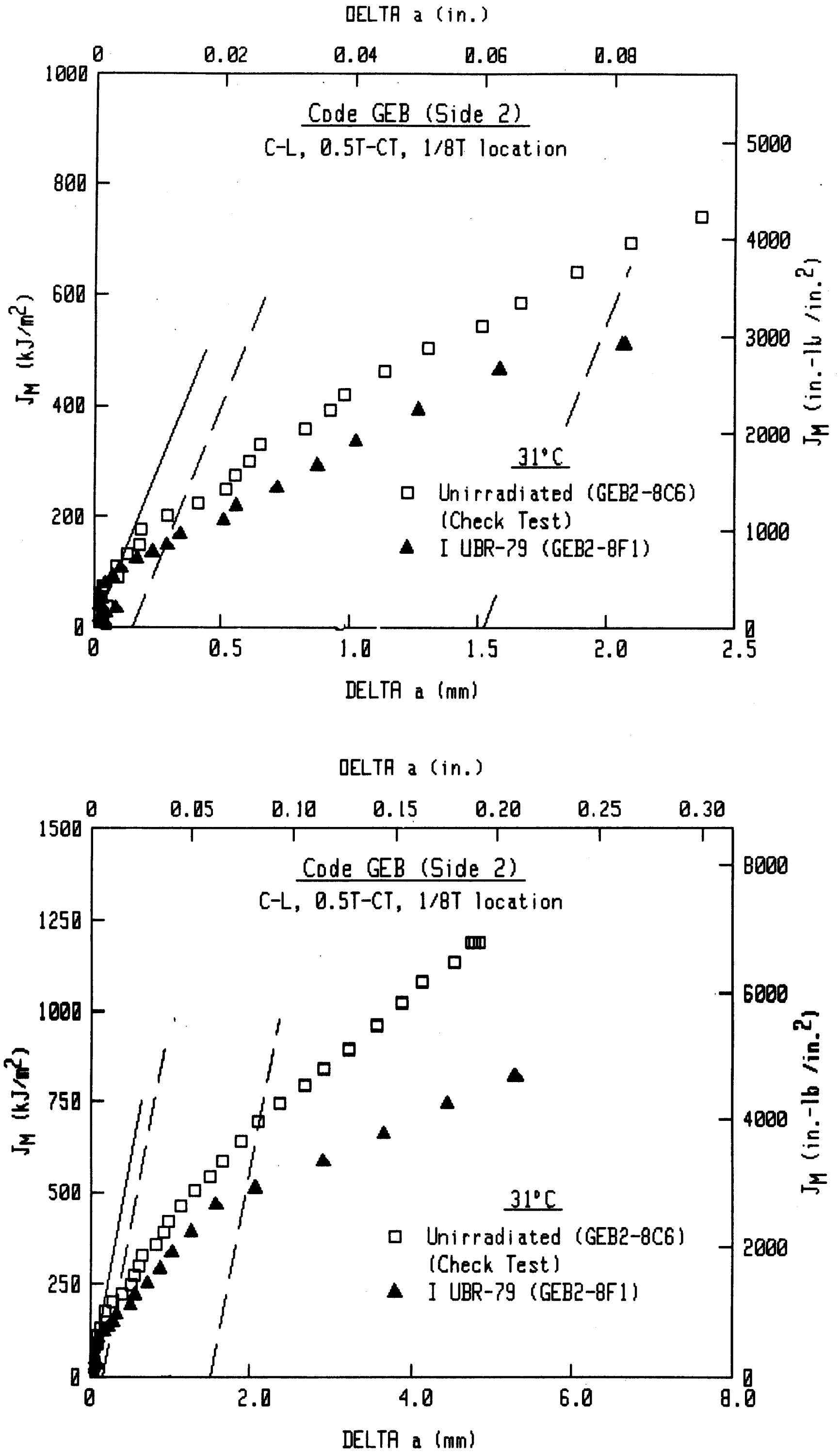


Fig. 31 J-R curves for unirradiated vs. UBR-79 irradiated conditions at 31°C. A fairly large reduction in J level is evident for the irradiated condition.

7.7 Irradiation Experiment UBR-80A

The experimental C_v data are illustrated in Fig. 32. The inclusion of C-L and L-C orientation specimens in this assembly provided a critical test of the orientation dependence of the upper shelf reduction. It should be noted that the blanks for the two specimen sets were located very close to one another and to the check test specimens in the archive material stock. A 36-J reduction in upper shelf energy level is described by the C-L orientation data whereas a 19-J reduction is found for the L-C orientation data. The greater reduction by the "strong" test orientation is consistent with the data from prior accelerated irradiation tests.

The transition temperature elevation recorded with this experiment, when joined with those of experiments UBR-68, UBR-78, and UBR-79A, provides the embrittlement trend with fluence shown in Fig. 33. The trend in yield strength with fluence is also shown. Where specimens of C-L and L-C orientations were available, a general independence of the yield strength elevation on test orientation is indicated. The data indicate the following relationship: $\Delta^\circ C$ (41-J temperature elevation) = 1.67 ΔMPa (yield strength elevation).

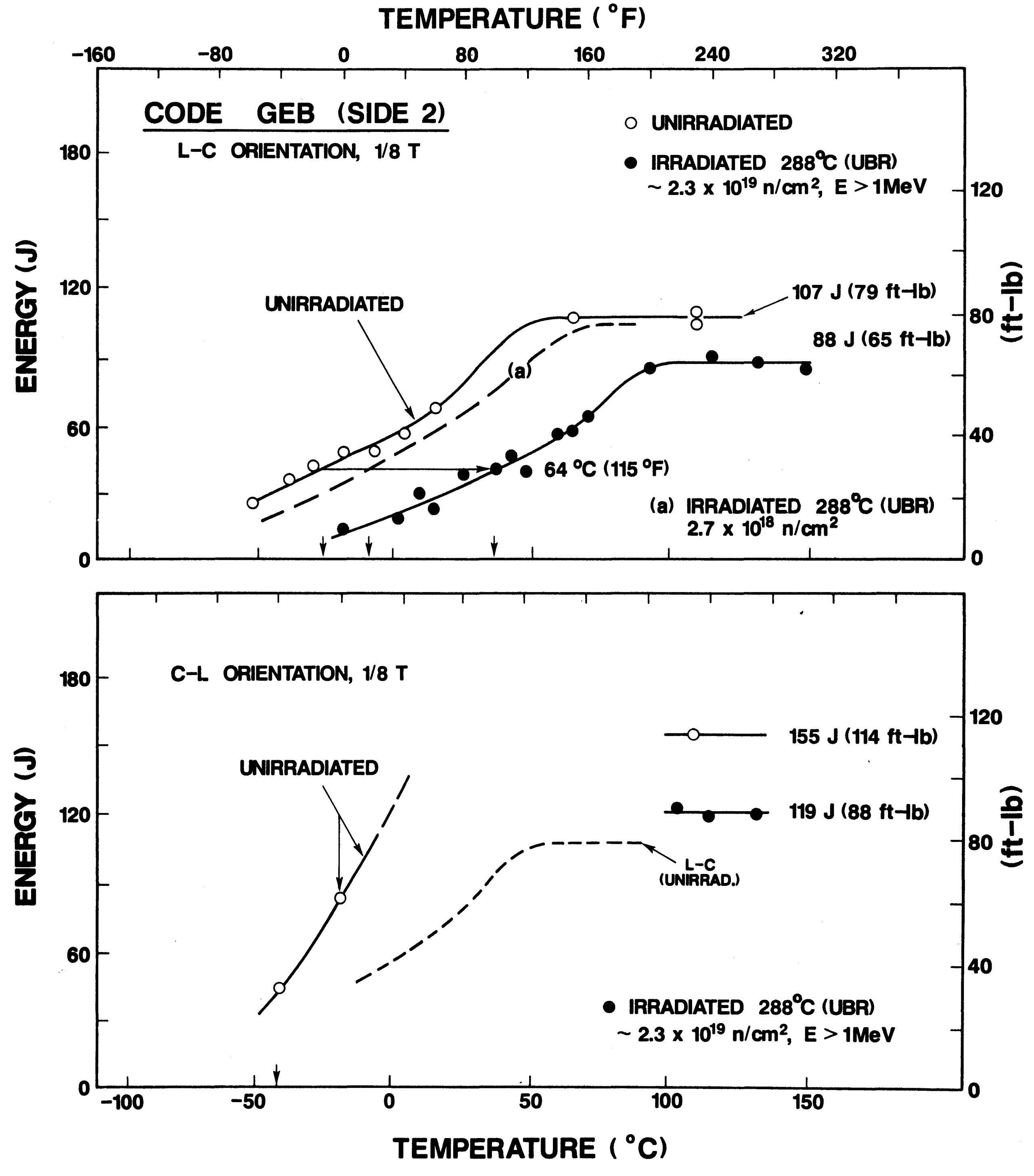


Fig. 32 Embrittlement of the Code GEB-2 material by a high fluence, 288°C irradiation. The upper and lower graphs present L-C orientation and C-L orientation data, respectively. The dashed curve in the upper graph indicates the data trend for a low fluence, 288°C irradiation test.

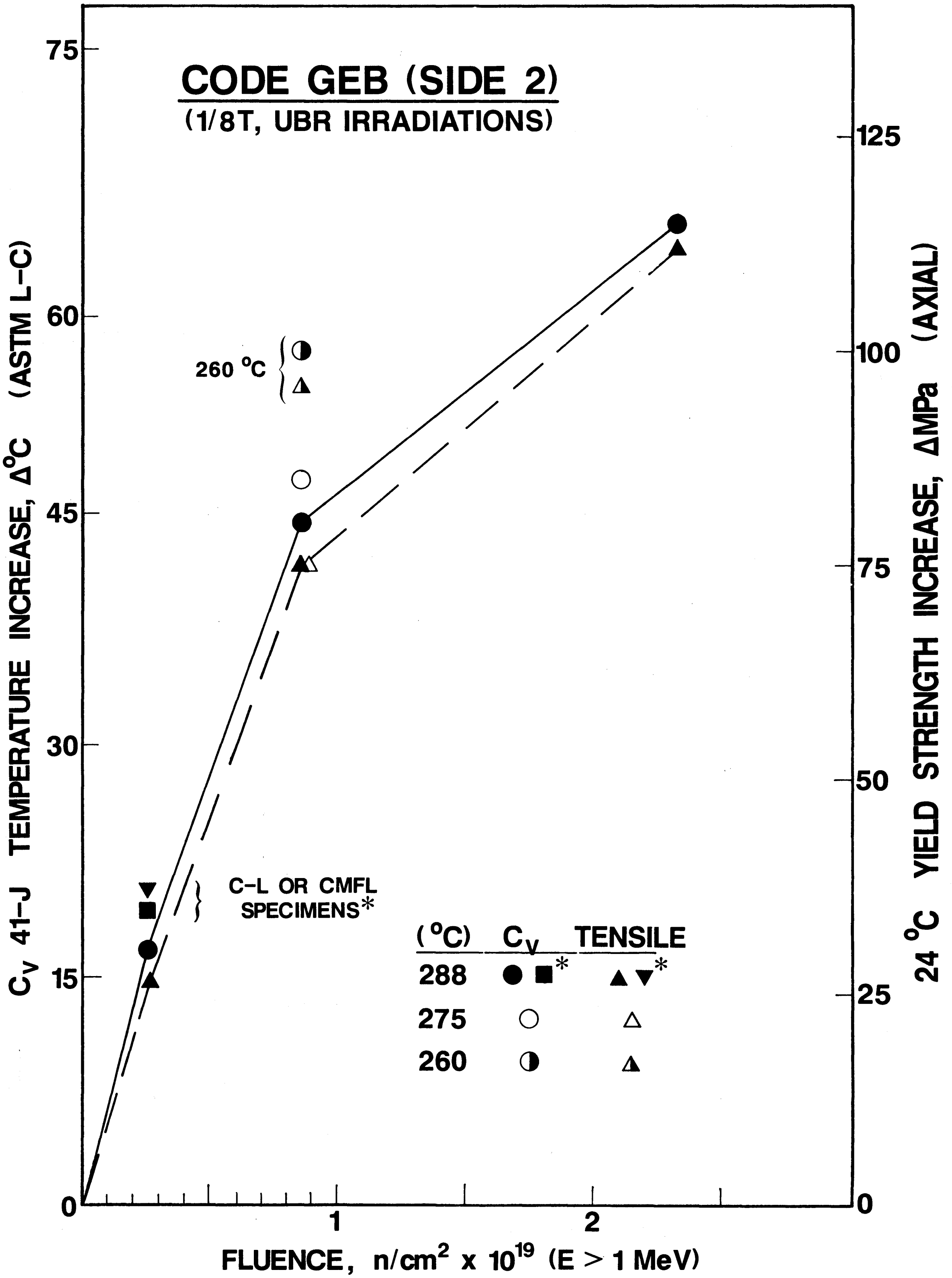


Fig. 33 Trends of Charpy-V 41-J transition temperature increase and 24°C yield strength increase with neutron fluence at 288°C. Data from 260°C and 275°C irradiation tests are also shown.

8. DISCUSSION

A reasonable explanation for the "anomalous" test orientation dependence of radiation embrittlement found for the material trepanned from the KRB-A vessel has not been provided by the second group of experiments with the archive material. Accordingly, the studies should continue.

The original NRC objective for the USA/FRG/UK investigation was to critically test the influence of fluence rate on irradiation embrittlement and postirradiation embrittlement relief by annealing. In view of the anomalous trepan data comparison, caution is advised in making a fluence-rate assessment in the present case. That is, the L-C orientation data for the archive material vs. the L-C orientation data for the vessel trepans suggest a fluence-rate effect while the C-L orientation data for the two materials do not. Fortunately, both test orientations of the trepan were evaluated at the outset; otherwise, potentially erroneous conclusions could have resulted. The prima facie evidence for the L-C orientation (only) could easily have provided a conclusion that a highly detrimental fluence-rate effect exists for this particular steel type or composition. The evidence now available does not preclude such a conclusion in the future, but the anomalously high radiation embrittlement sensitivity of the L-C orientation relative to the C-L orientation is not supported by present experience with other materials.

Metallurgical explanations for the anomalous set of results are being sought through state-of-the-art microscopy and direct analyses of the fracture surface properties, including composition. Perhaps some preferential radiation-induced segregation could be responsible for the greater embrittlement to the "weak" orientation compared to the "strong" orientation.

An explanation could reside in the fabrication history of the vessel ring forging itself. Nothwithstanding the good agreement found in verification tests between archive material and vessel material (composition, strength, microstructure, C-L orientation notch ductility), the documentation on preirradiation L-C orientation properties of the vessel material is practically nil. It is noted that ring forgings can exhibit significant differences in properties around their circumference. One forging material included in the second round of IAEA studies on the reliability of reactor pressure components (Refs. 13, 14, and 15) is an example. Carrying this forward, the properties of the archive material may not adequately represent the properties of the vessel material at the particular location at which the trepans were removed. The failure of trepan specimens annealed at 454°C to develop the same upper shelf level as the archive material specimens in the unirradiated condition (Ref. 1) may be indicative of such a scenario. In the broad sense, potential material variability in the preservice condition points to a conceivable problem in reactor vessel surveillance data applications on one hand, and a problem of data bank analyses for Regulatory Guide 1.99 application on the other, particularly at low fluences where the potential for large percentage errors are greatest. The performance of routine "check tests" of preirradiation properties as a precaution in critical data applications is one means of improving on this situation.

In the case of the present USA/FRG/UK program, MEA and MPA have proposed that the anomaly be resolved by a test reactor irradiation of specimens made from the outer (low fluence exposure) ligaments of the trepan. MEA experiment designs are available for this purpose. If the same orientation dependence of embrittlement sensitivity is indicated by this irradiation test, it could be concluded that the anomaly is rooted in the material tested and not the difference in fluence rates involved (UBR vs. KRB-A service). If the same orientation dependence is not indicated, it will confirm the fluence-rate effect. In similar fashion, the approach precludes any uncertainties in later material comparisons by microscopy for the mechanistic cause.

9. SUMMARY

The accomplishments and primary observations of this investigation are:

- Two welded ring segments obtained by the NRC from General Electric Company have been identified to a high degree of certainty as archive material for ring No. 7.1 of the Gundremmingen KRB-A reactor vessel. Verification tests involved metallurgical and composition tests and archive material comparisons against unused surveillance specimens and portions of the vessel removed by trepanning.

- Notch ductility, fracture toughness (J-R curve), and tensile properties of the archive material through its thickness were determined experimentally using full-size C_v specimens, 0.5T-CT specimens, and 5.74-mm diameter tensile specimens oriented in ASTM L-C and C-L orientations. Relatively good uniformity in properties was observed between 1/8T-, 1/4T-, 1/2T-, and 7/8T-thickness locations. The C_v upper shelf energy level of the L-C orientation was about 30% lower than that of the C-L orientation (107 J vs. 155 J); the yield strengths of the two orientations were about the same.

- The fluences received in through-wall locations were determined for the KRB-A pressure vessel. The fluence at approximately the 1/8T-thickness location was 2.7×10^{18} n/cm^2 uncorrected for neutron spectrum shape (fission spectrum assumption) and 2.38×10^{18} n/cm^2 for the calculated neutron spectrum conditions at the vessel trepan location. The vessel inner-wall fluence is much lower than that originally projected by the FRG at the time of decommissioning.

- The archive material was irradiated in the light-water cooled and moderated UBR test reactor to 2.7, 8.8, and 23×10^{18} n/cm^2 at 288°C and to ~ 8.7×10^{18} n/cm^2 ($E > 1$ MeV) at 260°C and 275°C. Good agreement in 41-J transition temperature elevation was observed for the L-C vs. C-L orientation; the upper shelf energy reduction for the C-L orientation was about equal to that for the L-C orientation at the lowest fluence condition evaluated but was greater than that for the L-C orientation at the higher fluences.

- The L-C orientation C_v data for the archive material irradiated in the test reactor (accelerated irradiation conditions) describe less embrittlement than L-C orientation data for the vessel material at about the same fluence. This can be interpreted as a fluence rate effect indication. Comparisons of C-L orientation data for the archive material and trepan material, however, show about the same radiation embrittlement at a matching fluence.

The L-C orientation comparison assumes that the preirradiation properties of the archive material represent those of the vessel material which are unknown.

- The large difference in apparent radiation embrittlement sensitivity between the C-L "strong" test orientation (low) vs. the L-C "weak" test orientation (high) is anomalous; one approach for resolving the anomaly is described.

- The transition temperature shift from fracture toughness tests (measured at the 100 MPa$\sqrt{m}$ level) tended to be slightly higher than that described by C_v tests for 288°C irradiation conditions. For fluences of ~ 2.7×10^{18} and ~ 8.6×10^{18} n/cm^2, the difference was 12°C and 4°C respectively.

- Upper shelf (J-R curve) fracture toughness was not degraded significantly by any of the test reactor irradiation exposures even though fluences were as high as 8.8×10^{18} n/cm^2 (E > 1 MeV).

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APPENDIX A

"Preirradiation Qualification of Materials Identified as KRB-A Archive"

J. R. Hawthorne

MEA Report No. MEA-2095

August 1985

MEA-2095

PREIRRADIATION QUALIFICATION OF MATERIALS IDENTIFIED AS KRB-A ARCHIVE

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Prepared by

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July 30, 1985

Prepared for

U. S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Materials Engineering Branch
Washington, DC 20555

Contract: NRC-04-84-102

MATERIALS ENGINEERING ASSOCIATES, INC.

MEA-2095

PREIRRADIATION QUALIFICATION OF MATERIALS IDENTIFIED AS KRB-A ARCHIVE

J. R. Hawthorne

1. BACKGROUND

MEA has the task of irradiating and evaluating Gundremmingen reactor vessel archival materials in support of NRC research on long-term, in-service irradiation effects. MEA's results, together with determinations by MPA of the Federal Republic of Germany (FRG) on materials trepanned from the KRB-A vessel itself, will be analyzed for the effects of neutron exposure rate, steel composition, through-thickness damage attenuation, and for the correlation of Charpy-V (C_v) notch ductility vs. fracture toughness vs. strength. Properties recovery by postirradiation heat treatment will also be investigated. The MEA and MPA programs are limited to studies of the base metal. Studies of the girth welds are not being performed. The NRC decision to forego weld metal investigations stemmed from the FRG determination that more than one filler metal was employed in completing the weld thickness; that is, each weld has a composition variation through its thickness.

In April, 1985, two pieces of weldment identified by stamp markings as "KRB Vessel", were acquired from the General Electric Company (GE) - Vallecitos site. Each of the pieces represents a ring segment. One weighing approximately 3,200 lb. contains a circumferential weld deposit located at the half-height of the ring; the second, weighing only 450 lb., also contains a circumferential weld. In this case, the weld is placed closer to one edge than the other. Both segments are approximately 4-11/16 in. thick. The smaller piece was given the code GEA by MEA; the larger pieces was assigned the code GEB. In this report, GEA and GEB are termed "archive materials." The two base metals of GEA were given the code number GEA-1 and GEA-2, respectively; those of GEB have the code number GEB-1 or GEB-2.

Initial task objectives were the determination of the chemical composition, hardness, tensile strength and notch ductility of each of the four base metals contained in the welded ring segments. Microstructures were also to be identified. The findings were to establish whether or not the base metals are from the same parent material (or steel melt). Additionally, the results were to be compared against documentation for the KRB-A vessel to determine if the material acquired from GE is in fact archive material for the vessel. Specifically, the material from GE is believed to be a portion of forging ring no. 7.1 of the KRB-A vessel.

This report summarizes the MEA findings on the archive materials to date.

2. APPROACH

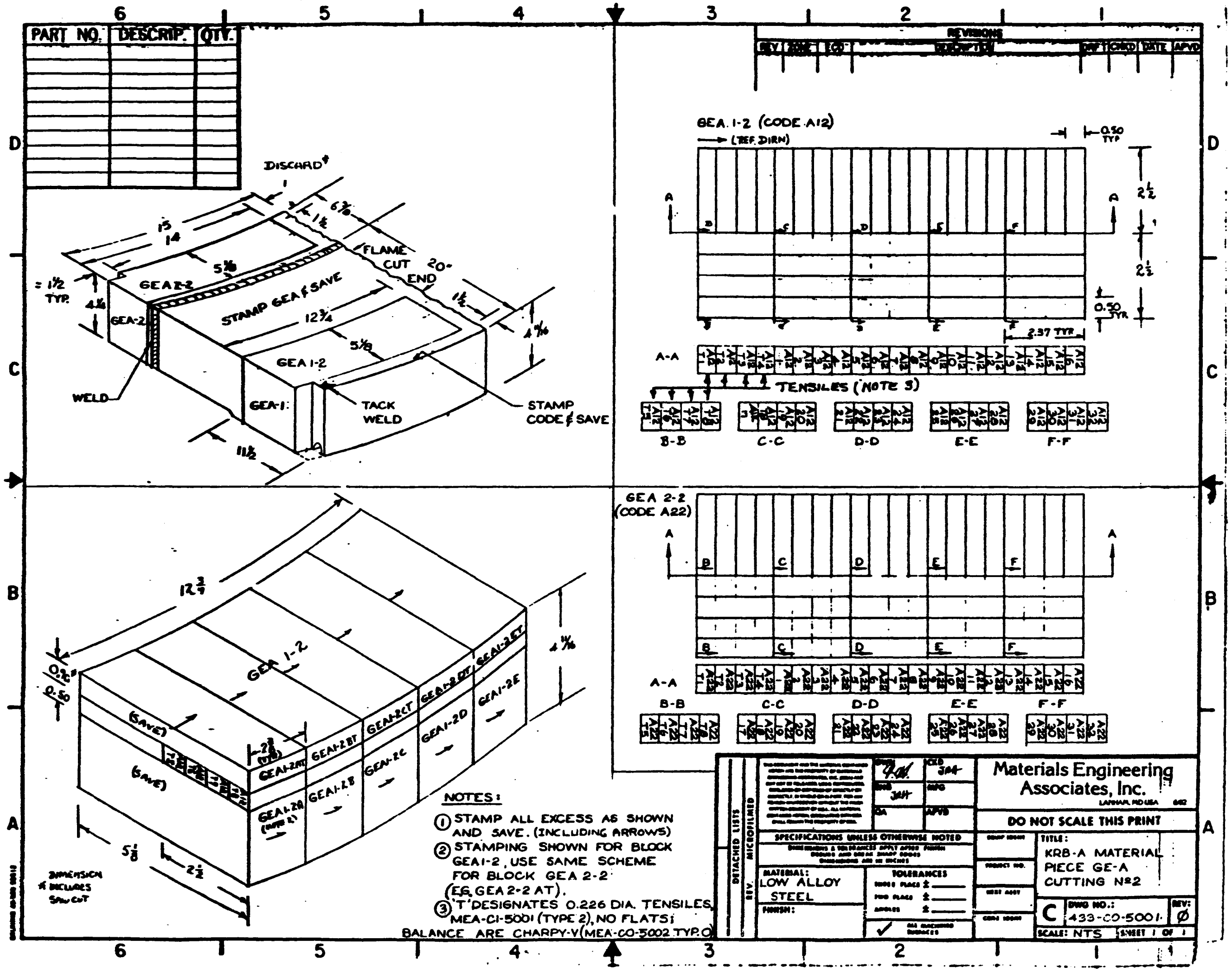
A phased approach to the qualification of the archive materials was chosen. Phase 1 included determination of material chemistry at the one quarter thickness position in each of the base materials, that is, GEA-1, GEA-2, GEB-1 and GEB-2, referenced to their inner (I.D.) surface. In addition, hardness levels and gradients through the thickness from the outer (O.D.) surface to midthickness were to be established. Metallographic examinations were also a part of Phase 1 efforts. Phase 2 involved the cutting, machining and testing of standard C_v and 5.74 mm (0.226 in.) gage diameter tensile specimens from the 1/4T location in each of the materials. The specimens were to be removed in two orientations: axial and circumferential. Figures 1 and 2 are cutting plans developed for the removal of specimen blanks. Phase 3 (future) will develop through-thickness mechanical properties for the one base metal to be chosen, based on Phase 1 and 2 findings, for the main irradiation study.

In addition to the evaluation of material from the rings GEA and GEB, MEA tested three HAZ C_v specimens from the original KRB-A vessel surveillance program primarily to obtain stock for check tests of the chemical composition of the surveillance base metal. The hardness of these specimens was also determined (before impact testing). The specimens, identified as D7M, D6E and D7Y were in the unirradiated, unaged condition and were obtained by Hawthorne (MEA) at the time of his visit to the reactor site. They were removed from top surface, 1/4T and 3/4T thickness positions, respectively, in the 122 mm (4.8 in.) thick weld made for the vessel surveillance program. Exact specimen locations in the weldment and other particulars are documented in Appendix A. In this regard, documentation which exists for the surveillance weld (and for the archive materials) is sparse. This is due, in part, to the vintage of the vessel and to the less stringent requirements generally in force at the time of vessel manufacture.

3. RESULTS

3.1 Chemical Composition Determinations

The chemical compositions of the archive materials are listed in Table 1 along with the composition of forging ring no. 7.1 given in the KRB-A documentation (Ref. 1). MEA findings for the base metal portion of the surveillance specimens D7M, D6E and D7Y are also included in this table. In the case of the archive materials, GEA and GEB, the determinations were made on drillings taken from a 38 x 38 x 13 mm (1.5 x 1.5 x 0.5 in.) thick sample centered approximately on the 1/4T plane of each base metal (Note: The cutting diagrams in Figs. 1 and 2 illustrate the general locations of the 38 x 38 mm x full thickness cutouts from which the stock for



NOTES:

① STAMP ALL EXCESS AS SHOWN AND SAVE. (INCLUDING ARROWS)

② STAMPING SHOWN FOR BLOCK GEA1-2, USE SAME SCHEME FOR BLOCK GEA 2-2 (E.G. GEA 2-2 AT).

③ 'T' DESIGNATES 0.226 DIA. TENSILES, MEA-CI-5001 (TYPE 2), NO FLATS; BALANCE ARE CHARPY-V (MEA-CO-5002 TYP. O)

DETACHED LISTS	MICROFILMED	Materials Engineering Associates, Inc. LANHAM, MD USA	
		DO NOT SCALE THIS PRINT	
SPECIFICATIONS UNLESS OTHERWISE NOTED		TITLE: KRB-A MATERIAL PIECE GE-A CUTTING Nº2	
MATERIAL: LOW ALLOY STEEL	TOLERANCES	C	DWG NO.: 433-CO-5001
FINISH:	✓	SCALE: NTS	SHEET 1 OF 1
		REV: Ø	

Fig. 1 Cutting Plan for removal of Charpy-V (C_V) and tensile (T) specimens from the quarter thickness region of Ring GEA (Base Metals GEA-1 and GEA-2).

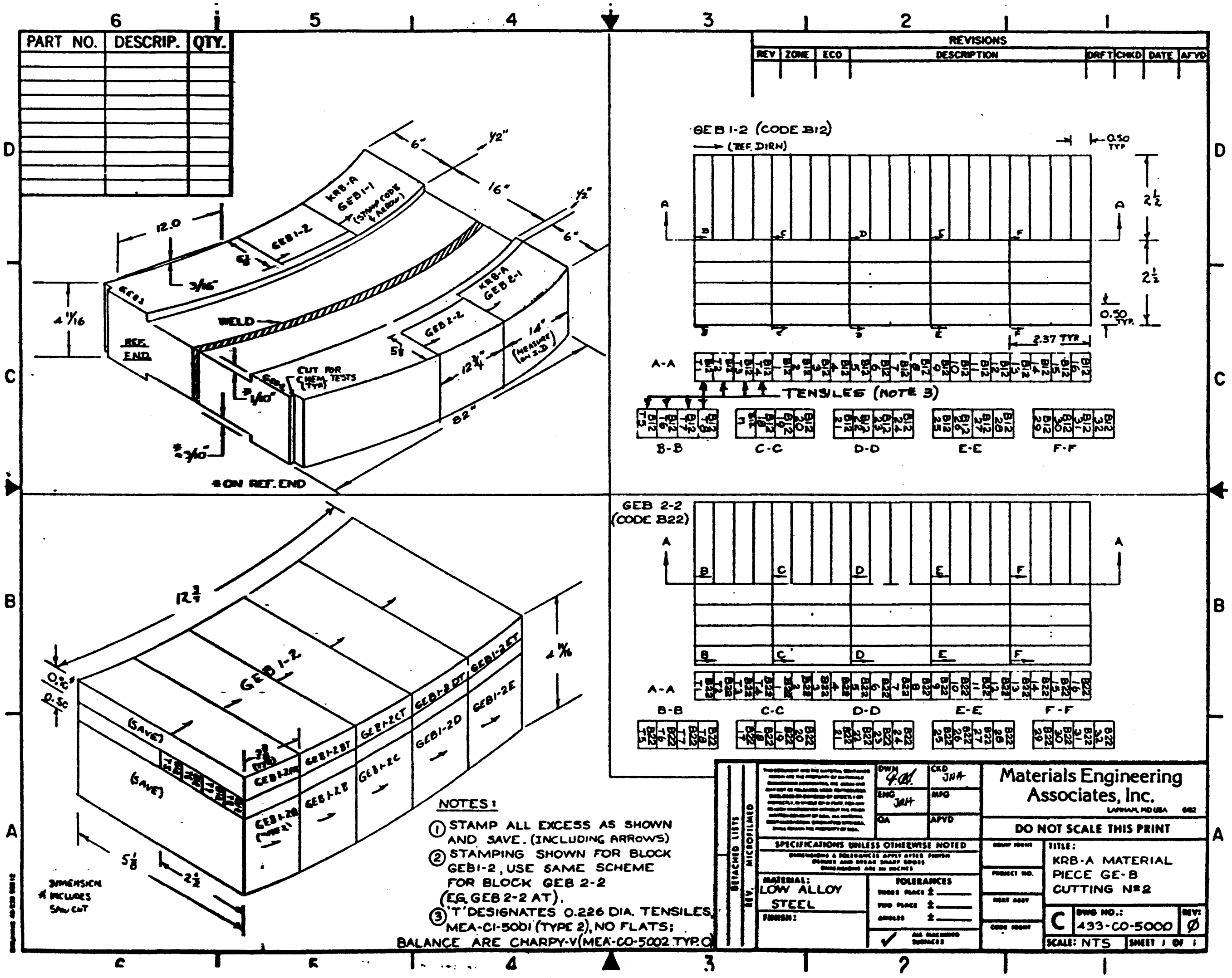


Fig. 2 **Cutting Plan** for removal of Charpy-V (C_V) and tensile (T) specimens **from the** quarter thickness region of Ring GEB (Base Metals GEB-1 and GEB-2).

Table 1 Chemical Compositions of Archival Materials, Codes GEA and GEB

Material	Chemical Compositions (Wt-%)												
	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	As	Sn	Sb	V
GEA-1	0.23	0.70	0.23	0.017	0.013	0.77	0.37	0.66	0.15	0.021	0.021	0.007	0.031
GEA-2	0.24	0.71	0.21	0.014	0.018	0.77	0.36	0.66	0.15	0.023	0.021	0.007	0.030
GEB-1	0.23	0.71	0.21	0.017	0.019	0.78	0.36	0.66	0.16	0.023	0.021	0.007	0.031
GEB-2	0.24	0.71	0.21	0.015	0.018	0.79	0.37	0.67	0.15	0.021	0.021	0.008	0.031
KRB-A Vessel[a] Ring 7.1 Melt 931-137	0.22	0.78	0.24	0.019	0.017	0.82	0.38	0.62	----[b]	-----	-----	-----	-----
D7M[c]	0.23	0.71	0.26	0.022	0.015	0.86	0.38	0.64	0.16	-----	-----	-----	-----
D6E[c]	0.23	0.71	0.25	0.026	0.019	0.84	0.36	0.63	0.15	-----	-----	-----	-----
D7Y[c]	0.24	0.71	0.25	0.022	0.015	0.85	0.37	0.65	0.16	-----	-----	-----	-----

[a] Reference: Schleimar, Untersuchungsbericht U 4152, Dec. 11, 1964.
[b] Not reported
[c] Surveillance Specimens

composition and hardness determinations was obtained.) Composition determinations on the HAZ C_v specimens also utilized drillings.

Composition data for the rings depict a close similarity in chemistry for all four archive materials. It appears reasonable that they were all from the same steel melt. The composition values also match well the reported composition for vessel ring no. 7.1 (Ref. 1). Furthermore, the archive material chemistries are close to the composition determinations for the individual surveillance specimens. In Table 1, the nickel content variation is not considered indicative of two or more materials at this time.

3.2 Hardness Determinations

Tests for material hardness and the hardness gradient in the ring thickness direction were made on the larger of the two pieces left over from the corner cutout after the chemical composition sample was removed (see Fig. 3). Pairs of indents were made at 12.7 mm (1/2 in.) intervals, starting at a location about 6.3 mm (1/4 in.) beneath the O.D. surface. Hardness readings are listed in Table 2. Here, GEB-1 and GEB-2 are observed to have comparable hardness levels and profiles. GEA-1 and GEA-2, on the other hand, have a small hardness difference, especially at test depths no. 3 and 4. No particular significance can be attached to this difference at this time.

3.3 Microstructure Examinations

Microstructures of GEA-1, GEA-2, GEB-1 and GEB-2 are shown in Figs. 4, 5, 6 and 7 respectively. Through-thickness determinations were made for GEA-1 and GEB-1; only the 3/4T position was examined for GEA-2 and GEB-2. In general, the structures illustrated are tempered upper bainite or tempered upper bainite in combination with free ferrite. For both the GEA-1 and GEB-1 materials, a through-thickness gradient is apparent in terms of the amount of free ferrite present. While absent at the 3/4T and surface locations, a significant amount of ferrite is present at midthickness. Also note that GEA-1 shows a greater proportion of this consitiuent than GEB-1 which infers a slight difference in their primary heat treatment history (or original section size). On the other hand, the structures of the GEA-1 and GEB-1 are quite similar at the 3/4T (and presumably, the 1/4T) location. In contrast, the structure of GEA-2 shows a greater proportion of ferrite, compared to GEA-1 at the 3/4T location. This could be due to local banding and is being investigated further.

The microstructures of the base metal portions of the three HAZ C_v surveillance specimens are currently being established and will be compared to those of the archive materials. As noted above, the specimen represent top surface, 1/4T or 3/4T thickness positions in the weldment made for the vessel surveillance program.

3.4 Strength Determinations

Tensile strength determinations (1/4T location) are summarized in Table 3. In general, a major difference between axial and

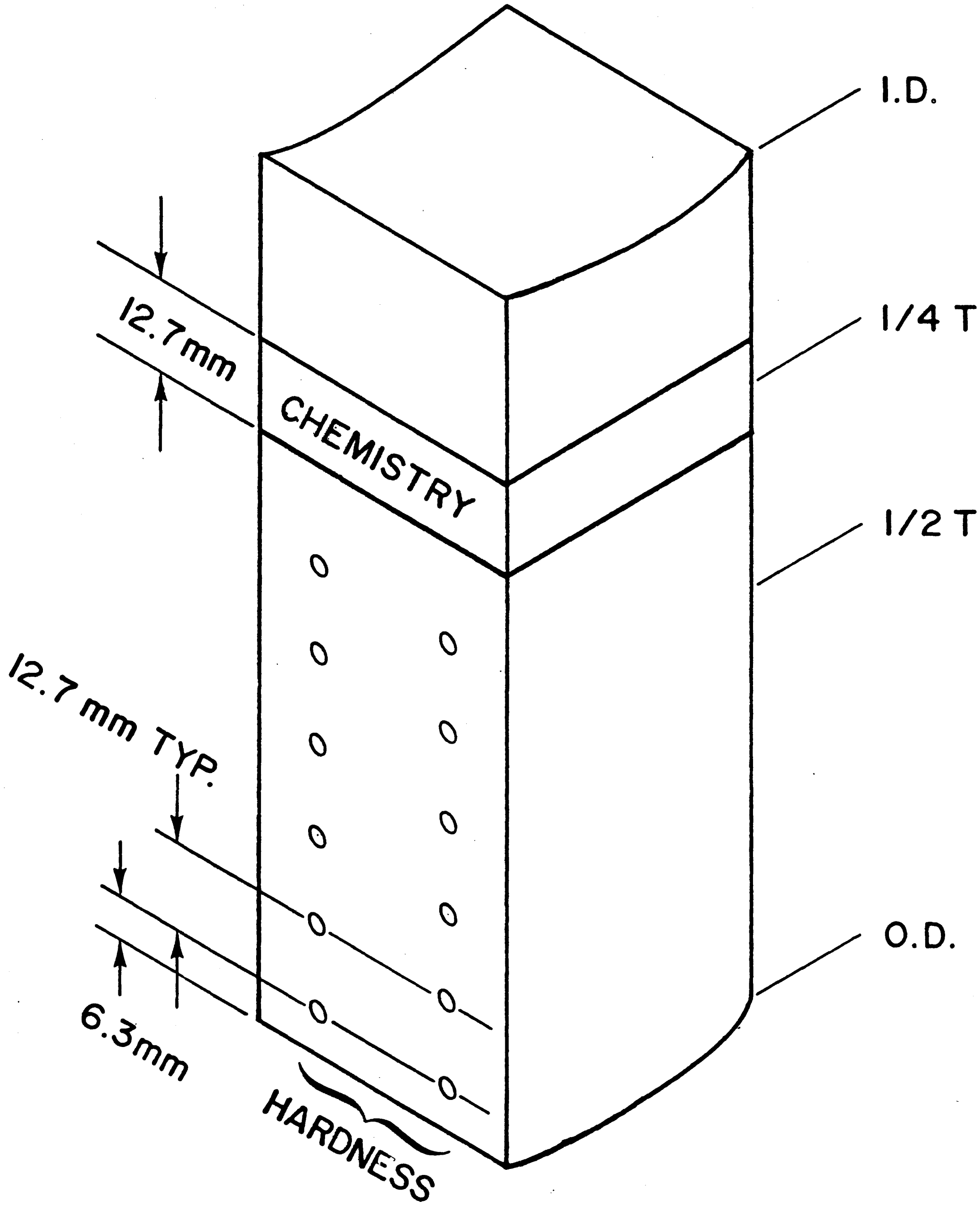


Fig. 3 Schematic illustration showing locations of chemical composition and hardness test samples in base metal thickness.

Table 2 In-Depth Hardness of KRB-A Archival Materials

Test Position	Hardness (Rockwell-B)							
	GEA-1		GEA-2		GEB-1		GEB-2	
1*	94.9	----	93.2	92.8	93.5	93.7	91.9	91.6
2	94.9	94.1	92.4	93.3	93.0	93.2	92.1	92.1
3	94.8	94.8	90.5	90.3	92.0	91.7	91.4	91.9
4	92.0	90.7	89.9	88.7	91.2	91.9	91.6	92.1
5	89.8	89.1	89.3	89.3	90.6	91.6	89.3	89.9
6	90.4	91.0	90.5	90.6	91.8	90.5	90.8	90.9

* 1/4-in. below O.D. surface

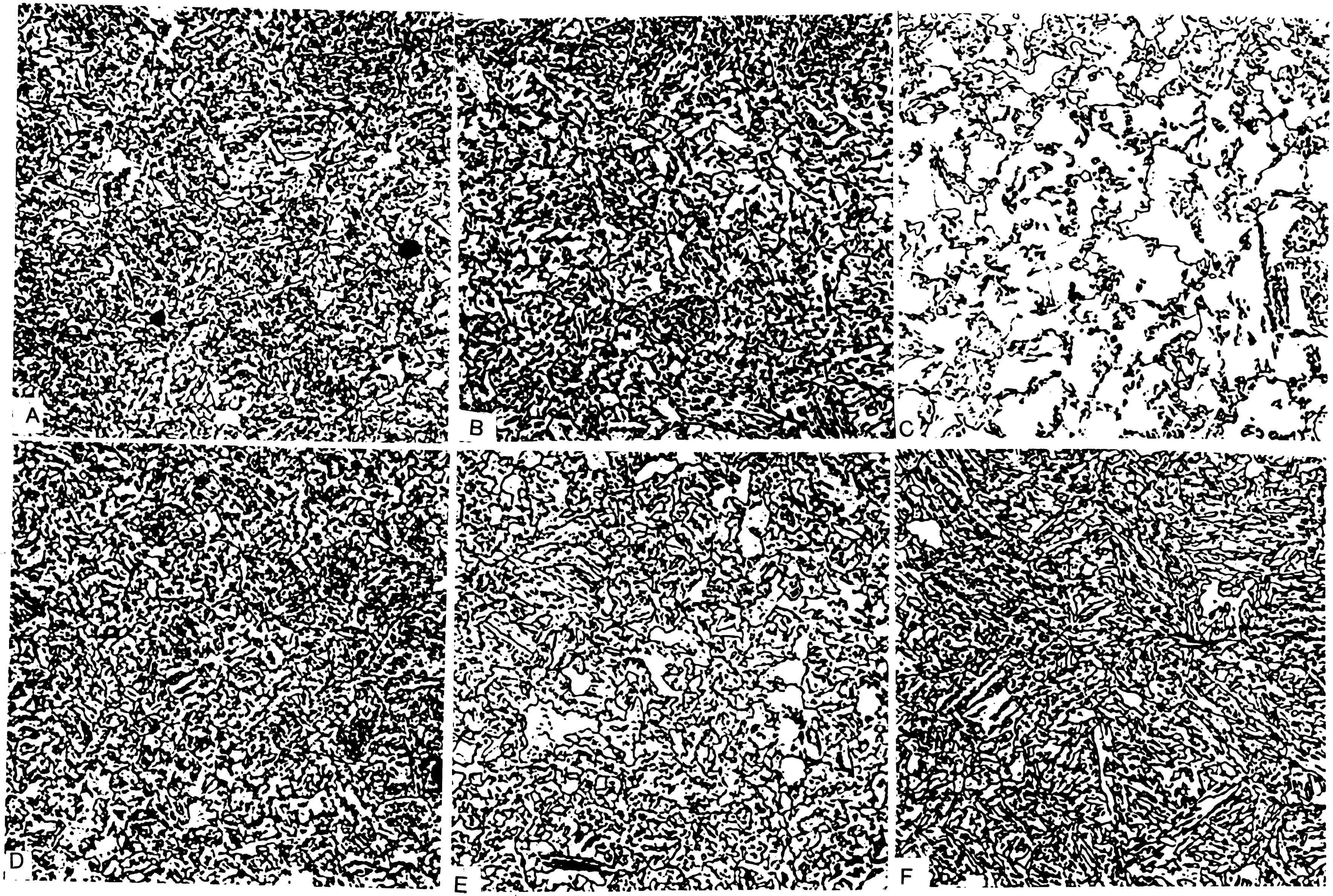


Fig. 4 Microstructures of Base Metals GEA-1 through its thickness:
A. I.D. Surface B. 1/8T Location C. 1/2T Location
D. 3/4T Location E. 7/8T Location F. O.D. Surface

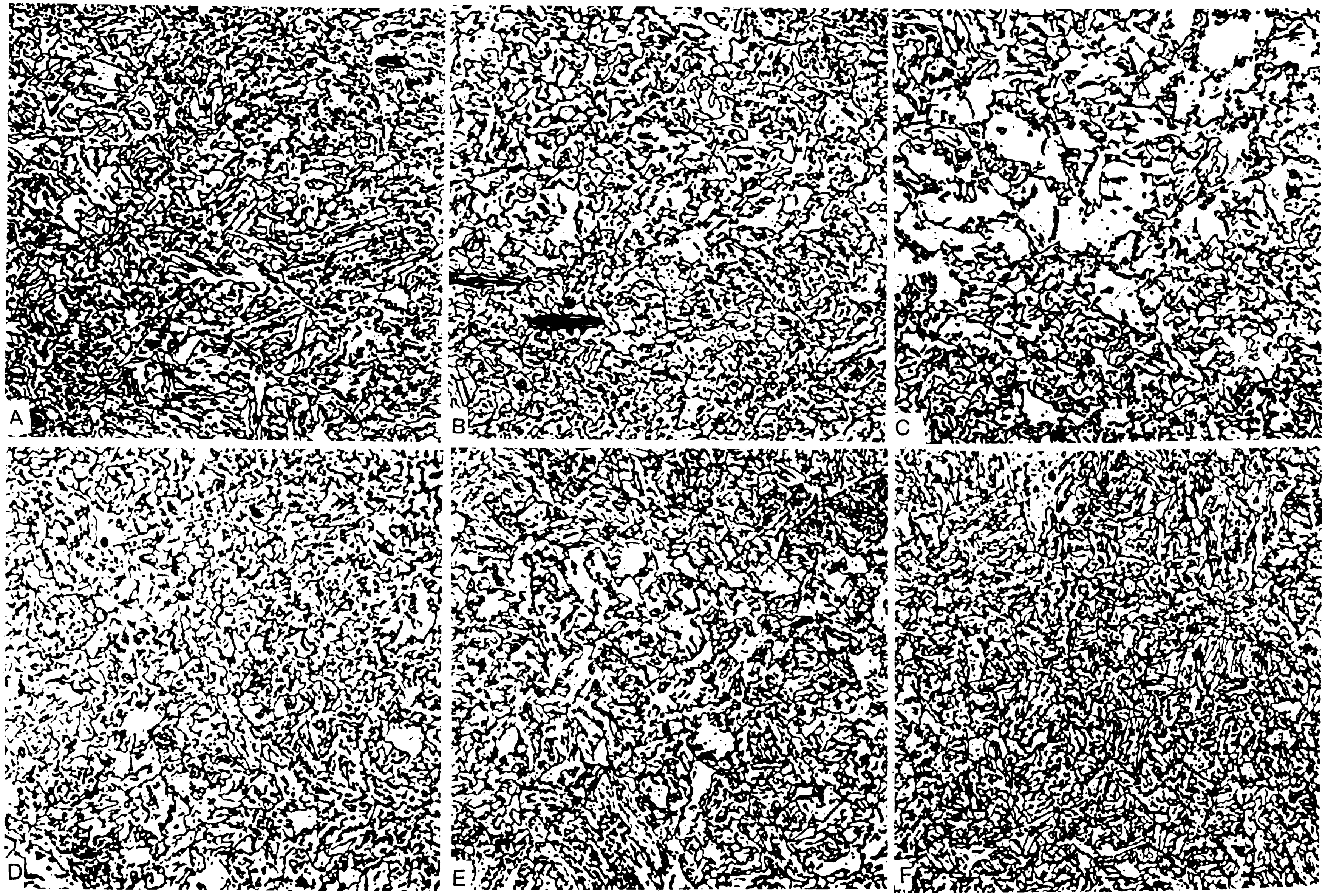


Fig. 6 Microstructures of Base Metal GEB-1 through its thickness:
A. I.D. Surface B. 1/8T Location C. 1/2T Location
D. 3/4T Location E. 7/8T Location F. O.D. Surface

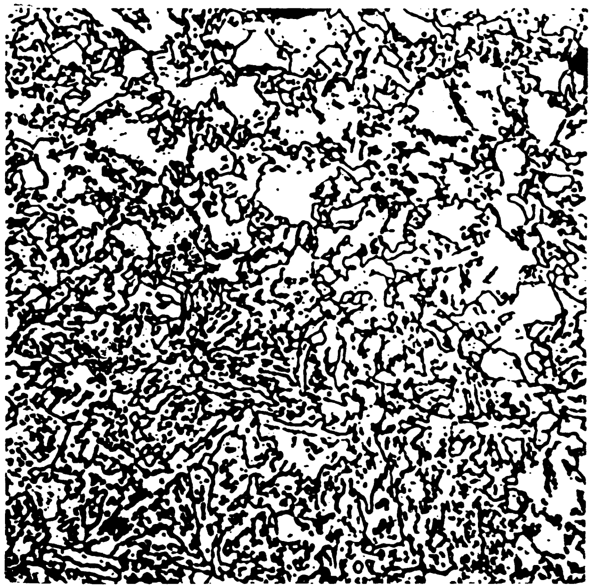


Fig. 7 Microstructure of Base Metal GEB-2 at 3/4T thickness location.

Table 3 Ambient Temperature Tensile Properties of Archive Materials

Material Code	Orientation	Specimen Number	Yield Strength[a]		Tensile Strength		Elongation in 12.7 mm	Reduction of Area
			(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
GEA-1	Axial	T1	507	73.5	652	94.5	36.2	61.6
		T4	514	74.5	658	95.4	37.2	61.1
	CMFL[b]	T5	507	73.6	648	94.0	40.0	66.8
		T8	512	74.2	651	94.4	38.6	66.8
GEA-2	Axial	T1	503	72.9	645	93.6	38.6	61.6
		T4	492	71.3	651	94.4	30.8	57.6
	CMFL	T5	500	72.5	643	93.2	----	----
		T8	487	70.6	643	93.2	34.8	62.6
GEB-1	Axial	T1	461	66.8	620	89.9	41.4	64.8
		T4	460	66.7	623	90.4	32.0	52.3
	CMFL	T5	478	69.3	625	90.6	44.2	68.3
		T8	475	68.9	621	90.1	43.0	69.3
GEB-2	Axial	T1	467	67.8	618	89.6	42.6	65.3
		T4	471	68.3	621	90.0	38.4	66.8
	CMFL	T5	464	67.3	617	89.5	42.8	69.1
		T8	467	67.7	620	89.9	43.0	69.3

[a] 0.2% Offset (5.74-mm gage diameter specimens)

[b] CMFL = Circumferential

circumferential (CMFL) test orientations was not observed for any of the four archive materials. Also, good agreement between properties of GEA-1 vs. GEA-2 and between properties of GEB-1 and GEB-2 is found. A significant difference in yield and tensile strengths, however, is noted on comparing GEA-1 and GEA-2 vs. GEB-1 and GEB-2. The reason for the lack of agreement is not known, although it could be related to some difference in postweld heat treatment condition, e.g., stress relief annealed vs. non-stress relief annealed, or a difference in locations of GEA and GEB in the original (full) ring forging, or a dissimilarity in specimen thickness positions in the forging. In regard to the last possibility, it is noted that the rings show evidence of rough machining, presumably from steps taken to make the rings "round" after fabrication. The depths of machining cuts on the O.D. and I.D. surfaces differ between GEA and GEB as pointed out in Figs. 1 and 2.

3.5 Notch Ductility Determinations

Charpy V-notch ductility test results obtained to date (1/4T location) are listed in Table 4 and are illustrated in Figs. 8 and 9. Unlike the tensile test findings, a large difference in notch ductility is observed between axial and circumferential orientations. Determinations at 93°C (200°F) for the axial orientation depict an upper shelf energy level approximately 30 percent lower than that of the circumferential direction. Compared to GEA, GEB materials have a somewhat higher upper shelf level consistent with their lower yield strength. The difference is more apparent in the axial orientation data.

In Figs. 8 and 9 the data developed for GEA and GEB are also compared to results developed in the mid-1960's for the vessel material (Ring 7.1, strong orientation) (Ref. 2,3). Overall, the results agree well with the earlier results. Table 5 lists the data developed by MEA for the three HAZ surveillance specimens. Figure 10 shows the results in relation to the data reported for the surveillance program. Again, a good correspondence is found.

4. SUMMARY

Two archive, forged rings carrying the stamp "KRB VESSEL" and containing a circumferential weld were acquired from GE-Vallecitos for the USA (NRC/MEA) - FRG (MPA) cooperative study of long-term, in service irradiation effects. The rings were given the identification codes GEA and GEB. MEA has developed chemical composition, hardness, strength and notch ductility properties for each of the base metals. The results show good agreement with existing documentation for forging ring no. 7.1 of the KRB-A vessel.

MEA also tested three Charpy V-notch HAZ surveillance specimens for notch ductility, hardness and composition. Results for these specimens agree well with prior data for the vessel surveillance program's HAZ material. In addition, the hardness and composition of the surveillance specimens (base metal portion) agree with MEA findings for the archive materials GEA and GEB.

Table 4 Charpy-V Notch Ductility of Archive Materials

Material Code	Orientation	Specimen Number	Temperature		Energy		Expansion	
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)
GEA-1	Axial	16	-40	-40	15	11	0.254	10
(Code A12)		7	-18	0	34	25	0.584	23
		5	-1	30	41	30	0.711	28
		3	24	75	53	39	0.940	37
		9	49	120	92	68	1.397	55
		1	93	200	96	71	1.626	64
	CMFL[a]	32	-40	-40	24	18	0.406	16
		21	-18	0	29	21	0.432	17
		20	-1	30	61	45	0.914	36
		19	24	75	92	68	1.346	53
		22	49	120	123	91	1.676	66
		18	93	200	134	103	1.803	71

[a] CMFL - Circumferential Orientation

Table 4 (Continued) Charpy-V Notch Ductility of Archive Materials

Material Code	Orientation	Specimen Number	Temperature		Energy		Expansion	
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)
GEA-2	Axial	16	-40	-40	18	13	0.229	9
(Code A22)		7	-18	0	24	18	0.432	17
		5	-1	30	34	25	0.610	24
		3	24	75	61	45	1.803	71
		9	49	120	84	62	1.321	52
		1	93	200	88	65	1.346	53
	CMFL[a]	32	-40	-40	11	8	0.178	7
		21	-18	0	39	29	0.610	24
		20	-1	30	52	38	0.940	37
		19	24	75	103	76	1.448	57
		22	49	120	119	88	1.778	70
		18	93	200	136	100	1.956	77

[a] CMFL - Circumferential Orientation

Table 4 (Continued) Charpy-V Notch Ductility of Archive Materials

Material Code	Orientation	Specimen Number	Temperature		Energy		Expansion	
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)
GEB-1	Axial	16	-40	-40	23	17	0.381	15
(Code B12)		7	-18	0	37	27	0.660	26
		5	-1	30	56	41	0.965	38
		3	24	75	76	56	1.245	49
		9	49	120	110	81	1.727	68
		1	93	200	108	80	1.651	65
	CMFL[a]	32	-40	-40	42	31	0.559	22
		21	-18	0	61	45	0.889	35
		20	-1	30	65	48	1.041	41
		19	24	75	107	79	1.626	64
		22	49	120	144	106	1.981	78
		18	93	200	141	104	2.210	87

[a] CMFL - Circumferential Orientation

Table 4 (Continued) Charpy-V Notch Ductility of Archive Materials

Material Code	Orientation	Specimen Number	Temperature		Energy		Expansion	
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)
GEB-2	Axial	16	-40	-40	24	18	0.457	18
(Code B22)		7	-18	0	35	26	0.660	26
		5	-1	30	54	40	0.868	34
		3	24	75	80	59	1.245	49
		9	49	120	102	75	1.753	61
		1	93	200	106	78	1.854	73
	CMFL[a]	32	-40	-40	35	26	0.533	21
		21	-18	0	50	37	0.868	34
		20	-1	30	71	52	1.092	43
		19	24	75	110	81	1.549	61
		22	49	120	146	108	1.829	72
		18	93	200	149	110	1.778	70

[a] CMFL - Circumferential Orientation

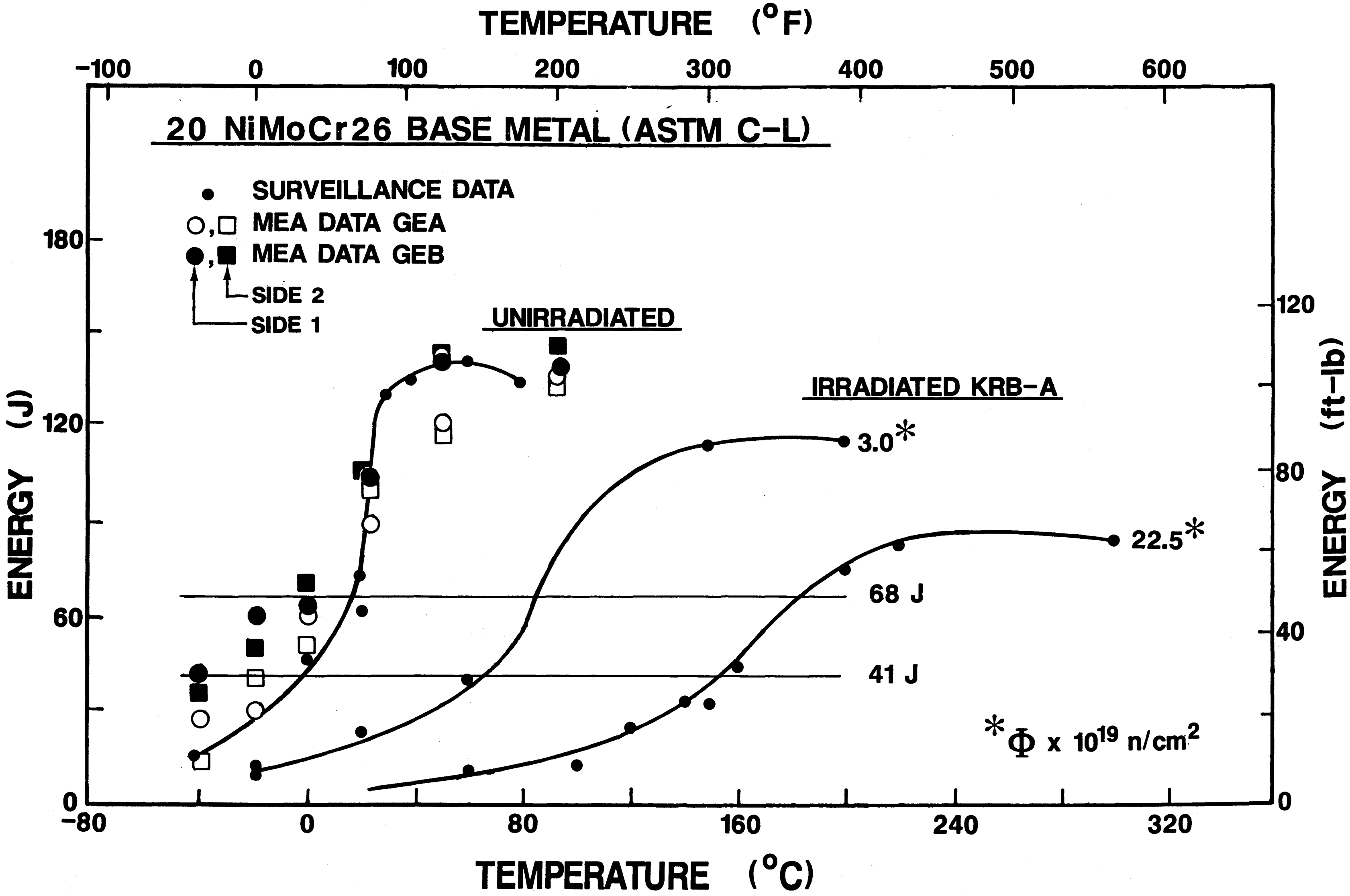


Fig. 8 Data developed for archive base metals (circumferential orientation) compared against surveillance program data for the same orientation. Surveillance data for two irradiated conditions are also shown.

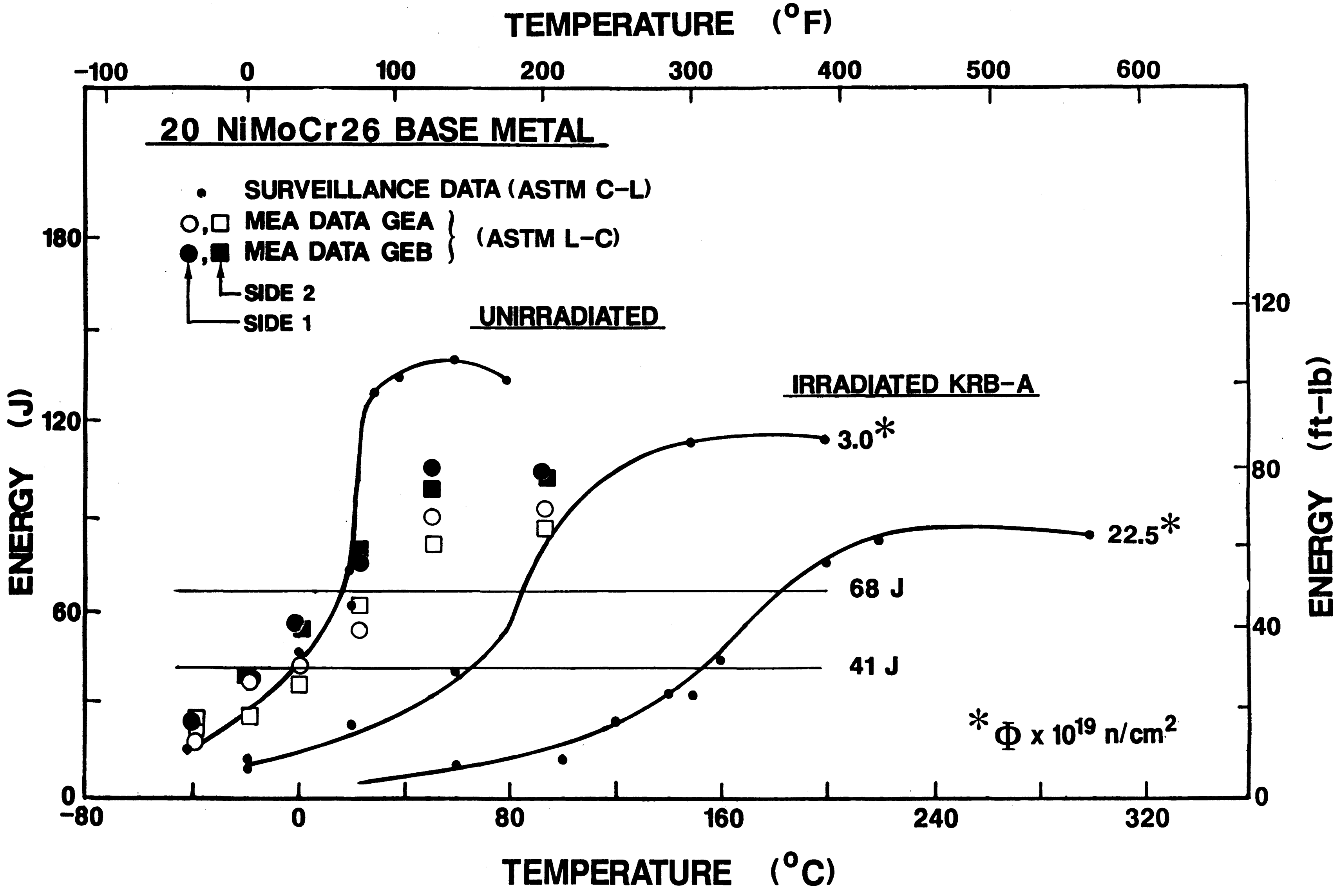


Fig. 9 Data developed for archive base metals (axial orientation) compared against surveillance program data for the circumferential orientation. Surveillance data for two irradiated conditions are also shown.

Table 5 Charpy-V Notch Ductility and Hardness of Surveillance Program Material (Melt 931 131)

Specimen Number	Orientation[a]	Thickness Location	Temperature		Energy		Expansion		Shear	Base Metal Hardness
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	(%)	(Rockwell B)
D7M	TL	Top Surface	-20	-5	30	22	0.203	8	25	92.2, 93.7
D6E	TL	1/4 T	90	195	87	64	0.813	32	100	91.6, 92.1
D7Y	TL	3/4 T	10	50	42	31	0.457	18	44	92.6, 92.7

[a] Transverse to rolling direction

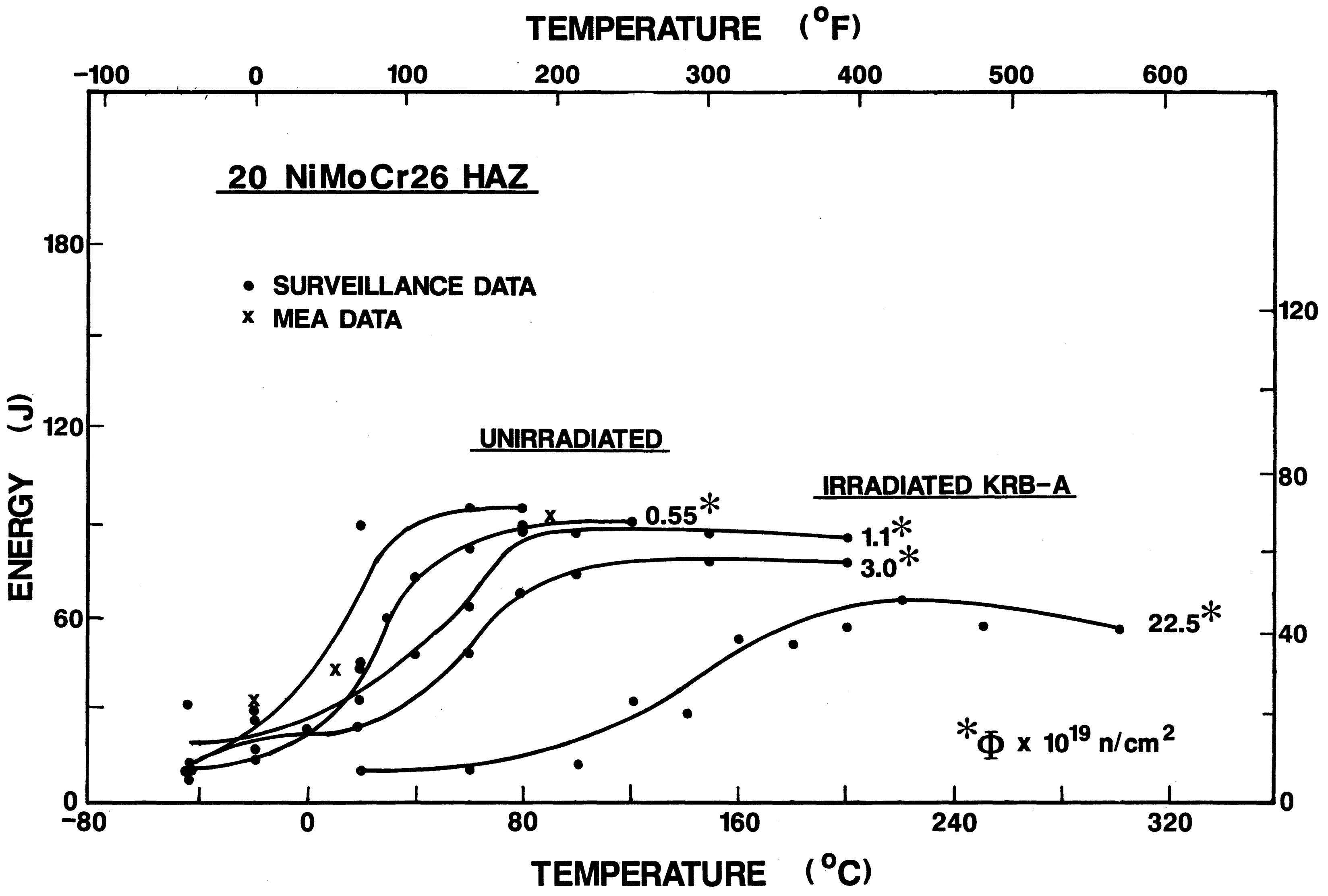


Fig. 10 Comparison of MEA data and prior data for surveillance base metal.

Differences in base metal yield strength and tensile strength were found on comparing GEA vs. GEB. Likewise, differences in C_v notch ductility between the base metals of GEA vs. GEB were noted. In particular, upper shelf energy levels for the axial test orientation were not the same. Potential sources of the noted material variability are suggested; however, the materials do appear to come from the same steel melt as that used for ring no. 7.1 of the reactor vessel. The two base metals within each ring have comparable properties. Thus, the selection of the base metal for the balance of the program reduces to two choices: that forming ring GEA or that forming ring GEB. Since the base metal remaining from GEA is a very small quantity, ring GEB should be the choice for the continuing program if at all possible.

REFERENCES

1. Schleimar, Untersuchungsbericht U4152, Dec. 11, 1964.
2. "Stellungnahme Zur Akkumultierten Neutronendosis an der Reaktordruck behalter wand des Kernkraftwerkes Gundremmingen (KRB-1)," KGB-TUV, Bayern Munchen 07-09, 1977.
3. Von N. Eickelpasch und R. Seepolt, "Experimentelle Ermittlung der Neutronendosis des KRB-Druckgefabes und deren betriebliche Bedeutung," Atomkernenergie (ATKE) Bd. 29 (1977) Lfg. 2, p. 149.

APPENDIX A

Plan for the Preparation of Test Samples

GENERAL ELECTRIC
ATOMIC POWER EQUIPMENT DEPARTMENT
SAN JOSE, CALIFORNIA
APPROVED - With regard to general design and controlling dimensions, except as noted. This does not constitute [illegible] functional or performance requirements established [illegible] the purchase contract.
APPROVED BY J. R. Kobsa
DATE Aug. 28 1964
DESIGN ENGINEERING
ENGINEERING SECTION

[illegible]
[illegible]

4 JUL 1964
RECD.
H. M. CONNELLY

1964

Henrichshütte, 8.7.1964
Schl./OL.-

FINAL

[illegible] PROJECT

GENERAL ELECTRIC
ATOMIC POWER EQUIPMENT DEPARTMENT
SAN JOSE, CALIFORNIA
Vendor Print File Number 914-74
Sheet Number ______ of 7
Purchase Order Number 00101
Equipment Piece Number [illegible]
DESIGN ENGINEERING
ENGINEERING SECTION

Notice

Subject: General Electric, 7.68.40359
Reactor Vessel Test Ring

Speakers: Mr. Kobsa
Mr. Kreckel
Mr. Schleimer

Plan for the Preparation of Test Samples

The test specimens requires by Paragraph 10.2 and Attachment C of APED Specification 21A1101 shall be prepared from the test ring fabricated from heat no. 931 131, ~~the same heat from which piece [illegible] of the reactor vessel was made~~. The results of tests performed on this ring after 5 3/4 hours of stress relief at 600°C minimum are presented in the test ring material report previously submitted.

The test ring shall be devided into coupons per Drawing 3 AT-40359-18/1 [illegible] and 3. These coupons shall be heat treated to simulate stress relief of the reactor vessel parts as follows:

The coupons per Drawing 3 AT-40359-18/3 shall be held at 600 to 630°C for an additional 15 hours, bringing the total time at stress relief temperature to 20 3/4 hours. Heating and cooling rates shall be the same as for the vessel pieces. The specimens for tests per Paragraph 10.2 of Specification 21A1101 shall be taken from this coupon.

The coupon per Drawing 3 AT-40359-18/1 shall be heat tested the same as above. The specimens for the fabrication tests required by Attachment C to Specification 21A1101 shall be made from this coupon.

The coupon per Drawing 3 AT-40359-18/2 shall be held at 600 to 630°C for an additional 4 1/4 hours, bringing the total time at temperature to 10 hours. Heating and cooling rates shall be the same as for the reactor vessel parts. The specimens for the surveillance test program per Attachment C of Specification 21A1101 shall be made from these coupons.

The preparation of samples and their marking shall be in accordance with the above drawings and the attached sketches, except that marking shall be only on one end.
The weld heat affected zone specimens shall be etched to determine the location of the fusion line. One fusion line shall be located within 1/8 inch (3 mm) from the center of the tensile specimens. The bottom of the notch of the Charpy V impact specimens shall be in the base metal within 1/8 inch (3 mm) from the fusion line

OE 7 x
H. Otto

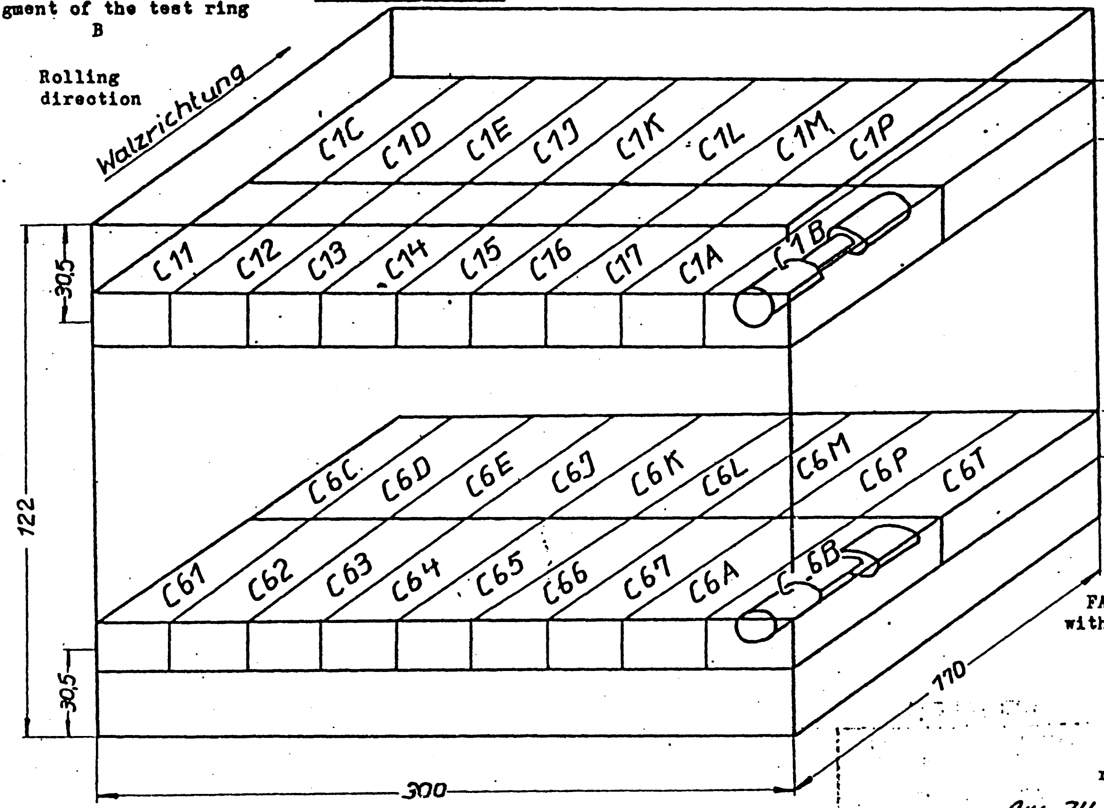
Kobsa

Schleimer

Surveillance Test, according to Attachment C, point 3.5, tensile test specimen 1/4" of the base metal, see also drawing 3AT-40359-18/2, tensile tests to point IV 2.

Segment of the test ring
B

1 Rolling direction



innen

interior

Specimens with TÜV stamp

Keep the rest of the material

außen

exterior

to be made 35 specimens acc. to spec., att. C, point 3.5. Marking acc. to FAB-Code in connection with letter of GE of 20-4-64

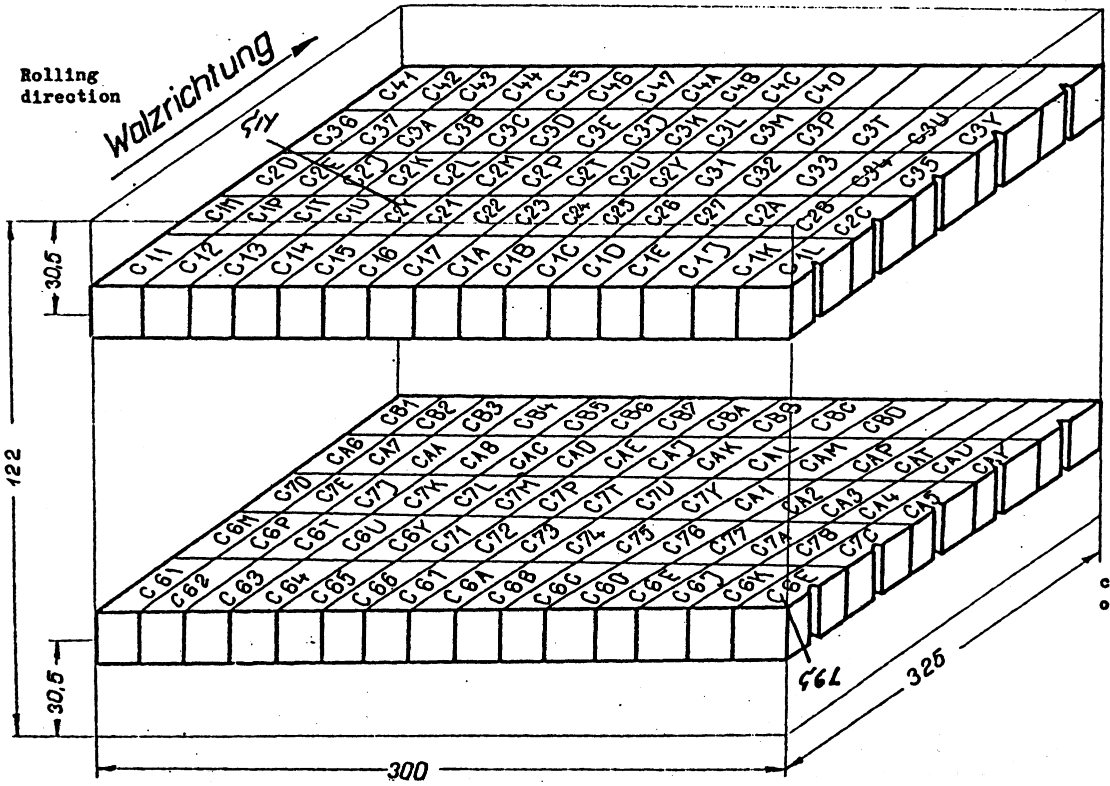
13.2.64
rev. 6.5.64

914-74
1 6
00 101

Segment of the test ring B

Surveillance Test, according to Attachment C, point 3.4, notch-impact specimens of the base metal, see also drawing 3AT-40359-18/2, notch-impact tests to point II/1.

2



Rolling direction

<u>Specimens with</u>

<u>TÜV stamp</u>

interior

Keep the rest of
the material

exterior

to be made 142 specimens acc. to spec., att. C, point 3.4. Marking acc. to FAB-Code in connection with letter of CE of 2o-4-64.

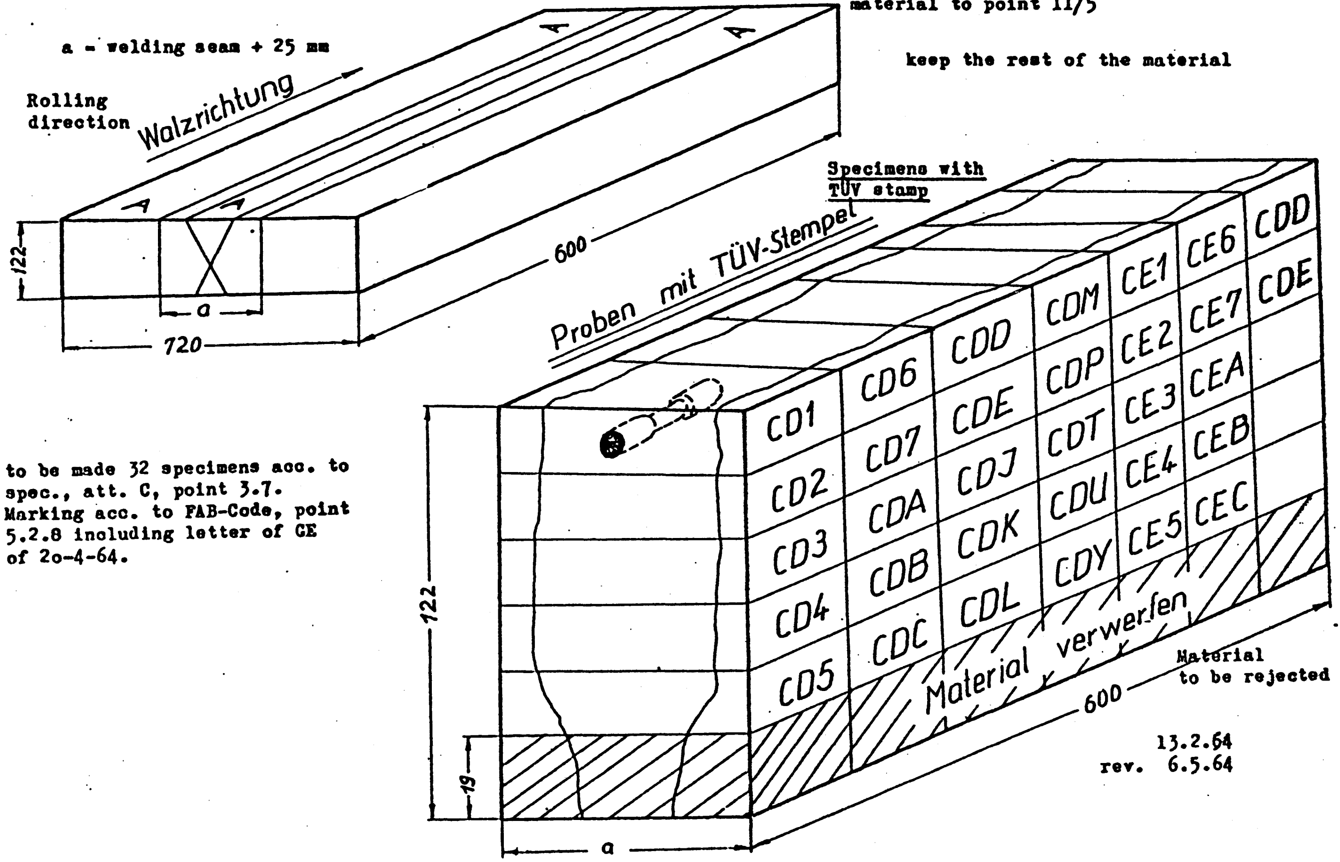
13.2.64
rev. 6.5.64

Segment of the test ring
B

Surveillance Test, according to Attachment C, point 3.7, tensile test specimens in the center of the welding material, see also drawing 3AT-4o359-18/2, welding material to point II/5

3 a - welding seam + 25 mm

keep the rest of the material



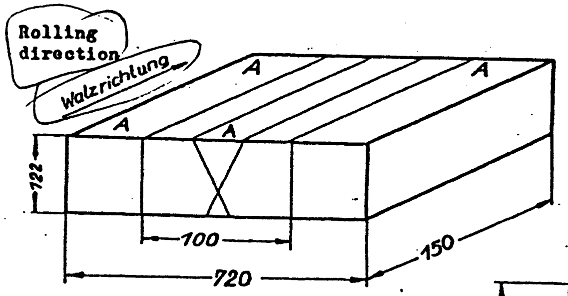
to be made 32 specimens acc. to spec., att. C, point 3.7. Marking acc. to FAB-Code, point 5.2.8 including letter of CE of 2o-4-64.

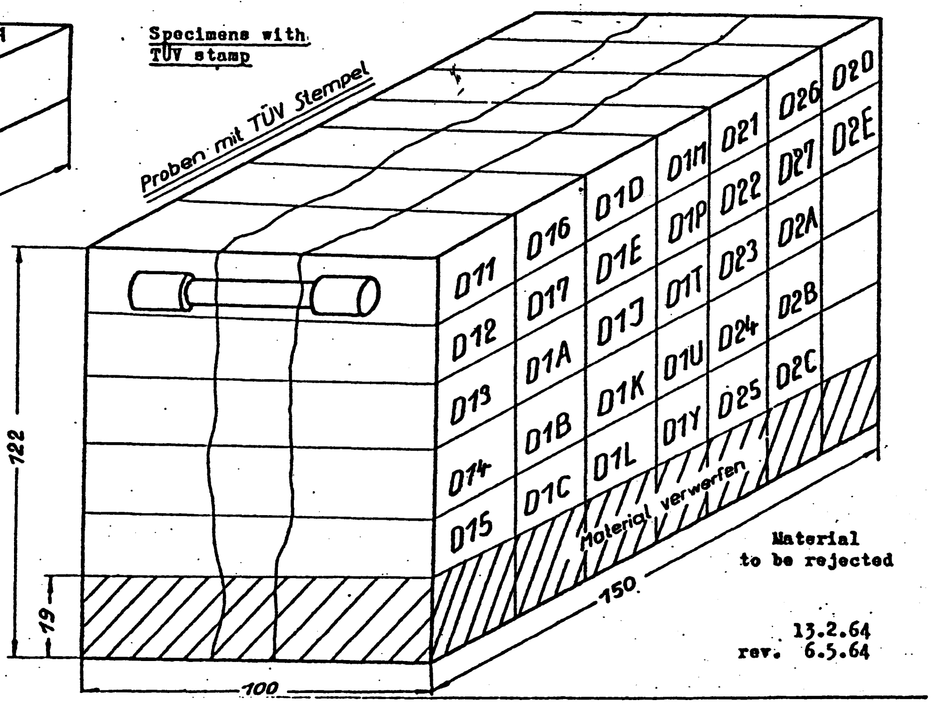
Segment of the test ring
B

4

Surveillance Test, according to Attachment C, point 3.8, tensile test specimens cross to the welding seam, see also drawing 3AT-40359-18/2, point II/6.

keep the rest of the material





Specimens with TÜV stamp

Material to be rejected

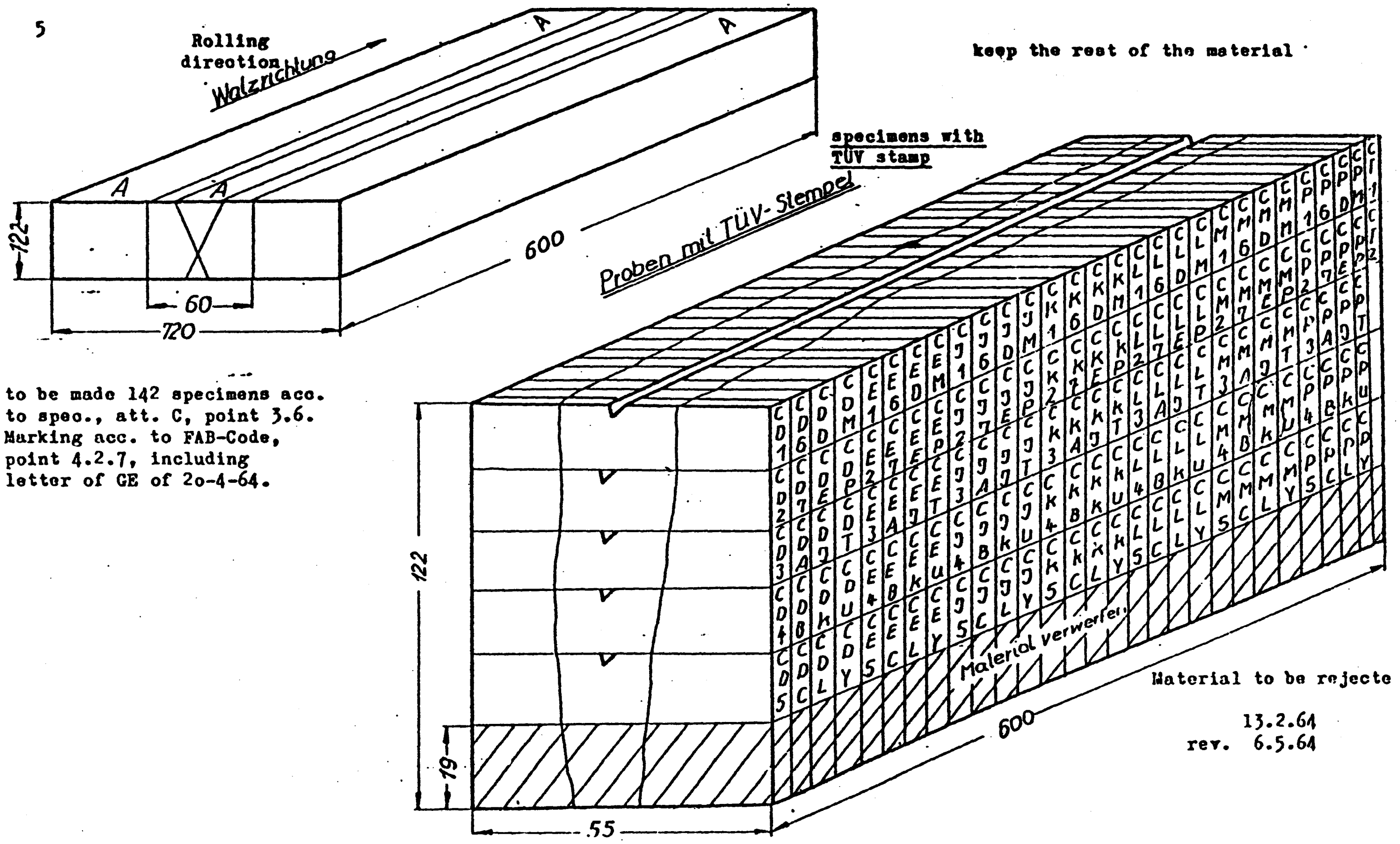
to be made 32 specimens acc. to spec., att. C, point 3.8.
Marking acc. to FAB-Code, point 6.2.6, including letter of GE of 20-4-64.

13.2.64
rev. 6.5.64

Segment of the test ring
B

Surveillance Test, according to Attachment C, point 3.6, notch-impact specimens in the center of the welding material, see also drawing 3AT-4o359-18/2, welding material to point II/5.

keep the rest of the material



to be made 142 specimens acc. to spec., att. C, point 3.6. Marking acc. to FAB-Code, point 4.2.7, including letter of GE of 2o-4-64.

Material to be rejecte

13.2.64
rev. 6.5.64

Segment of the test ring
B

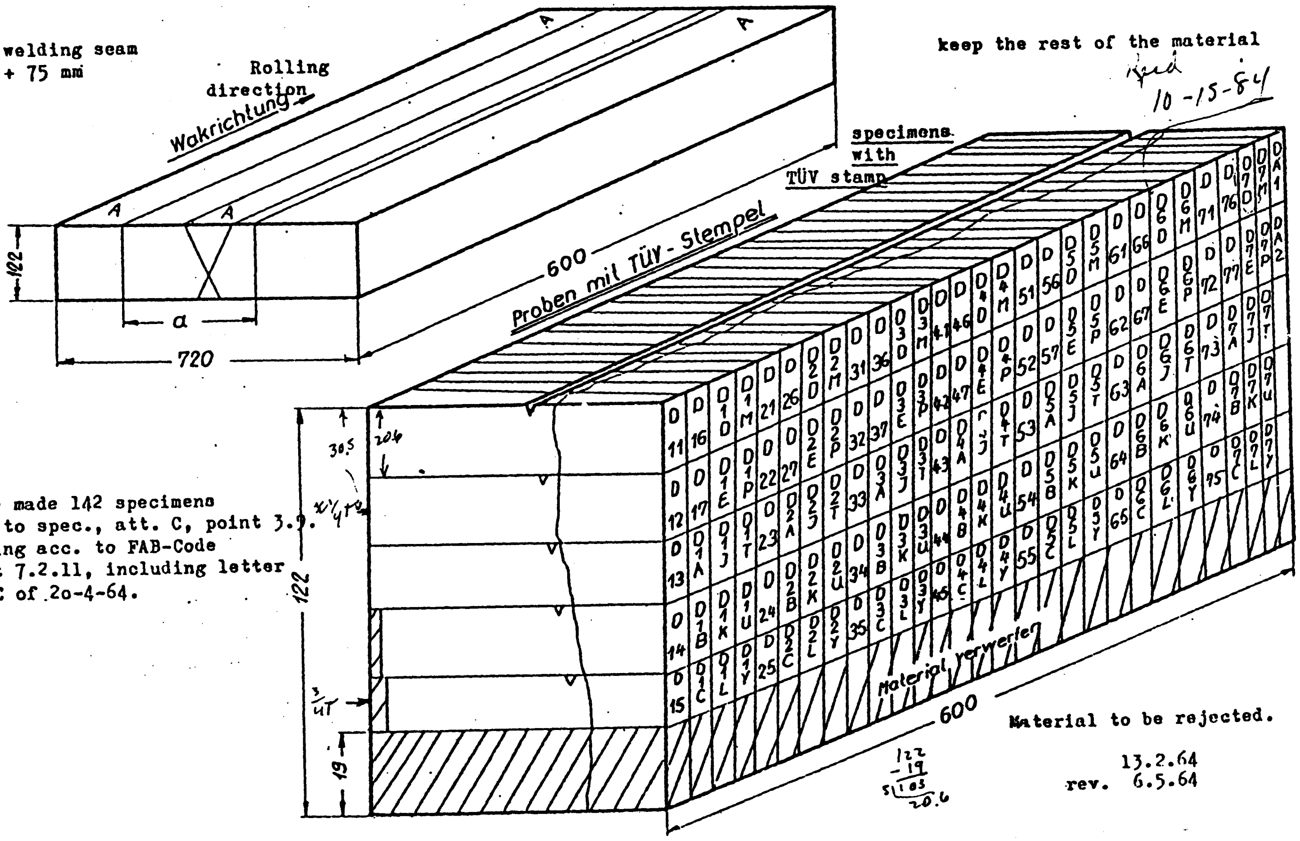
Surveillance Test, according to Attachment C, point 3.9, notch-impact specimens in the transition, see also drawing 3AT-40359-18/2, transition to point II/4.

6

a = welding seam
+ 75 mm

keep the rest of the material

Rcd
10-15-84



to be made 142 specimens
acc. to spec., att. C, point 3.9.
Marking acc. to FAB-Code
point 7.2.11, including letter
of CE of 20-4-64.

Material to be rejected.

122
-19
5|103
20.6

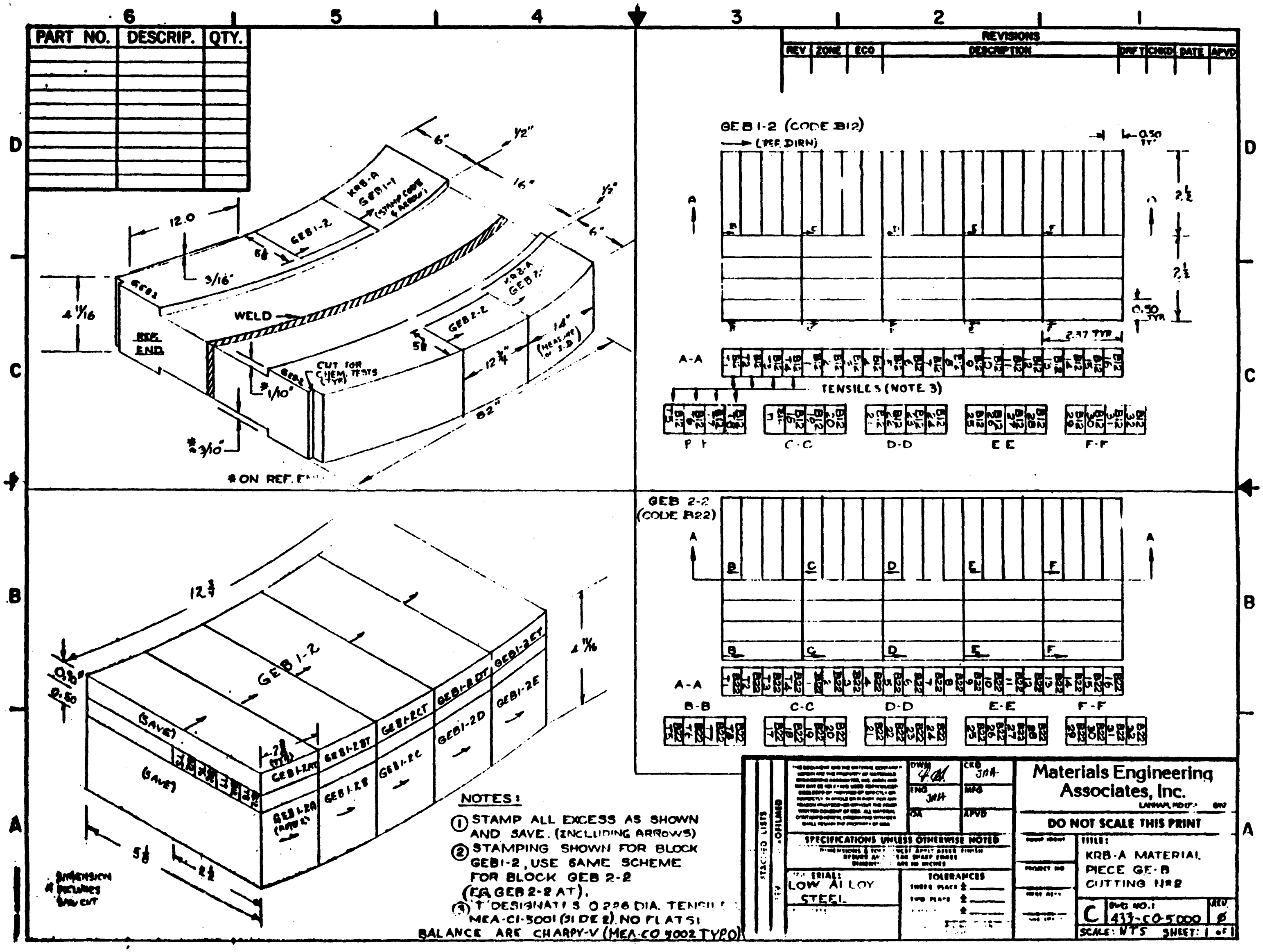
13.2.64
rev. 6.5.64

APPENDIX B

Cutting Plans for KRB-A Archive Ring Forging Materials, Code GEB-A and Code GEB-2

Table B-1 Cutting Diagrams Provided in Appendix B

Drawing No.	Title
433-CO-5000 Rev. 0	KRB-A Matl. Piece GEB Cutting No. 2
433-CO-5001 Rev. 1	KRB-A Matl. Piece GEA Cutting No. 2
433-CO-5002 Rev. 2	KRB-A Matl. Piece GEB (Side 2) Cutting No. 3
433-CO-5003 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 3
433-CO-5004 Rev. 1	KRB-A Matl. Piece GEB (Side 2) Cutting No. 4
433-CO-5005 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 5
433-CO-5006 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 6
433-CO-5008 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 7, Piece A
433-CO-5009 Rev. 0	K Matl. Piece GEB (Side 2) Cutting No. 7, Piece B
433-CO-5010 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 7, Piece C
433-CO-5011 Rev. 0	KRB-A Matl. Piece GEB (Side 2) Cutting No. 7, Piece D
433-CO-5012 Rev. 2	KRB-A Matl. Piece GEB (Side 2) Cutting No. 8
433-CO-5014 Rev. 1	KRB-A Matl. Piece, GEB (Side 2), Mods. to Cutting No. 7 and 8.



NOTES:

① STAMP ALL EXCESS AS SHOWN AND SAVE. (INCLUDING ARROWS)

② STAMPING SHOWN FOR BLOCK GEB1-2, USE SAME SCHEME FOR BLOCK GEB 2-2 (EG GEB 2-2 AT).

③ 'T' DESIGNATES 0.226 DIA. TENSILE MEA-CI-5001 (SIDE 2). NO FLATS. BALANCE ARE CHARPY-V (MEA-CO 5002 TYPO)

SPECIFICATIONS UNLESS OTHERWISE NOTED

MATERIAL:
LOW ALLOY
STEEL

TOLERANCES
THREE PLACE ±
TWO PLACE ±
±

DWN
CKD JAA
ENG JAA
MFG
QA
APVD

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LANHAM, MD

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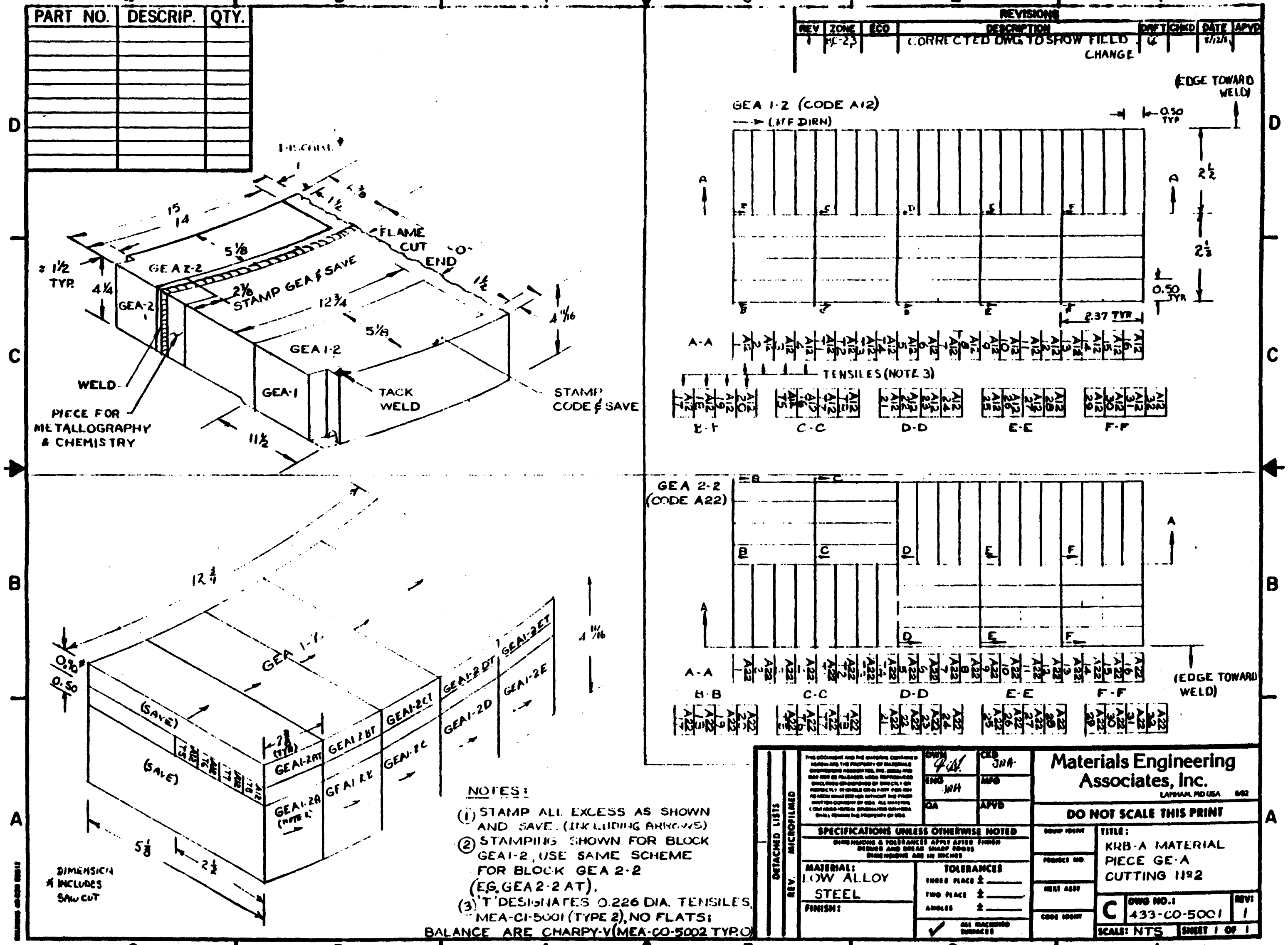
TITLE:
KRB-A MATERIAL
PIECE GE-B
CUTTING N° B

C
DWG NO.: 433-CO-5000
REV. 0
SCALE: NTS
SHEET: 1 of 1

PART NO.	DESCRIP.	QTY.

REVISIONS

REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD
1	C-2,3		CORRECTED DWG TO SHOW FIELD CHANGE			1/12/8	



NOTES:

(1) STAMP ALL EXCESS AS SHOWN AND SAVE. (INCLUDING ARROWS)

(2) STAMPING SHOWN FOR BLOCK GEA1-2, USE SAME SCHEME FOR BLOCK GEA 2-2 (E.G. GEA 2-2 AT).

(3) 'T' DESIGNATES 0.226 DIA. TENSILES, MEA-CI-5001 (TYPE 2), NO FLATS; BALANCE ARE CHARPY-V (MEA-CO-5002 TYP.O)

DETACHED LISTS
REV. MICROFILMED

DWN
CKD JNA
ENG WH
MFG
QA
APVD

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LANHAM, MD USA

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SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

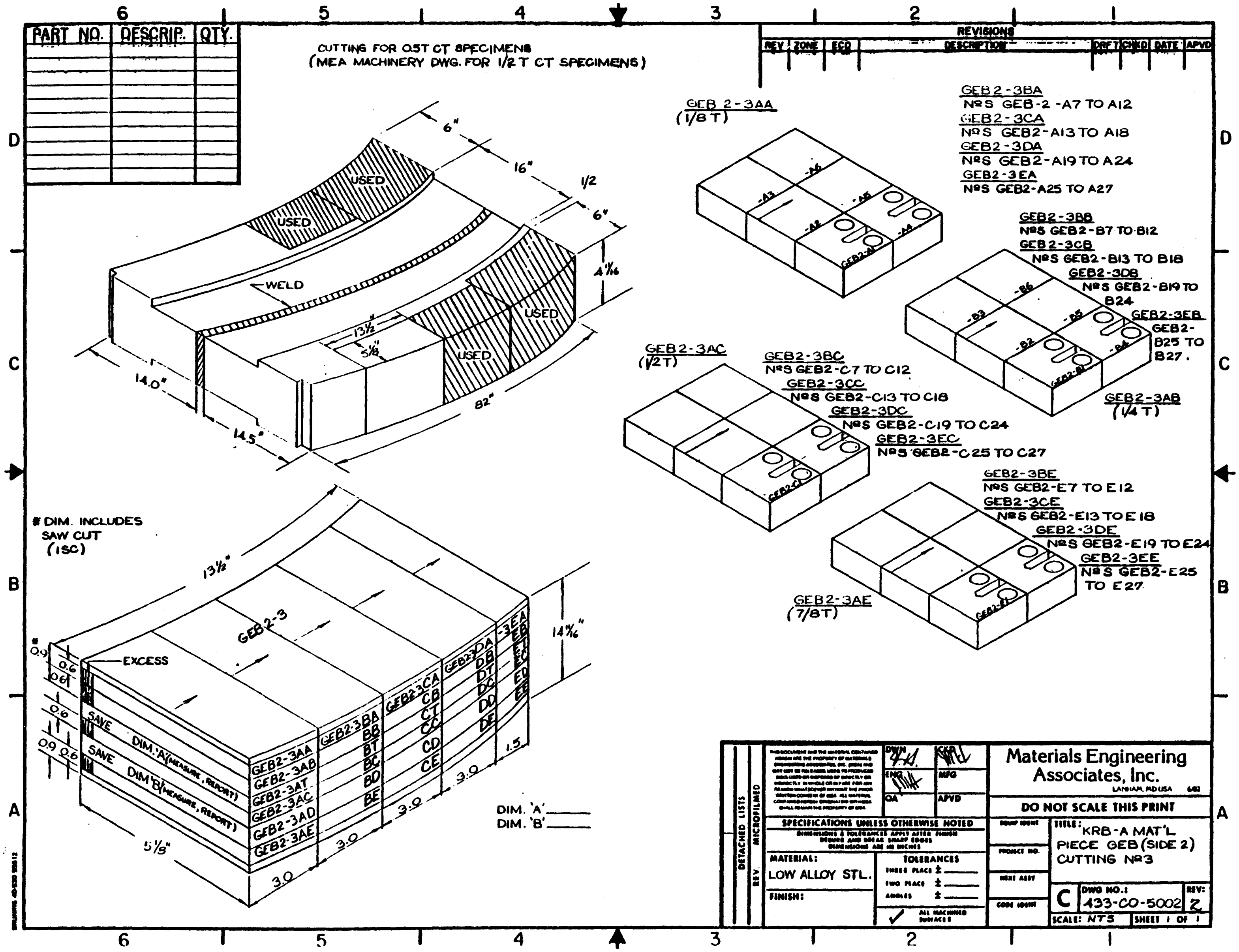
MATERIAL: LOW ALLOY STEEL
FINISH:

TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±
✓ ALL MACHINED SURFACES

TITLE: KRB-A MATERIAL PIECE GE-A CUTTING NO 2

C DWG NO.: 433-CO-5001 REV: 1

SCALE: NTS SHEET 1 OF 1



DETACHED LISTS	REV. MICROFILMED		DWN	CKD
			ENG	MFG
			QA	APVD

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LANHAM, MD USA 6/82

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SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

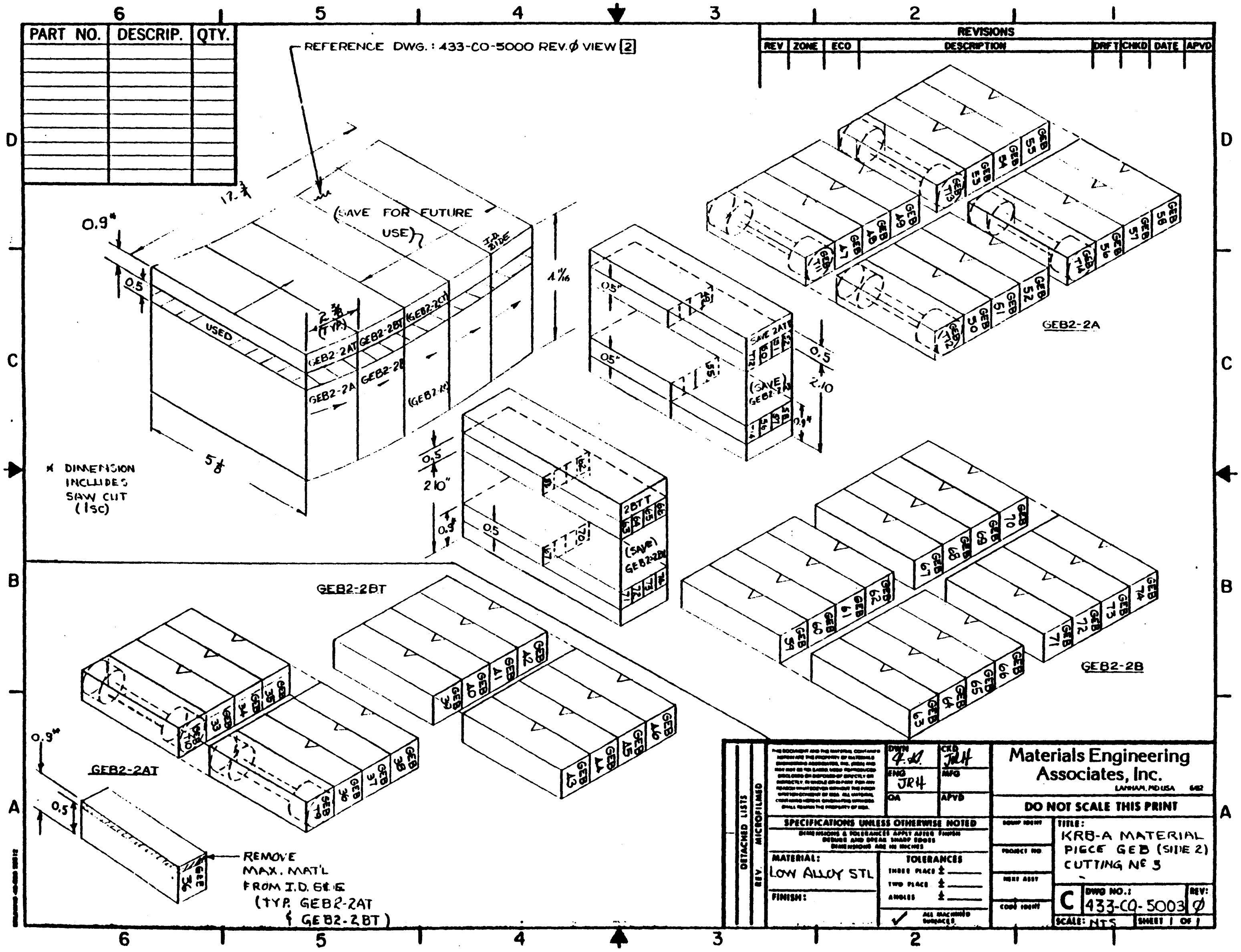
MATERIAL: LOW ALLOY STL.
FINISH:

TOLERANCES
THREE PLACE ± ____
TWO PLACE ± ____
ANGLES ± ____
✓ ALL MACHINED SURFACES

EQUIP IDENT
PROJECT NO.
NEXT ASSY
CODE IDENT

TITLE: KRB-A MAT'L PIECE GEB (SIDE 2) CUTTING NO3

C
DWG NO.: 433-CO-5002
REV: 2
SCALE: NTS
SHEET 1 OF 1

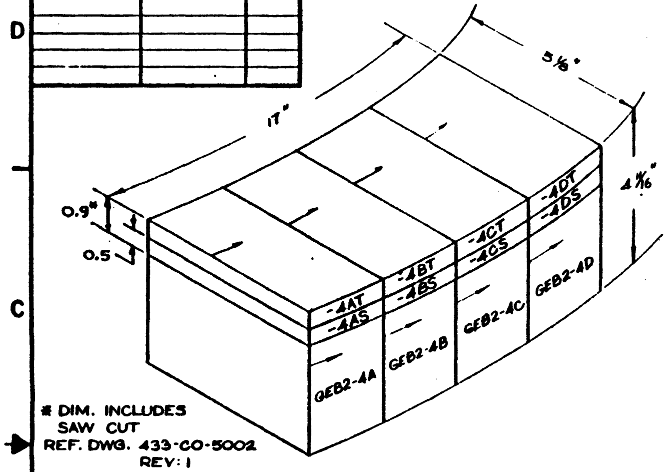

PART NO.
DESCRIP.
QTY.
REFERENCE DWG.: 433-CO-5000 REV.Ø VIEW 2
REVISIONS
REV
ZONE
ECO
DESCRIPTION
DRFT
CHKD
DATE
APVD
(SAVE FOR FUTURE USE)
I.D. SIDE
0.9*
0.5
12.7
USED
2 3/8 (TYP.)
GEB2-2AT
GEB2-2BT
GEB2-2CT
GEB2-2A
GEB2-2B
GEB2-2C
4 7/16
5 7/8
* DIMENSION INCLUDES SAW CUT (1sc)
.05"
SAVE 2AT
(SAVE) GEB2-2A
0.5
2.10
0.9*
2BT T
(SAVE) GEB2-2B
2.10"
GEB2-2A
GEB 47
GEB 48
GEB 49
GEB 50
GEB 51
GEB 52
GEB 53
GEB 54
GEB 55
GEB 56
GEB 57
GEB 58
GEB T11
GEB T12
GEB T13
GEB T14
GEB2-2BT
GEB 39
GEB 40
GEB 41
GEB 42
GEB 43
GEB 44
GEB 45
GEB 46
GEB2-2B
GEB 59
GEB 60
GEB 61
GEB 62
GEB 63
GEB 64
GEB 65
GEB 66
GEB 67
GEB 68
GEB 69
GEB 70
GEB 71
GEB 72
GEB 73
GEB 74
GEB2-2AT
GEB 33
GEB 34
GEB 35
GEB 36
GEB 37
GEB 38
GEB T10
GEB T9
REMOVE MAX. MAT'L FROM I.D. EDGE (TYP. GEB2-2AT & GEB2-2BT)
DETACHED LISTS
REV.
MICROFILMED
DWN
CKD
ENG
JRH
MFG
QA
APVD
Materials Engineering
Associates, Inc.
LANHAM, MD USA
DO NOT SCALE THIS PRINT
SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES
MATERIAL:
LOW ALLOY STL
FINISH:
TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±
✓ ALL MACHINED SURFACES
GROUP IDENT
PROJECT NO
NEXT ASSY
CODE IDENT
TITLE:
KRB-A MATERIAL
PIECE GEB (SIDE 2)
CUTTING No 3
C
DWG NO.:
433-CO-5003
REV:
Ø
SCALE: NTS
SHEET 1 OF 1
A
B
C
D
1
2
3
4
5
6

PART NO.	DESCRIP.	QTY.

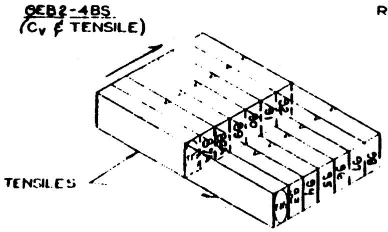
REVISIONS

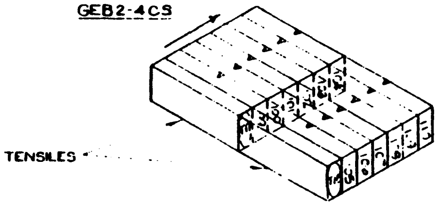
REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD
1	3C	—	ADD SUFFIX 'A' TO 87A,88A				

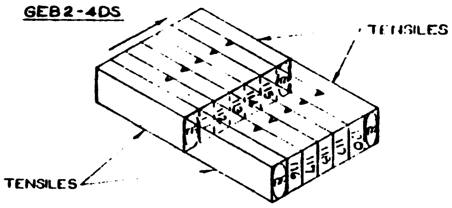
REFERENCE DWGS.
MACHINE CHARPYS TO: MEA-CO-5002
REV. 3
MACHINE TENSILES TO: MEA-CI-5001
REV. 2 (TYPE 2)

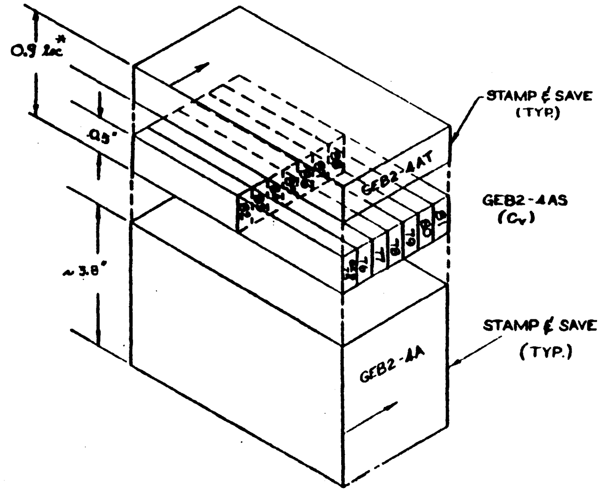


* DIM. INCLUDES SAW CUT
REF. DWG. 433-CO-5002
REV: 1









DETACHED LISTS
REV MICROFILMED

DWN 4.W. | CKD JHH
ENG JHH | MFG
QA | APVD

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LANHAM, MD USA

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SPECIFICATIONS UNLESS OTHERWISE NOTED

MATERIAL:
FINISH:

TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±
✓ ALL MACHINED SURFACES

CODE IDENT 02-03 //

TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING Nº 4.

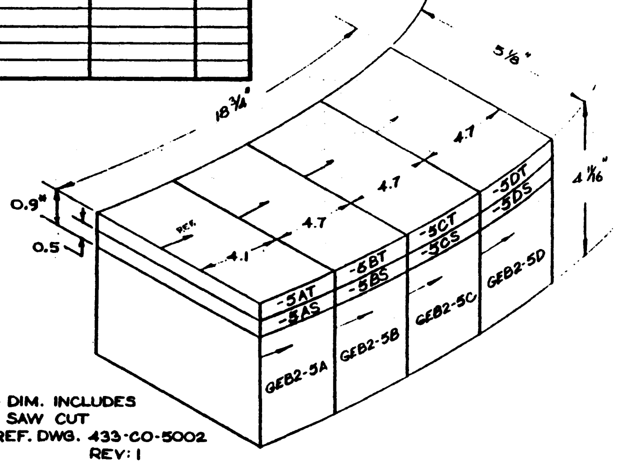
C DWG NO.: 433-CO-5004 REV: 1
SCALE NTS SHEET 1 OF 1

PART NO.	DESCRIP.	QTY.

REVISIONS

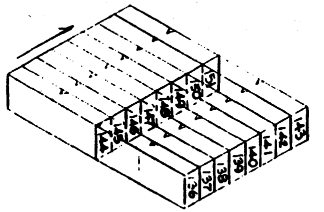
REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD

REFERENCE DWGS.
MACHINE CHARPYS TO: MEA-CO-5002
REV. 3

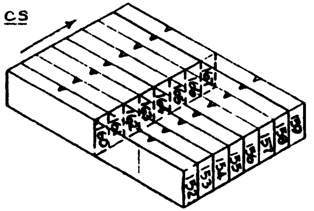


* DIM. INCLUDES
SAW CUT
REF. DWG. 433-CO-5002
REV: 1

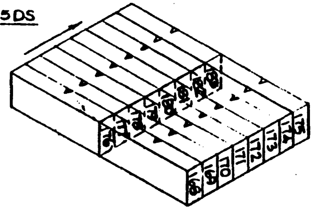
GEB2-5BS

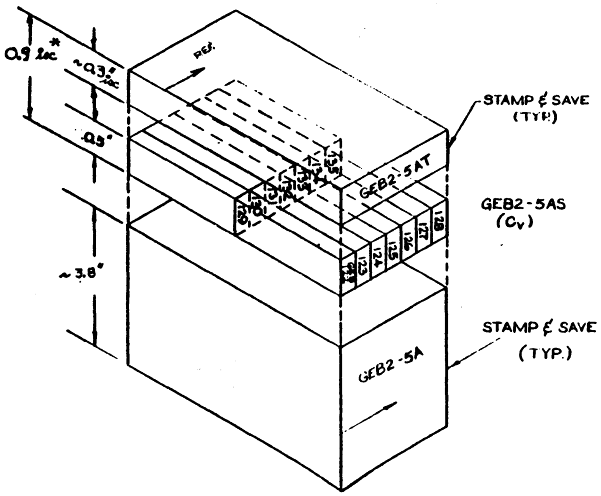


GEB2-5CS



GEB2-5DS





DETACHED LISTS	DWN 4.A.	CKD JHH	**Materials Engineering Associates, Inc.** LANHAM, MD USA
REV. MICROFILMED	ENG JHH	MFG	DO NOT SCALE THIS PRINT
	QA	APVD 1-24-86	

SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

MATERIAL: LOW ALLOY STL.
FINISH:

TOLERANCES
THREE PLACE ± ____
TWO PLACE ± ____
ANGLES ± ____
✓ ALL MACHINED SURFACES

CODE IDENT 02-03-86

TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING № 5

C DWG NO.: 433-CO-5005 REV: 0
SCALE: NTS SHEET 1 OF 1

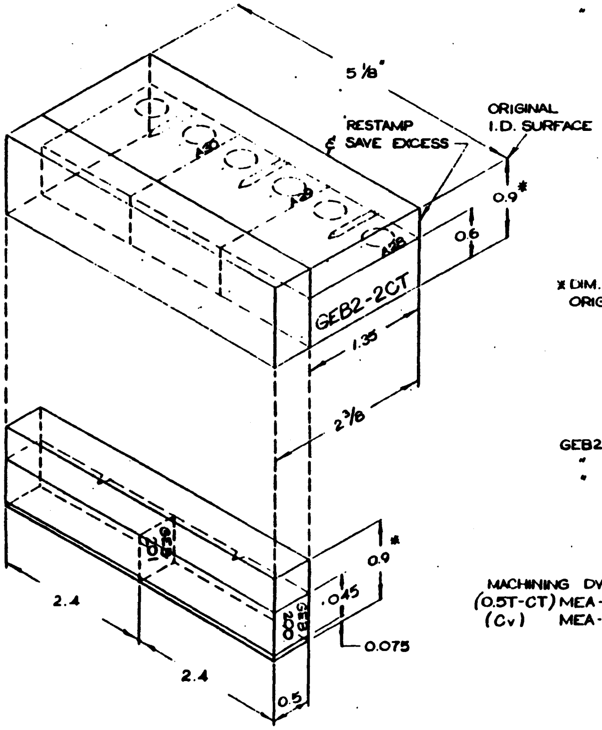
PART NO.	DESCRIP.	QTY.

REVISIONS

REV	ZONE	ECO	DESCRIPTION	DFT	CHKD	DATE	APVD

REF. DWG. MEA 433-CO-5000 REV. 0
(ORIGINAL CUTTING)

SUBBLOCK Nº.	0.5T-CT NºS
GEB2-2CT	# A28, A29, A30
" -2DT	# A31, A32, A33
" -2ET	# A34, A35, A36



* DIM. INCLUDES
ORIGINAL SAWCUT

	Cv NºS
GEB2-2CT	# 200, 201
" -2DT	# 202, 203
" -2ET	# 204, 205

MACHINING DWGS.
(0.5T-CT) MEA-AO-5003 REV. 0
(Cv) MEA-CO-5002 REV. 3

UBR CTS
CHECK TEST Cv S

DWN	CKD JRH
ENG JRH	MFG
QA	APVD

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LANHAM, MD USA 682

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SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

MATERIAL:

FINISH:

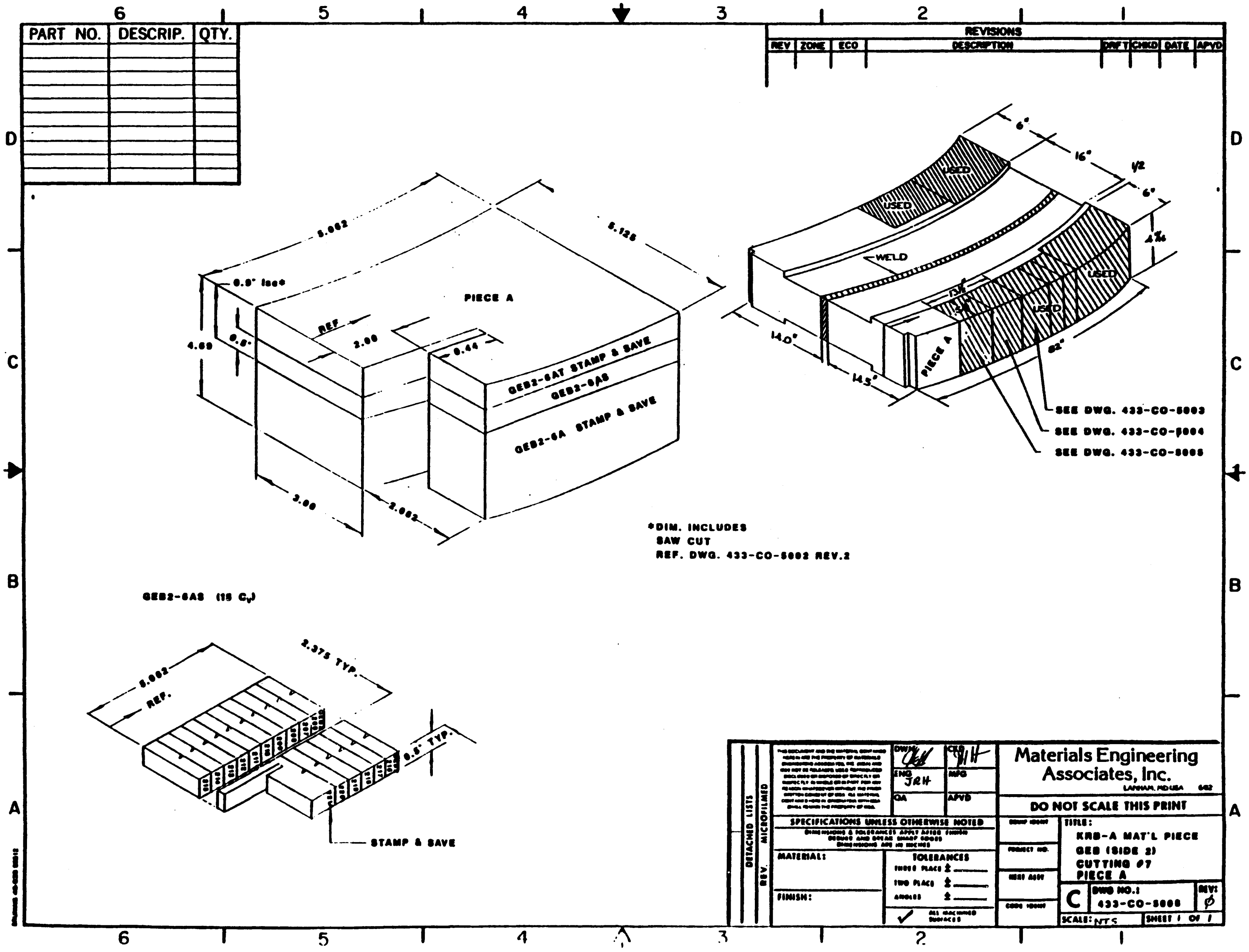
TOLERANCES
THREE PLACE ± ____
TWO PLACE ± ____
ANGLES ± ____
✓ ALL MACHINED SURFACES

DETACHED LISTS
REV. MICROFILMED

GROUP IDENT
PROJECT NO.
NEXT ASSY
CODE IDENT

TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING Nº 6

C
DWG NO.: 433-CO-5006
REV: 0
SCALE: NTS
SHEET 1 OF 1


6
5
4
3
2
1
D
C
B
A
PART NO.
DESCRIP.
QTY.
REVISIONS
REV
ZONE
ECO
DESCRIPTION
DRFT
CHKD
DATE
APVD
5.062
5.126
0.5" Ise*
PIECE A
REF
2.00
0.44
4.69
0.5"
GEB2-6AT STAMP & SAVE
GEB2-6AS
GEB2-6A STAMP & SAVE
3.00
2.062
*DIM. INCLUDES
SAW CUT
REF. DWG. 433-CO-5002 REV.2
6"
16"
1/2
6"
4 7/16
USED
USED
WELD
USED
USED
13/16
14.0"
14.5"
PIECE A
82"
SEE DWG. 433-CO-5003
SEE DWG. 433-CO-5004
SEE DWG. 433-CO-5005
GEB2-6AS (15 C_V)
5.062
REF.
2.375 TYP.
0.5" TYP.
STAMP & SAVE
DETACHED LISTS
REV.
MICROFILMED
DWN
CKD
ENG
JRH
MFG
QA
APVD
SPECIFICATIONS UNLESS OTHERWISE NOTED
MATERIAL:
FINISH:
TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±
✓ ALL MACHINED SURFACES
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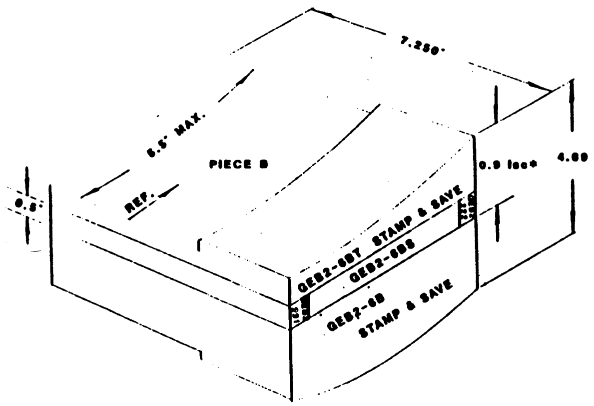
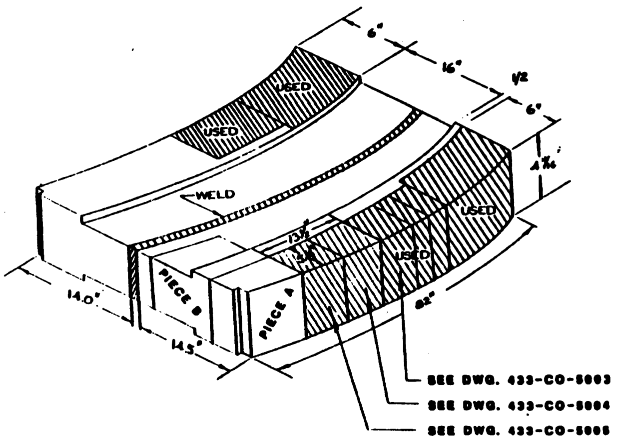
LANHAM, MD USA
DO NOT SCALE THIS PRINT
PROJECT NO.
NEXT ASSY
CODE IDENT
TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING #7
PIECE A
C
DWG NO.:
433-CO-5006
REV:
0
SCALE: NTS
SHEET 1 OF 1

PART NO.	DESCRIP.	QTY.

REVISIONS							
REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD

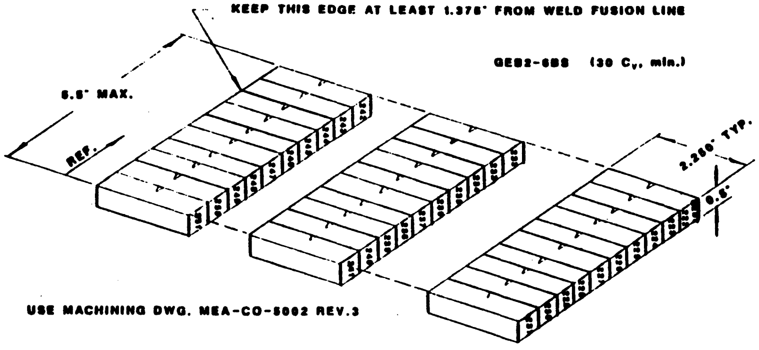




*DIM. INCLUDES
SAW CUT
REF. DWG. 433-CO-5002 REV.2

KEEP THIS EDGE AT LEAST 1.375" FROM WELD FUSION LINE

GEB2-6BS (30 C_v, min.)



USE MACHINING DWG. MEA-CO-5002 REV.3

DETACHED LISTS
REV. MICROFILMED

DWN Whl | CKD JH
ENG JRH | MFG
QA | APVD

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SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

MATERIAL:

FINISH:

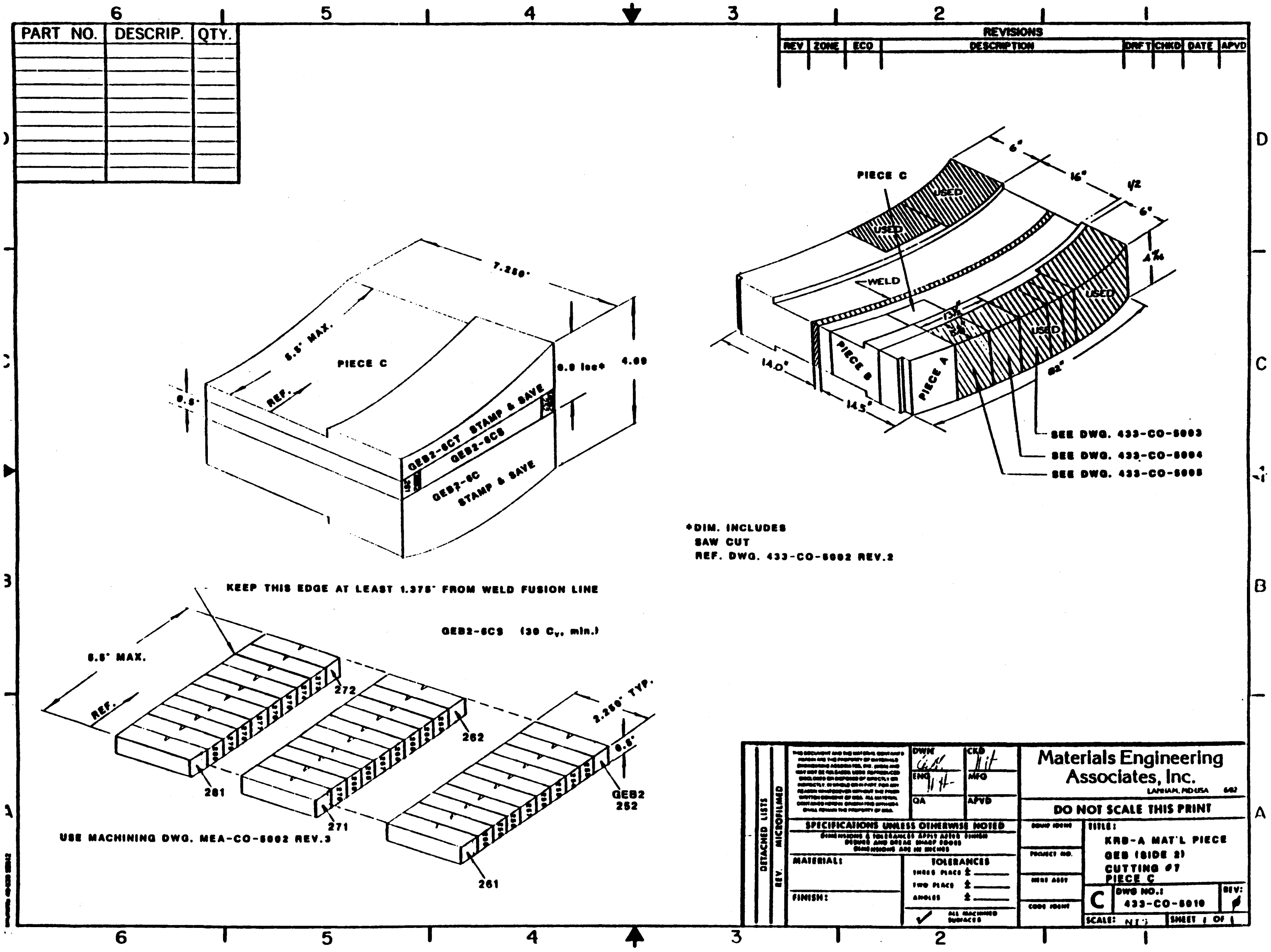
TOLERANCES
THREE PLACE ± ______
TWO PLACE ± ______
ANGLES ± ______
✓ ALL MACHINED SURFACES

GROUP IDENT
PROJECT NO
NEXT ASSY
CODE IDENT

TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING #7

C DWG NO.: 433-CO-5009 REV: 0

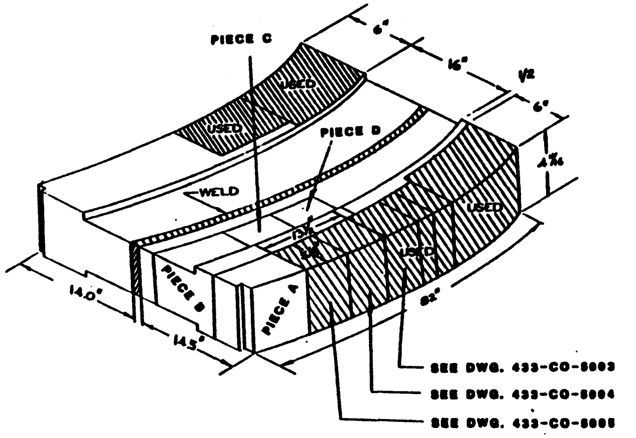
SCALE: NTS SHEET 1 OF 1


PART NO.
DESCRIP.
QTY.
REVISIONS
REV
ZONE
ECO
DESCRIPTION
DRFT
CHKD
DATE
APVD
7.250"
5.5" MAX.
PIECE C
REF.
0.5"
0.9 loc*
4.09
GEB2-6CT STAMP & SAVE
GEB2-6CS
GEB2-6C STAMP & SAVE
PIECE C
USED
USED
WELD
6"
16"
1/2
6"
4 7/16
USED
USED
62"
PIECE A
PIECE B
14.0"
14.5"
SEE DWG. 433-CO-5003
SEE DWG. 433-CO-5004
SEE DWG. 433-CO-5005
*DIM. INCLUDES
SAW CUT
REF. DWG. 433-CO-5002 REV.2
KEEP THIS EDGE AT LEAST 1.375" FROM WELD FUSION LINE
GEB2-6CS (30 Cv, min.)
5.5" MAX.
REF.
272
262
2.250" TYP.
0.5"
281
271
GEB2
252
261
USE MACHINING DWG. MEA-CO-5002 REV.3
DETACHED LISTS
REV.
MICROFILMED
DWN
CKD
ENG
MFG
QA
APVD
SPECIFICATIONS UNLESS OTHERWISE NOTED
MATERIAL:
TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±
FINISH:
ALL MACHINED SURFACES
Materials Engineering
Associates, Inc.
LANHAM, MD USA
DO NOT SCALE THIS PRINT
GROUP IDENT
PROJECT NO.
NEXT ASSY
CODE IDENT
TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING #7
PIECE C
C
DWG NO.:
433-CO-5010
REV:
SCALE: N.T.S.
SHEET 1 OF 1

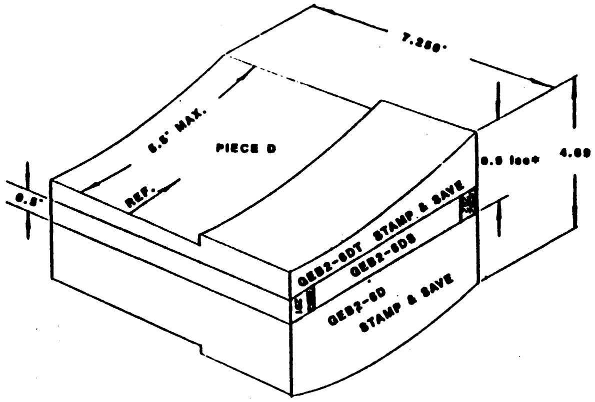
PART NO.	DESCRIP.	QTY.

REVISIONS

REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD



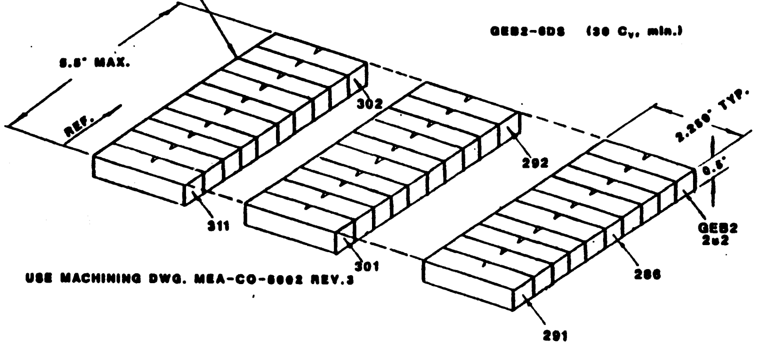
SEE DWG. 433-CO-5003
SEE DWG. 433-CO-5004
SEE DWG. 433-CO-5005



*DIM. INCLUDES
SAW CUT
REF. DWG. 433-CO-5002 REV.2

KEEP THIS EDGE AT LEAST 1.375" FROM WELD FUSION LINE

GEB2-6DS (30 C_v, min.)



USE MACHINING DWG. MEA-CO-5002 REV.3

DETACHED LISTS
REV. MICROFILMED

DWN | CKD
ENG | MFG
QA | APVD

SPECIFICATIONS UNLESS OTHERWISE NOTED

MATERIAL:

FINISH:

TOLERANCES
THREE PLACE ±
TWO PLACE ±
ANGLES ±

✓ ALL MACHINED SURFACES

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LANHAM, MD USA

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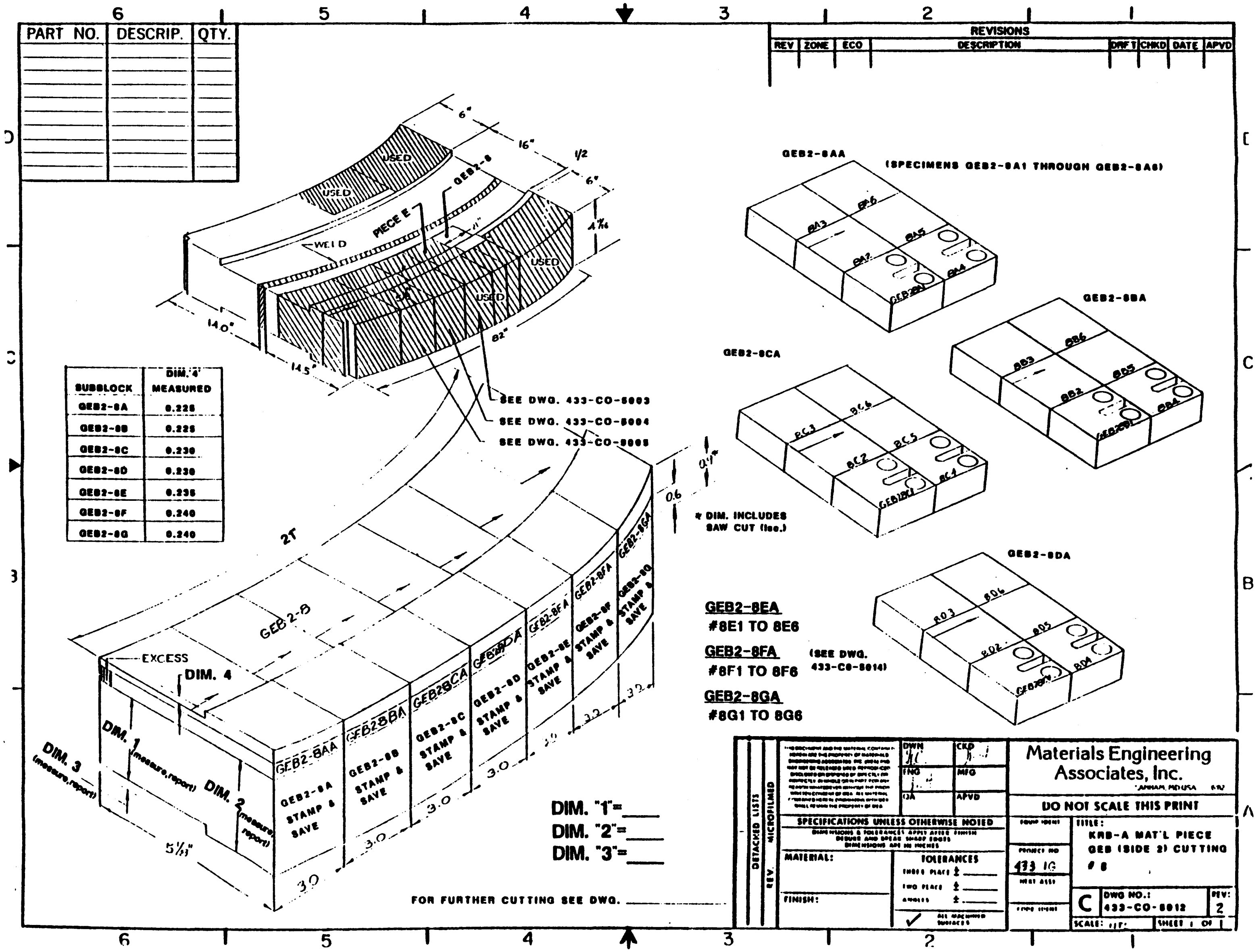
PROJECT NO.
NEXT ASSY
CODE IDENT

TITLE:
KRB-A MAT'L PIECE
GEB (SIDE 2)
CUTTING #7
PIECE D

C
DWG NO.: 433-CO-5011
REV: 0
SCALE: NTS
SHEET 1 OF 1



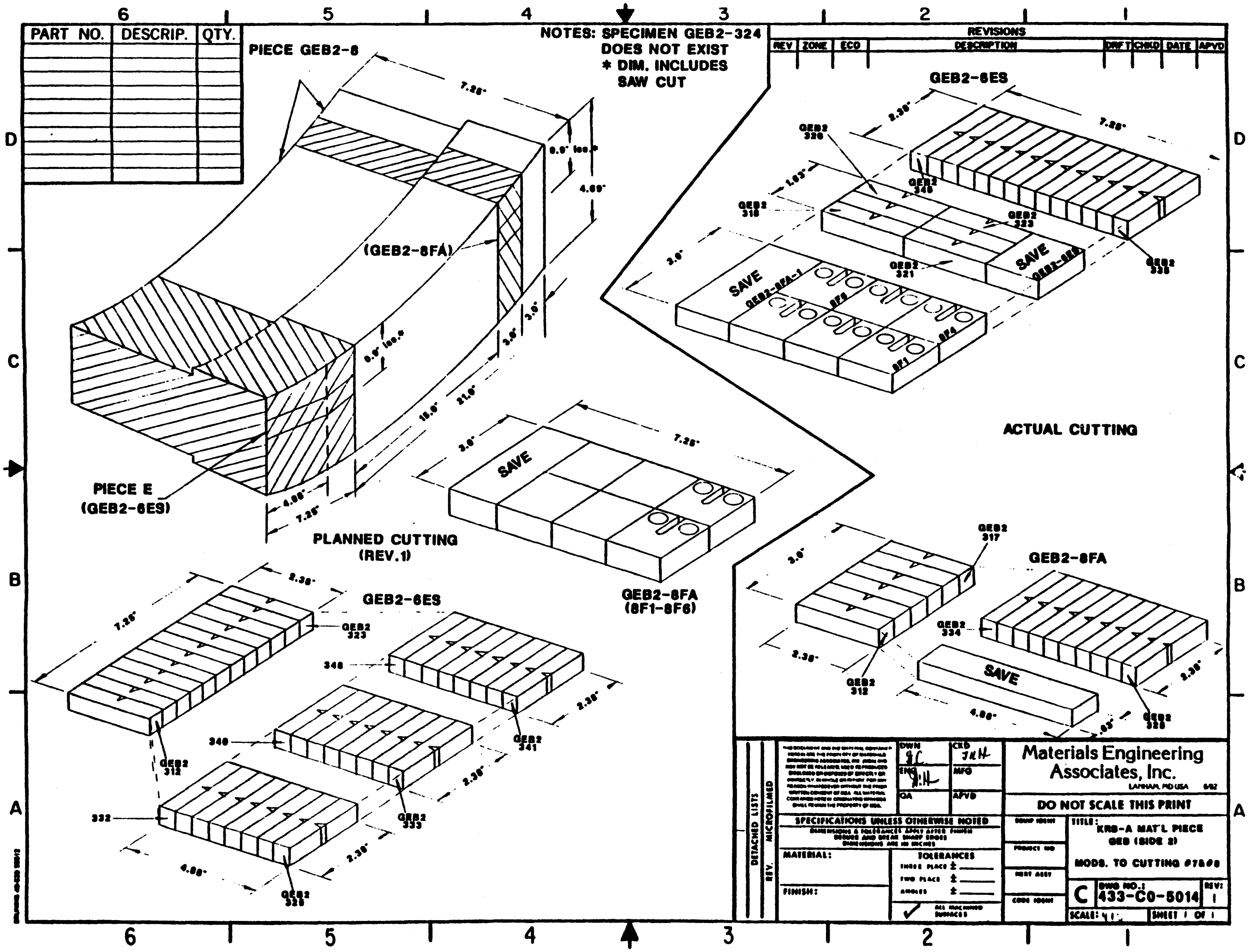
SUBBLOCK	DIM. '4' MEASURED
GEB2-8A	0.225
GEB2-8B	0.225
GEB2-8C	0.230
GEB2-8D	0.230
GEB2-8E	0.235
GEB2-8F	0.240
GEB2-8G	0.240

GEB2-8EA
#8E1 TO 8E6

GEB2-8FA
#8F1 TO 8F6

(SEE DWG. 433-CO-8014)

GEB2-8GA
#8G1 TO 8G6



PART NO.	DESCRIP.	QTY.

NOTES: SPECIMEN GEB2-324 DOES NOT EXIST
* DIM. INCLUDES SAW CUT

REVISIONS

REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD

DETACHED LISTS
REV. MICROFILMED

DWN $C.	CKD JKH
ENG J.H	MFG
QA	APVD

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LANHAM, MD USA 6/82

DO NOT SCALE THIS PRINT

SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

MATERIAL:

FINISH:

TOLERANCES
THREE PLACE ± ______
TWO PLACE ± ______
ANGLES ± ______
✓ ALL MACHINED SURFACES

GROUP IDENT
PROJECT NO
NEXT ASSY
CODE IDENT

TITLE: KRB-A MAT'L PIECE GEB (SIDE 2)
MODS. TO CUTTING #7&#8

C DWG NO.: 433-C0-5014 REV: 1
SCALE: ½ SHEET 1 OF 1

APPENDIX C

"Through-Thickness Mechanical Properties of KRB-A Archive Steel Forging GEB"

J. R. Hawthorne

MEA Report No. MEA-2159A

June 1986

MEA-2159A

THROUGH-THICKNESS MECHANICAL PROPERTIES OF KRB-A ARCHIVE STEEL FORGING GEB

J. R. Hawthorne

1. BACKGROUND

MEA has the task of irradiating and evaluating Gundremmingen reactor vessel archival materials in support of NRC research on long-term, in-service irradiation effects. MEA's results, together with determinations by Staatliche MaterialPruefungsanstalt (MPA) of the Federal Republic of Germany (FRG) on materials trepanned from the KRB-A vessel itself, will be analyzed for the effects of neutron exposure rate and through-thickness damage attenuation. The effects of steel compositions and the correlation of Charpy-V (C_v) notch ductility vs. fracture toughness vs. strength will be examined. The joint program will also investigate properties recovery by postirradiation heat treatment. The MEA and MPA efforts are limited to studies of the base metal. Studies of the girth welds are not being performed. The NRC decision to forego weld metal investigations stemmed from the FRG determination that more than one filler metal was employed in completing the weld thickness. Each weld thus could have a step-change in composition at some point in its thickness.

In April 1985, two pieces of weldment identified by stamp markings as "KRB Vessel" were acquired from the General Electric Company (GE) - Vallecitos site. Each of the pieces is a ring segment. One weighing approximately 7050 kg (3,200 lb) contains a circumferential weld deposit located at the half-height of the ring; the second, weighing only 990 kg (450 lb), also contains a circumferential weld. The weld in this case is closer to one edge of the ring segment than the other. Both segments are approximately 119-mm (4-11/16 in.) thick. The smaller piece has been given the code GEA by MEA; the larger piece has been assigned the code GEB. In this report, GEA and GEB are termed "archive materials." The two base metals of GEA are identified by the code numbers GEA-1 and GEA-2, respectively; those of GEB have the code number GEB-1 or GEB-2.

Initial task objectives were the determination of the chemical composition, microstructure, tensile strength, and notch ductility of each of the four base metals contained in the welded ring segments. MEA findings on these characteristics are given in Reference 1. From the composition tests, MEA and the NRC have concluded that the four base metals are from the same steel melt. Small differences in properties between the GEA-1 and GEA-2 vs. the GEB-1 and GEB-2 materials were found but may be a reflection of an (unknown) difference in heat treatment between the two ring segments. More important to this study, the findings, when compared against documentation for the KRB-A vessel, indicate a high probability that the four base materials and the vessel forging ring no. 7.1 were from the same steel melt and that the base materials are representative of the vessel forging as first placed in service.

2. APPROACH

The research plan called for a phased approach to the qualification of the materials from GE. Phase 1 focused on the determination of base metal chemistries, hardness levels and gradients through the thickness and microstructure determinations at points corresponding to the I.D. and O.D. surfaces, and to the 1/8T-, 1/4T-, 1/2T-, and 3/4T-thickness locations. Phase 2 involved the cutting, machining, and testing of standard Charpy-V (C_v) and 5.74-mm (0.226-in.) gage diameter tensile specimens from the 1/4T location in each of the materials. The specimens were removed in two testing orientations: axial and circumferential. The Phase 1 and Phase 2 findings are documented in Reference 1. The Phase 3 effort, reported here, assesses the through-thickness properties of the GEB-2 material selected for the continuing investigations. The information acquired on property gradients was to provide one basis for choosing one material thickness location for the subsequent (MEA) irradiation tests.

Properties evaluated in Phase 3 were notch ductility, tensile strength, and static fracture toughness including J-R curve behavior. Test procedures for the 0.5T-CT specimens are described in Reference 2. Tests were in conformance with ASTM Standard Methods E 8, E 23, E 399, and E 813 as applicable to the individual methods and test conditions.

3. SPECIMEN BLANKING AND MACHINING

Figures 1, 2, and 3 are cutting diagrams used for the acquisition of the specimen blanks. Not all blanks indicated were used for the development of through-thickness properties. The remainder are being applied to irradiation test needs. Note that the axial (weak) test orientation is depicted throughout; the ASTM Method E 399 defines this orientation as orientation code C-L.

Individual specimens were machined in accordance with MEA drawings MEA-CO-5002 Rev. 3, MEA-C1-5001 Rev. 1 Type 2, or MEA-A0-5003 Rev. 0 (see Figs. 4, 5, and 6). The 0.5T-CT specimens were fatigue precracked for a distance of 1.78 mm (0.070 in.), corresponding to an a/W ratio of 0.5. The K_f (maximum) for the entire distance of fatigue crack growth was less than 22 $MPa\sqrt{m}$ (20 $ksi\sqrt{in.}$). The CT specimens selected for testing in the upper shelf temperature regime were side grooved by 20% (10% each side) using a Vee-shaped cutter having the contour of the C_v specimen (see Fig. 4).

4. RESULTS

The experimental results are listed in Tables 1 through 6. The C_v data are illustrated in Fig. 7; K_J toughness determinations via CT tests are summarized in Fig. 8. J-R curves from tests of the four thickness locations at 66°C (150°F) are compared in Fig. 9.

Referring first to Table 1, the tensile strength determinations show a high degree of uniformity through the thickness. The difference in yield strength between the near surface locations (1/8T and 7/8T) and the midthickness location is less than 21 MPa (3 ksi); the difference in tensile strength between the two thickness positions is even less. Accordingly, the presence of free ferrite in the microstructure of the midwall location and absence of this component in the near surface location (Ref. 1) did not have a significant effect on material strength.

The C_v notch ductility determinations also revealed a high degree of uniformity through the thickness (see Fig. 7). A good correspondence of properties between the 1/8T- and the 7/8T-thickness positions again is observed. For the 1/4T- vs. 1/2T-thickness positions, good agreement of the data up to an energy level of about 81 J (60 ft-lb) is found; above this level, the energy absorption curves diverge such that the upper shelf level of the 1/4T specimens is greater than that of the 1/2T specimens. Important to the selection of thickness position for irradiation, the 1/4T vs. 1/8T positions have the same apparent C_v upper shelf levels [103 J (76 ft-lb)] and nearly the same C_v 41-J transition temperatures [-29°C (-20°F) vs. -18°C (0°F)].

The results of through-thickness 0.5T-CT specimen tests generally support the C_v and tensile test indications. Referring to Fig. 8, the K_J transition indications for 1/8T vs. 1/4T are displaced by about 17°C (30°F). Although somewhat greater than that observed in the C_v results, the displacement may be due to the greater thickness of the 0.5T-CT specimen. With this specimen, its greater thickness would encompass a greater proportion of "near surface" material than the C_v (see cutting diagrams). Such material could be expected to have a lower transition than the material closer to the central region of the forging. Comparable upper shelf performances were found for the four test locations however (see Fig. 9).

It is pointed out that the toughness values listed in Tables 3 to 6 and illustrated in Figs. 8 and 9 are based on the ambient temperature flow stress and thus are approximate values only. Tests to define the flow stress vs. temperature relationship for the range of interest [-140°C (240°F) to 288°C (550°F)] are scheduled for Phase 4. These data are expected by July 1986 and will be included in MEA's monthly progress report to the sponsor.

5. SUMMARY

The tensile strength, notch ductility, and fracture toughness of material code GEB-2 has been determined for 1/8-, 1/4T-, 1/2T-, and 7/8T-thickness locations and the axial (weak) test orientation. Good correspondence of properties between locations has been observed. Strength differences are less than 21 MPa (3 ksi). Differences in transition temperature indexed to the C_v 41-J energy level and to the K_J 100-MPa$\sqrt{m}$ toughness level are on the order of 11°C and 17°C, respectively. Upper shelf levels measured by C_v or CT test methods were the same for the four thickness positions.

Based on the findings reported here, MEA proposed that the 1/8T thickness position be used for the irradiation investigation (Ref. 3). In the vessel itself, this layer would have received a greater service-induced fluence than the 1/4T layer and, additionally, would better represent the small flaw case in PTS. This suggestion was accepted by the NRC (Ref. 4) on Jan. 30, 1986.

REFERENCES

1. J. R. Hawthorne, "Preirradiation Qualification of Materials Identified as KRB-A Archive," MEA-2095, August 1985.

2. A. L. Hiser, F. J. Loss, and B. H. Menke, "J-R Curve Characterization of Irradiated Low Upper Shelf Welds," USNRC Report NUREG/CR-3506, Washington, D.C., April 1984.

3. Letter from J. R. Hawthorne (MEA) to C. Z. Serpan (NRC) dated Jan. 27, 1986.

4. Telecom from C. Z. Serpan (NRC) to J. R. Hawthorne (MEA) on Jan. 30, 1986.

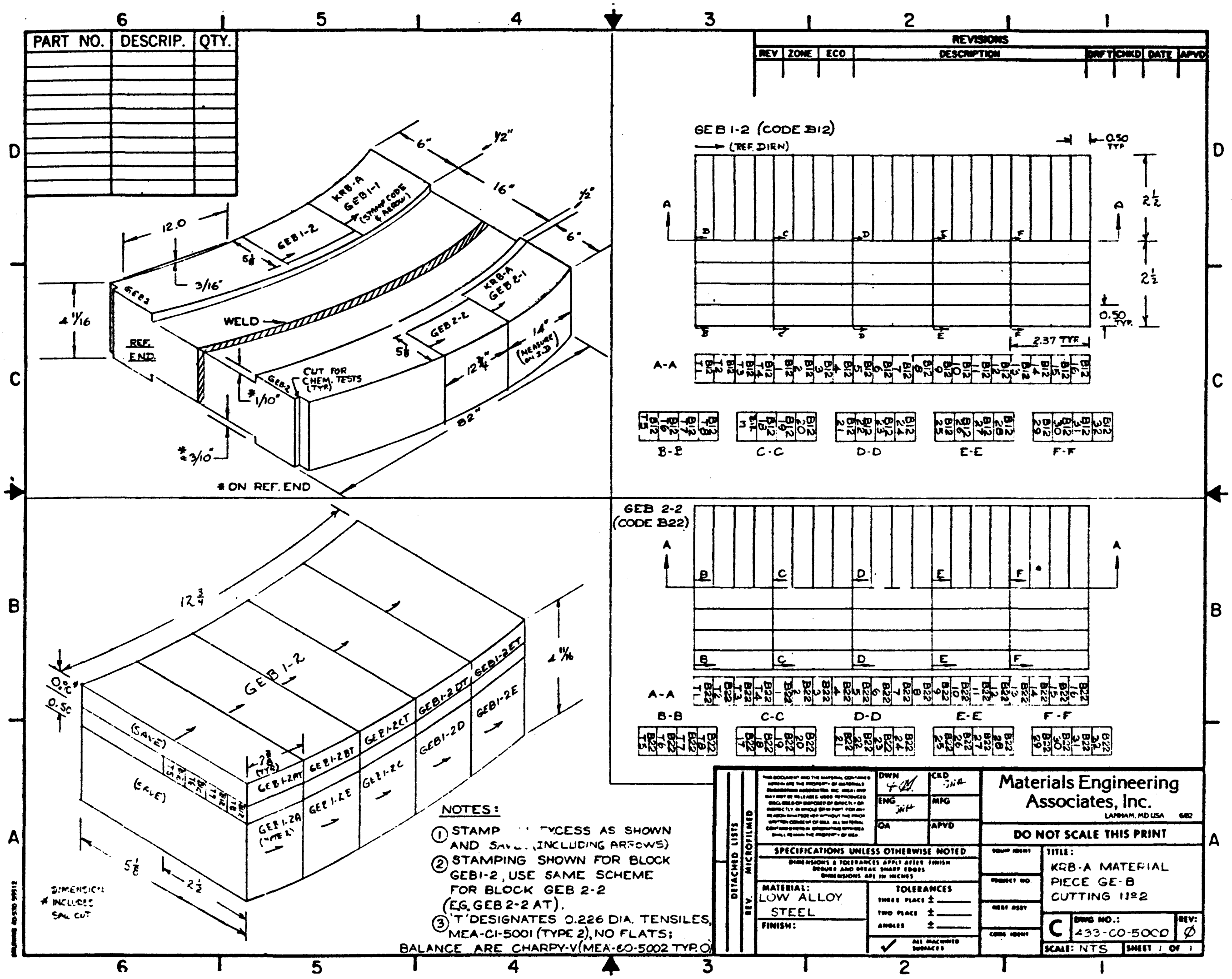


Fig. 1 Cutting plan for removal of Charpy-V (C_v) and tensile (T) specimens from the quarter-thickness location (1/4T) of ring segment GEB (base metals GEB-1 and GEB-2). Individual specimens represent axial or circumferential test orientations.

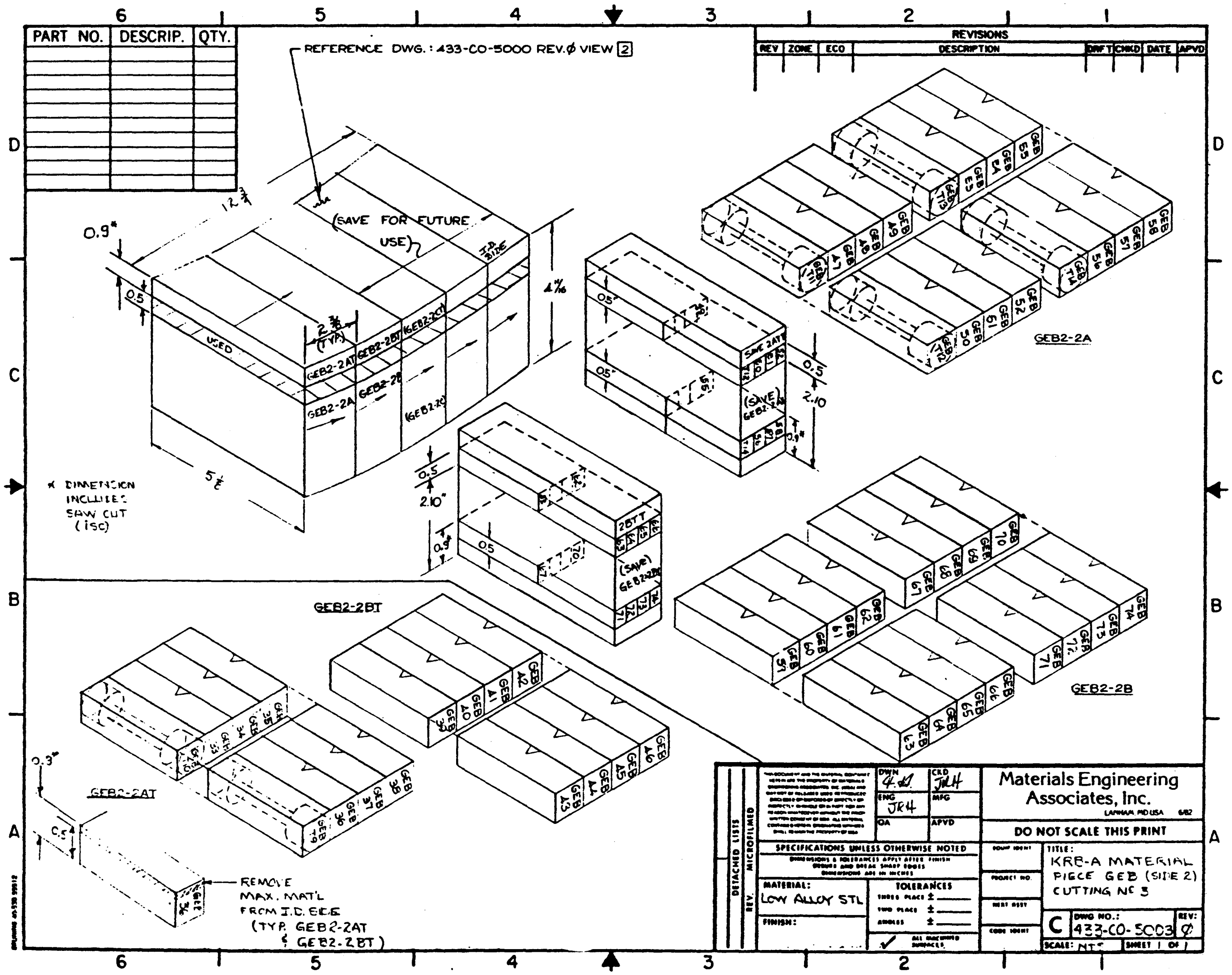


Fig. 2 Cutting plan for removal of Charpy-V (C_V) and tensile (T) specimens from the 1/8T, 1/2T, and 7/8T locations of ring segment GEB (base metal GEB-2). The specimens represent the axial test orientation only.

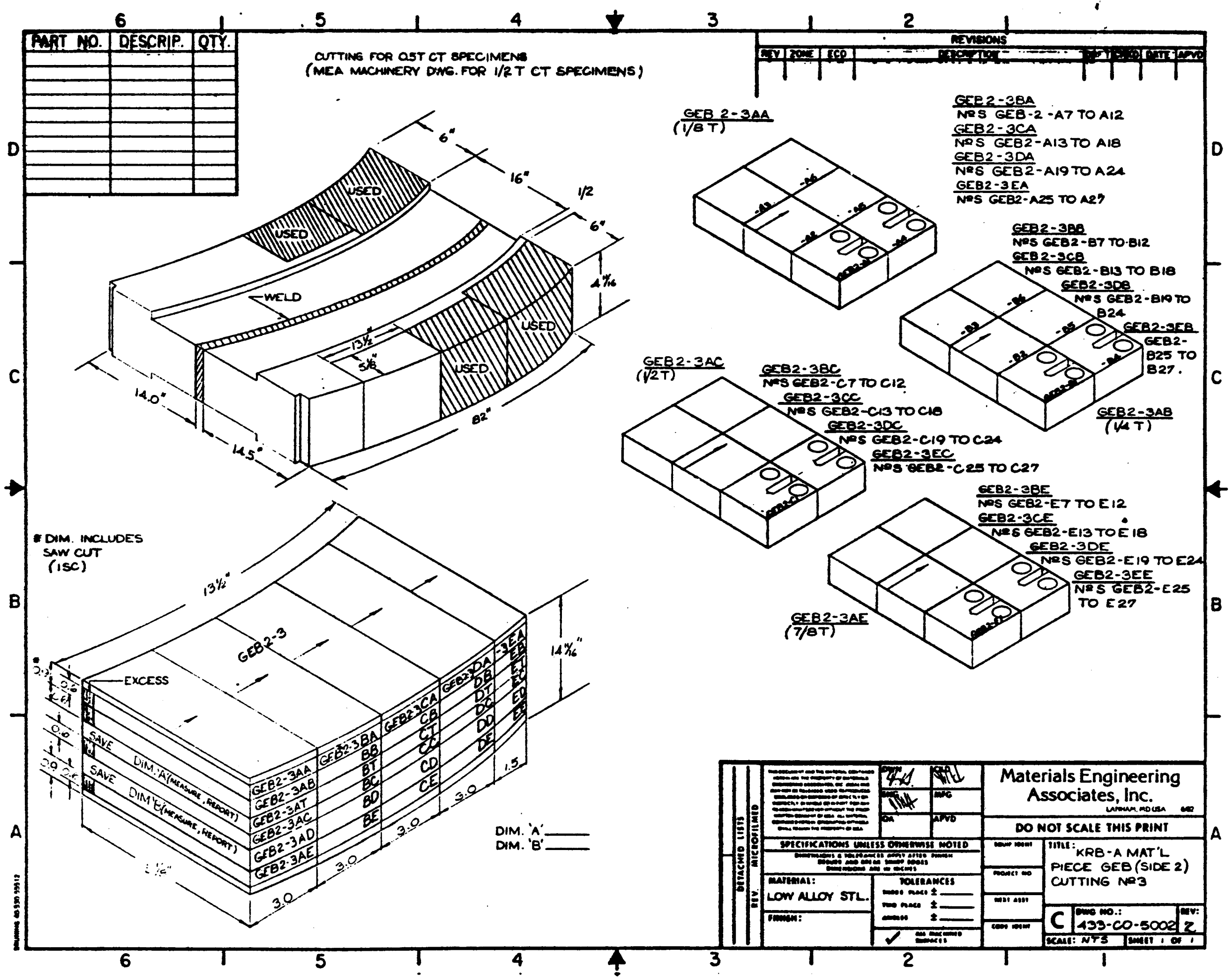
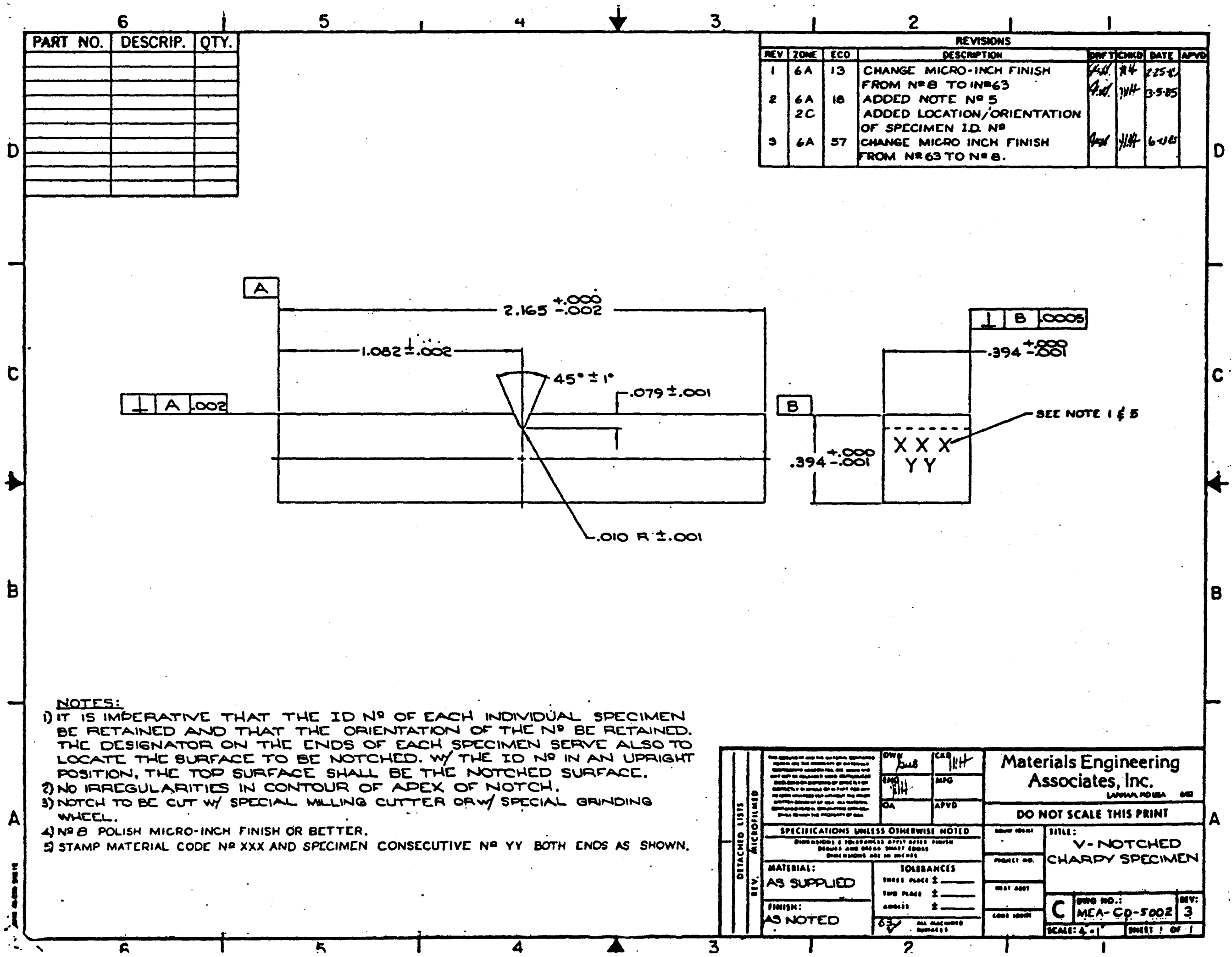


Fig. 3 Cutting plan for removal of 0.5T-CT fracture toughness specimens from the 1/8T, 1/4T, 1/2T, and 7/8T locations of ring segment GEB (base metal GEB-2). Axial test orientation.

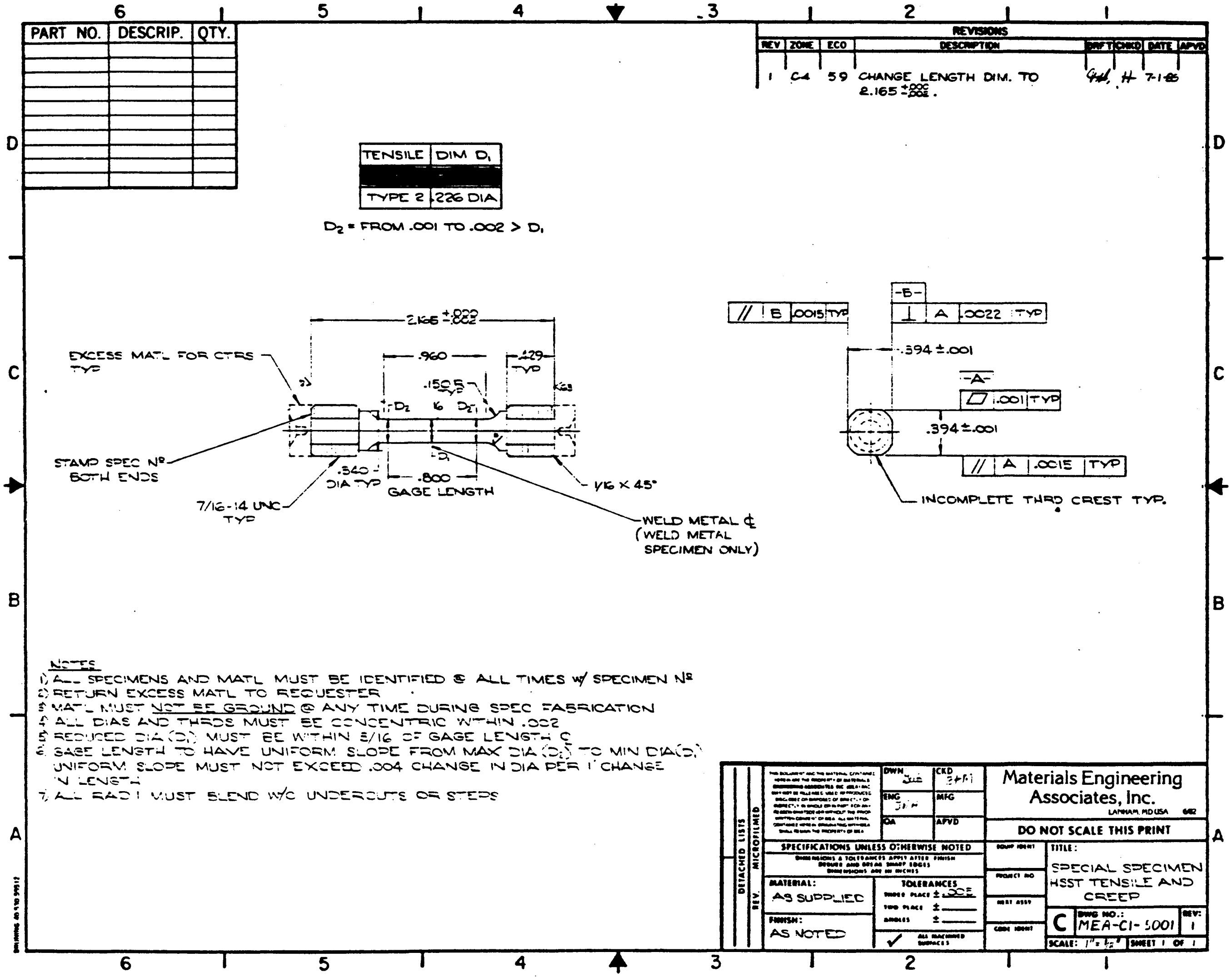


REVISIONS							
REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD
1	6A	13	CHANGE MICRO-INCH FINISH FROM Nº 8 TO IN º 63			2-25-85	
2	6A 2C	18	ADDED NOTE Nº 5 ADDED LOCATION/ORIENTATION OF SPECIMEN I.D. Nº			3-5-85	
3	6A	57	CHANGE MICRO INCH FINISH FROM Nº 63 TO Nº 8.			6-13-85	

NOTES:

1) IT IS IMPERATIVE THAT THE ID Nº OF EACH INDIVIDUAL SPECIMEN BE RETAINED AND THAT THE ORIENTATION OF THE Nº BE RETAINED. THE DESIGNATOR ON THE ENDS OF EACH SPECIMEN SERVE ALSO TO LOCATE THE SURFACE TO BE NOTCHED. W/ THE ID Nº IN AN UPRIGHT POSITION, THE TOP SURFACE SHALL BE THE NOTCHED SURFACE.
2) NO IRREGULARITIES IN CONTOUR OF APEX OF NOTCH.
3) NOTCH TO BE CUT W/ SPECIAL MILLING CUTTER OR W/ SPECIAL GRINDING WHEEL.
4) Nº 8 POLISH MICRO-INCH FINISH OR BETTER.
5) STAMP MATERIAL CODE Nº XXX AND SPECIMEN CONSECUTIVE Nº YY BOTH ENDS AS SHOWN.

Fig. 4 Design of the Charpy-V (C_V) specimen.



PART NO.	DESCRIP.	QTY.

REVISIONS

REV	ZONE	ECO	DESCRIPTION	DRFT	CHKD	DATE	APVD
1	C4	59	CHANGE LENGTH DIM. TO 2.165 +.000 -.002 .	GH	H	7-1-85	

TENSILE	DIM D1
TYPE 2	.226 DIA

D2 = FROM .001 TO .002 > D1

NOTES
1) ALL SPECIMENS AND MATL MUST BE IDENTIFIED @ ALL TIMES w/ SPECIMEN Nº
2) RETURN EXCESS MATL TO REQUESTER
3) MATL MUST NOT BE GROUND @ ANY TIME DURING SPEC FABRICATION
4) ALL DIAS AND THRDS MUST BE CONCENTRIC WITHIN .002
5) REDUCED DIA (D1) MUST BE WITHIN 3/16 OF GAGE LENGTH ℄
6) GAGE LENGTH TO HAVE UNIFORM SLOPE FROM MAX DIA (D2) TO MIN DIA (D1) UNIFORM SLOPE MUST NOT EXCEED .004 CHANGE IN DIA PER 1" CHANGE IN LENGTH
7) ALL RADII MUST BLEND W/O UNDERCUTS OR STEPS

Materials Engineering Associates, Inc.
LANHAM, MD USA

SPECIFICATIONS UNLESS OTHERWISE NOTED
DIMENSIONS & TOLERANCES APPLY AFTER FINISH
DEBURR AND BREAK SHARP EDGES
DIMENSIONS ARE IN INCHES

MATERIAL: AS SUPPLIED
FINISH: AS NOTED
TOLERANCES: THREE PLACE ± .005
✓ ALL MACHINED SURFACES

TITLE: SPECIAL SPECIMEN HSST TENSILE AND CREEP
C
DWG NO.: MEA-C1-5001
REV: 1
SCALE: 1" = 1/2"
SHEET 1 OF 1

Fig. 5   Design of the tension test specimen.

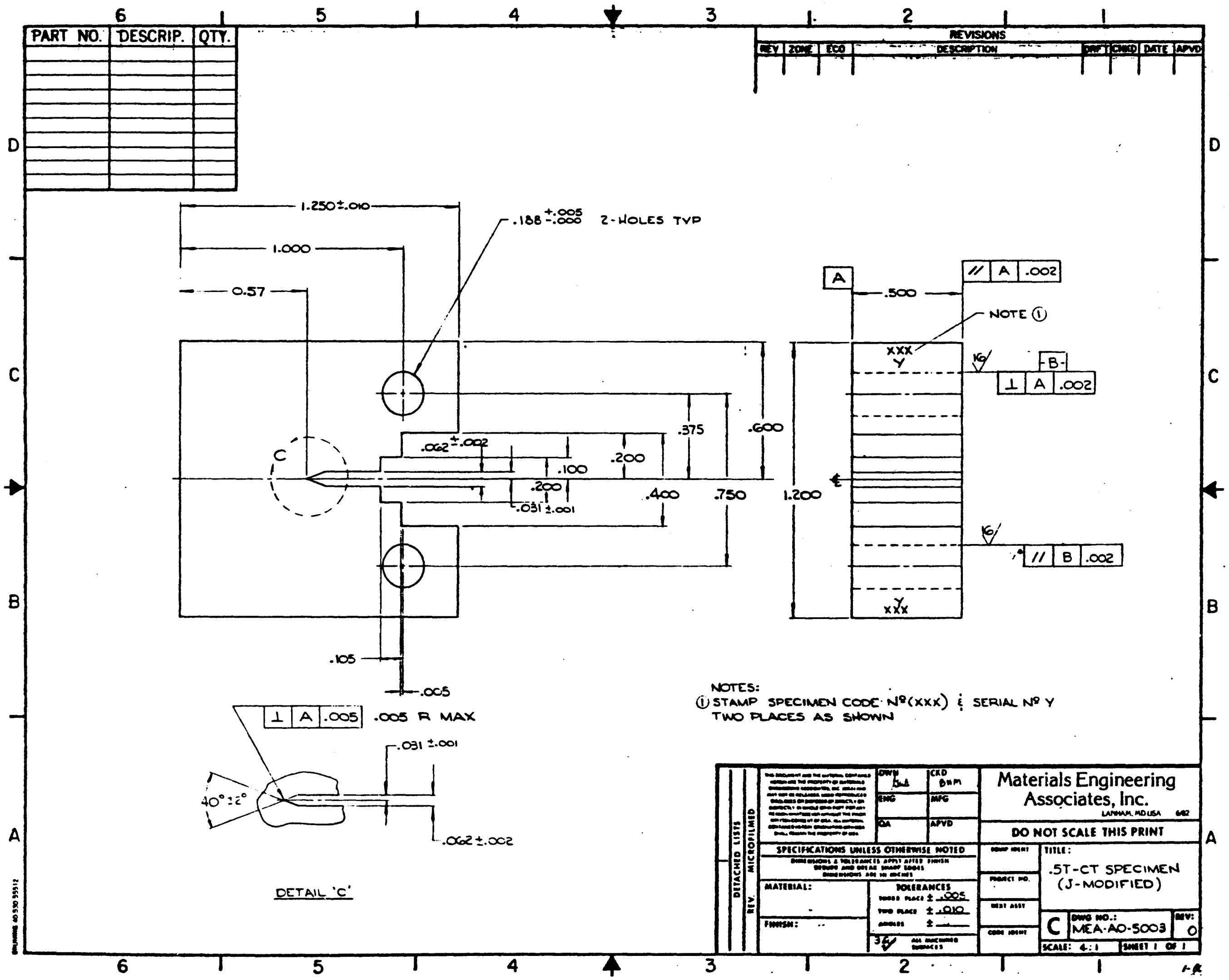


Fig. 6 Design of the 0.5T-CT fracture toughness test specimen.

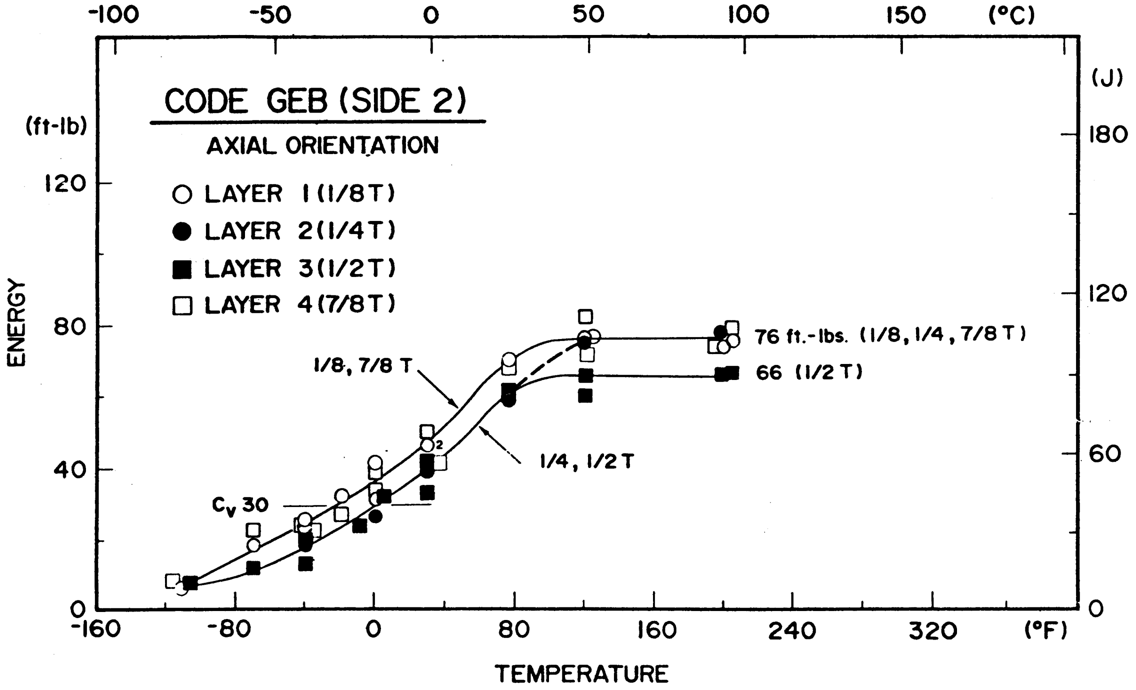


Fig. 7 Charpy-V notch ductility of code GEB-2 material at four locations through the thickness.

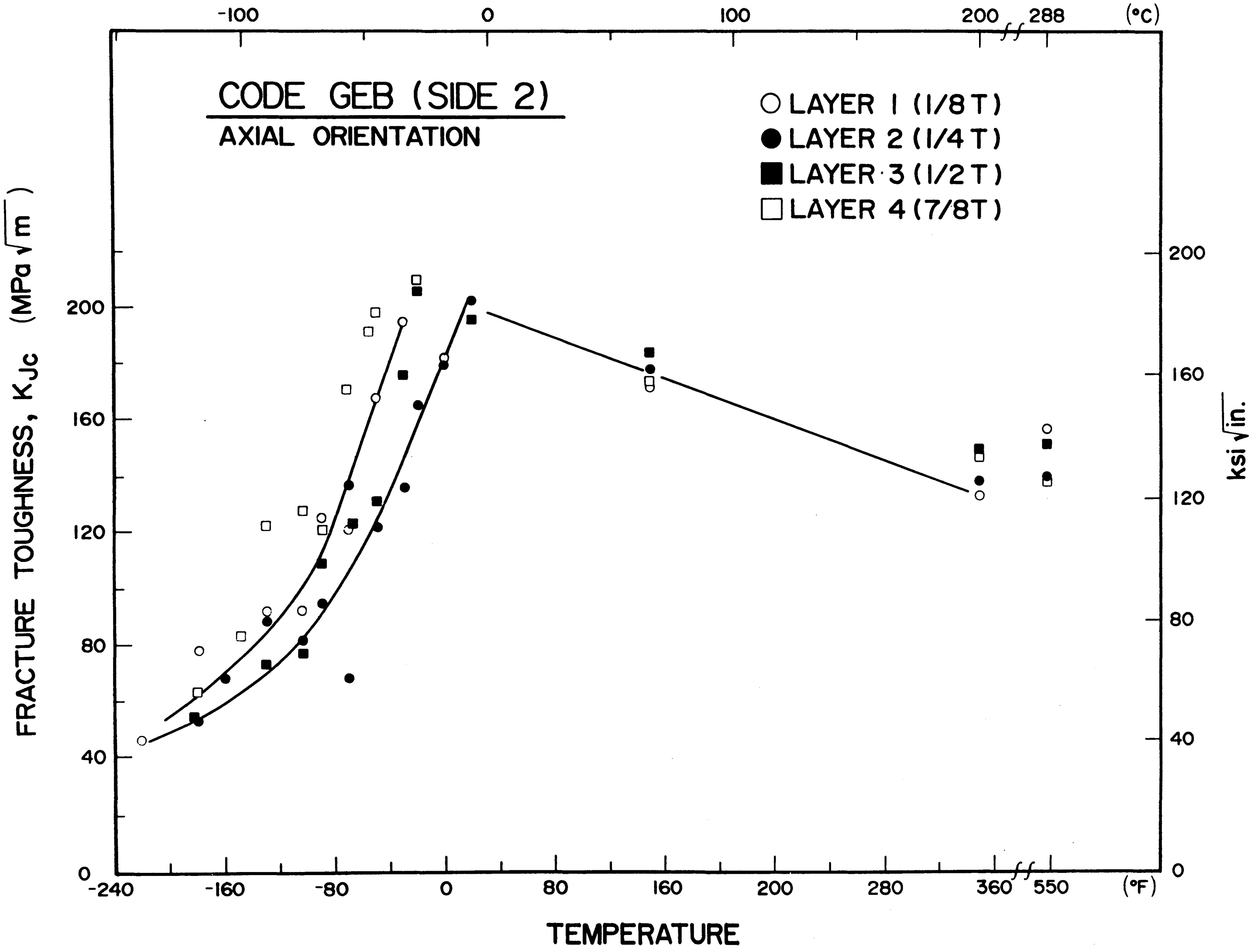


Fig. 8 Fracture toughness of code GEB-2 material at four locations through the thickness.

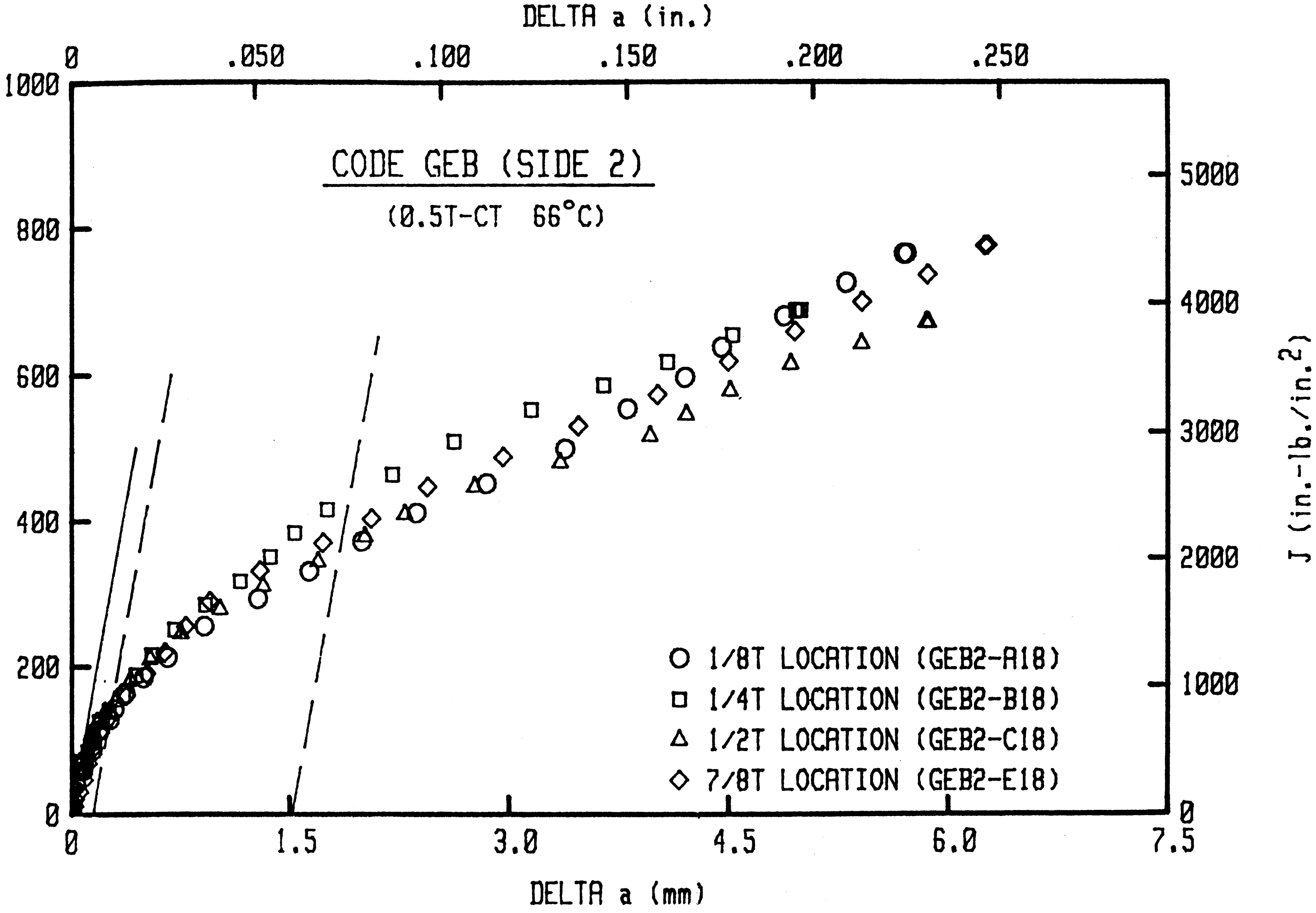


Fig. 9 J-R curve determinations for code GEB-2 material at four locations through the thickness (upper shelf test condition).

Table 1 Tensile Properties of Code GEB-2, Axial Orientation
(5.74-mm diameter, 12.7-mm gage length)

Thickness Location	Specimen Number	Tensile Strength		Yield Strength (0.2% Offset)		Elongation	Reduction
		(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
1/8T	GEB-T9	633	91.8	488	70.8	38.4	61.1
	GEB-T10	633	91.8	488	70.8	39.6	65.4
1/4T	GEB-T1	618	89.6	467	67.8	42.6	65.3
	GEB-T4	621	90.0	471	68.3	38.4	66.8
1/2T	GEB-T11	621	90.0	472	68.4	23.4[a]	57.3
	GEB-T12	621	90.0	467	67.8	40.6	61.6
7/8T	GEB-T13	629	91.3	488	70.8	40.8	65.9
	GEB-T14	631	91.6	488	70.8	40.0	66.4

[a] Failed in gage mark

Table 2 Charpy-V Notch Ductility of Code GEB-2, Axial Orientation

Thickness Layer	Specimen Number	Test Temperature		Energy Absorption		Lateral Expansion		Shear
		(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	(%)
1/8T	36	-1	30	62	46	0.940	37	—
	37	-57	-70	24	18	0.305	12	10
	38	-40	-40	33	24	0.457	18	—
	43	-18	0	43	32	0.432	17	34
	44	93	200	100	74	0.868	34	100
	45	-1	30	62	46	0.533	21	47
	46	49	120	104	77	1.956	69	100
	33	-29	-20	43	32	0.686	27	—
	34	-79	-110	9	7	0.127	5	0
	35	-40	-40	35	26	0.508	20	—
	39	-18	0	56	41	0.559	22	35
	40	93	200	107	79	1.981	78	99
	41	49	120	103	76	0.868	34	100
	42	24	75	95	70	1.600	63	—
1/4T	16	-40	-40	24	18	0.457	18	—
	7	-18	0	35	26	0.660	26	—
	5	-1	30	54	40	0.868	34	—
	3	24	75	80	59	1.245	49	—
	9	49	120	102	75	1.753	61	—
	1	93	200	106	78	1.854	73	100
1/2T	50	-1	30	48	35	0.762	30	—
	51	-57	-70	16	12	0.178	7	16
	52	-40	-40	29	21	0.432	17	—
	63	-18	0	43	32	0.457	18	34
	64	93	200	90	66	0.838	33	100
	65	-1	30	57	42	0.508	20	44
	66	49	120	90	66	1.524	60	—
	47	-23	-10	33	24	0.584	23	—
	48	-79	-110	11	8	0.127	5	0
	49	-40	-40	19	14	0.254	10	—
	59	-18	0	27	20	0.330	13	34
	60	93	200	90	66	1.549	61	99
	61	49	120	81	60	0.762	30	100
	62	24	75	84	62	1.295	51	—
7/8T	56	-1	30	57	42	0.838	33	—
	57	-57	-70	30	22	0.279	11	16
	58	-40	-40	33	24	0.559	22	—
	71	-18	0	46	34	0.483	19	56
	72	93	200	100	74	0.868	34	100
	73	-1	30	66	49	0.584	23	50
	74	49	120	98	72	1.346	53	99
	53	-29	-20	37	27	0.635	25	—
	54	-79	-110	11	8	0.102	4	0
	55	-40	-40	31	23	0.457	18	—
	67	-18	0	53	39	0.559	22	35
	68	93	200	104	77	1.930	76	100
	69	49	120	111	82	0.940	37	100
	70	24	75	92	68	1.499	59	—

Table 3 J-R Curve Results for Code GEB (Side 2)
(Axial Orientation, Layer 1/8T)

Specimen Number	Test Temperature (°C)	Test Temperature (°F)	$(a/W)_o$[a]	Δa_m[b] (mm)	Δa_p[c] (mm)	$\Delta a_p - \Delta a_m$ (mm)	J_{Ic} MEA (kJ/m^2)	J_{Ic} ASTM (kJ/m^2)	K_{Jc} MEA ($MPa\sqrt{m}$)	K_{Jc} ASTM ($MPa\sqrt{m}$)	$K_{\beta c}$ ($MPa\sqrt{m}$)	T_{avg} MEA	σ_f (MPa)	σ_y (MPa)
GEB2-A6	-140	-220	0.509	——[d]	——	——	8.9	——	46.0	45.5	43.4	—	773.9	703.2
GEB2-A13	-118	-180	0.508	——	——	——	26.0	——	78.2	65.3	61.4	—	738.0	667.4
GEB2-A4	-90	-130	0.502	——	——	——	36.1	——	91.8	60.1	64.8	—	695.9	625.3
GEB2-A15	-76	-105	0.509	——	——	——	36.2	——	91.7	52.6	63.8	—	676.5	605.7
GEB2-A2	-68	-90	0.517	——	——	——	67.8	——	125.4	59.6	72.9	—	665.8	595.0
GEB2-A14	-57	-70	0.515	——	——	——	63.7	——	121.5	50.8	70.9	—	651.7	580.7
GEB2-A1	-46	-50	0.502	——	——	——	121.6	——	167.5	56.4	79.8	—	638.3	567.1
GEB2-A3	-34	-30	0.516	——	——	——	165.7	——	195.3	59.3	83.4	—	624.4	552.9
GEB2-A5[e]	-18	0	0.509	——	——	——	137.4	118.1	177.3	164.4	——	—	607.0	535.0
GEB2-A18[e]	65	150	0.525	6.05	5.72	-0.33	129.2	127.4[f]	170.0	168.3	——	99	538.6	463.0
GEB2-A17[e]	177	350	0.522	6.53	6.19	-0.34	81.7	81.5	133.0	132.9	——	115	504.5	420.2
GEB2-A16[e]	288	550	0.514	6.09	6.04	-0.05	117.4	110.5[f]	156.9	152.2	——	56	536.4	439.5

[a] Pretest a/W

[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

[f] Valid J_{Ic}, per ASTM E 813-81

Table 4 J-R Curve Results for Code GEB (Side 2)
(Axial Orientation, Layer 1/4T)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p-\Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	$(MPa\sqrt{m})$	$(MPa\sqrt{m})$	$(MPa\sqrt{m})$		(MPa)	(MPa)
GEB2-B13	-118	-180	0.506	——[d]	——	——	11.9	——	52.9	51.3	47.5	—	726.4	653.5
GEB2-B27	-107	-160	0.504	——	——	——	19.6	——	67.8	59.9	55.3	—	707.9	634.3
GEB2-B4	-90	-130	0.497	——	——	——	33.6	——	88.6	58.1	62.7	—	680.6	606.1
GEB2-B15	-76	-105	0.517	——	——	——	28.8	——	81.9	52.9	59.2	—	659.5	584.2
GEB2-B2	-68	-90	0.508	——	——	——	38.8	——	94.9	58.1	63.0	—	647.9	572.2
GEB2-B14	-57	-70	0.507	——	——	——	20.1	——	68.2	50.5	52.5	—	632.7	556.4
GEB2-B26	-57	-70	0.526	——	——	——	81.2	——	137.1	45.1	72.8	—	632.7	556.4
GEB2-B1	-46	-50	0.506	——	——	——	63.9	——	121.5	56.1	68.1	—	618.2	541.3
GEB2-B25	-34	-30	0.510	——	——	——	80.6	——	136.1	50.6	70.2	—	603.2	525.7
GEB2-B6	-29	-20	0.509	——	——	——	118.2	——	164.7	56.1	75.2	—	597.2	519.5
GEB2-B5	-18	0	0.505	——	——	——	141.0	——	179.7	53.7	76.5	—	584.5	506.3
GEB2-B3[e]	-7	20	0.504	——	——	——	177.7	169.5	201.3	196.6	——	—	572.6	493.8
GEB2-B18[e]	65	150	0.519	5.40	4.97	-0.43	152.2	132.9[f]	184.5	172.4	——	125	512.6	430.7
GEB2-B17[e]	177	350	0.516	6.04	6.03	-0.01	98.0	83.5[f]	145.7	134.5	——	84	481.4	395.6
GEB2-B16[e]	288	550	0.521	6.14	6.05	-0.09	82.5	84.1[f]	131.5	132.8	——	62	525.2	436.7

[a] Pretest a/W
[b] Measured crack growth
[c] Crack growth predicted by compliance
[d] Cleavage failure precluded determination of this quantity
[e] Side grooved by 20%
[f] Valid J_{Ic}, per ASTM E 813-81

Table 5 J-R Curve Results for Code GEB (Side 2)
(Axial Orientation, Layer 1/2T)

Specimen Number	Test Temperature (°C)	Test Temperature (°F)	$(a/W)_o$[a]	Δa_m[b] (mm)	Δa_p[c] (mm)	$\Delta a_p - \Delta a_m$ (mm)	J_{Ic} MEA (kJ/m^2)	J_{Ic} ASTM (kJ/m^2)	K_{Jc} MEA ($MPa\sqrt{m}$)	K_{Jc} ASTM ($MPa\sqrt{m}$)	$K_{\beta c}$ ($MPa\sqrt{m}$)	T_{avg} MEA	σ_f (MPa)	σ_y (MPa)
GEB2-C13	-118	-180	0.509	——[d]	——	——	12.5	——	54.3	52.4	48.3	——	721.6	652.2
GEB2-C4	-90	-130	0.512	——	——	——	23.0	——	73.2	53.3	56.8	——	677.7	607.4
GEB2-C15	-76	-105	0.502	——	——	——	25.5	——	77.0	36.8	57.4	——	657.4	586.7
GEB2-C2	-68	-90	0.511	——	——	——	51.6	——	109.4	60.2	67.4	——	646.3	575.3
GEB2-C14	-57	-70	0.524	——	——	——	65.1	——	122.8	49.6	69.8	——	631.6	560.3
GEB2-C1	-46	-50	0.520	——	——	——	74.3	——	131.0	55.9	70.7	——	617.6	545.9
GEB2-C3	-34	-30	0.505	——	——	——	135.7	——	176.7	47.7	78.3	——	603.2	531.0
GEB2-C6	-29	-20	0.515	——	——	——	185.3	——	206.3	54.5	82.4	——	597.4	525.1
GEB2-C5[e]	-7	20	0.515	6.10	6.12	0.02	167.0	167.2[f]	195.2	195.3	——	78	573.6	500.4
GEB2-C18[e]	65	150	0.510	6.36	5.85	-0.51	155.5	159.4	186.5	188.8	——	99	515.0	438.6
GEB2-C17[e]	177	350	0.509	6.65	6.17	-0.48	115.4	120.1[f]	158.1	161.3	——	73	482.3	399.7
GEB2-C16[e]	288	550	0.498	5.92	6.23	0.31	110.2	99.5[f]	152.0	144.4	——	53	520.2	429.8

[a] Pretest a/W

[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

[f] Valid J_{Ic}, per ASTM E 813-81

Table 6 J-R Curve Results for Code GEB (Side 2)
(Axial Orientation, Layer 7/8T)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p - \Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)		(MPa)	(MPa)
GEB2-E13	-118	-180	0.499	——[d]	——	——	16.8	——	62.8	62.9	53.8	——	736.5	670.7
GEB2-E5	-101	-150	0.502	——	——	——	29.7	——	83.5	61.1	62.6	——	709.3	643.0
GEB2-E4	-90	-130	0.515	——	——	——	64.1	——	122.4	57.7	74.2	——	692.5	626.0
GEB2-E15	-76	-105	0.504	——	——	——	70.0	——	127.6	58.9	74.2	——	672.3	605.3
GEB2-E2	-68	-90	0.520	——	——	——	63.6	——	121.5	38.7	71.9	——	661.2	593.9
GEB2-E14	-57	-70	0.509	——	——	——	126.1	——	170.9	50.6	81.5	——	646.5	578.9
GEB2-E3	-51	-60	0.507	——	——	——	161.0	——	192.9	51.1	84.6	——	638.8	570.9
GEB2-E1	-46	-50	0.516	——	——	——	170.5	——	198.4	50.9	85.0	——	632.5	564.5
GEB2-E6	-29	-20	0.510	——	——	——	174.5	——	200.1	——	——	——	612.3	543.6
GEB2-E18[e]	65	150	0.515	6.43	6.25	-0.18	134.2	134.4	173.3	173.4	——	114	529.9	457.1
GEB2-E17[e]	177	350	0.502	6.46	6.21	-0.25	108.5	104.2[f]	153.3	150.3	——	69	497.2	418.2
GEB2-E16[e]	288	550	0.506	6.16	6.10	-0.06	89.9	88.5[f]	137.3	136.2	——	53	535.0	448.4

[a] Pretest a/W

[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

[f] Valid J_{Ic}, per ASTM E 813-81

APPENDIX D

Daily Operating Temperature Records: Irradiation Experiments UBR-68, UBR-78, UBR-79A, UBR-80A

Operating Temperature Records for UBR-68

(Capsules A and B)

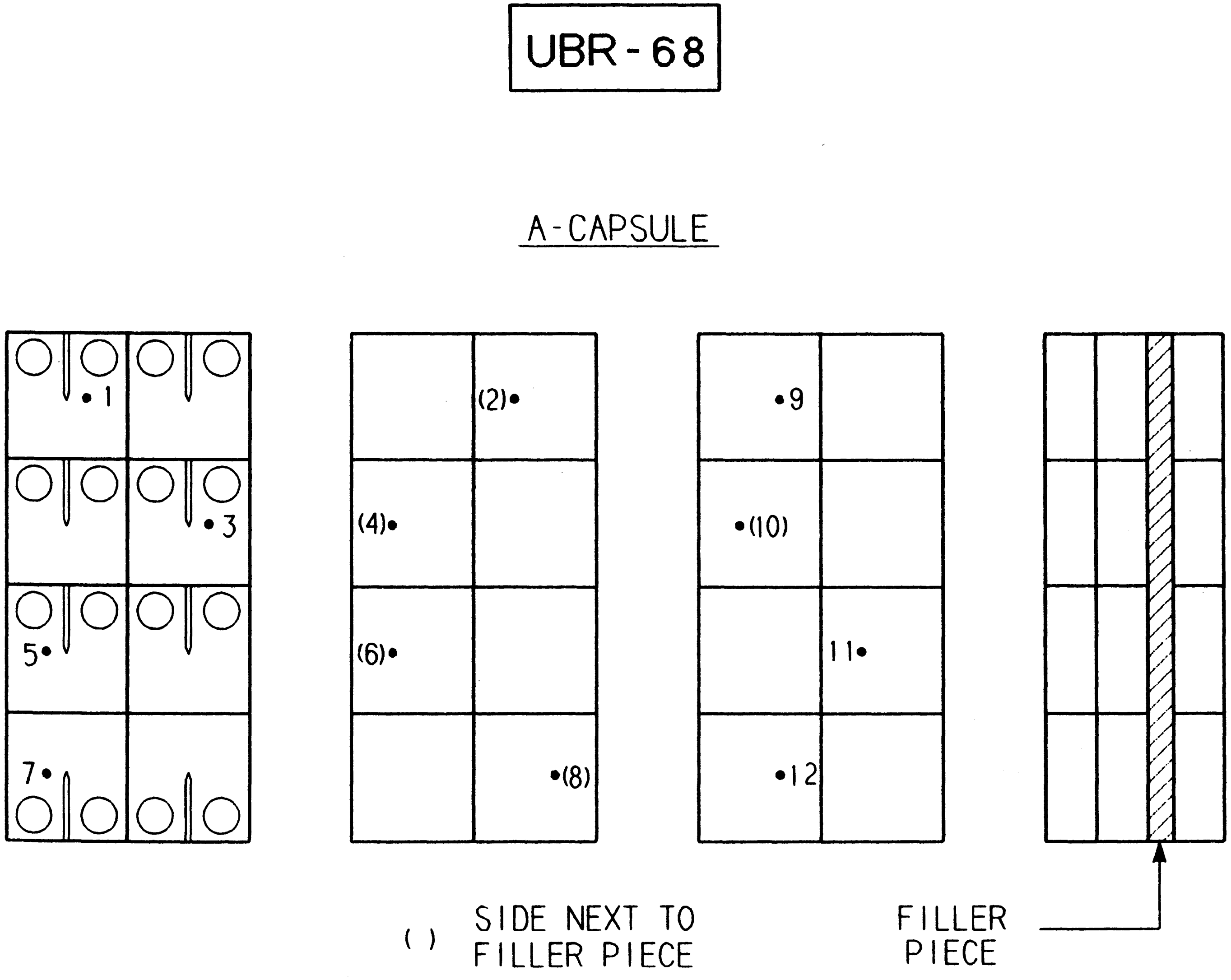


Fig. D-1 Thermocouple Placements on Compact Tension Specimens in Capsule A (UBR-68).

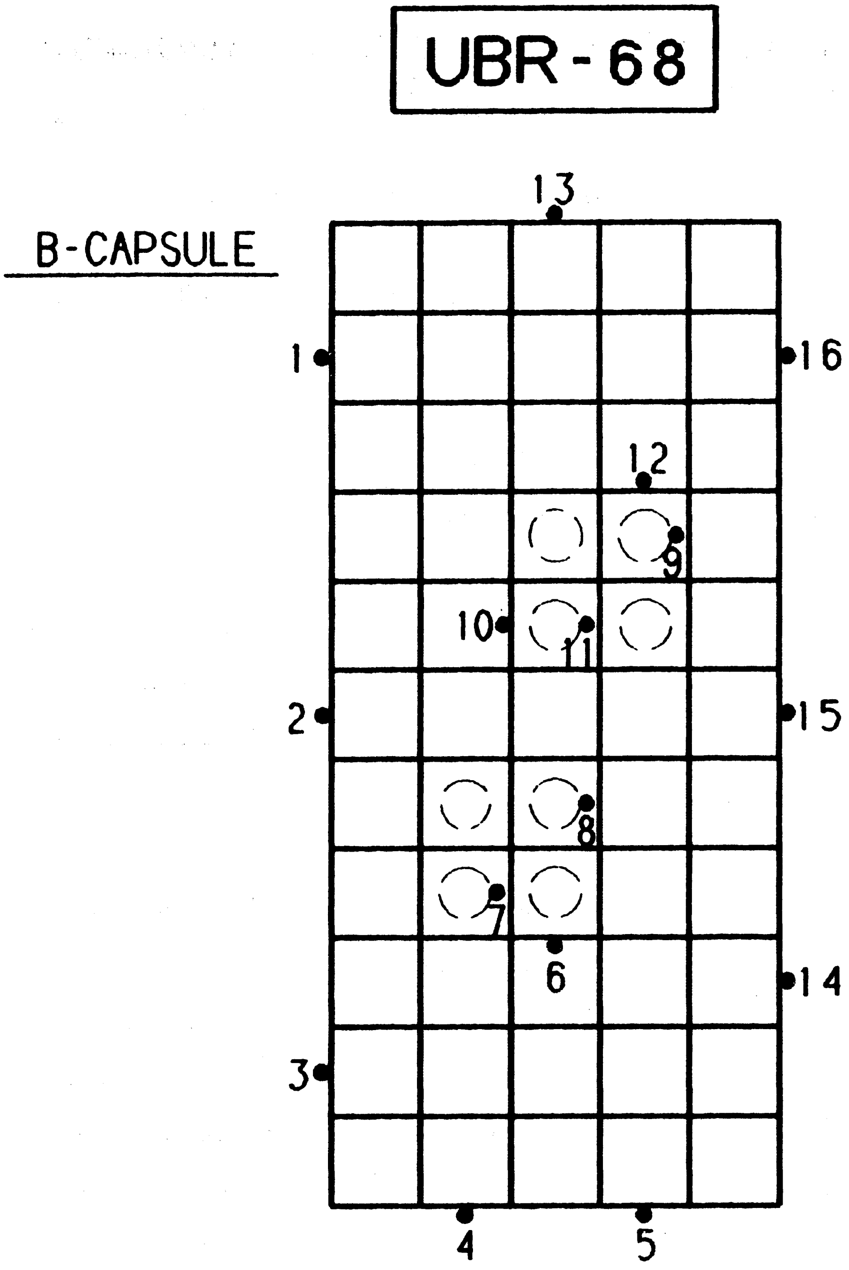


Fig. D-2 Thermocouple Placements on Charpy-V and Tension Test Specimens in Capsule B (UBR-68).

EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-4-86 OBSERVER: KCM

TC: TEMPERATURES, °F

	UNIT A		UNIT B		UNIT C
1	529	1	546	1	
2	535	2	559	2	
3	549	3	562	3	
4	554	4	561	4	
5	556	5	545	5	
6	559	6	550	6	
7	560	7	551	7	
8	556	8	561	8	
9	533	9	564	9	
10	505(?)	10	560	10	
11	548 *	11	556	11	
12	543	12	560	12	
13		13	537	13	
14		14	556	14	
15		15	553 *	15	
16		16	534	16	
	* = CTC		* = CTC		* = CTC

TEMPS TAKEN AT: A 1850 B 1914 C

AVERAGE: A 544 B 553 C
(Excluding CTC)

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-5-86 OBSERVER: DAS

TC: TEMPERATURES, °F

	UNIT A	UNIT B	UNIT C
1	536	543	
2	534	560	
3	557	561	
4	562	560	
5	558	559	
6	571	547	
7	550	562	
8	557	561	
9	541	563	
10	521 (?)	559	
11	554 *	556	
12	-	-	
13		540	
14		555	
15		550 *	
16		536	
	* = CTC	* = CTC	* = CTC

	A	B	C
TEMPS TAKEN AT:	0901	0847	
AVERAGE: (Excluding CTC)	549	554	

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-6-86 OBSERVER: DAS

TC: TEMPERATURES, °F

	UNIT A		UNIT B		UNIT C
1	536	1	545	1	
2	534	2	560	2	
3	557	3	560	3	
4	562	4	559	4	
5	557	5	559	5	
6	571	6	548	6	
7	550	7	562	7	
8	556	8	562	8	
9	542	9	562	9	
10	531	10	559	10	
11	555 *	11	557	11	
12	-	12	-	12	
13		13	542	13	
14		14	555	14	
15		15	551 *	15	
16		16	536	16	
	* = CTC		* = CTC		* = CTC

TEMPS TAKEN AT: A 0854 B 0848 C

AVERAGE: A 550 B 555 C
(Excluding CTC)

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-7-86 OBSERVER: DAS

TC: TEMPERATURES, °F

	UNIT A		UNIT B		UNIT C
1	537	1	541	1	
2	537	2	558	2	
3	559	3	560	3	
4	564	4	559	4	
5	558	5	559	5	
6	572	6	547	6	
7	550	7	562	7	
8	557	8	561	8	
9	544	9	563	9	
10	529	10	558	10	
11	555 *	11	556	11	
12	-	12	-	12	
13		13	538	13	
14		14	554	14	
15		15	550 *	15	
16	-	16	534	16	
	* = CTC		* = CTC		* = CTC

TEMPS TAKEN AT: A 1249 B 1300 C

AVERAGE: A 551 B 554 C
(Excluding CTC)

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-8-86 OBSERVER: DAS

TC: TEMPERATURES, °F

	UNIT A		UNIT B		UNIT C
1	539	1	542	1	
2	547	2	559	2	
3	559	3	560	3	
4	564	4	560	4	
5	558	5	559	5	
6	571	6	547	6	
7	551	7	562	7	
8	559	8	562	8	
9	544	9	564	9	
10	531	10	560	10	
11	555 *	11	558	11	
12	-	12	-	12	
13		13	539	13	
14		14	555	14	
15		15	551 *	15	
16		16	535	16	
* = CTC		* = CTC		* = CTC	

TEMPS TAKEN AT: A 0901 B 0853 C

AVERAGE: A - 552 B 554 C
(Excluding CTC)

EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-12-86 OBSERVER: DAS

TC: TEMPERATURES, °F

TC	UNIT A	UNIT B	UNIT C
1	541	532	
2	541	548	
3	558	551	
4	564	553	
5	574	556	
6	-	544	
7	569	553	
8	560	556	
9	538	558	
10	-	551	
11	550*	551	
12	-	-	
13		534	
14		555	
15		550 *	
16		534	
	* = CTC	* = CTC	* = CTC

TEMPS TAKEN AT: A 0830 B 0842 C

AVERAGE: A 555 B 548 C
(Excluding CTC)

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-13-86 OBSERVER: DAS

TC: TEMPERATURES, °F

	UNIT A	UNIT B	UNIT C
1	531	532	
2	528	549	
3	543	551	
4	551	553	
5	563	557	
6	-	546	
7	561	553	
8	546	557	
9	528	558	
10	-	551	
11	534 *	551	
12	-	-	
13		535	
14		556	
15		551 *	
16		536	
	* = CTC	* = CTC	* = CTC

TEMPS TAKEN AT:	A 1609	B 1606	C
AVERAGE: (Excluding CTC)	A 540	B 549	C

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EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-15-86 OBSERVER: DAS

TC: TEMPERATURES, °F

TC	UNIT A	UNIT B	UNIT C
1	534	534	
2	527	549	
3	545	549	
4	555	552	
5	565	554	
6	568	544	
7	561	548	
8	544	555	
9	531	556	
10	-	550	
11	534 *	550	
12	-	-	
13		535	
14		553	
15		550 *	
16		534	
	* = CTC	* = CTC	* = CTC

TEMPS TAKEN AT: A 1530 B 1501 C

AVERAGE: A 544 B 547 C
(Excluding CTC)

EXPERIMENT TEMPERATURE PERFORMANCE RECORD

EXPERIMENT NUMBER: UBR 68 A,B DATE: 5-19-86 OBSERVER: CLM

TC: TEMPERATURES, °F

TC	UNIT A	UNIT B	UNIT C
1	540	535	
2	531	548	
3	547	548	
4	558	550	
5	563	554	
6	572	546	
7	554	540	
8	539	555	
9	536	556	
10	-	552	
11	535 *	552	
12	-	-	
13	—	537	
14		553	
15		544 *	
16		537	
	* = CTC	* = CTC	* = CTC

TEMPS TAKEN AT: A 0815 B 0810 C

AVERAGE: A 546 B 547 C
(Excluding CTC)

503

Operating Temperature Records for UBR-78

(Capsule A)

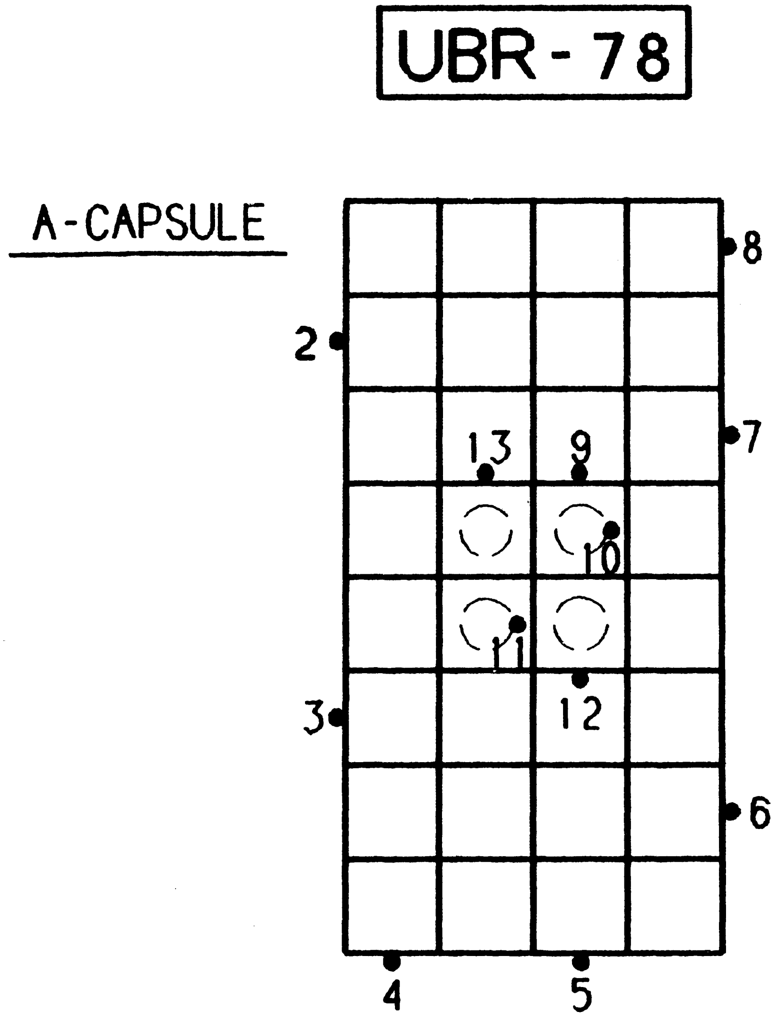

Fig. D-3 Thermocouple Placements on Charpy-V and Tension Test Specimens in Capsule A (UBR-78).

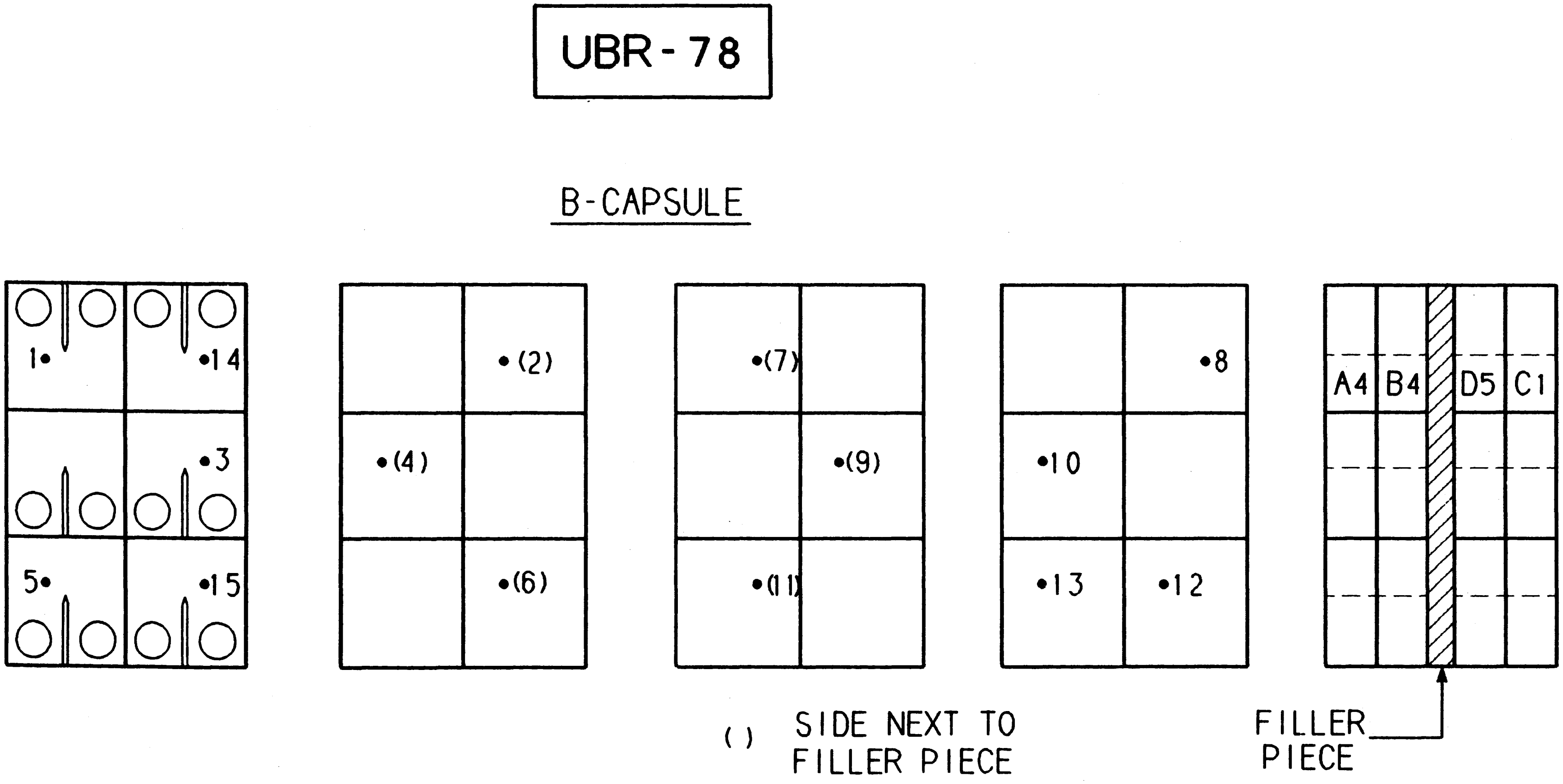

Fig. D-1 Thermocouple Placements on Compact Tension Specimens in Capsule B (UBR-68).

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UBR 78 DAILY TEMPERATURE PERFORMANCE RECORD

DATE 8-18-87 TIME 1025 OBSERVER WEP

TC	UNIT A TEMP, °F	UNIT B TEMP, °F
1	548	472 ‡
2	549	- *
3	517 ‡	456 ‡
4	535	550
5	542	541
6	538	551
7	-*	547
8	544	537
9	554	547
10	558	542
11	547	551
12	551	540
13	553	542
14	554	539
15	558	535
16		
AVG.	545	544

COMMENTS UNIT A : TC Nos. 1,14,15 not applicable to Cv,tensile specimen array

‡ Suspect TC detached from specimen

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

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UBR 78 DAILY TEMPERATURE PERFORMANCE RECORD

DATE 8-19-87 TIME 1130 OBSERVER WEP

TC	UNIT A TEMP, °F	UNIT B TEMP, °F
1	552	454 ‡
2	553	- *
3	521‡	454 ‡
4	540	564
5	546	557
6	541	567
7	- *	561
8	547	548
9	557	559
10	561	555
11	550	567
12	554	558
13	556	558
14	558	551
15	562	553
16		
AVG.	549	558

COMMENTS UNIT A : TC Nos. 1,14,15 not applicable to Cv,tensile specimen array

‡ Suspect TC detached from specimen

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

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UBR-78 DAILY TEMPERATURE PERFORMANCE RECORD

DATE 8-20-87 TIME 0955 OBSERVER WEP

	UNIT A	UNIT B
TC	TEMP, °F	TEMP, °F
1	549	441‡
2	550	- *
3	517‡	447‡
4	536	562
5	543	555
6	538	564
7	- *	559
8	545	544
9	555	555
10	559	552
11	548	565
12	552	555
13	554	557
14	557	548
15	560	552
16		
AVG.	546	556

COMMENTS UNIT A : TC Nos. 1,14,15 not applicable to Cv,tensile specimen array

‡ Suspect TC detached from specimen

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

Operating Temperature Records for UBR-79

(Capsule A)

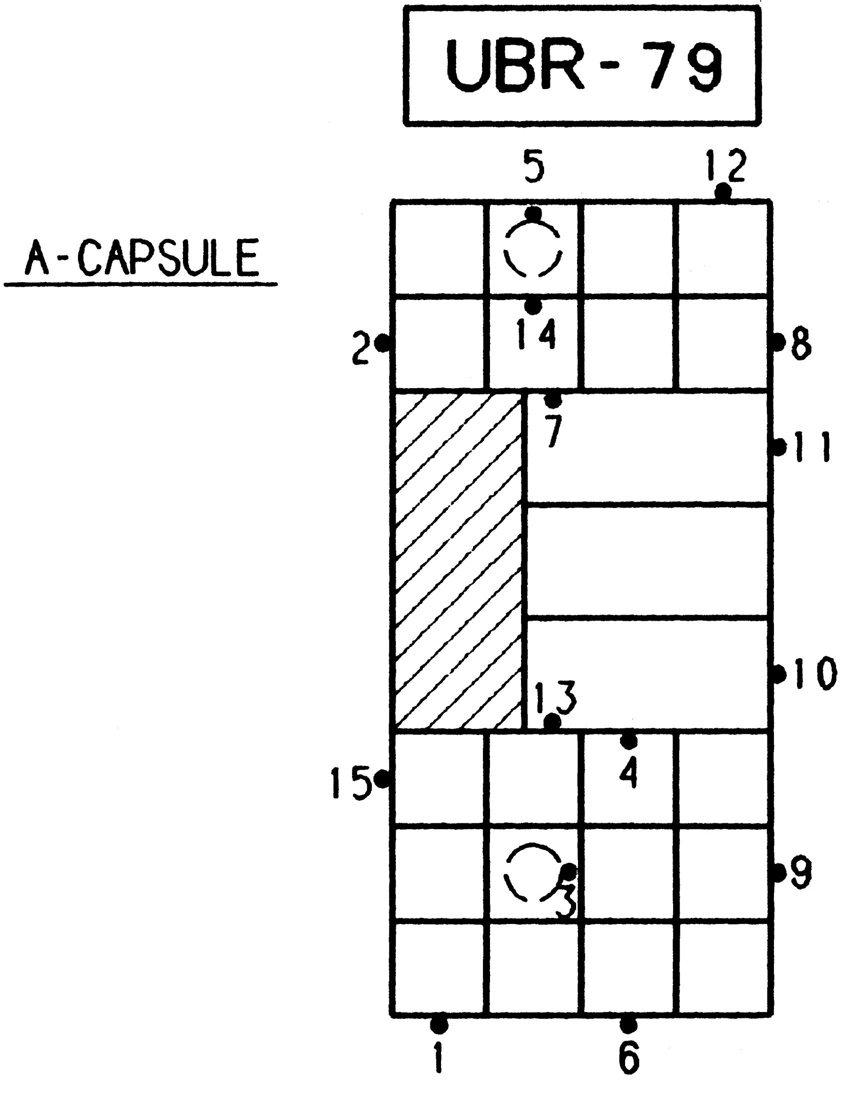

Fig. D-5 Thermocouple Placements on Charpy-V, Tensile and Compact Tension Specimens in Capsule A (UBR-79).

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DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-13-87 TIME 1758 OBSERVER WEP

UNIT 79A

TC	TEMP, °F
1	494
2	520
3	510
4	506
5	526
6	506
7	534
8	528
9	485 *
10	527
11	OPEN
12	519
13	515
14	532
15	494
16	
AVG.	-

COMMENTS (UBR-79A) C_v Set No. 1 : TC Nos. 2,5,8,12,14 ; Cv Set No. 2 :Balance of TC's

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

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DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-13-87 TIME 2012 OBSERVER WEP

UNIT 79A

TC	TEMP, °F
1	507
2	533
3	523
4	519
5	537
6	510
7	546
8	539
9	498*
10	539
11	OPEN
12	529
13	526
14	544
15	507
16	
AVG.	-

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

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DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-14-87 TIME 0915 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	507
2	536
3	524
4	520
5	541
6	510
7	549
8	543
9	495*
10	540
11	OPEN
12	533
13	528
14	548
15	507
16	
AVG.	-

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

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DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-15-87 TIME 1654 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	491
2	522
3	508
4	505
5	528
6	498
7	536
8	533
9	490*
10	540
11	open
12	527
13	521
14	542
15	502
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

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DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-15-87 TIME 2031 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	510
2	539.5
3	527
4	522
5	543
6	510
7	545
8	539
9	495*
10	534
11	open
12	527
13	541
14	521
15	501
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-16-87 TIME 1755 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	503
2	533
3	519
4	515
5	536
6	502
7	542
8	536
9	487*
10	533
11	open
12	525
13	519
14	539
15	499
16	
AVG.	-

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-16-87 TIME 1758 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	495
2	525
3	519
4	515
5	527
6	496
7	529
8	526
9	485*
10	520
11	open
12	513
13	512
14	533
15	493
16	
AVG.	-

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-17-87 TIME 1002 OBSERVER WEP

UNIT 79A

TC	TEMP, °F
1	499
2	528
3	514
4	509
5	531
6	497
7	537
8	525
9	485*
10	525
11	open
12	519
13	513
14	532
15	493
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-20-87 TIME 1937 OBSERVER WEP

UNIT 79A

TC	TEMP, °F
1	504
2	522
3	515
4	517
5	531
6	505
7	534
8	529
9	500*
10	528
11	open
12	523
13	520
14	531
15	497
16	
AVG.	–

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-22-87 TIME 1030 OBSERVER WEP

UNIT 79A

TC	TEMP, °F
1	505
2	531
3	518
4	521
5	542
6	508
7	543
8	539
9	500*
10	536
11	open
12	536
13	529
14	544
15	505
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-22-87 TIME 1657 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	503
2	529
3	515
4	518
5	540.5
6	505
7	541
8	536
9	500 *
10	533
11	open
12	533
13	526
14	541
15	501
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-23-87 TIME 2052 OBSERVER KCM

UNIT 79A

TC	TEMP, °F
1	505
2	529
3	517
4	519
5	537
6	503
7	537
8	533
9	500*
10	537
11	open
12	526
13	518
14	530
15	491
16	
AVG.	-

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-24-87 TIME 1430 OBSERVER DJM

UNIT 79A

TC	TEMP, °F
1	500
2	526
3	512
4	516
5	538
6	503
7	539
8	534
9	500*
10	530
11	open
12	531
13	524
14	539
15	499
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 9-25-87 TIME 0828 OBSERVER CLM

UNIT 79A

TC	TEMP, °F
1	493
2	520
3	506
4	508
5	531
6	496
7	533
8	527
9	490 *
10	525
11	open
12	525
13	518
14	533
15	493
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-1-87 TIME 1354 OBSERVER DJM

UNIT 79A

TC	TEMP, °F
1	498
2	530
3	515
4	512
5	538
6	503
7	542
8	536
9	490*
10	532
11	open
12	528
13	520
14	541
15	499
16	
AVG.	-

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

Operating Temperature Records for UBR-80

(Capsule A)

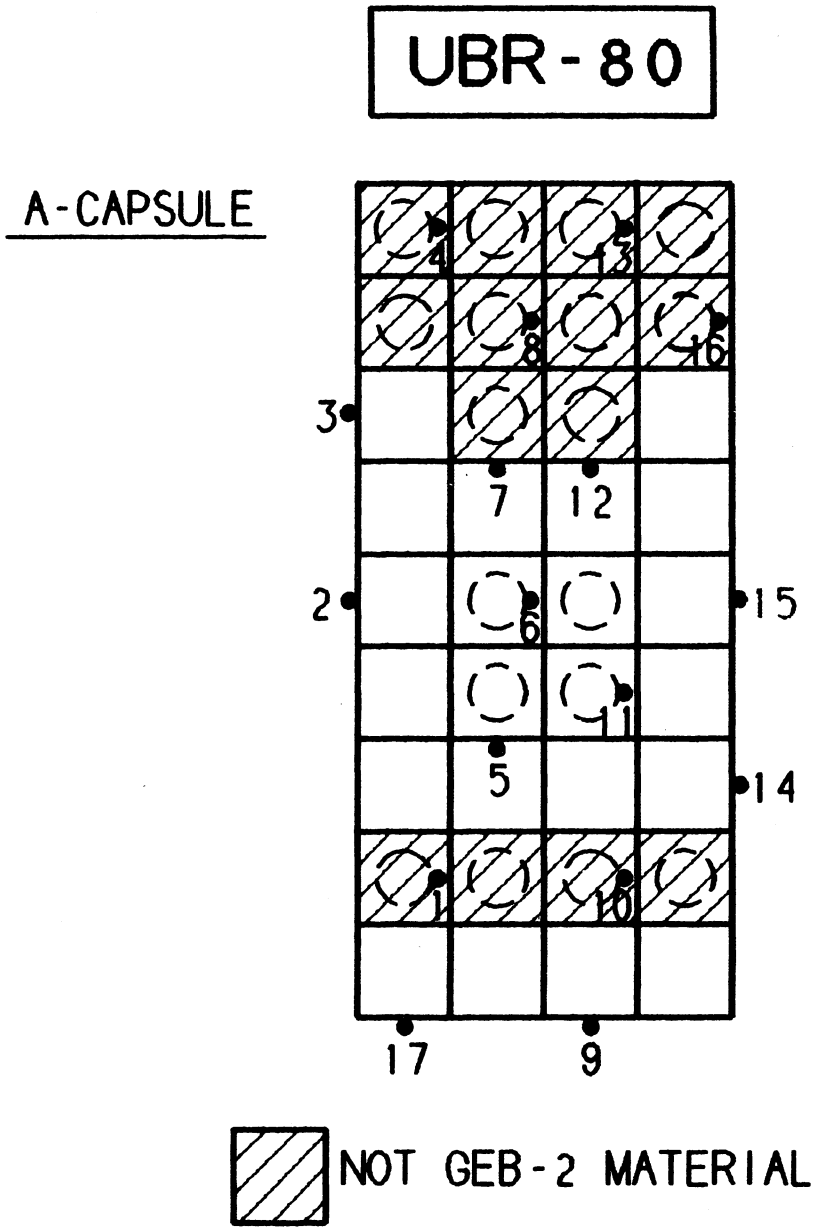

Fig. D-6 Thermocouple Placements on Charpy-V and Tensile Specimens in Capsule A (UBR-80).

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-4-87 TIME 1843 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	550
2	560*
3	547
4	552
5	551
6	559
7	556
8	560
9	535
10	534
11	549
12	554
13	562
14	544
15	536
16	543
17	536
Avg:	548

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-5-87 TIME 1023 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	539
2	560*
3	553
4	559
5	548
6	559
7	559
8	563
9	531
10	532
11	547
12	559
13	567
14	544
15	540
16	554
17	543
Avg:	550

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-6-87 TIME 1137 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	539
2	◯ 560*
3	556
4	563
5	549
6	560
7	561
8	565
9	530
10	532
11	547
12	561
13	570
14	543
15	540
16	556
17	540
Avg:	551

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-7-87 TIME 1039 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	537
2	560*
3	555
4	562
5	548
6	560
7	562
8	565
9	529
10	531
11	546
12	561
13	570
14	544
15	541
16	557
17	531
Avg:	550

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-8-87 TIME 1141 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	541
2	◯560*
3	559
4	566
5	552
6	563
7	565
8	569
9	532
10	534
11	549
12	564
13	573
14	546
15	543
16	560
17	533
Avg:	553

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-12-87 TIME 0901 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	538
2	555*
3	551
4	557
5	547
6	558
7	559
8	561
9	530
10	531
11	546
12	557
13	565
14	542
15	538
16	551
17	531
Avg:	548

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-13-87 TIME 1549 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	538
2	554*
3	552
4	558
5	547
6	558
7	560
8	563
9	530
10	541
11	546
12	560
13	569
14	543
15	540
16	555
17	531
Avg:	550

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-14-87 TIME 0806 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	539
2	560*
3	555
4	562
5	550
6	561
7	563
8	566
9	531
10	533
11	548
12	560
13	569
14	543
15	540
16	555
17	532
Avg:	517

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-15-87 TIME 1314 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	537
2	558*
3	554
4	562
5	549
6	560
7	562
8	566
9	530
10	532
11	547
12	560
13	571
14	544
15	541
16	556
17	531
Avg:	550

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-19-87 TIME 0230 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	539
2	558*
3	550
4	556
5	550
6	559
7	556
8	561
9	533
10	533
11	548
12	557
13	564
14	543
15	538
16	549
17	533
Avg:	550

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-20-87 TIME 1251 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	538
2	553*
3	549
4	551
5	541
6	551
7	558
8	562
9	529
10	531
11	546
12	558
13	568
14	563
15	539
16	553
17	532
Avg:	548

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-21-87 TIME 1520 OBSERVER CLM

UNIT 80A

TC	TEMP, °F
1	540
2	562*
3	565
4	574
5	563
6	574
7	574
8	579
9	545
10	546
11	561
12	573
13	583
14	557
15	553
16	566
17	545
Avg:	562

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-22-87 TIME 1309 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	538
2	558*
3	552
4	560
5	550
6	560
7	561
8	565
9	532
10	533
11	549
12	559
13	569
14	543
15	540
16	552
17	553
Avg:	551

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-25-87 TIME 1649 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	542
2	564*
3	554
4	561
5	553
6	561
7	560
8	567
9	539
10	541
11	555
12	559
13	571
14	549
15	546
16	553
17	536
Avg:	554

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-26-87 TIME 0928 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	541
2	555*
3	553
4	563
5	552
6	560
7	560
8	568
9	536
10	538
11	553
12	558
13	570
14	547
15	545
16	553
17	534
Avg:	552

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-27-87 TIME 0934 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	542
2	564*
3	554
4	564
5	551
6	560
7	560
8	568
9	536
10	538
11	554
12	560
13	574
14	548
15	547
16	557
17	535
Avg:	553

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-28-87 TIME 1829 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	534
2	550 *
3	550
4	559
5	546
6	534
7	555
8	556
9	535
10	533
11	549
12	554
13	568
14	541
15	540
16	549
17	528
Avg:	546

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
   * = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.

STRUCTURAL INTEGRITY TECHNOLOGY

CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-29-87 TIME 0713 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	534
2	557*
3	549
4	559
5	546
6	555
7	556
8	564
9	531
10	533
11	548
12	554
13	567
14	541
15	540
16	549
17	529
Avg:	548

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 10-30-87 TIME 1016 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	534
2	550*
3	548
4	558
5	546
6	554
7	555
8	563
9	531
10	533
11	548
12	552
13	565
14	540
15	538
16	546
17	528
Avg:	546

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-1-87 TIME 2040 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	534
2	557*
3	544
4	552
5	546
6	554
7	553
8	560
9	532
10	534
11	548
12	551
13	561
14	541
15	538
16	543
17	530
Avg:	546

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-2-87 TIME 1151 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	537
2	555*
3	550
4	560
5	549
6	558
7	557
8	566
9	534
10	536
11	551
12	556
13	569
14	544
15	542
16	550
17	532
Avg:	549

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

TES, INC.
ATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

11-1-87 TIME 2040 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	534
2	557*
3	544
4	552
5	546
6	554
7	553
8	560
9	532
10	534
11	548
12	551
13	561
14	541
15	538
16	543
17	530
Avg:	546

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
   * = CTC

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MATERIALS ENGINEERING ASSOCIATES, INC.
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1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-3-87 TIME 1721 OBSERVER KCM

UNIT 80A

TC	TEMP, °F
1	534
2	550*
3	548
4	558
5	546
6	555
7	555
8	564
9	531
10	534
11	549
12	553
13	567
14	540
15	538
16	546
17	528
Avg:	547

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

JG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-5-87 TIME 0922 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	533
2	557*
3	547
4	557
5	546
6	555
7	554
8	564
9	531
10	534
11	549
12	553
13	568
14	540
15	538
16	546
17	528
Avg:	547

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
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1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-8-87 TIME 1846 OBSERVER WEP

UNIT 80A

TC	TEMP, °F
1	535
2	557*
3	544
4	552
5	547
6	554
7	552
8	560
9	533
10	535
11	550
12	551
13	562
14	541
15	538
16	543
17	530
Avg:	546

COMMENTS

NOTE:
1. Temps are "omnical" unless otherwise noted
2. ○ = not included in avg.
* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

1G DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-10-87 TIME 1253 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	535
2	551 *
3	549
4	560
5	548
6	557
7	556
8	566
9	532
10	535
11	551
12	554
13	569
14	541
15	539
16	548
17	529
	Avg: 548

COMMENTS

NOTE:

1. Temps are "omnical" unless otherwise noted
2. ◯ = not included in avg.

* = CTC

MATERIALS ENGINEERING ASSOCIATES, INC.
STRUCTURAL INTEGRITY TECHNOLOGY
CORROSION FATIGUE • FRACTURE MECHANICS TESTING • IRRADIATIONS

IG DAILY TEMPERATURE PERFORMANCE RECORD

DATE 11-12-87 TIME 1418 OBSERVER DJM

UNIT 80A

TC	TEMP, °F
1	534
2	551*
3	549
4	560
5	548
6	556
7	556
8	566
9	533
10	535
11	551
12	555
13	571
14	543
15	541
16	549
17	530
Avg:	549

COMMENTS

NOTE: 1. Temps are "omnical" unless otherwise noted

2. ○ = not included in avg.

* = CTC

APPENDIX E

Neutron Dosimetry Determinations: Irradiation Experiments UBR-68, UBR-78 UBR-79A, UBR-80A

References

1. J. W. Rogers, "Neutron Fluence Rates for MEA-UBR Experiments: Letter Report JWR-34-86", Idaho Nuclear Engineering Laboratory, 17 November 1986.

2. J. W. Rogers, "Neutron Fluence Rates for MEA-UBR Experiments: Letter Report JWR-53-87", Idaho Nuclear Engineering Laboratory, 6 November 1987.

2. J. W. Rogers, "Neutron Fluence Rates for MEA-UBR Experiments: Letter Report JWR-29-88", Idaho Nuclear Engineering Laboratory, 10 August 1988.

Neutron Dosimetry Determinations Based on Fission Spectrum Assumption for UBR-68 (Capsules A and B)

Table E-1 Irradiation Experiment UBR-68 Capsule A Fluence-Rate Monitor Results (Ref. 1)

Monitor/Segment[a]		Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
A1	(Fe)	5.58	Specimens A25 to A30
	(Ni)	5.61	
A3	(Fe)	5.70	Specimens A27 to A34
A4	(Fe)	6.28	Specimens A7 to A29
A2	(Fe)	6.30	Specimens A9 to A35
A5	(Fe)	6.44	Specimens A26 to A31
	(Ni)	6.50	
A6	(Fe)	6.73	Specimens A23 to A36
A7	(Fe)	7.24	Specimens A24 to A8
A8	(Fe)	7.18	Specimens A21 to A28
	(AgCo)	4.14[c]	
Vial	(^{238}U)	8.26[d] (9.42)[e]	Filler piece, Specimens A32 to A8
	(Fe)	6.63	
	(Ni)	6.72	

[a] See Fig. 6 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns respectively. Corrections for epithermal neutron contributions are based on Co-Cadmium ratios obtained from a special MEA-HEDL-UBR mockup experiment irradiation (applies to Tables E-2 to E-6 also).

[b] Fission spectrum assumption; n/cm^2-s^{-1} (E >1 MeV) unless noted.

[c] Thermal fluence rate corrected for epithermal neutron contributions based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.

[d] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs, ^{140}BaLa.

[e] Calculated spectrum value.

Summary, Capsule UBR-68A

1. Average neutron fluence (all specimens): 8.6 x 10^{18} n/cm^2 E >1 MeV (calculated spectrum fluence).
2. Average dpa (E >1 MeV): 1.39 x 10^{-2}.
3. Exposure hours: 249.0 (C-2 facility).

Table E-2 Irradiation Experiment UBR-68 Capsule B Fluence-Rate Monitor Results (Ref. 1)

Monitor/Segment[a]		Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
B1	(Fe)	7.24	Between layers 1 and 2
	(AgCo)	3.64[c]	
B3	(Fe)	7.04	Between layers 3 and 4
	(Ni)	6.87	
B5	(Fe)	6.82	Between layers 6 and 7
	(Ni)	6.67	
B6	(Fe)	6.71	Between layers 8 and 9
	(Co)	3.40	
B7	(Fe)	6.52	Between layers 10 and 11
	(Ni)	6.39	
B2	(Fe)	-d-	Between layers 2 and 3
B8	(Fe)	6.65[e]	Immediately below layer 11
Vial	(^{238}U)	8.31[f] (9.47)[g]	Between layers 4 and 5
	(Fe)	6.79	
	(Ni)	6.97	

[a] See Fig. 6 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns, respectively.

[b] Fission spectrum assumption; n/cm^2-s^{-1} (E >1 MeV) unless noted.

[c] Thermal fluence rate corrected for epithermal neutron contributions based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.

[d] Lost in decanning experiment.

[e] Based on one dosimeter section only (data for two other sections not available).

[f] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs, ^{140}BaLa.

[g] Calculated spectrum value.

Summary, Capsule UBR-68B

1. Average neutron fluence (all specimens): 8.76 x 10^{18} n/cm^2 E >1 Mev (calculated spectrum fluence).
2. Average dpa (E >1 MeV): 1.42 x 10^{-2}.
3. Exposure hours: 249.0 (C-2 facility).

Neutron Dosimetry Determinations
Based on Fission Spectrum Assumption
for UBR-78 (Capsules A and B)

Table E-3 Irradiation Experiment UBR-78 Capsule A Fluence-Rate Monitor Results (Ref. 2)

Monitor/Segment[a]	Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
A2 (Fe)	6.50	Immediately above layer 1
(Ni)	6.26	
A3 (Fe)	6.59	Between layers 1 and 2
(Co)	1.96[c]	
A4 (Fe)	-d-	Between layers 3 and 4
(Ni)	-d-	
A5 (Fe)	6.80	Between layers 5 and 6
A6 (AgCo)	2.08[e]	Between layers 6 and 7
A7 (Fe)	6.82	Between layers 7 and 8
(Ni)	6.75	
Vial (^{238}U)	7.83[f]	Between layers 4 and 5
	(8.93)[g]	
(Fe)	6.71	
(Ni)	6.74	

[a] See Fig. 20 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns, respectively.

[b] Fission spectrum assumption; n/cm^2-s^{-1} (E >1 MeV) unless noted.

[c] Based on one dosimeter section only.

[d] Not available.

[e] Thermal fluence rate corrected for epithermal neutron contributions based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.

[f] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs, ^{140}BaLa.

[g] Calculated spectrum value.

Summary, Capsule UBR-78A

1. Average neutron fluence (all specimens): 2.67 x 10^{18} n/cm^2 E >1 Mev (calculated spectrum fluence).
2. Average dpa (E >1 MeV): 0.43 x 10^{-2}.
3. Exposure hours: 78.0 (B-4 facility).

Table E-4 Irradiation Experiment UBR-78 Capsule B Fluence-Rate Monitor Results (Ref. 2)

Monitor/Segment[a]		Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
B11	(Fe)	6.29	Specimen A3 to E3
B12	(Fe)	6.79	Specimen A4 to C1
B10	(Fe)	6.31[c]	Specimen D1 to D3
	(Ni)	5.76	
B13	(Fe)	7.22	Specimen D6 to D4
	(Ni)	7.10	
B8	(Fe)	5.71	Specimen E1 to B6
B9	(Fe)	6.61	Specimen C2 to B1
	(Co)	1.95[d]	
Vial	(^{238}U)	7.32[e] (8.34)[f]	Filler piece, Specimen D2 to A5
	(Fe)	6.17	
	(Ni)	6.30	

[a] See Fig. 20 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns, respectively.

[b] Fission spectrum assumption; n/cm^2-s^{-1} (E >1 MeV) unless noted.

[c] Based on two dosimeter sections only (data for two other sections not available).

[d] Based on one dosimeter section only.

[e] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs, ^{140}BaLa.

[f] Calculated spectrum value.

Summary, Capsule UBR-78B

1. Average neutron fluence (all specimens): 2.60 x 10^{18} n/cm^2 E >1 Mev (calculated spectrum fluence).
2. Average dpa (E >1 MeV): 0.42 x 10^{-2}.
3. Exposure hours: 78.0 (B-4 facility).

Neutron Dosimetry Determinations
Based on Fission Spectrum Assumption
for UBR-79 (Capsule A)

Table E-5 Irradiation Experiment UBR-79A Capsule A Fluence-Rate Monitor Results (Ref. 3)

Monitor/Segment[a]		Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
A3	(Fe)	6.64	Immediately above layer 1
	(Co)	3.30	
A8	(Fe)	6.62	Between layers 2 and 3
	(Ni)	6.34	
A21	(Fe)	6.76	Between layers 5 and 6
	(Ni)	6.50	
A13	(Fe)	6.87	Between layers 7 and 8
	(Ni)	6.60	
	(AgCo)	3.38[c]	
Vial	(^{238}U)	8.05[d] (9.18)[e]	Filler piece, layer 4
	(Fe)	6.77	
	(Ni)	6.53	

[a] See Fig. 21 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns, respectively.

[b] Fission spectrum assumption; n/cm^{2}-s^{-1} (E >1 MeV) unless noted.

[c] Thermal fluence rate corrected for epithermal neutron contributions based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.

[d] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs. ^{140}BaLa.

[e] Calculated spectrum value.

<u>Summary, Capsule UBR-79A</u>

1. Average neutron fluence C_V Group no. 1: 8.5 x 10^{18} n/cm^{2} E >1 Mev (calculated spectrum fluence).
   C_V Group no. 2: 8.8 x 10^{18} n/cm^{2} E >1 MeV.
   CT specimens: 8.6 x 10^{18} n/cm^{2} E >1 MeV.
2. Average dpa (E >1 MeV): C_V Group no. 1: 1.38 x 10^{-2}.
   C_V Group no. 2: 1.43 x 10^{-2}
   CT Specimens 1.39 x 10^{-2}
3. Exposure hours: 250 .03 (B-4 facility).

Neutron Dosimetry Determinations
Based on Fission Spectrum Assumption
for UBR-80 (Capsule A)

Table E-6 Irradiation Experiment UBR-80 Capsule A Fluence-Rate Monitor Results (Ref. 3)

Monitor/Segment[a]		Fluence Rate[b] x 10^{12} (Average)	Monitor Location in Specimen Array
A20	(Fe)	6.45	Immediately above layer 1
	(Ni)	6.21	
A2	(Fe)	6.50	Between layers 2 and 3
A11	(AgCo)	3.15[c]	Between layers 3 and 4
A27	(Fe)	6.57	Between layers 4 and 5
	(Ni)	6.25	
A10	(Fe)	-d-	Between layers 6 and 7
A26	(Co)	3.25[c]	Between layers 7 and 8
A7	(Fe)	6.82	Between layers 8 and 9
	(Ni)	6.49	
Vial	(^{238}U)	7.87[e] (8.97)[f]	Between layers 5 and 6
	(Fe)	6.42	
	(Ni)	6.65	

[a] See Fig. 22 in main text for monitor locii. The Fe,Ni and ^{238}U results are based on >1 MeV ^{235}U fission spectrum averaged cross sections of 115.2, 156.8, and 441 millibarns, respectively.

[b] Fission spectrum assumption; n/cm^{2}-s^{-1} (E >1 MeV) unless noted.

[c] Thermal fluence rate corrected for epithermal neutron contributions based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.

[d] Not available.

[e] Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}Cs, ^{140}BaLa.

[f] Calculated spectrum value.

Summary, Capsule UBR-80A

1. Average neutron fluence (GEB-2 specimens only); 2.25 x 10^{19} n/cm^{2} E > 1 MeV (calculated spectrum).
2. Average dpa (E >1 MeV): 3.65 x 10^{-2}
3. Exposure hours: 657.98 (B-4 facility).

APPENDIX F

Charpy-V Data Tabulation and Computer Curve Fits for Unirradiated Condition Tests and Irradiation Experiment UBR-68, UBR-78, UBR-79A, and UBR-80A Tests

OVERVIEW

The data curve fitting procedure employed the hyperbolic tangent curve fitting method. Two curves are provided here for each data set: the curve illustrated in the first figure for the set shows the results obtained with the available data; the curve in the companion figure is the result obtained when four fictitious data points (5 ft-lb energy absorption) are added at a temperature that is 50°F below the intercept of a line representing a linearized transition region, with the abscissa. The line in this case is an eyeball fit to the data; the choice of a larger temperature shift (up to 100°F) was found not to influence the result appreciably.

The intentional addition of the fictitious data serves to force the curve to a reasonably low, positive value in the toe region. This device is particularly useful for those cases where data are lacking in the toe region for guiding the computer in its setting of bounding conditions. It will be noted that the American Society for Testing and Materials has not issued a standard method or a standard guide for curve-fitting C_v data for the irradiated condition.

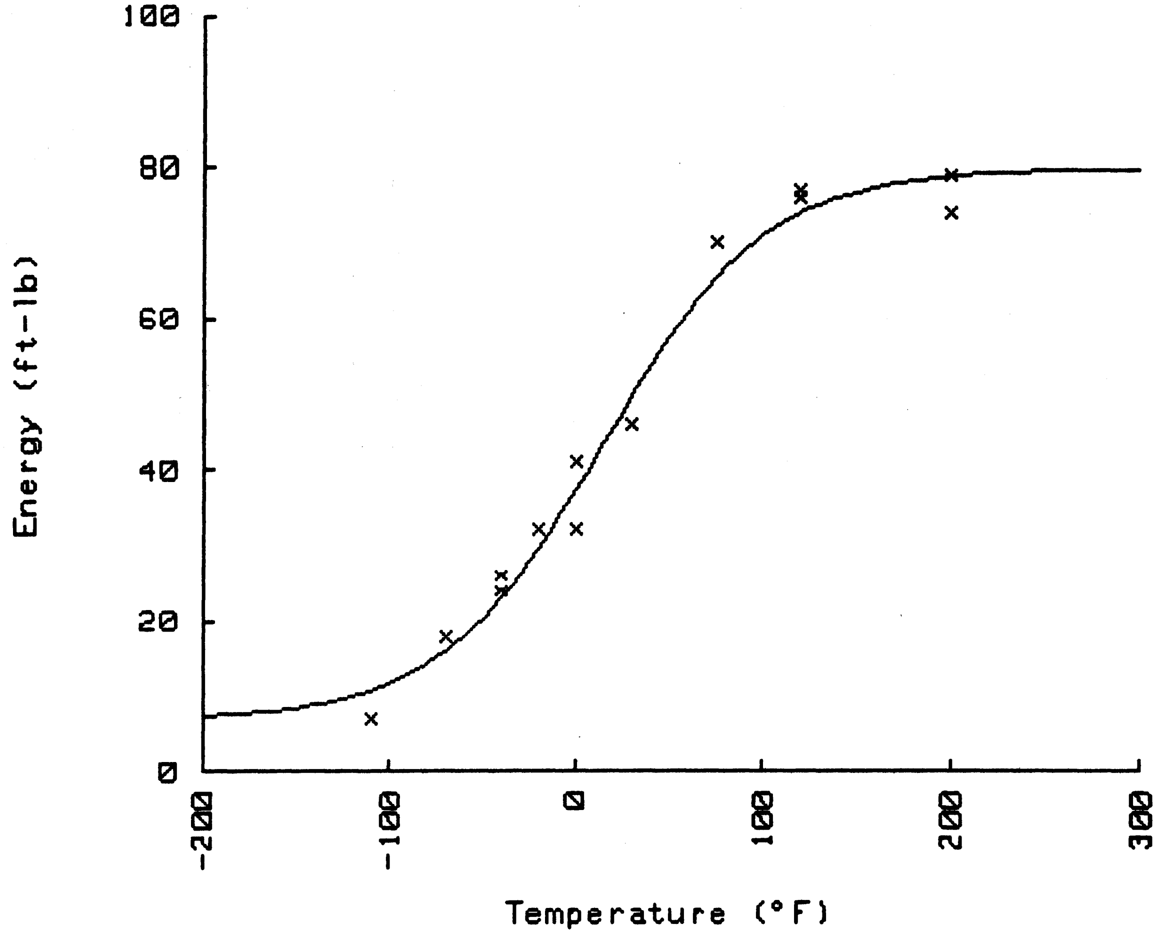
Unirradiated Condition Charpy-V Test Results

Including Special Check Test Data

Code GEB (Side 2) - Unirradiated Condition
1/8T Thickness Location
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	34	3 2	-110	7.0	5	0
2	37	3 1	-70	18.0	18	10
3	38	3 1	-40	24.0	18	<100
4	35	3 2	-40	26.0	20	<100
5	33	3 2	-20	32.0	27	<100
6	43	3 1	0	32.0	29	34
7	39	3 2	0	41.0	38	35
8	36	3 1	30	46.0	37	<100
9	45	3 1	30	46.0	40	47
10	42	3 2	75	70.0	63	<100
11	41	3 2	120	76.0	66	100
12	46	3 1	120	77.0	69	100
13	44	3 1	200	74.0	65	100
14	40	3 2	200	79.0	78	99

Cv data
File : U-1/8A

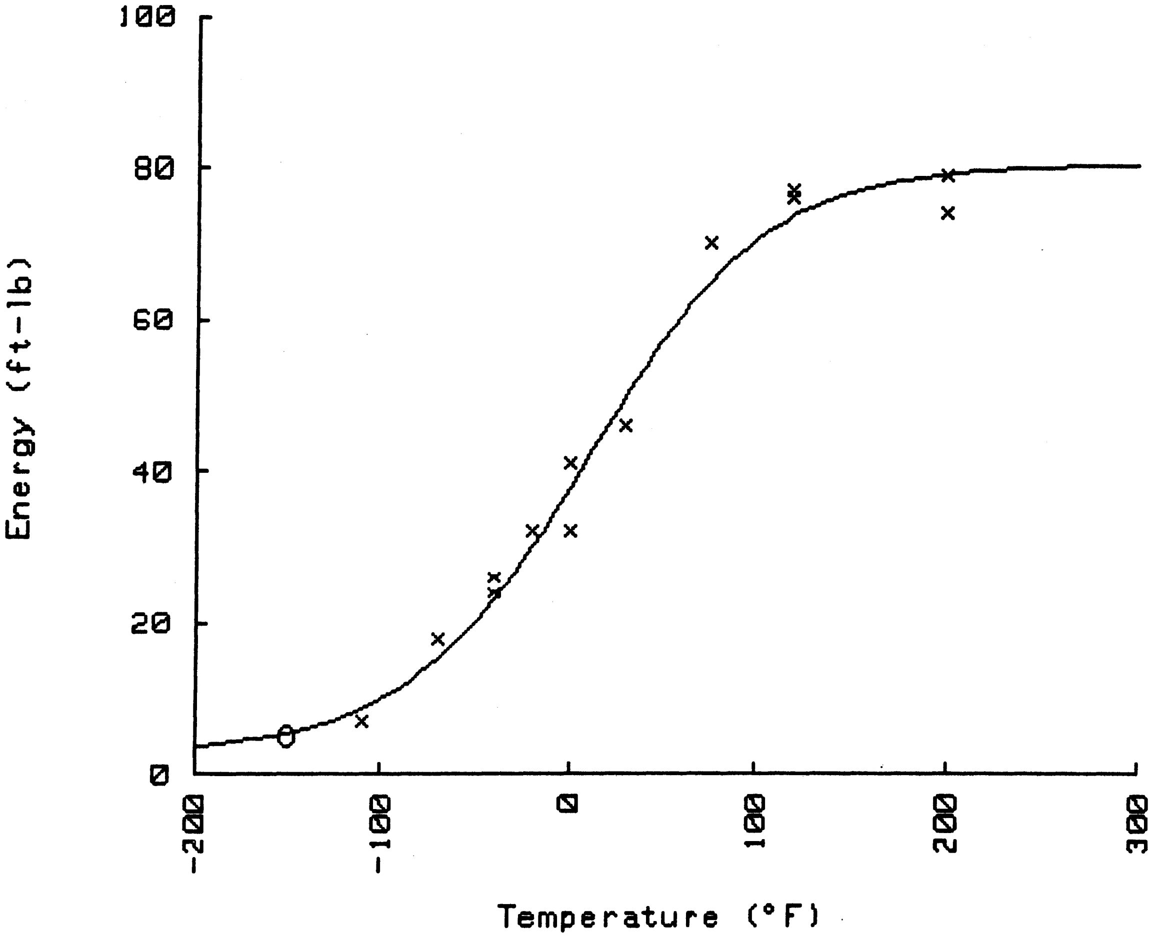


$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	43.39	58.84
B =	36.53	49.53
C =	86.89	48.27
To =	14.56	-9.69

Cv = 30 ft-lb or 41.7 J when T = -18.9 -28.3

Cv data
File : U-1/8A



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	41.68	56.51
B =	38.90	52.75
C =	95.43	53.01
To =	9.42	-12.55

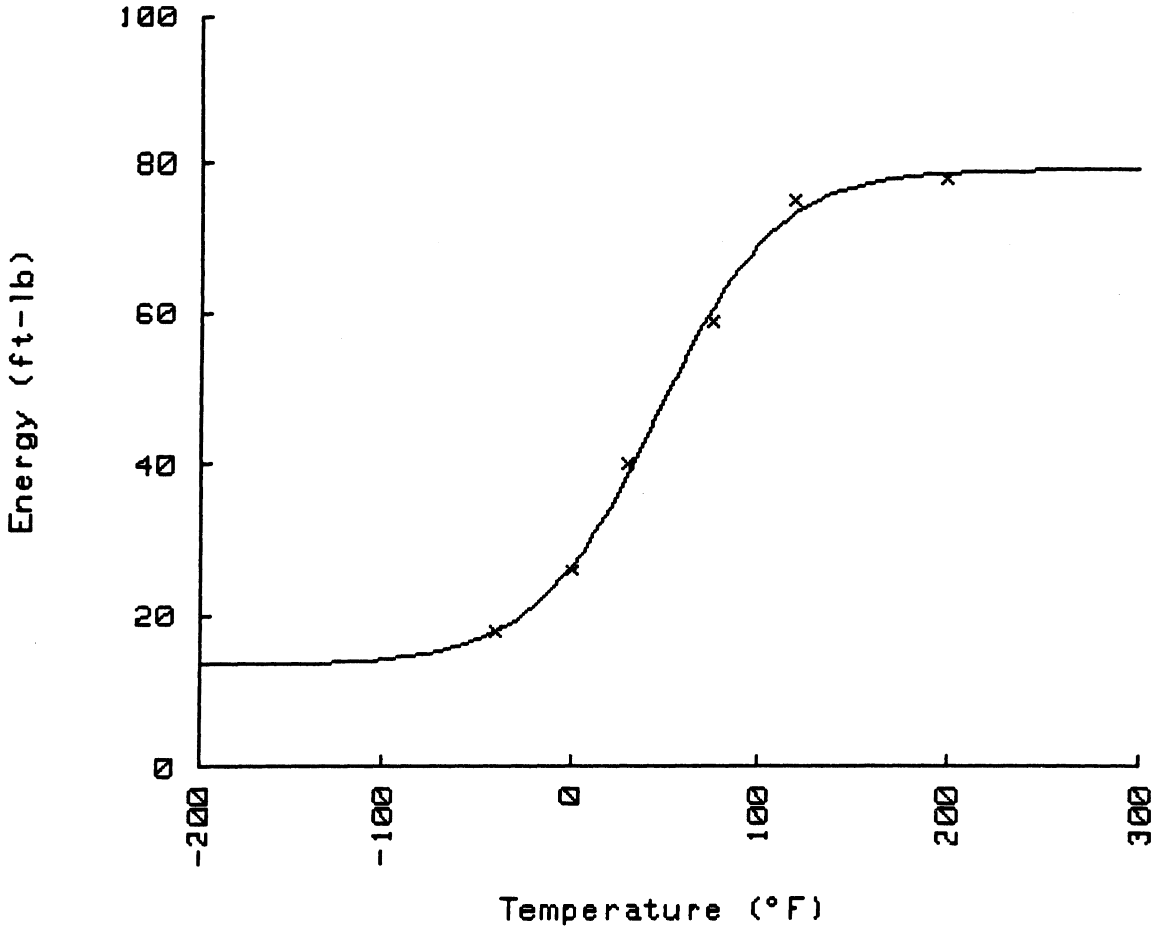
Cv = 30 ft-lb or 41.7 J when T = -20.1 -29.0

4 points added at location given by 'O' symbol.
4 points at (-150,5)

Code GEB (Side 2) - Unirradiated Condition
1/4T Thickness Location
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	16	1 2	-40	18.0	18	<100
2	7	1 2	0	26.0	26	<100
3	5	1 2	30	40.0	34	<100
4	3	1 1	75	59.0	49	<100
5	9	1 2	120	75.0	61	<100
6	1	1 1	200	78.0	73	100

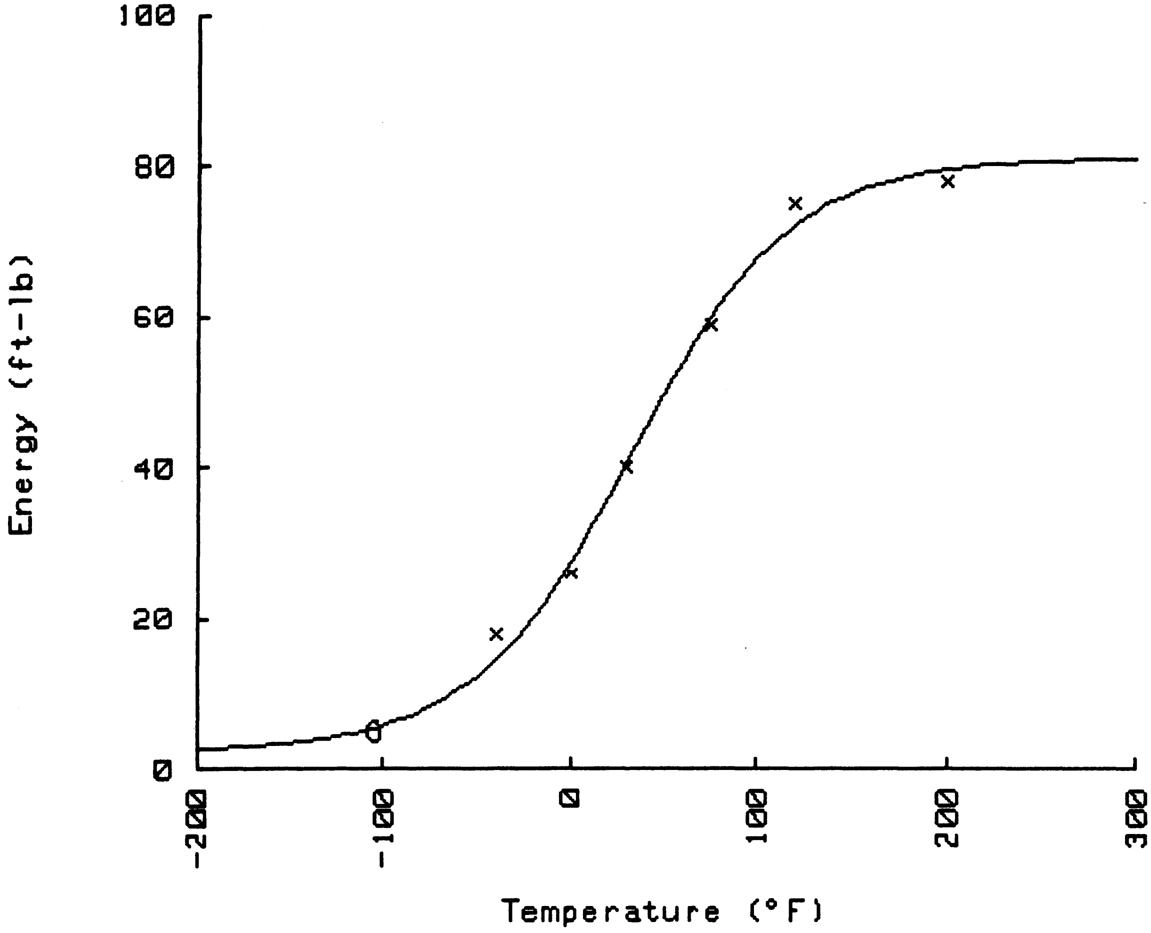
Cv data
File : U-1/4A



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	46.38	62.88
B =	32.94	44.66
C =	65.06	36.15
To =	45.12	7.29
Cv = 30 ft-lb or 41.7 J when T =	9.6	-12.4

Cv data
File : U-1/4A



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	41.78	56.65
B =	39.40	53.43
C =	85.61	47.56
To =	32.56	.31
Cv = 30 ft-lb or 41.7 J when T =	6.2	-14.4

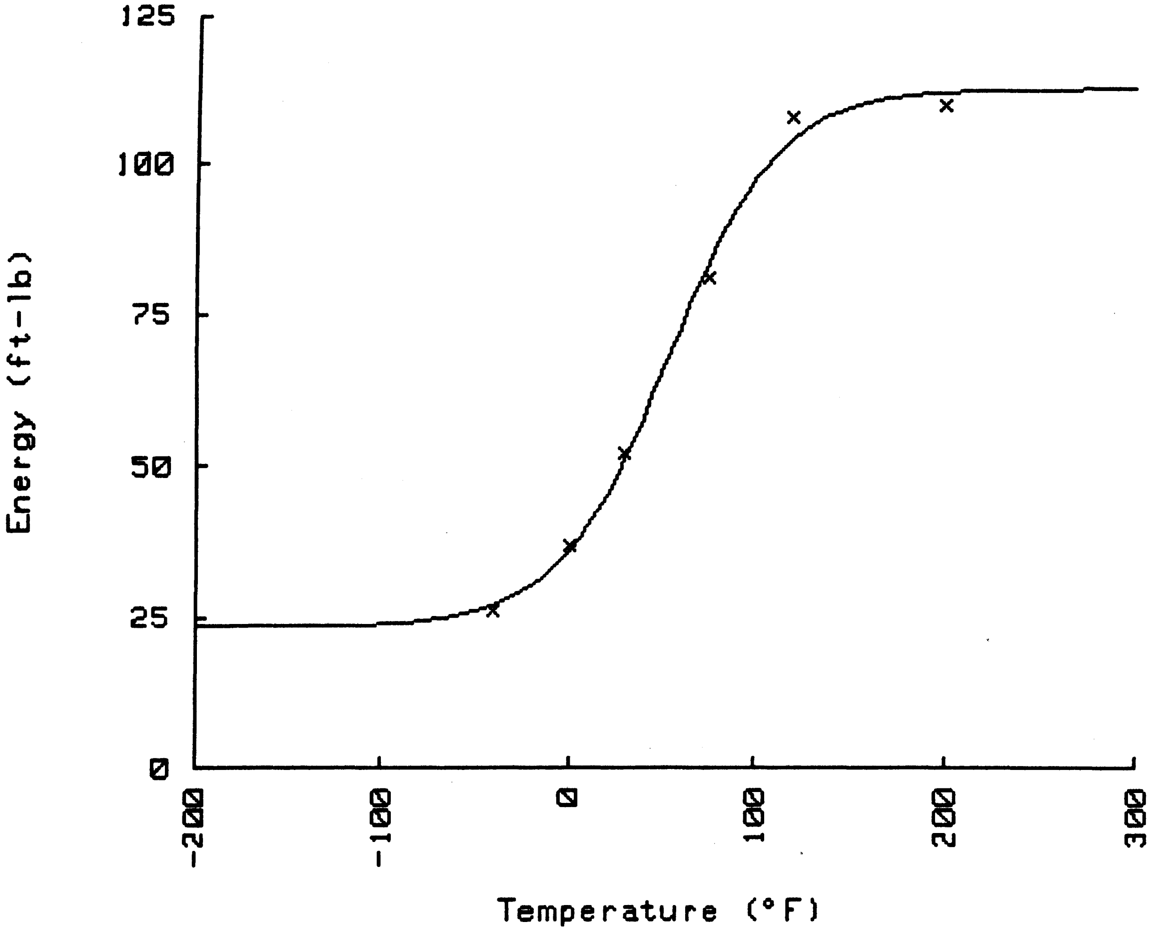
4 points added at location given by 'O' symbol.
4 points at (-105,5)

Code GEB (Side 2) - Unirradiated Condition

1/4T Thickness Location
ASTM C-L Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	32	1 1	-40	26.0	21	<100
2	21	1 1	0	37.0	34	<100
3	20	1 1	30	52.0	43	<100
4	19	1 1	75	81.0	61	<100
5	22	1 1	120	108.0	72	100
6	18	1 1	200	110.0	70	100

Cv data
File : U-1/4C

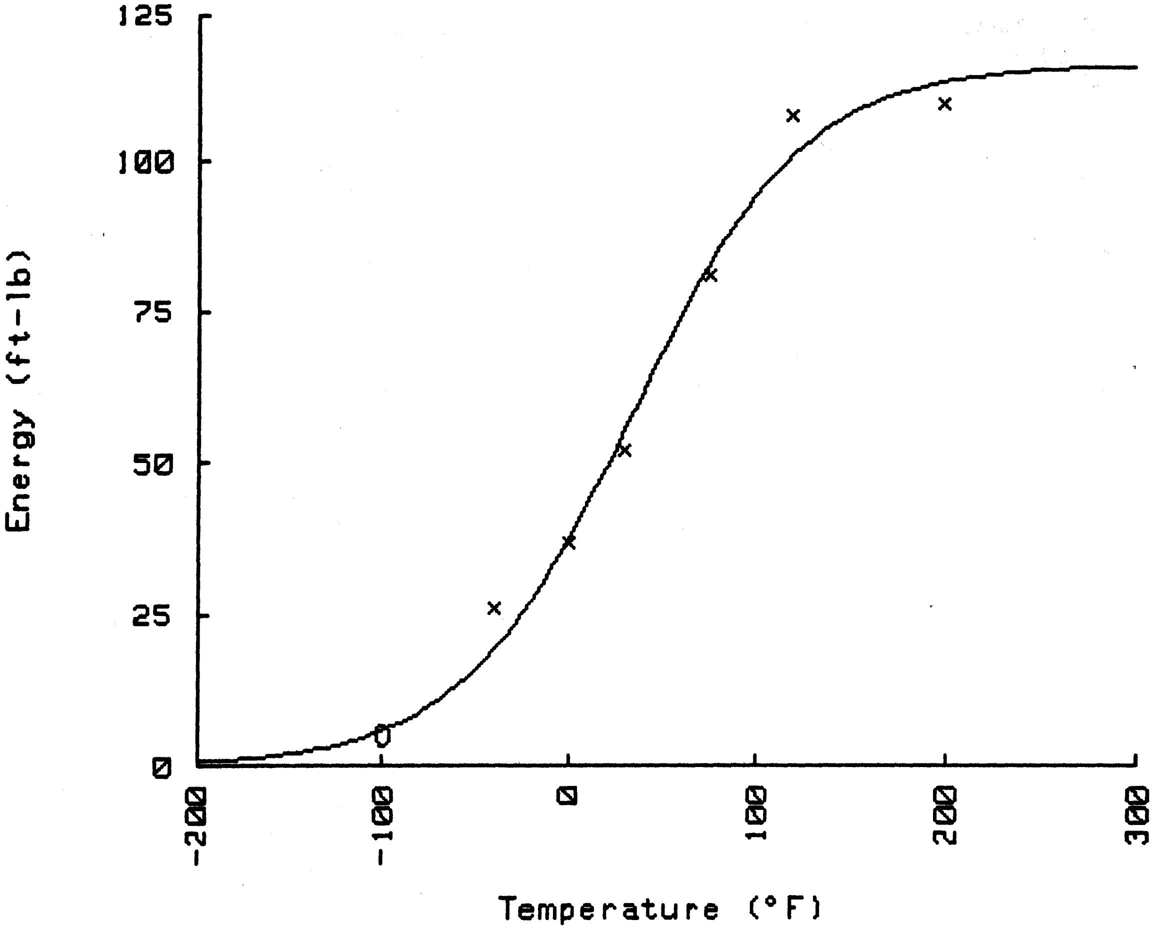


$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	68.04	92.25
B =	44.63	60.51
C =	59.03	32.79
To =	53.48	11.93

Cv = 30 ft-lb or 41.7 J when T = -21.2   -29.5

Cv data
File : U-1/4C



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	58.34	79.10
B =	58.30	79.05
C =	91.40	50.78
To =	34.08	1.15

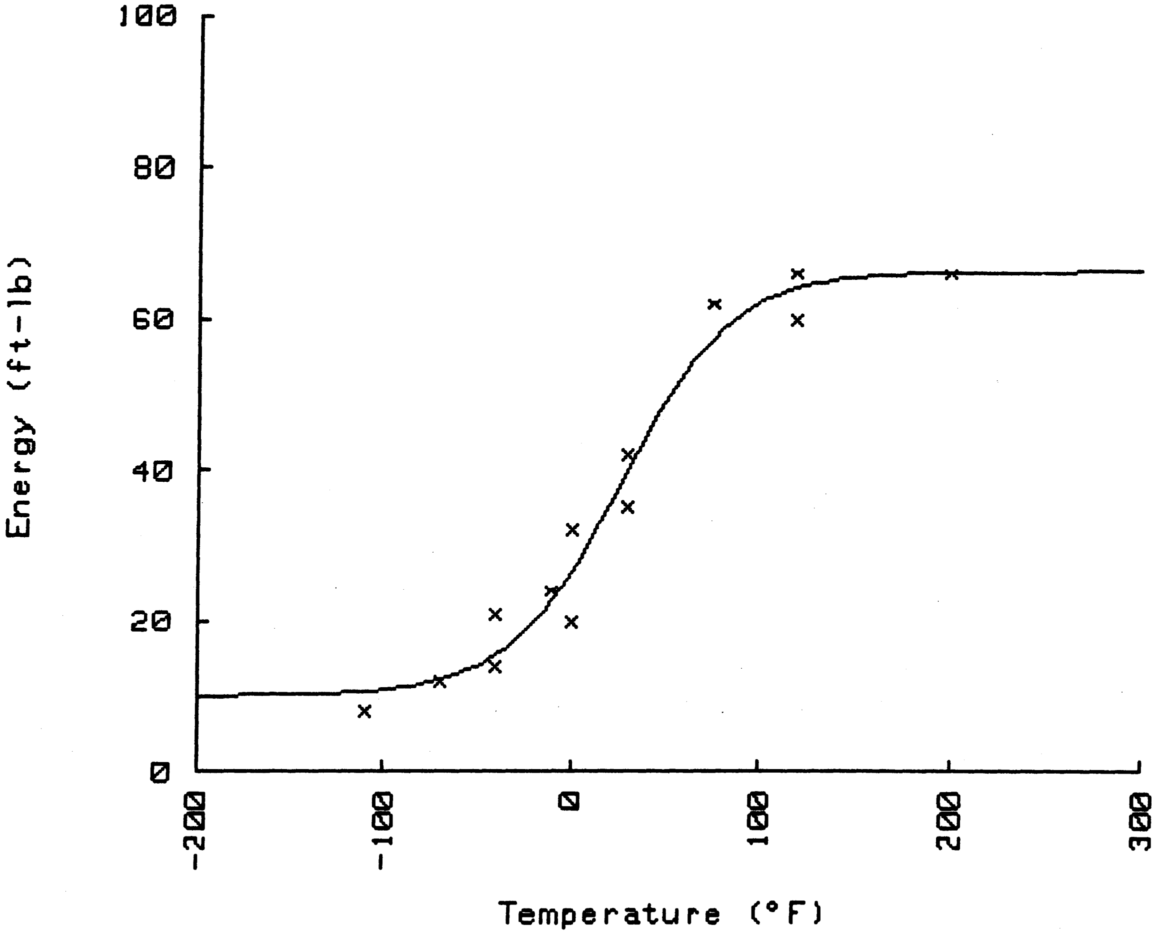
Cv = 30 ft-lb or 41.7 J when T = -14.5 -25.8

4 points added at location given by 'O' symbol.
4 points at (-100,5)

Code GEB (Side 2) - Unirradiated Condition
1/2T Thickness Location
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	48	3 2	-110	8.0	6	0
2	51	3 1	-70	12.0	10	16
3	49	3 2	-40	14.0	10	<100
4	52	3 1	-40	21.0	17	<100
5	47	3 2	-10	24.0	23	<100
6	59	3 2	0	20.0	21	34
7	63	3 1	0	32.0	31	34
8	50	3 1	30	35.0	30	<100
9	65	3 1	30	42.0	37	44
10	62	3 2	75	62.0	51	<100
11	61	3 2	120	60.0	55	100
12	66	3 1	120	66.0	60	<100
13	60	3 2	200	66.0	61	99
14	64	3 1	200	66.0	64	100

Cv data
File : U-1/2A

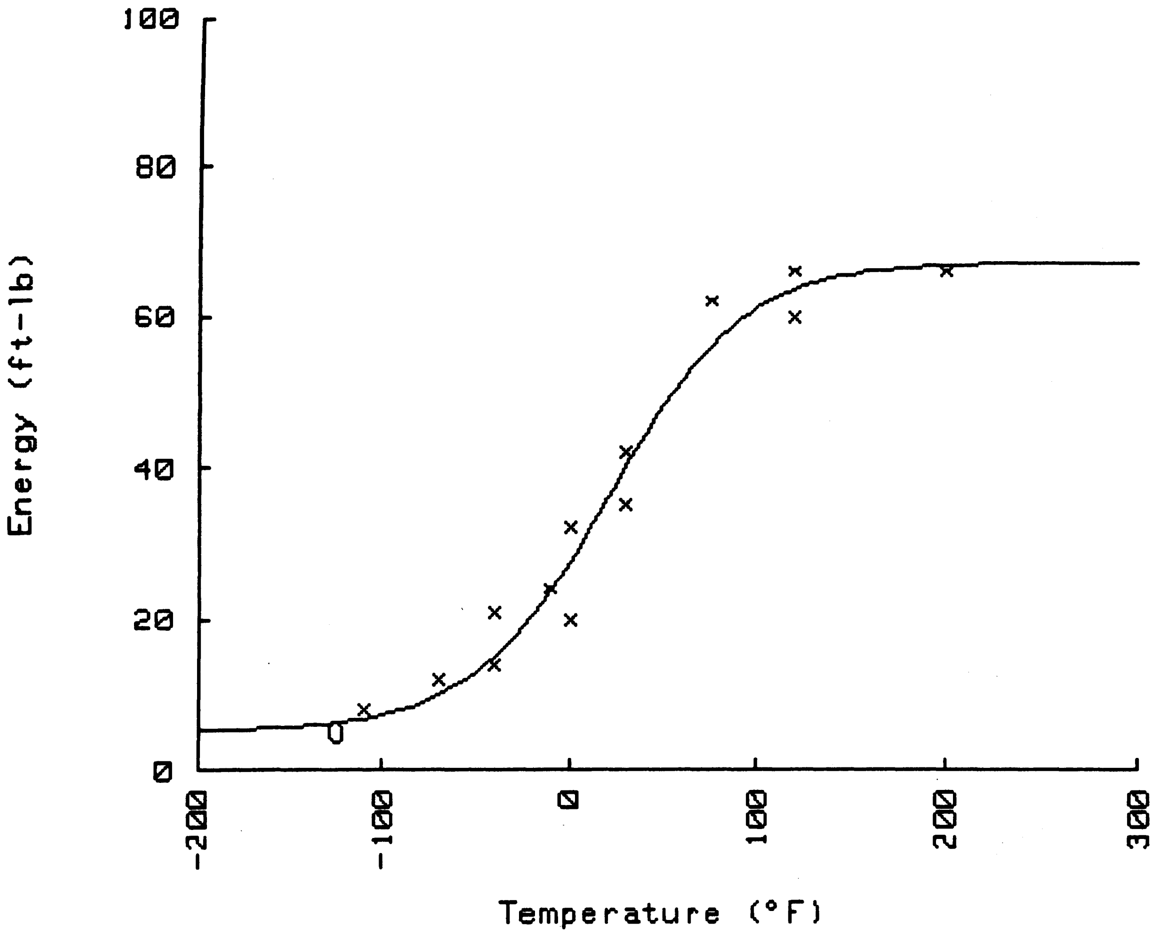


Cv = A + B tanh[(T - To)/C]

```
         English  Metric
A =        38.21   51.80
B =        28.12   38.12
C =        58.98   32.77
To =       25.99   -3.34
```

Cv = 30 ft-lb or 41.7 J when T = 8.3 -13.2

Cv data
File : U-1/2A



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	36.23	49.12
B =	31.02	42.06
C =	72.01	40.00
To =	20.56	-6.36

Cv = 30 ft-lb or 41.7 J when T = 5.9 -14.5

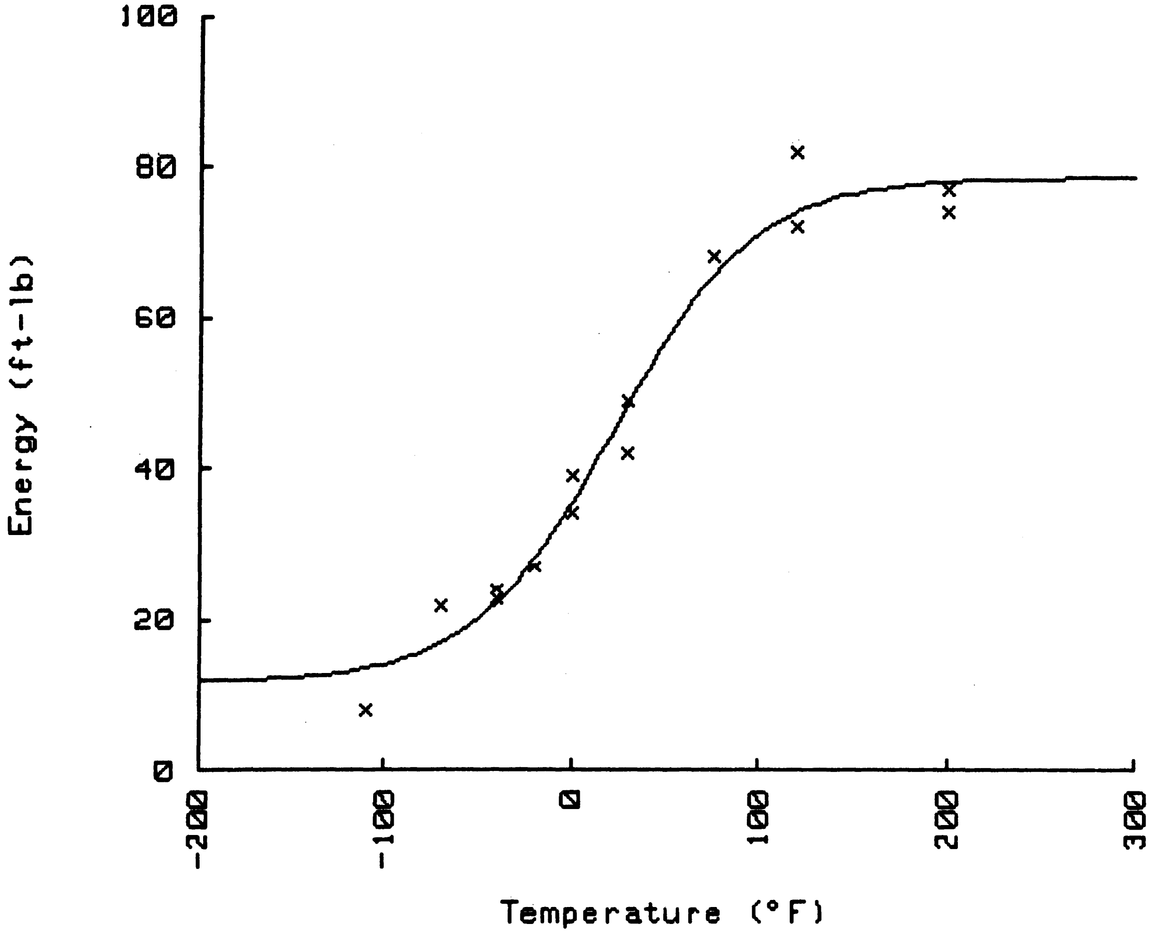
4 points added at location given by 'O' symbol.
4 points at (-125,5)

Code GEB (Side 2) - Unirradiated Condition

7/8T Thickness Location
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	54	3 2	-110	8.0	5	0
2	57	3 1	-70	22.0	19	16
3	55	3 2	-40	23.0	18	<100
4	58	3 1	-40	24.0	22	<100
5	53	3 2	-20	27.0	25	<100
6	71	3 1	0	34.0	32	56
7	67	3 2	0	39.0	36	35
8	56	3 1	30	42.0	33	<100
9	73	3 1	30	49.0	42	50
10	70	3 2	75	68.0	59	<100
11	74	3 1	120	72.0	53	99
12	69	3 2	120	82.0	69	100
13	72	3 1	200	74.0	67	100
14	68	3 2	200	77.0	76	100

Cv data
File : U-7/8A

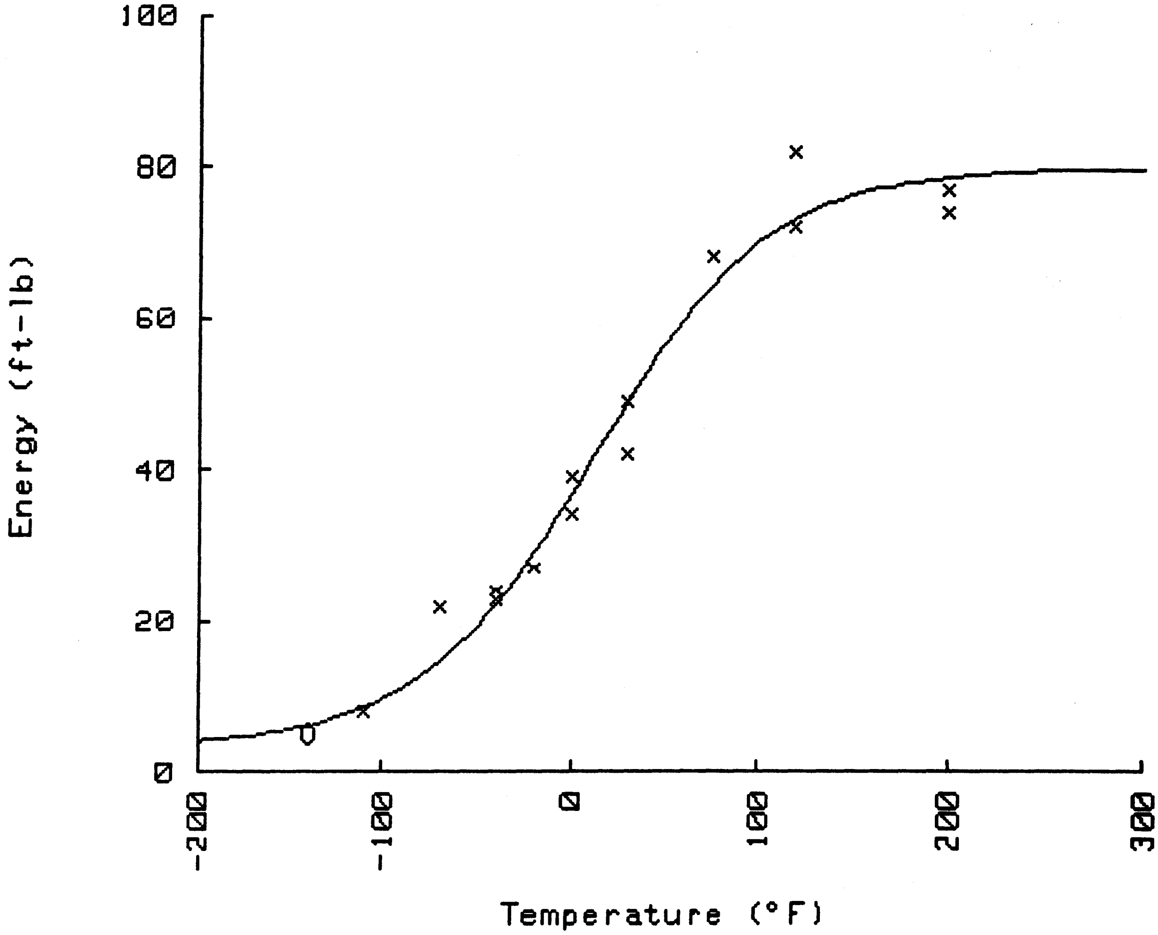


Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	45.14	61.20
B =	33.51	45.43
C =	74.75	41.53
To =	22.22	-5.43

Cv = 30 ft-lb or 41.7 J when T = -14.2   -25.7

Cv data
File : U-7/8A



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	41.67	56.49
B =	38.34	51.98
C =	93.08	51.71
To =	11.87	-11.18

Cv = 30 ft-lb or 41.7 J when T = -17.4   -27.4

4 points added at location given by 'O' symbol.
4 points at (-140,5)

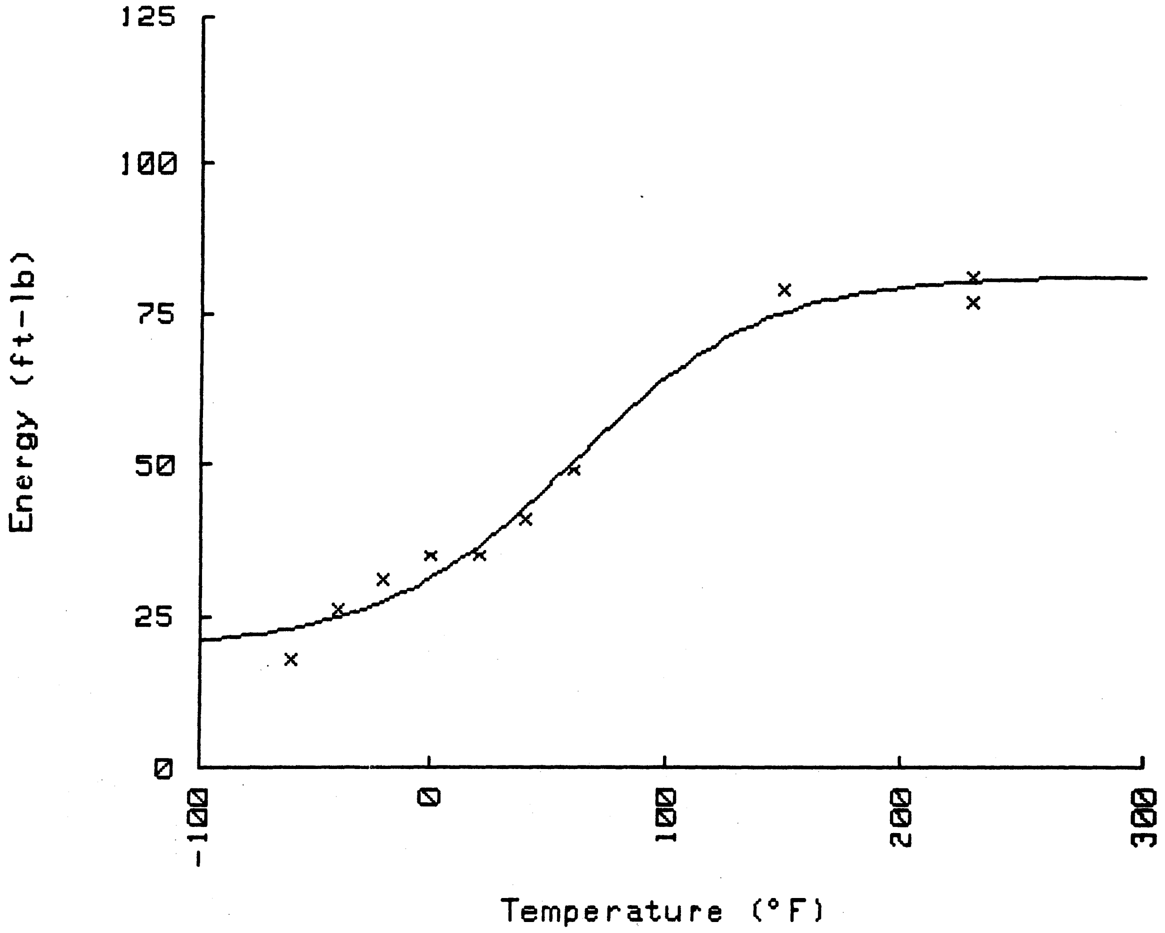
Check Tests for Experiments UB-78, 79, & 80
Code GEB (Side 2) - Unirradiated Condition
ASTM L-C Orientation[a]

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	256	C1	-60	18.0	18	<100
2	270	C2	-40	26.0	24	<100
3	303	D3	-20	31.0	31	<100
4	293	D2	0	35.0	35	<100
5	260	C1	20	35.0	33	<100
6	266	C2	40	41.0	39	<100
7	276	C3	60	49.0	47	<100
8	280	C3	150	79.0	72	95
9	283	D1	230	77.0	75	100
10	312A	F1	230	81.0	73	100
11	345	8F-CMFL[b]	-40	32.0	30	<100
12	325	8F-CMFL	0	61.0	50	<100
13	339	8F-CMFL	230	114.0	84	100
14	331	8F-CMFL	230	114.0	94	100

[a] Unless noted

[b] CMFL = ASTM C-L orientation

Cv data
File : UBR-U

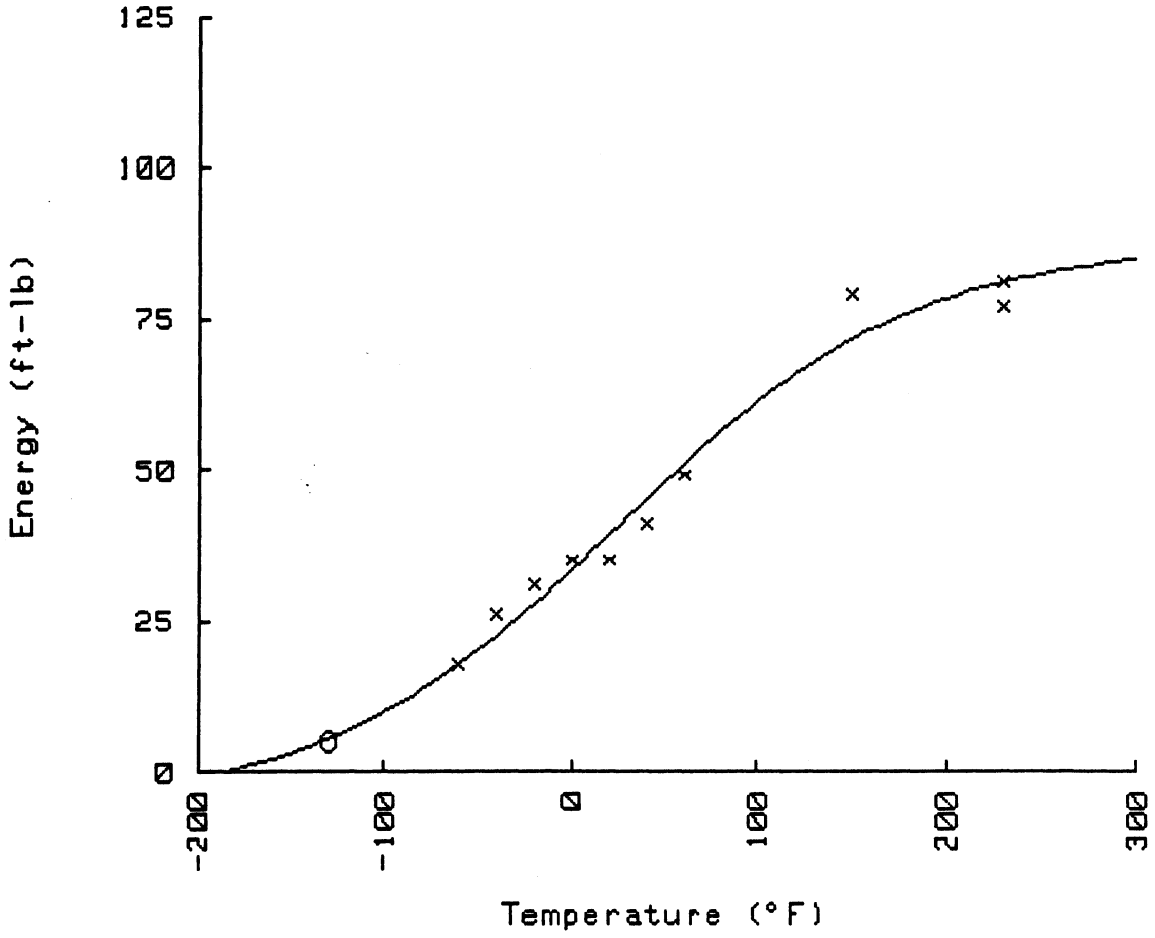


$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	50.58	68.57
B =	30.73	41.67
C =	81.92	45.51
To =	60.51	15.84

Cv = 30 ft-lb or 41.7 J when T = -5.8 -21.0

Cv data
File : UBR-U



$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	40.63	55.09
B =	47.04	63.77
C =	160.21	89.01
To =	24.78	-4.01

Cv = 30 ft-lb or 41.7 J when T = -12.1 -24.5

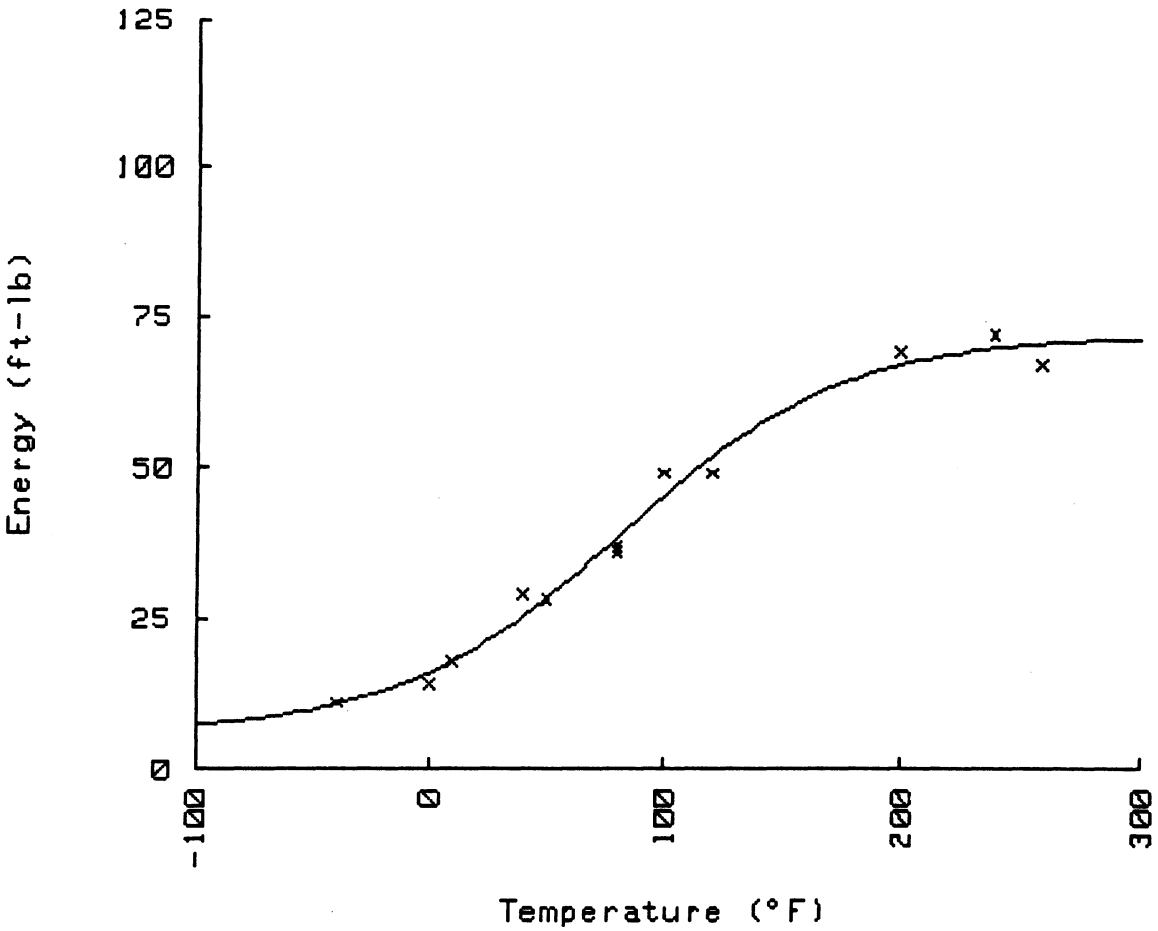
4 points added at location given by 'O' symbol.
4 points at (-130,5)

Irradiation Experiment UBR-68

Experiment UB-68 Unit B
Code GEB (Side 2) - As-Irradiated Condition
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	97	4B 1	-40	11.0	14	<100
2	94	4B 1	0	14.0	17	<100
3	90	4B 2	10	18.0	20	<100
4	78	4A 1	40	29.0	30	<100
5	107	4C 1	50	28.0	32	<100
6	104	4C 2	80	36.0	36	<100
7	83	4A 2	80	37.0	37	<100
8	117	4D 1	100	49.0	47	<100
9	112	4D 2	120	49.0	48	<100
10	110	4C 1	200	69.0	60	98
11	113	4D 2	240	72.0	61	100
12	77	4A 1	260	67.0	59	100

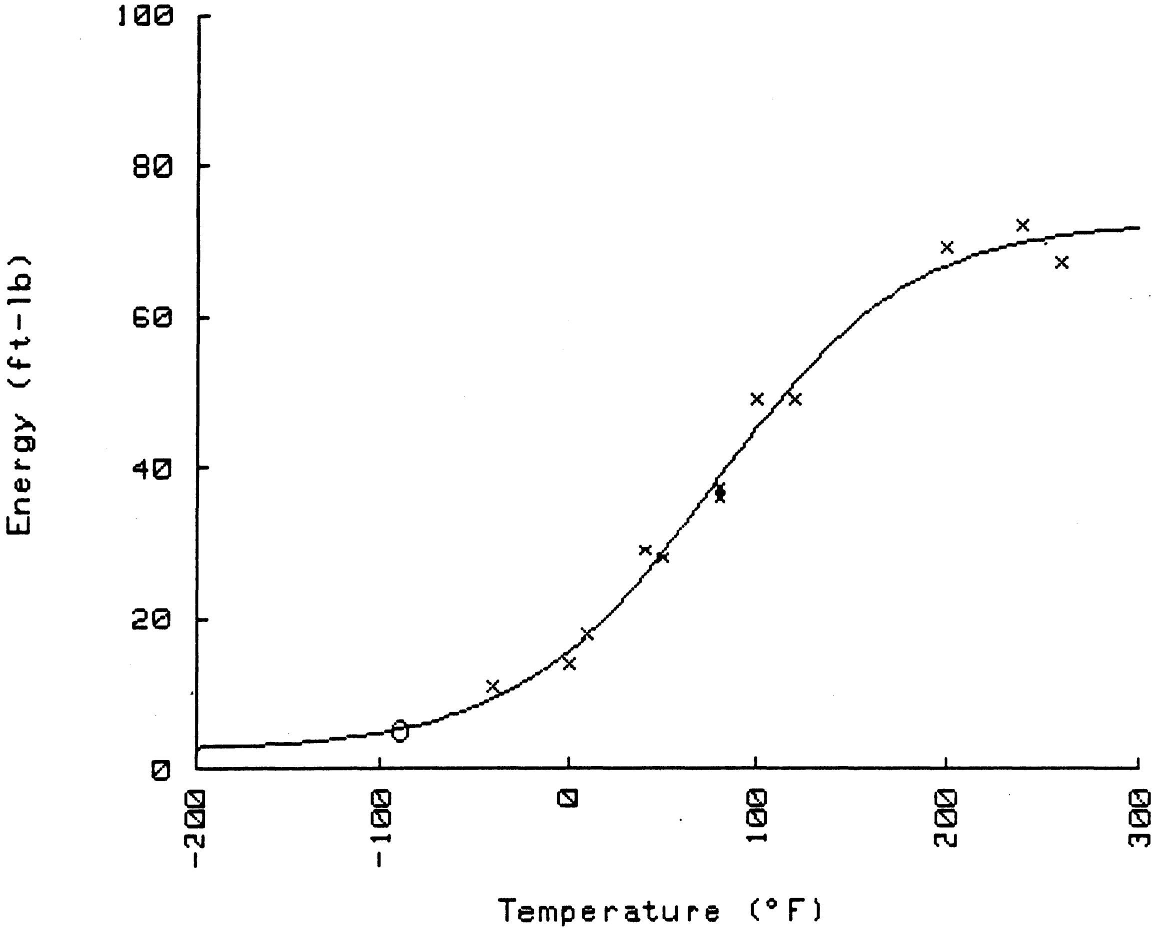
Cv data
File : U68I



$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	38.95	52.81
B =	33.00	44.75
C =	94.88	52.71
To =	81.61	27.56
Cv = 30 ft-lb or 41.7 J when T =	55.2	12.9

Cv data
File : U68ICv



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	37.63	51.02
B =	35.13	47.63
C =	104.78	58.21
To =	77.07	25.04

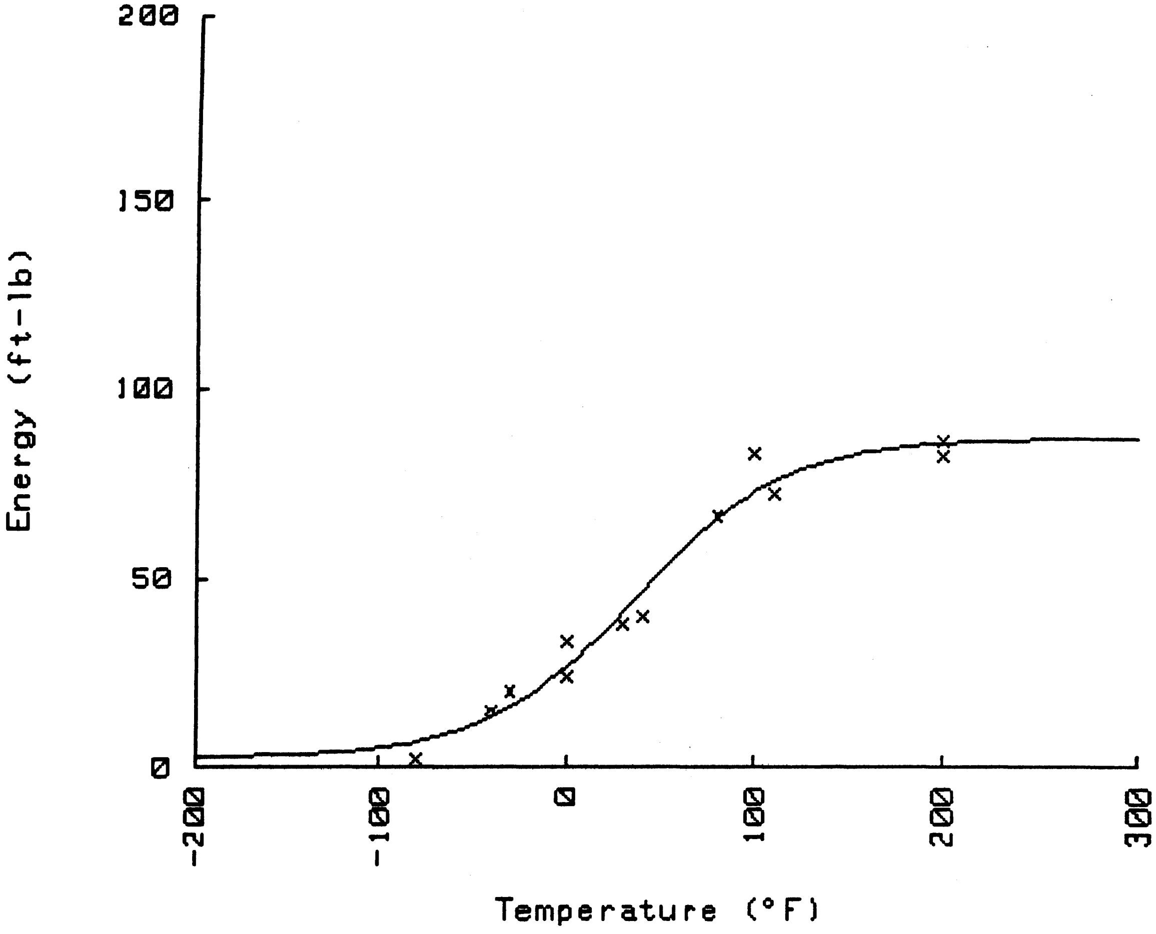
Cv = 30 ft-lb or 41.7 J when T = 54.0 12.2

4 points added at location given by 'O' symbol.
4 points at (-90,5)

Experiment UB-68 Unit B
Code GEB (Side 2) - Postirradiation Annealed 399°C (750°F) - 168h
ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	114	4D 2	-80	2.0	5	<100
2	98	4B 1	-40	15.0	13	<100
3	102	4C 2	-30	20.0	22	<100
4	91	4B 2	0	24.0	29	<100
5	118	4D 1	0	33.0	29	<100
6	80	4A 1	30	38.0	36	<100
7	82	4A 2	40	40.0	38	<100
8	100	4C 2	80	66.0	53	<100
9	95	4B 1	100	83.0	67	<100
10	175	5 1	110	72.0	59	<100
11	86	4A 2	200	82.0	70	100
12	76	4A 1	200	86.0	79	100

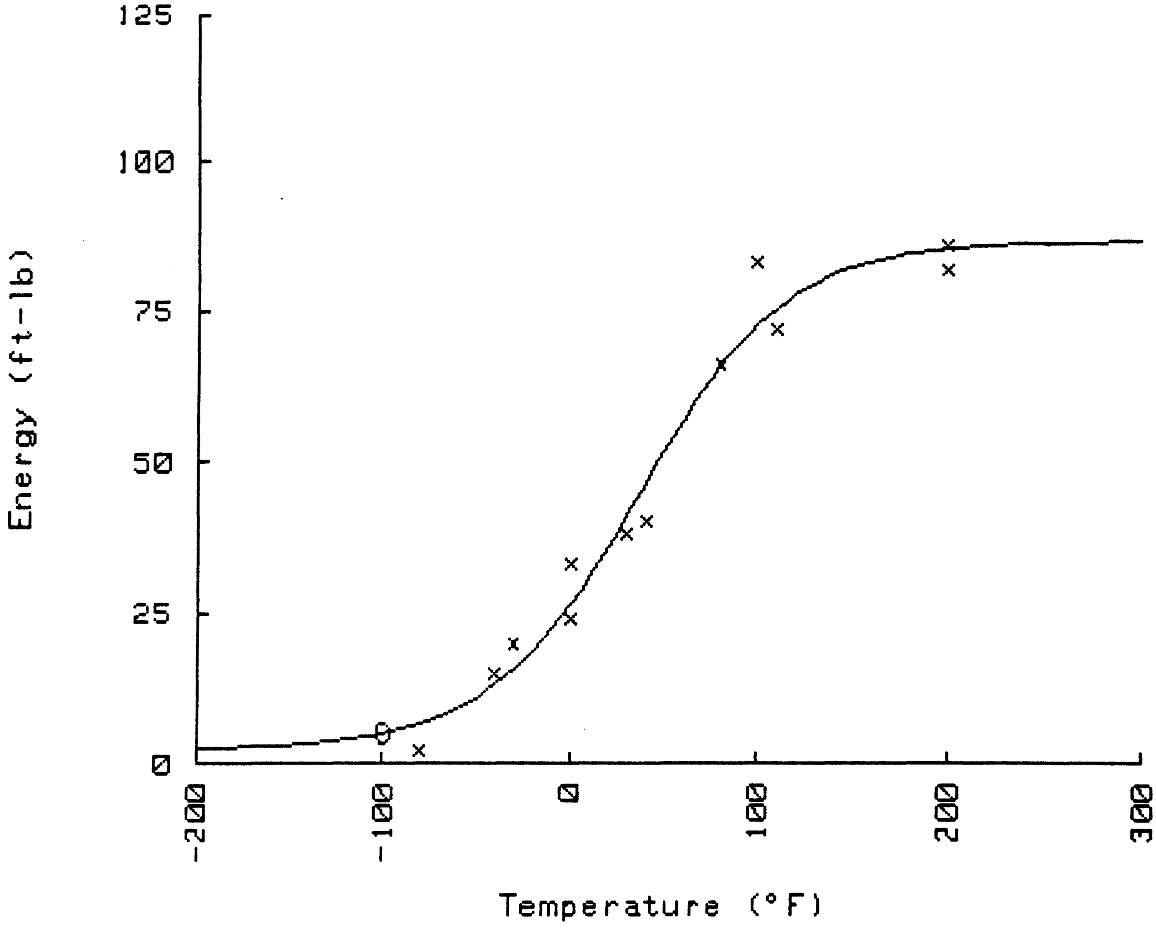
Cv data
File : U68A1



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	44.69	60.59
B =	42.07	57.04
C =	78.97	43.87
To =	36.63	2.57
Cv = 30 ft-lb or 41.7 J when T =	7.8	-13.4

Cv data
File : U68A1



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	44.59	60.46
B =	42.18	57.19
C =	79.26	44.03
To =	36.36	2.42
Cv = 30 ft-lb or 41.7 J when T =	7.8	-13.5

4 points added at location given by 'O' symbol.
4 points at (-100,5)

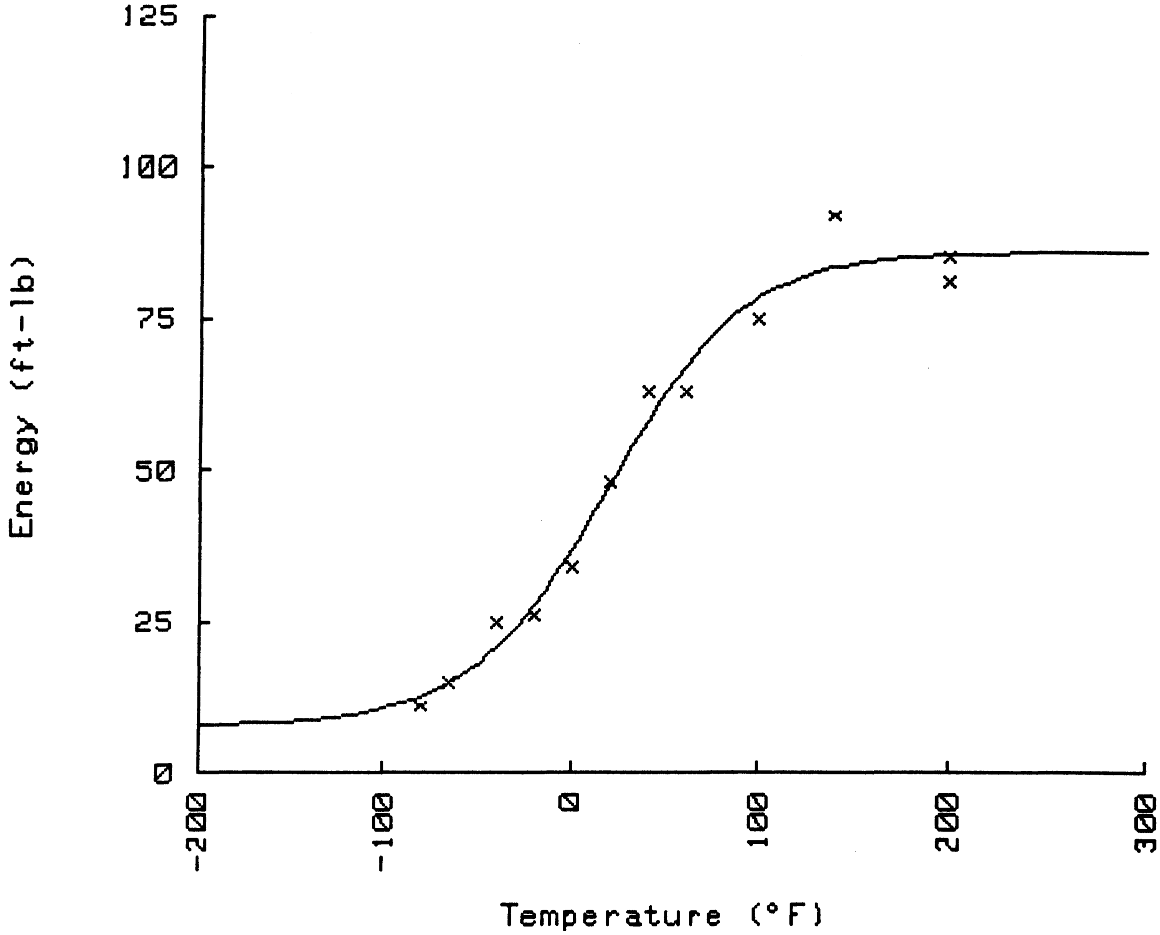
Experiment UB-68 Unit B

Code GEB (Side 2) - Postirradiation Annealed 454°C (850°F) - 168h

ASTM L-C Orientation

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	116	4D 1	-80	11.0	12	<100
2	106	4C 1	-65	15.0	15	<100
3	81	4A 1	-40	25.0	26	<100
4	93	4B 1	-20	26.0	24	<100
5	87	4A 2	0	34.0	33	<100
6	92	4B 2	20	48.0	36	<100
7	79	4A 1	40	63.0	49	<100
8	120	4D 1	60	63.0	54	<100
9	84	4A 2	100	75.0	66	90
10	109	4C 1	140	92.0	63	98
11	103	4C 2	200	81.0	68	100
12	99	4C 2	200	85.0	65	100

Cv data
File : U68A2

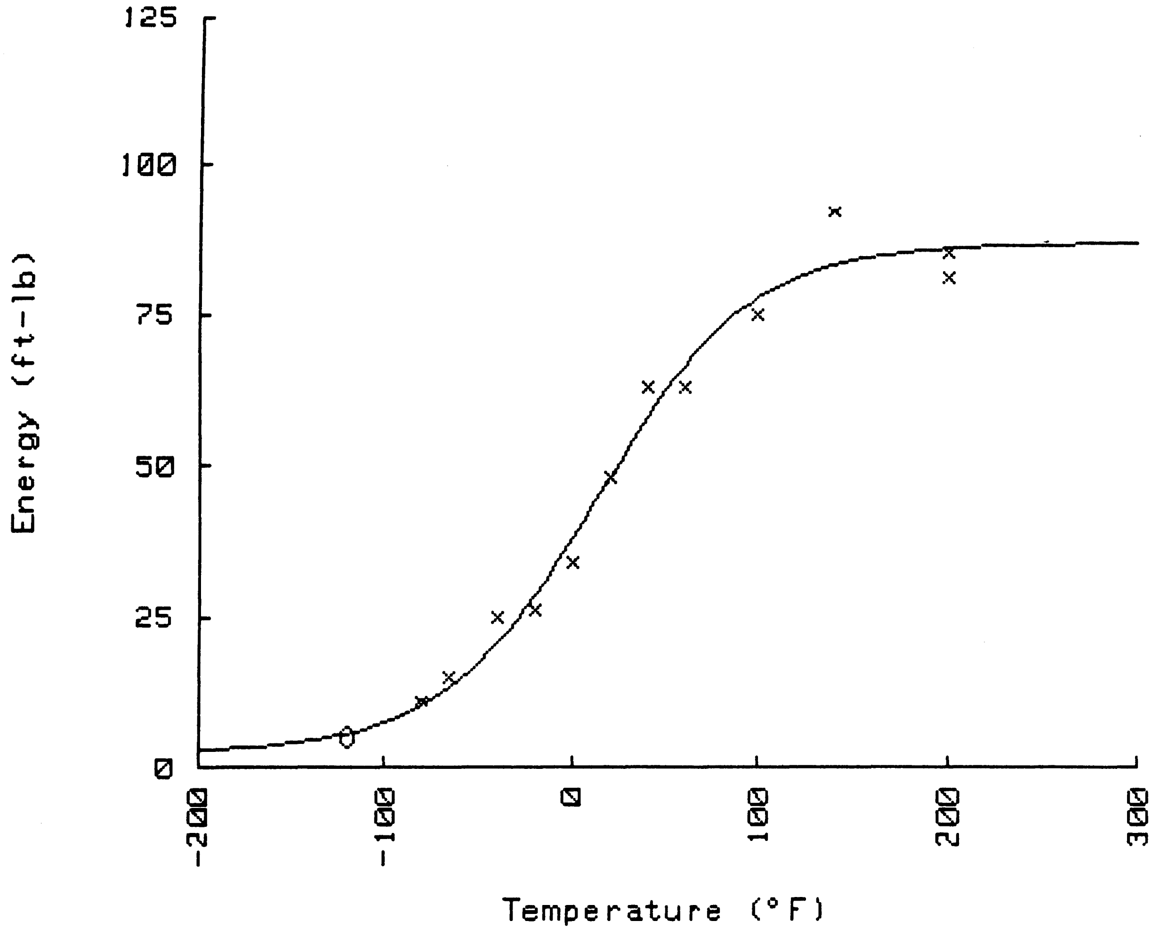


Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	46.91	63.60
B =	39.11	53.02
C =	72.75	40.42
To =	18.91	-7.27

Cv = 30 ft-lb or 41.7 J when T = -14.8   -26.0

Cv data
File : U68A2



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	44.61	60.48
B =	42.17	57.18
C =	82.32	45.73
To =	13.22	-10.43

Cv = 30 ft-lb or 41.7 J when T = -16.5   -27.0

4 points added at location given by 'O' symbol.
4 points at (-120,5)

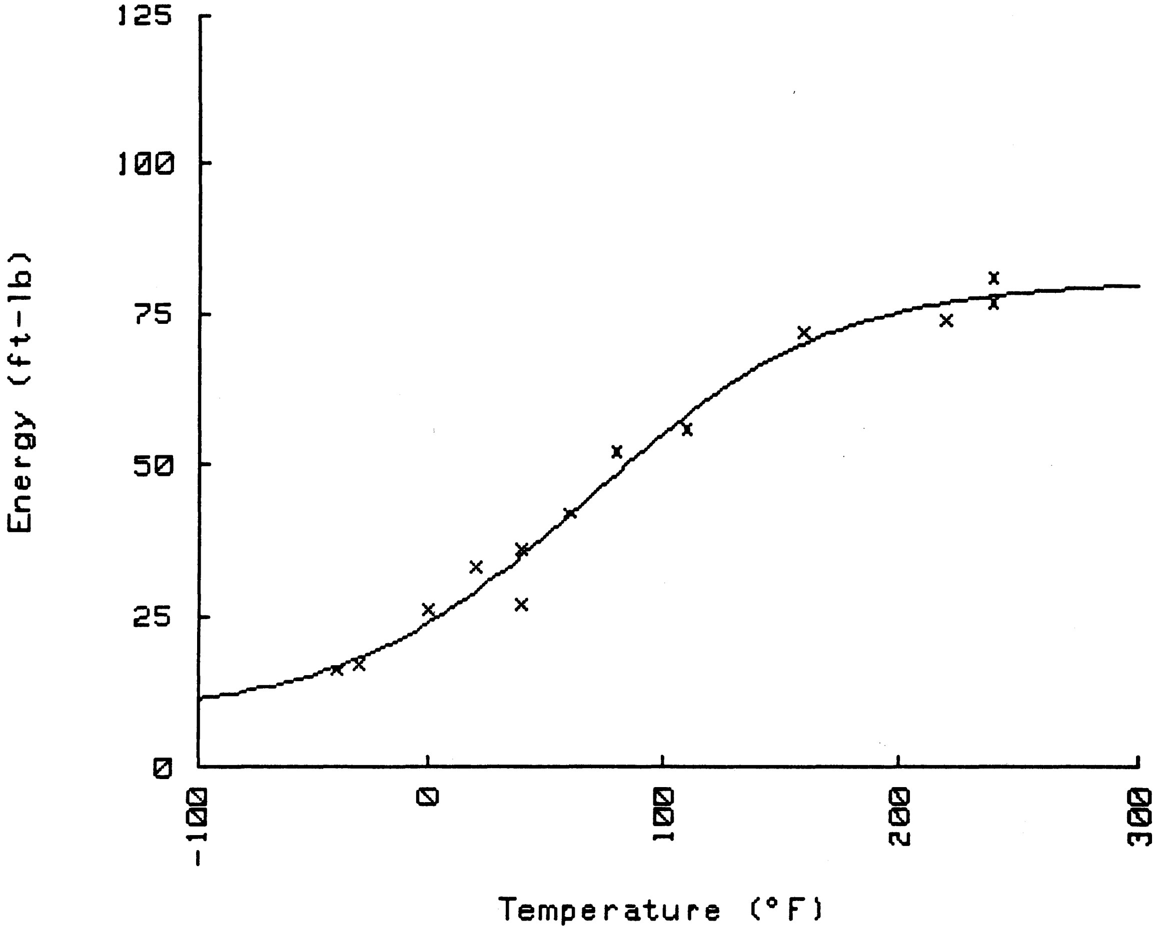
Irradiation Experiment UBR-78

Experiment UB-78 Unit A
Code GEB (Side 2) - As-Irradiated Condition
ASTM L-C Orientation[a]

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	286	D1	-40	16.0	15	<100
2	275	C3	-30	17.0	16	<100
3	284	D1	0	26.0	23	<100
4	267	C2	20	33.0	29	<100
5	296	D2	40	27.0	26	<100
6	277	C3	40	36.0	32	<100
7	255	C1	60	42.0	37	<100
8	306	D3	80	52.0	47	<100
9	269	C2	110	56.0	50	<100
10	308	D3	160	72.0	65	99
11	257	C1	220	74.0	75	<100
12	316	F3	240	77.0	75	100
13	322	E2	240	81.0	83	100
14	326	8F-CMFL[b]	-40	14.0	14	<100
15	333	8F-CMFL	-20	22.0	19	<100
16	328	8F-CMFL	0	41.0	33	<100
17	322	8F-CMFL	10	45.0	38	<100
18	336	6E-CMFL	40	49.0	45	<100
19	338	6E-CMFL	240	110.0	81	100
20	334	8F-CMFL	240	112.0	71	100

[a] Unless noted
[b] CMFL = ASTM C-L orientation

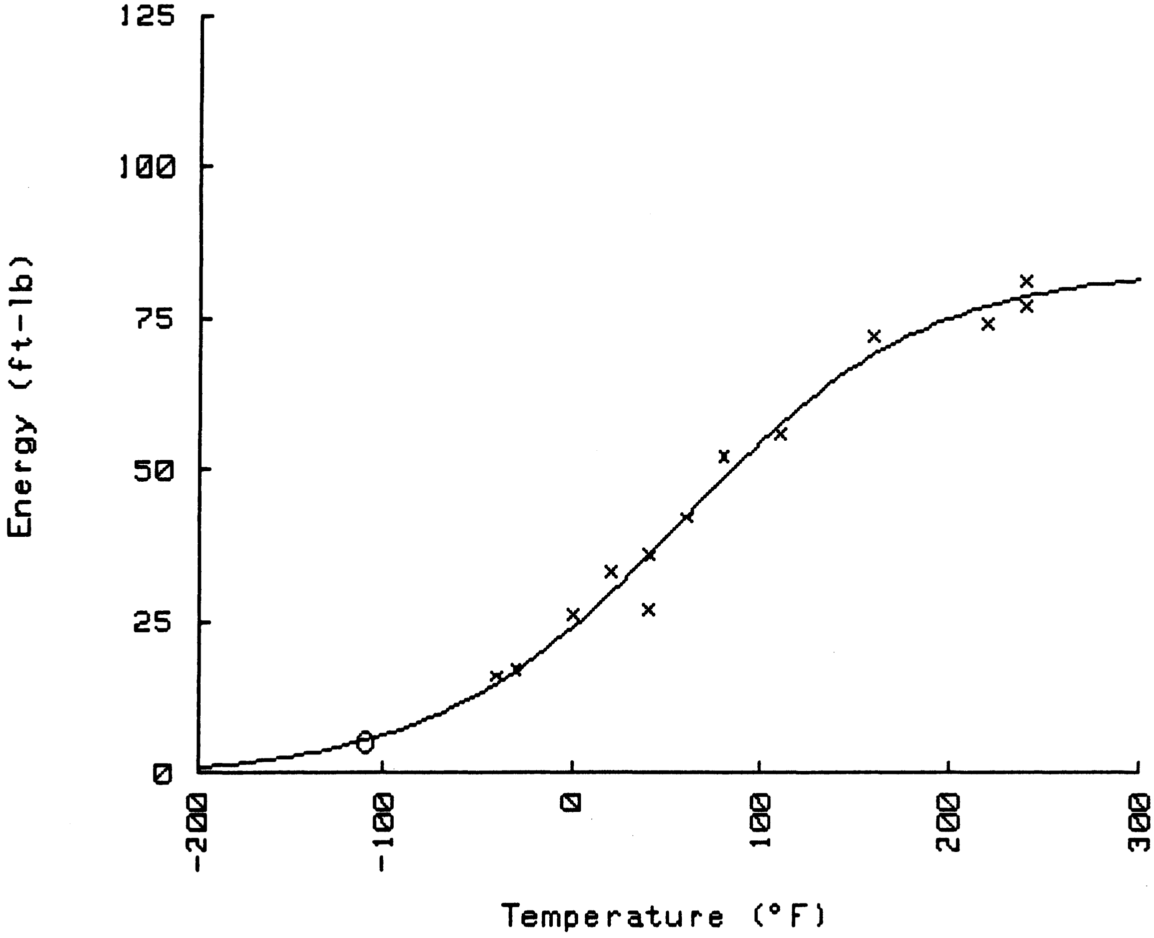
Cv data
File : UBR-78



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	44.62	60.49
B =	36.07	48.91
C =	104.37	57.99
To =	68.53	20.30
Cv = 30 ft-lb or 41.7 J when T =	23.7	-4.6

Cv data
File : UBR-78



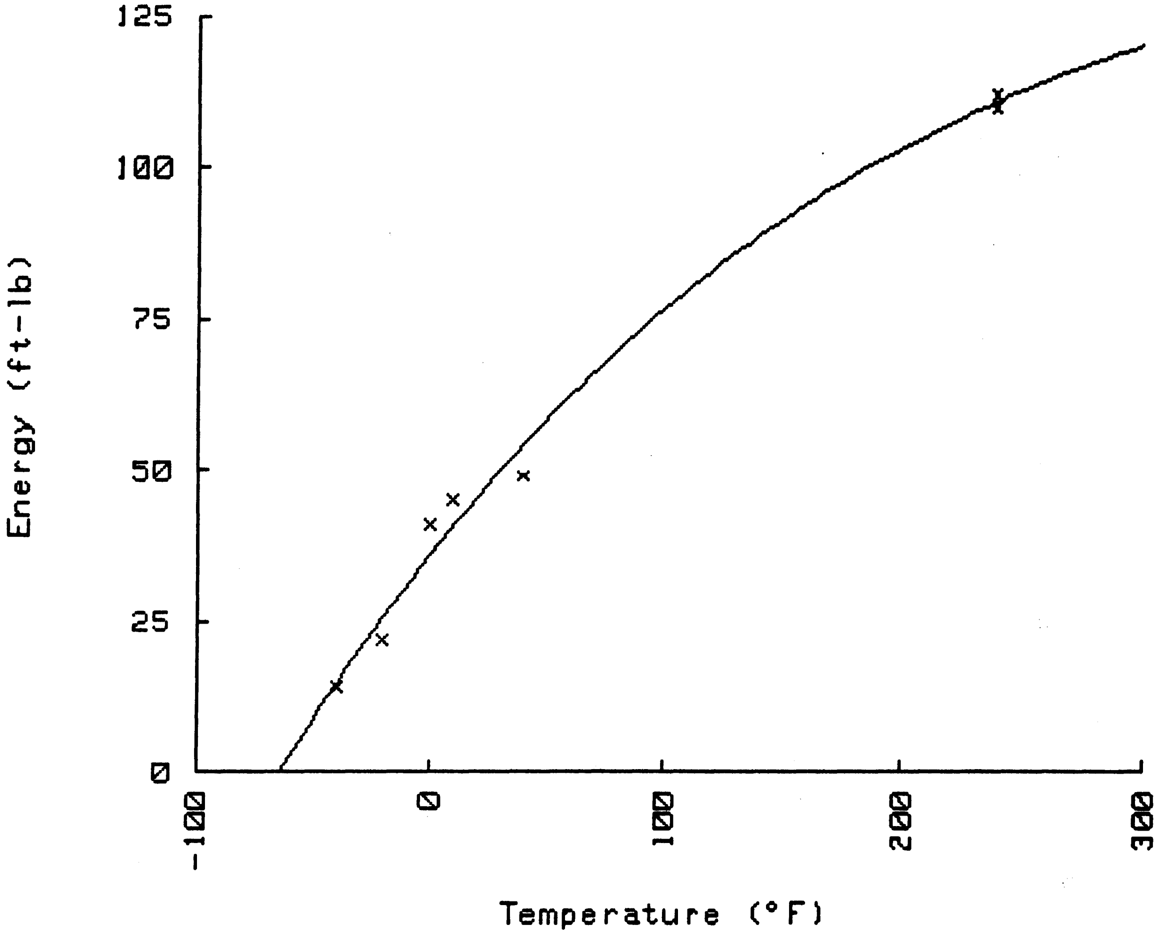
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	41.32	56.03
B =	41.97	56.90
C =	130.23	72.35
To =	57.30	14.05

Cv = 30 ft-lb or 41.7 J when T = 21.3 -6.0

4 points added at location given by 'O' symbol.
4 points at (-110,5)

Cv data
File : UBR-78 (CMFL)

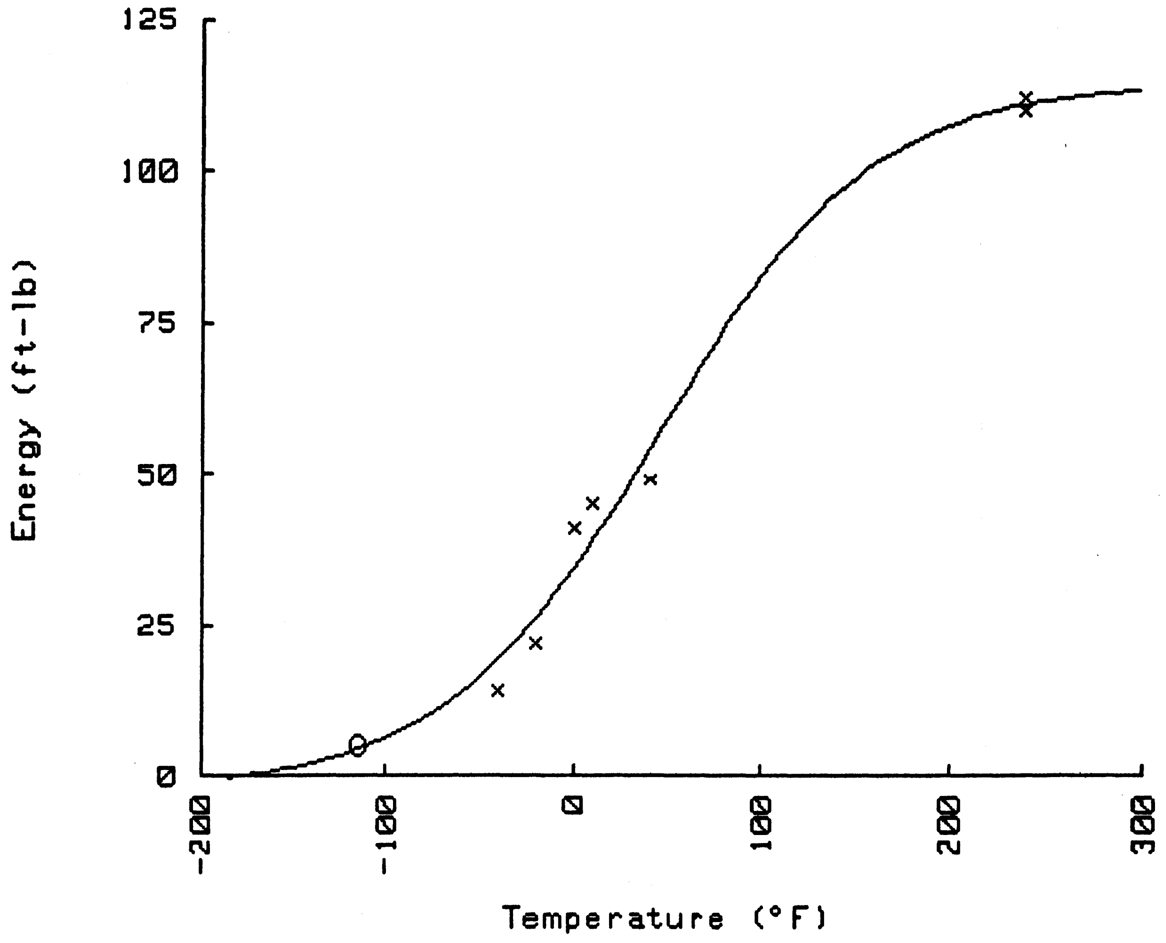


Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	-552.96	-749.71
B =	702.45	952.40
C =	423.33	235.18
To =	-514.67	-303.71

Cv = 30 ft-lb or 41.7 J when T = -11.8 -24.4

Cv data
File : UBR78C



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	56.13	76.11
B =	58.31	79.06
C =	113.35	62.97
To =	44.08	6.71

Cv = 30 ft-lb or 41.7 J when T = -10.6 -23.7

4 points added at location given by 'O' symbol.
4 points at (-115,5)

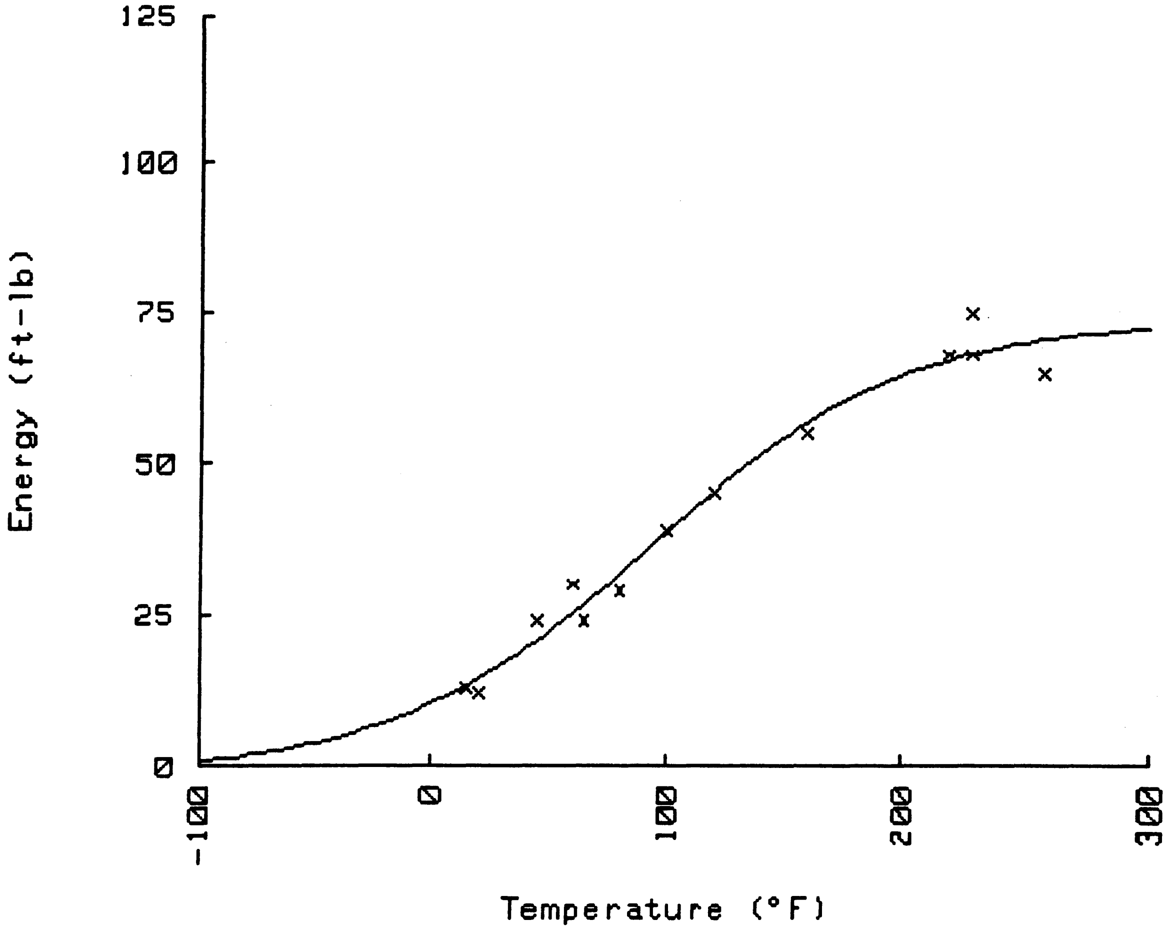
Irradiation Experiment UBR-79A

Experiment UB-79 Unit A
Code GEB (Side 2) - As-Irradiated Condition
ASTM L-C Orientation[a]

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	261	C1	15	13.0	13	<100
2	285	D1	45	24.0	19	<100
3	295	D2	60	30.0	27	<100
4	281	C3	100	39.0	31	<100
5	305	D3	230	68.0	60	100
6	278	C3	230	75.0	69	98
7	341	6E-CMFL[b]	230	98.0	81	100
8	298	D2	20	12.0	11	<100
9	287	D1	65	24.0	17	<100
10	307	D3	80	29.0	27	<100
11	289	D1	120	45.0	38	<100
12	309	D3	160	55.0		<100
13	297	D2	220	68.0	59	100
14	310	D3	260	65.0	55	99
15	348	6E-CMFL[b]	60	34.0	27	<100
16	344	6E-CMFL	105	52.0	39	<100
17	342	6E-CMFL	240	94.0	69	100
18	346	6E-CMFL	280	91.0	77	100

[a] Unless noted
[b] CMFL = ASTM C-L Orientation

Cv data
File : UBR-79

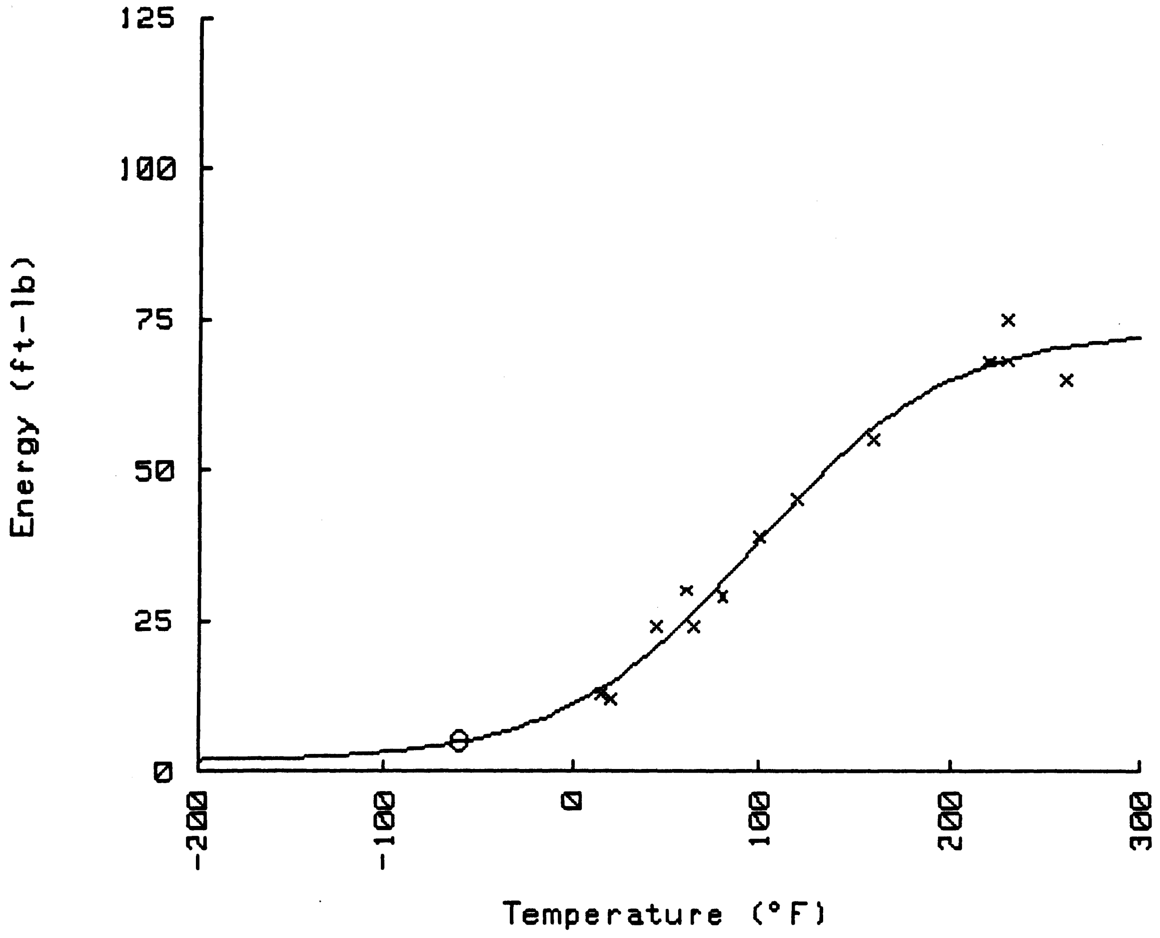


$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	36.33	49.25
B =	37.67	51.07
C =	109.81	61.01
To =	93.33	34.07

Cv = 30 ft-lb or 41.7 J when T = 74.7 23.7

Cv data
File : UBR-79



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	37.50	50.84
B =	35.79	48.52
C =	102.81	57.12
To =	97.24	36.25

Cv = 30 ft-lb or 41.7 J when T = 75.4 24.1

4 points added at location given by 'O' symbol.
4 points at (-60,5)

Irradiation Experiment UBR-80A

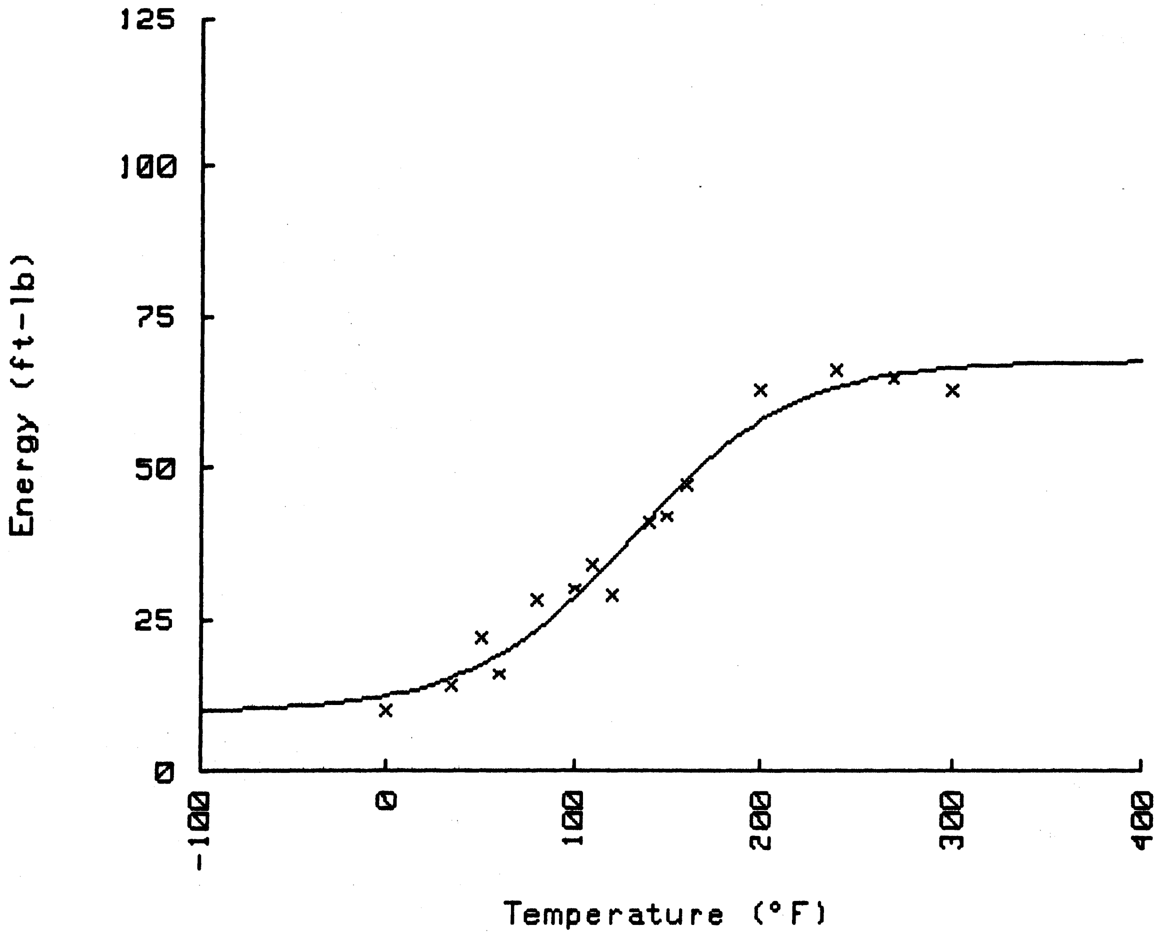
Experiment UB-80 Unit A
Code GEB (Side 2) - As-Irradiated Condition
ASTM L-C Orientation[a]

No	Specimen Number	Piece/ Row	Temp (°F)	Energy (ft-lb)	Lat Exp (mils)	Shear (%)
1	314	8F3	0	10.0		<100
2	288	D1	35	14.0	14	<100
3	313	8F3	50	22.0	16	<100
4	320	6E3	60	16.0	12	<100
5	300	D2	80	28.0	22	<100
6	304	D2	100	30.0	29	<100
7	319	6E3	110	34.0	28	<100
8	311	D3	120	29.0	26	<100
9	301	D2	140	41.0	37	<100
10	317	8F3	150	42.0	37	<100
11	299	D2	160	47.0	44	<100
12	290	D1	200	63.0	54	98
13	312	8F3	240	66.0	66	100
14	318	6E3	270	65.0	58	100
15	291	D1	300	63.0	58	100
16	337	6E-CMFL[b]	220	90.0	69	99
17	329	8F-CMFL	240	87.0	66	100
18	347	6E-CMFL	270	87.0	71	100

[a] Unless noted

[b] CMFL = ASTM C-L Orientation

Cv data
File : UBR-80

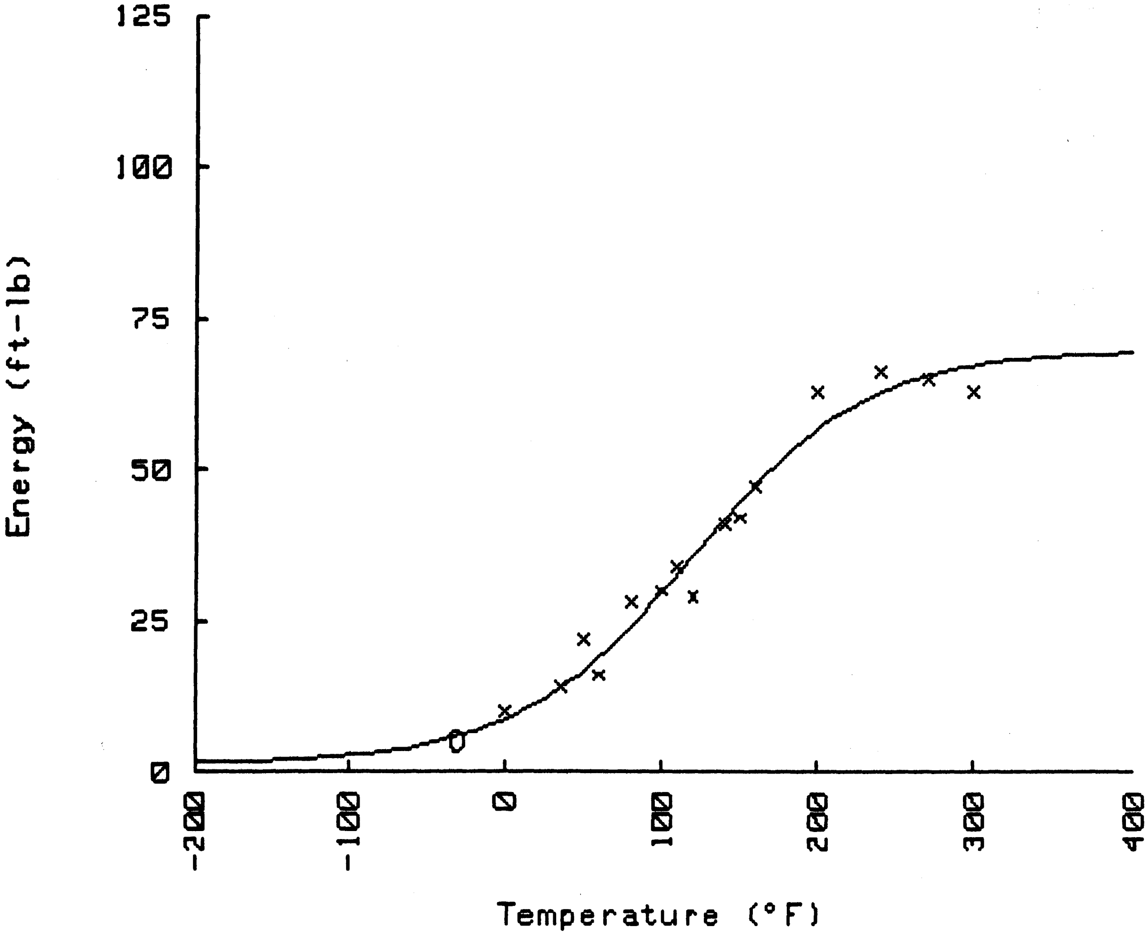


Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	38.75	52.54
B =	28.99	39.31
C =	86.59	48.10
To =	131.70	55.39

Cv = 30 ft-lb or 41.7 J when T = 104.7 40.4

Cv data
File : UBR-80



Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	35.60	48.27
B =	34.22	46.39
C =	112.11	62.28
To =	119.39	48.55

Cv = 30 ft-lb or 41.7 J when T = 100.9   38.3

4 points added at location given by 'O' symbol.
4 points at (-30,5)

APPENDIX G

Fracture Toughness Test Results for Unirradiated, Irradiated and Postirradiation Annealed Conditions

Table of Contents

Overview

The fracture toughness results provided in this appendix include those for all of the irradiation experiments and those for the unirradiated condition at the 1/8T location only (this location is consistent with that used for the irradiation experiments). A table summarizing the fracture toughness results is given for each condition. All evaluations of the J integral use the modified form of J, J_M, as opposed to those formulations specified in ASTM Standards E 813 and E 1152. J_M gives the same J values as the ASTM standards when maximum J values (J_{MAX}) from cleavage fracture tests are used, and only small changes in J_{Ic} values for J-R curve tests.

The transition regime data (K_{Jc}) are plotted and curve-fit to an exponential function, as given by

$$K_{Jc} = A + B \exp(T/C)$$

with A, B, and C evaluated from non-linear regression analysis. For the case of the annealed conditions only (with few data points), coefficient "A" was assigned a value of zero to improve the fitting results. The dashed lines given on each plot represent upper and lower bound curves at a 95% confidence level.

Lastly, for each condition, a summary sheet is provided for each test which resulted in a J-R curve. These summary sheets include a graphical plot of the J-R curve data, reference information for the test, and evaluation of the data using power law and linear curve-fitting methodologies. For the power law analyses, the data given under "MEA power law" utilize a user-defined range of data points in the power law curve fit; J_{Ic} is defined as the intersection of this power law curve with the 0.15 mm exclusion line. The "E 813-87" results are from an analysis using that ASTM standard, whereby J_{Ic} is defined as the intersection of the power law curve with a line parallel to the blunting line but offset by 0.2 mm. In general, the "E 813-87" values of J_{Ic} are higher than the "MEA power law" values of J_{Ic}.

The linear curve fit analyses are based upon ASTM Standard E 813-81. Specifically, values given under "E 813-81" are from a strict interpretation of that standard, whereas values given under "All Data" are from an analysis using all data points between the 0.15 mm and 1.5 mm exclusion lines. For both linear analyses, J_{Ic} is defined as the intersection of the linear curve with the ASTM blunting line ($J = 2\,\sigma_f\,\Delta a$, with σ_f the flow strength).

For all four J-R curve analyses (and for cleavage fracture tests as well), K_{Jc} values are evaluated from:

$$K_{Jc} = \sqrt{J_{Ic} \cdot E/(1 - \nu^2)}$$

where E is the value of Young's modulus at the test temperature and ν is Poisson's ratio (0.3). For cleavage fracture tests, J at fracture (i.e., J_{MAX}) is used in place of J_{Ic}. ($K_{\beta c}$ values are calculated for cleavage fracture tests, as in Ref. G-1.)

T_{avg} values are average values of tearing modulus, T, as given by the equation

$$T = \frac{E}{\sigma_f^2} \frac{dJ}{da}$$

For the linear analyses, dJ/da is taken to be the slope of the line. For the power law analyses, dJ/da is given from a closed form solution (see Appendix H of Reference G-2), as an average slope between the exclusion lines.

In the attached tables, values of J_{Ic} and K_{Jc} referred to as "ASTM" are from an ASTM E 813-81 analysis using J_M (for J-R curve tests); for cleavage fracture tests, K_{Jc} values are actually K_Q values using the procedures in ASTM standard E 399.

REFERENCES

G-1. A. L. Hiser, "Correlation of C_v and K_{Ic}/K_{Jc} Transition Temperature Increases Due to Irradiation, "USNRC Report NUREG/CR-4395, Nov. 1985.

G-2. A. L. Hiser, F. J. Loss and B. H. Menke, "J-R Curve Characterization of Irradiated Low Upper Shelf Welds," USNRC Report NUREG/CR-3506, Apr. 1984.

Unirradiated Condition (1/8T)

Table G-1 Fracture Toughness Results for Code GEB (Side 2), Unirradiated Condition

Specimen Number	Test Temperature (°C)	Test Temperature (°F)	$(a/W)_o$[a]	Δa_m[b] (mm)	Δa_p[c] (mm)	$\Delta a_p - \Delta a_m$ (mm)	J_{Ic} MEA (kJ/m^2)	J_{Ic} ASTM (kJ/m^2)	K_{Jc} MEA (MPa$\sqrt{m}$)	K_{Jc} ASTM (MPa$\sqrt{m}$)	$K_{\beta c}$ (MPa$\sqrt{m}$)	T_{avg} MEA	σ_f (MPa)	σ_y (MPa)
GEB2-A6	−140	−220	0.509	—[d]	—	—	8.9	—	46.0	45.5	43.4	—	773.9	703.2
GEB2-A13	−118	−180	0.508	—	—	—	26.0	—	78.2	65.3	61.4	—	738.0	667.4
GEB2-A4	−90	−130	0.502	—	—	—	36.1	—	91.8	60.1	64.8	—	695.9	625.3
GEB2-A15	−76	−105	0.509	—	—	—	36.2	—	91.7	52.6	63.8	—	676.5	605.7
GEB2-A2	−68	−90	0.517	—	—	—	67.8	—	125.4	59.6	72.9	—	665.8	595.0
GEB2-A14	−57	−70	0.515	—	—	—	63.7	—	121.5	50.8	70.9	—	651.7	580.7
GEB2-A1	−46	−50	0.502	—	—	—	121.6	—	167.5	56.4	79.8	—	638.3	567.1
GEB2-A3	−34	−30	0.516	—	—	—	165.7	—	195.3	59.3	83.4	—	624.4	552.9
GEB2-A5[e]	−18	0	0.509	—	—	—	137.4	118.1	177.3	164.4	—	—	607.0	535.0
GEB2-A18[e]	65	150	0.525	6.05	5.72	−0.33	129.2	127.4[f]	170.0	168.8	—	99	538.6	463.0
GEB2-A17[e]	177	350	0.522	6.53	6.19	−0.34	81.6	80.4[f]	133.0	132.0	—	115	504.5	420.2
GEB2-A16[e]	288	550	0.514	6.09	6.04	−0.05	117.4	110.5[f]	156.9	152.2	—	56	536.4	439.5

[a] Pretest a/W

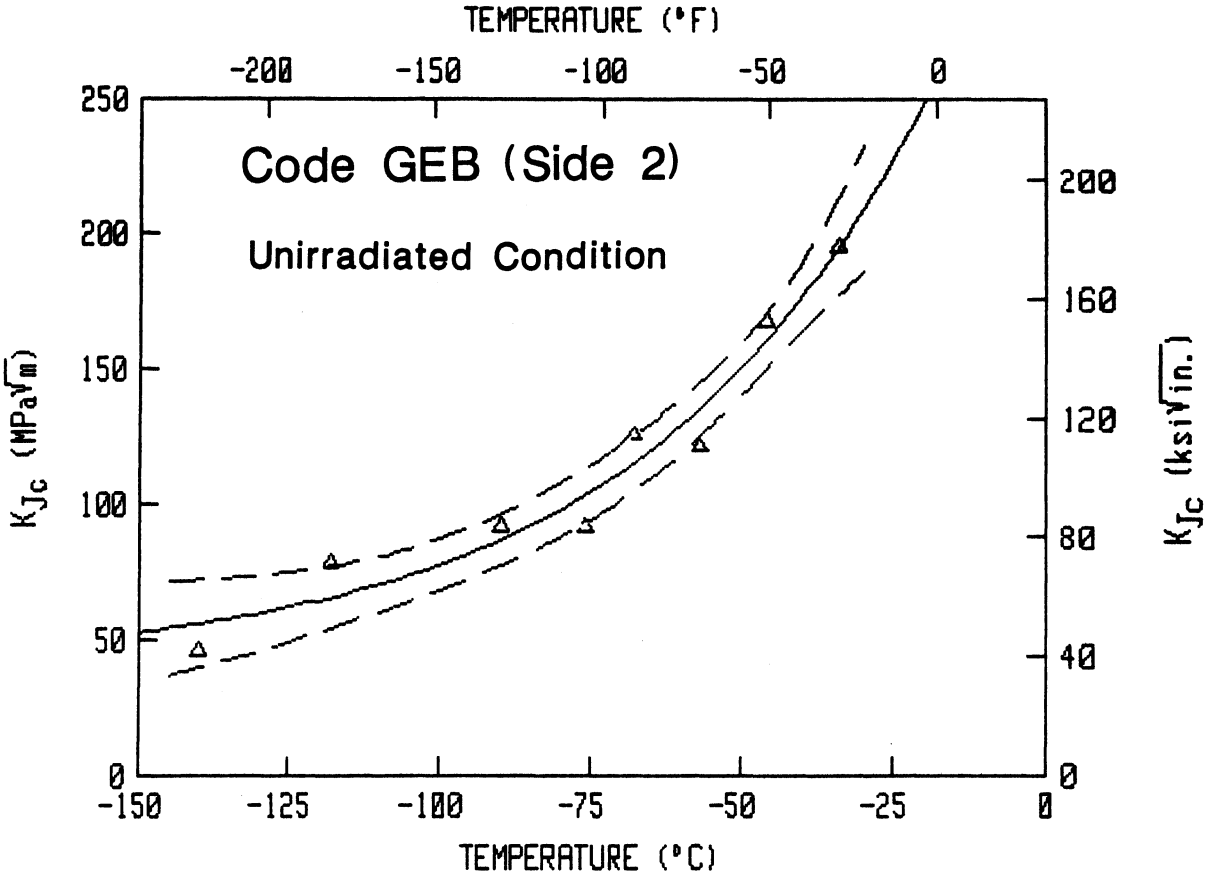
[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

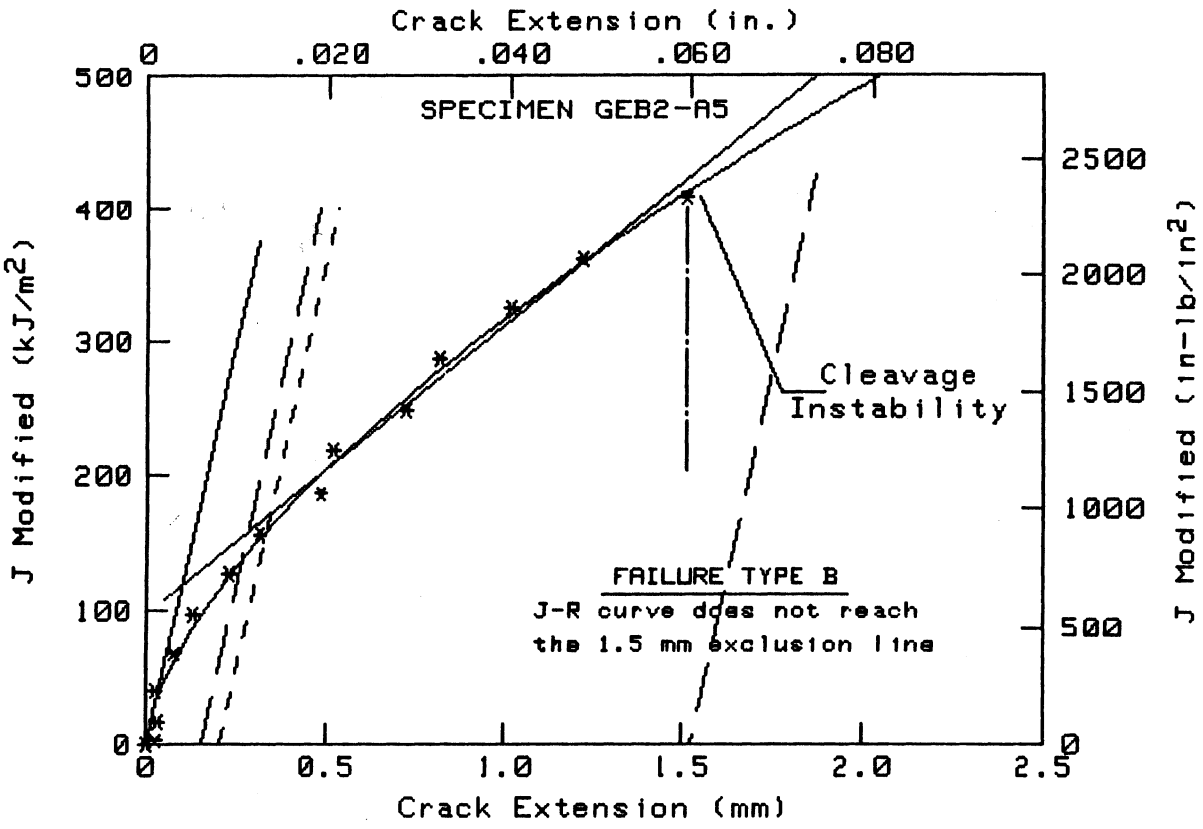
[f] Valid J_{Ic}, per ASTM E 813-81



Kjc = A + B exp(T/C)

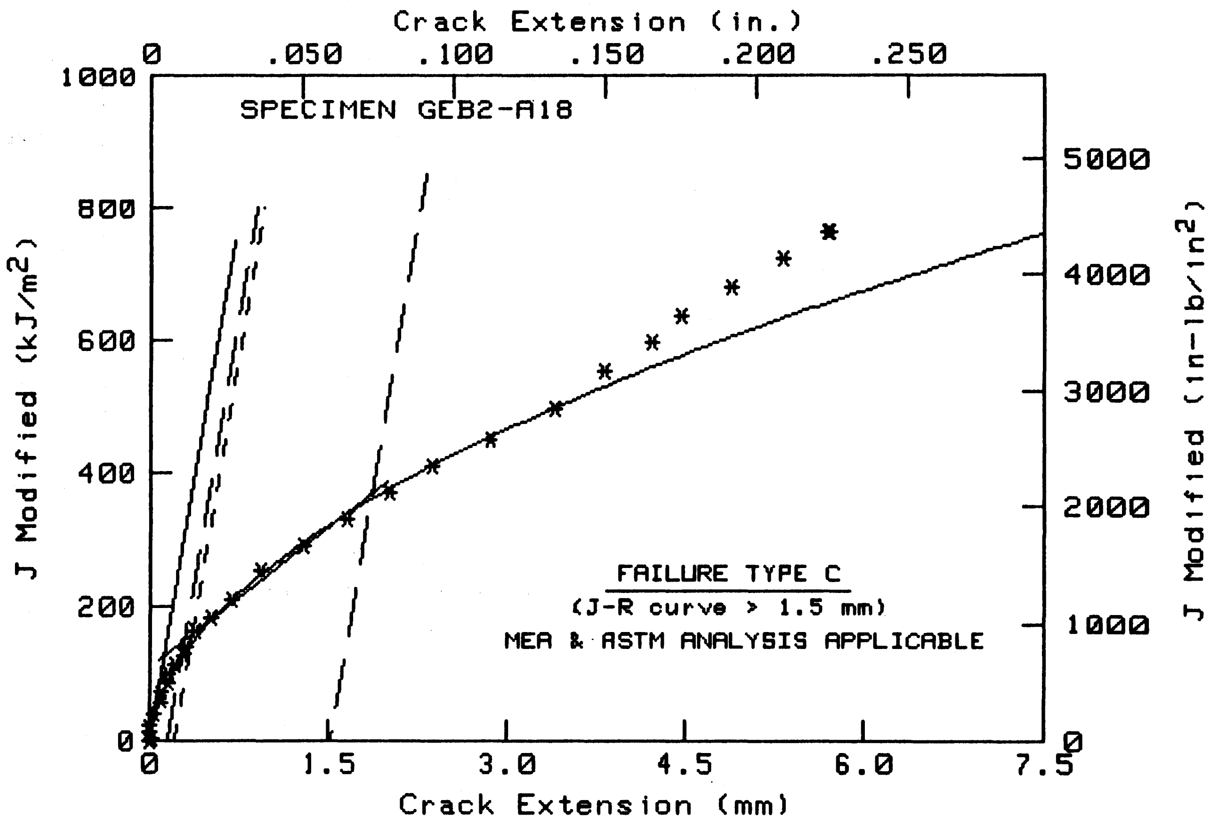
	Metric	English
A =	39.61	36.04
B =	321.80	292.85
C =	46.90	84.41

Upper Bound K = 100 when Temp =	-86	-123
Ave. K = 100 when Temp =	-78	-109
Lower Bound K = 100 when Temp =	-71	-96



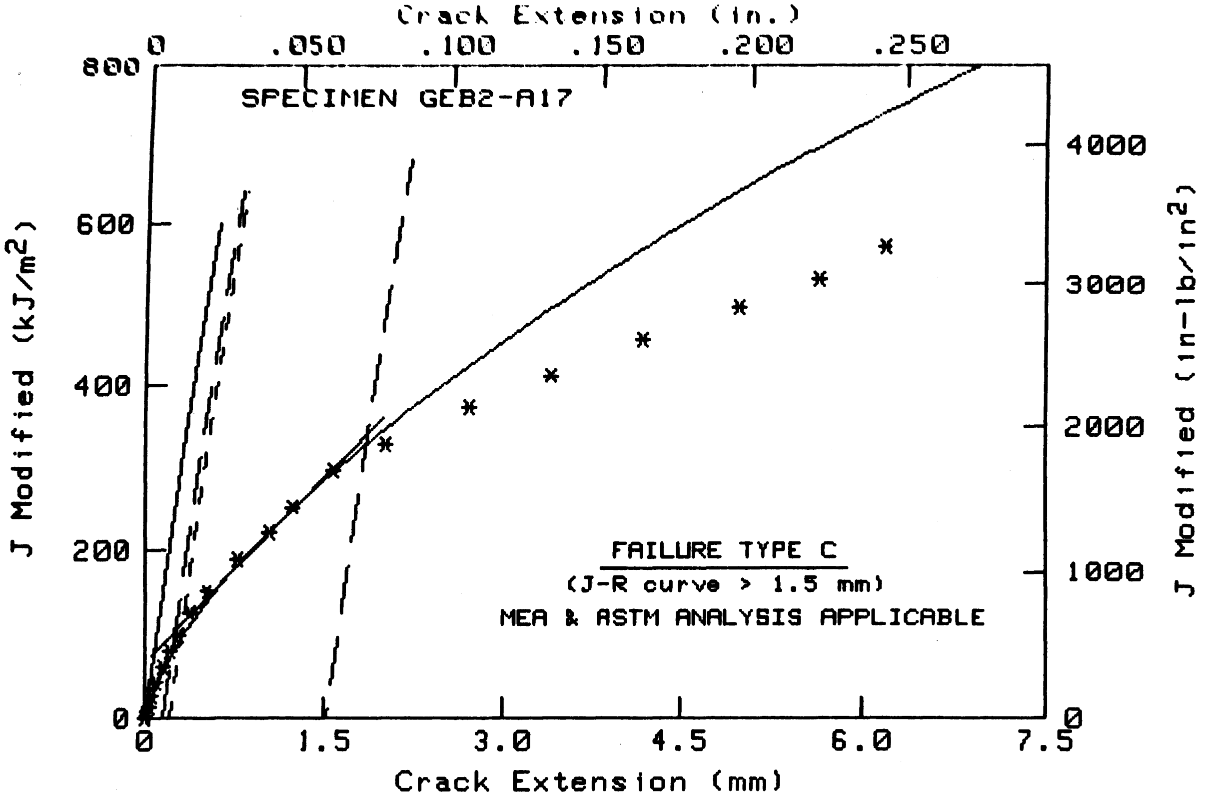
```
TEST SPECIMEN DATA

Test Temperature       = -18°C
Percent Side Groove    = 20%
Specimen Thickness     = 12.7 mm
Initial Crack Length   = 12.95 mm          Init a/W  = .509
Flow Stress            = 607 MPa
Youngs Modulus         = 208200 MPa         (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                         MEA Power Law        E813-87
Jic                    = 137.4 kJ/m²          157.5 kJ/m²
Kjc                    = 177.3 MPa√m          189.8 MPa√m
Exponent       N       = .6317                .6317
Coefficient    C       = 317.4 kJ/m²          317.4 kJ/m²
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                         All Data             E813-81
Jic                    = 118.1 kJ/m²          118.1 kJ/m²
Kjc                    = 164.4 MPa√m          164.4 MPa√m
Slope          M       = 214544.3 kJ/m³       214544.3 kJ/m³
Intercept      B       = 97.3 kJ/m²           97.3 kJ/m²
Validity (E813-81)     = VALID
Validity (E813-87)     = VALID
Validity (E1152-87)    = VALID
J maximum allowed      = 377.6 kJ/m²    (Jmax=B*Flow stress/20)
Delta a max. allowed   = 1.25 mm         (Delta a max = 0.1*bo)
Final Delta a          = 1.51 mm
Poisson's Ratio (v)    = .3
Points Left            = 0          Points Right = 0
```



```
TEST SPECIMEN DATA

Test Temperature      = 65°C
Percent Side Groove   = 20%
Specimen Thickness    = 12.7 mm
Initial Crack Length  = 13.36 mm         Init a/W  = .525
Final Crack Length    = 19.41 mm         Final a/W = .764
Flow Stress           = 538.6 MPa
Youngs Modulus        = 203500 MPa         (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                        MEA Power Law       E813-87
Jic                   = 129.2 kJ/m²        145.1 kJ/m²
Kjc                   = 170 MPa√m          180.1 MPa√m
J (@J/T=8.8)          = 482 kJ/m²
Exponent       N      = .5352              .5164
Coefficient    C      = 259.2 kJ/m²        258.8 kJ/m²
T (average)           = 99                 95
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                        All Data            E813-81
Jic                   = 119.9 kJ/m²        127.4 kJ/m²
Kjc                   = 163.7 MPa√m        168.8 MPa√m
Slope        M        = 145279.1 kJ/m³     139283.5 kJ/m³
Intercept    B        = 103.7 kJ/m²        110.9 kJ/m²
T (ASTM)              = 102                98
Validity (E813-81)    = VALID
Validity (E813-87)    = INVALID--c (.33 mm vs .27 mm)
Validity (E1152-87)   = INVALID--3 (.33 mm vs .18 mm)
J maximum allowed     = 324.1 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed  = 1.2 mm        (Delta a max = 0.1*bo)
Final Delta a         = 5.72 mm
Poisson's Ratio (v)   = .3
Points Left           = 4          Points Right = 2
```



TEST SPECIMEN DATA

Test Temperature = 177°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 13.26 mm   Init a/W = .522
Final Crack Length = 19.79 mm   Final a/W = .779
Flow Stress = 504.5 MPa
Youngs Modulus = 197100 MPa   (Estimated Value)

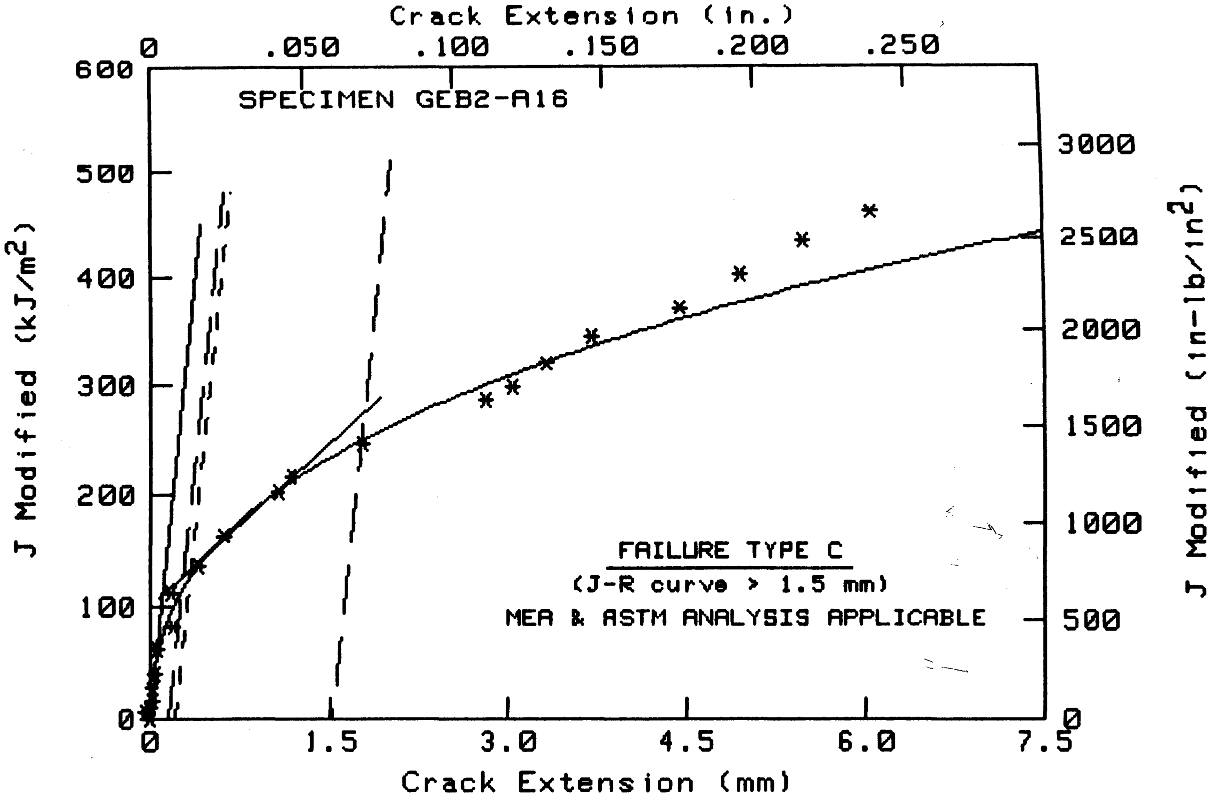
POWER LAW DATA J = C (Delta a)^N

		MEA Power Law	E813-87
Jic		= 81.6 kJ/m^2	108 kJ/m^2
Kjc		= 133 MPa$\sqrt{m}$	152.9 MPa$\sqrt{m}$
J (@J/T=8.8)		= 393.2 kJ/m^2	
Exponent	N	= .673	.6113
Coefficient	C	= 217.4 kJ/m^2	222.1 kJ/m^2
T (average)		= 115	107

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

		All Data	E813-81
Jic		= 80.4 kJ/m^2	80.4 kJ/m^2
Kjc		= 132 MPa$\sqrt{m}$	132 MPa$\sqrt{m}$
Slope	M	= 147542.3 kJ/m^3	147542.3 kJ/m^3
Intercept	B	= 68.6 kJ/m^2	68.6 kJ/m^2
T (ASTM)		= 114	114

Validity (E813-81) = VALID
Validity (E813-87) = INVALID--c (.34 mm vs .27 mm)
Validity (E1152-87) = INVALID--1, 3 (.34 mm vs .18 mm)
J maximum allowed = 306 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.21 mm   (Delta a max = 0.1*bo)
Final Delta a = 6.18 mm
Poisson's Ratio (v) = .3
Points Left = 4   Points Right = 2



TEST SPECIMEN DATA

Test Temperature = 288°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 13.07 mm   Init a/W = .514
Final Crack Length = 19.16 mm   Final a/W = .754
Flow Stress = 536.4 MPa
Youngs Modulus = 190800 MPa   (Estimated Value)

POWER LAW DATA $J = C\,(\text{Delta a})^N$

	MEA Power Law	E813-87
Jic	= 117.4 kJ/m^2	125.8 kJ/m^2
Kjc	= 156.9 $MPa\sqrt{m}$	162.4 $MPa\sqrt{m}$
J (@J/T=8.8)	= 331 kJ/m^2	
Exponent N	= .3959	.4111
Coefficient C	= 199.5 kJ/m^2	201.1 kJ/m^2
T (average)	= 56	58

LEAST SQUARE LINEAR LINE (ASTM) $J = M\,(\text{Delta a}) + B$

	All Data	E813-81
Jic	= 110.5 kJ/m^2	110.5 kJ/m^2
Kjc	= 152.2 $MPa\sqrt{m}$	152.2 $MPa\sqrt{m}$
Slope M	= 99244.7 kJ/m^3	99244.7 kJ/m^3
Intercept B	= 100.3 kJ/m^2	100.3 kJ/m^2
T (ASTM)	= 66	66

Validity (E813-81) = VALID
Validity (E813-87) = INVALID--b
Validity (E1152-87) = INVALID--2
J maximum allowed = 330.5 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.23 mm   (Delta a max = 0.1*bo)
Final Delta a = 6.05 mm
Poisson's Ratio (v) = .3
Points Left = 0   Points Right = 1

Irradiated Condition, Experiment UBR-68

Table G-2 Fracture Toughness for Code GEB (Side 2), I Condition (Irradiated Experiment UBR-68)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p-\Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
	(°C)	(°F)		(mm)	(mm)	(mm)	MEA (kJ/m^2)	ASTM (kJ/m^2)	MEA (MPa√m)	ASTM (MPa√m)	(MPa√m)	MEA	(MPa)	(MPa)
GEB2-A20	−80	−112	0.531	—[d]	—	—	16.1	—	61.3	57.4	52.6	—	719.7	656.9
GEB2-A29	−50	−58	0.514	—	—	—	18.1	—	64.7	65.2	53.2	—	680.9	617.7
GEB2-A25	−35	−31	0.528	—	—	—	29.4	—	82.3	69.9	60.1	—	663.2	599.7
GEB2-A24	−25	−13	0.490	—	—	—	61.4	—	118.7	71.7	70.8	—	652.2	588.4
GEB2-A31	−18	0	0.513	—	—	—	75.8	—	131.7	67.2	73.4	—	644.7	580.7
GEB2-A30	−5	+23	0.514	—	—	—	107.5	—	156.6	50.6	77.7	—	631.6	567.2
GEB2-A19	0	+32	0.554	—	—	—	117.1	—	163.4	51.5	78.6	—	626.8	562.2
GEB2-A36	40	+104	0.509	5.93	5.44	−0.49	139.1	97.7[e]	177.0	148.3	—	133	593.1	526.2
GEB2-A7[f]	177	+350	0.511	6.35	6.36	+0.01	106.7	107.3[e]	152.0	152.5	—	62	542.2	465.9
GEB2-A9[f]	288	+550	0.501	7.40	6.85	−0.55	100.4	98.1[e]	145.0	143.4	—	44	574.1	485.2

[a] Pretest a/W

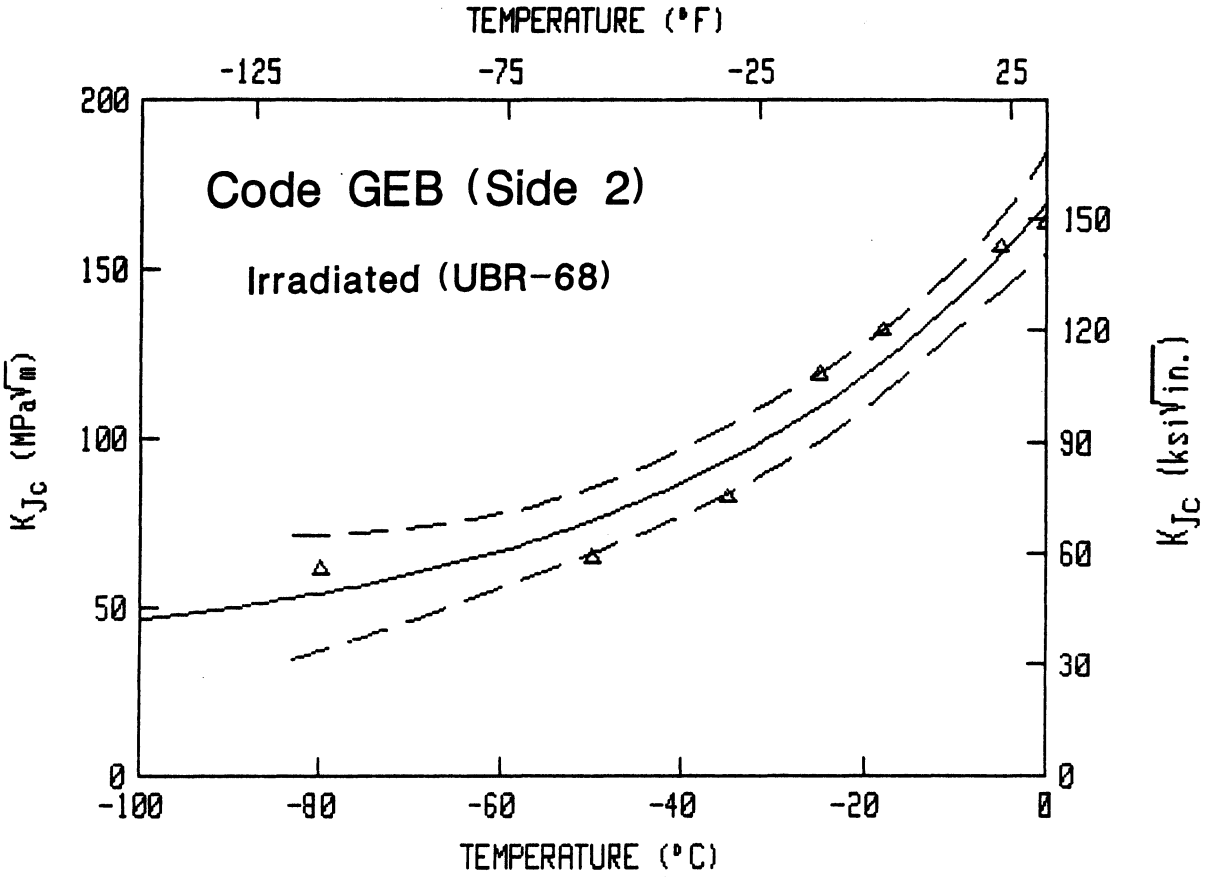
[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Valid J_{Ic}, per ASTM E 813-81

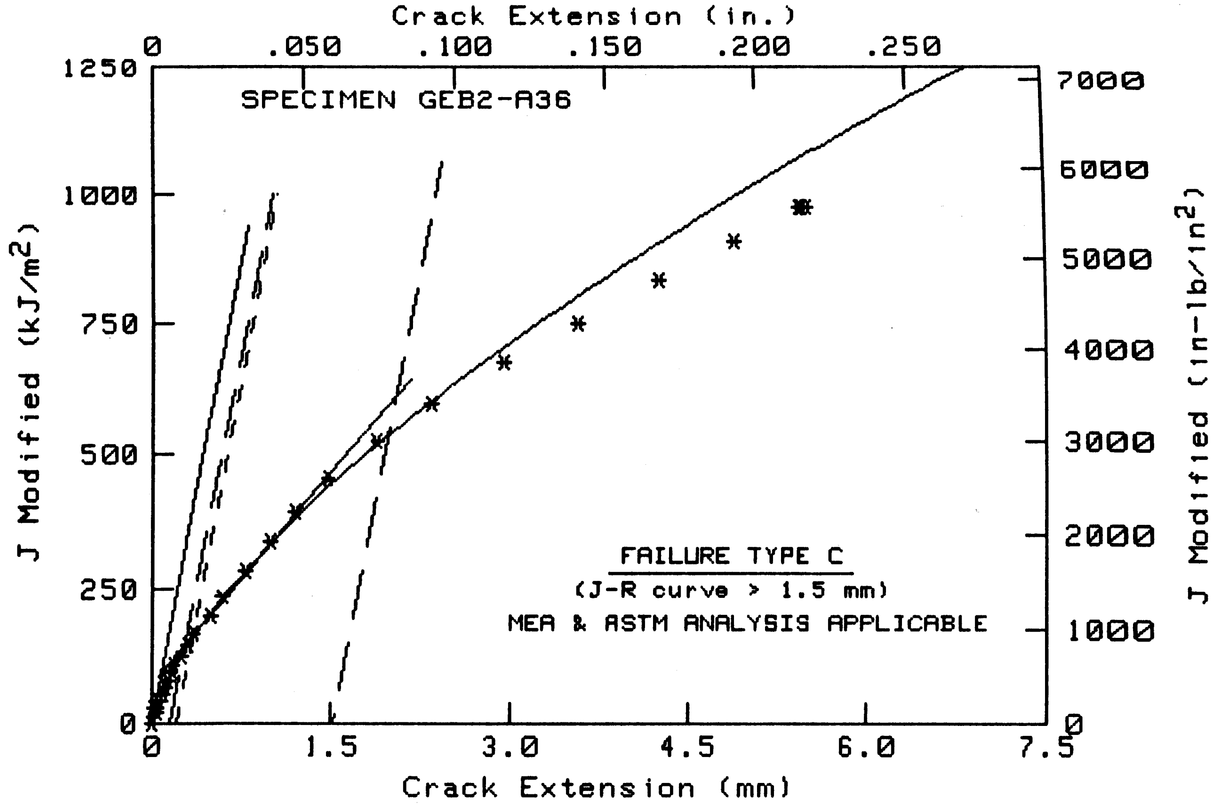
[f] Side grooved by 20%



Kjc = A + B exp(T/C)

	Metric	English
A =	33.26	30.27
B =	136.23	123.98
C =	42.71	76.89

	Metric	English
Upper Bound K = 100 when Temp =	-37	-35
Ave. K = 100 when Temp =	-30	-23
Lower Bound K = 100 when Temp =	-24	-11



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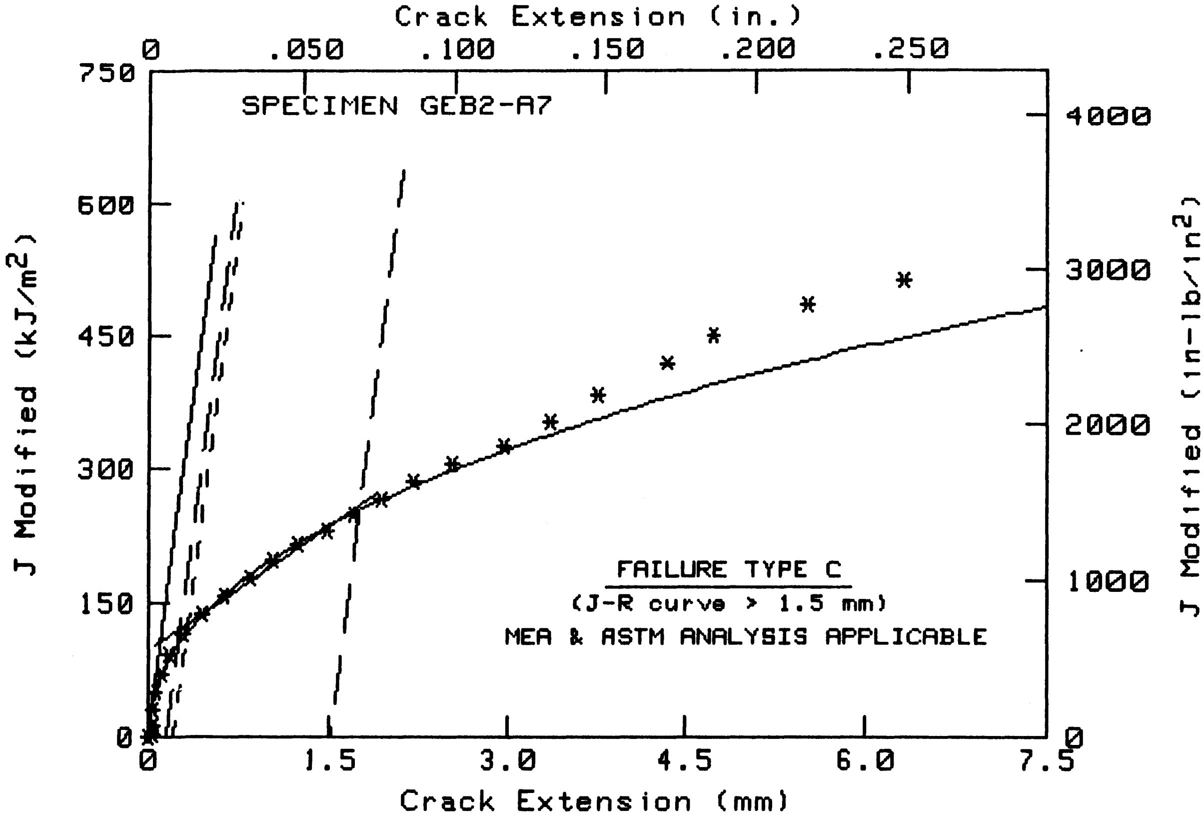
TEST SPECIMEN DATA

Test Temperature      = 40°C
Percent Side Groove   = 0%
Specimen Thickness    = 12.7 mm
Initial Crack Length  = 12.93 mm          Init a/W  = .509
Final Crack Length    = 18.86 mm          Final a/W = .742
Flow Stress           = 593.1 MPa
Youngs Modulus        = 204900 MPa         (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                        MEA Power Law       E813-87
Jic                   = 139.1 kJ/m²        159.1 kJ/m²
Kjc                   = 177 MPa√m          189.3 MPa√m
J (@J/T=8.8)          = 672.4 kJ/m²
Exponent     N        = .6789              .6968
Coefficient  C        = 338.6 kJ/m²        342 kJ/m²
T (average)           = 133                138
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                        All Data           E813-81
Jic                   = 110.5 kJ/m²        97.7 kJ/m²
Kjc                   = 157.8 MPa√m        148.3 MPa√m
Slope      M          = 243447.5 kJ/m³     262118.5 kJ/m³
Intercept  B          = 87.8 kJ/m²         76.1 kJ/m²
T (ASTM)              = 142                153
Validity (E813-81)    = VALID
Validity (E813-87)    = INVALID--c (.48 mm vs .29 mm)
Validity (E1152-87)   = INVALID--3 (.48 mm vs .18 mm)
J maximum allowed     = 369.6 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed  = 1.25 mm        (Delta a max = 0.1*bo)
Final Delta a         = 5.44 mm
Poisson's Ratio (v)   = .3
Points Left           = 0          Points Right = 2
```



TEST SPECIMEN DATA

Test Temperature = 177°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 12.83 mm   Init a/W = .505
Final Crack Length = 19.18 mm   Final a/W = .755
Flow Stress = 542.2 MPa
Youngs Modulus = 197100 MPa   (Estimated Value)

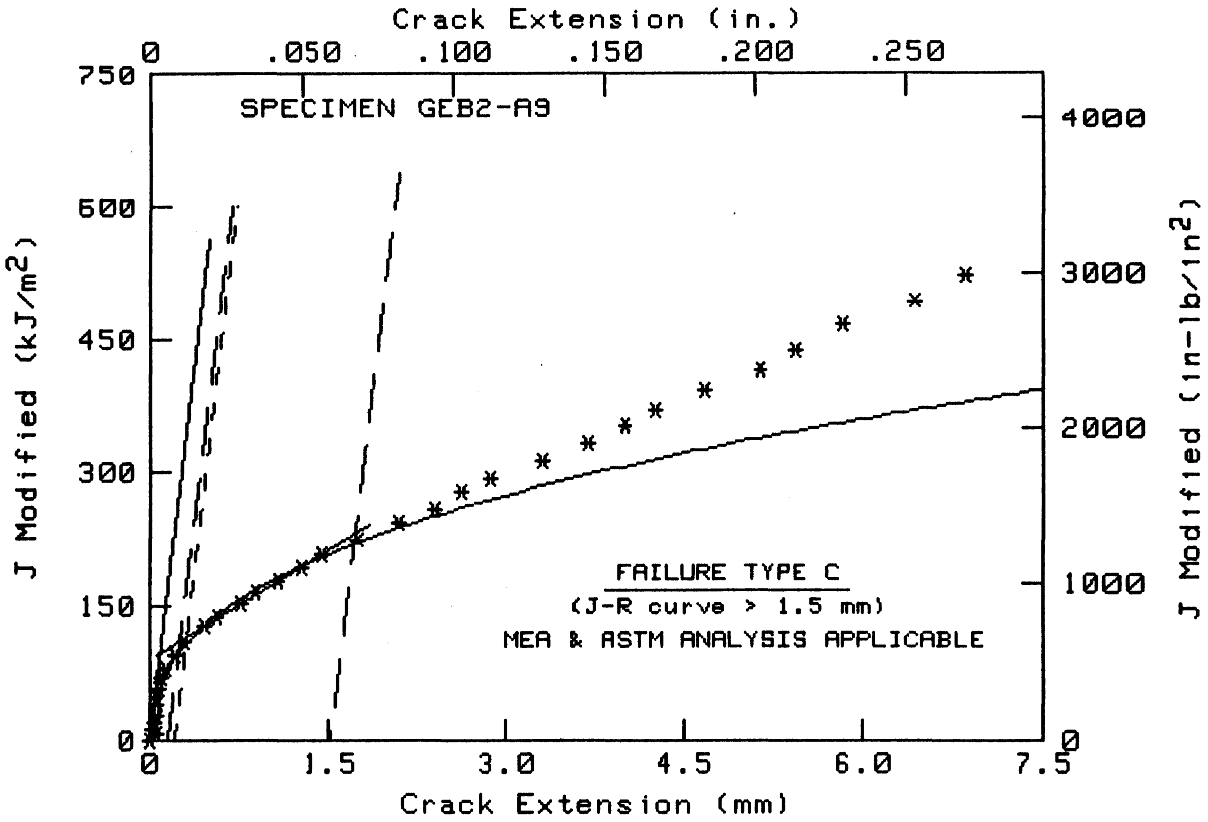
POWER LAW DATA J = C (Delta a)^N

	MEA Power Law	E813-87
Jic	= 106.7 kJ/m^2	119.7 kJ/m^2
Kjc	= 152 MPa$\sqrt{m}$	161 MPa$\sqrt{m}$
J (@J/T=8.8)	= 350 kJ/m^2	
Exponent N	= .445	.4244
Coefficient C	= 197.4 kJ/m^2	196.1 kJ/m^2
T (average)	= 62	59

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

	All Data	E813-81
Jic	= 107.3 kJ/m^2	107.3 kJ/m^2
Kjc	= 152.5 MPa$\sqrt{m}$	152.5 MPa$\sqrt{m}$
Slope M	= 91687.1 kJ/m^3	91687.1 kJ/m^3
Intercept B	= 98.3 kJ/m^2	98.3 kJ/m^2
T (ASTM)	= 62	62

Validity (E813-81) = VALID
Validity (E813-87) = VALID
Validity (E1152-87) = VALID
J maximum allowed = 340.6 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.26 mm   (Delta a max = 0.1*bo)
Final Delta a = 6.32 mm
Poisson's Ratio (v) = .3
Points Left = 2   Points Right = 2



TEST SPECIMEN DATA

Test Temperature = 288°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 12.73 mm   Init a/W = .501
Final Crack Length = 20.13 mm   Final a/W = .792
Flow Stress = 574.1 MPa
Youngs Modulus = 190800 MPa   (Estimated Value)

POWER LAW DATA $J = C \text{ (Delta a)}^N$

		MEA Power Law	E813-87
Jic	=	100.4 kJ/m^2	110.7 kJ/m^2
Kjc	=	145 MPa$\sqrt{m}$	152.3 MPa$\sqrt{m}$
J (@J/T=8.8)	=	300.5 kJ/m^2	
Exponent N	=	.3973	.38
Coefficient C	=	177 kJ/m^2	175.2 kJ/m^2
T (average)	=	44	42

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

		All Data	E813-81
Jic	=	98.1 kJ/m^2	98.1 kJ/m^2
Kjc	=	143.4 MPa$\sqrt{m}$	143.4 MPa$\sqrt{m}$
Slope M	=	81452.4 kJ/m^3	81452.4 kJ/m^3
Intercept B	=	91.2 kJ/m^2	91.2 kJ/m^2
T (ASTM)	=	47	47

Validity (E813-81) = VALID
Validity (E813-87) = INVALID--c (.55 mm vs .25 mm)
Validity (E1152-87) = INVALID--3 (.55 mm vs .19 mm)
J maximum allowed = 363.6 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.27 mm   (Delta a max = 0.1*bo)
Final Delta a = 6.85 mm
Poisson's Ratio (v) = .3
Points Left = 0   Points Right = 2

Irradiated (Experiment UBR-68)

Annealed (at 399°C for 168 h)

Table G-3 Fracture Toughness Results for Code GEB (Side 2), IA Condition
(Irradiated Experiment UBR-68, Annealed at 399°C for 168 h)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p-\Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)		(MPa)	(MPa)
GEB2-A27	−80	−112	0.520	——[d]	——	——	23.8	——	74.5	56.9	58.0	—	686.0	623.2
GEB2-A21	−57	−71	0.512	——	——	——	55.7	——	113.5	49.9	69.7	—	655.8	592.7
GEB2-A26	−50	−58	0.512	——	——	——	75.0	——	131.6	49.2	73.6	—	647.2	584.0
GEB2-A32	−34	−29	0.522	——	——	——	41.2	——	97.4	51.6	63.3	—	628.4	564.9
GEB2-A33	−18	0	0.507	——	——	——	137.4	——	117.4	49.6	79.8	—	611.0	547.0
GEB2-A35	0	+32	0.528	——	——	——	129.7	——	171.9	50.9	77.2	—	593.1	528.5
GEB2-A10[e]	177	+350	0.506	——[f]	6.75	——[f]	133.5	129.5[g]	170.0	167.5	-	89	508.5	432.2

[a] Pretest a/W

[b] Measured crack growth

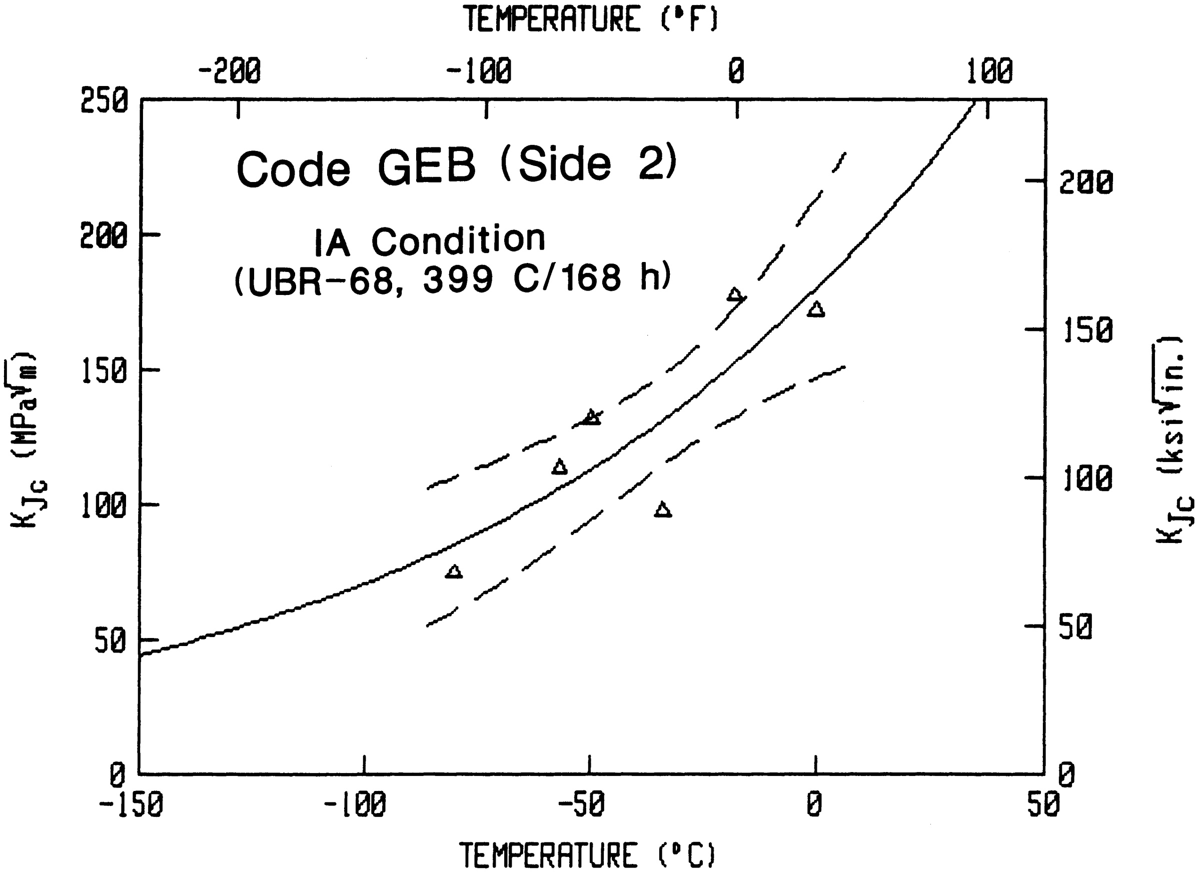
[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

[f] Cannot be determined

[g] Valid J_{Ic}, per ASTM E 813-81



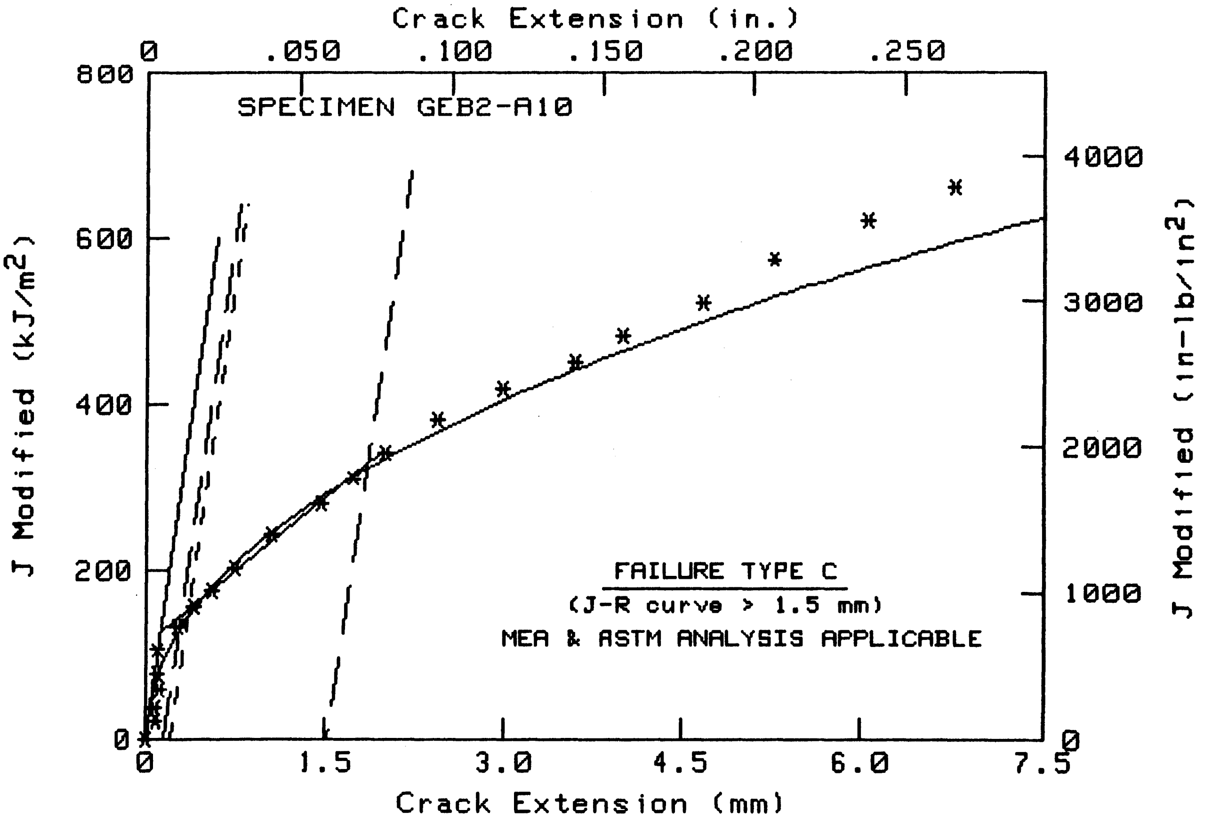
Kjc = B * exp(T/C)

	Metric	English
B =	180.10	163.90
C =	106.84	192.32

Upper Bound K = 100 when Temp = -96 -141

Ave. K = 100 when Temp = -63 -81

Lower Bound K = 100 when Temp = -45 -49



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TEST SPECIMEN DATA
Material Type          = A-336 Forging
Test Temperature       = 177°C
Percent Side Groove    = 20%
Specimen Thickness     = 12.7 mm
Initial Crack Length   = 12.87 mm         Init a/W  = .506
Flow Stress            = 508.5 MPa
Youngs Modulus         = 197100 MPa         (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                         MEA Power Law       E813-87
Jic                    = 133.5 kJ/m²        143.3 kJ/m²
Kjc                    = 170 MPa√m          176.2 MPa√m
J (@J/T=8.8)           = 489.6 kJ/m²
Exponent      N        = .4717              .4709
Coefficient   C        = 241.8 kJ/m²        237.4 kJ/m²
T (average)            = 89                 87
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                         All Data            E813-81
Jic                    = 129.5 kJ/m²        129.5 kJ/m²
Kjc                    = 167.5 MPa√m        167.5 MPa√m
Slope         M        = 115550.7 kJ/m³     115550.7 kJ/m³
Intercept   B          = 114.8 kJ/m²        114.8 kJ/m²
T (ASTM)               = 88                 88
Validity (E813-81)     = VALID
Validity (E813-87)     = VALID
Validity (E1152-87)    = VALID
J maximum allowed      = 318.5 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed   = 1.25 mm        (Delta a max = 0.1*bo)
Final Delta a          = 6.77 mm
Poisson's Ratio (v)    = .3
Points Left            = 1          Points Right = 2
```

Irradiated (Experiment UBR-68)

Annealed (at 454°C for 168 h)

Table G-4 Fracture Toughness Results for Code GEB (Side 2), IA Condition (Irradiated Experiment UBR-68, Annealed at 454°C for 168 h)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p - \Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)		(MPa)	(MPa)
GEB2-A23	-110	-166	0.528	——[d]	——	——	11.3	——	51.6	49.1	46.4	——	711.2	644.1
GEB2-A34	-90	-130	0.524	——	——	——	52.7	——	110.9	52.1	70.3	——	681.6	614.4
GEB2-A8	-65	-85	0.519	——	——	——	51.6	——	109.4	47.0	67.7	——	647.6	580.1
GEB2-A28	-38	-36	0.524	——	——	——	59.4	——	117.0	45.4	67.4	——	614.6	546.6
GEB2-A11	-24	-11	0.519	——	——	——	111.7	——	160.1	47.4	75.3	——	599.0	530.7
GEB2-A12[e]	177	+350	0.541	6.28	6.04	-0.24	123.7	120.2[f]	163.7	161.3	——	83	490.2	409.3

[a] Pretest a/W

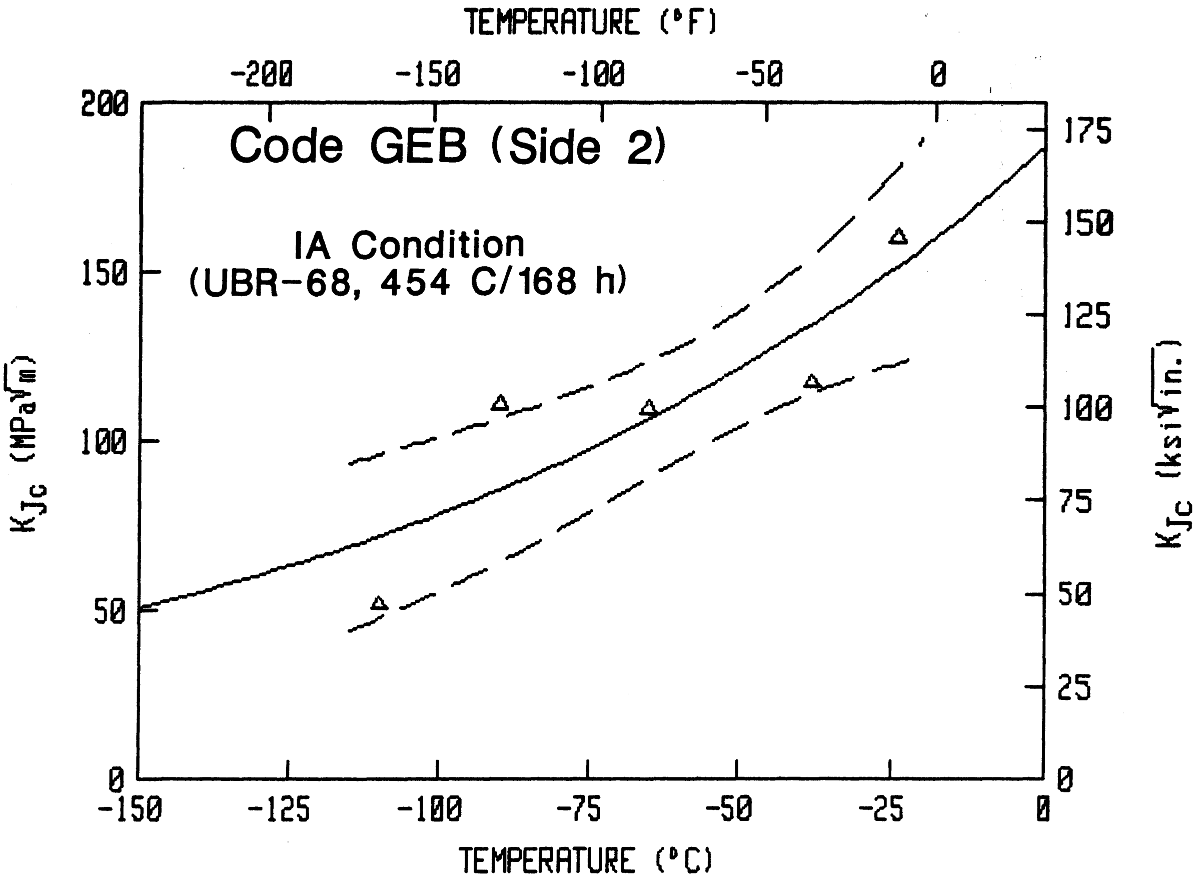
[b] Measured crack growth

[c] Crack growth predicted by compliance

[d] Cleavage failure precluded determination of this quantity

[e] Side grooved by 20%

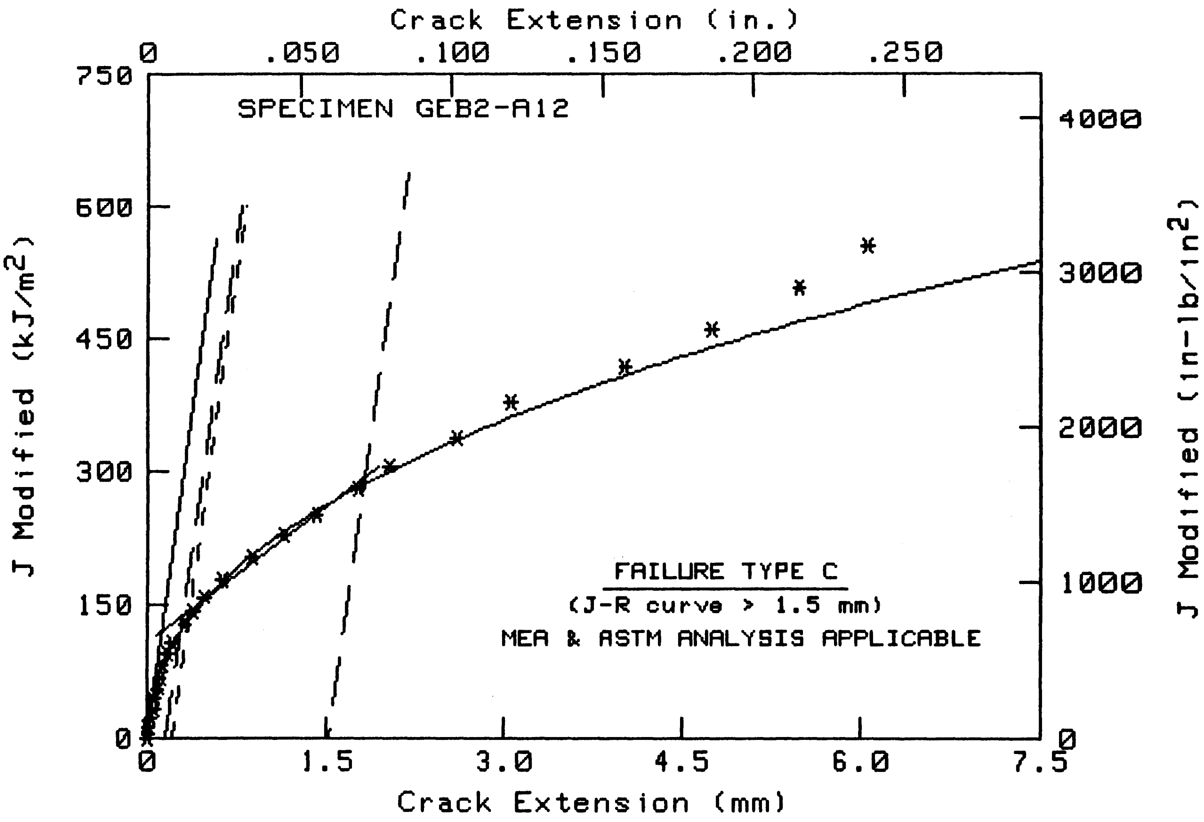
[f] Valid J_{Ic}, per ASTM E 813-81



```
                          Kjc = B * exp(T/C)

                              Metric      English
                        B =   186.99      170.17
                        C =   114.93      206.87

Upper Bound K = 100 when Temp =-102        -152
       Ave. K = 100 when Temp = -72         -97
Lower Bound K = 100 when Temp = -54         -65
```



TEST SPECIMEN DATA

Test Temperature = 177°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 13.75 mm Init a/W = .541
Final Crack Length = 20.03 mm Final a/W = .788
Flow Stress = 490.2 MPa
Youngs Modulus = 197100 MPa (Estimated Value)

POWER LAW DATA J = C (Delta a)^N

		MEA Power Law	E813-87
Jic		= 123.7 kJ/m^2	136 kJ/m^2
Kjc		= 163.7 $MPa\sqrt{m}$	171.6 $MPa\sqrt{m}$
J (@J/T=8.8)		= 399.6 kJ/m^2	
Exponent	N	= .4473	.4352
Coefficient	C	= 219.1 kJ/m^2	217.4 kJ/m^2
T (average)		= 83	80

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

		All Data	E813-81
Jic		= 120.2 kJ/m^2	120.2 kJ/m^2
Kjc		= 161.3 $MPa\sqrt{m}$	161.3 $MPa\sqrt{m}$
Slope	M	= 101955.6 kJ/m^3	101955.6 kJ/m^3
Intercept	B	= 107.7 kJ/m^2	107.7 kJ/m^2
T (ASTM)		= 84	84

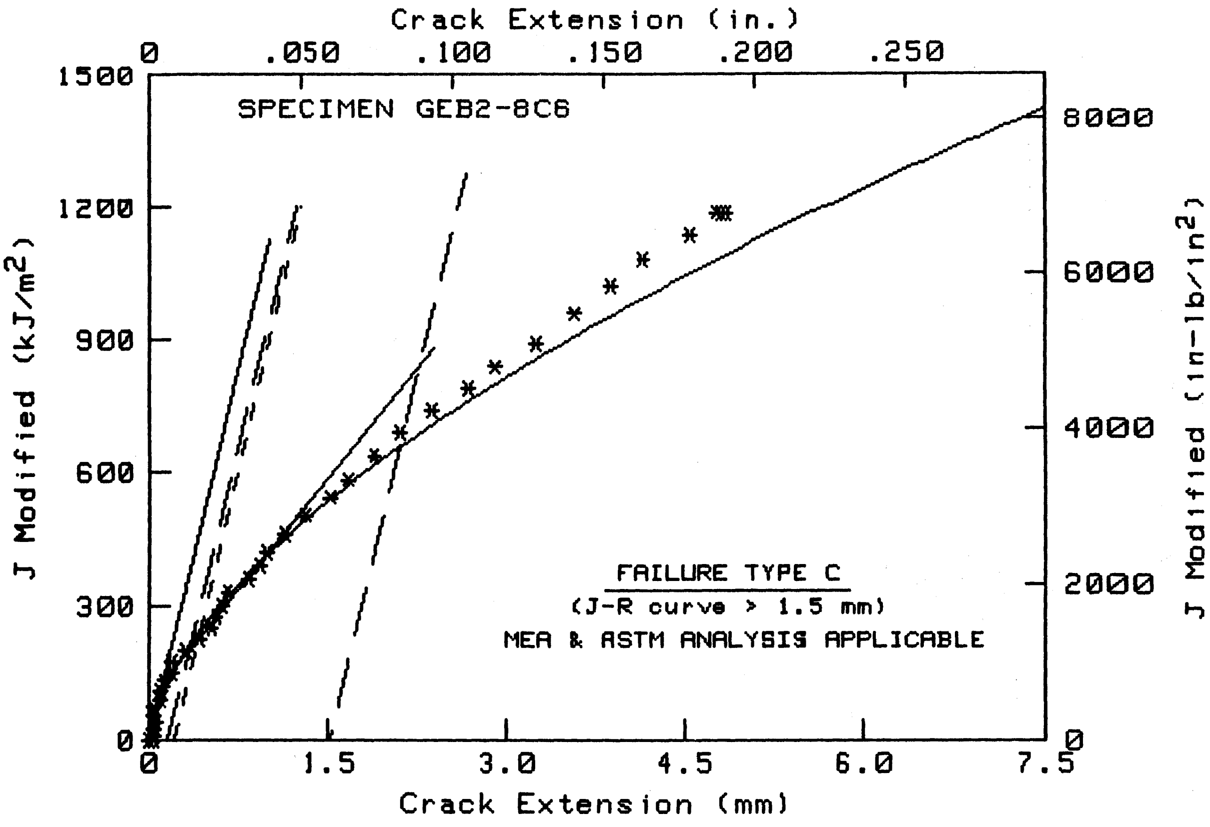
Validity (E813-81) = VALID
Validity (E813-87) = VALID
Validity (E1152-87) = INVALID--3 (.22 mm vs .17 mm)
J maximum allowed = 285.2 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.16 mm (Delta a max = 0.1*bo)
Final Delta a = 6.05 mm
Poisson's Ratio (v) = .3
Points Left = 0 Points Right = 2

<u>Unirradiated Condition Check-Tests</u>

Table G-5 Fracture Toughness Results for Code GEB (Side 2), Unirradiated Condition (Check-Tests)

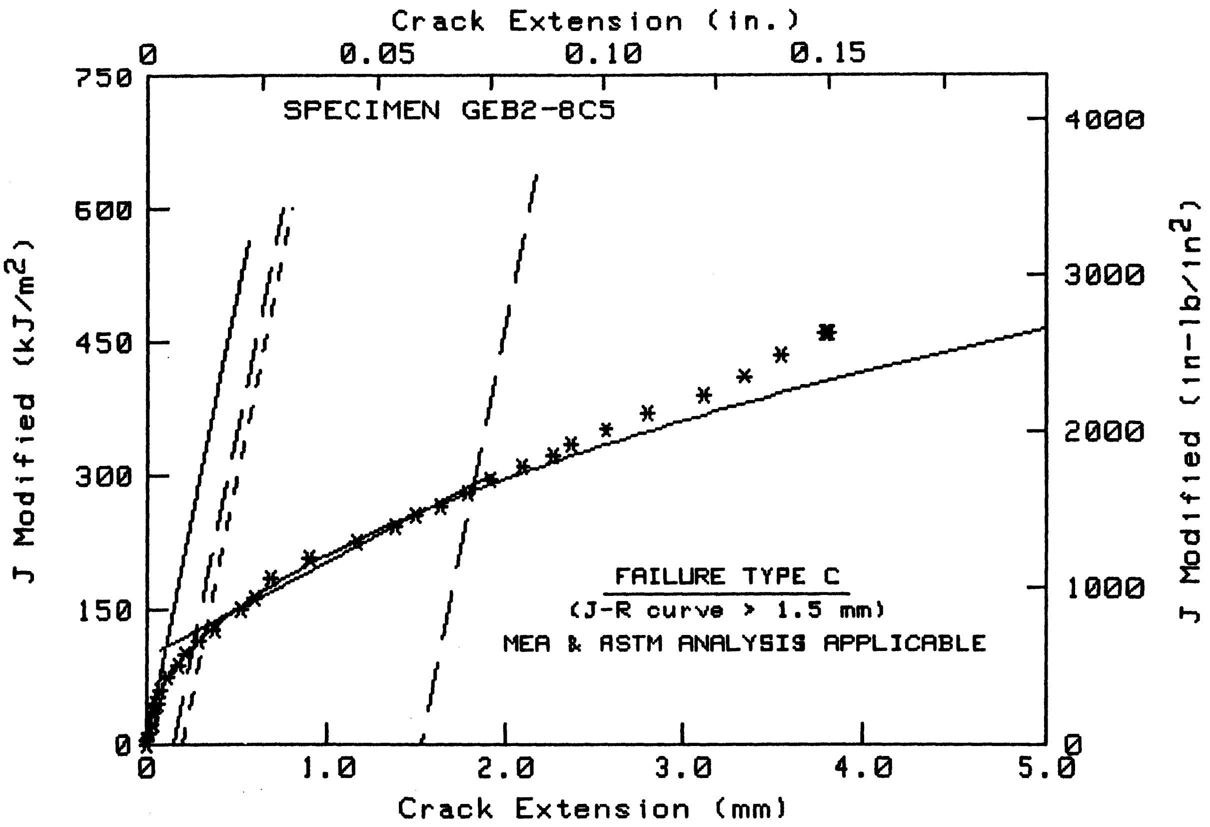
Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p - \Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)		(MPa)	(MPa)
GEB2-8E4	-107	-160	0.507	——[d]	——	——	26.5	——	78.1	55.1	60.7	—	720.9	650.4
GEB2-8E5	-73	-100	0.509	——	——	——	63.8	——	121.8	49.7	72.4	—	672.4	601.7
GEB2-8C4	-40	-40	0.509	——	——	——	113.9	——	161.9	50.1	73.0	—	631.2	559.9
GEB2-8C6	31	88	0.517	6.06	4.76	-1.30	222.1	130.1	223.9	171.4	——	157	562.2	483.8
GEB2-8C5[e]	177	350	0.656	4.18	3.78	-0.40	109.4	108.3	153.9	153.2	——	83	504.5	420.2
GEB2-8E6[e]	177	350	0.515	6.71	5.66	-1.15	136.0	137.7	171.6	172.7	——	87	504.5	420.2

[a] Pretest a/W
[b] Measured crack
[c] Crack growth predicted by compliance
[d] Cleavage failure precluded determination of this quantity
[e] Side grooved by 20%



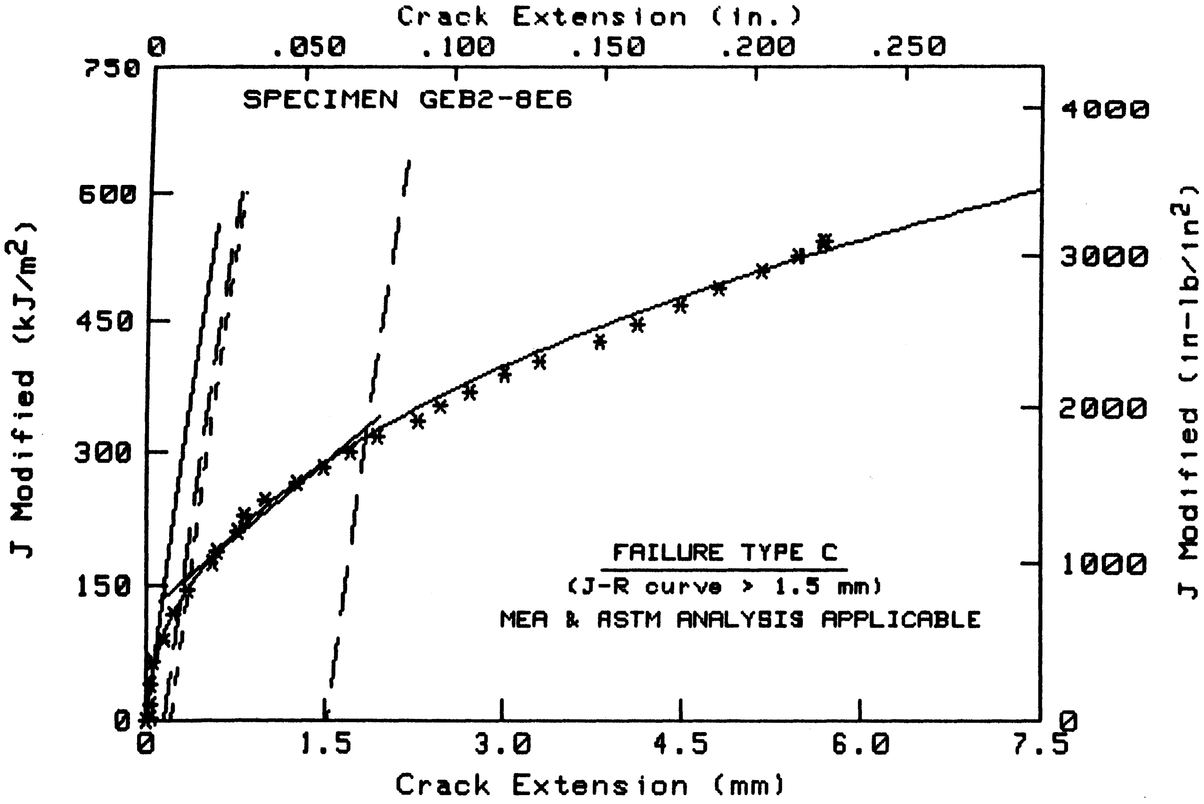
```
TEST SPECIMEN DATA

Test Temperature      = 31°C
Percent Side Groove   = 0%
Specimen Thickness    = 12.7 mm
Initial Crack Length  = 13.13 mm          Init a/W  = .517
Final Crack Length    = 19.19 mm          Final a/W = .755
Flow Stress           = 562.2 MPa
Youngs Modulus        = 205400 MPa          (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                        MEA Power Law        E813-87
Jic                   = 222.1 kJ/m²          219.7 kJ/m²
Kjc                   = 223.9 MPa√m          222.7 MPa√m
J (@J/T=8.8)          = 1014.6 kJ/m²
Exponent      N       = .6059                .6864
Coefficient   C       = 419.4 kJ/m²          415.8 kJ/m²
T (average)           = 157                  178
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                        All Data             E813-81
Jic                   = 175.2 kJ/m²          130.1 kJ/m²
Kjc                   = 198.9 MPa√m          171.4 MPa√m
Slope         M       = 272884.1 kJ/m³       331012.5 kJ/m³
Intercept     B       = 132.7 kJ/m²          91.7 kJ/m²
T (ASTM)              = 177                  216
Validity (E813-81)    = INVALID--b, c (1.29 mm vs .9 mm)
Validity (E813-87)    = INVALID--c (1.29 mm vs .32 mm)
Validity (E1152-87)   = INVALID--3 (1.29 mm vs .18 mm)
J maximum allowed     = 344.6 kJ/m²    (Jmax=B*Flow stress/20)
Delta a max. allowed  = 1.23 mm         (Delta a max = 0.1*bo)
Final Delta a         = 4.76 mm
Poisson's Ratio (v)   = .3
Points Left           = 2           Points Right = 0
```



TEST SPECIMEN DATA

```
Test Temperature     = 177°C
Percent Side Groove  = 20%
Specimen Thickness   = 12.7 mm
Initial Crack Length = 16.67 mm          Init a/W  = .656
Final Crack Length   = 20.85 mm          Final a/W = .82
Flow Stress          = 504.5 MPa
Youngs Modulus       = 197100 MPa          (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                       MEA Power Law        E813-87
Jic                  = 109.4 kJ/m²         121.2 kJ/m²
Kjc                  = 153.9 MPa√m         162 MPa√m
J (@J/T=8.8)         > 461.1 kJ/m²
Exponent       N     = .4902               .4902
Coefficient    C     = 211.3 kJ/m²         211.3 kJ/m²
T (average)          = 83                  83
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                       All Data             E813-81
Jic                  = 108.3 kJ/m²         108.3 kJ/m²
Kjc                  = 153.2 MPa√m         153.2 MPa√m
Slope         M      = 106765.3 kJ/m³      106765.3 kJ/m³
Intercept   B        = 96.8 kJ/m²          96.8 kJ/m²
T (ASTM)             = 83                  83
Validity (E813-81)   = VALID
Validity (E813-87)   = INVALID--c (.39 mm vs .27 mm)
Validity (E1152-87)  = INVALID--3 (.39 mm vs .13 mm)
J maximum allowed    = 220 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed = .87 mm       (Delta a max = 0.1*bo)
Final Delta a        = 3.78 mm
Poisson's Ratio (v)  = .3
Points Left          = 0          Points Right = 0
```



```
TEST SPECIMEN DATA

Test Temperature      = 177°C
Percent Side Groove   = 20%
Specimen Thickness    = 12.7 mm
Initial Crack Length  = 13.09 mm            Init a/W  = .515
Final Crack Length    = 19.8 mm             Final a/W = .779
Flow Stress           = 504.5 MPa
Youngs Modulus        = 197100 MPa            (Estimated Value)
POWER LAW DATA  J = C (Delta a)N
                        MEA Power Law          E813-87
Jic                   = 136 kJ/m²              148.6 kJ/m²
Kjc                   = 171.6 MPa√m            179.4 MPa√m
J (@J/T=8.8)          = 395.1 kJ/m²
Exponent     N        = .4568                  .4568
Coefficient  C        = 240.4 kJ/m²            240.4 kJ/m²
T (average)           = 87                     87
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                        All Data               E813-81
Jic                   = 137.7 kJ/m²            137.7 kJ/m²
Kjc                   = 172.7 MPa√m            172.7 MPa√m
Slope        M        = 111621.2 kJ/m³         111621.2 kJ/m³
Intercept    B        = 122.5 kJ/m²            122.5 kJ/m²
T (ASTM)              = 87                     87
Validity (E813-81)    = INVALID--c (1.04 mm vs 1 mm)
Validity (E813-87)    = INVALID--c (1.04 mm vs .27 mm)
Validity (E1152-87)   = INVALID--3 (1.04 mm vs .18 mm)
J maximum allowed     = 310.3 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed  = 1.23 mm        (Delta a max = 0.1*bo)
Final Delta a         = 5.66 mm
Poisson's Ratio (v)   = .3
Points Left           = 0          Points Right = 0
```

Irradiated Condition, Experiment UBR-78

Table G-6 Fracture Toughness Results for Code GEB (Side 2), Irradiated Condition (Experiment UBR-78)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p - \Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m²)	(kJ/m²)	(MPa√m)	(MPa√m)	(MPa√m)		(MPa)	(MPa)
GEB2-8D3	-110	-166	0.510	——[d]	——	——	5.0	——	46.6	45.3[e]	44.2	——	800.7	737.0
GEB2-8B4	-90	-130	0.506	——	——	——	21.8	——	71.3	53.2	59.5	——	771.1	707.3
GEB2-8A2	-80	-112	0.516	——	——	——	29.2	——	82.4	55.5	64.3	——	757.1	693.2
GEB2-8D6	-50	-58	0.504	——	——	——	42.4	——	98.0	51.9	68.5	——	718.3	654.0
GEB2-8B3	-40	-40	0.509	——	——	——	61.9	——	119.4	52.4	74.5	——	706.4	641.9
GEB2-8D1	-30	-22	0.495	——	——	——	62.5	——	119.8	47.8	73.8	——	695.0	630.3
GEB2-8B2	-25	-13	0.499	——	——	——	101.9	——	152.9	50.7	81.5	——	689.6	624.7
GEB2-8D4[f]	0	+32	0.505	——	——	——	162.3	——	192.2	——	——	——	664.2	598.5
GEB2-8A5[g]	177	350	0.546	7.33	6.61	-0.72	121.8	114.3[h]	162.4	157.3	——	56	579.6	502.2
GEB2-8B5[g]	288	550	0.537	5.55	5.63	+0.08	86.9	81.1[h]	135.0	130.4	——	48	611.5	521.5

[a] Pretest a/W

[b] Measured crack growth

[c] Crack growth predicted by compliance

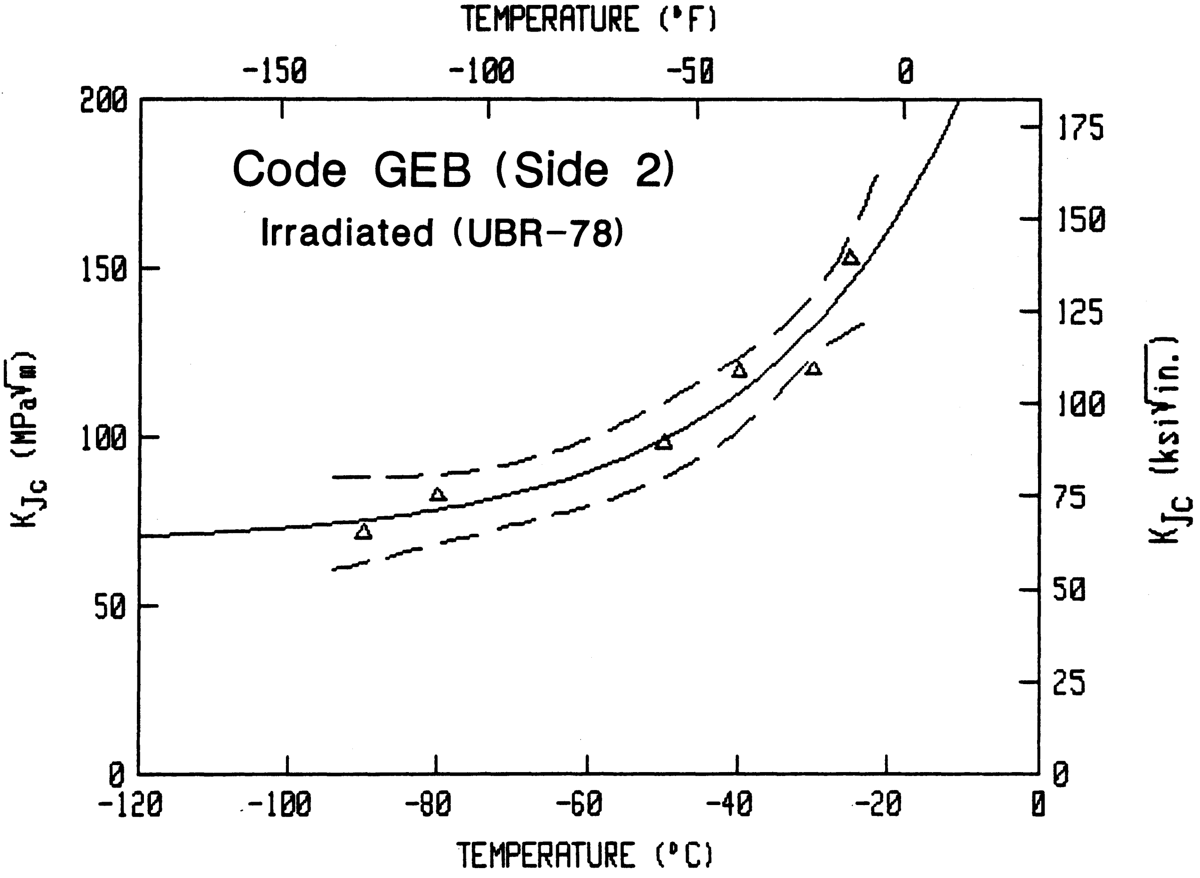
[d] Cleavage failure precluded determination of this quantity

[e] Valid K_{Ic}, per ASTM E 399

[f] Data exceed the 0.15 mm exclusion before cleavage

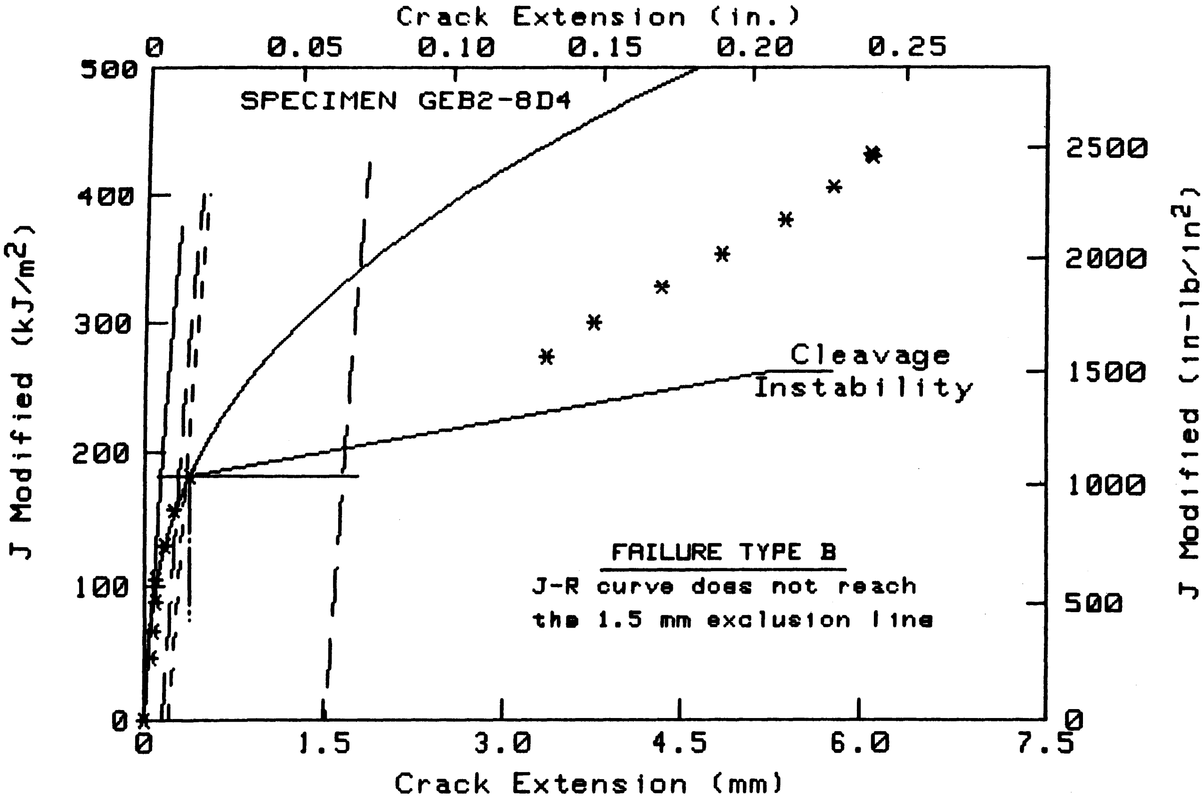
[g] Side grooved by 20%

[h] Valid J_{Ic}, per ASTM E 813-81



$$K_{jc} = A + B \exp(T/C)$$

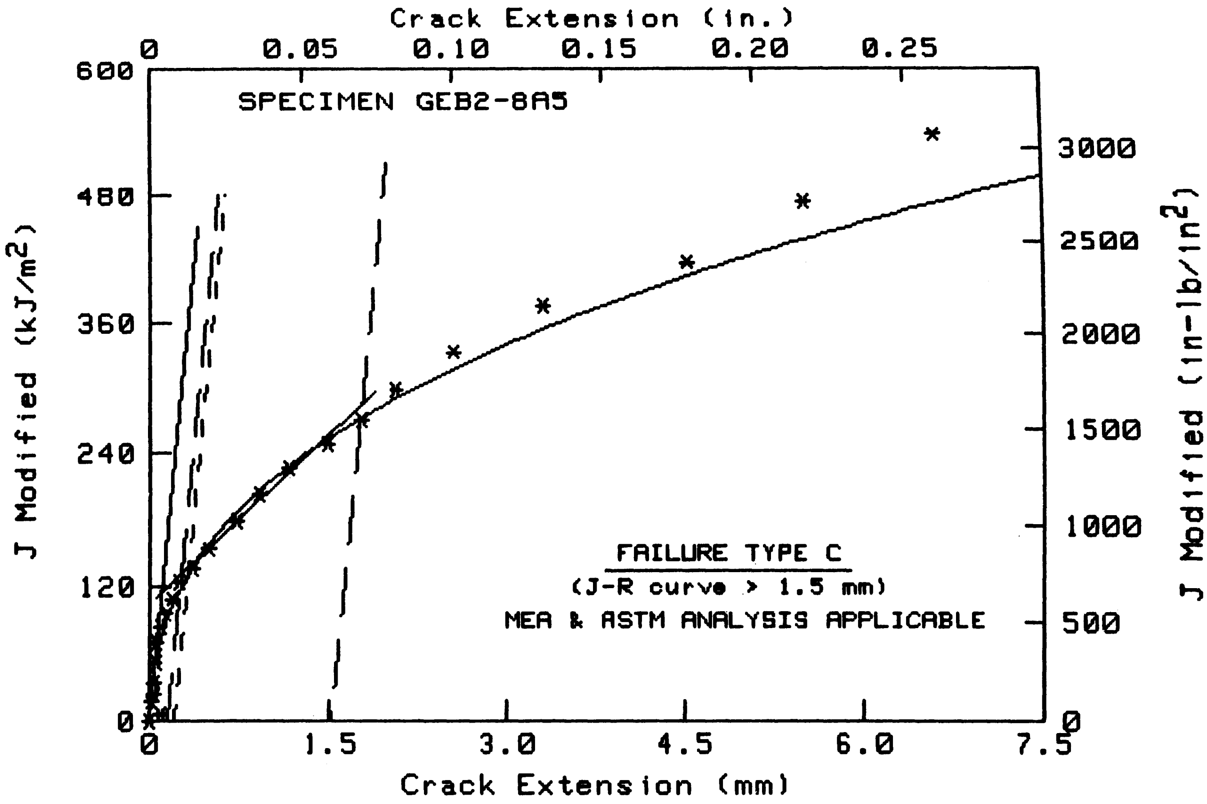
	Metric	English
A =	68.25	62.11
B =	195.75	178.14
C =	27.00	48.60
Upper Bound K = 100 when Temp =	-59	-74
Ave. K = 100 when Temp =	-49	-56
Lower Bound K = 100 when Temp =	-41	-42



```
TEST SPECIMEN DATA

Test Temperature      = 0°C
Percent Side Groove   = 0%
Specimen Thickness    = 12.7 mm
Initial Crack Length = 12.83 mm          Init a/W  = .505
Flow Stress           = 664.2 MPa
Youngs Modulus        = 207200 MPa         (Estimated Value)
POWER LAW DATA  J = C (Delta a)^N
                        MEA Power Law        E813-87
Jic                   = 162.3 kJ/m²         173.5 kJ/m²
Kjc                   = 192.2 MPa√m         198.8 MPa√m

Exponent      N       = .3988               .3988
Coefficient   C       = 271.7 kJ/m²         269.1 kJ/m²
LEAST SQUARE LINEAR LINE (ASTM)  J = M (Delta a) + B
                        All Data             E813-81
Jic                   = 0 kJ/m²             181.8 kJ/m²
Kjc                   = 0 MPa√m             203.5 MPa√m
Slope        M        = 0 kJ/m³             2.7 kJ/m³
Intercept    B        = 0 kJ/m²             181.8 kJ/m²
Validity (E813-81)    = INVALID--a, b
Validity (E813-87)    = INVALID--a, b
Validity (E1152-87)   = INVALID--2
J maximum allowed     = 417.3 kJ/m²    (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.26 mm          (Delta a max = 0.1*bo)
Final Delta a         = 6.07 mm
Poisson's Ratio (v)   = .3
Points Left           = 2           Points Right = 0
```



TEST SPECIMEN DATA

Test Temperature = 177°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 13.88 mm   Init a/W = .546
Final Crack Length = 21.21 mm   Final a/W = .835
Flow Stress = 579.6 MPa
Youngs Modulus = 197100 MPa   (Estimated Value)

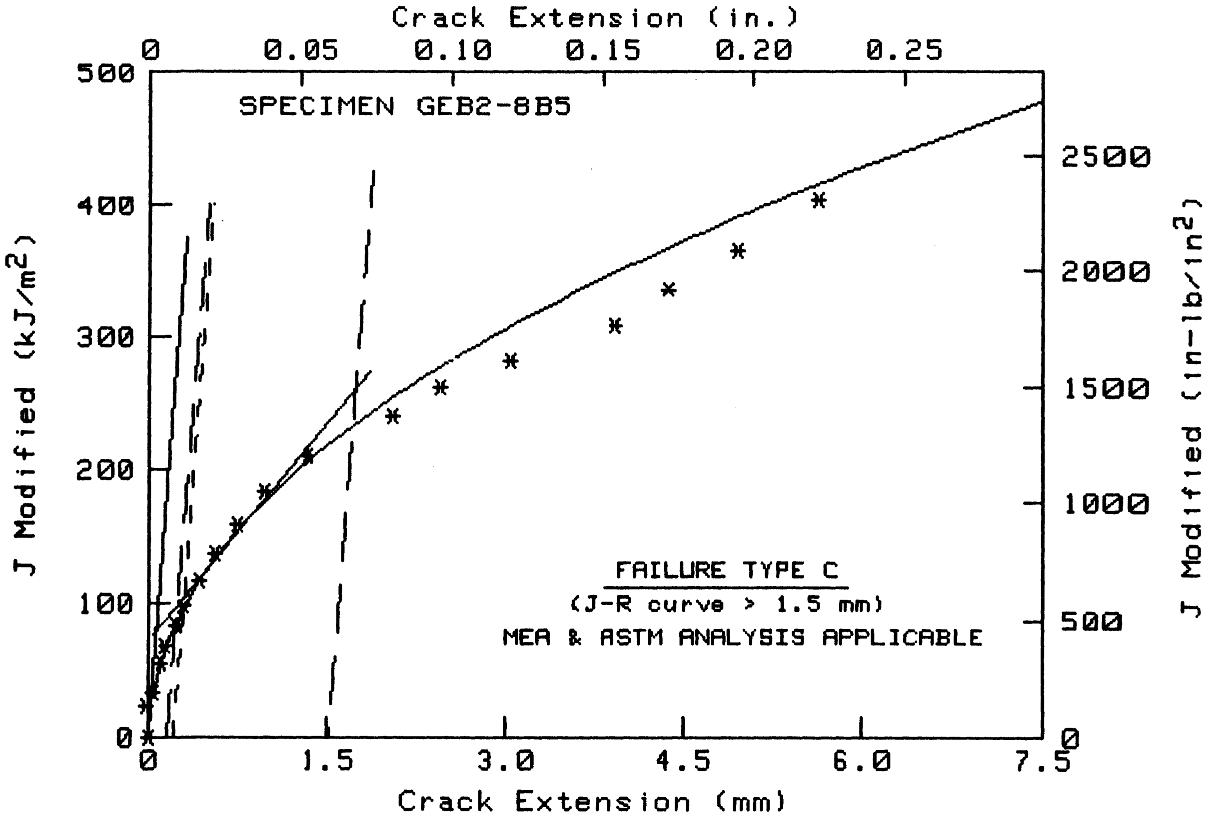
POWER LAW DATA J = C (Delta a)^N

	MEA Power Law	E813-87
Jic	= 121.8 kJ/m^2	127.4 kJ/m^2
Kjc	= 162.4 MPa$\sqrt{m}$	166.1 MPa$\sqrt{m}$
J (@J/T=8.8)	= 331 kJ/m^2	
Exponent N	= .4185	.4315
Coefficient C	= 214.9 kJ/m^2	210.6 kJ/m^2
T (average)	= 56	57

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

	All Data	E813-81
Jic	= 114.3 kJ/m^2	114.3 kJ/m^2
Kjc	= 157.3 MPa$\sqrt{m}$	157.3 MPa$\sqrt{m}$
Slope M	= 102427.1 kJ/m^3	102427.1 kJ/m^3
Intercept B	= 104.2 kJ/m^2	104.2 kJ/m^2
T (ASTM)	= 60	60

Validity (E813-81) = VALID
Validity (E813-87) = INVALID--c (.71 mm vs .26 mm)
Validity (E1152-87) = INVALID--3 (.71 mm vs .17 mm)
J maximum allowed = 333.6 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.15 mm   (Delta a max = 0.1*bo)
Final Delta a = 6.61 mm
Poisson's Ratio (v) = .3
Points Left = 2   Points Right = 3



TEST SPECIMEN DATA

Test Temperature = 288°C
Percent Side Groove = 20%
Specimen Thickness = 12.7 mm
Initial Crack Length = 13.65 mm   Init a/W = .537
Final Crack Length = 19.2 mm   Final a/W = .755
Flow Stress = 611.5 MPa
Youngs Modulus = 190800 MPa   (Estimated Value)

POWER LAW DATA J = C (Delta a)^N

	MEA Power Law	E813-87
Jic	= 86.9 kJ/m²	95.4 kJ/m²
Kjc	= 135 MPa$\sqrt{m}$	141.4 MPa$\sqrt{m}$
J (@J/T=8.8)	= 226.9 kJ/m²	
Exponent N	= .4849	.5214
Coefficient C	= 179.8 kJ/m²	185.2 kJ/m²
T (average)	= 48	53

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

	All Data	E813-81
Jic	= 74.7 kJ/m²	81.1 kJ/m²
Kjc	= 125.2 MPa$\sqrt{m}$	130.4 MPa$\sqrt{m}$
Slope M	= 114079 kJ/m³	107644.7 kJ/m³
Intercept B	= 67.7 kJ/m²	74 kJ/m²
T (ASTM)	= 58	55

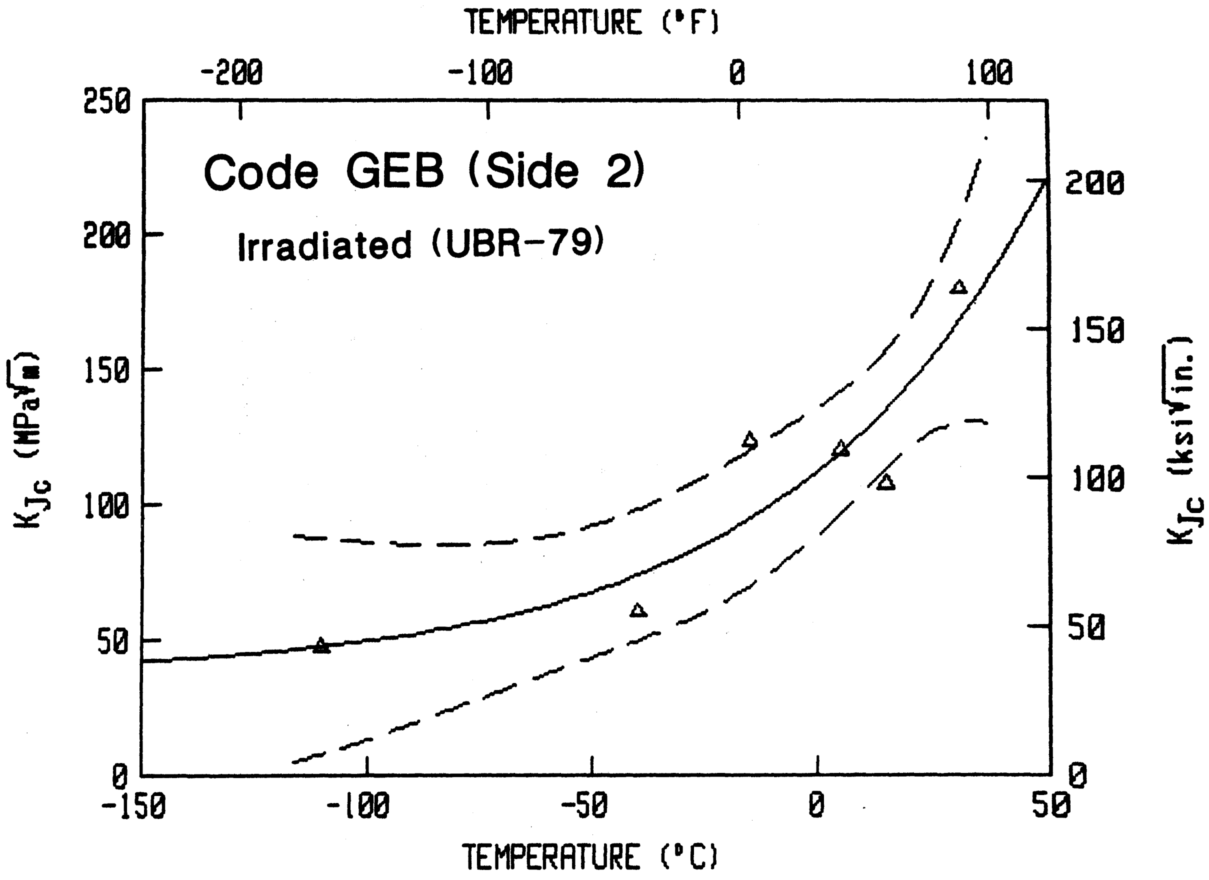
Validity (E813-81) = VALID
Validity (E813-87) = VALID
Validity (E1152-87) = INVALID--1
J maximum allowed = 359 kJ/m²   (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.18 mm   (Delta a max = 0.1*bo)
Final Delta a = 5.63 mm
Poisson's Ratio (v) = .3
Points Left = 1   Points Right = 1

Irradiated Condition, Experiment UBR-79

Table G-7 Fracture Toughness Results for Code GEB (Side 2), Irradiated Condition (Experiment UBR-79)

Specimen Number	Test Temperature		$(a/W)_o$[a]	Δa_m[b]	Δa_p[c]	$\Delta a_p - \Delta a_m$	J_{Ic}		K_{Jc}		$K_{\beta c}$	T_{avg}	σ_f	σ_y
							MEA	ASTM	MEA	ASTM		MEA		
	(°C)	(°F)		(mm)	(mm)	(mm)	(kJ/m^2)	(kJ/m^2)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)	(MPa$\sqrt{m}$)		(MPa)	(MPa)
GEB2-8F2	−110	−116	0.504	—[d]	—	—	9.5	—	47.3	46.7[e]	44.1	—	747.9	682.9
GEB2-8F5	−40	−40	0.502	—	—	—	15.9	—	60.5	54.8	50.1	—	653.6	587.8
GEB2-8F4	−15	+5	0.494	—	—	—	66.8	—	123.6	57.2	70.0	—	626.2	559.7
GEB2-8F3	+5	+41	0.513	—	—	—	63.6	—	120.2	54.0	67.7	—	606.7	539.5
GEB2-8F6	+15	+59	0.503	—	—	—	50.8	—	107.4	54.4	63.9	—	597.8	530.2
GEB2-8F1	+31	+88	0.508	6.48	5.29	-1.19	142.8	98.9	179.6	149.4	—	126	584.6	516.3

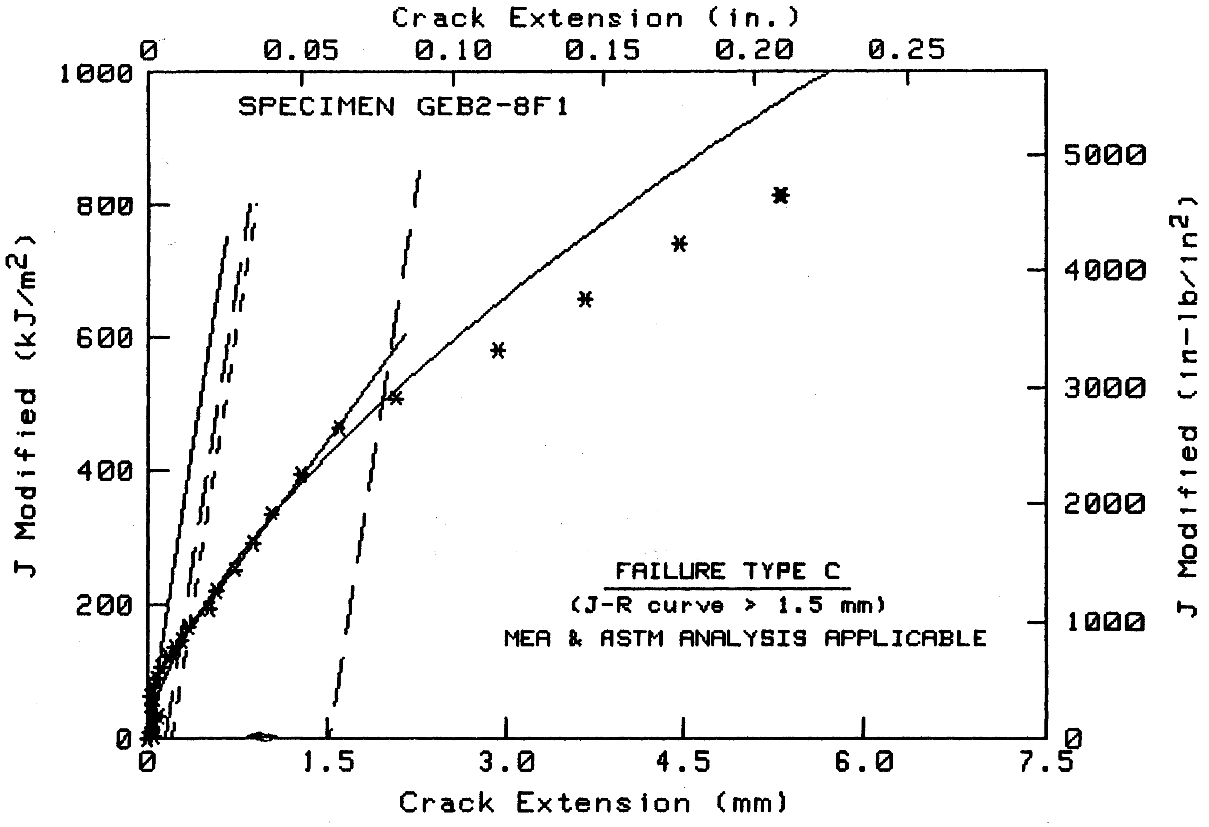
[a] Pretest a/W
[b] Measured crack growth
[c] Crack growth predicted by compliance
[d] Cleavage failure precluded determination of this quantity
[e] Valid K_{Ic}, per ASTM E 399



Kjc = A + B exp(T/C)

	Metric	English
A =	37.05	33.72
B =	75.18	68.42
C =	55.73	100.31

Upper Bound K = 100 when Temp =	-37	-35
Ave. K = 100 when Temp =	-10	14
Lower Bound K = 100 when Temp =	7	45



TEST SPECIMEN DATA

Test Temperature = 31°C
Percent Side Groove = 0%
Specimen Thickness = 12.7 mm
Initial Crack Length = 12.9 mm   Init a/W = .508
Final Crack Length = 19.38 mm   Final a/W = .763
Flow Stress = 584.6 MPa
Youngs Modulus = 205500 MPa   (Estimated Value)

POWER LAW DATA J = C (Delta a)^N

	MEA Power Law	E813-87
Jic	= 142.8 kJ/m^2	157.9 kJ/m^2
Kjc	= 179.6 MPa$\sqrt{m}$	188.8 MPa$\sqrt{m}$
J (@J/T=8.8)	= 499.1 kJ/m^2	
Exponent N	= .6418	.6684
Coefficient C	= 327.3 kJ/m^2	328.2 kJ/m^2
T (average)	= 126	131

LEAST SQUARE LINEAR LINE (ASTM) J = M (Delta a) + B

	All Data	E813-81
Jic	= 98.9 kJ/m^2	98.9 kJ/m^2
Kjc	= 149.4 MPa$\sqrt{m}$	149.4 MPa$\sqrt{m}$
Slope M	= 246405.1 kJ/m^3	246405.1 kJ/m^3
Intercept B	= 78.1 kJ/m^2	78.1 kJ/m^2
T (ASTM)	= 148	148

Validity (E813-81) = INVALID--c (1.18 mm vs .97 mm)
Validity (E813-87) = INVALID--c (1.18 mm vs .29 mm)
Validity (E1152-87) = INVALID--3 (1.18 mm vs .18 mm)
J maximum allowed = 365 kJ/m^2 (Jmax=B*Flow stress/20)
Delta a max. allowed = 1.25 mm   (Delta a max = 0.1*bo)
Final Delta a = 5.29 mm
Poisson's Ratio (v) = .3
Points Left = 1   Points Right = 0

APPENDIX H

Trepan G Fluence Determinations: Procedures and Results

INEL
Idaho National Engineering Laboratory

March 4, 1987

Mr. J. R. Hawthorne
Materials Engineering Associates
9700-B George Palmer Highway
Lanham, MD 20706-1837

ANALYSES OF GUNDREMMINGEN KRB-A VESSEL TREPAN - JWR-04-87

Dear Russ,

The through-thickness slice of the Gundremmingen KRB-A vessel trepan (G,115°) which we received from MPA Universitat Stuttgart has been sampled, the radioactivities of the samples measured and the fast neutron fluences calculated for each sample. Samples were taken by cutting through the slice with an ordinary hacksaw. Samples were taken at the 0.02T, 0.15T, 0.27T, 0.47T, 0.74T and 0.98T depths referenced to the cladding interface with the steel. A diagram is attached showing the size, shape, dimensions and locations of the cuts and pieces. The orientations of all pieces were carefully documented and the pieces are shaped or marked for positive identification. A portion of three depths (0.02T, 0.15T and 0.27T) was dissolved to make standard radioactive sources to verify that results from the solid pieces were correct. All samples and pieces have been retained for future use if necessary.

It was possible to measure the ^{54}Mn activity in the material without chemical separation using calibrated Ge detector based gamma-ray spectrometry. A half-life of 312.2$\pm$0.1 days was used for ^{54}Mn. A cross section of 115$\pm$6 millibarns for the ^{54}Fe(n,p)^{54}Mn reaction was used to determine >1MeV "fast" neutron fluence rates and fluences assuming a ^{235}U fission neutron energy spectrum. The material was assumed to be 97.07 weight percent iron.

Based on a cobalt content of 0.02 weight percent in the material, it was possible to measure the reaction rate for the ^{59}Co(n,γ)^{60}Co reaction. The ^{60}Co activity was measured by gamma-ray spectrometry. A half-life of 5.271$\pm$0.001 years was used for ^{60}Co. A cross section of 37.2 barns was used to determine "thermal" neutron fluence rates and fluences. No corrections were made for epithermal neutron response.

To obtain the saturated reaction rates at the end of irradiation (January 13, 1977) the irradiation history provided by MPA was used. From the history a total exposure of 2643 effective full power days was calculated.

The results are summarized in the attached table. The estimated uncertainties given in this table are for the 1σ confidence level and include only those components associated with the counting and cross section. No estimates of the errors due to the exposure history or actual cross sections have been included.

If you have any questions or comments please contact me.

Very truly yours,

JWRogers

JW Rogers
Chemcial Science

clt

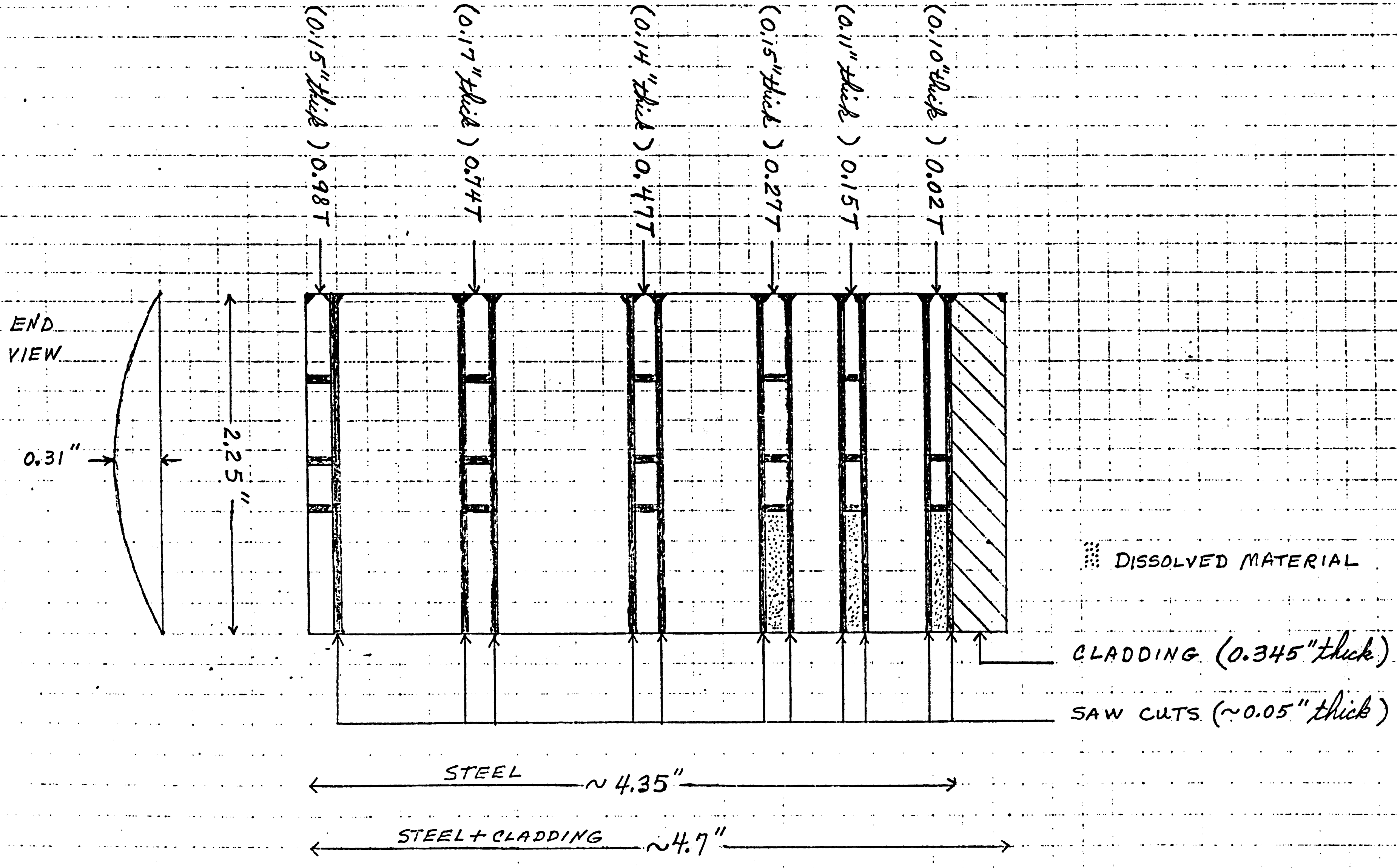
Attachments:
As Stated

cc: J. O. Zane, EG&G Idaho (w/o Attach.)

GUNDREMMINGEN VESSEL KRB-A SAMPLE RESULTS

Sample ID	Mass(g)	^{54}Mn Bq/g (1-13-77)	>1MeV Neutron Fluence Rate (n/cm^2/s)	>1MeV Neutron Fluence (n/cm^2)	^{60}Co Bq/g (1-13-77)	Thermal Neutron Fluence Rate (n/cm^2/s)	Thermal Neutron Fluence (n/cm^2)
0.02T	1.8162	7.19+0.49E5	1.46±0.12E10	3.34±0.28E18	6.00±0.31E5	1.45±0.08E10	3.23±0.18E18
0.15T	1.7793	5.84±0.36E5	1.18±0.10E10	2.71±0.22E18	2.89±0.15E5	6.99±0.36E9	1.60±0.08E18
0.27T	2.8309	4.57±0.28E5	9.29±0.75E9	2.11±0.17E18	1.62±0.08E5	3.92±0.20E9	8.95±0.46E17
0.47T	1.1943	3.19±0.20E5	6.28±0.51E9	1.47±0.12E18	8.70±0.44E4	2.10±0.11E9	4.80±0.24E17
0.74T	1.7710	1.98±0.13E5	4.02±0.33E9	9.13±0.75E17	5.61±0.29E4	1.35±0.07E9	3.10±0.16E17
0.98T	1.6817	1.28±0.08E5	2.59±0.21E9	5.89±0.48E17	6.13±0.31E4	1.48±0.08E9	3.39±0.17E17

GUNDREMMINGEN VESSEL
KRB-A TREPAN SLICE



INEL
Idaho National Engineering Laboratory

MAR 1 4 1988

March 7, 1988

J. R. Hawthorne
Materials Engineering Associates, Inc.
9700-B George Palmer Highway
Lanham, MD 20706-1837

FAST NEUTRON DISTRIBUTIONS IN GUNDREMMINGEN VESSEL KRB-A - JWR-10-88

Dear Russ:

Based upon your request of 3-2-88 for the subject information I have complied the attached summary of results. These results are based on the calculated neutron spectra found in the report IKE 6-FB-35 (NUREG/CR-4791) by G. Prillinger and the ^{54}Mn reaction rates measured at our laboratory. The ENDF/B-V Dosimetry File cross-section data was used to obtain the spectrum averaged cross-sections. If you have any questions or comments please let me know.

Very truly yours,

JW Rogers

JW Rogers
Chemical Science

clt

Attachment:
As Stated

cc: G. Prillinger, IKE
C. Z. Serpan, NRC-HQ
J. O. Zane, EG&G Idaho (w/o Attach)

FAST NEUTRON DISTRIBTUIONS IN GUNDREMMINGEN VESSEL KRB-A

(G, 117°)

Location(1)	^{54}Mn Bq/g(2)	>1 MeV $n/cm^2/sec$	>1 MeV n/cm^2	>0.1 MeV $n/cm^2/sec$	>0.1 MeV n/cm^2	Ratio 0.1/1.0
0.02T	7.19±0.49E5	1.13±0.09E10	2.59±0.22E18	2.25±0.18E10	5.16±0.43E18	1.99
0.15T	5.84±0.36E5	1.04±0.09E10	2.38±0.19E18	2.42±0.20E10	5.56±0.45E18	2.33
0.27T	4.57±0.28E5	8.95±0.72E9	2.05±0.17E18	2.32±0.19E10	5.33±0.43E18	2.59
0.47T	3.19±0.20E5	6.94±0.56E9	1.59±0.13E18	2.19±0.18E10	5.02±0.41E18	3.15
0.74T	1.98±0.13E5	5.14±0.42E9	1.18±0.10E18	1.97±0.16E10	4.51±0.37E18	3.83
0.98T	1.28±0.08E5	3.47±0.28E9	7.95±0.65E17	1.53±0.12E10	3.50±0.29E18	4.40

(1) Relative to steel-cladding interface with a steel thickness of 4.35 inches.

(2) On 1-13-77.

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7. AUTHOR(S)
J.R. Hawthorne, A.L. Hiser

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9700-B Martin Luther King, Jr. Highway
Lanham, Maryland 20706-1837

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16. ABSTRACT *(200 words or less)*

The 250-MW boiling water Gundremmingen reactor, KRB-A, in the Federal Republic of Germany (FRG) has been decommissioned. A joint USA/FRG/UK study is underway to evaluate material removed from the vessel for a critical assessment of power reactor vs. test reactor environment effects. The vessel operated at 288°C; the inner wall fluence estimate at decommissioning was about 1×10^{19} n/cm^2, E > 1 MeV.

This report describes test reactor irradiation assessments of a forging segment believed to be archive material from the KRB-A vessel fabrication. Charpy-V (C_v), compact tension (CT) and tension test specimens were evaluated in five as-irradiated and two postirradiation annealed conditions. With 288°C irradiations, the elevation in 100 MPa$\sqrt{m}$ temperature was found to match the elevation in 41-J temperature tests within 12°C. The latter elevation was predicted well by Regulatory Guide 1.99.

The L-C orientation data for the archive material vs. the vessel trepans suggest a fluence-rate effect. The C-L orientation data, however, do not. A test orientation dependence of radiation embrittlement sensitivity, described by the trepan material but not the archive material, is responsible and is anomalous.

17. KEY WORDS AND DOCUMENT ANALYSIS

Gundremmingen KRB-A Reactor
Radiation Embrittlement
Postirradiation Annealing
Compact Tension Test
Fluence Rate Effects
20NiMoCr26 Steel
A 336 Steel
Pressure Vessels
Notch Ductility
Fracture Toughness
Neutron Dosimetry
Test Reactor

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