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Accelerated Irradiation Test of Gundremmingen Reactor Vessel Trepan Material

Prepared by
J. R. Hawthorne

Materials Engineering Associates, Inc.

Prepared for
U.S. Nuclear Regulatory Commission

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Prepared by
J. R. Hawthorne

Materials Engineering Associates, Inc.
9700-B Martin Luther King, Jr. Highway
Lanham, MD 20706-1837

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
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ABSTRACT

Initial mechanical properties tests of beltline material trepanned from the decommissioned KRB-A pressure vessel and archive material irradiated in the UBR test reactor revealed a major anomaly in relative radiation embrittlement sensitivity. Poor correspondence of material behavior in test vs. power reactor environments was observed for the weak test orientation (ASTM L-C) whereas correspondence was good for the strong orientation (ASTM C-L). To resolve the anomaly directly, Charpy-V specimens from a low (essentially-nil) fluence region of the vessel were irradiated together with archive material at 279°C in the UBR test reactor.

Properties tests before UBR irradiation revealed a significant difference in 41-J transition temperature and upper shelf energy level between the materials. However, the materials exhibited essentially the same radiation embrittlement sensitivity (both orientations), proving that the anomaly is not due to a basic difference in material irradiation resistances. Possible causes of the original anomaly and the significance to NRC Regulatory Guide 1.99 are discussed.

Key Words: Charpy V-notch, Fluence-Rate Effects, Nuclear Reactors, Pressure Vessels, Radiation Embrittlement, Steel.

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FOREWORD

The work reported here was performed at Materials Engineering Associates (MEA) under the program, Irradiation Embrittlement of Reactor Pressure Vessel Steels, 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 E. M. Hackett.

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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 inner wall fluence of about 3×10^{18} n/cm^2, E > 1 MeV (Ref. 1). 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 allowed direct testing of the effect of fluence rate (dose rate) on the degradation of Charpy-V (C_v) notch ductility and fracture toughness properties and the elevation of yield strength by neutron radiation. In addition, the materials permitted verification tests of present prediction methods for radiation-induced embrittlement (Ref. 2,3) and the attenuation of radiation effects through the vessel thickness (Ref. 2). The NRC subsequently put in place a joint USA/FRG program to (a) investigate the vessel's properties and (b) conduct accelerated irradiation tests of the archive material for power vs. test reactor comparisons. Materials Engineering Associates (MEA) and Material Pruefungsanstalt (MPA) were the lead laboratories for the two countries, respectively.

Qualification tests of the archive material located in storage at the General Electric Company provided evidence which, when coupled with vessel documentation, led to conclusions by MEA and MPA that (a) the base metal and Vessel Forging No. 7.1 were from the same steel melt and (b) the base metal is representative of the vessel forging as first placed in service (Ref. 4). The material was in the form of two circumferentially-welded ring segments; the weld is suspected of being a portion of the weld made for the reactor vessel surveillance program. One ring segment, approximately 119-mm thick and weighing about 1450 kg, was used for the primary MEA investigations of irradiation behavior. It is identified in this report as the Code GEB material. The chemical composition of the GEB base material and that of the vessel's Forging Ring No. 7 are given in Table 1 and are identical for practical purposes. Composition test results for the base metal used in the reactor surveillance program also are indicated. The reactor surveillance program was in place at the commencement of initial commercial operations; however, only ASTM C-L orientation base metal specimens (strong orientation) were included in the surveillance capsules along with the weld metal and heat affected zone (HAZ) specimens. This was the recommendation of ASTM Practice E 185 in the early 1960's.

Table 1 Chemical Compositions of Archive Material GEB, KRB-A Vessel Trepan G and Surveillance Program Base Metal (Ref. 4)

Material	Composition (wt-%)												
	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	As	Sn	Sb	V
GEB (Side 2) (MEA)	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 (Trepan G) (MPA)[a]	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
GEB (Side 1) (MPA)[a]	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
Surveillance[b] Base Metal (MEA)	0.23	0.71	0.25	0.023	0.016	0.85	0.37	0.64	0.16	--	--	--	--

[a] MPA composition determination by Quantovac Spectroscopy.

[b] Average of tests of three surveillance specimens.

2. THE ANOMALY

Tests of the irradiated trepan material by MPA and initial tests of UBR test reactor-irradiated archive material by MEA provided a major anomaly (Ref. 1,4). The archive material was in the form of ASTM L-C orientation (weak) C_v specimens only; the specimens had been irradiated to ~8.8 x 10^{18} n/cm^2, E > 1 MeV, at 288°C. These exposure parameters reflect FRG best estimates of the vessel operating conditions and its end-of-life (EOL) exposure at program initiation in 1984. (Both parameters were later revised downward based on new information supplied to MPA.) As illustrated in Figure 1, the service-induced embrittlement appeared to be much greater than that produced by the UBR irradiation. Notice that the fluence to the trepan specimens (MPA determination) was approximately 2.4 x 10^{18} n/cm^2 or about one-third that received by the archive material. A second observation suggested by the data is that the trepan C-L orientation suffered much less embrittlement than the L-C orientation. The cited L-C orientation vs. C-L orientation data comparison for relative induced-embrittlement, constitutes the anomalous behavior.

Prior experience in test reactor irradiation studies and the few L-C vs. C-L orientation data comparisons available from RPV surveillance programs (both orientations contained in the same capsule) have led investigators to expect roughly-comparable elevations in 41-J transition temperature. Table 2, an excerpt from the NRC embrittlement data base (Ref. 5) lists many of the comparison data available from surveillance. A companion expectation is a greater "absolute" reduction in upper shelf energy level by that orientation having the higher preirradiation C_v energy level, that is, the "strong" test orientation. The preirradiation difference must be pronounced for this observation. This is one reason that estimation procedures of NRC Regulatory Guide 1.99 for the upper shelf reduction is in terms of percentage decrease rather than an absolute change for a given fluence. A follow-on 288°C UBR irradiation of the archive material using both L-C and C-L orientation specimens, removed from the 1/8T thickness location, demonstrated that the GEB material conforms to both expectations (see Fig. 2, Ref. 4). The target fluence was 2.7 x 10^{18} n/cm^2 to better approximate the vessel inner wall (1/8 T) condition.

Mechanistic explanations are not in hand to account for the suggested difference in radiation sensitivity between test orientations. Embrittlement mechanisms identified from empirical data and experimental tests, in combination with theory by-in-large involve precipitation phenomena either enhanced or induced by irradiation[1] (Ref. 6-10). Primarily the scenarios involve copper-rich precipitates or phosphorus-rich precipitates. A precipitation phenomenon would not explain the test orientation dependence (directionality) of radiation embrittlement sensitivity suggested by the KRB-A trepan data (Fig. 1). A radiation-induced weakening of the interface between MnS stringers and the matrix, on the other hand, would explain such a dependence. (Ref. 11).

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[1] F. Frisius, R. Kampmann, R. Wagner, and P. A. Beaven, "SANS Analysis of Irradiated and Unirradiated Fe Alloys Containing Cu, Ni, P: Final Report," MEA Report 2296, Materials Engineering Associates, Inc., Lanham, MD, March 1988.

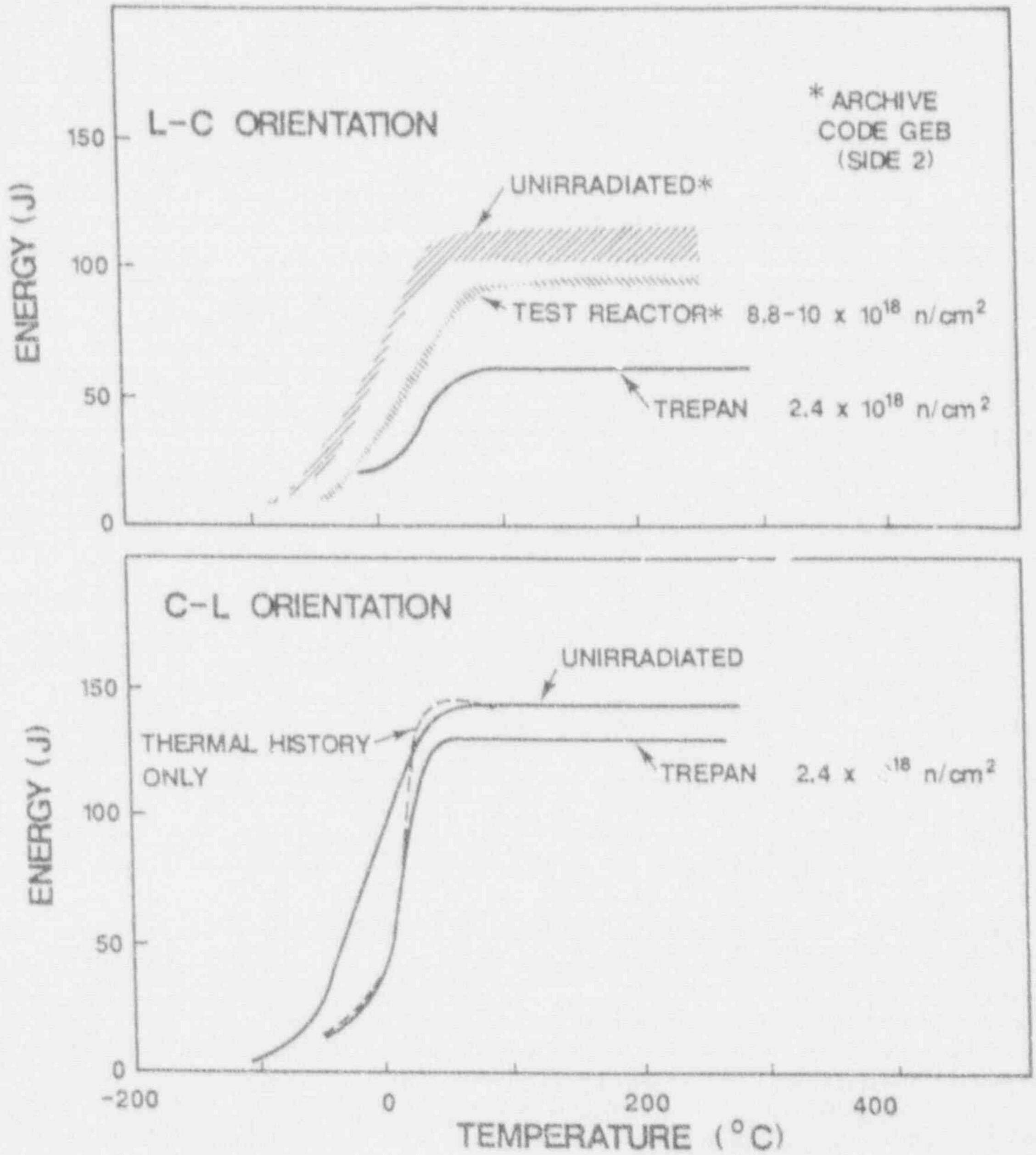

Fig. 1 Charpy-V notch ductility of KRB-A vessel material before and after irradiation service. Data from accelerated (test reactor) irradiations of the archive material by MEA and the Harwell Laboratory are indicated in the upper graph by the trend band; the dashed line in the lower graph shows the effect of long-term thermal conditioning (years) without irradiation (Ref. 1).

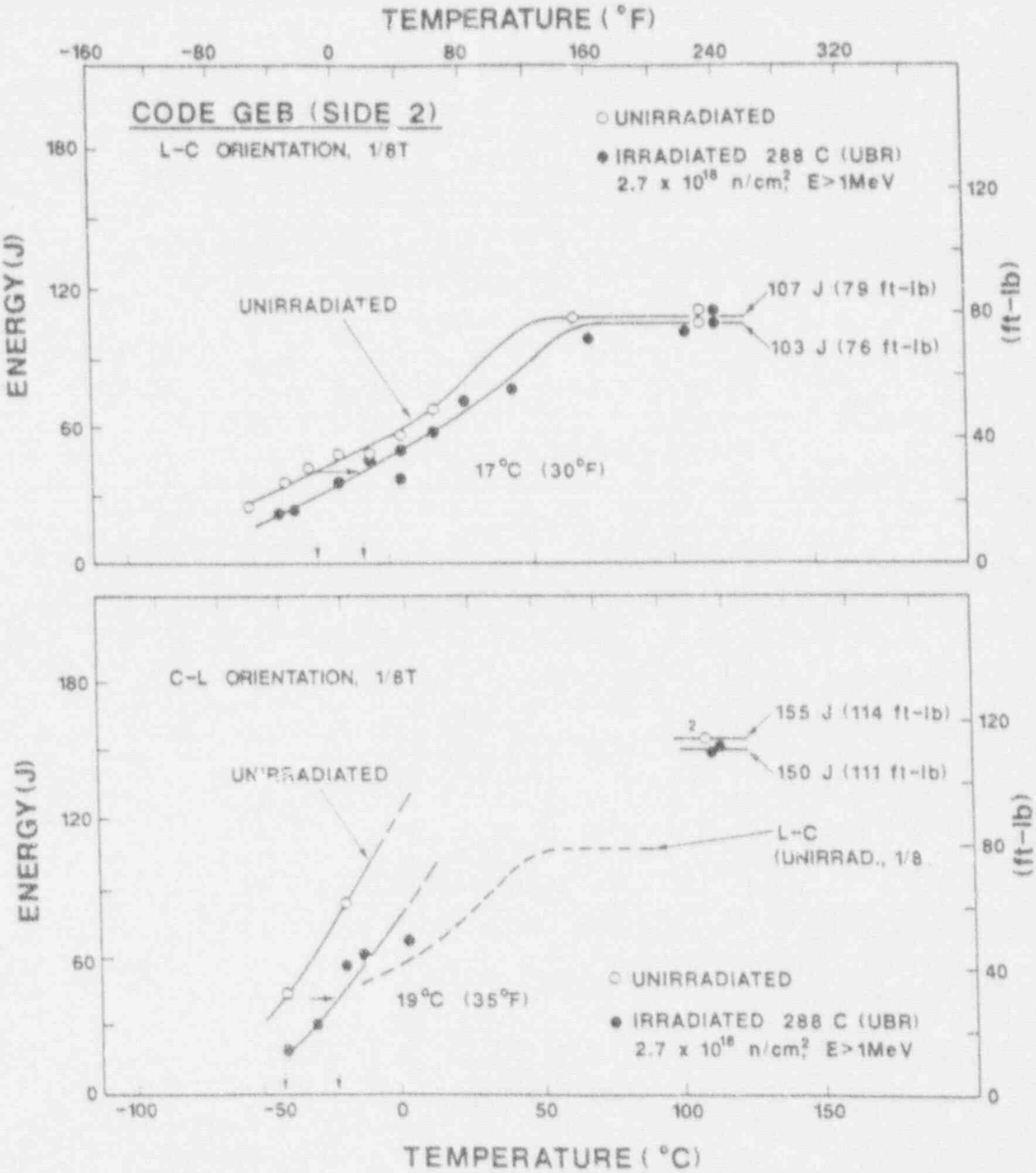

Fig. 2 Embrittlement of the archive material by a fluence matching that received by the KRB-A vessel in service (MEA Experiment Assembly UBR-78) (Ref. 4).

Table 2 Comparison of LT vs. TL Orientation Embrittlement Data from RPV Surveillance (Ref. 5)

Entry	C_v Upper Shelf Energy Reduction[a] in ft-lb		
	LT Orientation	TL Orientation	Difference (LT-TL)
1	24	11	13
2	14	25	-11
3	24	17	7
4	35	2	33
5	20	5	15
6	19	3	16
7	24	18	6
8	30	8	22
9	26	10	16
10	12	0	12
11	36	26	10
12	28	19	9
13	22	9	13
14	33	22	11
15	71	44	27
16	40	12	28
17	25	10	15
18	0	13	-13
19	3	-19	22
20	22	-6	28
21	20	12	8
22	25	13	12
23	60	30	30
24	43	18	25
25	16	7	9
26	14	13	1
27	23	10	13
28	17	15	2
29	33	22	11
30	15	2	13
31	18	0	18
32	24	14	10
33	16	6	10
34	4	11	-7
35	8	14	-6
36	14	8	6

[a] Fluence range represented is 7.27×10^{17} to 7.85×10^{19} n/cm^2, E > 1 MeV.

The directionality, if verified, could have a major impact on the application of Regulatory Guide 1.99 and the growing consideration of possible plant lifetime extensions (PLEX). To verify (or disprove) the anomaly, the present irradiation test was proposed.

3. APPROACH

The approach centered on the simultaneous irradiation of archive and trepan material specimens in one UBR assembly. The target irradiation temperature (279°C) and the target fluence level (2.6×10^{18} n/cm^2) were intended to match, as closely as practical, those of the vessel trepans at their 1/8T location. A key aspect of the approach was the use of samples from outer layers of the trepans which had received a considerably lower fluence than the inner layers in prior service. The samples for the UBR assembly had received $8\text{-}9 \times 10^{17}$ n/cm^2 beforehand. MPA kindly provided the samples in the form of finish-machined C_v specimens, under the auspices of the continuing USA/FRG joint program.

4. MATERIAL SAMPLING FOR THE UBR IRRADIATION TEST

4.1 Trepan Material

The specimens for UBR-irradiation were cut from Trepan P as illustrated in Figure 3. Layers 10 and 11 provided the samples for the L-C orientation assessments; Layers 8, 9, 10 and 11 provided the samples for the C-L orientation assessments. The fluences received by the various layers from KRB-A service are listed in Table 3. Table 3 also gives the fluences received by these layers in the companion Trepans C, D and G from which samples were taken earlier for MPA's reference condition tests. In this report, the reference condition of Forging Ring No. 7.1 is that condition at the time of the KRB-A decommissioning.

The diameter of the trepans was 107 mm. The trepans were cut from the reactor vessel in a 3 (vertical) x 4 (circumferential) array, at a location somewhat below the reactor mid-plane. Trepan C and D were in the row nearest the reactor mid-plane; Trepan G was in the middle row; Trepan P was in the row furthest from the mid-plane. The specimens were removed by electrical-discharge machining. The V-notch was produced by a milling machine cutter; no further machining was required.

4.2 Archive Material

C_v samples and tension test samples were cut for both irradiation tests and check tests. The specimens were saw cut from the 1/8-T thickness layer indexed to the original inner diameter, that is, the as-forged surface. Samples for check tests of the unirradiated condition were taken from the same forging location as samples for the irradiation. As will be evident below, the check test data agree very well with the initial forging qualification data (Ref. 4).

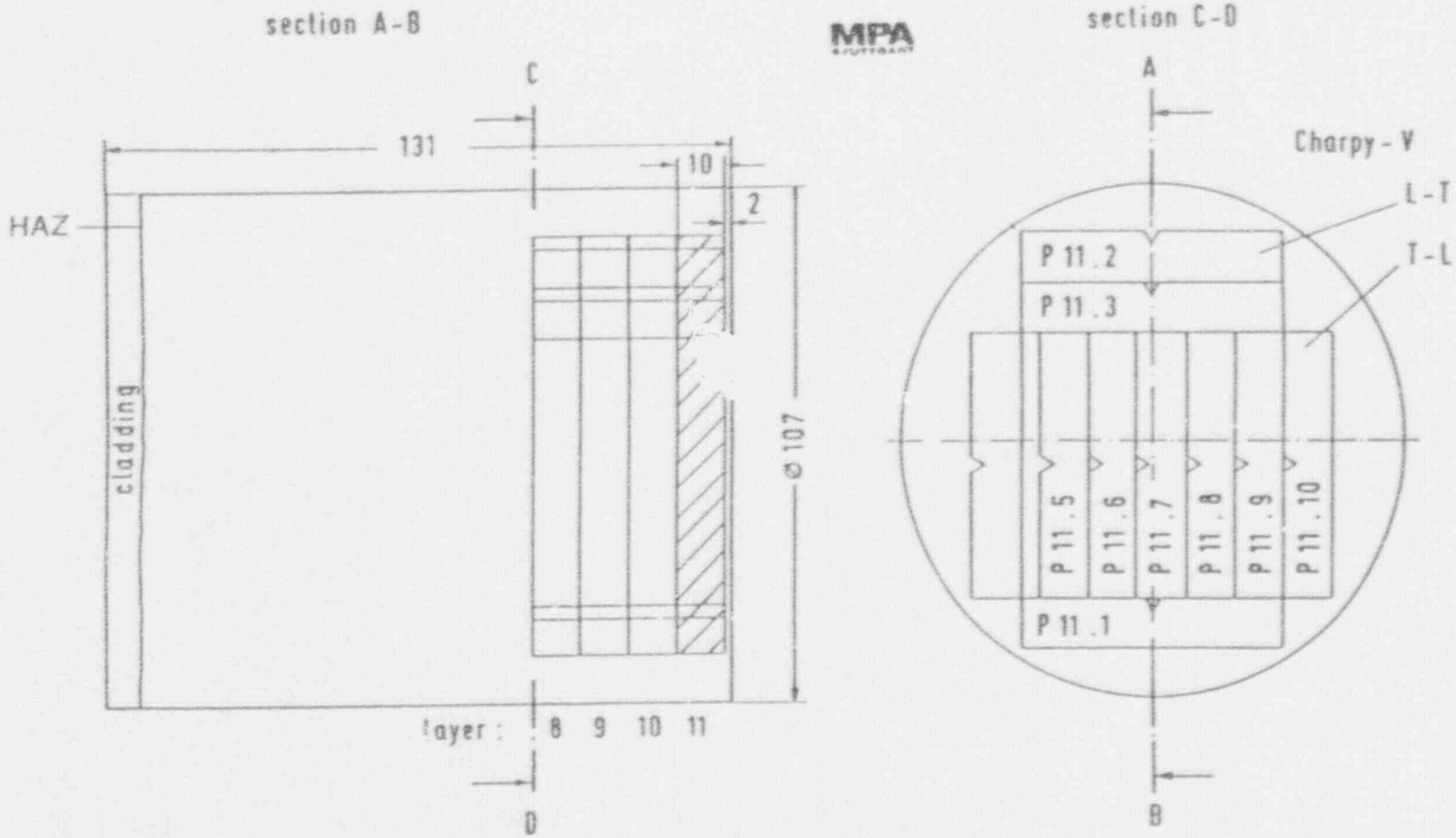

Fig. 3 Schematic illustration showing the Charpy-V specimen cutting plan for Trepan P. Not all of the specimens were irradiated in Experiment Assembly UBR-83A.

Table 3 Neutron Fluences received by Specimen Layers 8 to 11 of Trepans P, C, D and G in KRB-A Service (Courtesy MPA)

Specimen Layer	Neutron Fluence (n/cm^2, E > 1 MeV)			
	Trepan P[a]	Trepan C	Trepan D	Trepan G
8	1.202	1.356	1.448	1.285
9	1.047	1.179	1.261	1.118
10	0.906	1.022	1.081	0.969
11	0.782	0.882	0.942	0.836

[a] The UBR irradiation test involved L-C orientation samples from Layers 10 and 11 (only) and C-L orientation samples from Layers 8 to 11 of Trepan P.

5. MATERIAL IRRADIATION

The specimens were irradiated in MEA Assembly UBR-83A in the UBR B-4 fuel lattice position. The fluence received was 2.6×10^{18} n/cm^2, E > 1 MeV. The irradiation time was 81.0 hours. Irradiation temperatures were monitored continuously with thermocouples welded to the specimen mid-lengths and were controlled externally by automatic instrumentation.

To preclude any exposure condition differences, the specimens of the two materials were randomized within the assembly. Specimen and thermocouple placements are documented in Figures 4 and 5, respectively. Iron, nickel, copper and titanium dosimeter wires were placed within the specimen array and arranged over its length for fast neutron fluence (n/cm^2, E > 1 MeV) and fluence-gradient determinations. Two ^{238}U neutron dosimeters were also placed within the specimen array. For thermal fluence determinations, Co-Al and Ag-Al dosimeter wires were used. Neutron dosimeter placements are indicated in Figure 4.

Fluence values (E > 1 MeV) reported here are based on the calculated neutron energy spectrum for the irradiation facility[2] (Ref. 12,13). The values can be converted to displacements per atom (dpa) exposure values by:

$$\text{dpa} = \text{calculated spectrum fluence, } E > 1\text{ MeV } (1.47 \times 10^{-21}) \quad (1)$$

Appendix A provides average fluence rates determined from individual neutron dosimeters. The UBR reactor operating history for Assembly UBR-83A is given in Appendix B.

The uncertainties in fluence rates from the iron, nickel and ^{238}U dosimetry are judged by the counting laboratory, EG&G Idaho, Inc. to be ±8, ±7 and ±5% for the 1 σ confidence level, respectively. These values do not include the uncertainties that would be associated with actual spectrum averaged cross-sections of the irradiation fields or with burnout of the reaction products of interest. The uncertainty in cross-sections from the neutron spectrum calculation is less than 15%.

Because the trepan specimens had a residual radioactivity from prior KRB-A service the irradiation assembly was final-fabricated on-site at the UBR which is located in the Buffalo Materials Research Center. A standard MEA irradiation assembly design nonetheless was used and standard MEA QA procedures were followed.

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2 E. P. Lippincott, "Buffalo Light Water Reactor Calculation," Letter Communication Serial No. 7754977, Hanford Engineering Development Laboratory, P. O. Box 1970, Richland, WA 99352, to J. R. Hawthorne dated November 16, 1977.

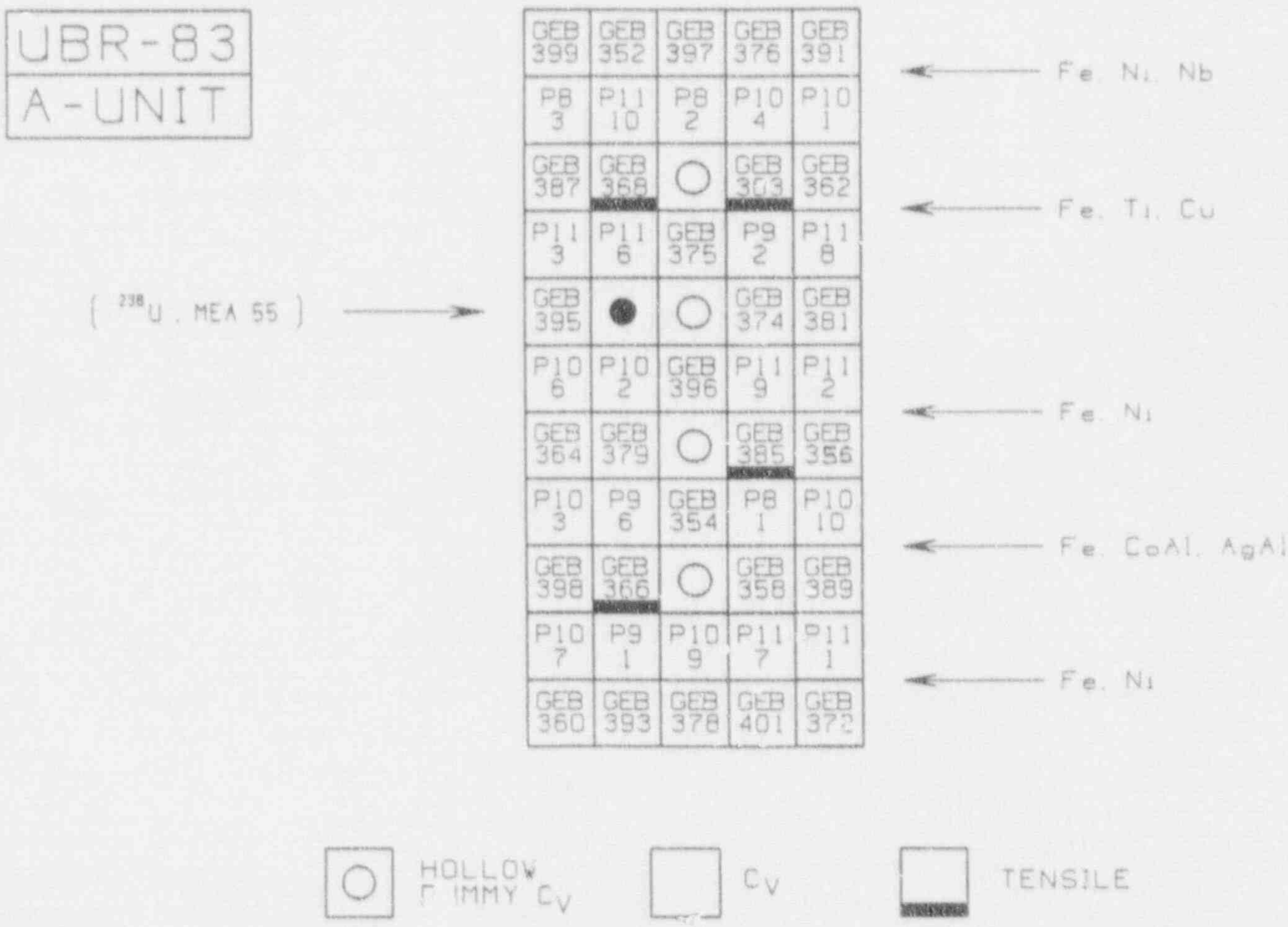

Fig. 4 Placement of Charpy-V and tensile specimens in Irradiation Assembly UBR-83A (Elevation View). Locations of dosimeter wires and the location of the vial containing the ^{238}U dosimeter are also indicated. The wires span the five specimen-wide array and were placed in the V-notches of the Charpy specimens.

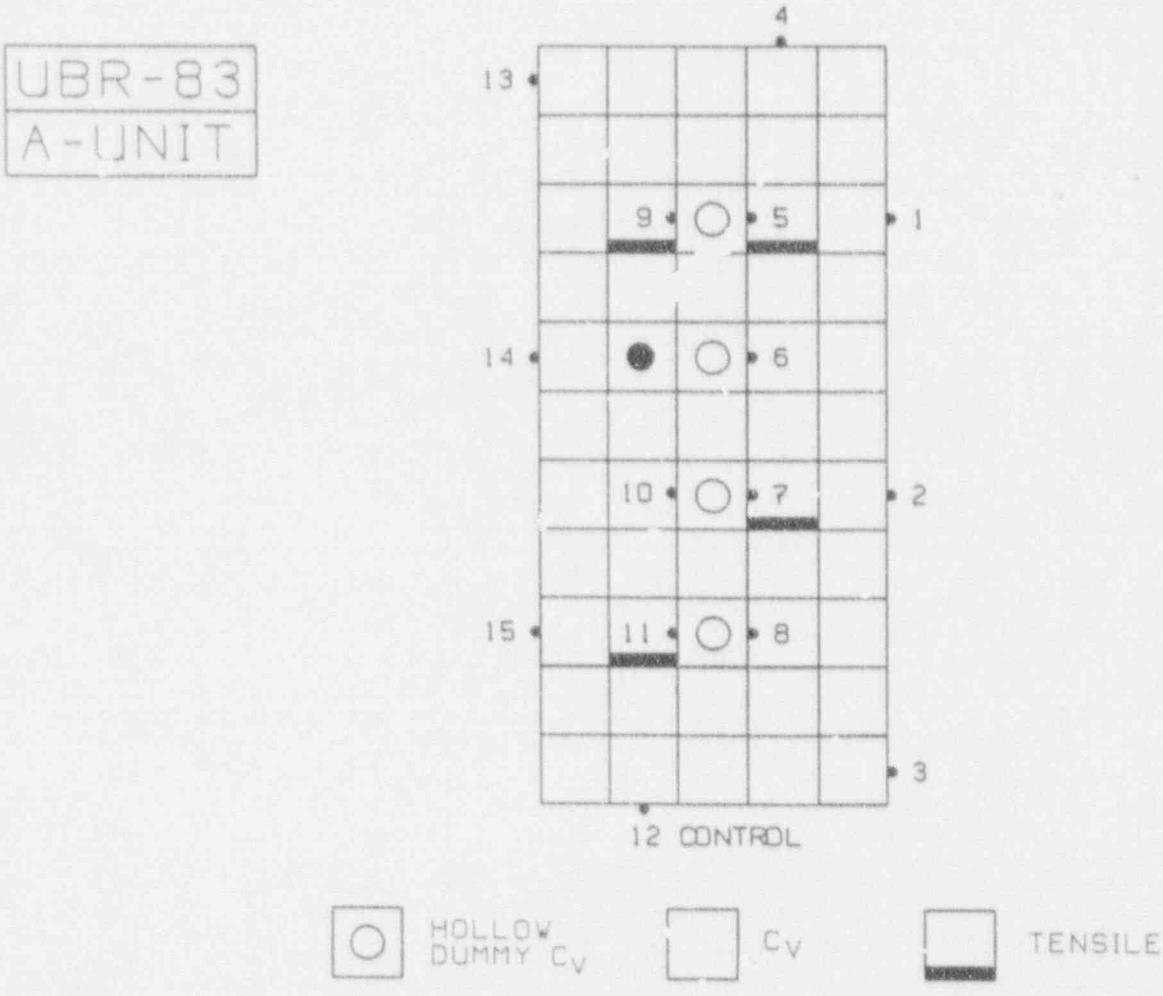

Fig. 5 Irradiation Assembly UBR-83A showing thermocouple placements in the specimen array.

6. POSTIRRADIATION TESTING

The C_v specimens were broken on a 407-J (300 ft-lb) capacity Tinius Olsen impact tester equipped with Dynatup instrumentation for recording applied load vs. time-of-fracture information during each test. The same machine was used by MEA for the irradiated, unirradiated and reference condition specimens. The machine was calibration-tested per ASTM Standard Method E 23 just before testing the present group of specimens[3]. Appendix C provides the individual specimen data for the pre-UBR irradiation condition and the post-UBR irradiated condition. Computer-curve fits of the data and values of curve fitting parameters are provided also. In the text data figures below, the brittle-ductile transition curves are visual best fits to the data.

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3 R. Pasternak, Letter Report, U. S. Army Laboratory Command, Department of the Army, Watertown, Ma 02172, to J. R. Hawthorne, May 26, 1989.

7. RESULTS

7.1 Archive Material

Table 4 summarizes the results for the archive material and the trepan material. The C_v test data for the former are illustrated in Fig. 6. The transition temperature elevations for the L-C and C-L orientations were, respectively, 20°C (35°F) and 17°C (30°F). Fig. 7 compares the postirradiation data to that from the earlier irradiation test (UBR-78) at 288°C to the same nominal fluence. Excellent agreement is observed. UBR irradiations of L-C orientation samples of GEB2 at 275°C and 288°C to a much higher fluence, ~8.6 x 10^{18} n/cm^2, revealed an essentially-nil sensitivity of the material to irradiation temperature differences in this range (Ref. 4). In turn, the excellent agreement of the data found in Fig. 7 confirms the high reproduceability of results from UBR irradiation tests. Only a slight difference in transition trend curve is discernable in the region between ~75 J (55 ft-lb) and the upper shelf regime. This may be simply a facet of the scatter pattern for the limited data available.

The observed reproduceability of postirradiation properties rules out the possibility (remote) that the anomaly under investigation is some manifestation of the UBR irradiation procedure or postirradiation test procedures. Good reproduceability of data with UBR irradiations has been shown by other RPV material studies (Ref. 14).

7.2 Trepan Material

The L-C and C-L orientation data for the Trepan P material in Assembly UBR-83A are illustrated in Fig. 6. Postirradiation data trends for the archive material from Fig. 7 are also shown for comparison.

Initial inspection of the trepan data reveals no particular difference in postirradiation notch ductility due to thickness location in the trepan or the associated service-related fluence. The extent of data scatter is small; only one postirradiation test point in each plot could be considered an outlier.

7.3 Trepan vs. Archive Material

The positions of the transition temperature curves for trepan vs. archive materials in Fig. 8 mirror the data which originally suggested an anomaly. The trepan curves fall to the right and below the archive material curves which could be construed as a manifestation of a material radiation sensitivity difference. Also, the transition temperature elevation and the upper shelf reduction for the trepan L-C orientation is greater than those for the trepan C-L orientation. However, the indexing of the UBR-83A test results to the MPA data base for the reference condition, (tests of Trepans C, G and D) presents a different picture (Fig. 9). Such indexing indicates transition temperature elevations of only 11°C and 14°C for the L-C and C-L orientations, respectively, not the elevations of 58°C (105°F) and 44°C (80°F) found when the data are indexed to the preirradiation properties of the archive material (Fig. 8). Likewise, the difference in upper shelf energy reduction is 5 J, not 27 J for the L-C orientation. For the C-L orientation, an upper shelf reduction of 19 J is described by both indexing methods.

Table 4 Charpy-V Notch Ductility Determinations for Archive Material GEB and KRB-A Vessel Trepan Material Before and After UBR Irradiation

Material	Specimen Orientation[a]	UBR Exp.	C_v 41-J Temperature						C_v Upper Shelf Energy					
			Initial		Irradiated		Increase		Initial		Irradiated		Reduction	
			°C	°F	°C	°F	Δ°C	Δ°F	J	ft-lb	J	ft-lb	ΔJ	Δft-lb
Archive (GEB2)	L-C[b]	--	-29	-20	--	--	--	--	103	76	--	--	--	--
	L-C[c]	UBR-78	(-26)	(-15)	(-9)	(15)	(17)	(30)	(107)	(79)	(103)	(76)	(4)	(3)
	C-L[c]	UBR-78	(-40)	(-40)	(-21)	(-5)	(19)	(35)	(155)	(114)	(151)	(111)	(4)	(3)
	L-C[d]	UBR-83	-29	-20	-9	15	20	35	107	79	103	76	4	3
	C-L[d]	UBR-83	-40	-40	-23	-10	17	30	153	113	144	106	9	7
Trepan P (KRB-A)	L-C (8)[e]	--	21	70	--	--	--	--	80	59	--	--	--	--
	L-C (9)	--	23	73	--	--	--	--	83	61	--	--	--	--
	L-C (10)	--	18	65	--	--	--	--	85	63	--	--	--	--
	L-C (10,11)	UBR-83	18	65	29	85	11	20	85	63	80	59	5	4
	C-L (8)	--	-7	20	--	--	--	--	160	118	--	--	--	--
	C-L (9)	--	-9	15	--	--	--	--	157	116	--	--	--	--
	C-L (10)	--	-9	15	--	--	--	--	153	113	--	--	--	--
	C-L (8-11)	UBR-83	-9	15	4	40	14	25	153	113	134	99	19	14
Trepan P[f] (Indexed to GEB)	L-C (10,11)	UBR-83	-29	-20	29	85	58	105	107	79	80	59	27	20
	C-L (8-11)	UBR-83	-40	-40	4	40	44	80	153	113	134	99	19	14

[a] 1/8T thickness location unless noted.

[b] Specimen Set No. 1.

[c] Specimen Set No. 2.

[d] Specimen Set No. 3.

[e] Trepan thickness layer.

[f] Unirradiated Archive GEB (Side 2) vs. UBR-irradiated Trepan P.

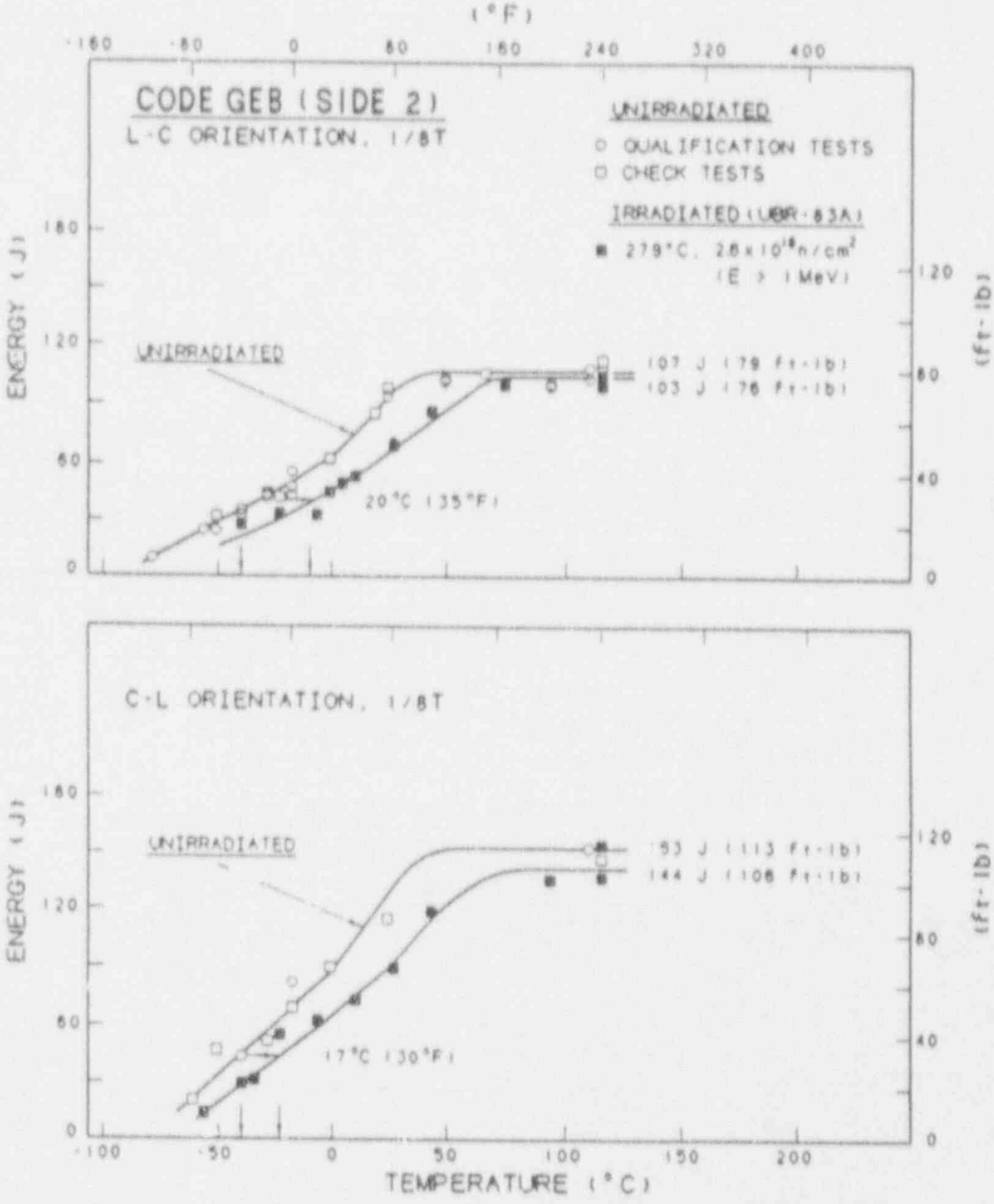

Fig. 6 Charpy-V notch ductility of the archive material before and after irradiation in Experiment Assembly UBR-83A. The unirradiated condition check test specimens and the specimens for irradiation were in close proximity to one another in the forging stock.

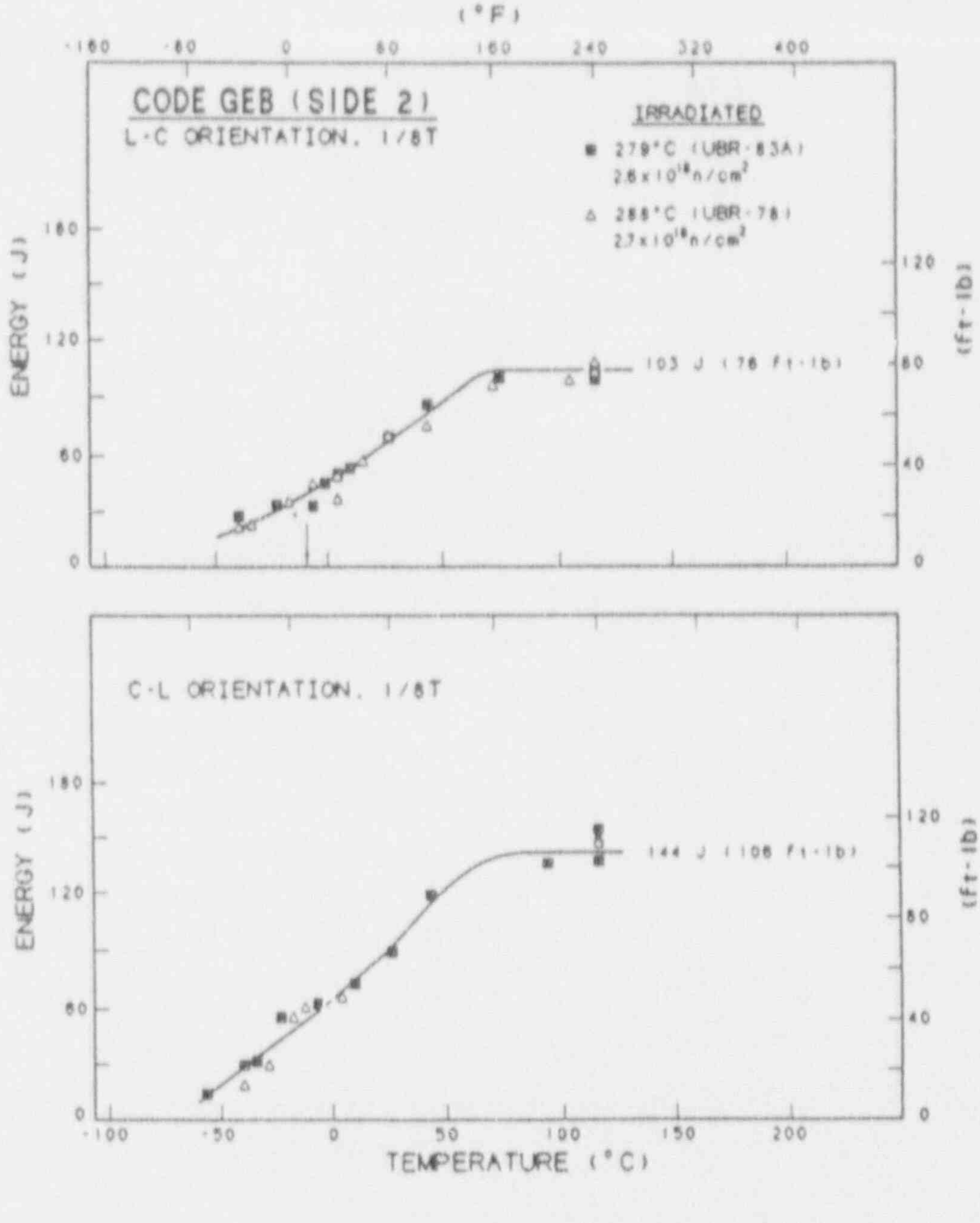

Fig. 7 Postirradiation Charpy-V data for the archive material from two UBR experiment assemblies showing the reproduceability of postirradiation properties. The irradiation temperature difference (279°C vs. 288°C) was shown not significant by other tests.

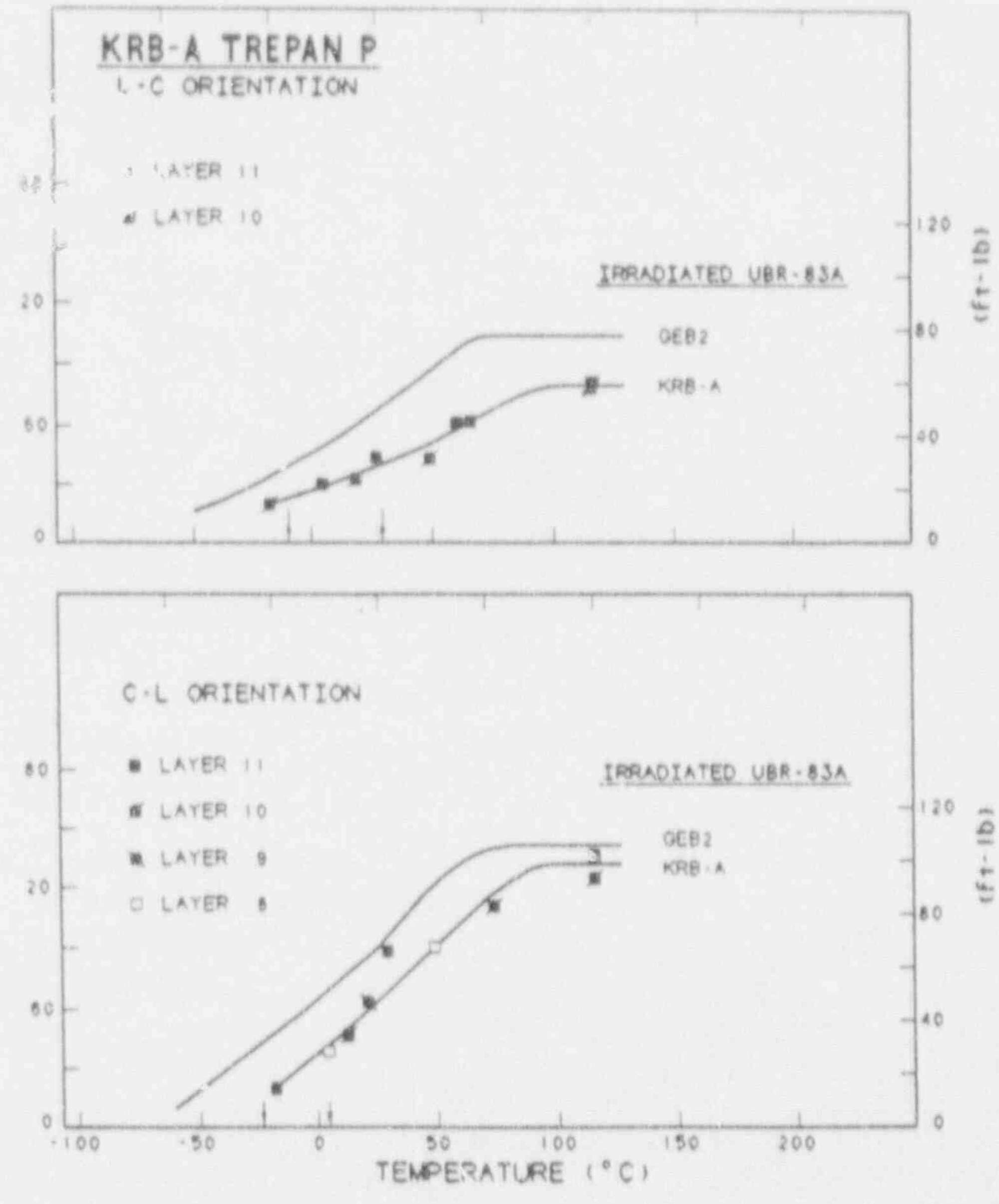

Fig. 8 Charpy-V notch ductility of the trepan material and the archive material after irradiation in Experiment Assembly UBR-83A.

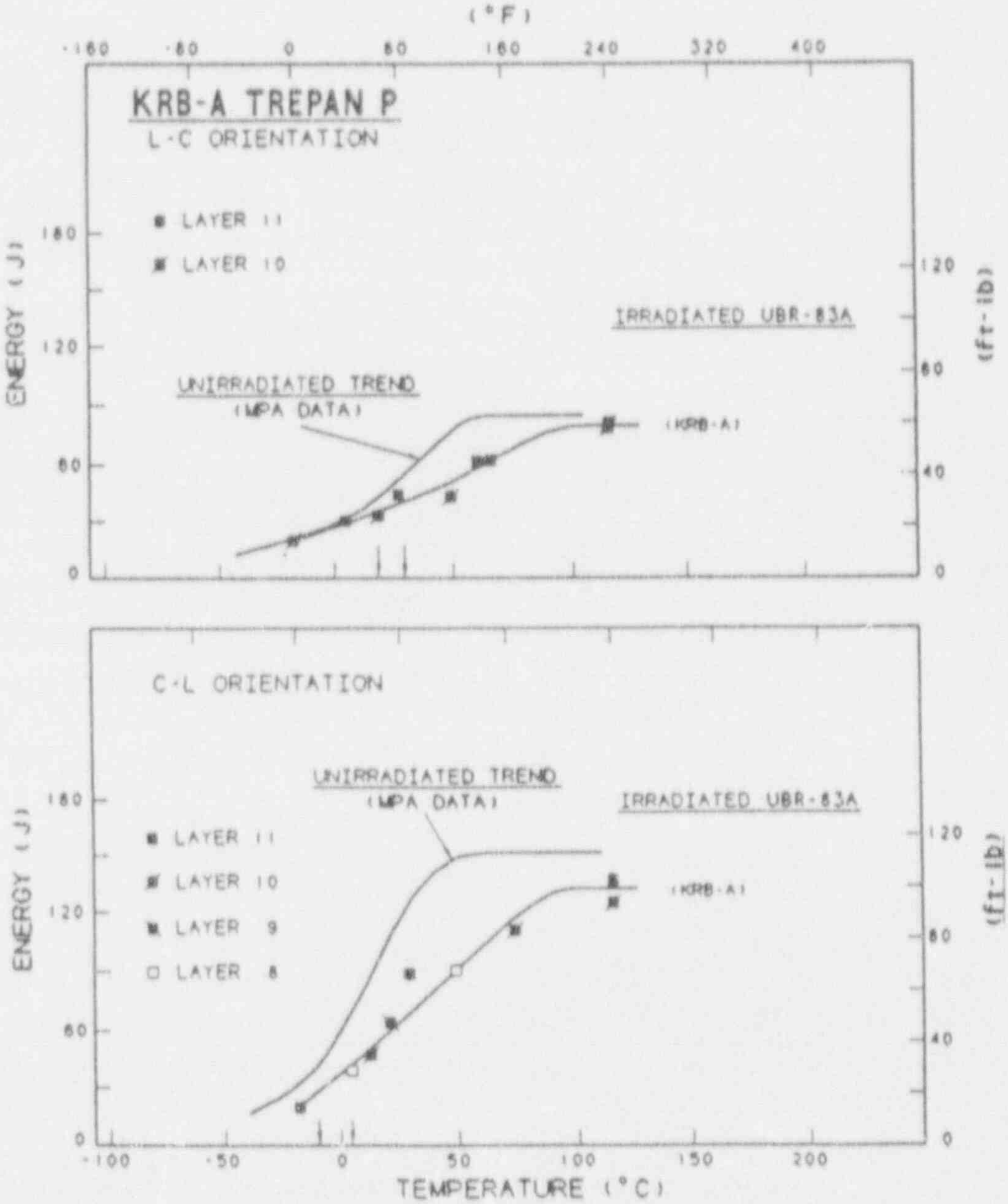

Fig. 9 Charpy-V notch ductility of the trepan material after irradiation in Experiment Assembly UBR-83A indexed to the post KRB-A service condition indicated by MPA test results.

The 11°C and 14°C transition temperature elevations for the UBR irradiation of the trepan material agree well with the 20°C and 17°C transition temperature elevations found for the archive material. (The 9°C difference for the L-C orientation is considered not significant.) The upper shelf energy reductions for the trepan material likewise agree well with those for the archive material. If the reasonable assumption is made that the properties of Trepan C, D and G represent well those of Trepan P, it can be concluded that the radiation embrittlement sensitivity of the trepan material, at least that of Layers 10 and 11 and quite possibly Layers 8 and 9, is the same as that of the 1/8T thickness location of the archive material for the accelerated-irradiation exposure case.

The difference in pre-UBR exposure properties of the trepan material vs. the archive material could stem from one or more of the following sources:

(1) Across-forging difference in unirradiated condition properties. The archive material represents one end of the forging while the trepan material depicts a location well-displaced (axially and/or circumferentially) from the archive material locus in the forging.

(2) An undocumented difference in material heat treatments, particularly in stress relief heat treatment(s) after welding. It can be envisaged that the duration of the heat treatment of the archive weldment made for the surveillance program is quite different from that of the vessel's Forging Ring No. 7.1 as placed in service.

(3) The long time-at-temperature of the vessel (years) during its service life. As noted in Figure 1, coupons of the archive material suspended in the vessel well away from the fuel core did show a significant change in transition temperature for the C-L orientation due to a temperature effect alone. The archive material was not similarly aged.

(4) Contrary to the extensive evidence and archive material markings, the archive material was not from the same steel melt as the vessel's Forging Ring No. 7.1.

(5) Some aspect of trepan removel, specimen blanking or specimen machining altered the properties of the material.

The above possibilities are reviewed in the Discussion Section below relative to their potential impact on Regulatory Guide 1.99 applications and RPV surveillance programs. It is MEA's opinion that the first and third possibilities are the strongest in this case. Again, it is stated that the apparent radiation sensitivities of the two materials shown in the UBR irradiation were the same. Accordingly, the anomaly cannot be ascribed to some basic difference in material resistance to a 279°C nuclear environment.

7.4 Trepan Data (Inner Wall vs. Outer Wall Layers - Preservice Condition)

The MPA data for Layers 8 to 10 of Trepans C, D and G are illustrated in Figure 10. Listings of these data are included in Appendix C. Plotting the data by individual layers, 41-J transition temperatures and upper shelf levels could be established. Superposition of the curves showed very little through-thickness differences in either property. In tests of the archive material, a

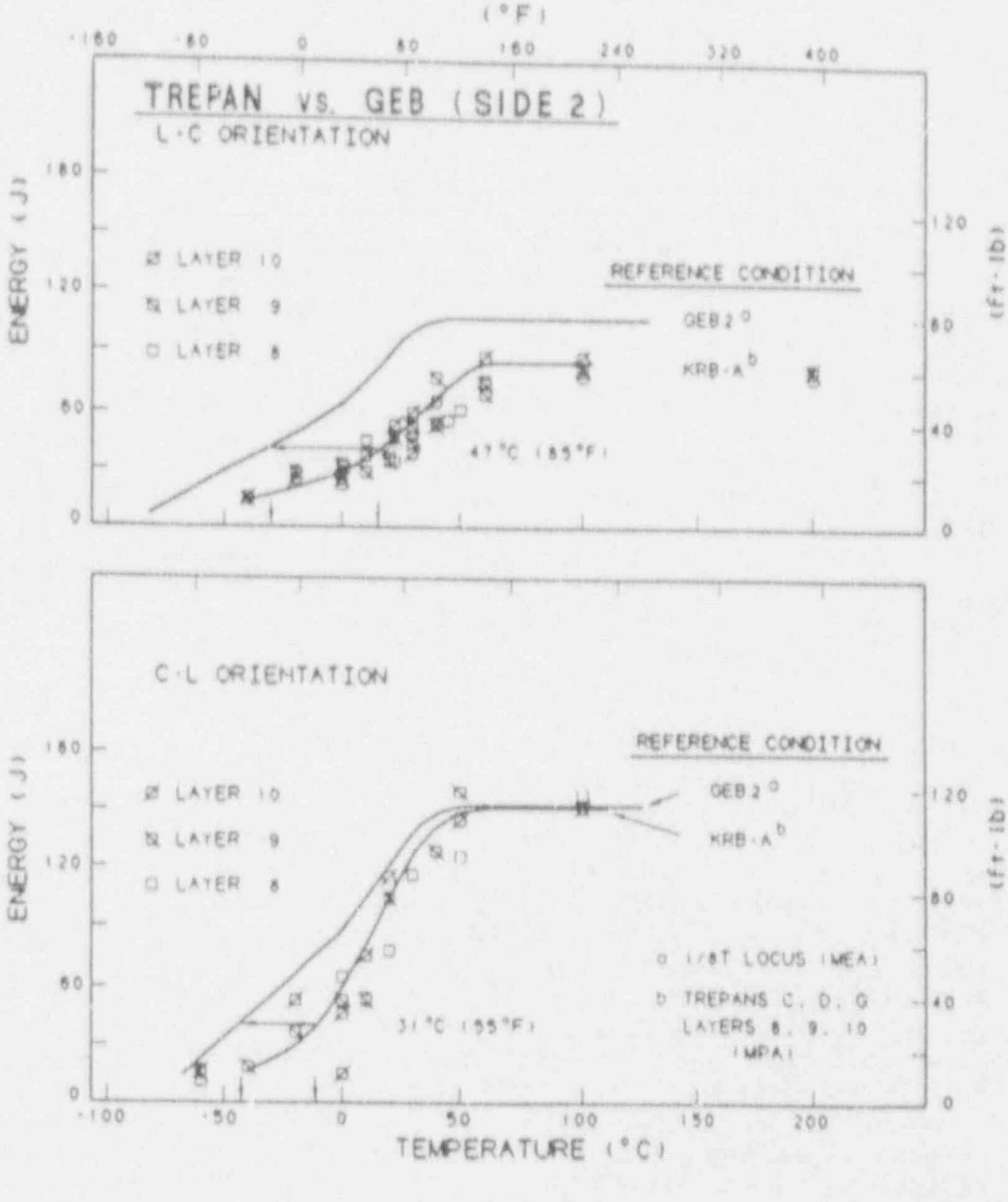

Fig. 10 Comparison of the notch ductility of the trepan material and the archive material before irradiation in the UBR. Notice the agreement of data for the three trepan layers; the trend curves are based on Layer 9 and 10 data primarily.

good correspondence of 1/4T, vs. 1/8T and 7/8T thickness location upper shelf properties was also observed. Only a small difference in 41-J temperature (11°C) was noted for 1/4T vs. 1/8T (or 7/8T thickness) locations. With this evidence, it is assumed here for discussion purposes that the 1/8T and 7/8T properties of the vessel as placed in service were the same.

7.5 Trepan Data (Inner Wall-Postservice vs. Outer Wall-UBR Irradiated)

Figure 11 compares the data for the UBR irradiation of the trepan (outer wall) to the data for the service-irradiated trepan (inner wall). Referring to the lower graph for the C-L orientation and temporarily ignoring the shapes of the curves, one observes that the upper shelf energy levels (and the 41-J transition temperatures) are about the same. This correspondence suggests no fluence-rate effect between the two reactors (KRB-A vs. UBR).

In contrast, the L-C orientation data yield two curves that are in general agreement up to an energy absorption level of about 61 J (45 ft-lb) but diverge above this level, that is, above 71°C (160°F). At 71°C (160°F), both the C-L orientation curve and the L-C orientation curve for the UBR irradiation of the trepan specimens have a positive slope. The curves do not show an onset of upper shelf behavior until about 104°C (220°F). The onset of upper shelf behavior for the UBR-irradiated outer-wall material at 104°C vs. much lower temperatures for the service-irradiated inner-wall material in spite of the similarity in 41-J temperatures, is in itself an anomaly.

Of further puzzlement is the relative positions and shapes of the KRB-A service-irradiated inner-wall material vs. outer-wall material in the transition region (C-L orientation). The lower portion of the curve for the inner-wall material lies slightly to the right of that for the outer-wall material (expected relationship), but the upper portion of the curve for the inner-wall material lies well to the left of that for the outer-wall material signifying better notch ductility and less radiation-induced embrittlement (unexpected). For the outer-wall material, since both orientations in the service-irradiated condition and the UBR-irradiated condition describe an internally-consistent family of curves, it can be concluded that they are reasonably accurate depictions of the properties. (A change in slope of curves by irradiation has been observed with other materials.) An explanation for the particular shape of the transition curve for the inner-wall material cannot be offered at this time. While both Trepan C and S supplied inner-wall location specimens for development of this curve, no pronounced properties difference due to sample location was reported by MPA (Ref. 1).

Of the two unusual data patterns cited above, the pattern of most concern is the difference in postirradiation upper shelf levels for the L-C orientation. Two observations may provide a clue. The upper shelf energy decreases for the inner-wall location indexed to the outer-wall location (postservice condition) are essentially the same, that is, 26 J (C-L) and 23 J (L-C). Secondly, it is observed that the upper shelf levels for the C-L orientation and L-C orientation commence at roughly 16°C and 77°C, respectively. A mechanistic explanation for this large temperature difference is absent.

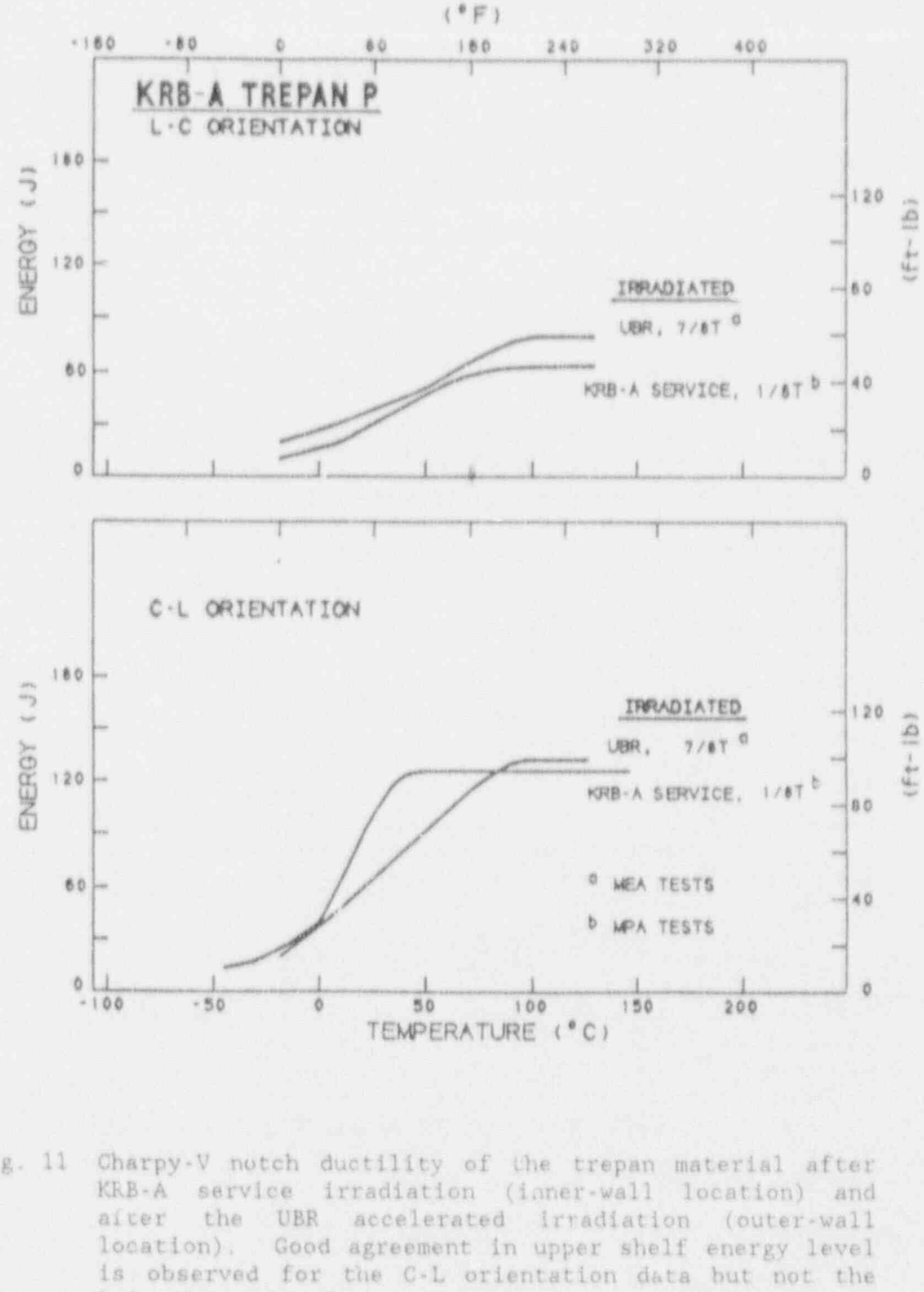

Fig. 11 Charpy-V notch ductility of the trepan material after KRB-A service irradiation (inner-wall location) and after the UBR accelerated irradiation (outer-wall location). Good agreement in upper shelf energy level is observed for the C-L orientation data but not the L-C orientation data.

8. DISCUSSION

The present investigation has proven that the initially-reported anomaly (Ref. 1,4) is not due to a basic difference in radiation-embrittlement sensitivity between the test materials. That is, the archive GEB material and the Trepan P material (outer-wall layers) exhibited comparable embrittlement after simultaneous irradiation in the UBR test reactor.

A large difference in notch ductility between the archive material (preirradiation condition) vs. the trepan material (post-service reference condition, outer-wall layer) is apparent with one exception: the C-L orientations of these materials have about the same upper shelf energy level. Analyses of the data provide the following concerns. If the "cause" of the overall difference in reference properties is due to the difference in forging locations represented by the materials and not to a low fluence effect and/or a thermal aging effect, the implication is one of a general problem for forgings and their sampling. In this scenario, the archive material selected for surveillance may not be providing the worst-case properties for the vessel material and in fact, may lead to underestimates of the actual 41-J temperature and overestimates of the actual upper shelf energy level by significant margins. Conversely, if the cause is the low level fluence exposure of the outerwall layer and not some across-forging variability, the 31 to 47°C difference in 41-J temperature suggests that we have not been attaching proper significance to the effects of this fluence regime. Thirdly, it could be that long-term thermal aging effects likewise have been underestimated. Fortunately, the second and third scenarios do not impact the validity of surveillance capsule data except for the possibility of large disparities between surveillance capsule time-at-temperatures and vessel wall time-at-temperatures. With a 3:1 lead factor, for example, a surveillance capsule might have only 3 years at temperature vs. a 9 year time at temperature for the vessel. Little is known about time-at-temperature effects for those very long periods of time equated to RPV design lifetimes and PLEX operations.

The comparison made of UBR-irradiated trepan material (outer wall layers) vs. the service-irradiated trepan material (inner wall layers) has reduced the scope of the original anomaly to the question of the low upper shelf energy level of the L-C orientation. The possibility of the anomaly being the result of some heretofore unobserved dose rate effect that is test-orientation dependent, cannot be dismissed on the basis of the latest UBR irradiation comparison of the archive vs. trepan materials. The outer wall layer of the vessel material and the archive material describe higher upper shelf energy levels after UBR irradiation.

The answer may reside in the seeming inconsistencies in the trepan inner-wall notch ductility properties relative to outer-wall properties, for example, the large disparity in upper shelf level between 1/8T and 7/8T locations for the L-C but not the C-L orientation. It is believed that the explanation will not be found simply though additional mechanical property testing. Instead, the trepan and archive materials should be examined with state-of-the-art microscopy focusing on those aspects governing upper shelf energy absorption. To help expedite resolution, the materials have been offered to the International Group on Radiation Damage Mechanisms in Pressure Vessel Steels (IG-RDM). Mechanisms identification is important to better understand and project in-service embrittlement behavior and PLEX capabilities (Ref. 15).

9. CONCLUSIONS

The findings from the simultaneous test reactor irradiation of the trepan material from the Gundremmingen KRB-A reactor vessel and the archive material has greatly reduced the uncertainties regarding the cause(s) of the originally reported anomalous property differences between the materials in the post-irradiation condition. The important observations and determinations from this investigation can be enumerated:

(1) The UBR irradiation at 279°C produced 41-J transition temperature elevations of 11°C and 14°C for the trepan material (L-C and C-L orientation, respectively) vs. 20°C and 17°C for the archive material.

(2) The UBR irradiation at 279°C produced upper shelf energy reductions of 5 J and 19 J for the trepan material (L-C and C-L orientation, respectively) vs. 4 J and 9 J for the archive material.

(3) From (1) and (2), the radiation embrittlement sensitivities of the trepan material (outer wall region) and the archive material (1/8T region) are essentially the same. This proves that the originally-observed differences are not due to a basic difference between material radiation resistances.

(4) The pre-UBR irradiation C_v properties of the trepan and archive materials are not the same. For the L-C orientation, the 41-J temperature of the trepan material was 47°C (85°F) higher and the upper shelf energy level was 22 J (16 ft-lb) lower than those of the archive material. For the C-L orientation, the 41-J temperature of the trepan material was 31°C (55°F) higher than that for the archive material but the upper shelf energy levels were the same ~153 J (113 ft-lb).

(5) More than one cause may be responsible for the differences in preirradiation properties cited in (4).

(6) The properties dissimilarities in (4) would explain some (but not all) of the apparently greater radiation embrittlement found for the trepan material (inner wall, L-C orientation) compared to UBR-irradiated archive material.

(7) For both L-C and C-L orientations, the 41-J transition temperatures of the service-irradiated trepan material (inner wall) and the UBR-irradiated trepan material (outer wall) are about the same, illustrating an absence of a fluence rate effect on this property.

(8) The upper shelf energy levels of the service-irradiated trepan material (inner wall) and the UBR-irradiated trepan material (outer wall) are about the same in the C-L orientation (strong) but differ greatly in the L-C orientation (weak).

(9) Proven metallurgical or mechanistic explanations for the L-C orientation difference of (8) are not yet available. Seeming inconsistent notch ductility relationships which may constitute clues to the remaining anomalous data indications, are identified.

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APPENDIX A

Neutron Dosimetry Determinations Based on Fission Spectrum Assumption for Irradiation Experiment UBR-83A

Table A-1 Irradiation Assembly UBR-83A Fluence-Rate Monitor Results (Ref. A.1)

Monitor/Segment[a]	Fluence Rate[b] x 10W (average)	Monitor Location in Specimen Array
A8 (Fe)	6.15	Between layers 1 and 2
(Ni)	6.44	
A1 (Fe)	6.20	Between layers 3 and 4
(Ti)	5.64	
(Cu)	5.24	
A7 (Fe)	6.28	Between layers 6 and 7
(Ni)	6.62	
A11 (Fe)	6.47	Between layers 8 and 9
(Co-Ag)	2.99[c]	
A4 (Fe)	6.47	Between layers 10 and 1
(Ni)	6.85	
Vial (^{238}U)	7.93[d] (9.04)[e]	At layer 5
(Fe)	6.34	
(Ni)	6.61	

a See Fig. 4 in main text for monitor loci. The Fe, Ni and ^{238}U results are based on > 1 MeV ^{238}U fission spectrum averaged cross sections of 115.2, 156.8 and 441 millibarns, respectively.
b Fission spectrum assumption; $n/cm^2 \cdot s^{-1}$ (E > 1 MeV) unless noted.
c Thermal fluence rate corrected for epithermal neutron contribution based on ^{109}Ag and ^{59}Co reaction rates and their cross sections.
d Average of separate determinations for ^{95}Zr, ^{103}Ru, ^{137}As and $^{140}BaLa$
e Calcuted spectrum value.

Summary, Capsule UBR-83A

1. Average neutron fluence: 2.63×10^{18} n/cm^2 E > 1 MeV (calculated spectrum).
2. Average dpa (E > 1 MeV): 3.9×10^{-3}
3. Exposure hours: 81.00 (B-4 facility)

REFERENCE

A.1 J. W. Rogers, "Neutron Fluence Rates for MEA-UBR Experiments," Letter Report JWR-30-92, Idaho Nuclear Engineering Laboratory, May 28, 1992.

APPENDIX B

Reactor Operations History: Irradiation Assembly UBR-83

Table B-1 Exposure History

Experiment UBR-83A

Date In	Time In	Date Out	Time Out	Exposure Hours	Sigma Hours	Core Position
2-27-89	2246	3-2-89	1445	63.98	63.98	B-4
3-02-89	1550	3-3-89	0851	17.02	81.00	

APPENDIX C

Charpy-V Data Tabulations and Computer Curve Fits
for Unirradiated Condition Tests and Irradiation
Experiment UBR-83A Tests

Tabulations of Charpy-V Data

Table C-1 Pre UBR Irradiation C_v Data for Archive GEB-2 Material

Specimen No.[a]	ASTM Orientation	Temperature (°C)	(°F)	Energy (J)	(ft-lb)	Lateral Expansion (mm)	(mils)	Shear (%)
400	C-L	-62	-79	20	15.0	0.356	14	<100
390	C-L	-51	-60	47	34.5	0.711	28	<100
392	C-L	-29	-20	52	38.0	0.813	32	<100
388	C-L	-18	0	69	51.0	1.016	40	<100
382	C-L	-1	30	91	67.0	1.422	56	<100
394	C-L	24	75	117	86.0	1.676	66	<100
380	C-L	116	240	157	116.0	2.337	92	100
402	C-L	116	240	157	115.5	1.854	73	100
371	L-C	-51	-60	32	23.5	0.508	20	<100
363	L-C	-29	-20	44	32.5	0.737	29	<100
355	L-C	-23	-10	42	31.0	0.737	29	<100
361	L-C	-1	30	62	46.0	1.016	40	<100
351	L-C	18	65	86	63.5	1.372	54	<100
377	L-C	24	75	99	73.0	1.676	66	<100
357	L-C	116	240	114	84.0	1.676	66	100
359	L-C	116	240	108	80.0	1.448	57	100

[a] Specimen taken from 1/8 T thickness layer of the material.

Table C-2 Pre UBR Irradiation C_v Data for KRB-A Vessel Trepans C, D, G (Courtesty MPA)

Layer	Trepan	ASTM Orientation	Temperature (°C)	(°F)	Energy (J)	(ft-lb)
8	C	C-L	-60	-76	10.5	8
			-20	-4	37	27
			10	50	54	40
			30	86	118	87
			40	104	84	62
			50	122	127.5	[illegible]4
			275	527	154	1[illegible]
	G	C-L	0	32	64.5	48
			20	68	78.5	58
			100	212	160.5	118
	C	L-C	30	86	47	35
			50	122	61	45
			275	527	81.5	60
	D	L-C	0	32	21	16
			20	68	35.5	26
			30	86	51	38
			45	113	56	41
			60	140	68.5	51
			100	212	79	58
			200	392	79	58
	G	L-C	-20	-4	27	20
			0	32	33	24
			10	50	44.5	33
			22	72	34.5	25
			40	104	54	40
			60	140	75.5	56
			100	212	81	60
9	C	C-L	-6C	-76	14.5	11
			-40	-40	18.5	14
			-20	-4	37	27
			10	50	53	39
			40	104	130	96
			50	122	161	119
			275	527	160	118
	G	C-L	0	32	52.5	39
			20	68	105.5	78
			100	212	153.5	113

Table C-2 Cont'd Pre UBR Irradiation C_v Data for KRB-A Vessel
Trepans C, D, G (Courtesty MPA)

Layer	Trepan	ASTM Orientation	Temperature (°C)	Temperature (°F)	Energy (J)	Energy (ft-lb)
	C	L-C	-40	-40	13	10
			30	86	53	39
			275	527	83	61
	D	L-C	0	32	30.5	23
			20	68	34	25
			30	86	43.5	32
			40	104	53	39
			60	140	69.5	51
			100	212	82.5	61
			200	392	81	60
	G	L-C	-20	-4	29	21
			0	32	25	18
			10	50	29	21
			22	72	45.5	34
			40	104	77	57
			60	140	75	55
			100	212	83	61
10	C	C-L	-40	-40	16.5	12
			-20	-4	52.5	39
			0	32	46	34
			10	50	76	56
			50	122	146	108
			275	527	158	117
	G	C-L	0	32	38.5	28
			20	68	117	86
			100	212	153	113
	C	L-C	-40	-40	15.5	11
			30	86	38.5	28
			275	527	83.5	62
	D	L-C	0	32	29	21
			20	68	40.5	30
			30	86	59.5	44
			40	104	52.5	39
			60	140	88	65
			100	212	82.5	61
			200	392	83	61

Table C-2 Cont'd Pre UBR Irradiation C_v Data for KRB-A Vessel Trepans C, D, G (Courtesty MPA)

Layer	Trepan	ASTM Orientation	Temperature (°C)	Temperature (°F)	Energy (J)	Energy (ft-lb)
	G	L-C	-20	-4	25	18
			0	32	24.5	18
			10	50	36.5	27
			22	72		39
			40	104	65.5	48
			60	140	88	65
			100	212	88	65

Table C-3 Post UBR Irradiation C_v Data for Archive GEB-2 Material

Specimen No.[a]	ASTM Orientation	Temperature (°C)	Temperature (°F)	Energy (J)	Energy (ft-lb)	Lateral Expansion (mm)	Lateral Expansion (mils)	Shear (%)
396	C-L	-57	-70	14	10.0	0.152	6	<100
387	C-L	-40	-40	29	21.5	0.432	17	<100
391	C-L	-34	-30	31	23.0	0.508	20	<100
393	C-L	-23	-10	55	40.5	0.868	34	<100
379	C-L	-7	20	62	46.0	0.991	39	<100
401	C-L	10	50	73	54.0	1.168	46	<100
399	C-L	27	80	90	6[illegible].5	1.372	54	<100
395	C-L	43	110	121	89.0	1.473	58	<100
397	C-L	93	200	138	101.5	1.854	73	99
381	C-L	116	240	156	115.0	2.540	100	100
398	C-L	116	240	139	102.5	2.362	93	100
389[b]	C-L	-	-	-	-	-	-	-
354	L-C	-40	-40	27	20.0	0.432	17	<100
360	L-C	-23	-10	33	24.5	0.635	25	<100
358	L-C	-7	20	33	24.0	0.635	25	<100
352	L-C	-1	30	45	33.0	0.711	28	<100
364	L-C	4	40	49	36.5	0.889	35	<100
372	L-C	10	50	53	39.0	0.991	39	<100
362	L-C	27	80	69	51.0	1.219	48	<100
378	L-C	43	110	87	64.0	1.626	64	<100
375	L-C	74	165	101	74.5	1.575	62	98
356	L-C	116	240	106	78.0	1.880	74	100
374	L-C	116	240	100	74.0	1.524	60	100
376	L-C	177	350	95	70.0	1.727	68	100

[a] Specimen taken from 1/8T thickness layer of material.
[b] Specimen "lost" in testing.

Table C-4 Post UBR Irradiation C_v Data for Trepan P Material

Trepan P Layer	Specimen No.	ASTM Orientation	Temperature (°C)	Temperature (°F)	Energy (J)	Energy (ft-lb)	Lateral Expansion (mm)	Lateral Expansion (mils)	Shear (%)
8	P8-1	C-L	49	120	92	67.5	1.321	52	<100
	P8-2	C-L	116	240	139	102.5	1.854	73	100
	P8-3	C-L	4	40	39	28.5	0.711	28	<100
9	P9-1	C-L	21	70	64	47.0	1.194	47	<100
10	P10-1	C-L	116	240	127	93.5	1.803	71	98
	P10-2	C-L	74	165	113	83.0	1.676	66	<100
	P10-3	C-L	13	55	47	34.5	0.868	34	<100
11	P11-1	C-L	-18	0	197	14.5	0.254	10	<100
	P11-2	C-L	29	85	89	66.0	1.295	51	<100
	P11-3	C-L	116	240	138	102.0	1.651	65	100
10	P10-4	L-C	116	240	79	58.0	1.778	70	99
	P10-6	L-C	18	65	33	24.0	0.610	24	<100
	P10-7	L-C	116	240	81	59.5	1.397	55	100
	P10-9	L-C	-18	0	17	12.5	0.203	8	<100
	P10-10	L-C	49	120	43	31.5	0.813	32	<100
11	P11-6	L-C	116	240	81	60.0	1.499	59	100
	P11-7	L-C	66	150	62	45.5	1.143	45	<100
	P11-8	L-C	27	80	43	32.0	0.838	33	<100
	P11-9	L-C	4	40	30	22.0	0.584	23	<100
	P11-10	L-C	60	140	61	45.0	1.016	40	<100
9	P9-2[a]	C-L	-	-	-	-	-	-	-
	P9-6[a]	L-C	-	-	-	-	-	-	-

[a] Specimen not tested (held in reserve).

Computer Curve Fits of Charpy-V Data

OVERVIEW

The data curve fitting procedure employed the hyperbolic tangent (Tanh) curve fitting method as given by:

$$C_v = A + B \tanh \frac{T - T_o}{C}$$

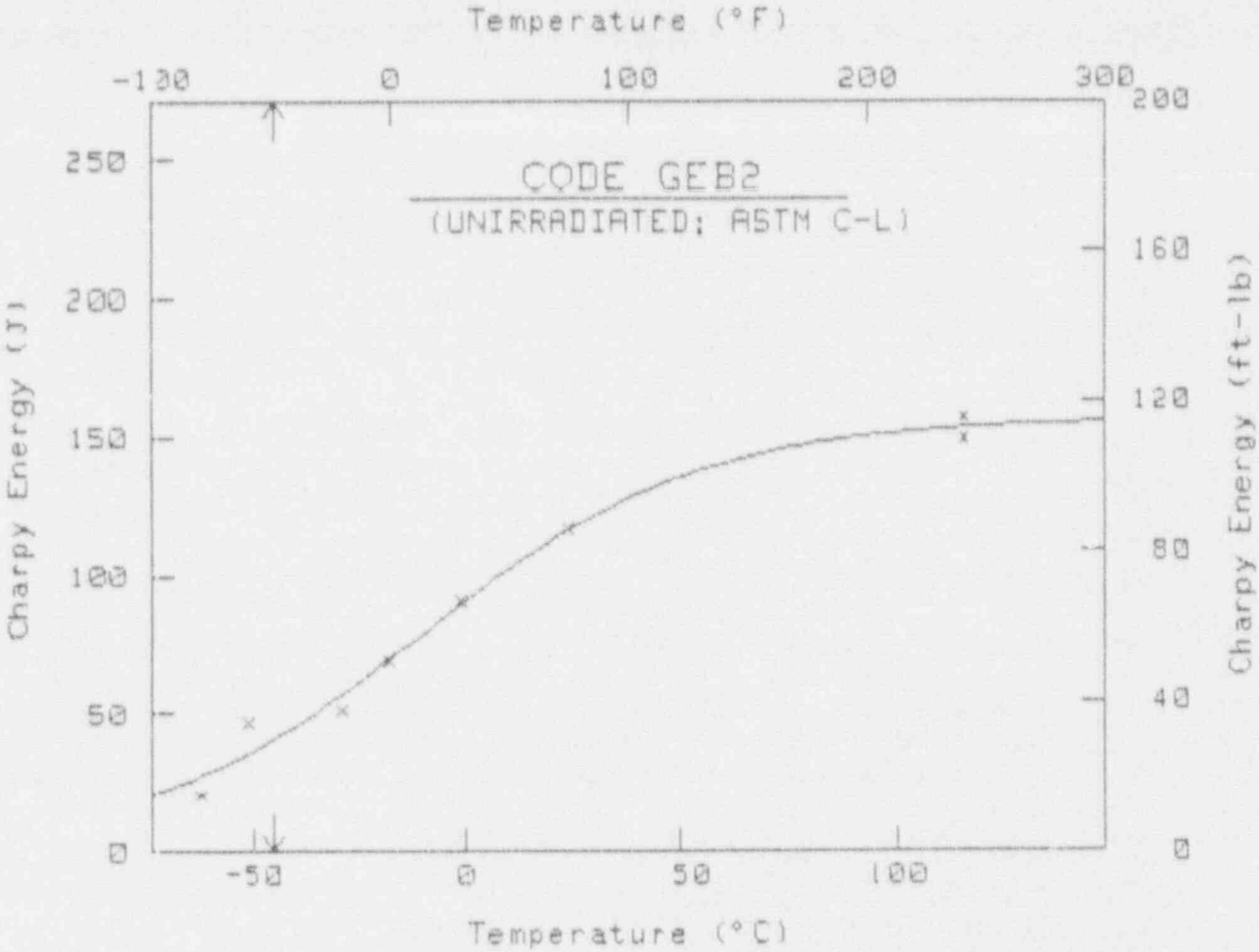
Parameters A, B, C and T_o are determined from non-linear regression analysis.

The quality of the fit to each data set generally depends upon the number of specimens tested and the availability of data defining the upper shelf and lower shelf for the data set. For many of the present data sets, both requirements are satisfied and an acceptable curve fit results. In other cases, either few tests were conducted or the data did not adequately define the lower shelf for the data set. For such cases, the lower shelf from a standard Tanh fit gives a lower shelf which is either above 27 J (20 ft-lb) or negative. Since such results are not satisfactory from either engineering or aesthetic standpoints, two modified curve fits (Case A and Case B) can be applied.

Case A is the result obtained when four fictitious data points with 7 J (5 ft-lb) of energy absorption are added at a temperature that is 28°C (50°F) below the intercept with the abscissa, of a line representing a linearized transition region. The line in this case is an eyeball fit to the data; the choice of a larger temperature shift (up to 56°C or 100°F) generally is found not to influence the result appreciably. Case B represents use of a fixed lower shelf of 7 J (5 ft-lb); this lower shelf is attained at a temperature of -∞.

The use of the modified curve fits serve to force the curves to a reasonably low, positive value in the lowere shelf region. This device is particularly useful for those cases where data are lacking in the lower shelf region for guiding the computer in its setting of bounding conditions. It should 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 conditon

Within this appendix, the first curvefit sheet for a given material/material condition represents a standard evaluation using the Tanh equation. The second curvefit sheet if present, gives the Case A results. For Case A, the fictitious data points are denoted by "O" on the graph and in the data tabulation on the curvefit sheet.

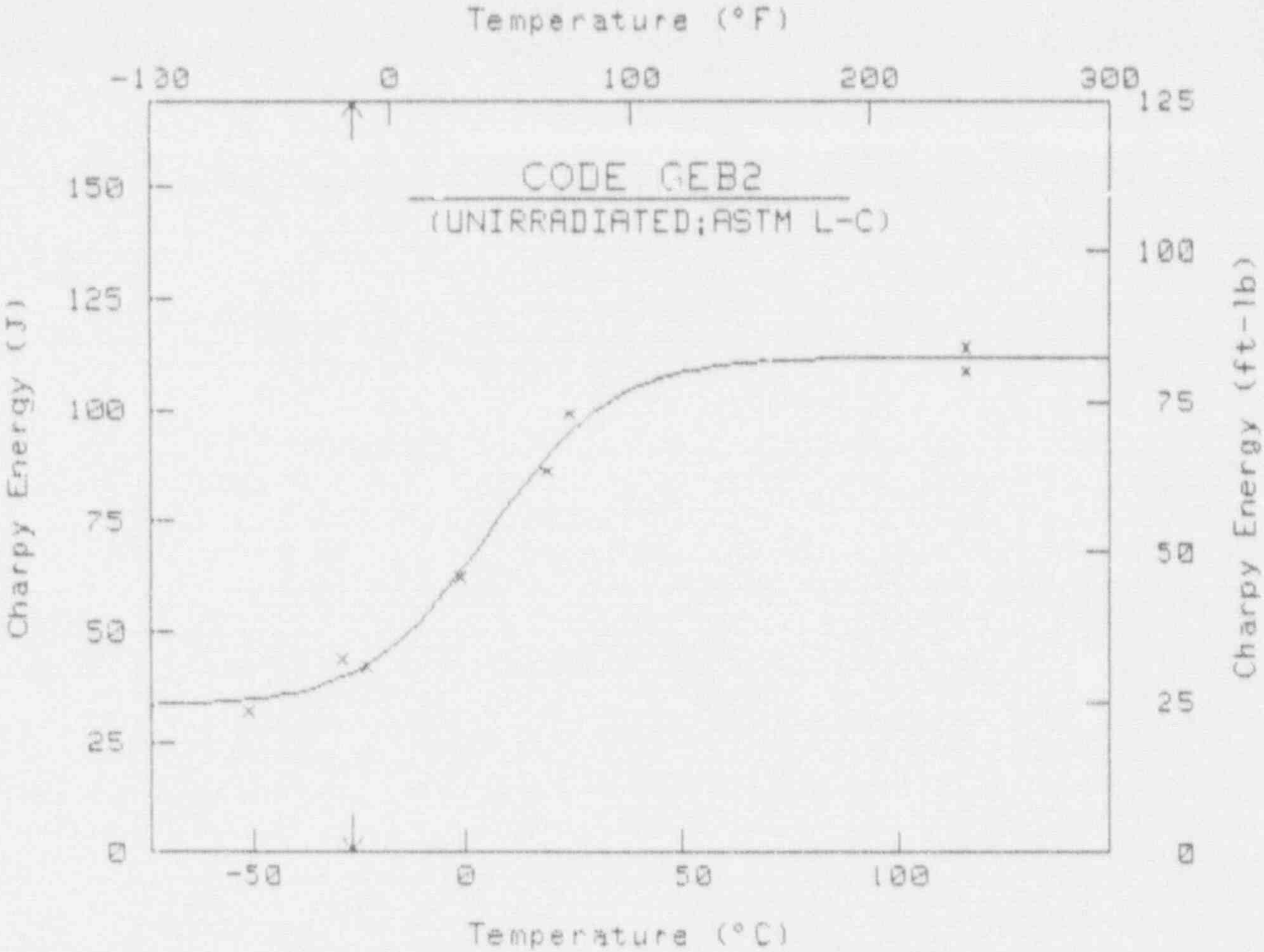


$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	57.91 ft-lb	78.52 J
B =	57.22 ft-lb	77.58 J
C =	116.61 °F	64.78 °C
To =	13.31 °F	-10.38 °C
Cv = 30 ft-lb (41 J) at T =	-48.9 °F	-44.9 °C
Upper Shelf Energy =	115.1 ft-lb	156.1 J

PT #	Temp (°F)	Energy (ft-lb)
1	-79	15.0
2	-60	34.5
3	-20	38.0
4	0	51.0
5	30	67.0
6	75	86.0
7	240	110.0
8	240	115.5

O = Fictitious Point Added * = Test Point Not Included



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

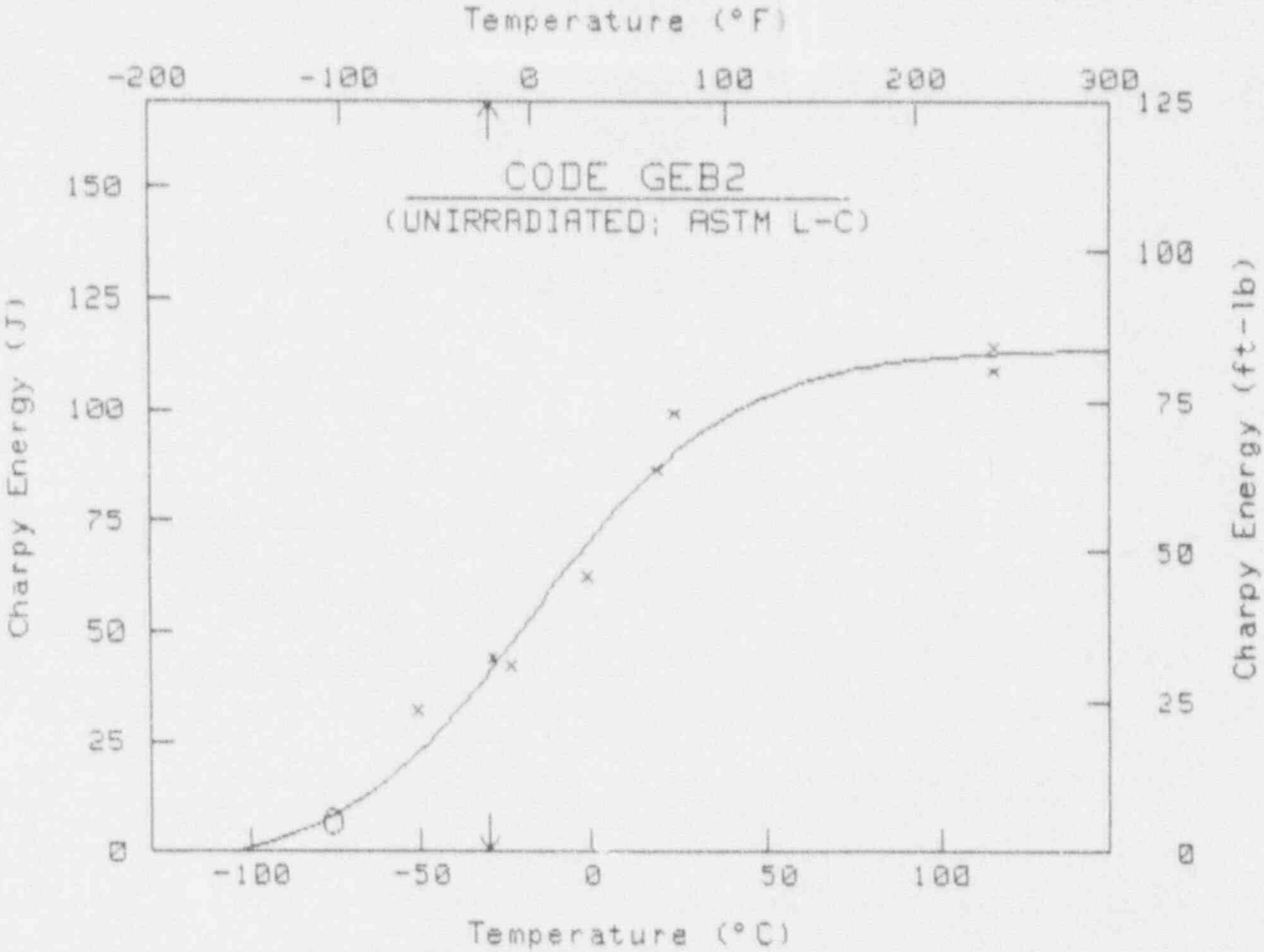
		English	Metric
A	=	53.38 ft-lb	72.37 J
B	=	28.96 ft-lb	39.26 J
C	=	51.[illegible]9 °F	28.49 °C
To	=	41.63 °F	5.35 °C

Cv = 30 ft-lb (41 J) at T	=	-15.8 °F	-26.5 °C
Upper Shelf Energy	=	82.3 ft-lb	111.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-60	23.5
2	-20	32.2
3	-10	31.0
4	30	46.0
5	65	63.5
6	75	73.0
7	240	80.0
8	240	84.0

0 = Fictitious Point Added   * = Test Point Not Included



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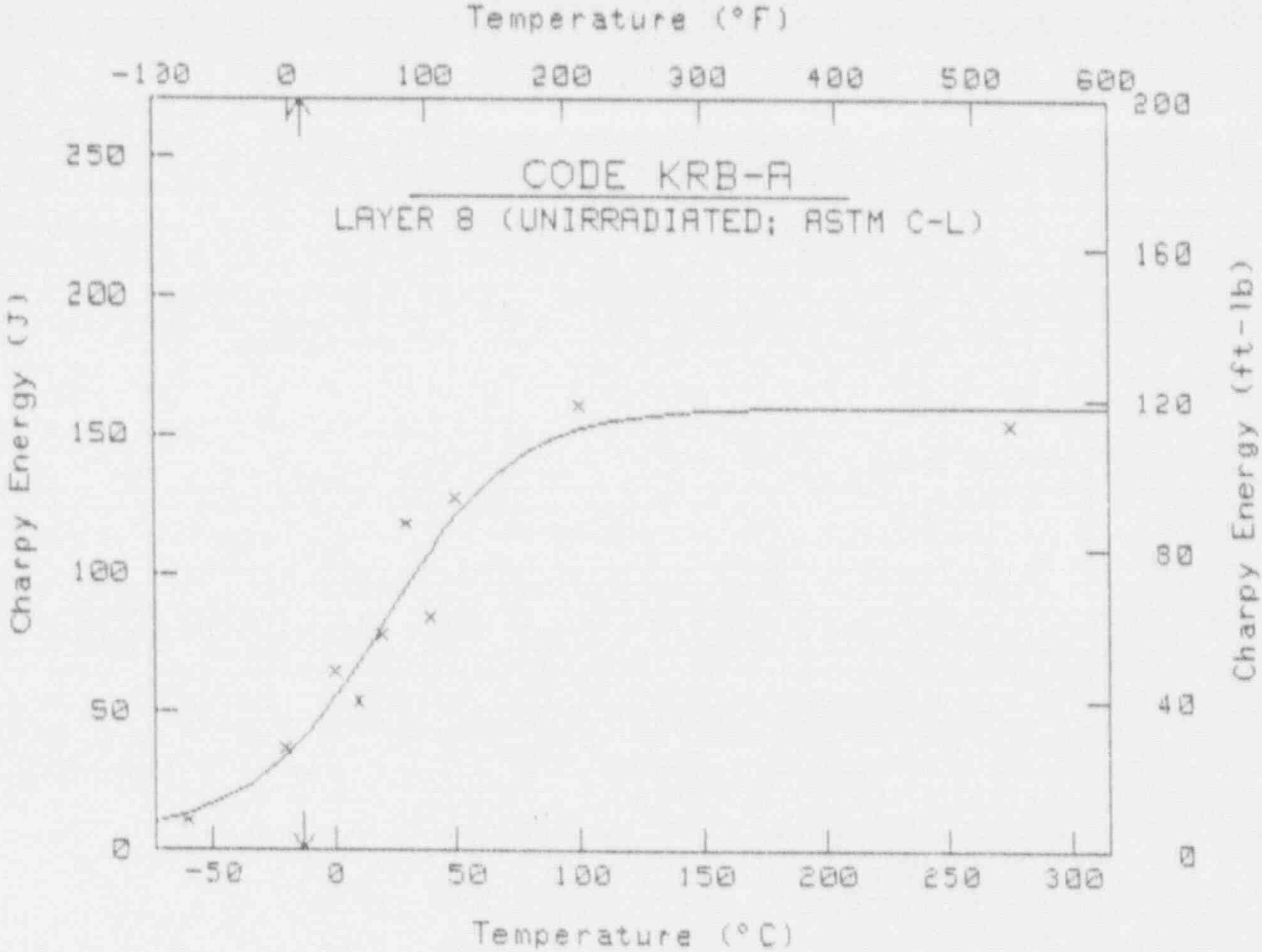
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	39.94 ft-lb	54.15 J
B =	43.83 ft-lb	59.43 J
C =	103.71 °F	57.62 °C
To =	2.14 °F	-16.59 °C
Cv = 30 ft-lb (41 J) at T =	-21.8 °F	-29.9 °C
Upper Shelf Energy =	83.8 ft-lb	113.6 J

****

PT #		Temp (°F)	Energy (ft-lb)
1		-60	23.5
2		-20	32.2
3		-10	31.0
4		30	46.0
5		65	63.5
6		75	73.0
7		240	80.0
8		240	84.0
9	0	-105	5.0
10	0	-105	5.0
11	0	-105	5.0
12	0	-105	5.0

0 = Fictitious Point Added * = Test Point Not Included



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

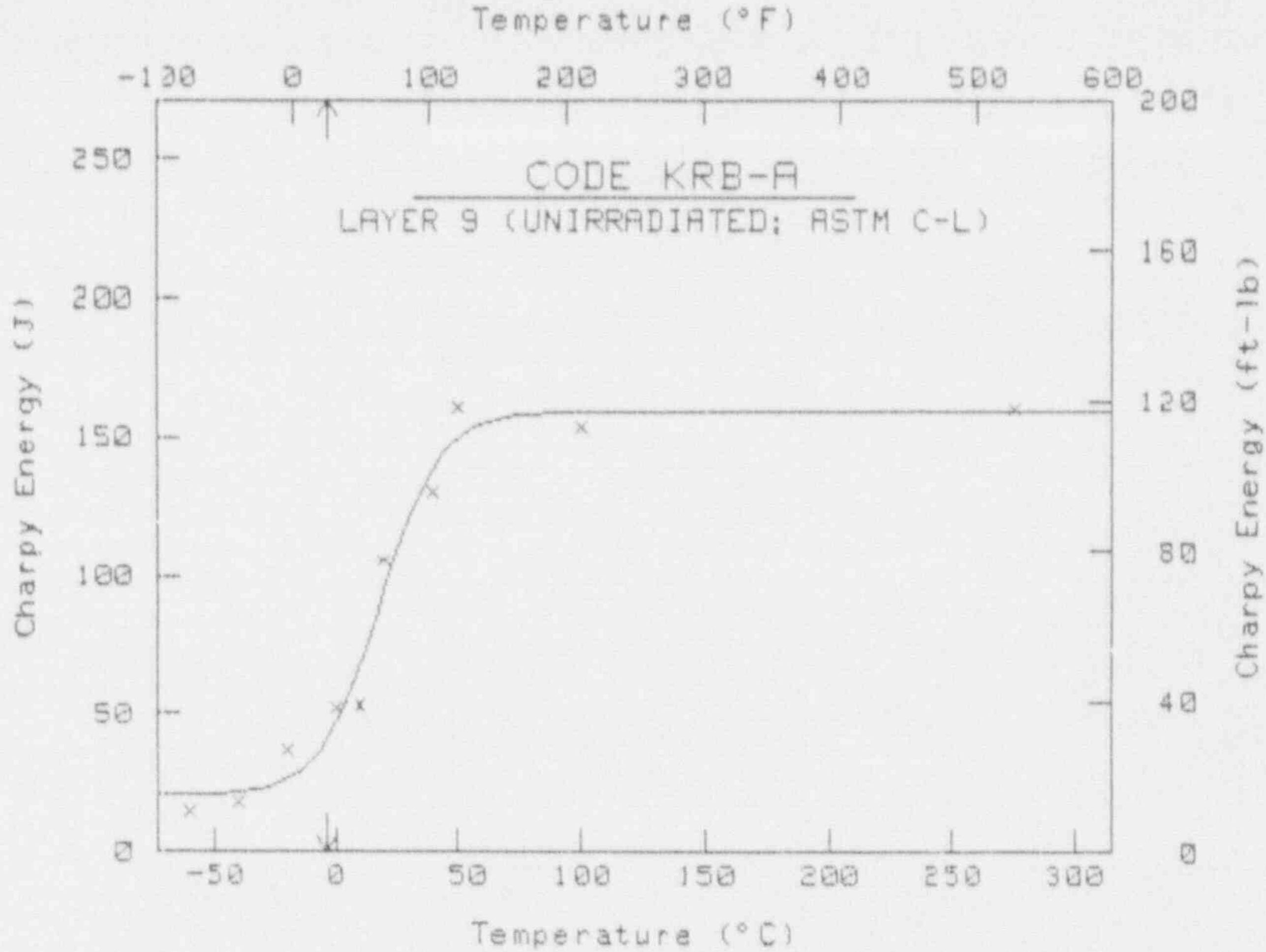
	English	Metric
A =	61.01 ft-lb	82.71 J
B =	56.90 ft-lb	77.15 J
C =	98.33 °F	54.63 °C
To =	69.31 °F	20.73 °C

Cv = 30 ft-lb (41 J) at T =	9.2 °F	-12.7 °C
Upper Shelf Energy =	117.9 ft-lb	159.9 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-76	7.7
2	-4	27.3
3	32	47.6
4	50	39.8
5	68	57.9
6	86	87.0
7	104	62.0
8	122	94.0
9	212	118.4
10	527	113.3

0 = Fictitious Point Added   * = Test Point Not Included



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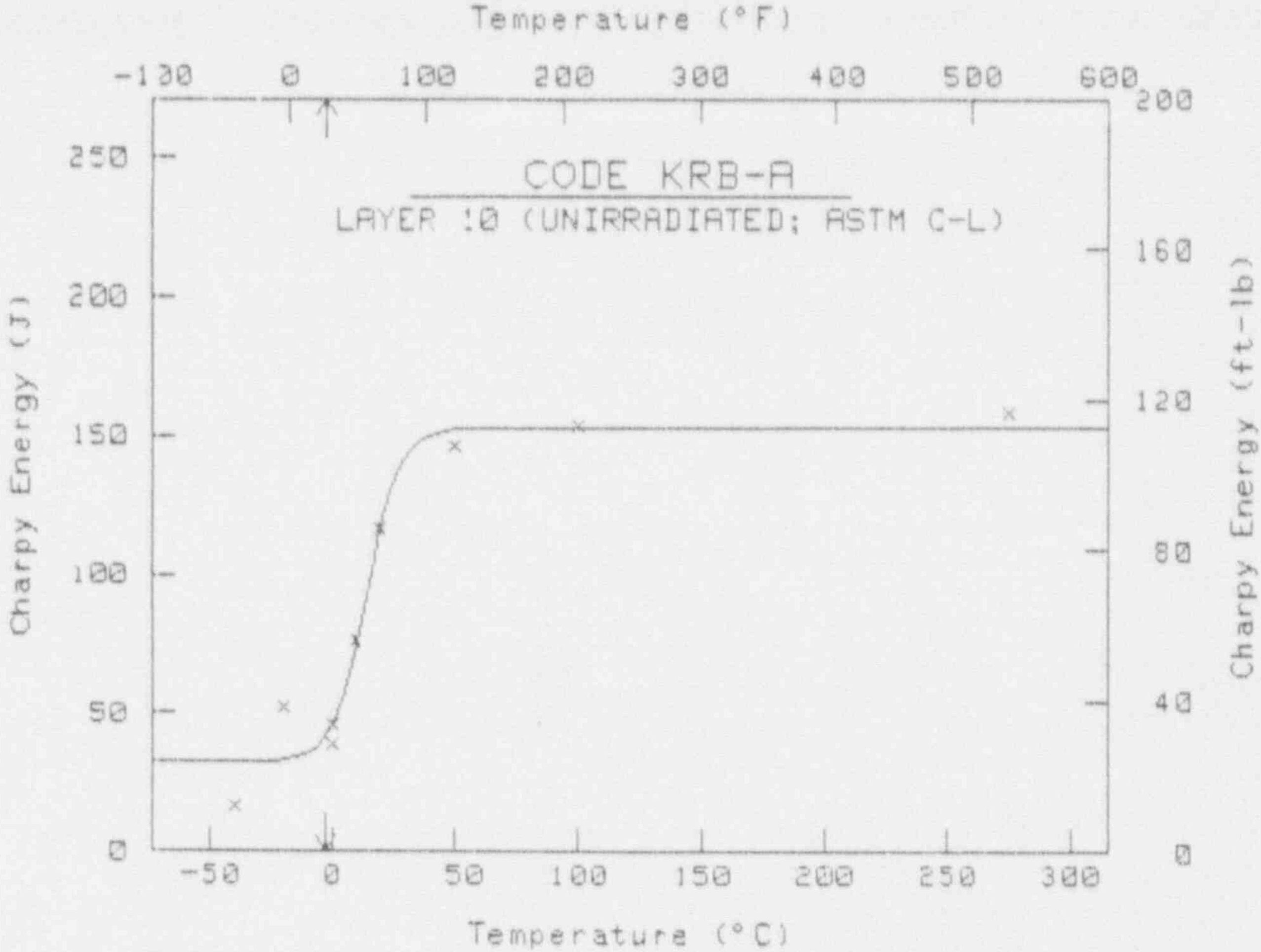
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	66.09 ft-lb	89.60 J
B =	51.12 ft-lb	69.30 J
C =	44.39 °F	24.66 °C
To =	64.25 °F	17.92 °C
Cv = 30 ft-lb (41 J) at T =	25.2 °F	-3.8 °C
Upper Shelf Energy =	117.2 ft-lb	158.9 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-76	10.7
2	-40	13.6
3	-4	27.3
4	32	38.7
5	50	39.1
6	68	77.8
7	104	95.9
8	122	118.5
9	212	112.9
10	527	118.0

0 = Fictitious Point Added   * = Test Point Not Included



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

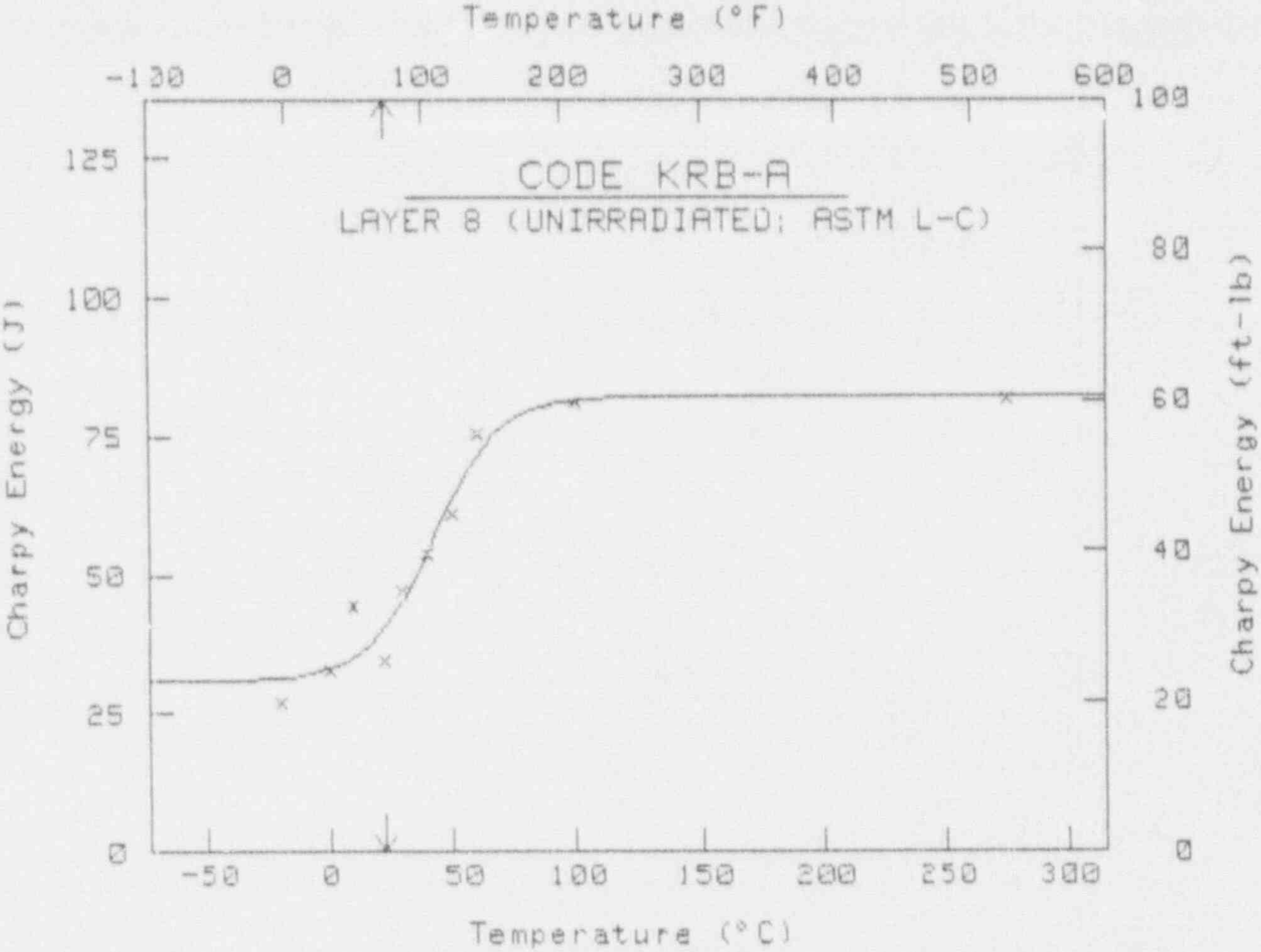
	English	Metric
A =	68.21 ft-lb	92.46 J
B =	44.30 ft-lb	60.06 J
C =	23.66 °F	13.14 °C
To =	57.56 °F	14.20 °C

Cv = 30 ft-lb (41 J) at T =	26.7 °F	-2.9 °C
Upper Shelf Energy =	112.5 ft-lb	152.5 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	12.2
2	-4	38.7
3	32	28.4
4	32	33.9
5	50	56.1
6	68	86.3
7	122	107.7
8	212	112.9
9	527	116.5

0 = Fictitious Point Added   * = Test Point Not Included



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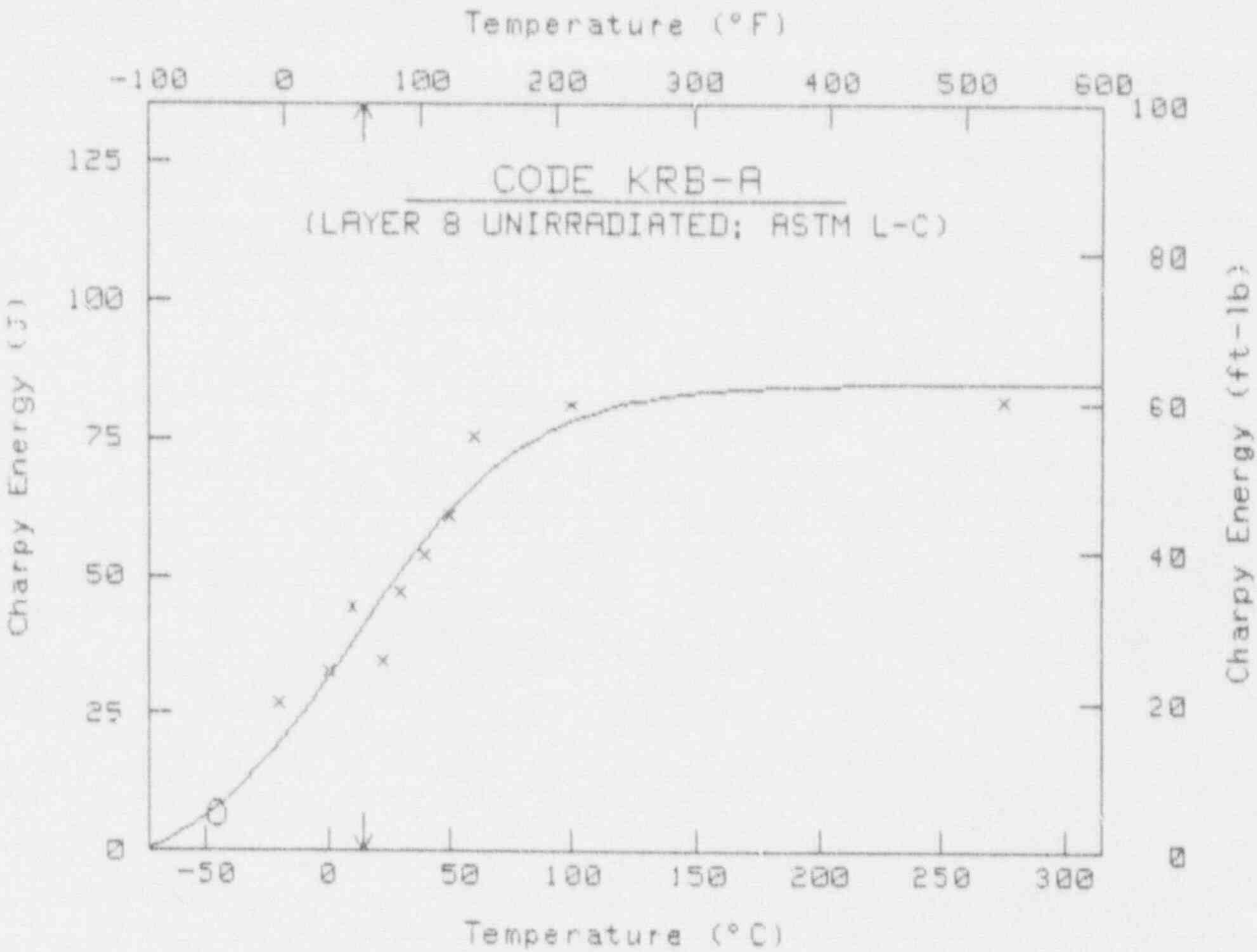
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	41.74 ft-lb	56.59 J
B =	18.86 ft-lb	25.58 J
C =	47.66 °F	26.48 °C
To =	108.10 °F	42.28 °C
Cv = 30 ft-lb (41 J) at T =	73.4 °F	23.0 °C
Upper Shelf Energy =	60.6 ft-lb	82.2 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-4	19.9
2	32	24.3
3	50	32.8
4	72	25.4
5	86	34.7
6	104	39.8
7	122	45.0
8	140	55.7
9	212	59.7
10	527	60.1

0 = Fictitious Point Added   * = Test Point Not Included



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

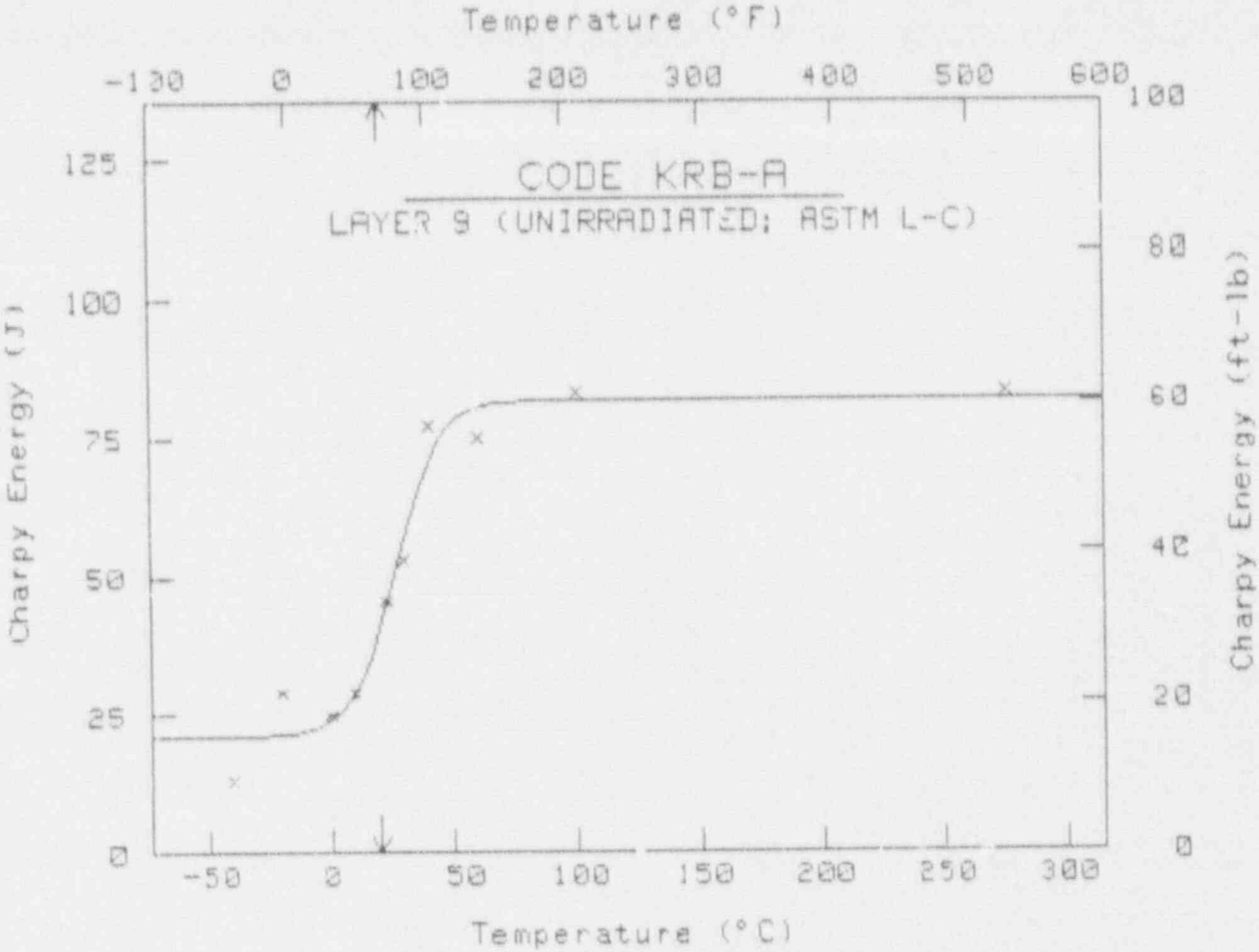
		English	Metric
A	=	28.64 ft-lb	38.83 J
B	=	33.95 ft-lb	46.03 J
C	=	126.16 °F	70.09 °C
To	=	52.29 °F	11.27 °C

Cv = 30 ft-lb (41 J) at T	=	57.3 °F	14.1 °C
Upper Shelf Energy	=	62.6 ft-lb	84.9 J

****

PT #		Temp (°F)	Energy (ft-lb)
1		-4	19.9
2		32	24.3
3		50	32.8
4		72	25.4
5		86	34.7
6		104	39.8
7		122	45.0
8		140	55.7
9		212	59.7
10		527	60.1
11	O	-50	5.0
12	O	-50	5.0
13	O	-50	5.0
14	O	-50	5.0

O = Fictitious Point Added * = Test Point Not Included



****

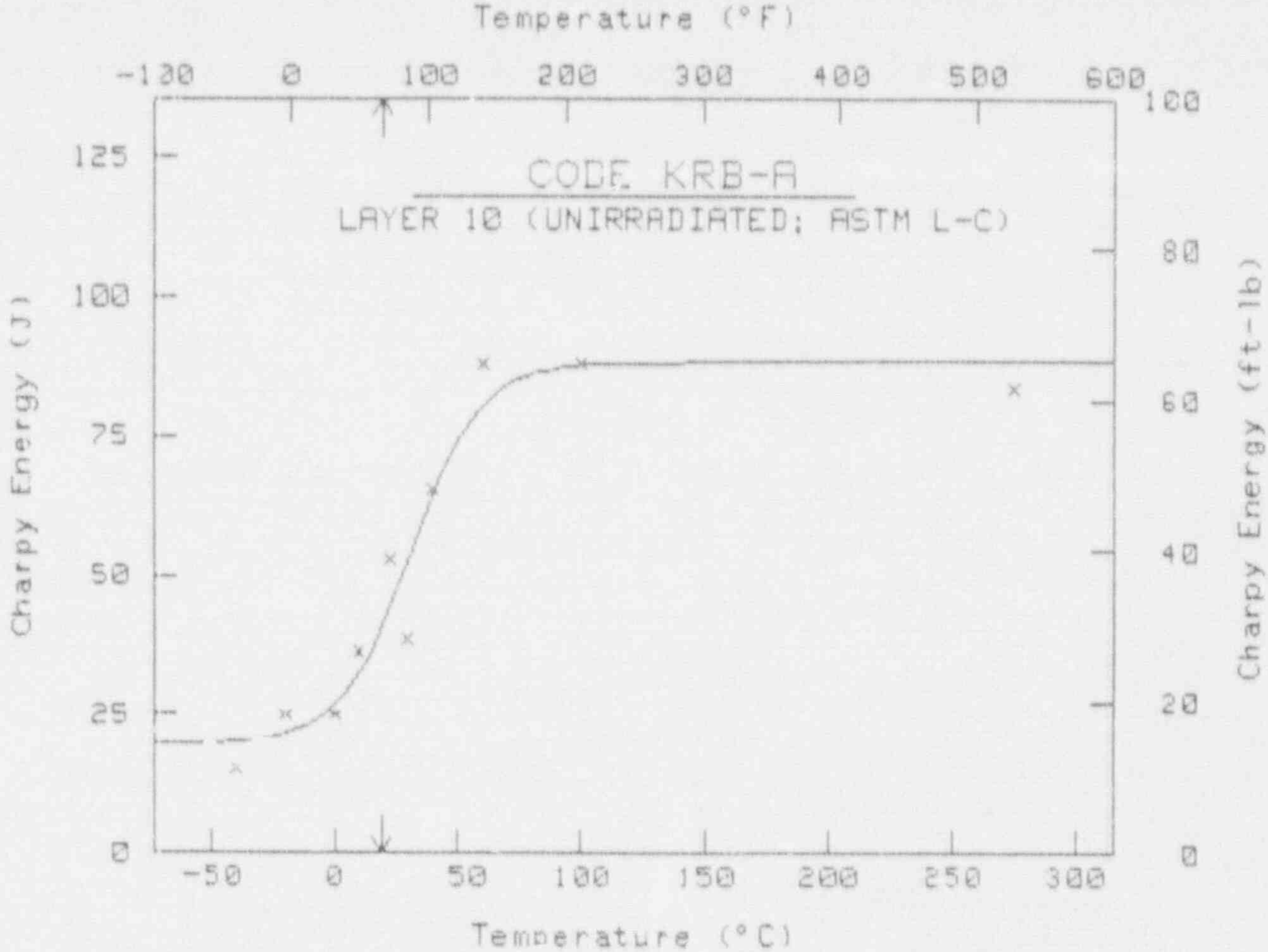
$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	37.93 ft-lb	51.42 J
B =	22.28 ft-lb	30.20 J
C =	31.16 °F	17.31 °C
To =	79.55 °F	26.42 °C
Cv = 30 ft-lb (41 J) at T =	68.0 °F	20.0 °C
Upper Shelf Energy =	60.2 ft-lb	81.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	9.6
2	-4	21.4
3	32	18.4
4	50	21.4
5	72	33.6
6	86	39.1
7	104	56.8
8	140	55.3
9	212	61.2
10	527	61.2

0 = Fictitious Point Added * = Test Point Not Included



****

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

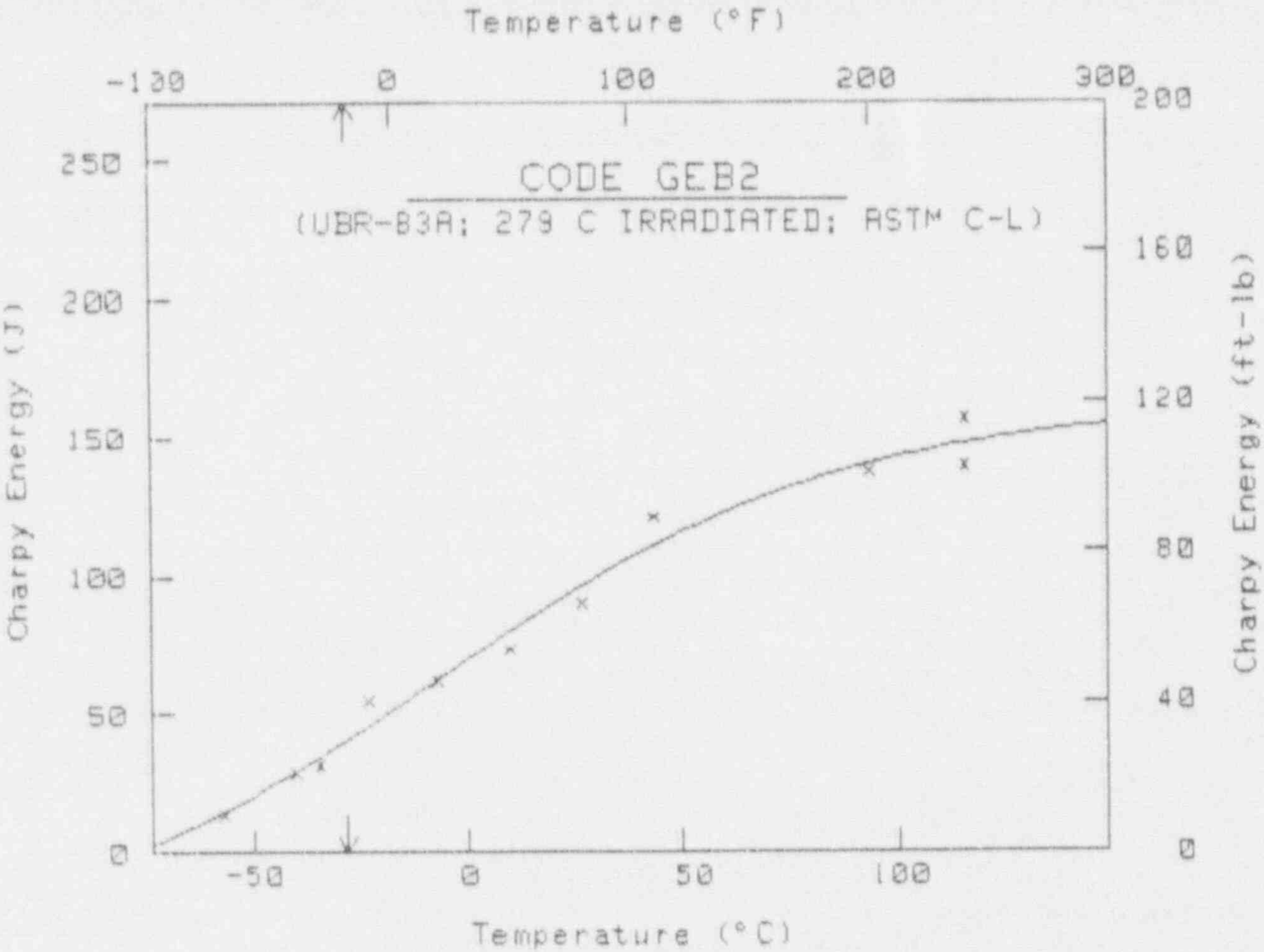
		English	Metric
A	=	39.77 ft-lb	53.93 J
B	=	25.[illegible] ft-lb	34.23 J
C	=	51.[illegible] °F	28.44 °C
To	=	87.56 °F	30.87 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	66.7 °F	19.3 °C
Upper Shelf Energy =	65.0 ft-lb	88.2 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	11.4
2	-4	18.4
3	32	18.4
4	50	26.9
5	72	39.1
6	86	28.4
7	104	48.3
8	140	64.9
9	212	64.9
10	527	61.6

0 = Fictitious Point Added   * = Test Point Not Included



****

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

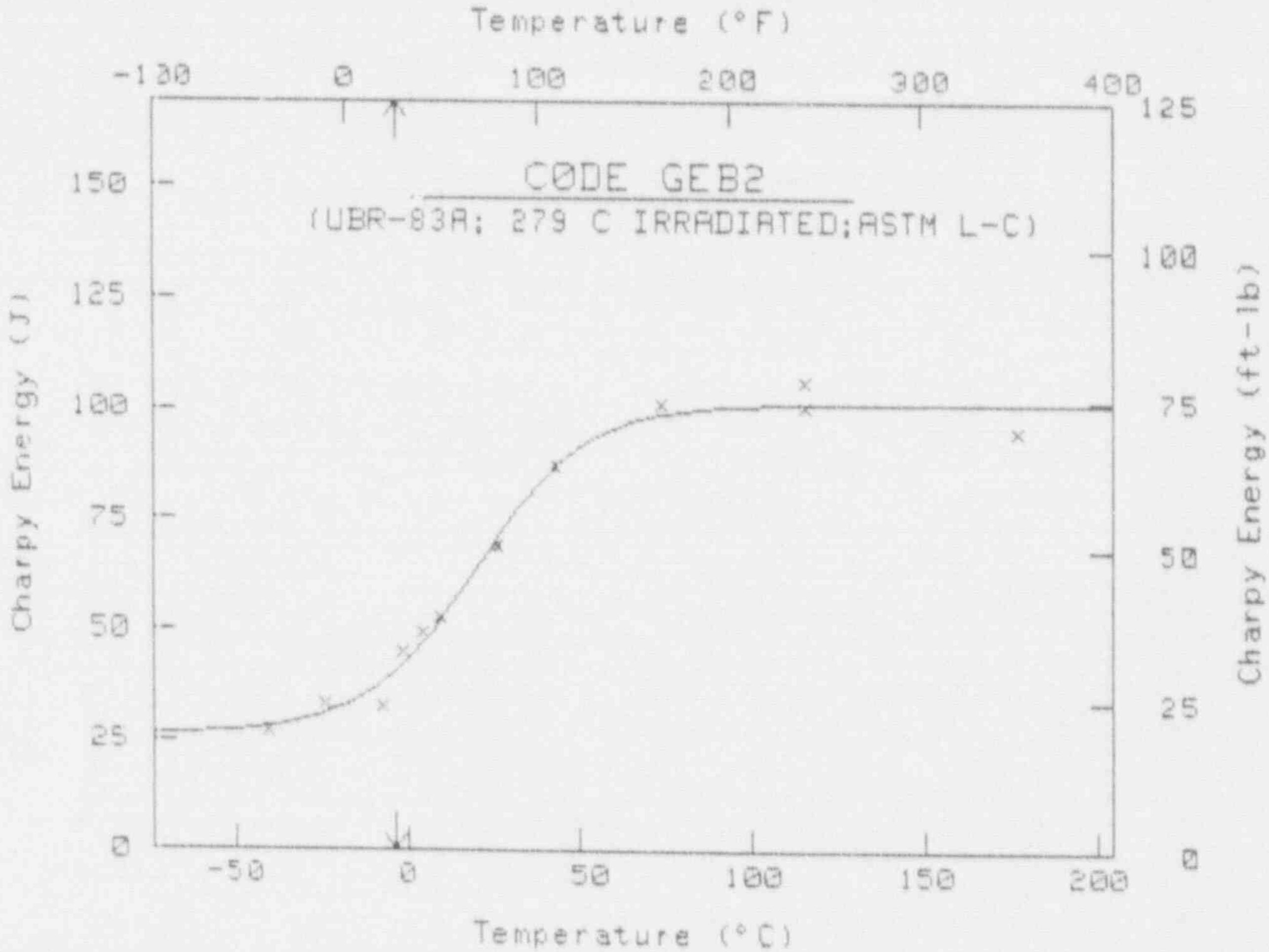
	English	Metric
A =	45.85 ft-lb	62.17 J
B =	72.92 ft-lb	98.87 J
C =	170.27 °F	94.60 °C
To =	19.03 °F	-7.20 °C

Cv = 30 ft-lb (41 J) at T =	-18.6 °F	-28.1 °C
Upper Shelf Energy =	118.8 ft-lb	161.0 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-70	10.0
2	-40	21.5
3	-30	23.0
4	-10	40.5
5	20	46.0
6	50	54.0
7	80	66.5
8	110	89.0
9	200	101.5
10	240	115.0
11	240	102.5

0 = Fictitious Point Added   * = Test Point Not Included

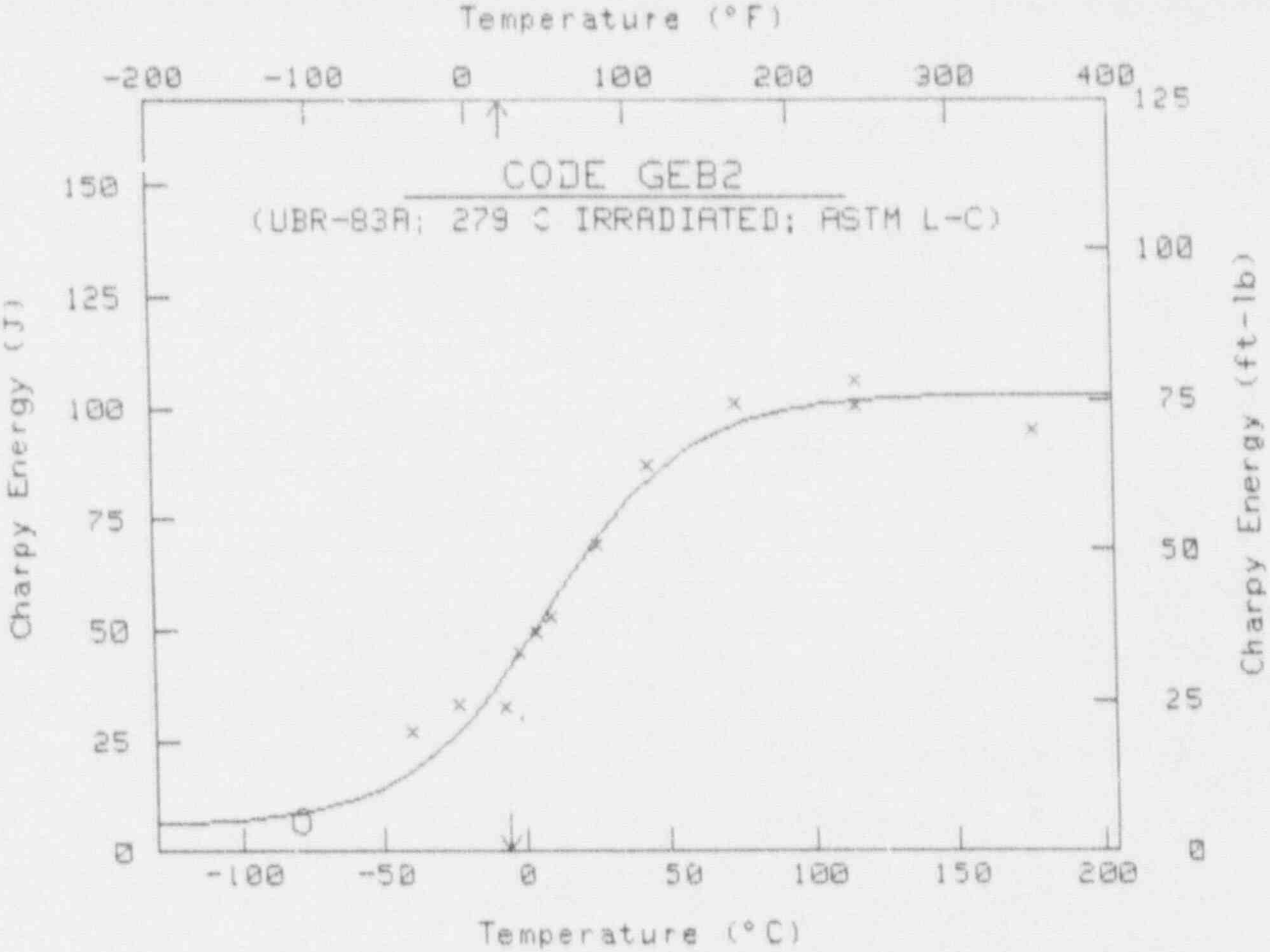


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	46.91 ft-lb	63.60 J
B =	27.64 ft-lb	37.47 J
C =	58.29 °F	32.38 °C
To =	67.95 °F	19.97 °C
Cv = 30 ft-lb (41 J) at T =	26.5 °F	-3.1 °C
Upper Shelf Energy =	74.5 ft-lb	101.1 J

PT #	Temp (°F)	Energy (ft-lb)
1	-40	20.0
2	-10	24.5
3	20	24.0
4	30	33.0
5	40	36.5
6	50	39.0
7	80	51.0
8	110	64.6
9	165	74.5
10	240	74.0
11	240	78.0
12	350	70.0

0 = Fictitious Point Added   * = Test Point Not Included



****

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

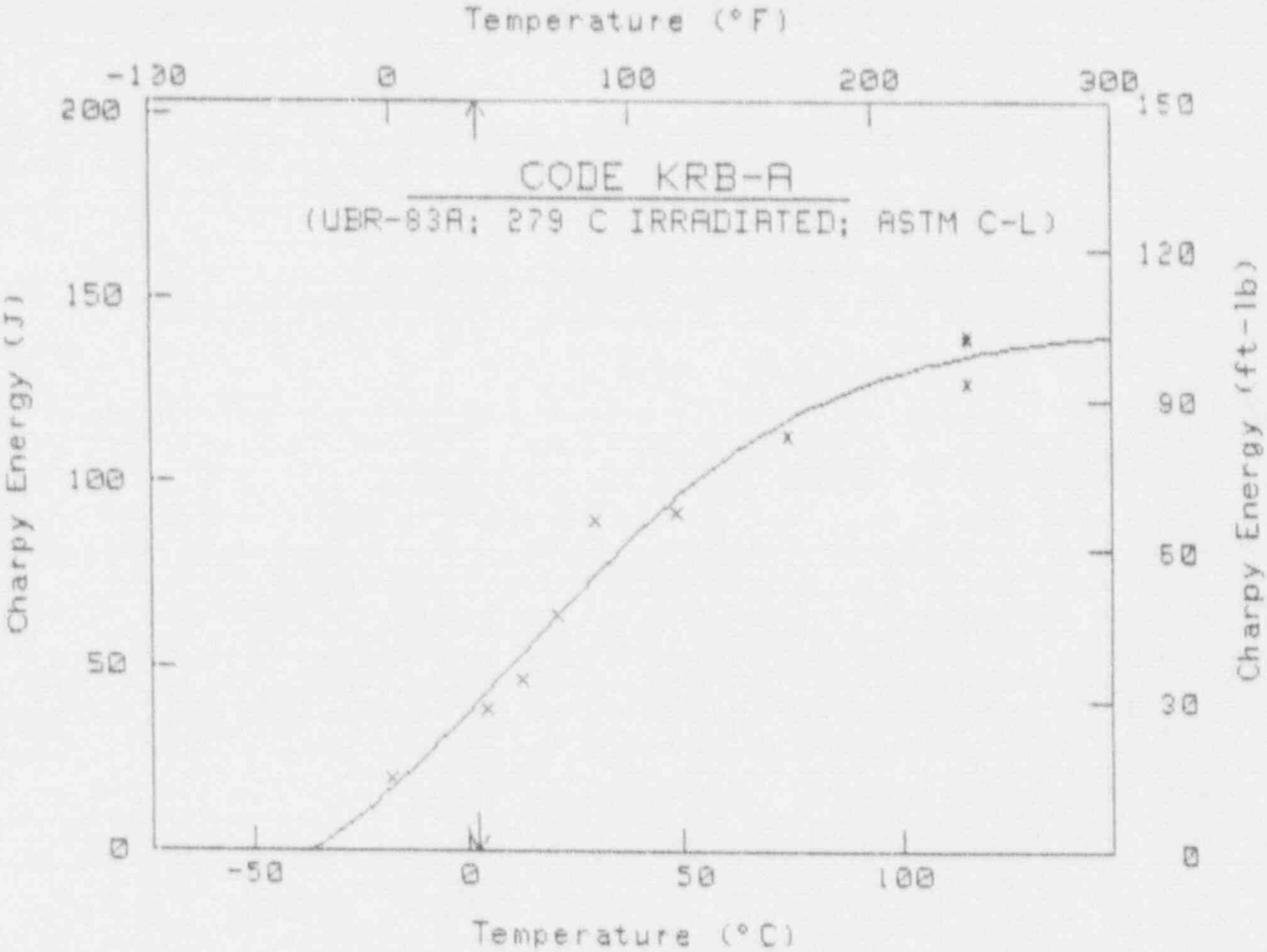
	English	Metric
A =	40.03 ft-lb	54.27 J
B =	35.83 ft-lb	48.58 J
C =	90.99 °F	50.55 °C
To =	47.88 °F	8.82 °C

Cv = 30 ft-lb (41 J) at T =	21.7 °F	-5.7 °C
Upper Shelf Energy =	75.9 ft-lb	102.9 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-40	20.0	9	165	74.5
2	-10	24.5	10	240	74.0
3	20	24.0	11	240	78.0
4	30	33.0	12	350	70.0
5	40	36.5	13 O	-110	5.0
6	50	39.0	14 O	-110	5.0
7	80	51.0	15 O	-110	5.0
8	110	64.0	16 O	-110	5.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

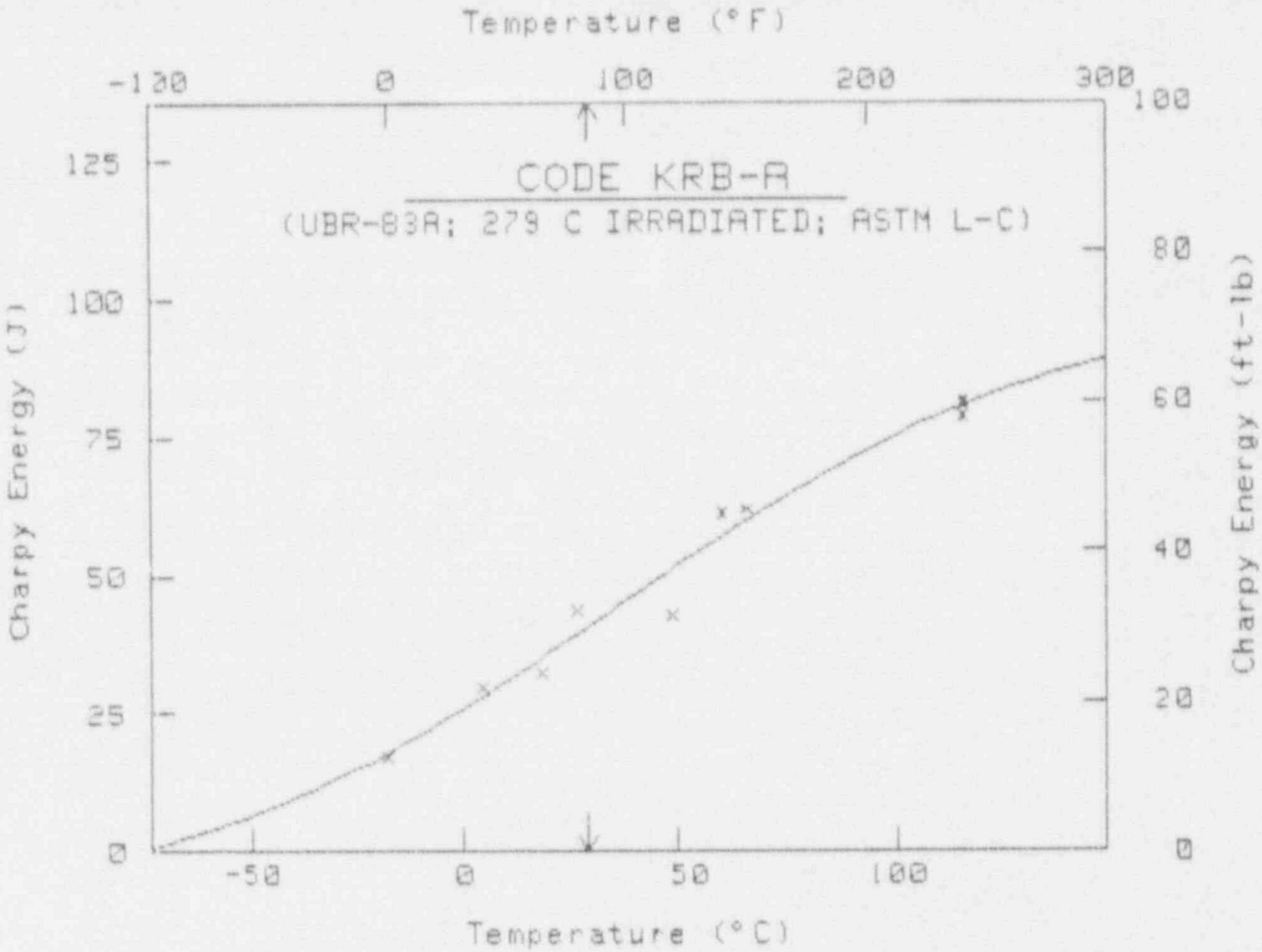
		English	Metric
A	=	40.19 ft-lb	54.49 J
B	=	65.09 ft-lb	88.25 J
C	=	124.57 °F	69.21 °C
To	=	56.38 °F	13.54 °C

Cv = 30 ft-lb (41 J) at T	=	36.7 °F	2.6 °C
Upper Shelf Energy	=	105.3 ft-lb	142.7 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	0	14.5
2	40	28.5
3	55	34.5
4	70	47.0
5	85	66.0
6	120	67.5
7	165	83.0
8	240	93.5
9	240	102.5
10	240	102.0

O = Fictitious Point Added * = Test Point Not Included



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

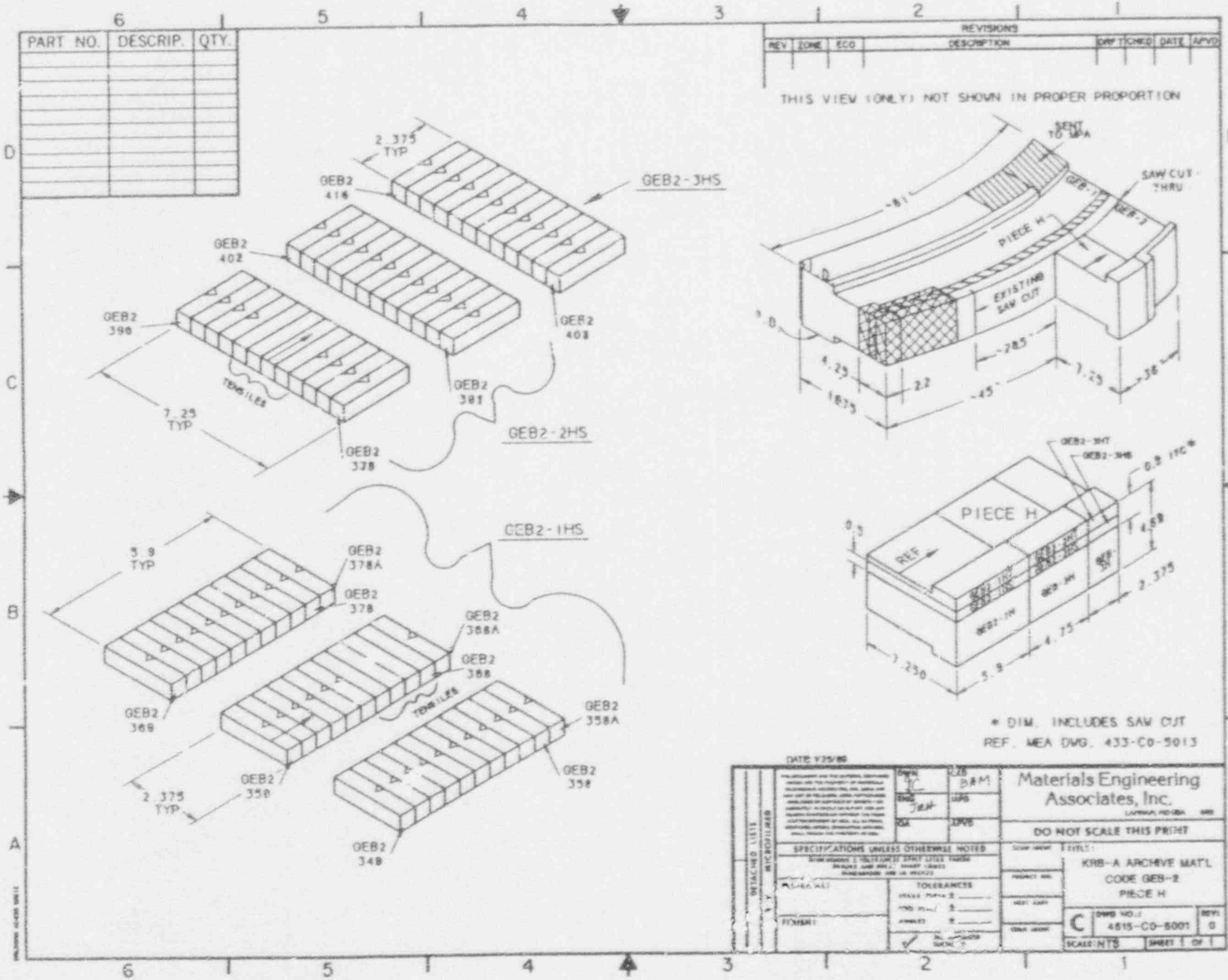
	English	Metric
A =	32.84 ft-lb	44.53 J
B =	41.36 ft-lb	56.07 J
C =	188.17 °F	104.54 °C
To =	97.64 °F	36.47 °C

Cv = 30 ft-lb (41 J) at T =	84.7 °F	29.3 °C
Upper Shelf Energy =	74.2 ft-lb	100.6 J

PT #	Temp (°F)	Energy (ft-lb)
1	0	12.5
2	40	22.0
3	65	24.0
4	80	32.0
5	120	31.5
6	140	45.0
7	150	45.5
8	240	58.0
9	240	60.0
10	240	59.5

O = Fictitious Point Added   * = Test Point Not Included

Specimen Locations in Archive GEB-2 Material



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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Initial mechanical properties tests of beltline material trepanned from the decommissioned KRB-A pressure vessel and archive material irradiated in the UBR test reactor revealed a major anomaly in relative radiation embrittlement sensitivity. Poor correspondence of material behavior in test vs. power reactor environments was observed for the weak test orientation (ASTM L-C) whereas correspondence was good for the strong orientation (ASTM C-L). To resolve the anomaly directly, Charpy-V specimens from a low (essentially-nil) fluence region of the vessel were irradiated together with archive material at 279°C in the UBR test reactor.

Properties tests before UBR irradiation revealed a significant difference in 41-J transition temperature and upper shelf energy level between the materials. However, the materials exhibited essentially the same radiation embrittlement sensitivity (both orientations), proving that the anomaly is not due to a basic difference in material irradiation resistances. Possible causes of the original anomaly and the significance to NRC Regulatory Guide 1.99 are discussed.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Charpy V-notch, Fluence-Rate Effects, Nuclear Reactors, Pressure Vessels, Radiation Embrittlement, Steel

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