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Correlation of Irradiation-Induced Transition Temperature Increases from C_v and K_{Jc}/K_{Ic} Data

Final Report

Prepared by A. L. Hiser

Materials Engineering Associates, Inc.

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Reactor pressure vessel (RPV) surveillance capsules contain Charpy-V (C_v) specimens, but many do not contain fracture toughness specimens; accordingly, the radiation-induced shift (increase) in the brittle-to-ductile transition region (ΔT) is based upon the ΔT determined from notch ductility (C_v) tests. Since the ASME K_{Ic} and K_{IR} reference fracture toughness curves are shifted by the ΔT from C_v, assurance that this ΔT does not underestimate ΔT associated with the actual irradiated fracture toughness is required to provide confidence that safety margins do not fall below assumed levels.

To assess this behavior, comparisons of ΔT's defined by elastic-plastic fracture toughness and C_v tests have been made using data from RPV base and weld metals in which irradiations were made under test reactor conditions. Using "as-measure" fracture toughness values (K_{Jc}), average comparisons between $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ are:

(a) All data: $\Delta T(K_{Jc}$ @ $100\ MPa\sqrt{m}) - \Delta T(C_v$ @ $41\ J) +10°C$

(b) Plates only: $\Delta T(K_{Jc}$ @ $100\ MPa\sqrt{m}) - \Delta T(C_v$ @ $41\ J) +15°C$

(c) Welds only: $\Delta T(K_{Jc}$ @ $100\ MPa\sqrt{m}) - \Delta T(C_v$ @ $41\ J) -1°C$

Fluence rate is found to have no significant effect on the relationship between $\Delta T(C_v)$ and $\Delta T(K_{Jc})$.

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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.

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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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1. INTRODUCTION

A previous report (Ref. 1) investigated the relationship between the irradiation-induced transition temperature increase (ΔT) found with Charpy-V (C_v) impact data and that found with fracture toughness data. Reference 1 used data available at that time as an initial assessment of the suitability of using ΔT from C_v data to estimate that from fracture toughness data. Among the initial conclusions in Ref. 1 was a finding that the ΔT from C_v tended to yield reasonable estimates of the ΔT from fracture toughness data for weld metals, such as Linde 80 welds. In contrast, the ΔT from C_v tended to underestimate the ΔT from fracture toughness for base materials, such as plate and forging materials. This report provides a more complete assessment of the relationship between the two measures of ΔT, primarily by adding to the data bank that was used in Ref. 1.

Assessing the suitability of ΔT from C_v data as an estimate of that from fracture toughness data is important to assure that non-conservative estimates of the fracture toughness of irradiated reactor pressure vessel (RPV) steels are not made. The K_{IR} (reference stress intensity factor) curve in Appendix G of Section III of the ASME Code is used as a lower bound estimate of the fracture toughness of RPV steels. This curve, and its companion the K_{Ic} curve in Appendix A of Section XI of the ASME Code, is indexed by the reference temperature or RT_{NDT} of the subject material. RT_{NDT} is defined in the ASME code as the greater of T_{NDT} (the nil-ductility transition temperature of drop-weight tests) and T_{Cv}-60°F, where T_{Cv} is either the index at which each C_v test (of three) "shall exhibit at least 35 mils lateral expansion and not less than 50 ft-lb absorbed energy" or the temperature at which the lower bound C_v curve exhibits 50 ft-lb and 35 mils. To account for irradiation effects, Appendix G of 10CFR50 (Title 10, Part 50 of the Code of Federal Regulations) states that "adjusted reference temperature" means the reference temperature as adjusted for irradiation effects by adding to RT_{NDT} the temperature shift (ΔT), measured at the 30-ft-lb (41-J) level, in the average Charpy curve for the irradiated material relative to that for the unirradiated material.

For calculation of pressure-temperature (P-T) curves, Appendix G of the 10 CFR 50 assumes that the K_{Ic} curve of the irradiated material is defined by shifting the K_{IR} curve as indexed by the "adjusted reference temperature" mentioned above. (For accident analyses, the K_{Ic} curve in Appendix A of Section XI of the ASME Code is used as the reference curve which is indexed at the "adjusted reference temperature.") Since the K_{IR} and the K_{Ic} curves are lower bound curves, a determination that the ΔT from C_v data is a reasonable estimate of the ΔT from fracture toughness data would give justifiable confidence that non-conservative estimates of fracture toughness for the case of irradiated RPV steels does not occur.

2. MATERIALS

The materials used in this study have been characterized over several years, initially at the Naval Research Laboratory (NRL), and more recently at MEA (Ref. 2 to 8). Included in the study are an A 508 and a 20NiMoCr26 forging, several heats of A 533-B and A 302-B plate, and submerged-arc welds made with Linde 80, Linde 0091 and Linde 124 fluxes. A listing of the chemical composition for the subject heats is given in Table 1. All of the irradiations were conducted in test reactors, under accelerated fluence rate conditions, at a nominal temperature of 288°C, although a data set for the 20NiMoCr26 forging (GEB), specifically UBR-79 was irradiated at 275°C. Several different fluence rates were used, as classified by the broad categories of "high" ($7\text{-}9 \times 10^{12}$ $n/cm^2\text{-}s^{-1}$), "low" (8×10^{10} $n/cm^2\text{-}s^{-1}$) and "intermediate" ($2\text{-}8 \times 10^{11}$ $n/cm^2\text{-}s^{-1}$).

3. DATA ANALYSIS PROCEDURES

3.1 Notch Ductility (C_v)

Notch ductility was determined using Charpy-V impact specimens. The Charpy-V energy (C_vE) data for each heat and condition (irradiated or unirradiated) were fit to a hyperbolic tangent function:

$$C_vE = A_0 + A_1 \tanh \left[\frac{T - T_0}{A_2} \right] \quad (1)$$

where A_0, A_1, A_2 and T_0 are determined through a nonlinear regression analysis. Both shelf (upper and lower) and transition data were included in the same fit to Eq. 1, as opposed to using only transition data for a transition region fit, etc. Since few data were determined in a lower shelf region, some of the fits drop to negative C_v levels at low temperatures. A non-negative lower shelf was not forced, since the purpose for using the chosen equation was to model the data and not to force the data to a model. (The "negative" C_v levels given by some of these fits do not have any impact on the results used here.) A nonsloping upper shelf fit was used since justification for a sloping upper shelf was generally not evident for cases in which sufficient characterization of the upper shelf trends was available.

Once a given set of data had been fit to Eq. 1, the upper shelf level and the transition temperatures at any C_v index can be determined from:

$$\text{Upper Shelf Energy (USE)} = A_0 + A_1 \quad (2)$$

$$T_{Index} = T_0 + A_2 \tanh^{-1} \left[\frac{C_vE_{Index} - A_0}{A_1} \right] \quad (3)$$

where C_vE_{Index} was selected as 41 J (30 ft-lb per Appendix G of 10CFR50).

Table 1 Chemical Compositions of the Subject Heats (Wt. %)

Material	Code	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V	As	Sn	N	B
A 508-2 Forging	BCB[c]	0.212	0.63	0.006	0.012	0.26	0.38	0.55	0.62	0.036	0.002	0.004	0.011	0.013	0.0002
20NiMoCr26[d] Forging	GEB[d,e]	0.24	0.71	0.96	0.017	0.22	0.37	0.78	0.66	0.15	0.031	0.022	0.021	a	a
A 533-B Plate	CAB[c]	0.25	1.41	0.008	0.014	0.26	0.11	0.46	0.49	0.12	0.003	0.012	0.008	0.008	0.0007
	CBB[c]	0.21	1.45	0.006	0.009	0.23	0.05	0.55	0.64	0.013	0.003	0.035	0.015	0.014	0.0004
	3P[f]	0.20	1.26	0.011	0.018	0.25	0.10	0.56	0.45	0.12	a	a	a	a	a
	02G[g]	0.23	1.55	0.009	0.014	0.20	0.04	0.67	0.53	0.16	0.003	a	a	a	a
	67C[h]	0.23	1.31	0.025	0.018	0.20	< 0.003	0.70	0.51	0.002	a	a	< 0.004	0.009	0.0004
	68A[h]	0.23	1.31	0.003	0.017	0.22	< 0.003	0.70	0.52	0.30	a	a	0.004	0.010	0.0006
	68C[h]	0.23	1.31	0.028	0.017	0.22	< 0.003	0.70	0.52	0.30	a	a	0.004	0.010	0.0006
	23G[i]	0.22	1.40	0.017	0.008	0.19	0.19	0.63	0.54	0.20	a	a	a	a	a
A 302-B Plate	N[c]/F23[c,f]/23F[i]	0.24	1.34	0.011	0.023	0.23	0.11	0.18	0.51	0.20	0.001	a	0.037	0.008	0.0001
	6A2[h]	0.23	1.29	0.002	0.013	0.22	a	0.045	0.53	0.28	a	a	0.004	a	a
Welds (Linde 80 φ)	E19[c]	0.12	1.37	0.007	0.013	0.53	0.04	0.59	0.44	0.43	a	a	0.01	0.011	0.01
	E23[c]	0.11	1.36	0.008	0.013	0.52	0.04	0.60	0.44	0.24	a	a	0.01	0.013	0.01
	71W[g]	0.124	1.58	0.011	0.011	0.54	0.12	0.63	0.45	0.046	0.005	a	a	a	a
	W8A[i,j]	0.083	1.33	0.011	0.016	0.77	0.12	0.59	0.47	0.39	0.003	0.061	0.002	a	0.000
(Linde 0091 φ)	E24[c]	0.16	1.25	0.005	0.009	0.17	0.04	0.59	0.44	0.37	a	a	0.01	0.011	0.01
	68W[g]	0.15	1.38	0.008	0.009	0.16	0.04	0.13	0.60	0.04	0.007	a	a	a	a
	69W[g]	0.14	1.19	0.010	0.009	0.19	0.09	0.10	0.54	0.12	0.005	a	a	a	a
	W9A[i,j]	0.19	1.24	0.010	0.008	0.23	0.10	0.70	0.49	0.39	a	a	0.003	a	a
(Linde 124 φ)	70W[g]	0.10	1.48	0.011	0.011	0.44	0.13	0.63	0.47	0.056	0.004	a	a	a	a
	E4[c]	0.08	1.38	0.013	0.018	0.49	0.10	0.65	0.44	0.16	0.005	0.008	0.004	a	0.001

[a] Not determined [b] Not available [c] Ref. 2 [d] Similar to A 336 [e] Ref. 7 [f] Ref. 3 [g] Ref. 4 [h] Ref. 5 [i] Ref. 6 [j] Ref. 8

3.2 Fracture Toughness (K_{Jc})

The fracture toughness data of interest here are only those within the brittle-to-ductile transition region. Data with stable crack growth of more than 0.15 mm are generally not included.

The static fracture toughness data were determined using compact toughness (CT) specimens. These specimens were full thickness 1T- and 0.5T-CT designs, with several differences from the standard ASTM E 399 design. The major difference was in enlargement of the notch region to permit placement of razor blades on the "load line" for mounting of a displacement transducer. The enlargement of the notch forced an increased spacing of the pin holes and in some cases a reduction in the pin hole diameter. The pin hole changes were required to maintain sufficient ligaments above and below the holes to prevent bending or bulging of the ligaments.

Because of the small specimen size forced by the constraints of the test reactor irradiation facility, the maximum K_{Ic} levels which could be obtained by ASTM E 399 were below 50 MPa$\sqrt{m}$ (~ 45 ksi$\sqrt{in.}$), much too low to provide a meaningful result. For cases in which only a K_Q number was obtainable, the J integral, an elastic-plastic fracture parameter, was used for data analysis. Specifically, the J value at test termination was taken to be J_{Crit}, since by definition that was the J value at the initiation of "crack growth," albeit fast cleavage fracture. A K_{Jc} value was then calculated from:

$$K_{Jc} = \sqrt{EJ_{Crit} / (1 - \nu^2)} \qquad (4)$$

where E is Young's modulus at the test temperature, and ν is Poisson's ratio, taken as 0.3 for all of these data. For cases in which a K_{Ic} value could be determined from the test record, the K_{Jc} value from Eq. 4 (with $\nu = 0.3$) matched the K_{Ic} value within 5%.

As with the C_v data, the K_{Jc} data were modeled with a mathematical expression, in this case an exponential function of the form:

$$K_{Jc} = B_0 + B_1 e^{(T/B_2)} \qquad (5)$$

where B_0, B_1, and B_2 are determined through a nonlinear regression analysis. Since the regression results were not restricted to $B_0 \geq 0$, in many cases the resultant curve will give negative K_{Jc} values at low temperatures.

The transition temperatures at various indices can be determined from Eq. 5 in the following form:

$$T_{Index} = B_2 \quad \ln \left[\frac{K_{Index} - B_0}{B_1} \right] \qquad (6)$$

with a K_{Index} value of 100 $MPa\sqrt{m}$ used. For comparisons with C_v data at 41 J (30 ft-lb), a K_{Index} value of 100 $MPa\sqrt{m}$ was used, based upon correlations from Rolfe and Novak (Ref. 9) and Sailors and Corten (Ref. 10). From Reference 9,

$$K_{Ic} = \sqrt{0.00022\ E}\quad (C_v)^{0.75} \tag{7}$$

and, with E = 206800 MPa and C_v = 41 J, then

$$K_{Ic} = 109\ MPa\sqrt{m}$$

From Reference 10,

$$K_{Ic} = 14.6\ (C_v)^{0.5} \tag{8}$$

and with C_v = 41 J,

$$K_{Ic} = 93\ MPa\sqrt{m}$$

The average of these two is ~ 100 $MPa\sqrt{m}$.

4. TEST METHOD COMPARISONS

The focus in this section is on the change in temperature (ΔT) at a specific index due to irradiation, as opposed to the absolute temperature at the index level. Comparisons between ΔT's from C_v and fracture toughness are based on product form (i.e., plate, forging or weld), with comparisons at a C_v level of 41 J and a fracture toughness level of 100 $MPa\sqrt{m}$. The first group of comparisons will look at all data from a given product form. Later comparisons will examine the various materials for which multiple data points are available, as compared to the overall data sets (weld or base metal as appropriate).

Data sheets for each of the C_v data sets are given in Appendix A with those for the fracture toughness data given in Appendix B. These sheets give the regression parameters from fit to Eq. 1 for C_v data and Eq. 5 for fracture toughness data. Also included on these sheets are a listing of the data used in the fit and a data plot comparing the regression fit to the data. In some cases extra data points (frequently upper shelf K_{Jc} data for fracture toughness data) were included in the fit, or anomalous points were excluded from the fit. These modifications to the data tended to result in modest (< 2°C) changes in the temperature at the appropriate index level. The regression parameters are given in Table 2 for C_v data and Table 3 for fracture toughness data.

Two of the data sets are considered anomalous at this time. The first set is for the A 508 Forging BCB. As described in Ref. 1, the data

Table 2 Curve-Fit Parameters for Charpy-V Data

	$C_v = A_o + A_1 \text{ TANH } [(T-T_o)/A_2]$				Temp. @ 41 J (°C)
	A_o (J)	A_1 (J)	A_2 (°C)	T_o (°C)	
<u>A 508-2 Forging (BCB)</u>					
Unirradiated	-114.88	314.71	101.59	-79.81	-24.8
Irrad. (BSR-6)	92.22	85.55	28.31	13.97	-5.8
<u>20NiMoCr26 Forging (GEB)</u>					
Unirradiated	58.83	49.52	48.24	-9.71	-28.3
Irrad. (UBR-68)	52.82	44.73	52.67	27.57	12.9
IA 399°C (UBR-68)	60.57	57.03	43.85	2.54	-13.4
IA 454°C (UBR-68)	63.59	53.02	40.42	-7.27	-26.0
Unirrad. (Check)	68.58	41.61	45.33	15.82	-21.0
Irrad. (UBR-78)	60.50	48.90	57.97	20.30	-4.6
Irrad. (UBR-79, 275°C)	52.70	54.92	67.60	35.03	20.0
<u>A 533-B Plate (CAB)</u>					
Unirradiated	63.06	72.01	65.10	23.13	2.2
Irrad. (BSR-2)	51.34	81.77	103.50	48.61	35.0
Irrad. (BSR-3)	73.69	57.88	49.09	94.54	62.7
Irrad. (BSR-5)	74.81	53.14	37.87	93.46	64.6
<u>A 533-B Plate (CBB)</u>					
Unirradiated	76.83	59.07	31.02	22.83	0.7
Irrad.	67.69	54.91	18.16	101.19	91.4
<u>A 533-B Plate (3P)</u>					
Unirradiated	76.51	73.36	57.86	31.33	0.4
Irrad. (SSC-1)	72.21	47.27	25.70	92.67	72.0
Irrad. (SSC-2)	61.84	46.50	40.03	103.91	84.2
Irrad. (Wall-1)	64.22	44.25	37.67	96.67	74.3
Irrad. (Wall-2)	57.85	54.43	55.62	81.78	63.6
Irrad. (Wall-3)	72.23	53.76	40.17	80.35	53.3
<u>A 533-B Plate (02G)</u>					
Unirradiated	74.95	65.46	45.15	29.48	3.2
Irrad. (HSST 4th)	70.21	50.28	40.53	96.51	69.2
<u>A 533-B Plate (67C)</u>					
Unirradiated	75.37	78.59	61.26	15.40	-13.7
Irrad. (UBR-58)	68.45	51.00	47.46	84.82	55.8
<u>A 533-B Plate (68A)</u>					
Unirradiated	81.58	71.14	64.70	28.78	-13.6
Irrad. (UBR-61)	58.32	40.53	44.22	143.80	123.2

Table 2 Curve-Fit Parameters for Charpy-V Data (continued)

	$C_v = A_o + A_1$ TANH $[(T-T_o)/A_2]$				Temp. @ 41 J
	A_o (J)	A_1 (J)	A_2 (°C)	T_o (°C)	(°C)
A 533-B Plate (68C)					
Unirradiated	76.95	69.59	57.14	23.21	-9.8
Irrad. (UBR-58)	51.78	31.84	33.58	147.64	135.4
A 533-B Plate (23G)					
Unirradiated	74.72	73.98	41.14	-8.43	-28.9
Irrad. (UBR-38)	62.64	87.36	97.96	45.87	20.7
Irrad. (UBR-77)	77.98	54.05	29.99	31.45	6.0
A 302-B Plate					
Unirrad. (T-L, N, 1/4T)	36.94	23.29	30.93	8.48	13.5
Irrad. (BSR-7)	29.91	17.46	21.29	76.26	91.6
Unirrad. (L-T, N, 1/4T)	64.00	51.63	29.75	7.66	-6.8
Irrad. (UBR-31)	49.19	32.29	14.94	92.69	88.7
Unirrad. (L-T, F23, 1/4T)	57.17	51.67	40.34	10.42	-2.9
Irrad. (SSC-1)	51.95	32.94	22.15	86.29	78.4
Irrad. (SSC-2)	45.24	29.28	12.18	92.23	90.3
Irrad. (Wall-1)	48.01	35.38	32.62	78.47	71.6
Irrad. (Wall-2)	37.59	42.15	52.53	47.55	51.4
Irrad. (Wall-3)	44.21	37.94	39.45	49.74	46.1
Unirrad. (L-T, 23F, 1/2T)	75.02	51.08	30.09	10.67	-13.9
Irrad. (UBR-38)	67.73	48.81	29.07	57.07	38.9
Irrad. (UBR-44)	55.27	54.64	51.83	57.28	43.1
Irrad. (UBR-46)	56.84	50.45	47.67	64.58	48.7
Irrad. (UBR-45)	57.11	39.25	24.20	70.33	59.5
Irrad. (UBR-65)	62.33	46.42	30.95	46.64	31.0
Irrad. (UBR-75)	61.10	47.91	37.21	62.10	45.2
Irrad. (UBR-76)	56.03	45.88	34.41	67.75	55.8
A 302-B Plate (6A2)					
Unirradiated	76.13	70.36	49.16	41.59	14.3
Irrad. (UBR-61)	58.36	61.91	67.44	109.79	90.0
Linde 80 Weld (E19)					
Unirradiated	52.83	33.31	51.41	4.37	-15.3
Irrad. (BSR-8)	35.47	28.11	62.18	64.50	76.2
Irrad. (BSR-9)	42.95	38.09	61.97	39.82	36.1
Irrad. (BSR-10)	36.13	21.46	50.24	93.01	103.8
Linde 80 Weld (E23)					
Unirradiated	53.99	37.27	40.84	-0.96	-16.2
Irradiated	45.15	28.84	45.33	76.64	69.5

Table 2 Curve-Fit Parameters for Charpy-V Data (continued)

	$C_v = A_o + A_1$ TANH $[(T-T_o)/A_2]$				Temp. @ 41 J (°C)
	A_o (J)	A_1 (J)	A_2 (°C)	T_o (°C)	
Linde 80 Weld (71W)					
Unirradiated	52.76	51.78	43.93	2.82	-7.6
Irrad. (HSST 4th)	42.89	73.95	81.54	17.60	15.2
Linde 80 Weld (W8A)					
Unirradiated	-481.36	563.39	139.53	-244.96	-17.0
Irrad. (UBR-42C)	35.82	14.79	8.74	111.84	114.8
IAR (UBR-41B)	39.23	18.10	5.29	96.34	96.8
Irrad. (UBR-41C)	32.15	22.52	29.28	84.00	95.7
Irrad. (UBR-44)	31.76	20.77	24.90	89.86	101.3
Irrad. (UBR-46)	29.80	19.30	26.75	92.28	109.3
Irrad. (UBR-45)	28.23	15.78	25.58	104.89	131.8
Irrad. (UBR-65)	-261.58	324.34	119.02	-127.83	71.3
Irrad. (UBR-75)	30.96	24.77	63.50	71.41	97.7
Irrad. (UBR-76)	35.11	17.29	33.43	98.95	110.1
Linde 0091 Weld (E24)					
Unirradiated	91.91	87.37	44.09	-43.86	-73.5
Irradiated	69.83	74.78	77.42	37.66	5.8
Linde 0091 Weld (68W)					
Unirradiated	100.07	94.69	33.64	-34.67	-59.5
Irrad. (HSST 4th)	109.21	103.31	32.78	-22.93	-49.1
Linde 0091 Weld (69W)					
Unirradiated	78.61	69.54	31.70	-0.07	-19.5
Irrad. (HSST 4th)	70.36	76.44	54.45	28.96	6.6
Linde 0091 Weld (W9A)					
Unirradiated	-536.18	706.25	113.34	-191.29	-61.3
Irrad. (UBR-42C)	60.61	44.71	46.10	69.77	47.7
IAR (UBR-41B)	52.93	59.39	61.65	38.78	25.9
Irrad. (UBR-41C)	51.16	67.16	82.97	44.65	31.6
Irrad. (UBR-77)	72.49	50.44	40.92	33.52	3.1
Linde 124 Weld (70W)					
Unirradiated	75.87	58.44	32.70	-16.74	-39.5
Irrad. (HSST 4th)	70.58	62.21	50.62	6.59	-19.9
Linde 124 Weld (E4)					
Unirradiated	67.56	71.07	41.46	-21.24	-37.7
Irradiated	65.49	38.78	46.55	85.84	50.6

Table 3 Curve-Fit Parameters for Transition Regime Fracture Toughness Data

	$K_{Jc} = B_0 + B_1 \exp[(T-T_o)/B_2]$			Temp. at 100 $MPa\sqrt{m}$
	B_0 ($MPa\sqrt{m}$)	B_1 ($MPa\sqrt{m}$)	B_2 (°C)	(°C)
A 508-2 Forging (BCB)				
Unirradiated	-372.73	559.44	402.05	-68
Irrad. (BSR-6)	83.47	4.45	21.20	28
20NiMoCr26 (GEB)				
Unirradiated	39.61	321.80	46.90	-78
Irrad. (UBR-68)	33.26	136.23	42.71	-30
IA 399°C (UBR-68)	-122.84	300.90	209.33	-63
IA 454°C (UBR-68)	-169.74	345.97	300.41	-75
Unirrad. (Check)	-92.57	322.13	172.76	-89
Irrad. (UBR-78)	68.25	195.75	27.00	-49
Irrad. (UBR-79, 275°C)	37.05	75.18	55.73	-10
A 533-B Plate (CAB)				
Unirradiated	-557.95	735.41	412.40	-46
Irrad (BSR-2)	63.55	8.63	18.42	27
Irrad. (BSR-3)	40.98	8.70	24.65	47
Irrad. (BSR-5)	-2304.77	2355.45	1715.82	36
A 533-B Plate (CBB)				
Unirradiated	-372.59	577.99	248.50	-50
Irrad.	-30.86	16.69	32.48	67
A 533-B Plate (3P)				
Unirradiated	56.21	88.68	24.08	-17
Irrad. (SSC-1)	47.46	0.79	12.46	52
Irrad. (SSC-2)	13.61	50.00	159.76	87
Irrad. (Wall-1)	35.75	9.81	30.53	57
Irrad. (Wall-2)	34.82	27.65	42.65	37
Irrad. (Wall-3)	32.29	41.19	49.29	24
A 533-B Plate (02G)				
Unirradiated	35.87	107.86	46.72	-24
Irrad. (HSST 4th)	52.38	3.12	23.65	64
A 533-B Plate (67C)				
Unirradiated	34.68	166.83	38.79	-36
Irrad. (UBR-58)	40.33	23.13	47.90	45
A 533-B Plate (68A)				
Unirradiated	49.67	131.48	39.80	-38
Irrad. (UBR-61)	-0.11	42.46	114.45	98

Table 3 Curve-Fit Parameters for Transition Regime Fracture Toughness Data (continued)

	$K_{Jc} = B_0 + B_1 \exp[(T-T_o)/B_2]$			Temp. at $100\ MPa\sqrt{m}$ (°C)
	B_0 ($MPa\sqrt{m}$)	B_1 ($MPa\sqrt{m}$)	B_2 (°C)	
A 533-B Plate (68C)				
Unirradiated	36.77	109.24	58.51	-32
Irrad. (UBR-58)	32.12	5.76	50.81	125
A 533-B Plate (23G)				
Unirradiated	29.21	276.59	60.83	-83
Irrad. (UBR-38)	41.25	51.03	50.92	7
Irrad. (UBR-77)	30.60	131.34	84.53	-54
A 302-B Plate				
Unirrad. (T-L, N, 1/4T)	-26.32	186.58	118.79	-46
Irrad. (BSR-7)	30.63	6.45	34.37	82
Unirrad. (L-T, N, 1/4T)	-59.99	240.24	115.90	-47
Irrad. (UBR-31)	-128.70	158.10	132.14	49
Unirrad. (L-T, F23, 1/4T)	13.82	275.26	54.00	-63
Irrad. (SSC-1)	12.42	47.12	80.67	50
Irrad. (SSC-2)	35.09	10.28	34.92	64
Irrad. (Wall-1)	31.44	26.62	46.36	44
Irrad. (Wall-2)	43.92	19.64	31.42	33
Irrad. (Wall-3)	20.17	63.19	61.10	14
Unirrad. (L-T, 23F, 1/2T)	34.31	211.21	37.31	-44
Irrad. (UBR-38)	33.34	54.49	55.01	11
Irrad. (UBR-44)	62.37	5.06	15.66	31
Irrad. (UBR-46)	4.90	70.51	109.48	33
Irrad. (UBR-45)	-21.45	94.06	118.56	30
Irrad. (UBR-65)	-94.80	209.40	175.56	-13
Irrad. (UBR-75)	-41.11	129.66	103.43	9
Irrad. (UBR-76)	37.03	26.47	46.09	40
A 302-B Plate (6A2)				
Unirradiated	34.48	89.47	86.45	-27
Irrad. (UBR-61)	-79.12	142.53	250.21	57
Linde 80 Weld (E19)				
Unirradiated	56.76	630.12	21.85	-59
Irrad. (BSR-8)	63.75	4.30	29.08	62
Irrad. (BSR-9)	70.28	71.22	14.78	-13
Irrad. (BSR-10)	58.47	0.33	9.81	47
Linde 80 Weld (E23)				
Unirradiated	74.92	71.72	47.66	-50
Irrad.	-3.12	72.76	68.18	24

Table 3 Curve-Fit Parameters for Transition Regime Fracture Toughness Data (continued)

	$K_{Jc} = B_0 + B_1 \exp[(T-T_o)/B_2]$			
	B_0 (MPa$\sqrt{m}$)	B_1 (MPa$\sqrt{m}$)	B_2 (°C)	Temp. at 100 MPa$\sqrt{m}$ (°C)
Linde 80 Weld (71W)				
Unirradiated	-180.65	312.49	355.28	-38
Irrad. (HSST 4th)	48.94	97.36	34.55	-22
Linde 80 Weld (W8A)				
Unirradiated	45.18	210.89	43.47	-59
Irrad. (UBR-48A)	21.16	19.82	44.29	61
IAR (UBR-48B)	-14.89	87.63	157.30	43
Irrad. (UBR-50)	51.38	11.55	15.36	22
Unirrad. (Check)	-30.21	188.13	164.52	-61
Irrad. (UBR-44)	45.32	10.88	42.56	69
Irrad. (UBR-46)	44.49	12.18	52.99	80
Irrad. (UBR-45)	51.10	7.49	34.96	66
Irrad. (UBR-65)	25.58	48.46	50.23	22
Irrad. (UBR-75)	44.93	13.89	36.91	51
Irrad. (UBR-76)	-49.78	93.48	154.78	73
Linde 0091 Weld (E24)				
Unirradiated	-108.62	419.68	131.71	-92
Irradiated	14.64	66.72	49.15	12
Linde 0091 Weld (68W)				
Unirradiated	-19.51	341.54	87.07	-91
Irrad. (HSST 4th)	-5247.39	5478.95	3798.68	-92
Linde 0091 Weld (69W)				
Unirradiated	16.08	108.85	72.96	-19
Irrad. (HSST 4th)	42.50	35.57	53.40	26
Linde 0091 Weld (W9A)				
Unirradiated	22.40	519.22	44.24	-84
Irrad. (UBR-48A)	33.66	40.10	52.66	27
IAR (UBR-48B)	53.32	28.14	29.63	15
Irrad. (UBR-50)	-70.52	178.82	166.31	-8
Irrad. (UBR-77)	13.69	91.27	94.29	-5
Linde 124 Weld (70W)				
Unirradiated	-13.91	228.96	98.13	-69
Irrad. (HSST 4th)	-5.93	170.28	94.85	-45
Linde 124 Weld (E4)				
Unirradiated	-70.51	298.26	141.49	-79
Irradiated	19.55	75.18	85.22	6

for this forging exhibit the greatest difference between ΔT from C_v and ΔT from K_{Jc} (19°C vs. 96°C). No explanation was found for the large difference, although the limited number of specimens and the irradiation temperatures (down to just over 200°C in some cases per Ref. 2) are probable causes.

The second anomalous set is for the 20NiMoCr26 Forging GEB, specifically the set irradiated at 275°C (UBR-79). As will be illustrated in a later section, this set does not follow the trend established by the other sets for this forging. One probable cause for this discrepancy is the difference in the irradiation temperatures for the C_v and the fracture toughness specimens. A promising finding for this forging is the overall lack of differences between ΔT from C_v and K_{Jc} as was found with the A 508 forging, implying that the cited differences may not be generic with forging materials.

4.1 Overall Comparisons

This method used to compare ΔT's from the two test methods is to graphically plot ΔT from C_v against that from K_{Jc}. The various plots to be used include a 45° line representing 1:1 correspondence. Data points falling above this line are conservative estimates of ΔT from K_{Jc}, with data points below the line indicative of non-conservative estimates of ΔT from K_{Jc}. Table 4 compares the ΔT values for the C_v and the K_{Jc} data, along with fluences and other important information for each data set. Table 5 then gives average differences and standard deviations for various sub-sets of this data base.

Figure 1 compares all of the available data. The data generally follow the 1:1 line, although many of the data points for the base metals are found to lie below the line, i.e., non-conservative. From Table 5, using all data (exclusive of the two sets cited above) yields an average underestimate of 8°C. A product form dependence is apparent, as the welds exhibit estimates of $\Delta T(K_{Jc})$ which are conservative by 1°C on average and plates exhibit estimates which are non-conservative by 15°C on average. All of these numbers represent some improvement from those reported in Ref. 1.

In Fig. 2, the plate and the weld data are sub-divided by type, into A 533-B and A 302-B for the plates and Linde 80 for the welds. For the plates in particular, there are no significant differences between the two plate types. In contrast, the non-Linde 80 welds exhibit somewhat non-conserative estimates of $\Delta T(K_{Jc})$ by $\Delta T(C_v)$, although well within the scatter in each data set.

Separation of the plate and the weld data according to irradiation fluence rate also reveals no significant trend (Fig. 3). For the welds only three data sets are from the low and intermediate fluence rates.

4.2 20NiMoCr26 Forging (GEB)

This forging was found to be archive material for the Gundremmingen reactor (KRB-A), as described in Ref. 7. Of the five data sets for this forging (Fig. 4), two represent data for as-irradiated conditions

Table 4 Summary of ΔT Values from K_{Jc} and C_v Data

Heat ID	Capsule ID	Fluence Rate	Fluence	Temperature at		Temp. Shift at	
			([a])	41 J (°C)	100 MPa$\sqrt{m}$ (°C)	41 J (°C)	100 MPa$\sqrt{m}$ (°C)
BCB	Unirrad.	----	---------	-24.8	-68	-	--
BCB	BSR-6	High	2.80/2.89	-5.8	28	19.0	96
GEB	Unirrad.	----	---------	-28.3	-78	-	-
GEB	UBR-68	High	0.88/0.86	12.9	-30	41.2	48
GEB	IA 399°C	High	0.88/0.86	-13.4	-63	14.9	15
GEB	IA 454°C	High	0.88/0.86	-26.0	-75	2.3	3
GEB	U (Check)	----	---------	-21.0	-89	-	-
GEB	UBR-78	High	0.27/0.26	-4.6	-49	16.4	40
GEB	UBR-79	High	0.88/0.86	20.0	-10	41.0	79
CAB	Unirrad.	----	---------	2.2	-46	-	-
CAB	BSR-2	High	1.20/1.15	35.0	27	32.8	73
CAB	BSR-3	High	1.70/1.86	62.7	47	60.5	93
CAB	BSR-5	High	2.10/2.18	64.6	36	62.4	82
CBB	Unirrad.	----	---------	0.7	-50	-	-
CBB	BSR-4	High	4.40/4.82	91.4	67	90.7	117
3P	Unirrad.	----	---------	0.4	-17	-	-
3P	SSC-1	High	2.35/2.28	72.0	52	71.6	69
3P	SSC-2	High	4.97/4.90	84.2	87	83.8	104
3P	Wall-1	Int.	3.47/3.64	74.3	57	73.9	74
3P	Wall-2	Int.	1.99/1.98	63.6	37	63.2	54
3P	Wall-3	Int.	0.98/0.95	53.3	24	52.9	41
O2G	Unirrad.	----	---------	3.2	-24	-	-
O2G	HSST 4th	High	1.77/1.95	69.2	64	66.0	88
67C	Unirrad.	----	---------	-13.7	-36	-	-
67C	UBR-58	High	1.55/1.78	55.8	45	69.5	81
68A	Unirrad.	----	---------	-13.6	-38	-	-
68A	UBR-61	High	1.53/1.73	123.2	98	136.8	136
68C	Unirrad.	----	---------	-9.8	-32	-	-
68C	UBR-58	High	1.55/1.78	135.4	125	145.2	157
23G	Unirrad.	----	---------	-28.9	-83	-	-
23G	UBR-38	Low	0.54/0.57	20.7	7	49.6	90
23G	UBR-77	High	0.45/0.47	6.0	-54	34.9	29
N	Unirrad.	----	---------	13.5	-46	-	-
N	BSR-7	High	2.70/2.64	91.6	82	78.1	128
N	Unirrad.	----	---------	-6.8	-47	-	-
N	UBR-31	High	3.60/3.64	88.7	49	95.5	96
F23	Unirrad.	----	----------	-2.9	-63	-	-
F23	SSC-1	High	2.59/2.40	78.4	50	81.3	113
F23	SSC-2	High	5.41/5.06	90.3	64	93.2	127
F23	Wall-1	Int.	3.73/3.78	71.6	44	74.5	107
F23	Wall-2	Int.	2.15/2.08	51.4	33	54.3	96
F23	Wall-3	Int.	1.05/0.99	46.1	14	49.0	77

[a] 10^{19} n/cm^2 (E > 1 MeV), with C_v/K_{Jc}.

Table 4 Summary of ΔT Values from K_{Jc} and C_v Data (continued)

Heat ID	Capsule ID	Fluence Rate	Fluence ([a])	Temperature at 41 J (°C)	Temperature at 100 MPa√m (°C)	Temp. Shift at 41 J (°C)	Temp. Shift at 100 MPa√m (°C)
23F	Unirrad.	----	---------	-13.9	-44	-	-
23F	UBR-38	Low	0.54/0.57	38.9	11	52.8	55
23F	UBR-44	Int.	0.79/0.88	43.1	31	57.0	75
23F	UBR-46	Int.	1.50/1.64	48.7	33	62.6	77
23F	UBR-45	Int.	3.85/4.01	59.5	30	73.4	74
23F	UBR-65	High	0.56/0.53	31.0	-13	44.9	31
23F	UBR-75	High	1.22/1.02	45.2	9	59.1	53
23F	UBR-76	High	2.23/1.95	55.8	40	69.7	84
6A2	Unirrad.	----	---------	14.3	-27	-	-
6A2	UBR-61	High	1.53/1.73	90.0	57	75.7	84
E19	Unirrad.	----	---------	-15.3	-59	-	-
E19	BSR-8	High	0.10/0.11	76.2	62	91.5	121
E19	BSR-9	High	0.73/0.75	36.1	-13	51.4	46
E19	BSR-10	High	2.50/2.53	103.8	47	119.1	106
E23	Unirrad.	----	---------	-16.2	-50	-	-
E23	BSR-12	High	0.69/0.67	69.5	24	85.7	74
71W	Unirrad.	----	---------	-7.6	-38	-	-
71W	HSST 4th	High	1.65/1.78	15.2	-22	22.8	16
W8A	Unirrad.	----	---------	-17.0	-59	-	-
W8A	42C/48A	High	2.03/2.10	114.8	61	131.8	120
W8A	IAR (41B/48B)	High	2.19/2.22	96.8	43	113.8	102
W8A	41C/50A	High	1.34/1.50	95.7	22	112.7	81
W8A	U (Check)	----	---------	-	-61	-	-
W8A	UBR-44	Int.	0.79/0.88	101.3	69	118.3	130
W8A	UBR-46	Int.	1.50/1.64	109.3	80	126.3	141
W8A	UBR-45	Int.	3.85/4.01	131.8	66	148.8	127
W8A	UBR-65	High	0.56/0.53	71.3	22	88.3	83
W8A	UBR-75	High	1.22/1.02	97.7	51	114.7	112
W8A	UBR-76	High	2.23/1.95	110.1	73	127.1	134
E24	Unirrad.	----	---------	-73.5	-92	-	-
E24	BSR-4,15	High	0.72/0.74	5.8	12	79.3	104
68W	Unirrad.	----	---------	-59.5	-91	-	-
68W	HSST 4th	High	1.35/1.34	-49.1	-92	10.4	-1
69W	Unirrad.	----	---------	-19.5	-19	-	-
69W	HSST 4th	High	1.22/1.32	6.6	26	26.1	45
W9A	Unirrad.	----	---------	-61.3	-84	-	-
W9A	42C/48A	High	2.03/2.10	47.7	27	109.0	111
W9A	IAR(41B/48B)	High	2.19/2.22	25.9	15	87.2	99
W9A	41C/50	High	1.34/1.50	31.6	-8	92.9	76
W9A	UBR-77	High	0.45/0.47	3.1	-5	64.4	79
70W	Unirrad.	----	---------	-39.5	-69	-	-
70W	HSST 4th	High	1.65/1.81	-19.9	-45	19.6	24
E4	Unirrad.	----	---------	-37.7	-79	-	-
E4	BSR-13	High	2.20/2.34	50.6	6	88.3	85

[a] 10^{19} n/cm^2 (E > 1 MeV), with C_v/K_{Jc}.

Table 5 Statistical Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$

Subset	K_o (°C)	± 1-σ (°C)	1-σ Range (°C)	# of Data Pts
	$\Delta T(K_{Jc}) = \Delta T(C_v) + K_o$			
All Data	+9.9	22.5	-12.6: +32.4	59
All Data (except BCB and UBR-79)	+8.3	19.8	-11.5: +28.1	57
All Welds	-0.6	15.4	-16.0: +14.8	23
All Plates	+15.0	23.5	-8.5: +38.5	30
All Forgings	+24.4	39.7	-15.3: +64.1	6
Linde 80	-4.2	16.3	-20.5: +12.1	14
Non-Linde 80 Weld	+5.0	14.9	-9.9: +19.9	9
Weld W8A	-5.8	16.5	-22.3: +10.7	9
A 533-B	+12.9	22.0	-9.1: +34.9	15
A 302-B	+17.1	25.7	-8.6: +42.8	15
Plate 23F	+4.2	12.7	-8.5: +16.9	7
Forging GEB	+13.8	22.4	-8.6: +36.2	5

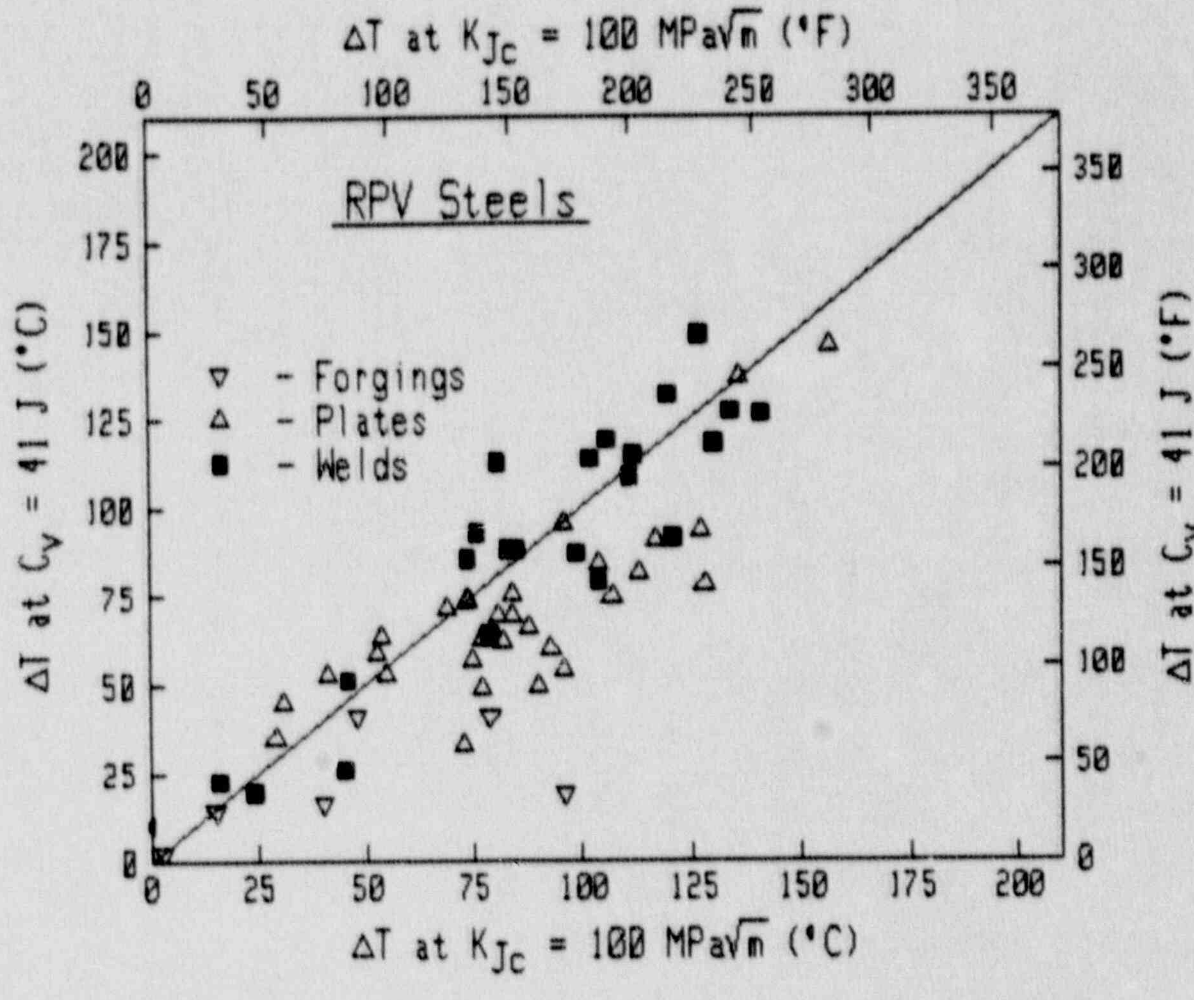
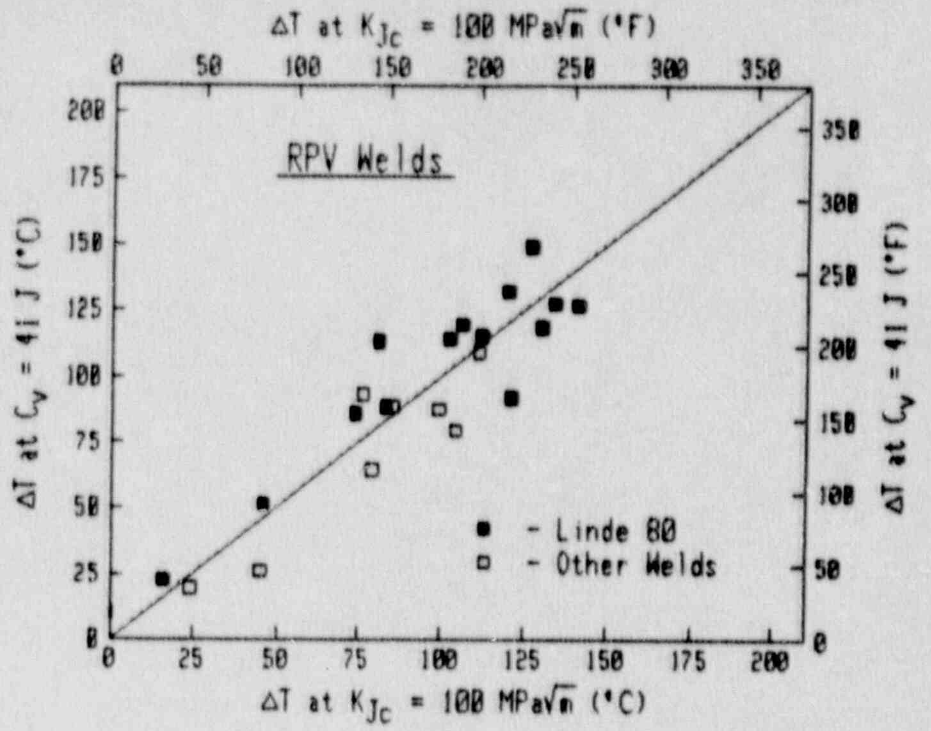


Fig. 1 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for all data from the materials.



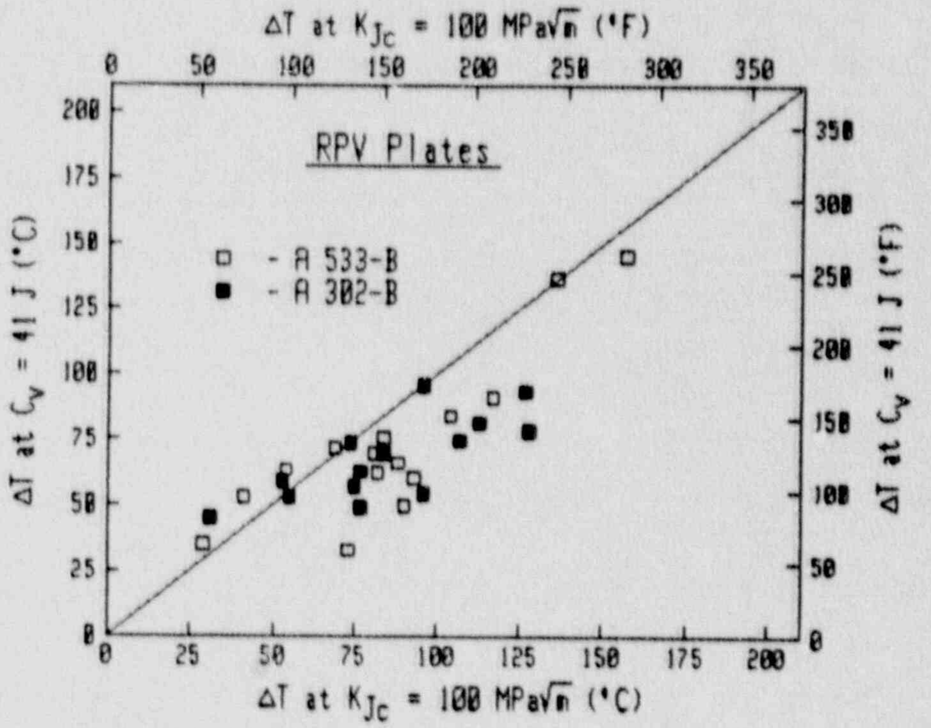


Fig. 2 Comparison of data for A 533-B and A 302-B plates, and Linde 80 and the other welds.

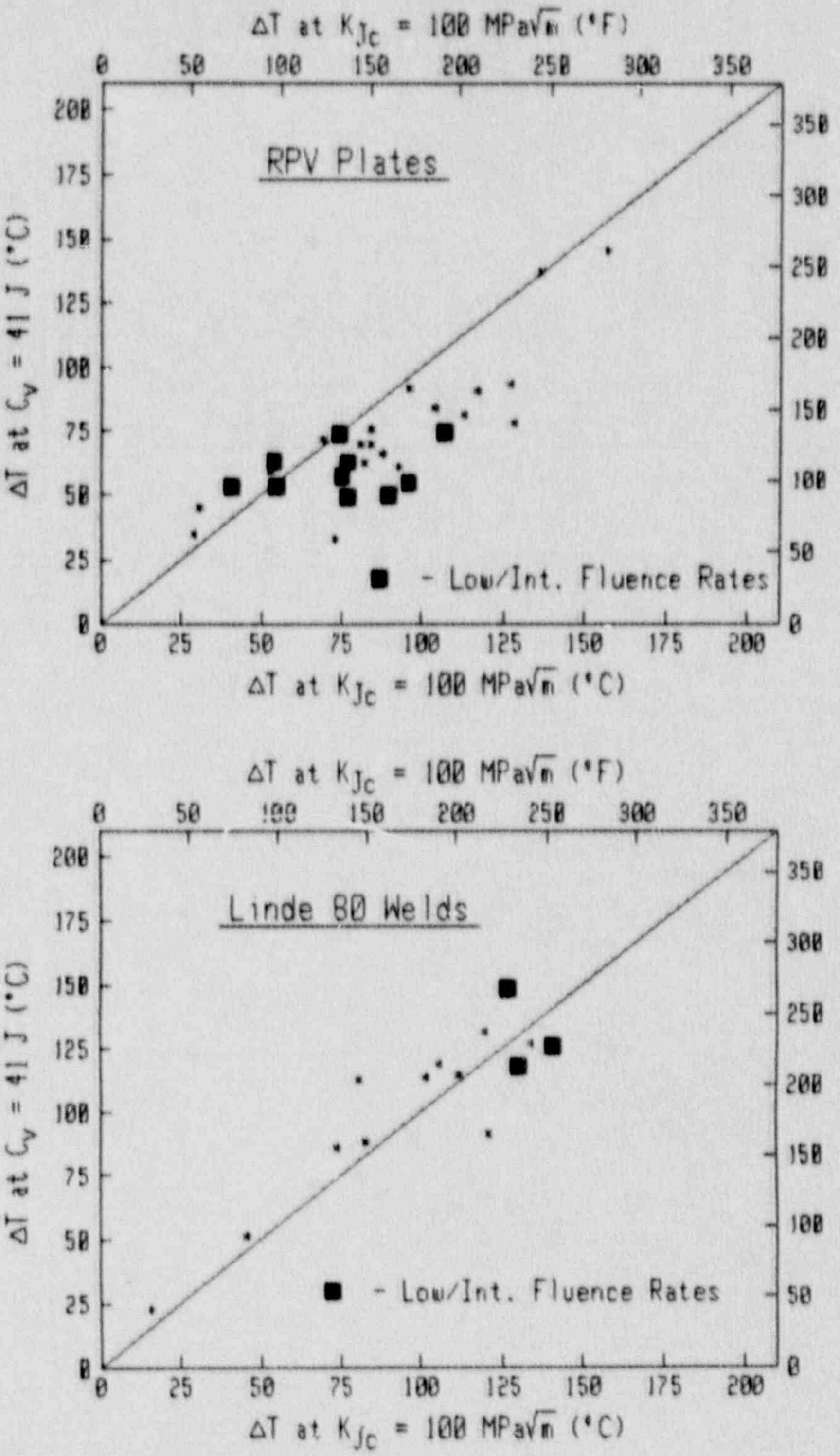


Fig. 3 Comparison of data from low and intermediate fluence rate irradiations with the overall data base.

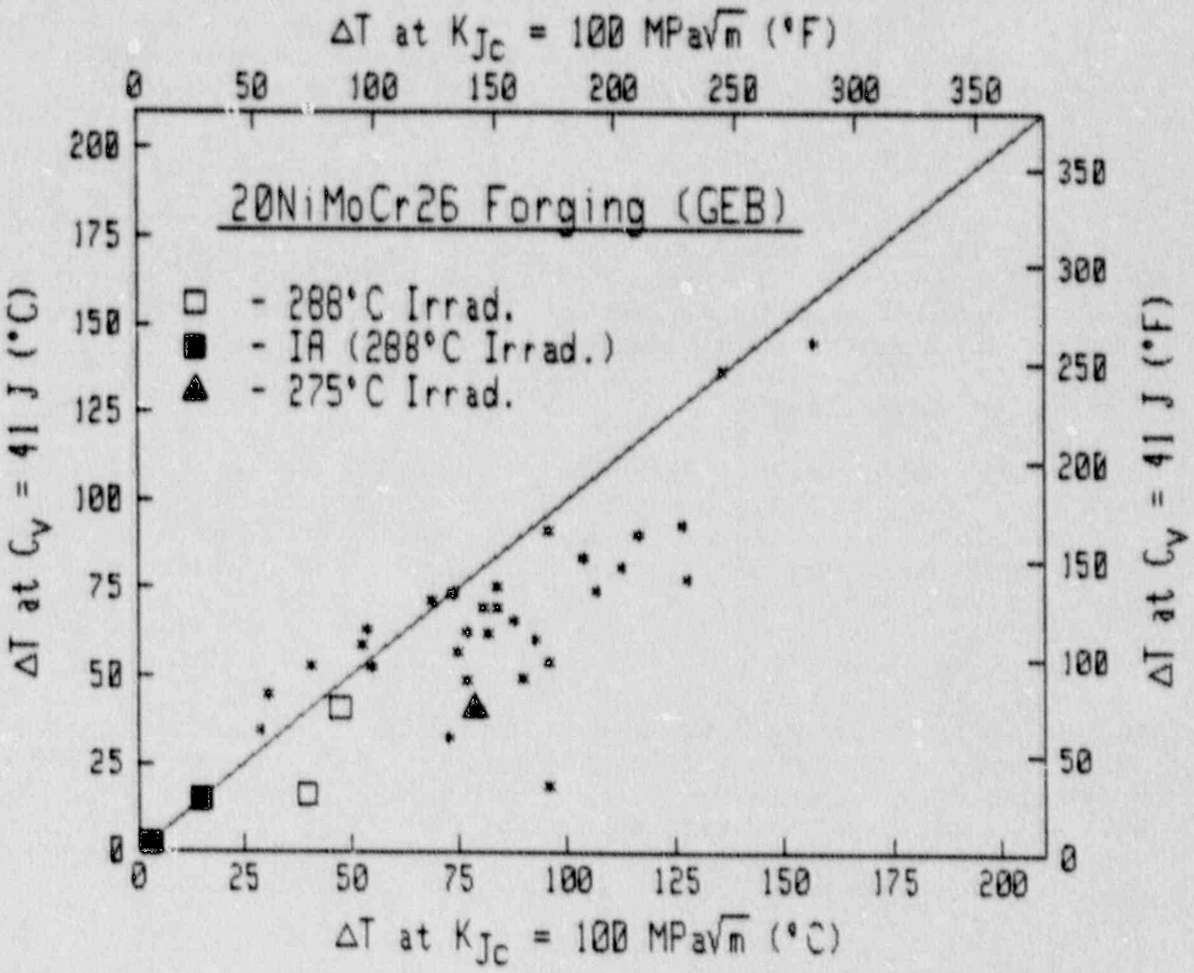


Fig. 4 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the 20NiMoCr26 forging GEB with the overall data base for base metals.

(288°C irradiation), two represent IA (irradiate-anneal) conditions (annealing at 399°C and 454°C), and the last set is from an irradiation at 275°C. In general, data for the IA conditions and the highest fluence of the 288°C-irradiated conditions are in good overall agreement. In contrast, data for the 275°C-irradiated condition and the lowest fluence of the 288°C-irradiated conditions demonstrate somewhat non-conservative estimates of $\Delta T(K_{Jc})$ by $\Delta T(C_v)$. Possible causes for the differences are the lack of adequate baseline testing for referencing of the two latter conditions and the small number of specimens for the two conditions.

4.3 A 533-B Plate CAB

This plate was irradiated in three high fluence rate capsules (Ref. 2). The three resultant data points are in good agreement with one another (Fig. 5). The offset of the data from the 1:1 line may be due to improper reference data or possibly a time-at-temperature effect for either the fracture toughness or the C_v data.

4.4 A 533-B Plate 23G

This plate was irradiated at a low fluence rate and a high fluence rate (Fig. 6). As described in Ref. 6, the fracture toughness data for the low fluence rate irradiation exhibit an unexpected high transition temperature shift, in comparison to the C_v data and data for the high fluence rate.

4.5 A 533-B Plate 3P

This plate was irradiated as a part of the Light Water Reactor Surveillance Dosimetry Improvement Program (Ref. 3) in Simulated Surveillance Capsules (SSC) at a high fluence rate and simulated in-wall capsules at an intermediate fluence rate (Fig. 7). Overall, the data for the SSC and the wall capsules follow a similar trend, as this plate yields good overall comparisons between $\Delta T(K_{Jc})$ and $\Delta T(C_v)$.

4.6 A 302-B Plate N, F23 and 23F

The plate denoted by the designations N, F23 and 23F are actually the same plate, specifically the ASTM A 302-B Reference Plate, with the 23F and F23 designations from one piece of this plate and the N designations from a different portion of this plate. The irradiation set designated UBR-31 represents irradiation of the L-T orientation from the plate 1/4T location, whereas BSR-7 represents irradiation of the T-L orientation from the plate 1/4T location. The SSC and Wall irradiations were companion to those of the A 533-B Plate 3P (Ref. 3), and were T-L orientation from the 1/4T location. The remaining UBR irradiations used the T-L orientation from the 1/2T location. From one viewpoint, data for this plate (Fig. 8) tend to follow a similar trend to that found with the A 533-B Plate 3P, as a given increment of $\Delta T(K_{Jc})$ is followed by a lesser increment of $\Delta T(C_v)$. From a different viewpoint, data from the 1/2T location and the 1/4T location independently indicate a similar trend, with an offset of ~ 30°C. The latter postulate is verified to some degree by comparing the baseline data for the 1/4T and the 1/2T locations. From C_v data, the 41 J

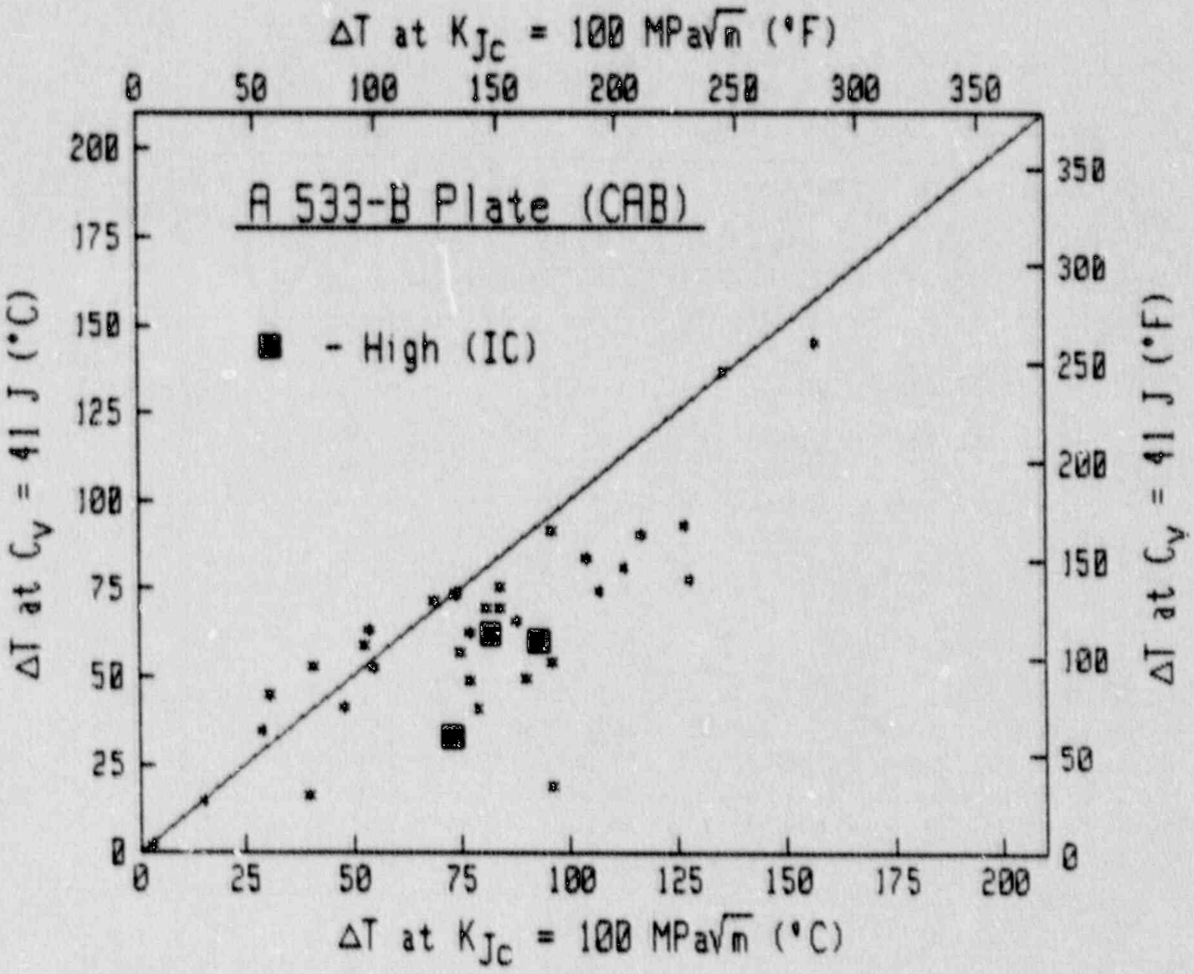


Fig. 5 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the A 533-B Plate CAB with the overall data base for base metals.

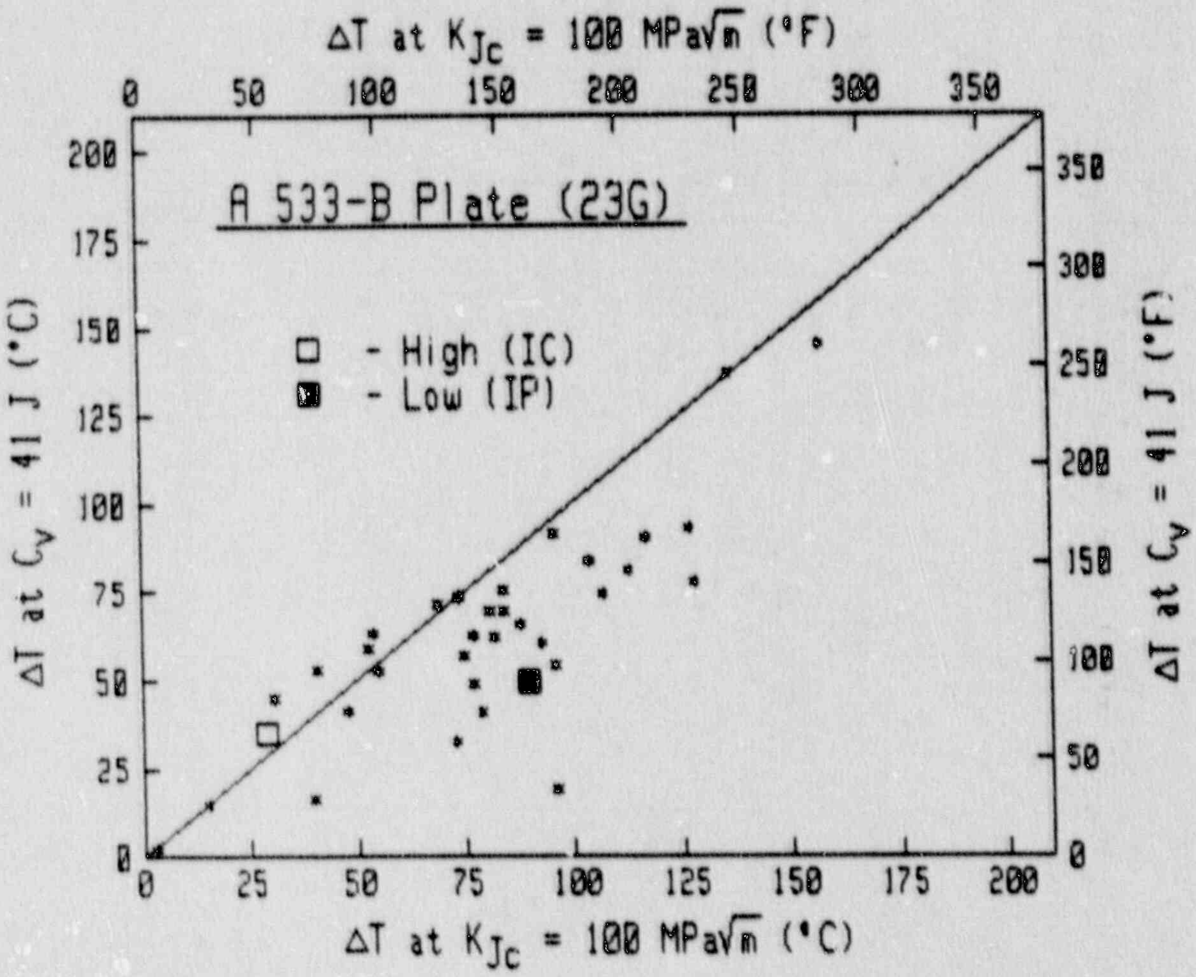


Fig. 6 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the A 533-B Plate 23G with the overall data base for base metals.

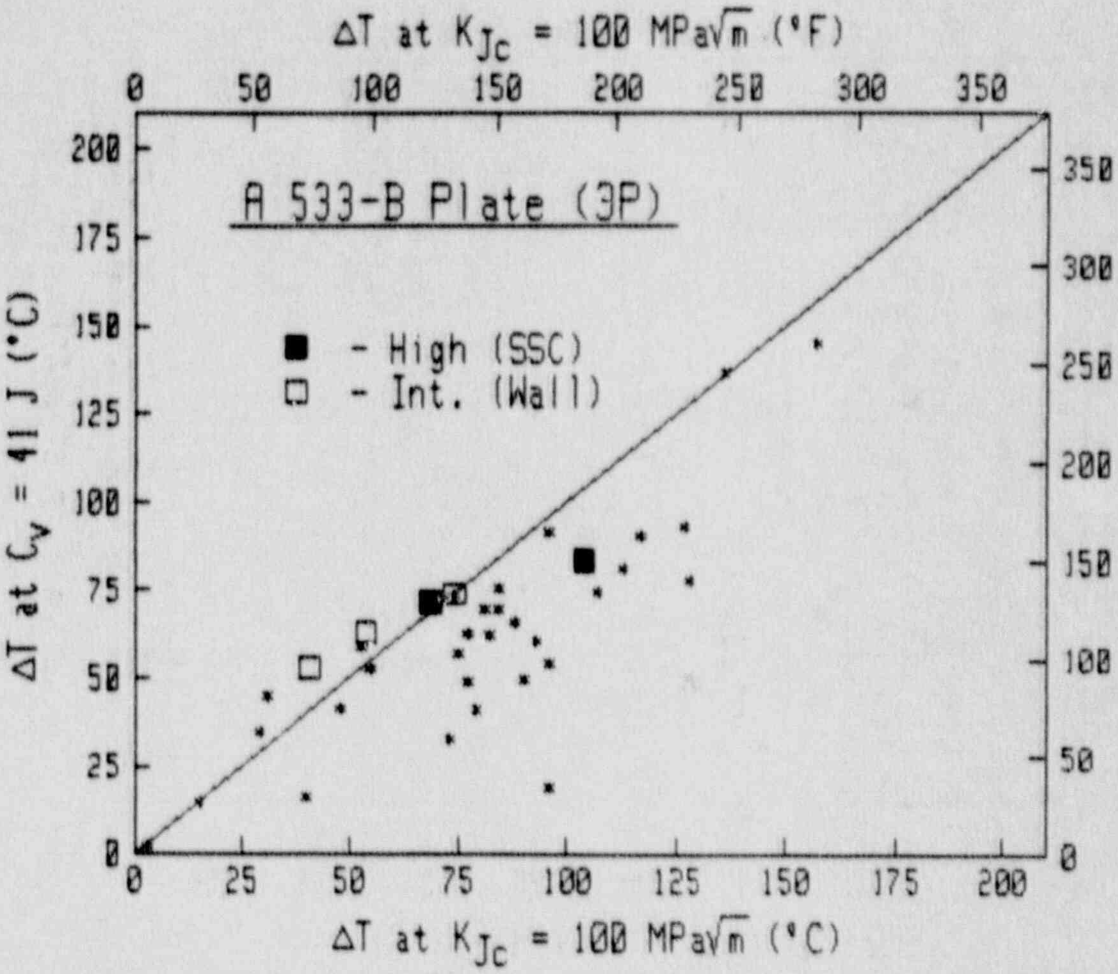


Fig. 7 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the A 533-B Plate 3P with the overall data base for base metals.

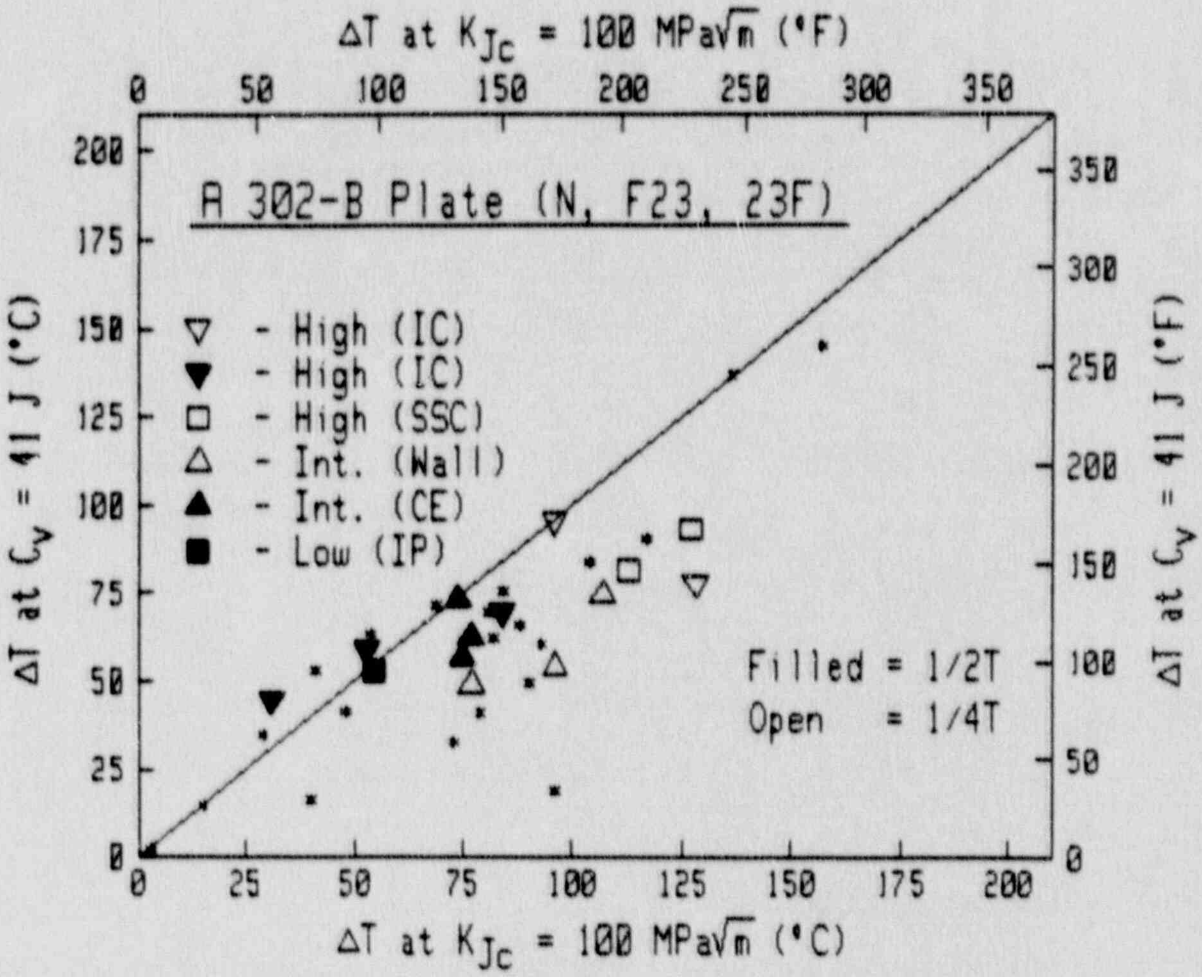


Fig. 8 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the A 302-B Plate N, F23 and 23F with the overall data base for base metals.

transition temperature occurs at -3°C for the 1/4T location and -14°C for the 1/2T location. In contrast for the fracture toughness data, the 100 MPa$\sqrt{m}$ transition temperature occurs at -63°C for the 1/4T location and -44°C for the 1/2T location (the transition temperature used here for the 1/4T location differs from those used in Refs. 3 and 6 due to the fact that previously-reported value is from a hand-fit to the fracture toughness data). Therefore, the C_v data indicate higher transition toughness for the 1/4T location (by 11°C) but the fracture toughness data indicate lower transition toughness for the 1/4T location (by 19°C). One would expect the two test types to indicate a change of properties in the same direction; causes for the mismatch are not known but warrant investigation. Accounting for the 30°C offset (11°C + 19°C) in the baseline properties would bring all of these data into much improved agreement.

4.7 Linde 80 Weld E19

This weld was irradiated to three fluences at a high fluence rate (Ref. 2). All three data points are in good agreement in bounding the 1:1 line (Fig. 9).

4.8 Linde 0091 Weld W9A

This weld (Fig. 10) was tested in four irradiated conditions representing a high fluence rate, with one of those actually an IAR condition (irradiate-anneal-reirradiate). Prior to the development of data for UBR-77 and additional data for Linde 80 Weld W8A, an apparent trend had developed for this weld and Weld W8A in that the IAR conditions indicated minimal increase in $\Delta T(C_v)$ but a larger increase in $\Delta T(K_{Jc})$, in contrast to that from a lower fluence as-irradiated condition tests. With the addition of a third as-irradiated condition (UBR-77), the differences between the previous as-irradiated condition data and the IAR-condition data do not exceed those between the three as-irradiated conditions.

4.9 Linde 80 Weld W8A

For this weld, data from as-irradiated conditon testing of high fluence rate and low fluence rate irradiations lie within the same trend as a data point from an IAR condition after a high fluence rate irradiation (Fig. 11). In addition, all of these data bound the 1:1 line, indicative of good agreement between $\Delta T(K_{Jc})$ and $\Delta T(C_v)$.

4.10 Other Data

Additional data comparing C_v and fracture toughness results are from the Heavy Secti : Steel Technology (HSST) Fifth Irradiation Series (Ref. 11) and from a German forging and a German weld (Ref. 12). As illustrated in Fig. 12, these additional data are consistent with the data base used in this report. Data for the Fifth Irradiation are of particular note due to the wide range of large specimens (up to 8T-CT for unirradiated and 4T-CT for irradiated) tested. The reader is referred to the final report on this test series for a more complete description of test parameters and results.

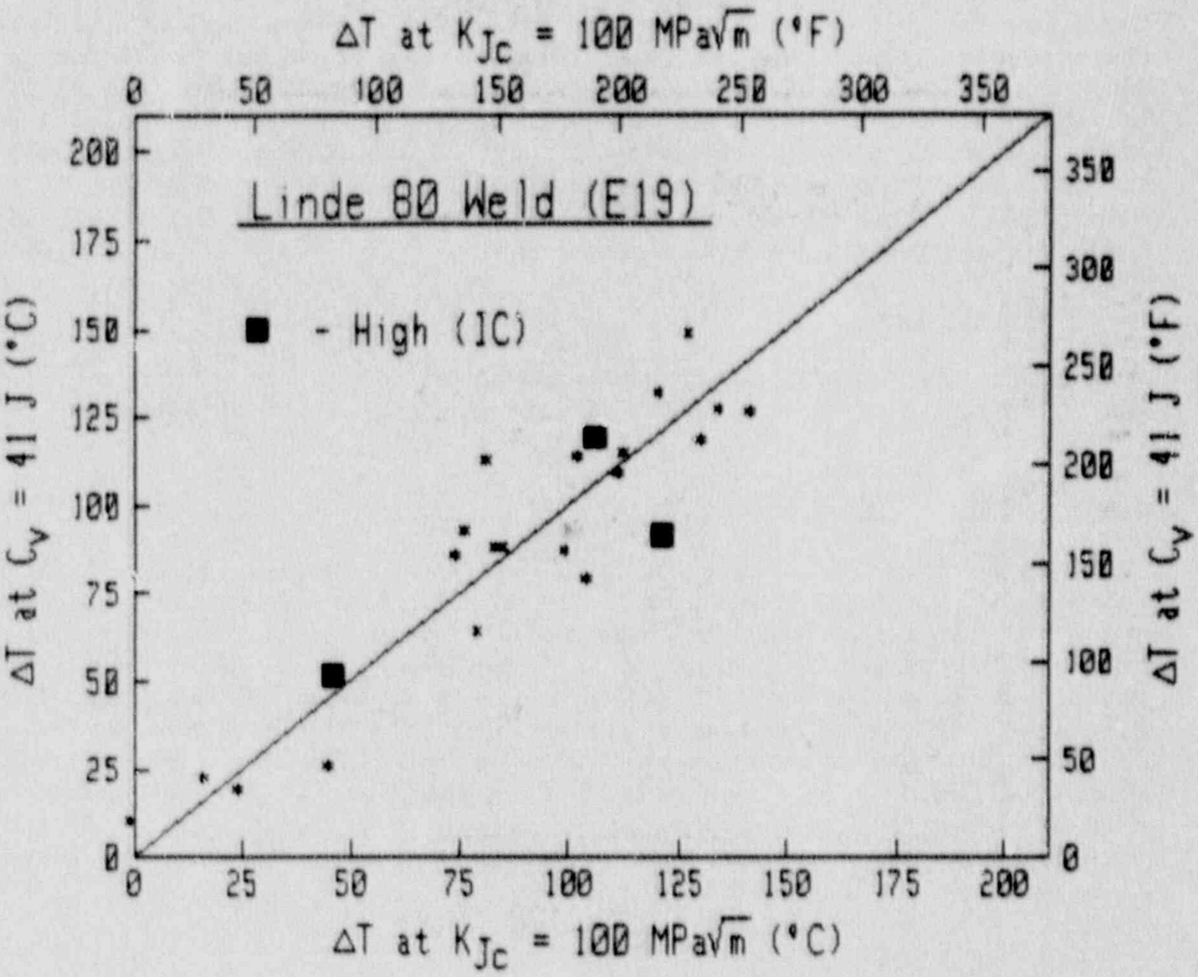


Fig. 9 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the Linde 80 Weld E19 with the overall data base for weld metals.

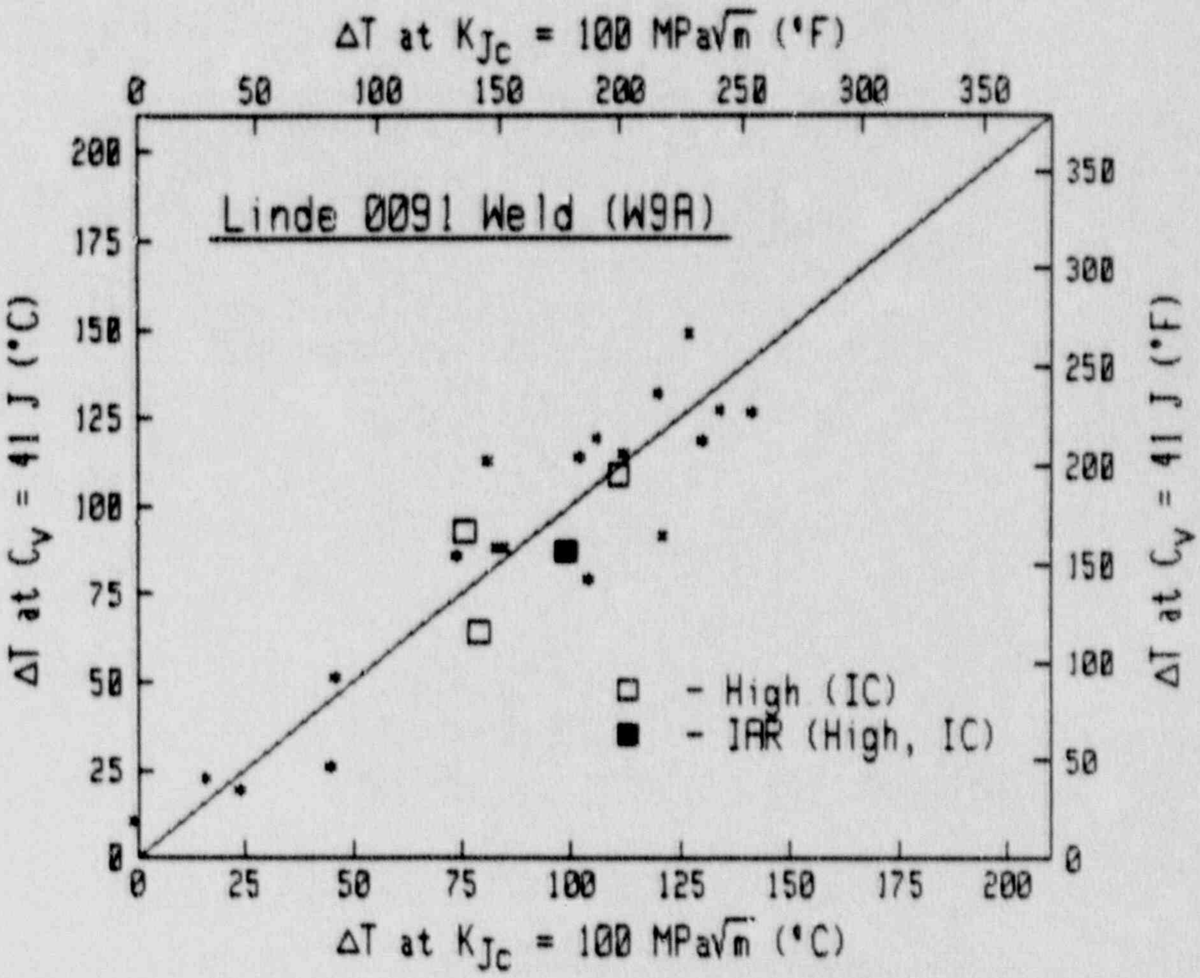


Fig. 10 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the Linde 0091 Weld W9A with the overall data base for weld metals.

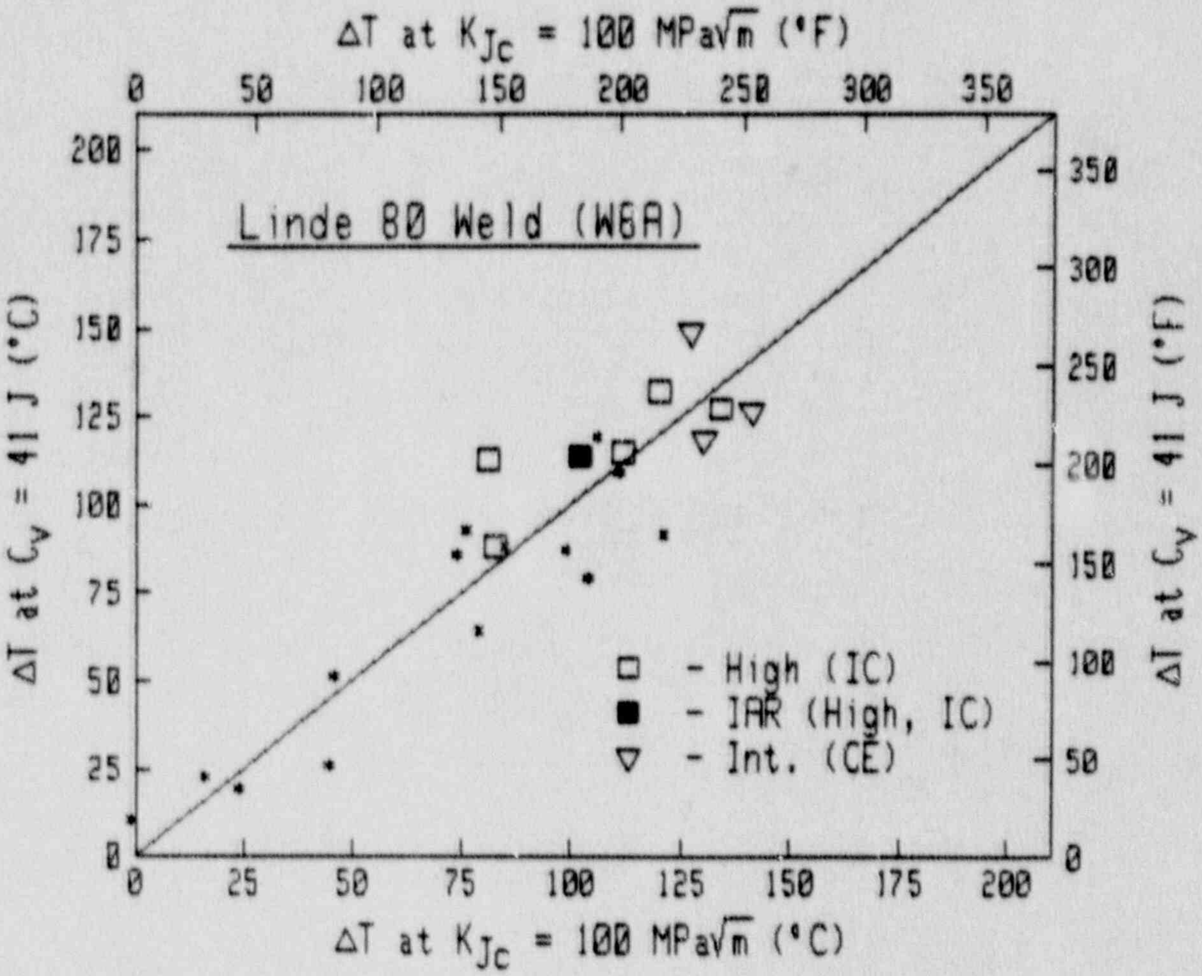


Fig. 11 Comparison of $\Delta T(C_v)$ and $\Delta T(K_{Jc})$ for the Linde 80 Weld W8A with the overall data base for weld metals.

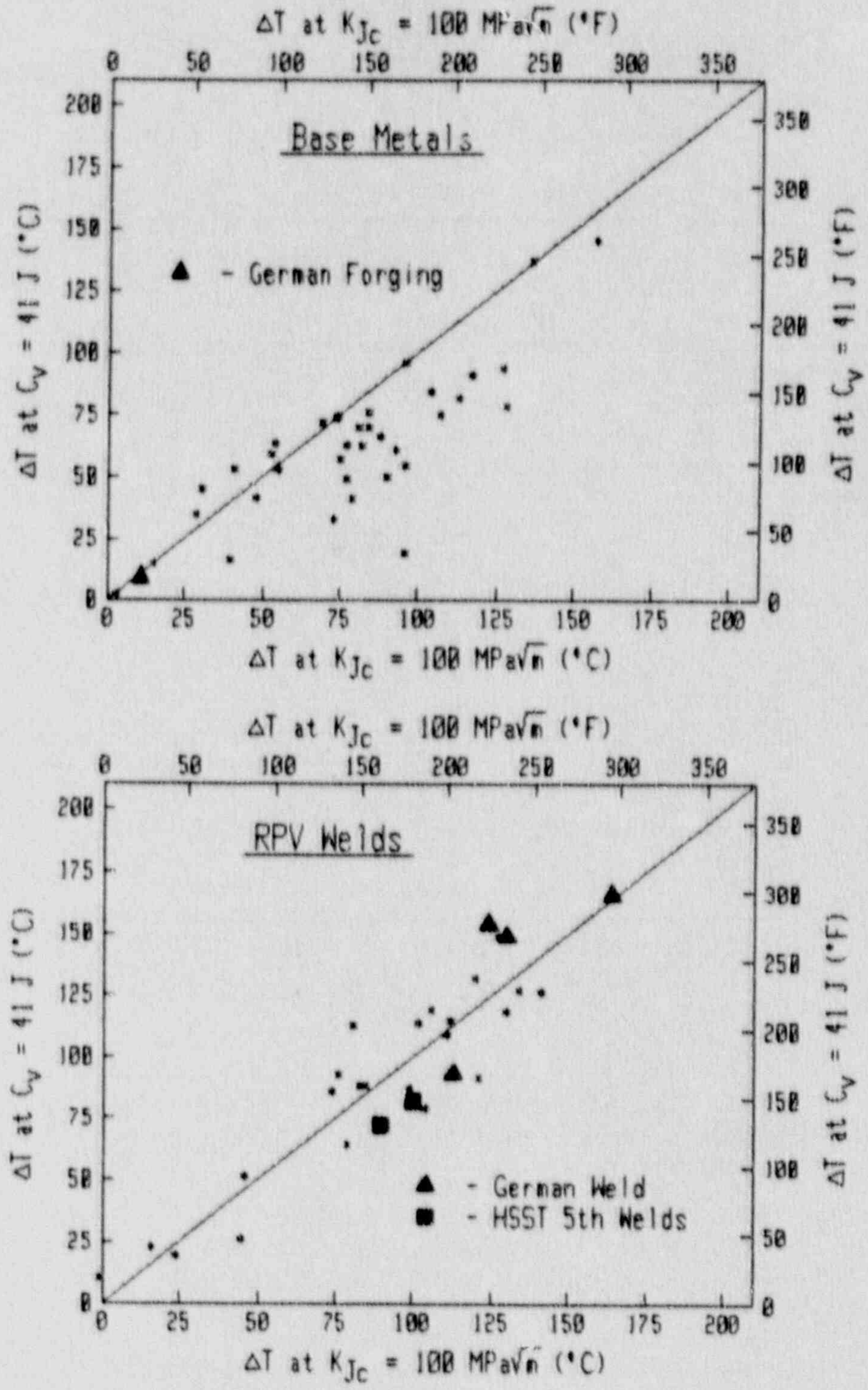


Fig. 12 Comparison of additional data from Refs. 11 and 12 with the overall data base.

5. SUMMARY AND CONCLUSIONS

For RPV safety assessments, knowledge of the fracture toughness (K_{Ic}) of the RPV materials is required. Since surveillance irradiations of sufficiently-large fracture toughness specimens for valid K_{Ic} measurements are not possible, estimates of the irradiated K_{Ic} properties are required. These approximations are made by using pre-irradiation properties (RT_{NDT}) and the transition temperature shift from Charpy-V specimens [$\Delta T(C_v)$] to index the ASME K_{Ic} and K_{IR} curves. To assess the appropriateness of using $\Delta T(C_v)$ to estimate $\Delta T(K_{Ic})$, comparisons of notch ductility (C_v) and fracture toughness (K_{Jc}) assessments of transition temperature shifts for RPV base metals and welds were made.

From a strict statistical standpoint, plates and welds tend to exhibit different trends for relating fracture toughness and notch ductility assessments of irradiation-induced transition temperature shifts (ΔT). This observation is supported in Table 5 where $\Delta T(C_v)$ for plates underestimates $\Delta T(K_{Jc})$ on average, while $\Delta T(C_v)$ for welds overestimates $\Delta T(K_{Jc})$ on average. Data in Fig. 1 demonstrate that $\Delta T(C_v)$ for welds gives a consistent estimate of $\Delta T(K_{Jc})$ at all ΔT levels. However, $\Delta T(C_v)$ for plates tends to underestimate large $\Delta T(K_{Jc})$ shifts, although improved agreement has been found at large $\Delta T(K_{Jc})$ levels in contrast to that found in Ref. 1.

Conclusions from this study are:

- Transition temperature shifts (ΔT's) measured by fracture toughness methods (K_{Jc} at 100 MPa$\sqrt{m}$) are only slightly greater than ΔT's from notch ductility (C_v at 41 J) tests, on average by 10°C.

- A product form effect influences the $\Delta T(K_{Jc})$ vs. $\Delta T(C_v)$ relationship, whereby $\Delta T(K_{Jc})$ for welds is overestimated by 1°C on average by C_v results and $\Delta T(K_{Jc})$ for plates is underestimated by 15°C on average by C_v results.

- For the A 508-2 forging, $\Delta T(K_{Jc})$ is much greater than the $\Delta T(C_v)$. This behavior is atypical of the other heats in the data base, including the other forging.

- For Linde 80 welds, $\Delta T(C_v)$ conservatively estimates $\Delta T(K_{Jc})$ on average.

- Fluence rate does not in general have any effect on the relationship between $\Delta T(C_v)$ and $\Delta T(K_{Jc})$.

The above conclusions must be balanced by the understanding that many of the fracture toughness curves were composed of six or fewer data points. In general, irradiations of fracture toughness specimens result in too few specimens of too small a thickness to provide for complete and unambiguous definition of the fracture toughness behavior with temperature. Several bench-mark irradiations of many small (thickness) specimens of several compositions and product forms would be an excellent supplement to the HSST Fifth Irradiation Series.

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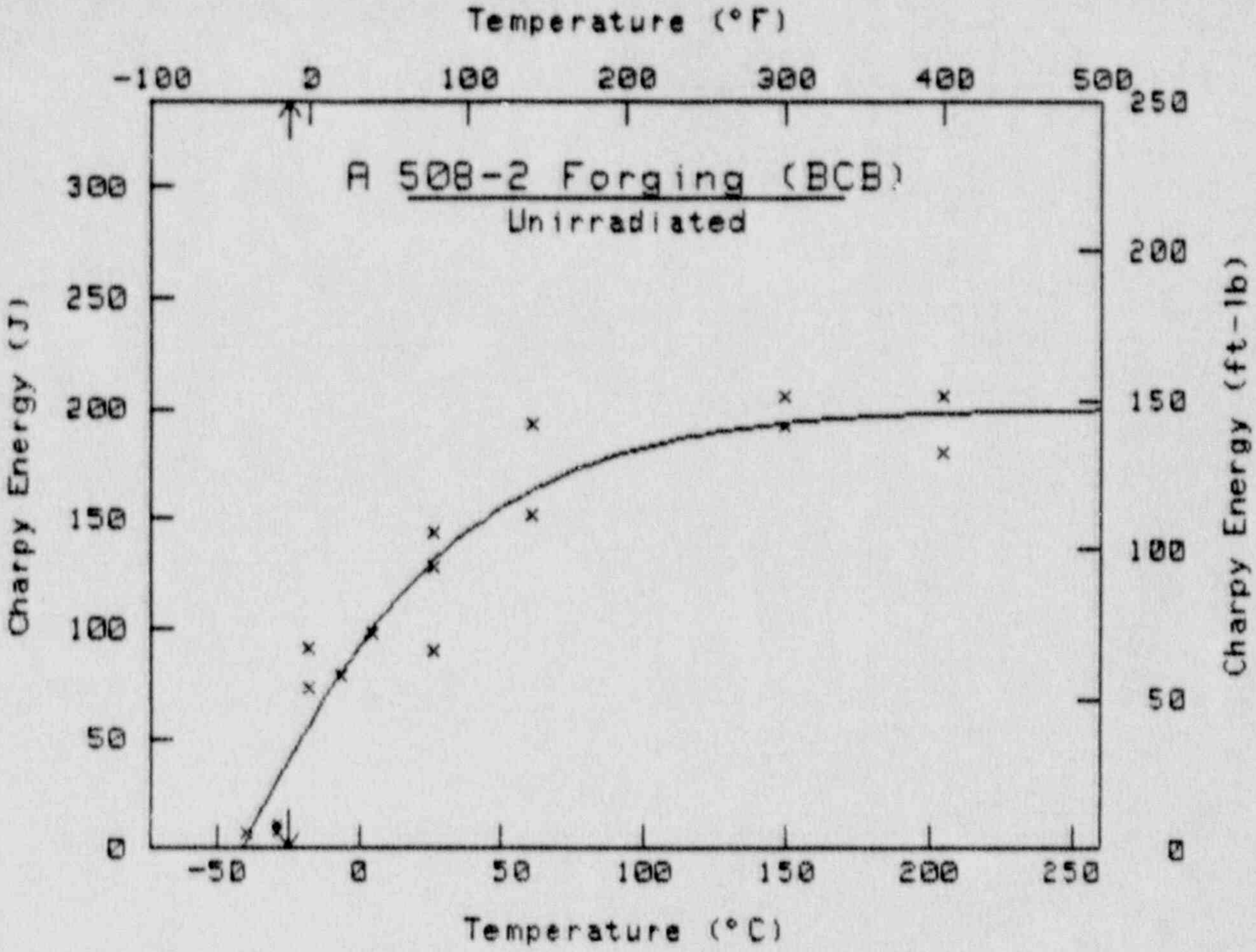
APPENDIX A

Curve-Fit Results for the Charpy-V Data



****

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

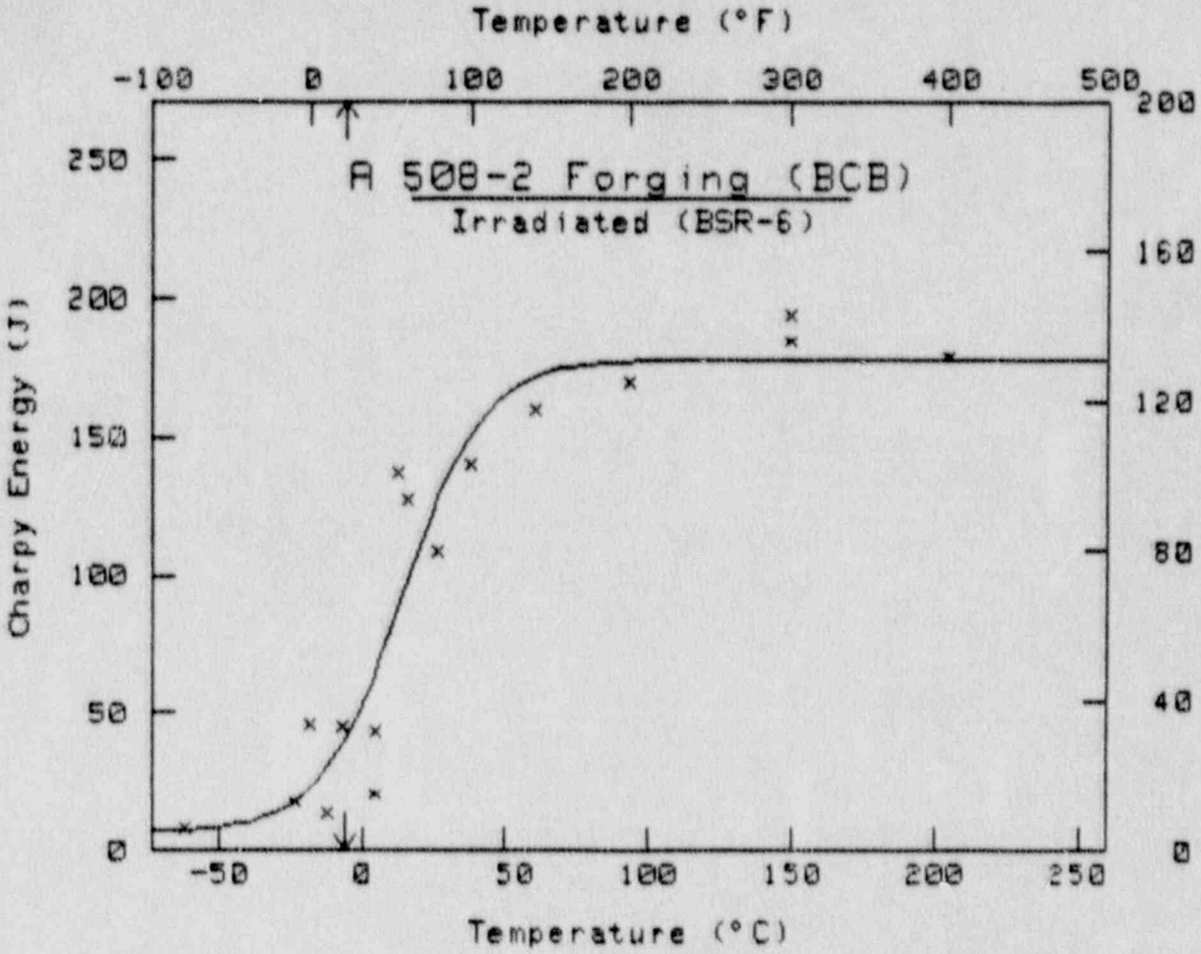
		English	Metric
A	=	-84.73 ft-lb	-114.88 J
B	=	232.12 ft-lb	314.71 J
C	=	182.85 °F	101.59 °C
To	=	-111.65 °F	-79.81 °C

Cv = 30 ft-lb (41 J) at T	=	-12.6 °F	-24.8 °C
Upper Shelf Energy	=	147.4 ft-lb	199.8 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-40	5.0	10	80	94.0
2	-40	5.0	11	80	66.0
3	-20	6.0	12	80	106.0
4	-20	8.0	13	140	142.0
5	0	54.0	14	140	112.0
6	0	67.0	15	300	141.0
7	20	58.0	16	300	151.0
8	40	72.0	17	400	151.0
9	40	72.0	18	400	132.0

O = Fictitious Point Added   * = Test Point Not Included



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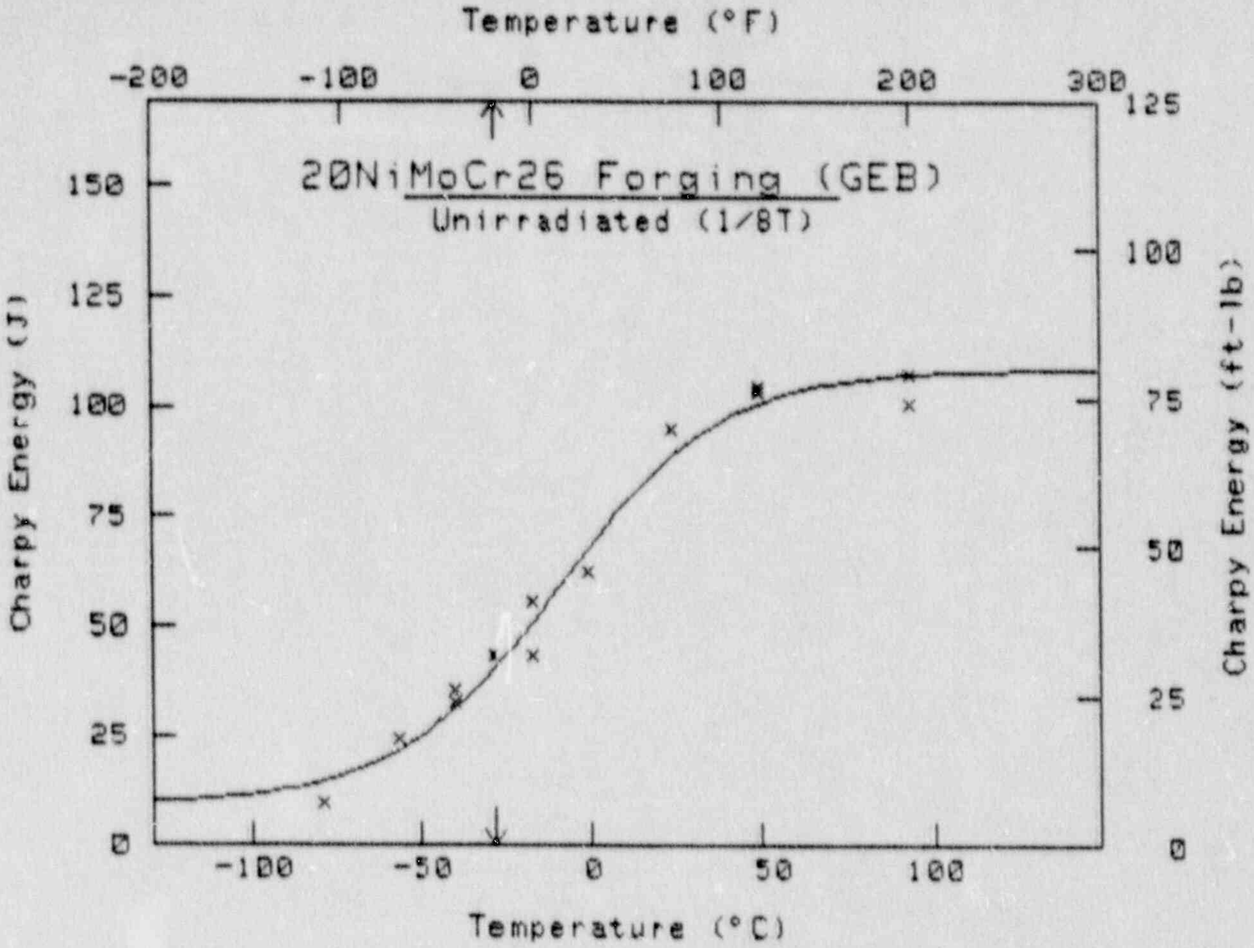
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	68.02 ft-lb	92.22 J
B =	63.10 ft-lb	85.55 J
C =	50.97 °F	28.31 °C
To =	57.15 °F	13.97 °C
Cv = 30 ft-lb (41 J) at T =	21.6 °F	-5.8 °C
Upper Shelf Energy =	131.1 ft-lb	177.8 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-80	6.0	9	60	94.0
2	-10	13.0	10	80	80.0
3	0	34.0	11	100	103.0
4	10	10.0	12	140	118.0
5	20	33.0	13	200	125.0
6	40	15.0	14	300	136.0
7	40	32.0	15	300	143.0
8	55	101.0	16	400	132.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

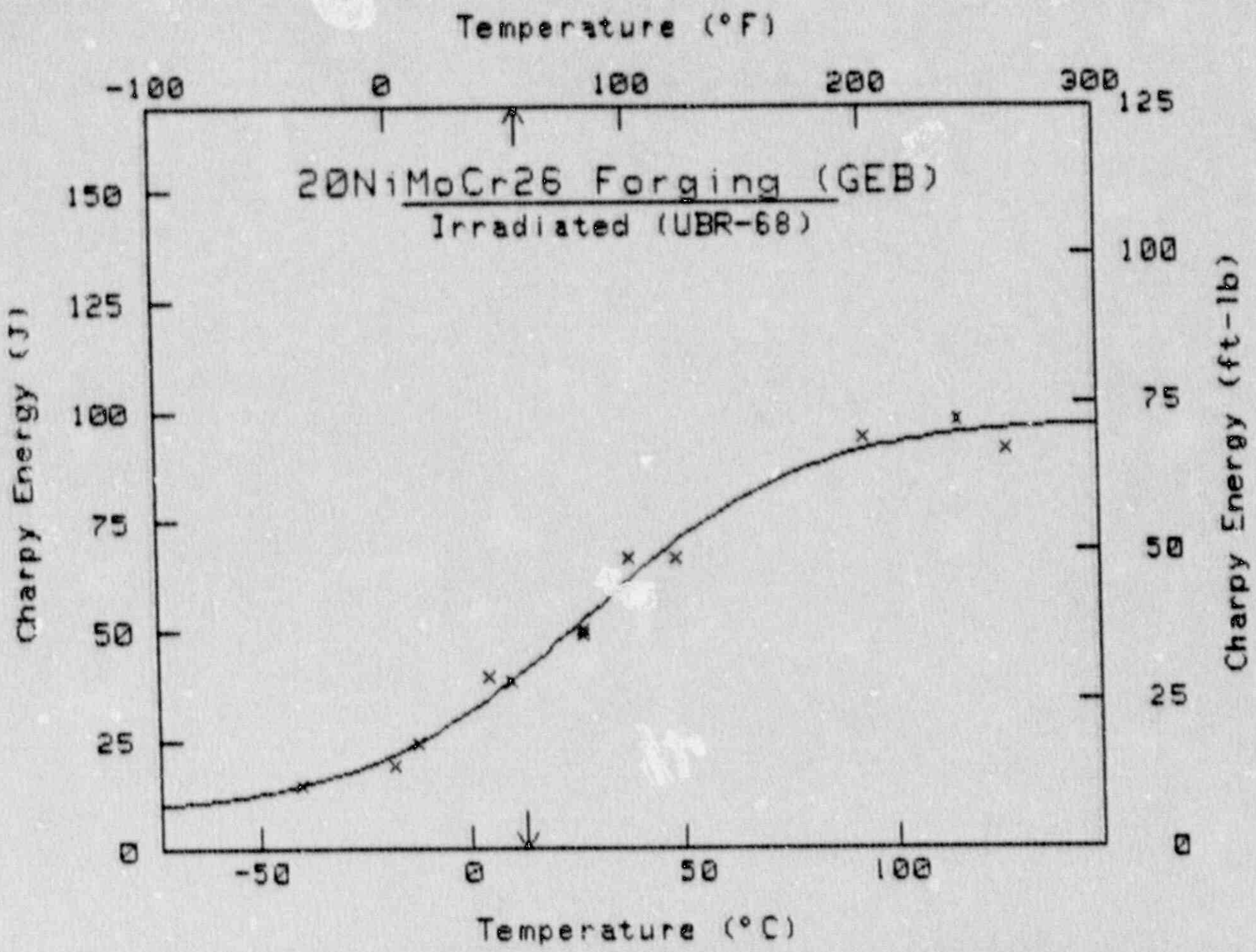
	English	Metric
A =	43.39 ft-lb	58.83 J
B =	36.53 ft-lb	49.52 J
C =	86.83 °F	48.24 °C
To =	14.53 °F	-9.71 °C

Cv = 30 ft-lb (41 J) at T =	-18.9 °F	-28.3 °C
Upper Shelf Energy =	79.9 ft-lb	108.4 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-110	7.0
2	-70	18.0
3	-40	24.0
4	-40	26.0
5	-20	32.0
6	0	32.0
7	0	41.0
8	30	46.0
9	30	46.0
10	75	70.0
11	120	76.0
12	120	77.0
13	200	74.0
14	200	79.0

O = Fictitious Point Added   * = Test Point Not Included



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

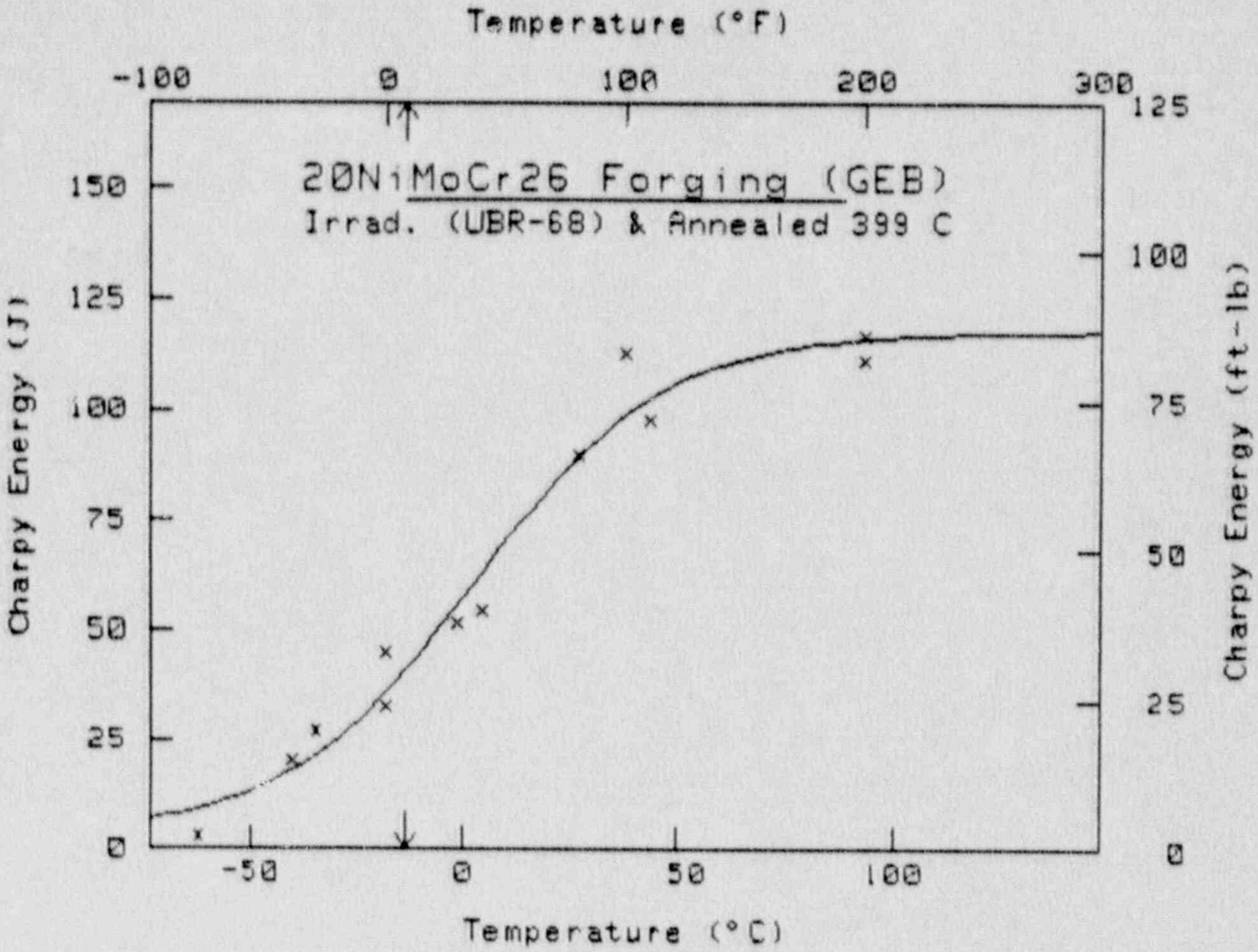
		English	Metric
A	=	38.96 ft-lb	52.82 J
B	=	32.99 ft-lb	44.73 J
C	=	94.81 °F	52.67 °C
To	=	81.62 °F	27.57 °C

Cv = 30 ft-lb (41 J) at T	=	55.2 °F	12.9 °C
Upper Shelf Energy	=	72.0 ft-lb	97.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	11.0
2	0	14.0
3	10	18.0
4	40	29.0
5	50	28.0
6	80	36.0
7	80	37.0
8	100	49.0
9	120	49.0
10	200	69.0
11	240	72.0
12	260	67.0

O = Fictitious Point Added * = Test Point Not Included



****

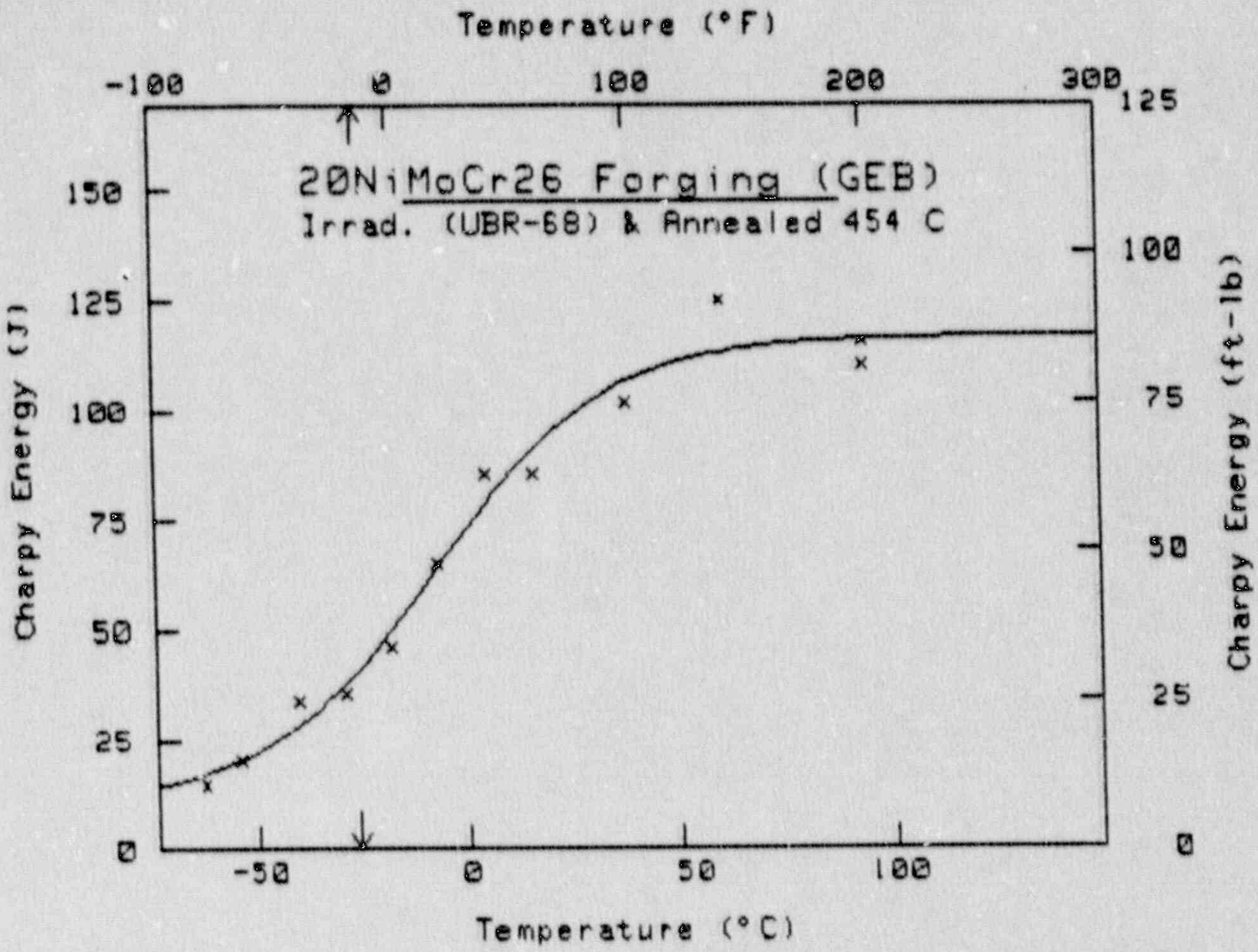
$C_v = A + B \tanh[(T - T_o)/C]$

	English	Metric
A =	44.68 ft-lb	60.57 J
B =	42.06 ft-lb	57.03 J
C =	78.94 °F	43.85 °C
To =	36.58 °F	2.54 °C
Cv = 30 ft-lb (41 J) at T =	7.8 °F	-13.4 °C
Upper Shelf Energy =	86.7 ft-lb	117.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-80	2.0
2	-40	15.0
3	-30	20.0
4	0	24.0
5	0	33.0
6	30	38.0
7	40	40.0
8	80	66.0
9	100	83.0
10	110	72.0
11	200	82.0
12	200	86.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

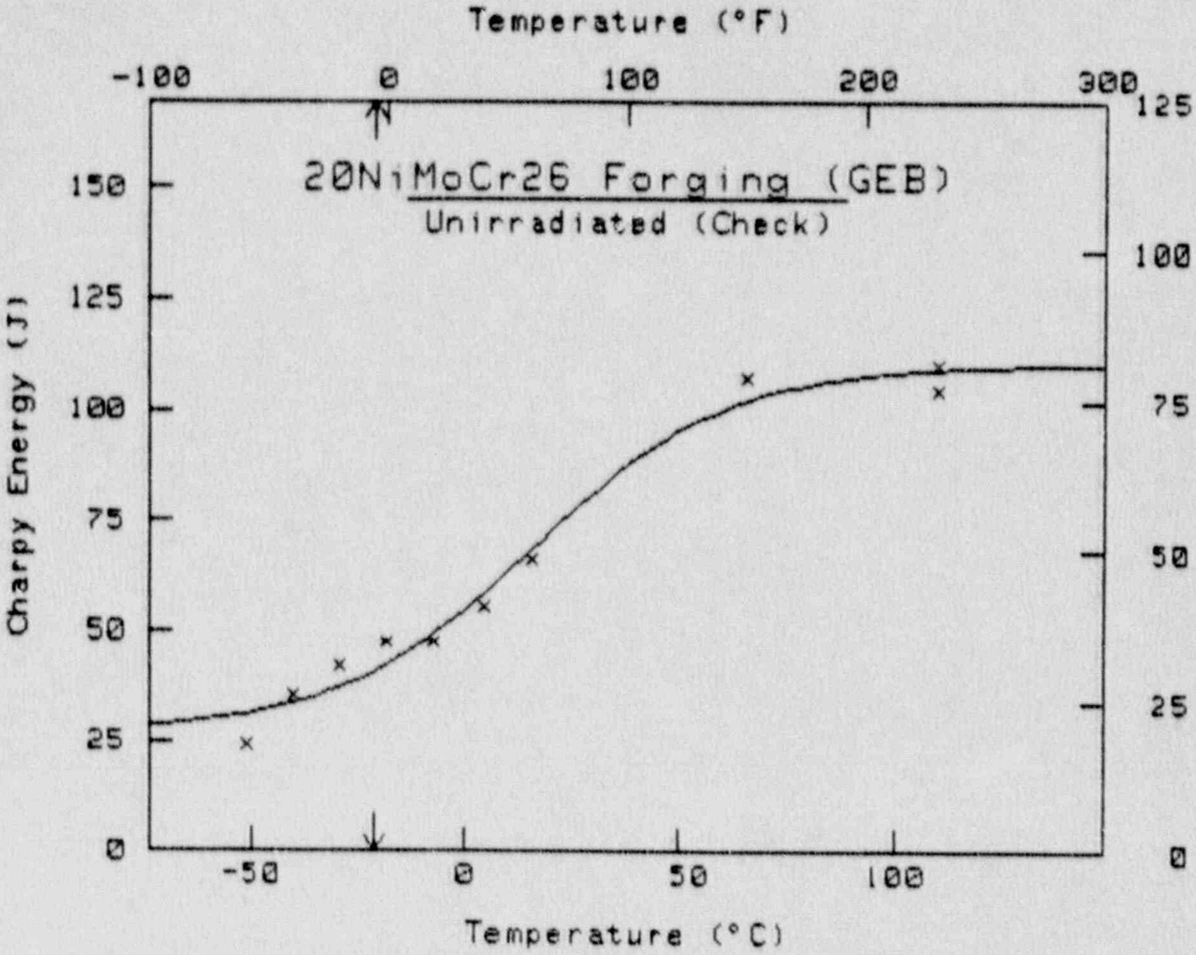
	English	Metric
A =	46.91 ft-lb	63.59 J
B =	39.10 ft-lb	53.02 J
C =	72.75 °F	40.42 °C
To =	18.91 °F	-7.27 °C

Cv = 30 ft-lb (41 J) at T =	-14.8 °F	-26.0 °C
Upper Shelf Energy =	86.0 ft-lb	116.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-80	11.0
2	-65	15.0
3	-40	25.0
4	-20	26.0
5	0	34.0
6	20	48.0
7	40	63.0
8	60	63.0
9	100	75.0
10	140	92.0
11	200	81.0
12	200	85.0

O = Fictitious Point Added   * = Test Point Not Included



****

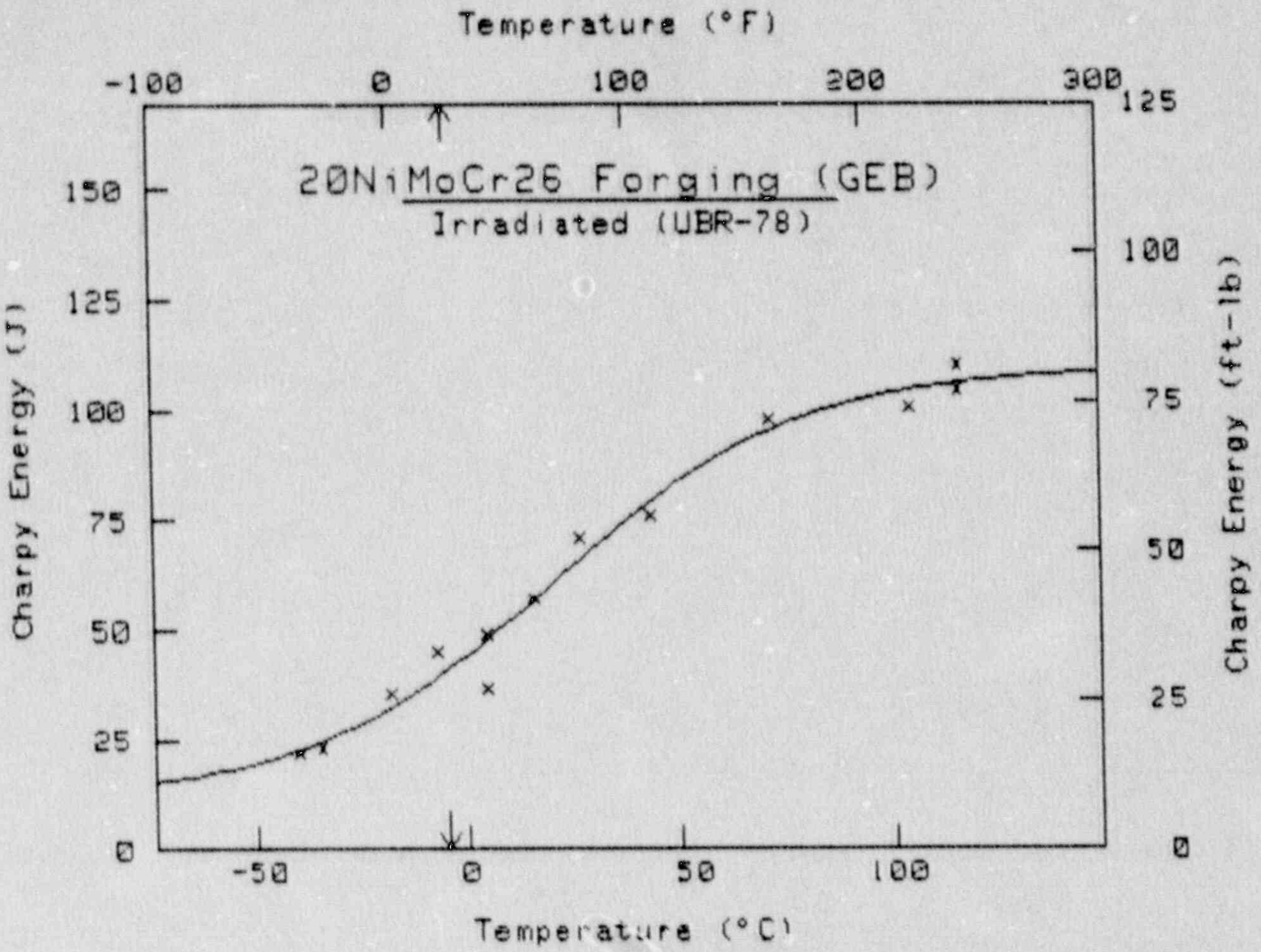
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	50.58 ft-lb	68.58 J
B =	30.69 ft-lb	41.61 J
C =	81.59 °F	45.33 °C
To =	60.48 °F	15.82 °C
Cv = 30 ft-lb (41 J) at T =	-5.8 °F	-21.0 °C
Upper Shelf Energy =	81.3 ft-lb	110.2 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-60	18.0
2	-40	26.0
3	-20	31.0
4	0	35.0
5	20	35.0
6	40	41.0
7	60	49.0
8	150	79.0
9	230	77.0
10	230	81.0

O = Fictitious Point Added   * = Test Point Not Included



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

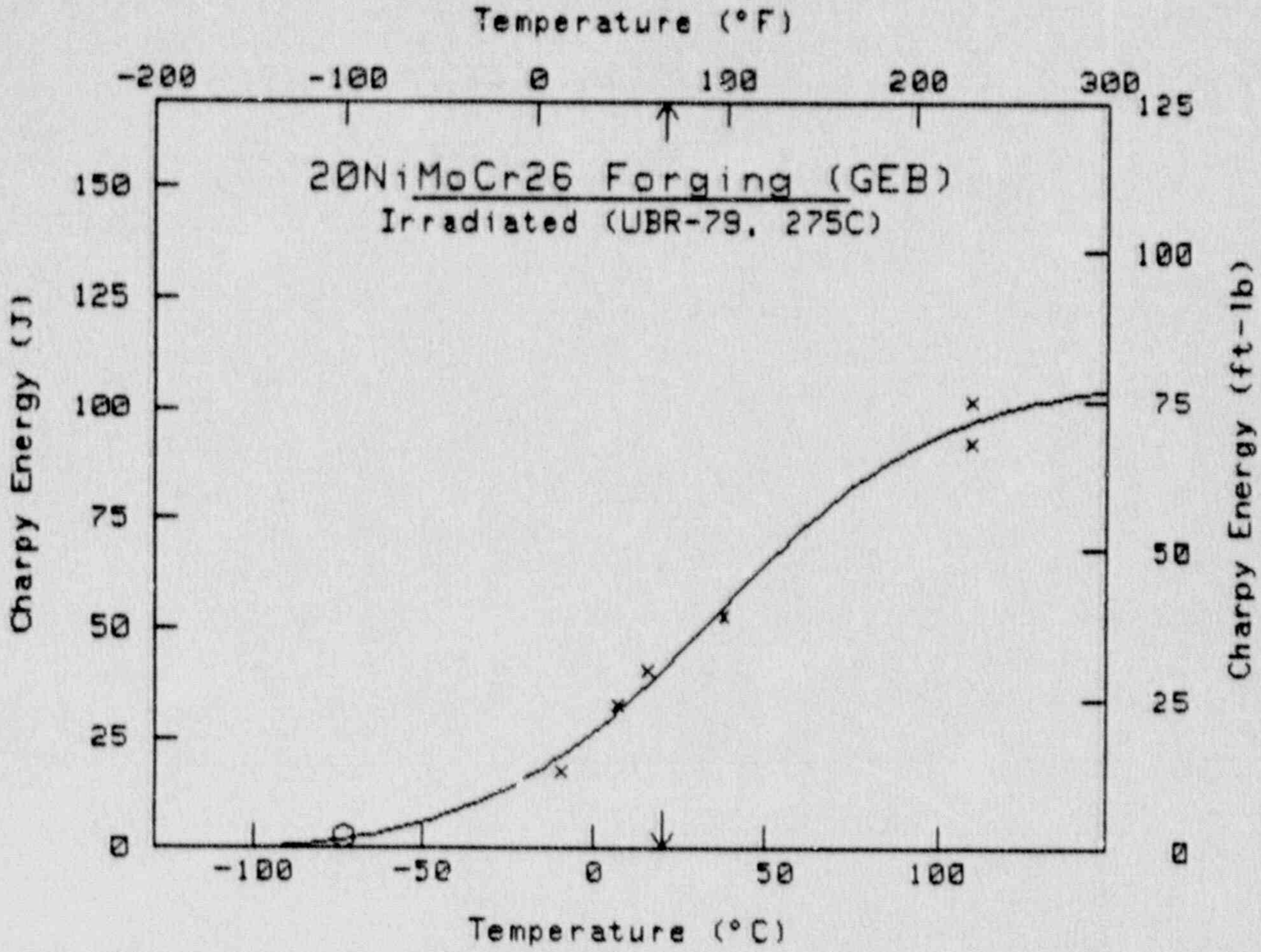
	English	Metric
A =	44.62 ft-lb	60.50 J
B =	36.07 ft-lb	48.90 J
C =	104.34 °F	57.97 °C
To =	68.54 °F	20.30 °C

Cv = 30 ft-lb (41 J) at T =	23.7 °F	-4.6 °C
Upper Shelf Energy =	80.7 ft-lb	109.4 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	16.0
2	-30	17.0
3	0	26.0
4	20	33.0
5	40	27.0
6	40	36.0
7	60	42.0
8	80	52.0
9	110	56.0
10	160	72.0
11	220	74.0
12	240	77.0
13	240	81.0

D = Fictitious Point Added   * = Test Point Not Included



****

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

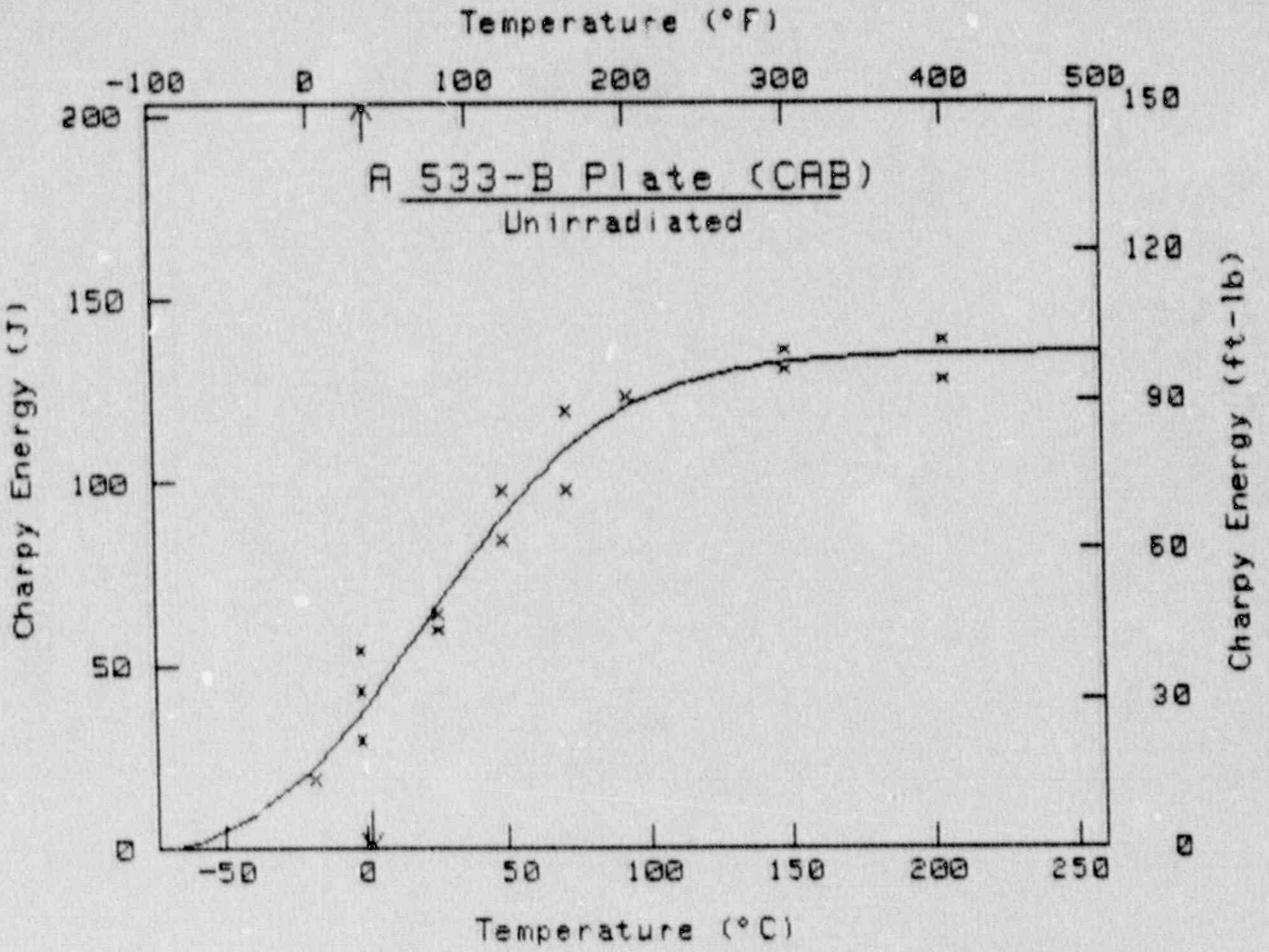
		English	Metric
A	=	38.87 ft-lb	52.70 J
B	=	40.51 ft-lb	54.92 J
C	=	121.67 °F	67.60 °C
To	=	95.06 °F	35.03 °C

Cv = 30 ft-lb (41 J) at T	=	68.0 °F	20.0 °C
Upper Shelf Energy	=	79.4 ft-lb	107.6 J

****

PT #		Temp (°F)	Energy (ft-lb)
1		15	13.0
2		45	24.0
3		60	30.0
4		100	39.0
5		230	68.0
6		230	75.0
7	O	-100	2.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

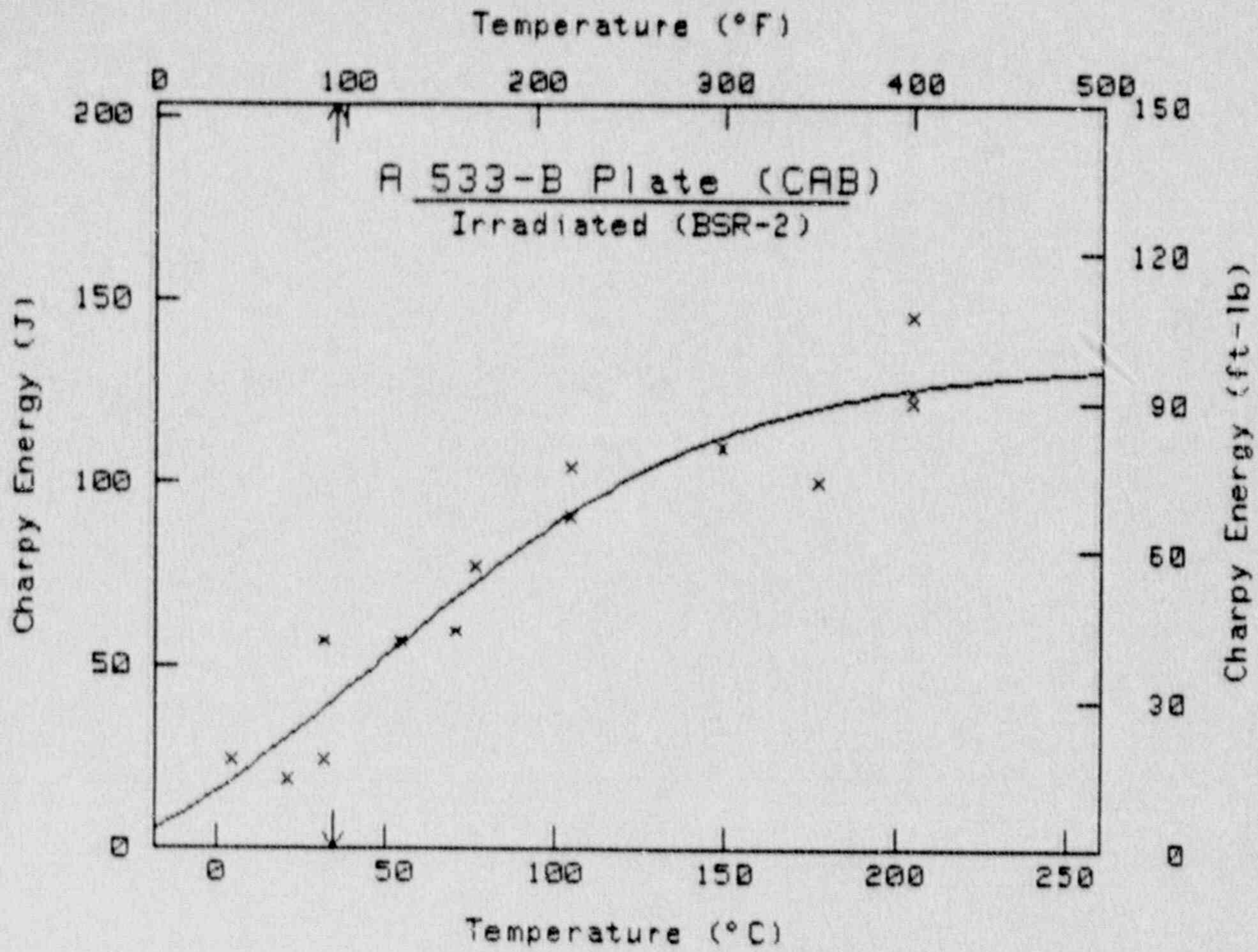
	English	Metric
A =	46.51 ft-lb	63.06 J
B =	53.11 ft-lb	72.01 J
C =	117.18 °F	65.10 °C
To =	73.63 °F	23.13 °C

Cv = 30 ft-lb (41 J) at T =	36.0 °F	2.2 °C
Upper Shelf Energy =	99.6 ft-lb	135.1 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	0	14.0	9	120	72.0
2	0	14.0	10	160	72.0
3	30	32.0	11	160	88.0
4	30	40.0	12	200	91.0
5	30	22.0	13	300	100.0
6	80	47.0	14	300	96.0
7	80	44.0	15	400	94.0
8	120	62.0	16	400	102.0

0 = Fictitious Point Added　　　　* = Test Point Not Included



****

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

		English	Metric
A	=	37.87 ft-lb	51.34 J
B	=	60.31 ft-lb	81.77 J
C	=	186.30 °F	103.50 °C
To	=	119.49 °F	48.61 °C

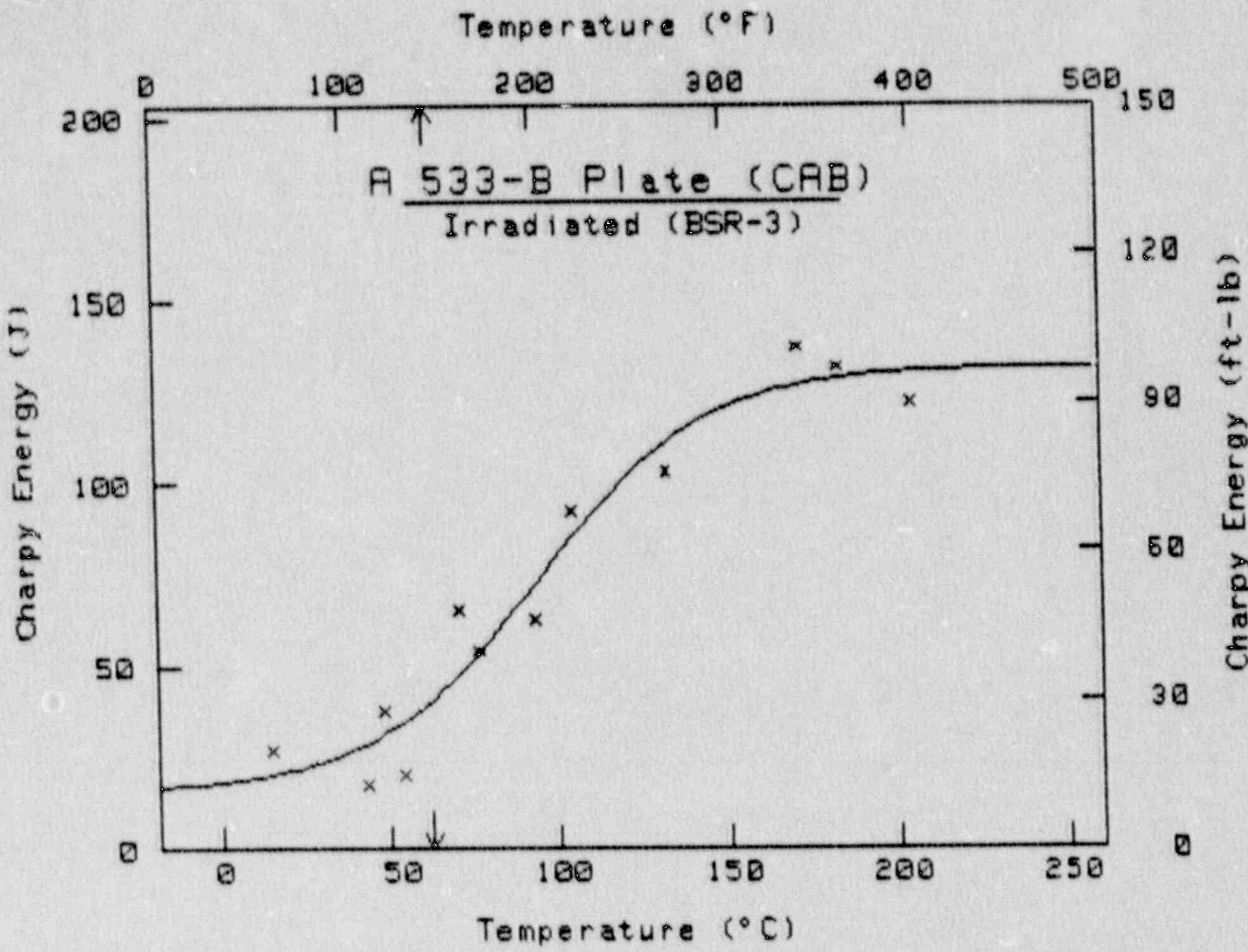
Cv = 30 ft-lb (41 J) at T = 95.0 °F 35.0 °C

Upper Shelf Energy = 98.2 ft-lb 133.1 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	40	18.0
2	70	14.0
3	90	42.0
4	90	18.0
5	130	42.0
6	160	44.0
7	170	57.0
8	220	77.0
9	220	67.0
10	300	81.0
11	350	74.0
12	400	90.0
13	400	92.0
14	400	107.0

0 = Fictitious Point Added * = Test Point Not Included



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

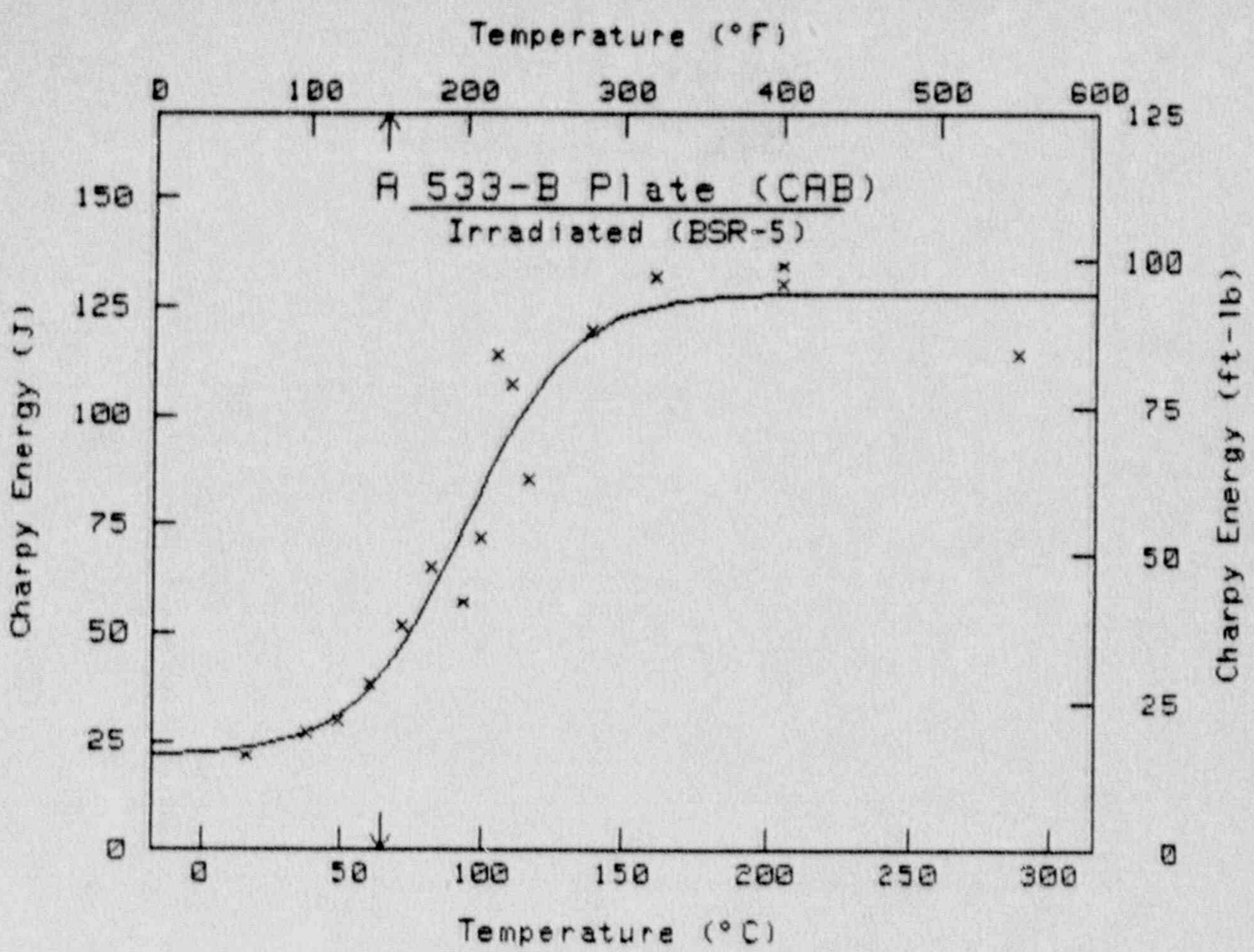
	English	Metric
A =	54.35 ft-lb	73.69 J
B =	42.69 ft-lb	57.88 J
C =	88.35 °F	49.09 °C
To =	202.17 °F	94.54 °C

Cv = 30 ft-lb (41 J) at T =	144.9 °F	62.7 °C
Upper Shelf Energy =	97.0 ft-lb	131.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	60	20.0
2	110	13.0
3	120	28.0
4	130	15.0
5	160	48.0
6	170	40.0
7	200	46.0
8	220	68.0
9	270	76.0
10	340	101.0
11	360	97.0
12	400	90.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

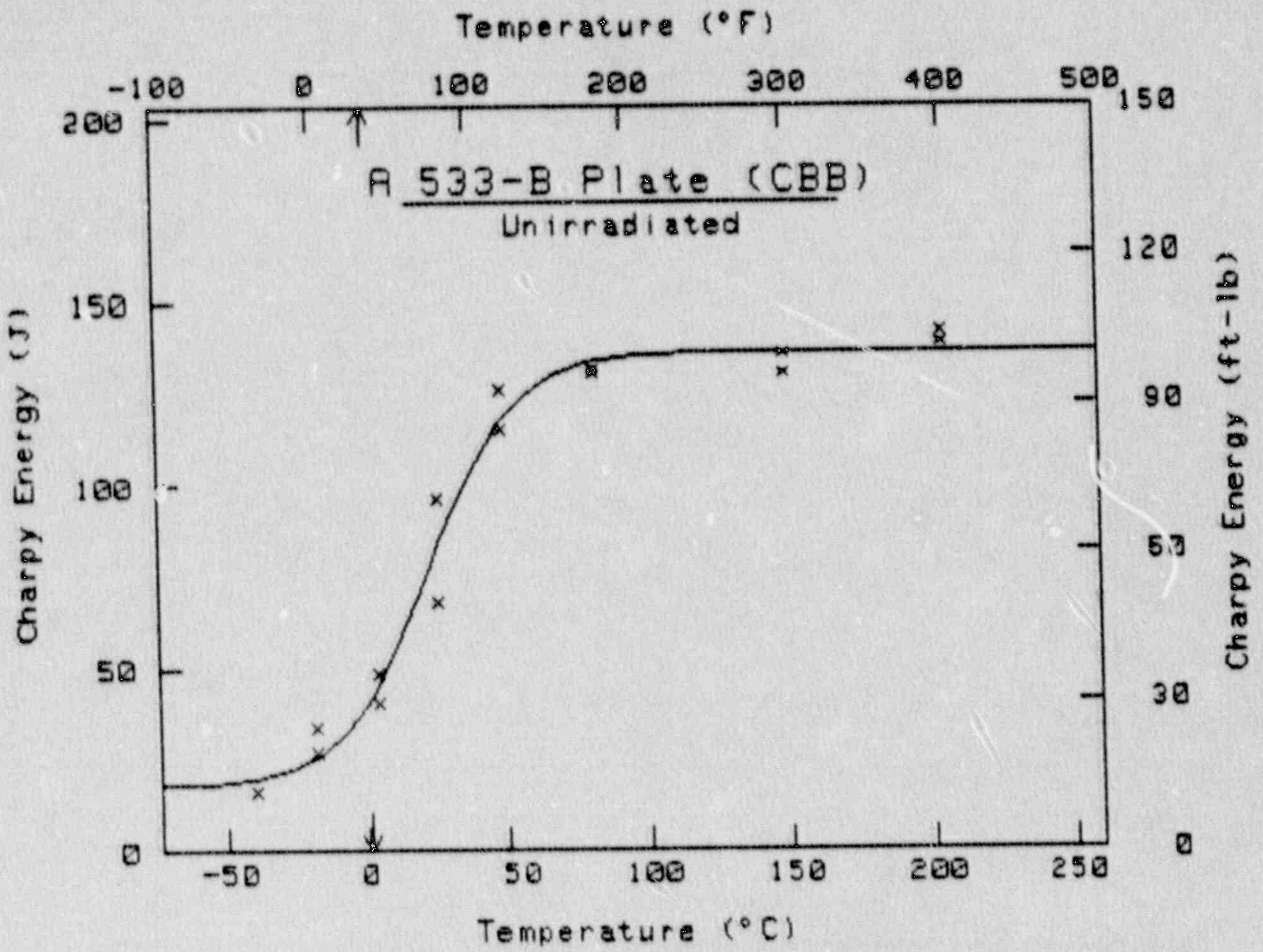
	English	Metric
A =	55.18 ft-lb	74.81 J
B =	39.20 ft-lb	53.14 J
C =	68.17 °F	37.87 °C
To =	200.23 °F	93.46 °C

Cv = 30 ft-lb (41 J) at T =	148.3 °F	64.6 °C
Upper Shelf Energy =	94.4 ft-lb	128.0 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	60	16.0	9	220	84.0
2	100	20.0	10	230	79.0
3	120	22.0	11	240	63.0
4	140	28.0	12	280	88.0
5	160	38.0	13	320	97.0
6	180	48.0	14	400	99.0
7	200	42.0	15	400	96.0
8	210	53.0	16	550	84.0

O = Fictitious Point Added   * = Test Point Not Included



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

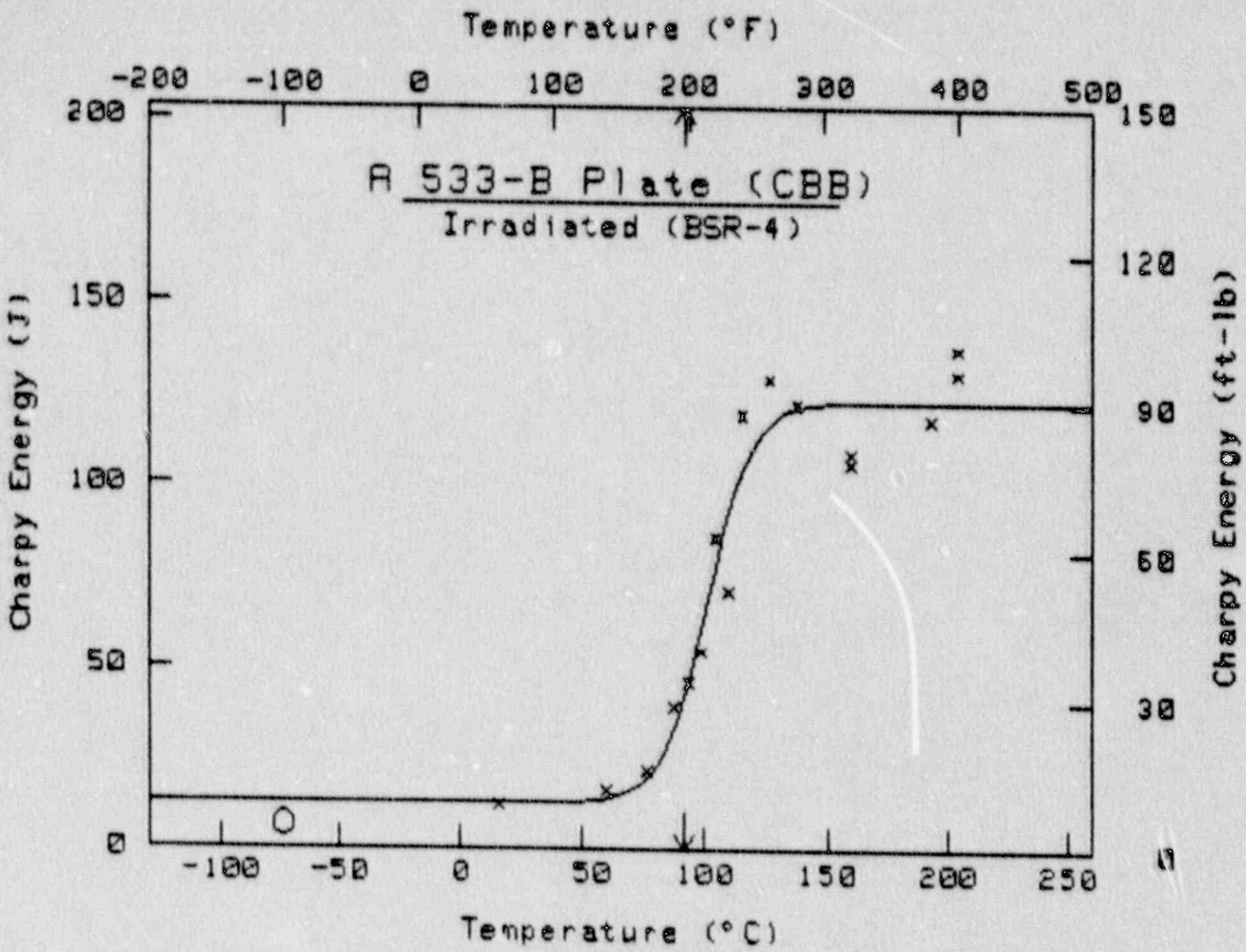
	English	Metric
A =	56.67 ft-lb	76.83 J
B =	43.57 ft-lb	59.07 J
C =	55.84 °F	31.02 °C
To =	73.10 °F	22.83 °C

Cv = 30 ft-lb (41 J) at T =	33.3 °F	.7 °C
Upper Shelf Energy =	100.2 ft-lb	135.9 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-40	12.0	9	120	93.0
2	-40	12.0	10	120	85.0
3	0	20.0	11	180	96.0
4	0	25.0	12	180	97.0
5	40	36.0	13	300	100.0
6	40	30.0	14	300	96.0
7	80	71.0	15	400	104.0
8	80	50.0	16	400	102.0

O = Fictitious Point Added * = Test Point Not Included



****

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

		English	Metric
A	=	49.93 ft-lb	67.69 J
B	=	40.50 ft-lb	54.91 J
C	=	32.69 °F	18.16 °C
To	=	214.14 °F	101.19 °C

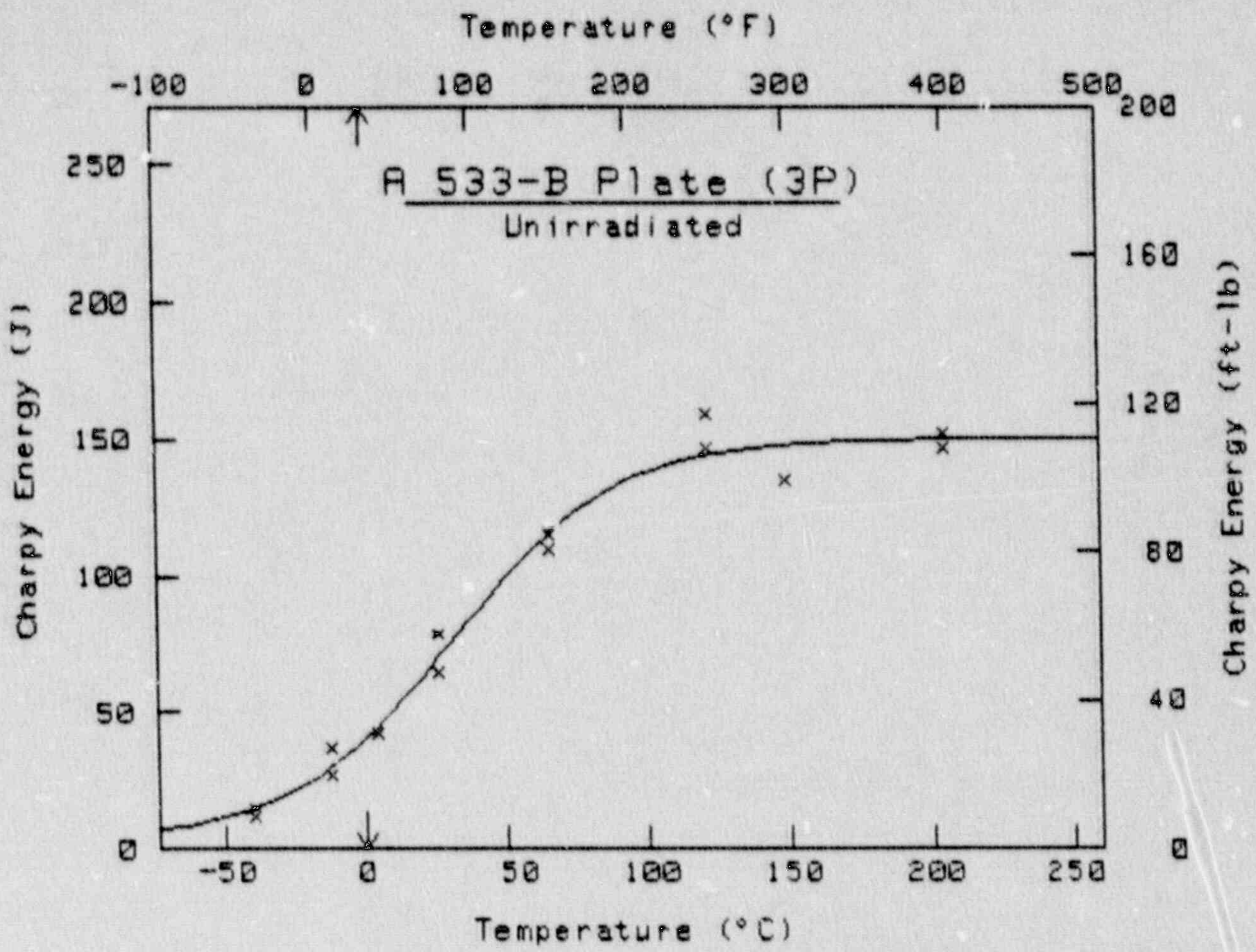
Cv = 30 ft-lb (41 J) at T	=	196.5 °F	91.4 °C
Upper Shelf Energy	=	90.4 ft-lb	122.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	60	9.0
2	140	12.0
3	170	16.0
4	190	29.0
5	200	34.0
6	210	40.0
7	220	63.0
8	230	52.0
9	240	88.0

PT #	Temp (°F)	Energy (ft-lb)
10	260	95.0
11	280	90.0
12	320	80.0
13	320	78.0
14	380	87.0
15	400	96.0
16	400	101.0
17 O	-100	5.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

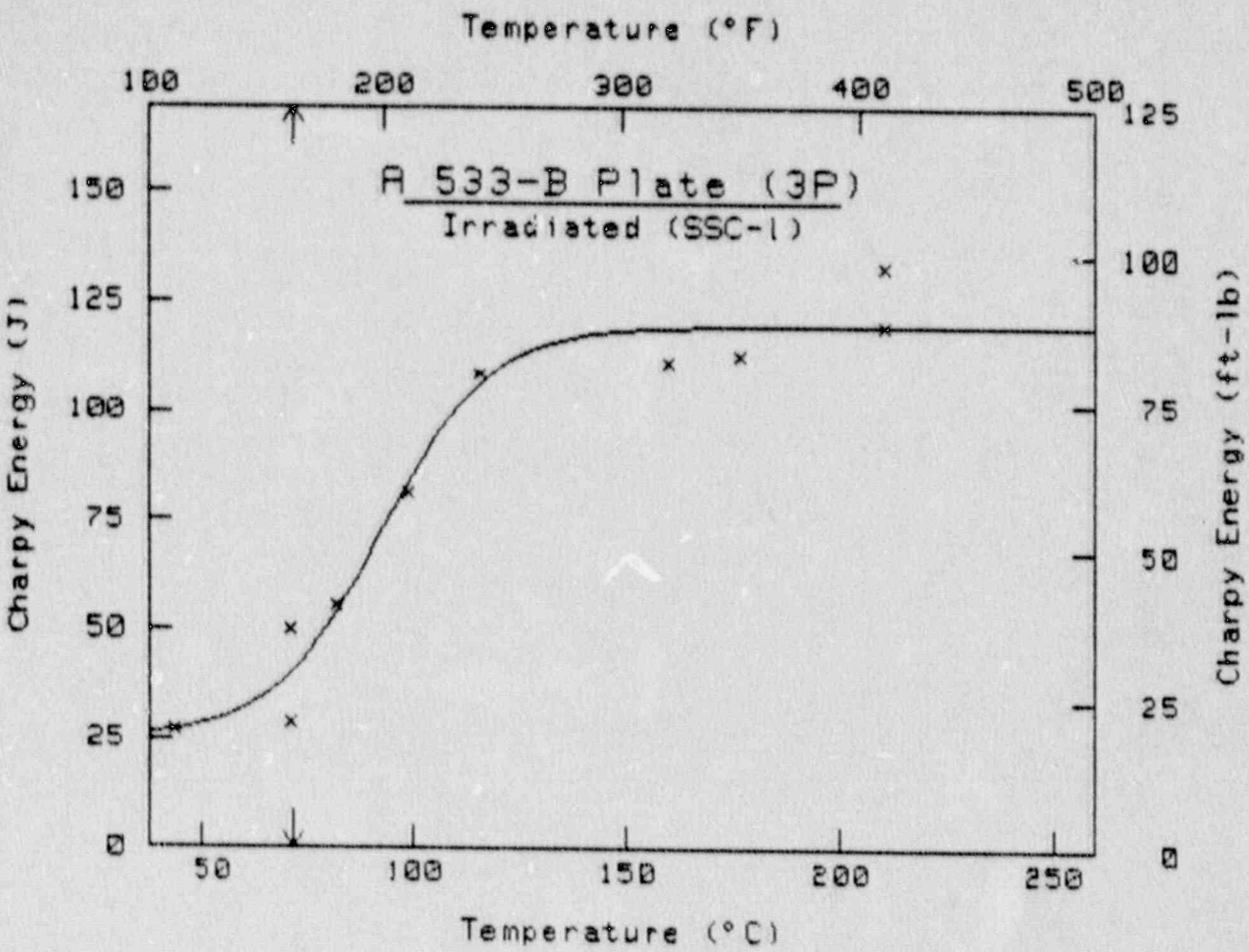
	English	Metric
A =	56.43 ft-lb	76.51 J
B =	54.10 ft-lb	73.36 J
C =	104.14 °F	57.86 °C
To =	88.39 °F	31.33 °C

Cv = 30 ft-lb (41 J) at T =	32.8 °F	.4 °C
Upper Shelf Energy =	110.5 ft-lb	149.9 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	11.0
2	-40	9.0
3	10	27.0
4	10	20.0
5	40	31.0
6	80	58.0
7	80	48.0
8	150	81.0
9	150	85.0
10	250	117.0
11	250	108.0
12	300	99.0
13	400	112.0
14	400	108.0

0 = Fictitious Point Added   * = Test Point Not Included



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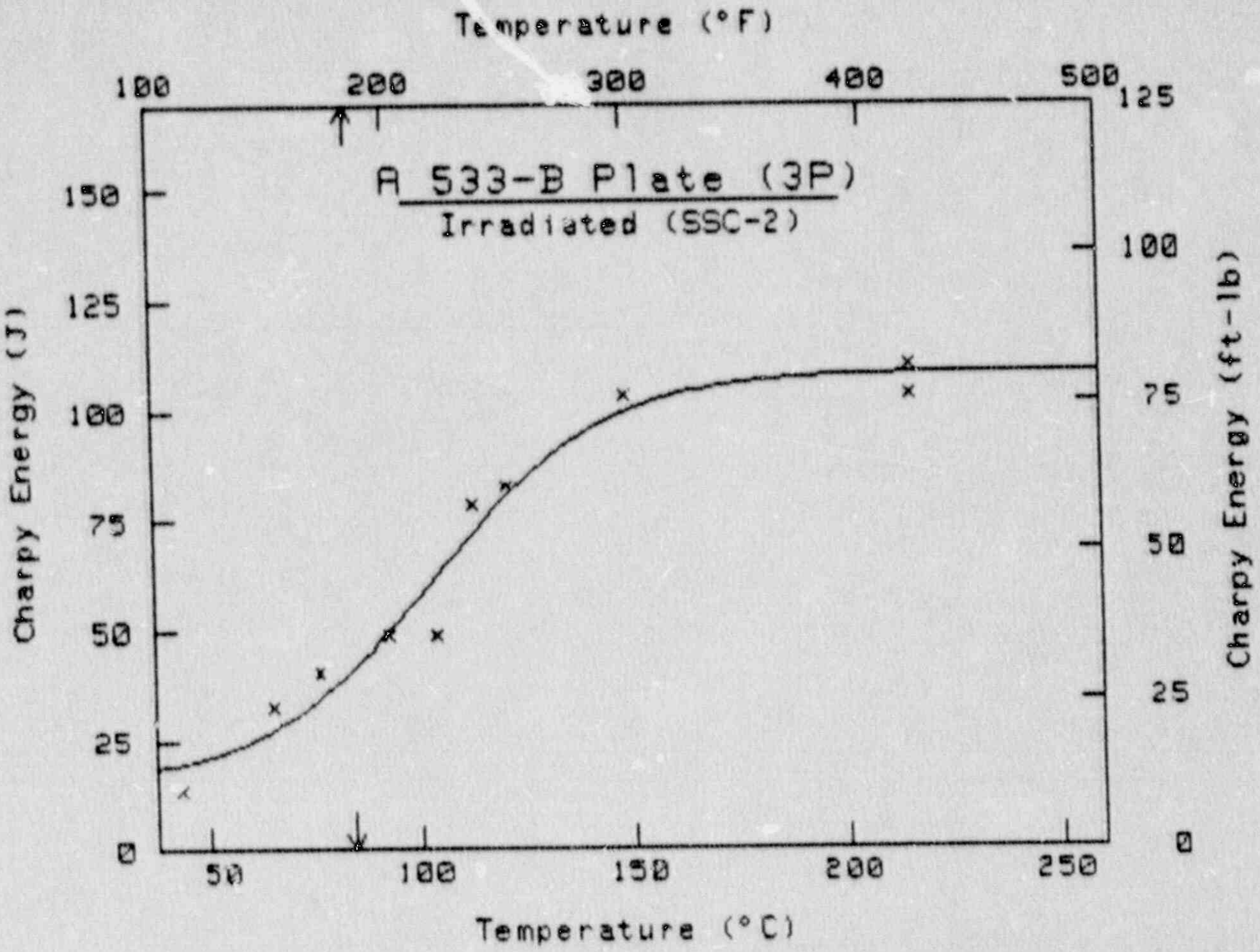
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	53.26 ft-lb	72.21 J
B =	34.86 ft-lb	47.27 J
C =	46.26 °F	25.70 °C
To =	198.81 °F	92.67 °C
Cv = 30 ft-lb (41 J) at T =	161.6 °F	72.0 °C
Upper Shelf Energy =	88.1 ft-lb	119.5 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	110	20.0
2	160	37.0
3	160	21.0
4	180	41.0
5	210	60.0
6	240	80.0
7	320	82.0
8	350	83.0
9	410	98.0
10	410	88.0

0 = Fictitious Point Added   * = Test Point Not Included



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

	English	Metric
A =	45.61 ft-lb	61.84 J
B =	34.30 ft-lb	46.50 J
C =	72.06 °F	40.03 °C
To =	219.03 °F	103.91 °C

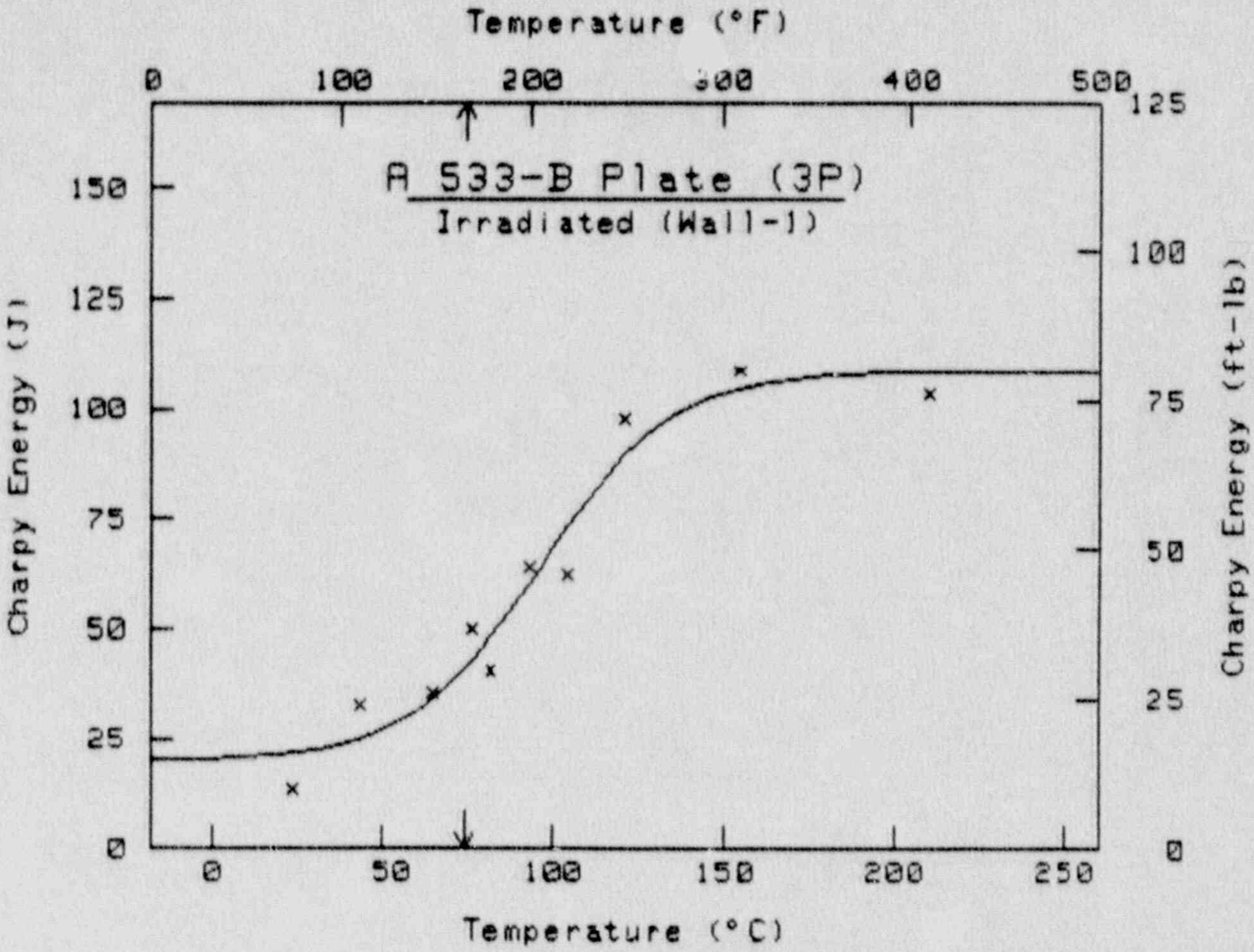
Cv = 30 ft-lb (41 J) at T = 183.6 °F 84.2 °C

Upper Shelf Energy = 79.9 ft-lb 108.3 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	110	10.0
2	150	24.0
3	170	30.0
4	200	36.0
5	220	36.0
6	235	58.0
7	250	61.0
8	300	76.0
9	420	76.0
10	420	81.0

O = Fictitious Point Added * = Test Point Not Included



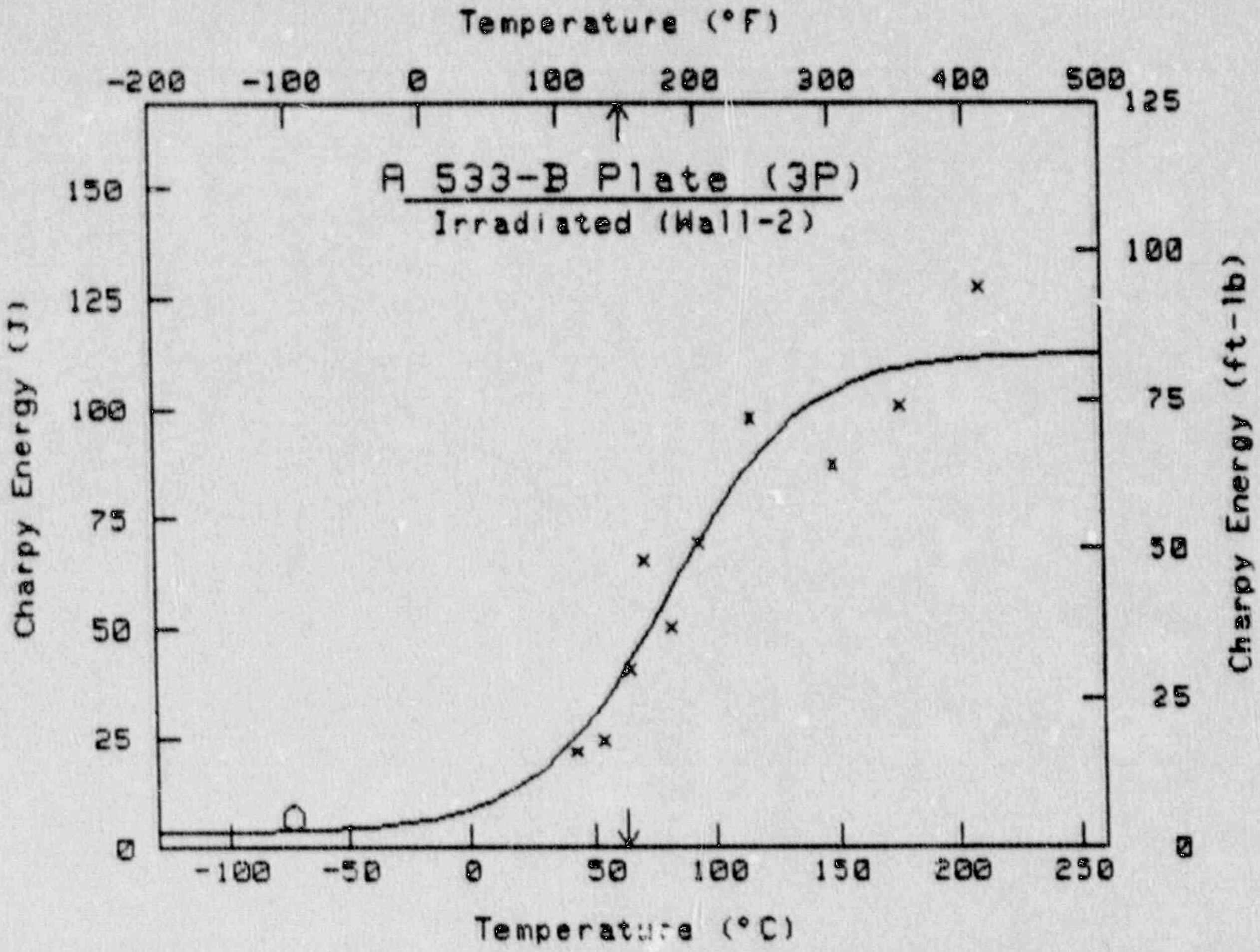
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	47.36 ft-lb	64.22 J
B	=	32.63 ft-lb	44.25 J
C	=	67.81 °F	37.67 °C
To	=	206.01 °F	96.67 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	165.8 °F	74.3 °C
Upper Shelf Energy =	80.0 ft-lb	108.5 J

PT #	Temp (°F)	Energy (ft-lb)
1	75	10.0
2	110	24.0
3	150	26.0
4	170	37.0
5	180	30.0
6	200	47.0
7	220	46.0
8	250	72.0
9	310	80.0
10	410	76.0

O = Fictitious Point Added * = Test Point Not Included



****

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

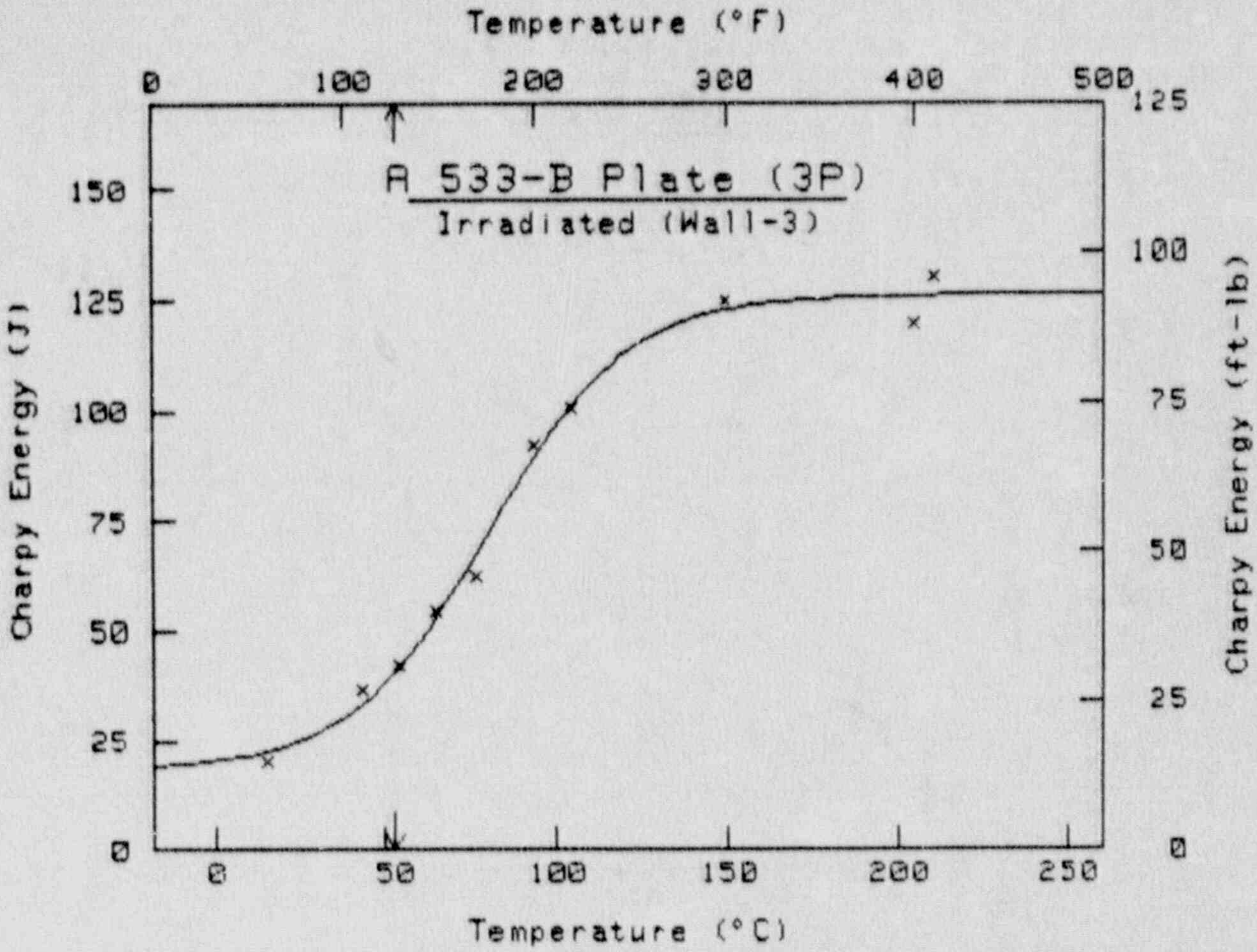
	English	Metric
A =	42.67 ft-lb	57.85 J
B =	40.14 ft-lb	54.43 J
C =	100.11 °F	55.62 °C
To =	179.21 °F	81.78 °C

Cv = 30 ft-lb (41 J) at T =	146.5 °F	63.6 °C
Upper Shelf Energy =	82.8 ft-lb	112.3 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	110	16.0
2	130	18.0
3	150	30.0
4	160	48.0
5	180	37.0
6	200	51.0
7	240	72.0
8	300	64.0
9	350	74.0
10	410	94.0
11 O	-100	5.0

O = Fictitious Point Added * = Test Point Not Included



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

		English	Metric
A	=	53.28 ft-lb	72.23 J
B	=	39.65 ft-lb	53.76 J
C	=	72.31 °F	40.17 °C
To	=	176.63 °F	80.35 °C

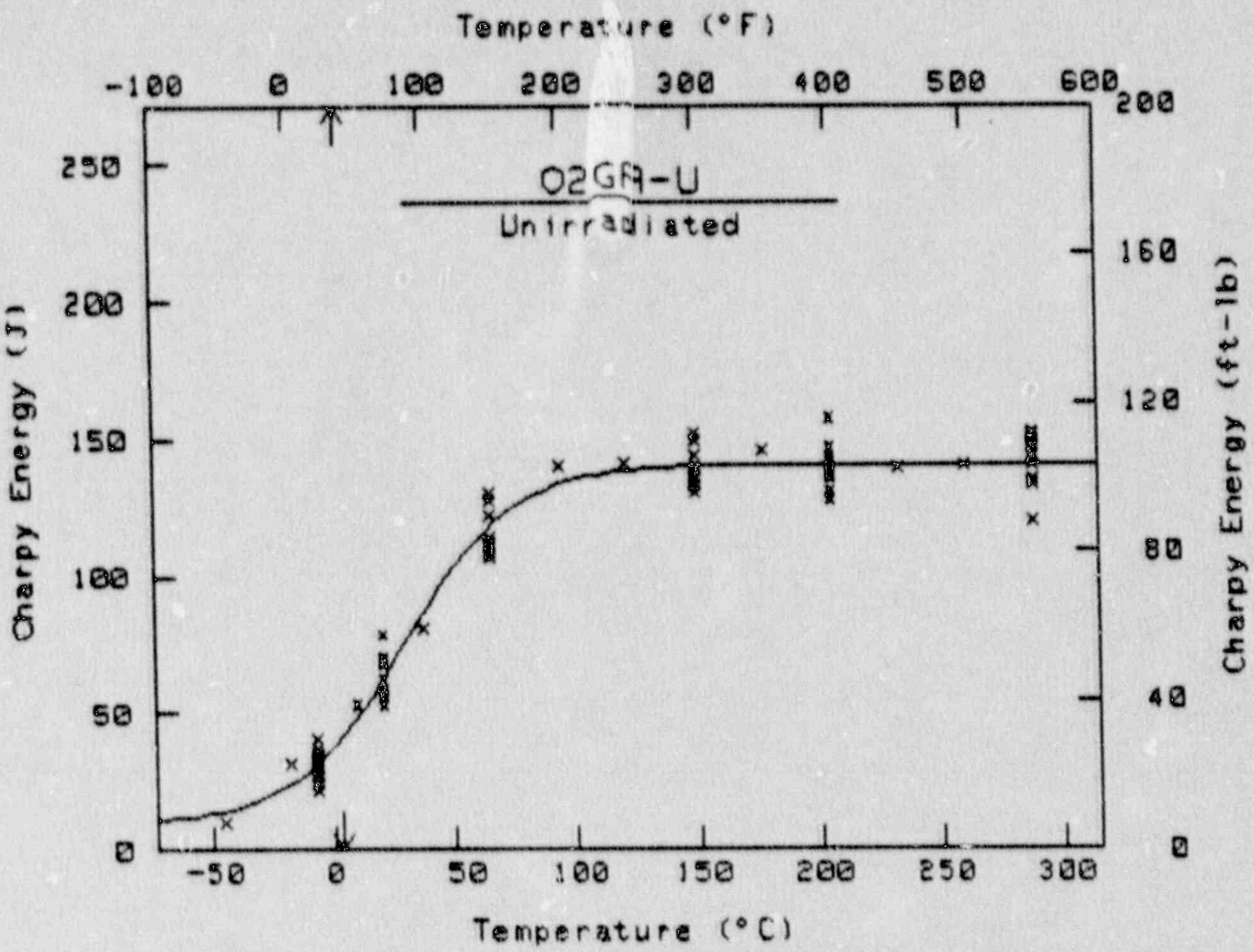
Cv = 30 ft-lb (41 J) at T = 128.0 °F 53.3 °C

Upper Shelf Energy = 92.9 ft-lb 126.0 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	60	15.0
2	110	27.0
3	130	31.0
4	150	40.0
5	170	46.0
6	200	68.0
7	220	74.0
8	300	92.0
9	400	88.0
10	410	96.0

O = Fictitious Point Added * = Test Point Not Included



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

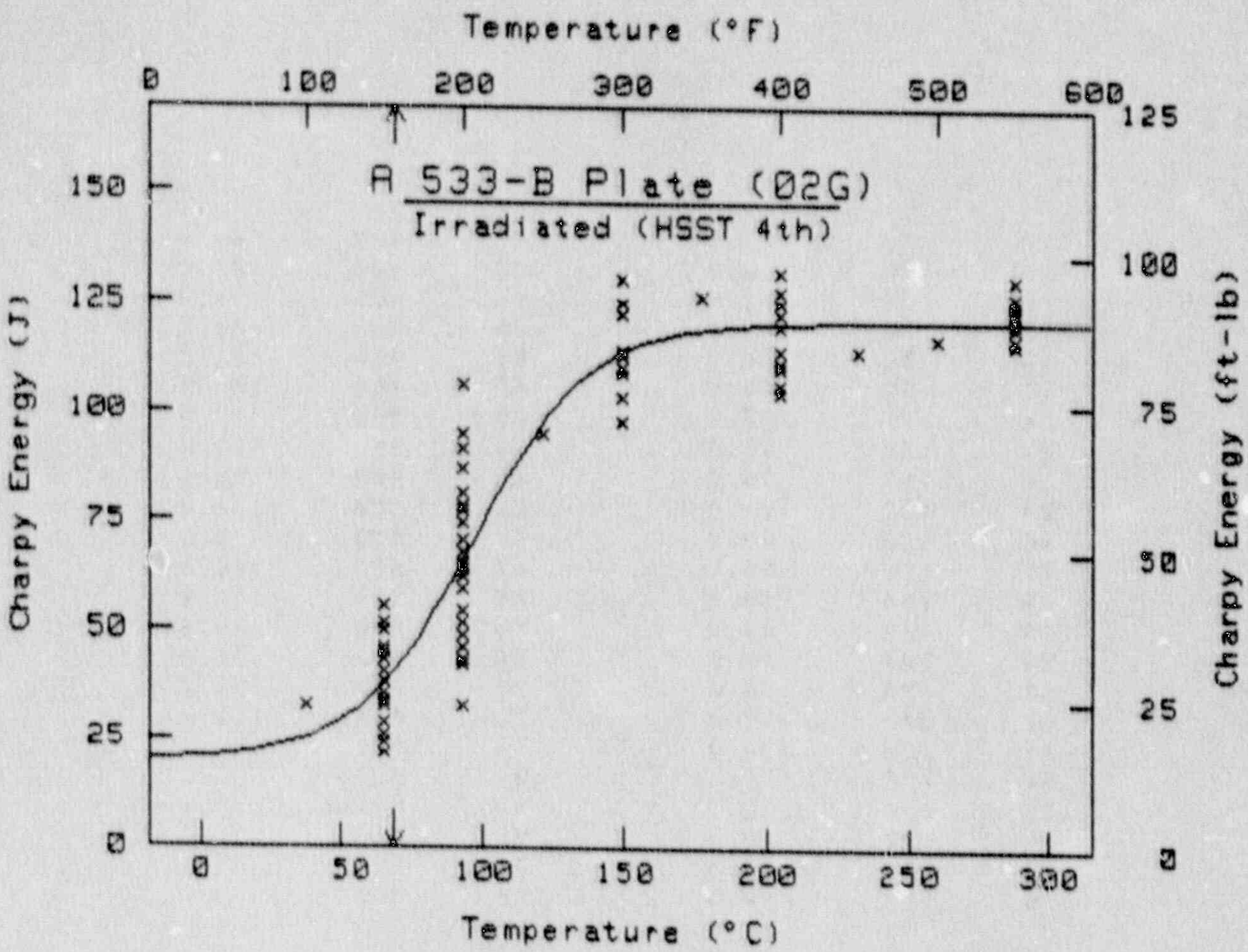
	English	Metric
A =	55.28 ft-lb	74.95 J
B =	48.28 ft-lb	65.46 J
C =	81.27 °F	45.15 °C
To =	85.06 °F	29.48 °C

Cv = 30 ft-lb (41 J) at T =	37.8 °F	3.2 °C
Upper Shelf Energy =	103.6 ft-lb	140.4 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-50	7.5	38	300	103.0
2	0	23.0	39	300	102.0
3	20	27.0	40	300	96.0
4	20	24.0	41	300	98.0
5	20	18.0	42	300	100.0
6	20	20.0	43	300	102.0
7	20	1[illegible].0	44	300	110.0
8	20	22.0	45	300	106.0
9	20	25.0	46	300	112.0
10	20	30.0	47	300	98.0
11	20	26.0	48	300	106.0
12	20	20.0	49	350	107.0
13	50	39.0	50	400	105.0
14	70	41.0	51	400	96.0
15	70	50.0	52	400	108.0
16	70	39.0	53	400	116.0
17	70	42.0	54	400	100.0
18	70	43.0	55	400	100.5
19	70	58.0	56	400	94.0

20	70	51.0	57	400	104.0
21	70	43.0	58	400	102.0
22	70	52.0	59	400	96.0
23	70	46.0	60	400	101.0
24	100	59.5	61	450	102.5
25	150	90.0	62	500	103.5
26	150	84.0	63	550	110.0
27	150	83.0	64	550	103.0
28	150	79.0	65	550	98.0
29	150	83.0	66	550	108.0
30	150	82.0	67	550	99.0
31	150	80.0	68	550	106.0
32	150	94.0	69	550	111.0
33	150	96.0	70	550	108.0
34	150	96.0	71	550	105.0
35	150	94.0	72	550	88.0
36	200	103.0	73	550	112.0
37	250	104.0			

O = Fictitious Point Added   * = Test Point Not Included



****

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

	English	Metric
A =	51.78 ft-lb	70.21 J
B =	37.08 ft-lb	50.28 J
C =	72.96 °F	40.53 °C
To =	205.73 °F	96.51 °C

Cv = 30 ft-lb (41 J) at T =	156.6 °F	69.2 °C
Upper Shelf Energy =	88.9 ft-lb	120.5 J

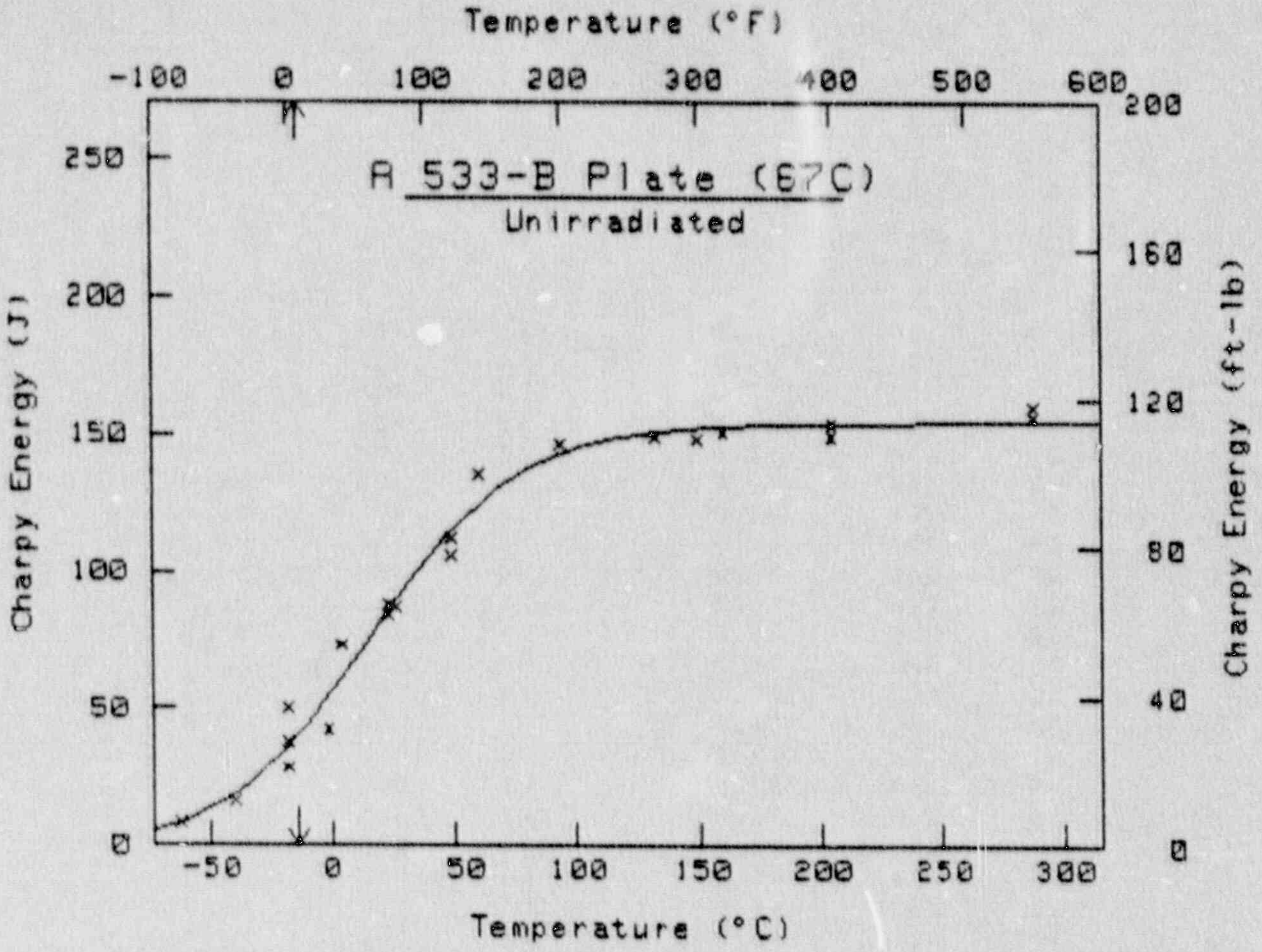
****

PT #	Temp (°F)	Energy (ft-lb)
1	100	24.0
2	150	41.0
3	150	24.0
4	150	34.0
5	150	21.0
6	150	33.0
7	150	19.0
8	150	24.0
9	150	16.0
10	150	28.0
11	150	18.0
12	150	25.0
13	150	30.0
14	150	18.0
15	150	30.0
16	150	26.0
17	150	28.0
18	150	24.0
19	150	28.0

PT #	Temp (°F)	Energy (ft-lb)
47	200	44.0
48	200	67.5
49	200	55.0
50	250	70.0
51	300	84.0
52	300	90.0
53	300	76.0
54	300	81.0
55	300	80.0
56	300	92.0
57	300	96.0
58	300	83.0
59	300	80.0
60	300	72.0
61	300	84.0
62	300	81.0
63	350	93.0
64	400	78.0
65	400	81.0

20	150	30.0	66	400	77.0
21	150	38.0	67	400	92.0
22	150	37.0	68	400	90.0
23	150	28.0	69	400	88.0
24	150	32.0	70	400	90.0
25	150	28.0	71	400	92.0
26	200	47.0	72	400	92.0
27	200	64.0	73	400	82.0
28	200	58.0	74	400	94.0
29	200	24.0	75	400	84.0
30	200	40.0	76	400	97.0
31	200	38.0	77	450	84.0
32	200	32.0	78	500	86.0
33	200	34.0	79	550	90.0
34	200	78.0	80	550	92.0
35	200	31.0	81	550	93.0
36	200	70.0	82	550	86.0
37	200	48.0	83	550	89.0
38	200	44.0	84	550	88.0
39	200	47.0	85	550	92.0
40	200	46.0	86	550	91.0
41	200	50.0	87	550	91.0
42	200	52.0	88	550	90.0
43	200	36.0	89	550	96.0
44	200	60.0	90	550	85.0
45	200	57.0	91	550	92.0
46	200	58.0			

O = Fictitious Point Added   * = Test Point Not Included

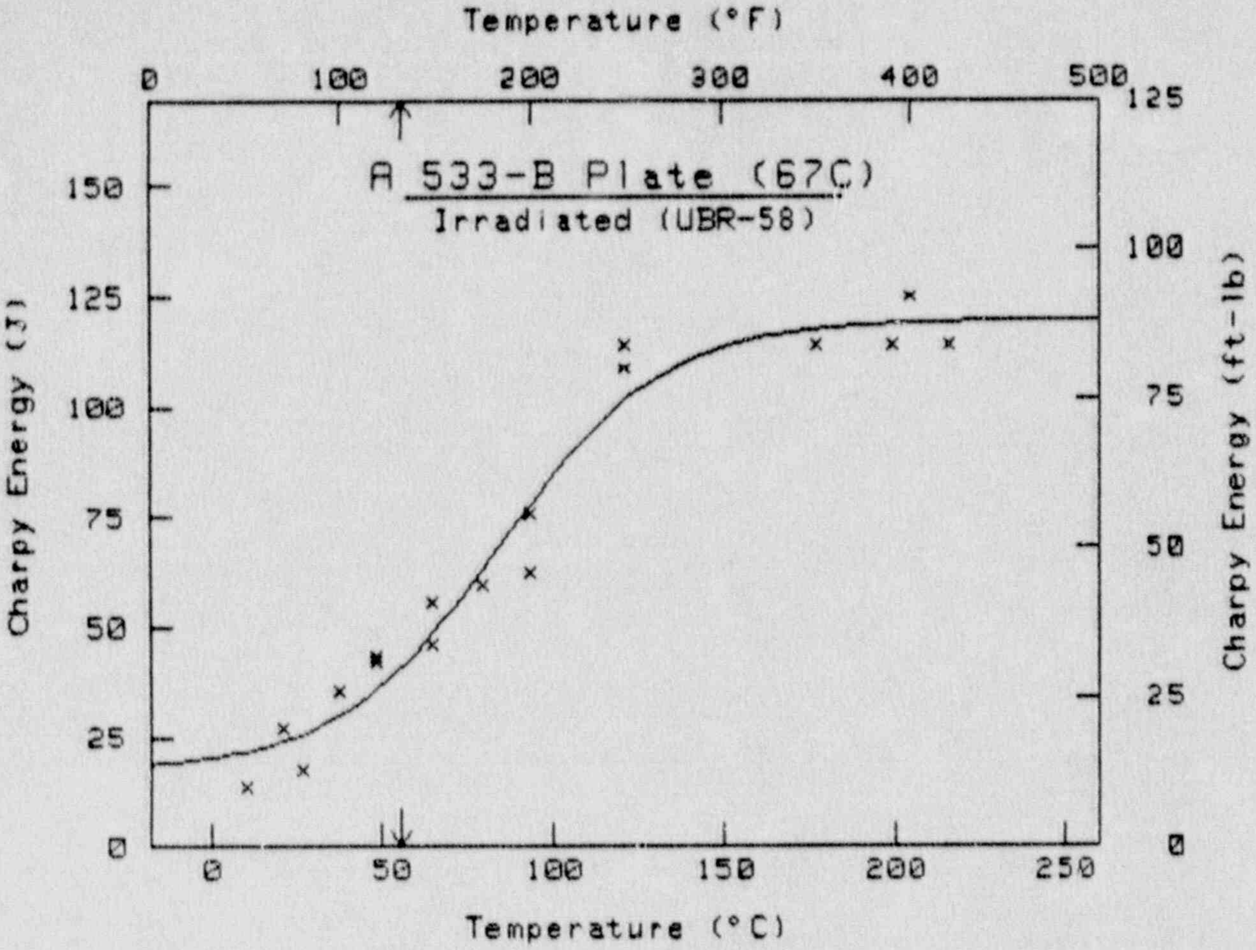


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	55.59 ft-lb	75.37 J
B =	57.96 ft-lb	78.59 J
C =	110.27 °F	61.26 °C
To =	59.71 °F	15.40 °C
Cv = 30 ft-lb (41 J) at T =	7.4 °F	-13.7 °C
Upper Shelf Energy =	113.6 ft-lb	154.0 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-80	6.0	12	120	78.0
2	-40	12.0	13	140	100.0
3	0	37.0	14	200	108.0
4	0	28.0	15	270	110.0
5	0	21.0	16	300	109.0
6	30	31.0	17	320	111.0
7	40	54.0	18	400	110.0
8	75	65.0	19	400	113.0
9	75	62.0	20	550	115.0
10	80	64.0	21	550	118.0
11	120	83.0			

0 = Fictitious Point Added * = Test Point Not Included

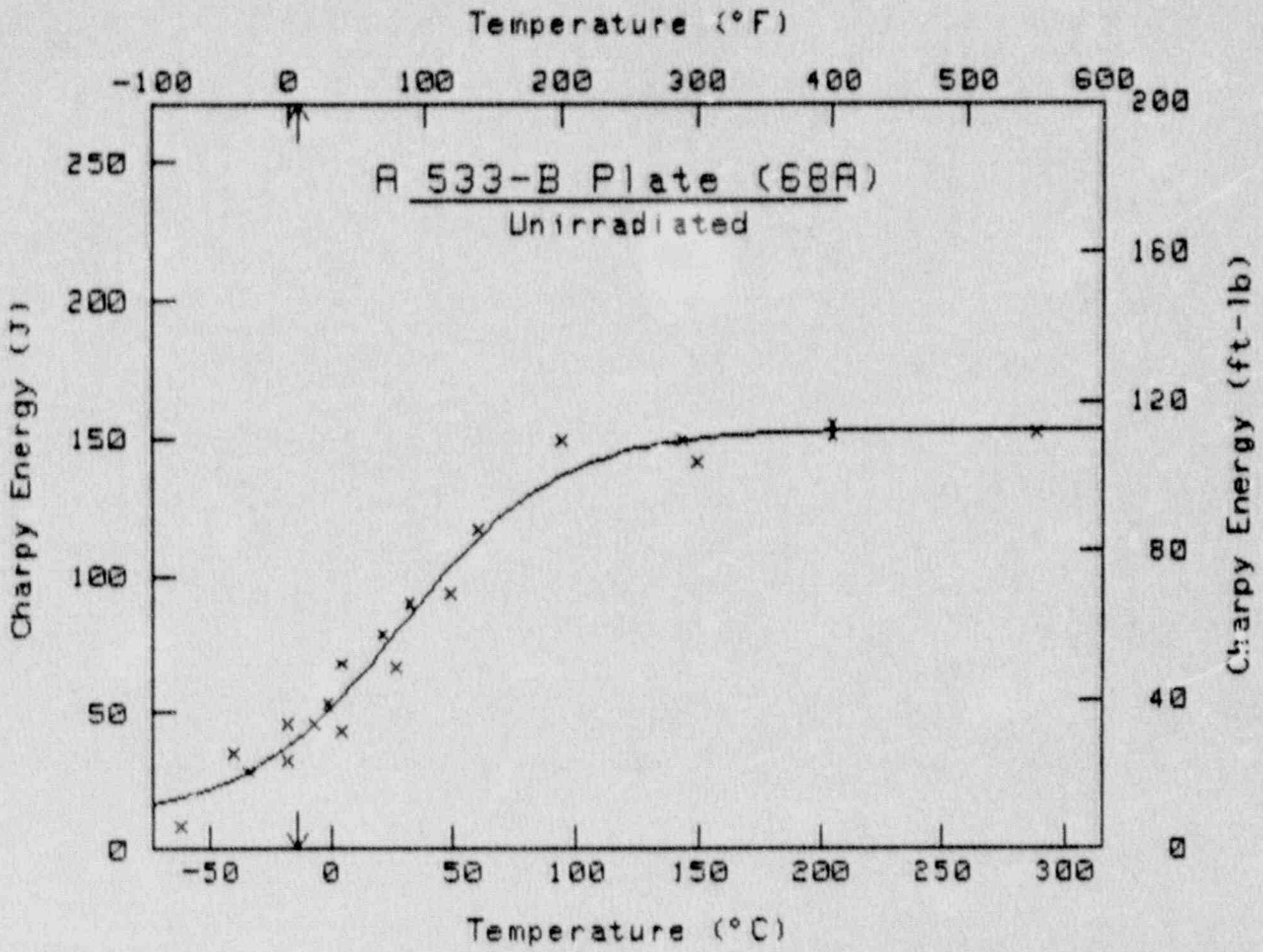


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	50.49 ft-lb	68.45 J
B =	37.62 ft-lb	51.00 J
C =	85.43 °F	47.46 °C
To =	184.68 °F	84.82 °C
Cv = 30 ft-lb (41 J) at T =	132.5 °F	55.8 °C
Upper Shelf Energy =	88.1 ft-lb	119.5 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	50	10.0	10	175	44.0
2	70	20.0	11	200	46.0
3	80	13.0	12	200	56.0
4	100	26.0	13	250	80.0
5	120	31.0	14	250	84.0
6	120	32.0	15	350	84.0
7	150	34.0	16	390	84.0
8	150	41.0	17	400	92.0
9	175	44.0	18	420	84.0

0 = Fictitious Point Added   * = Test Point Not Included



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

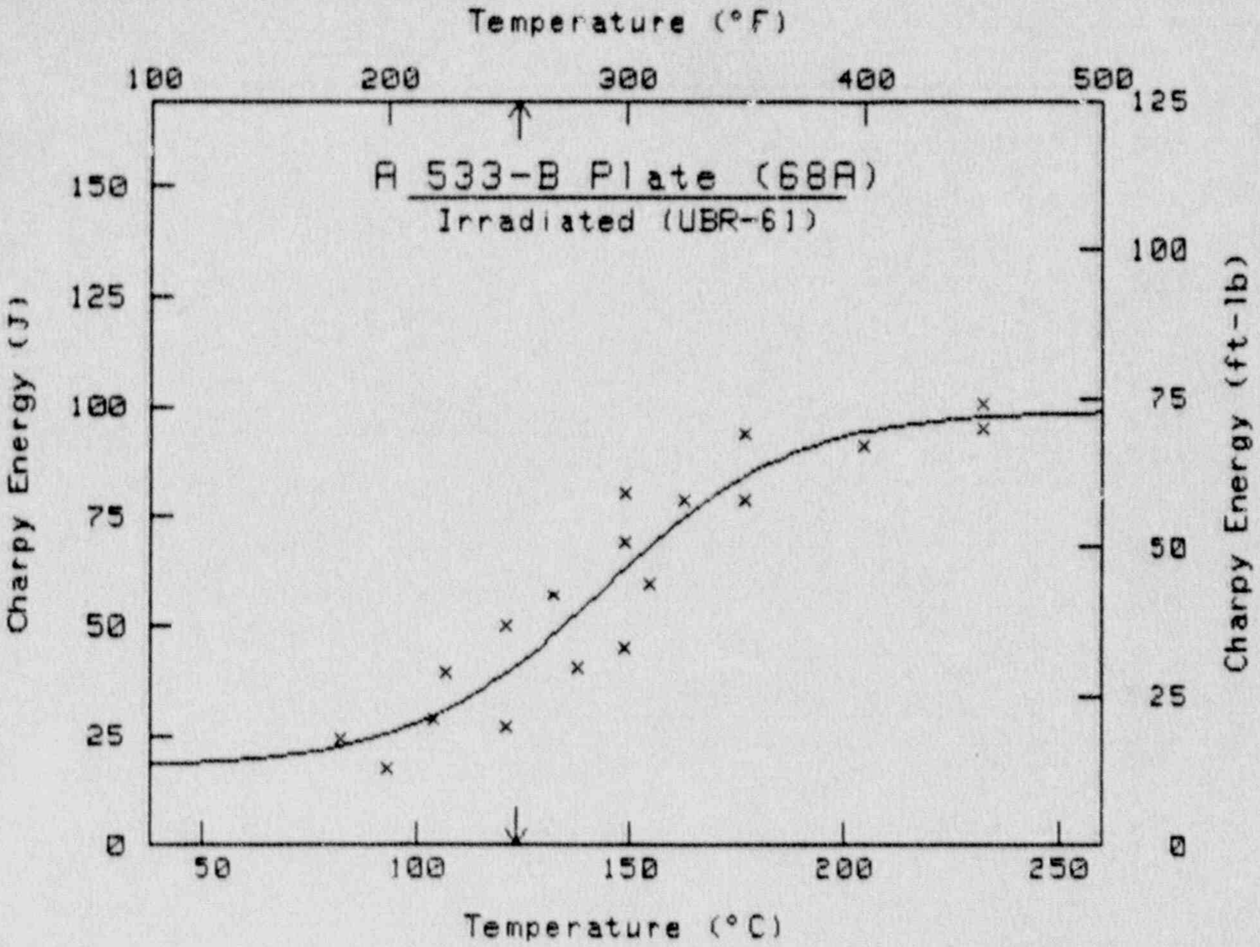
		English	Metric
A	=	60.17 ft-lb	81.58 J
B	=	52.47 ft-lb	71.14 J
C	=	116.46 °F	64.70 °C
To	=	83.80 °F	28.78 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	7.5 °F	-13.6 °C
Upper Shelf Energy =	112.6 ft-lb	152.7 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-80	6.0	11	80	49.0
2	-40	26.0	12	90	66.0
3	-30	21.0	13	120	69.0
4	0	34.0	14	140	86.0
5	0	24.0	15	200	110.0
6	20	34.0	16	290	110.0
7	30	39.0	17	300	104.0
8	40	50.0	18	400	114.0
9	40	32.0	19	400	111.0
10	70	58.0	20	550	112.0

0 = Fictitious Point Added   * = Test Point Not Included



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

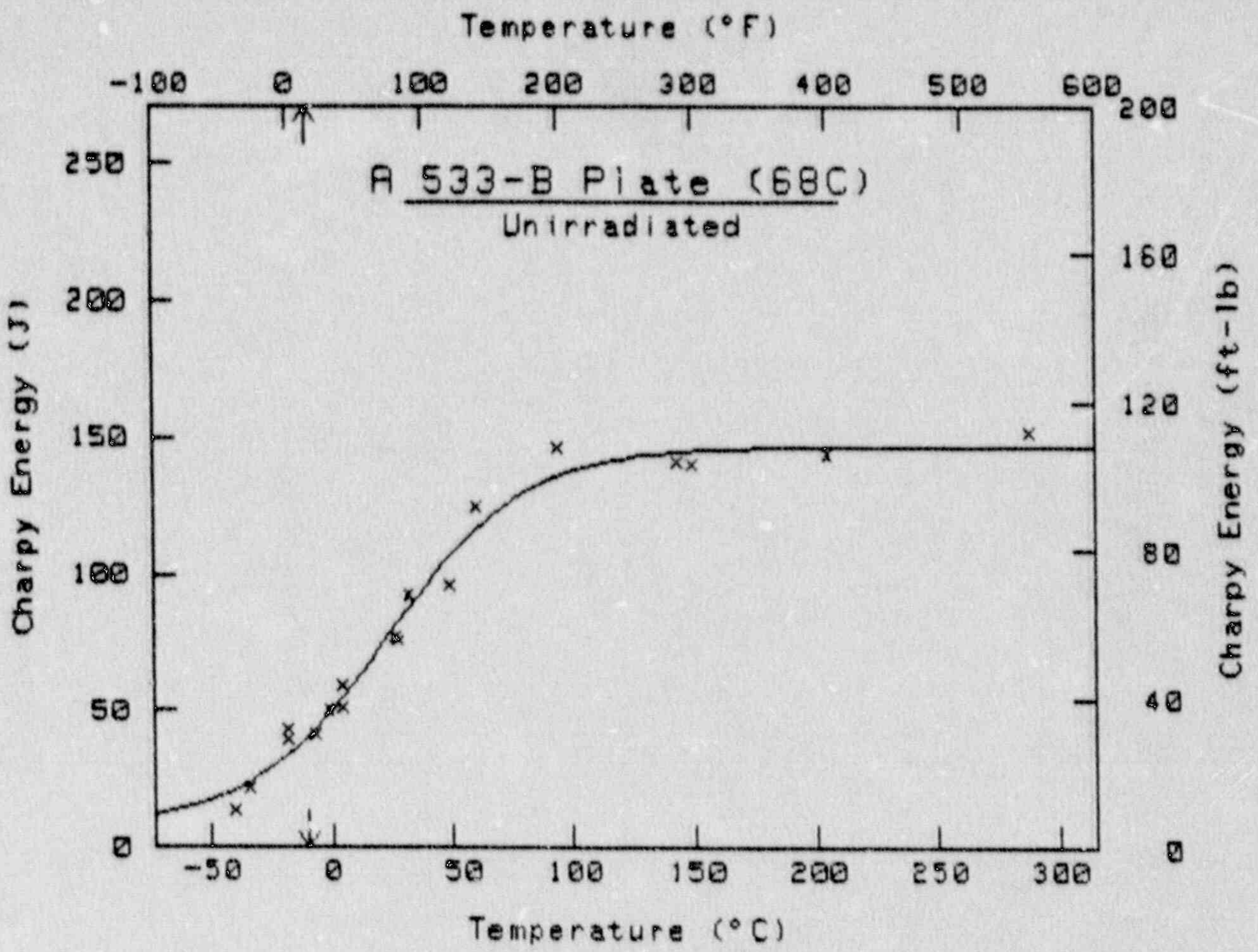
	English	Metric
A =	43.01 ft-lb	58.32 J
B =	29.90 ft-lb	40.53 J
C =	79.59 °F	44.22 °C
To =	290.84 °F	143.80 °C

Cv = 30 ft-lb (41 J) at T =	253.7 °F	123.2 °C
Upper Shelf Energy =	72.9 ft-lb	98.9 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	180	18.0	10	300	51.0
2	200	13.0	11	300	59.0
3	220	21.0	12	310	44.0
4	225	29.0	13	325	58.0
5	250	20.0	14	350	58.0
6	250	37.0	15	350	69.0
7	270	42.0	16	400	67.0
8	280	30.0	17	450	70.0
9	300	33.0	18	450	74.0

O = Fictitious Point Added   * = Test Point Not Included

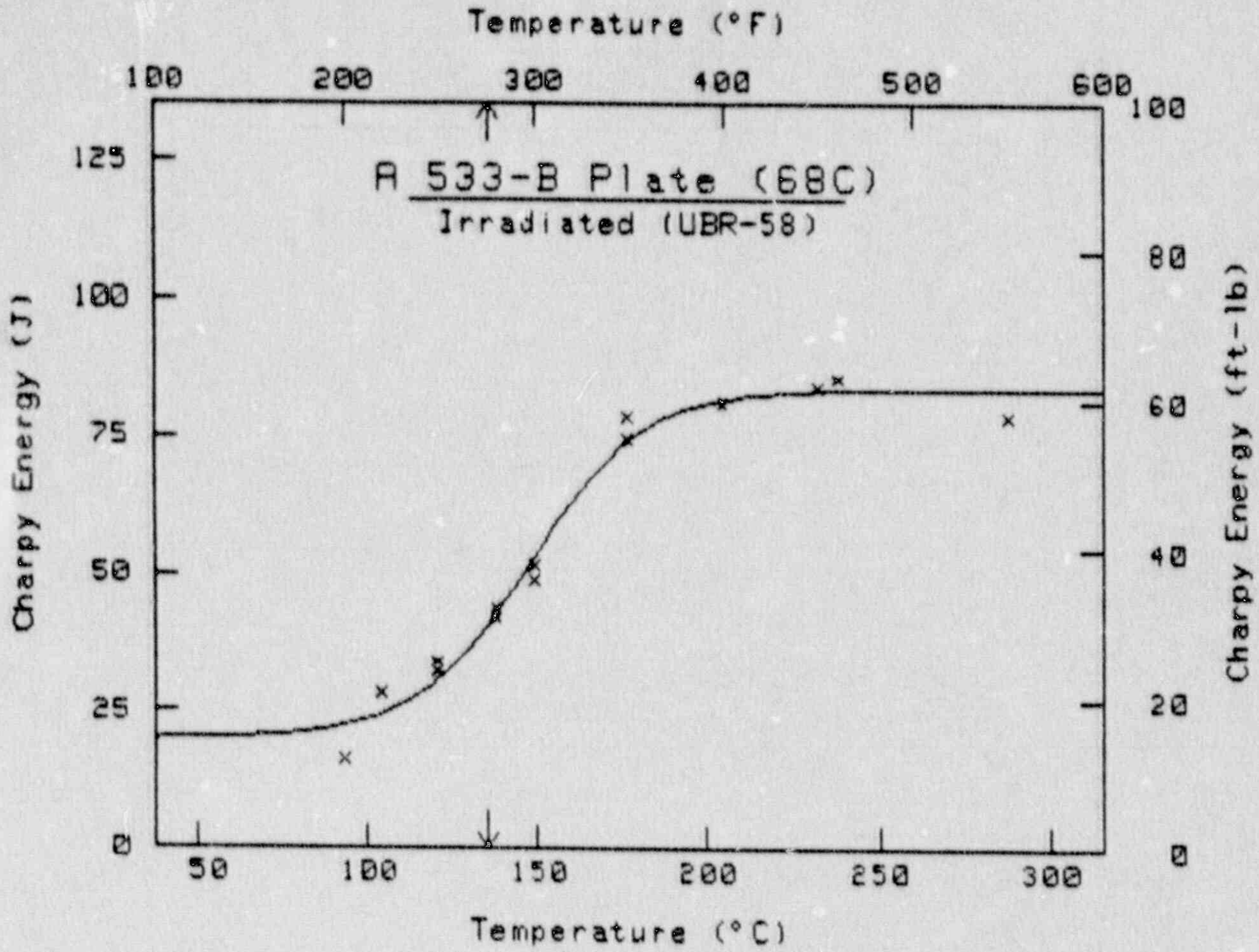


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	56.76 ft-lb	76.95 J
B =	51.33 ft-lb	69.59 J
C =	102.85 °F	57.14 °C
To =	73.78 °F	23.21 °C
Cv = 30 ft-lb (41 J) at T =	14.3 °F	-9.8 °C
Upper Shelf Energy =	108.1 ft-lb	146.5 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-40	10.0	11	90	68.0
2	-30	16.1	12	120	71.0
3	0	32.0	13	140	92.0
4	0	29.0	14	200	108.0
5	20	30.5	15	290	104.0
6	30	37.0	16	300	103.0
7	40	38.0	17	400	106.0
8	40	44.0	18	400	106.0
9	80	57.0	19	550	112.0
10	82	56.0			

O = Fictitious Point Added * = Test Point Not Included



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

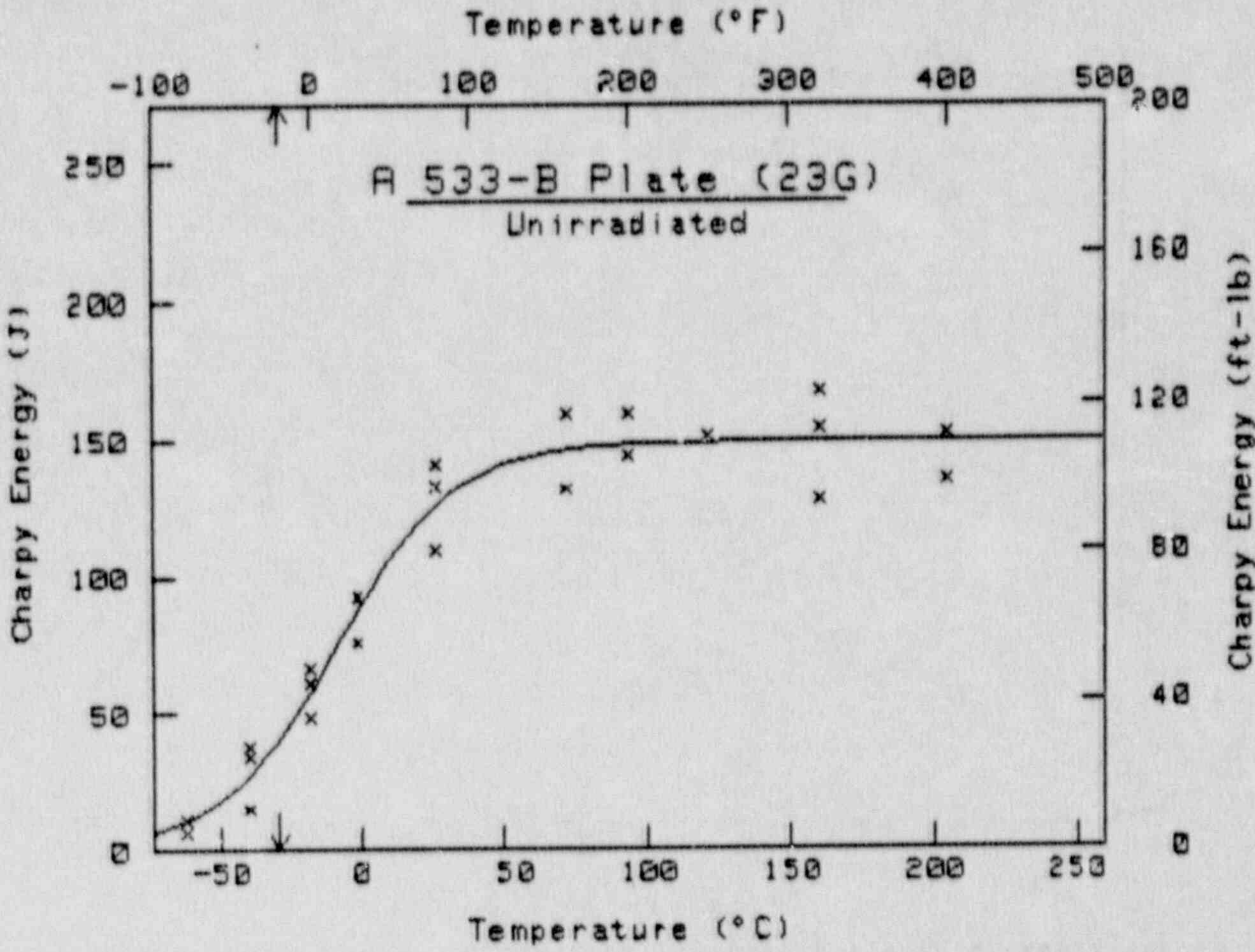
		English	Metric
A	=	38.19 ft-lb	51.78 J
B	=	23.49 ft-lb	31.84 J
C	=	60.45 °F	33.58 °C
To	=	297.75 °F	147.64 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	275.8 °F	135.4 °C
Upper Shelf Energy =	61.7 ft-lb	83.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	200	12.0
2	220	21.0
3	250	24.0
4	250	25.0
5	280	31.0
6	280	32.0
7	300	36.0
8	300	38.0
9	350	55.0
10	350	58.0
11	400	60.0
12	400	60.0
13	450	62.0
14	460	63.0
15	550	58.0

0 = Fictitious Point Added   * = Test Point Not Included



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

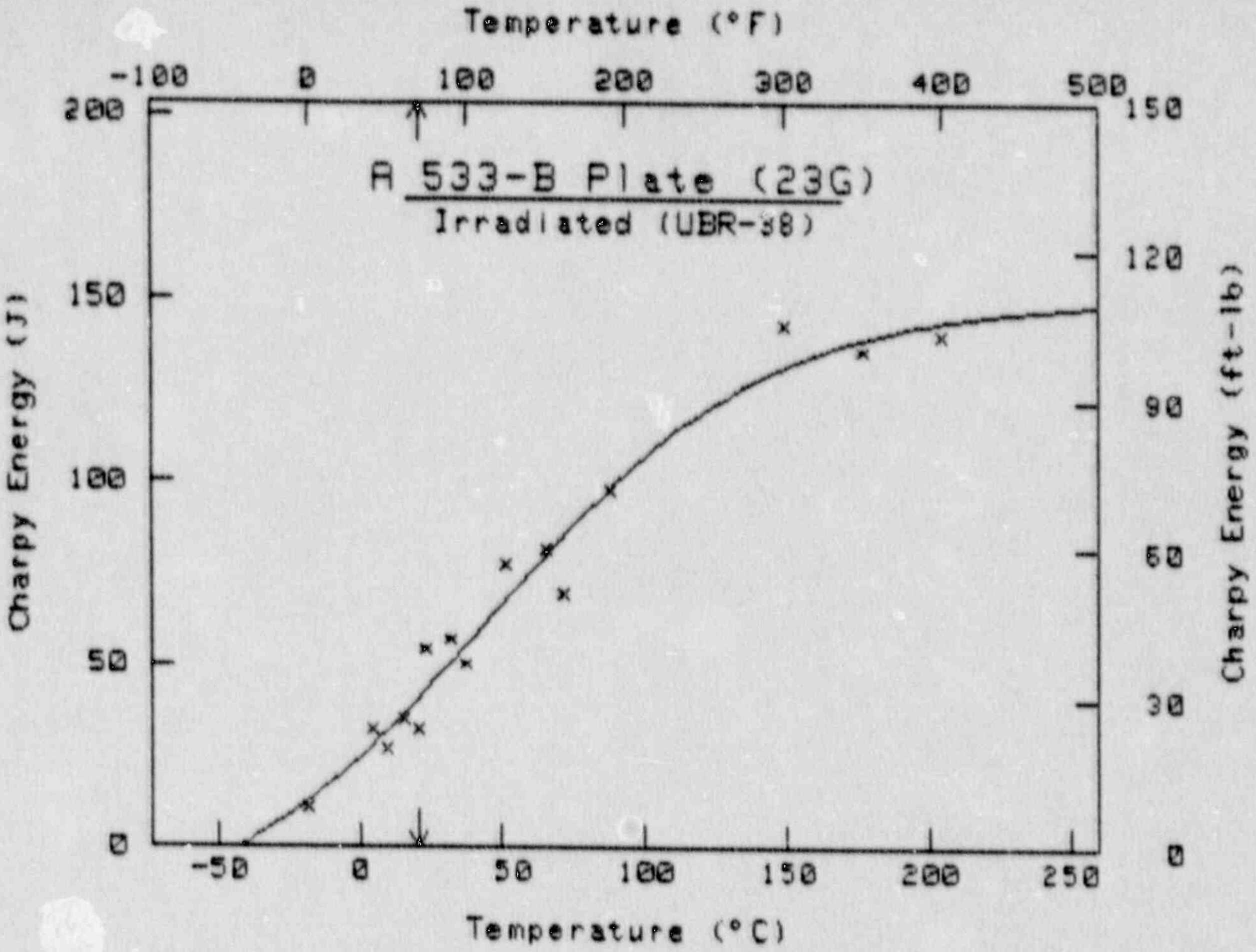
	English	Metric
A =	55.11 ft-lb	74.72 J
B =	54.57 ft-lb	73.98 J
C =	74.06 °F	41.14 °C
To =	16.83 °F	-8.43 °C

Cv = 30 ft-lb (41 J) at T =	-20.0 °F	-28.9 °C
Upper Shelf Energy =	109.7 ft-lb	148.7 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-80	8.0	13	80	81.0
2	-80	5.0	14	160	97.0
3	-40	28.0	15	160	117.0
4	-40	25.0	16	200	117.0
5	-40	11.0	17	200	106.0
6	0	49.0	18	250	111.0
7	0	36.0	19	320	123.0
8	0	45.0	20	320	113.0
9	30	68.0	21	320	94.0
10	30	56.0	22	400	99.0
11	80	104.0	23	400	112.0
12	80	98.0			

0 = Fictitious Point Added   * = Test Point Not Included



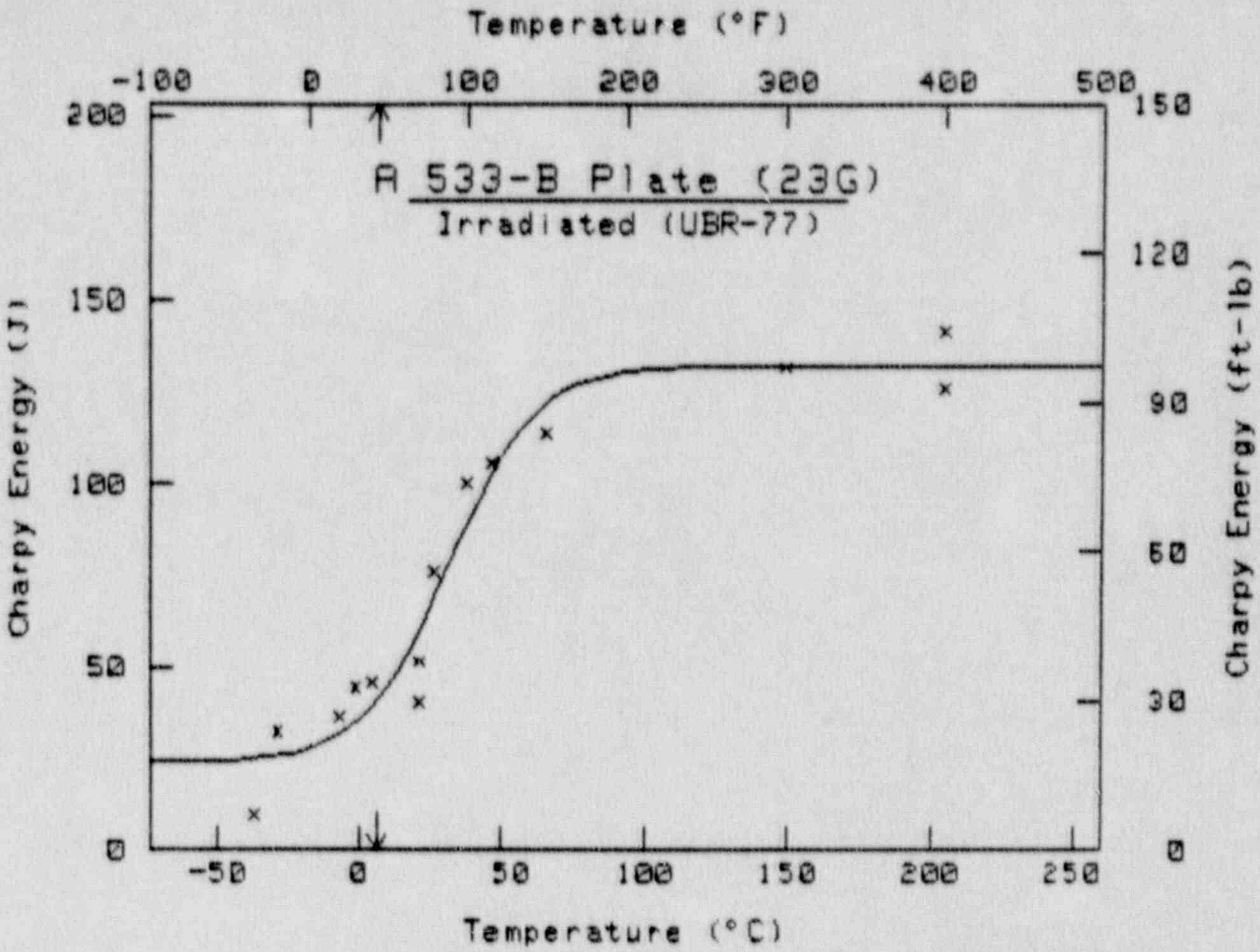
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	46.20 ft-lb	62.64 J
B	=	64.43 ft-lb	87.36 J
C	=	176.32 °F	97.96 °C
To	=	114.57 °F	45.87 °C

Cv = 30 ft-lb (41 J) at T	=	69.3 °F	20.7 °C
Upper Shelf Energy	=	110.6 ft-lb	150.0 J

PT #	Temp (°F)	Energy (ft-lb)
1	0	8.0
2	40	24.0
3	50	20.0
4	60	26.0
5	70	24.0
6	75	40.0
7	90	42.0
8	100	37.0
9	125	57.0
10	150	60.0
11	160	51.0
12	190	72.0
13	300	105.0
14	350	100.0
15	400	103.0

0 = Fictitious Point Added   * = Test Point Not Included



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

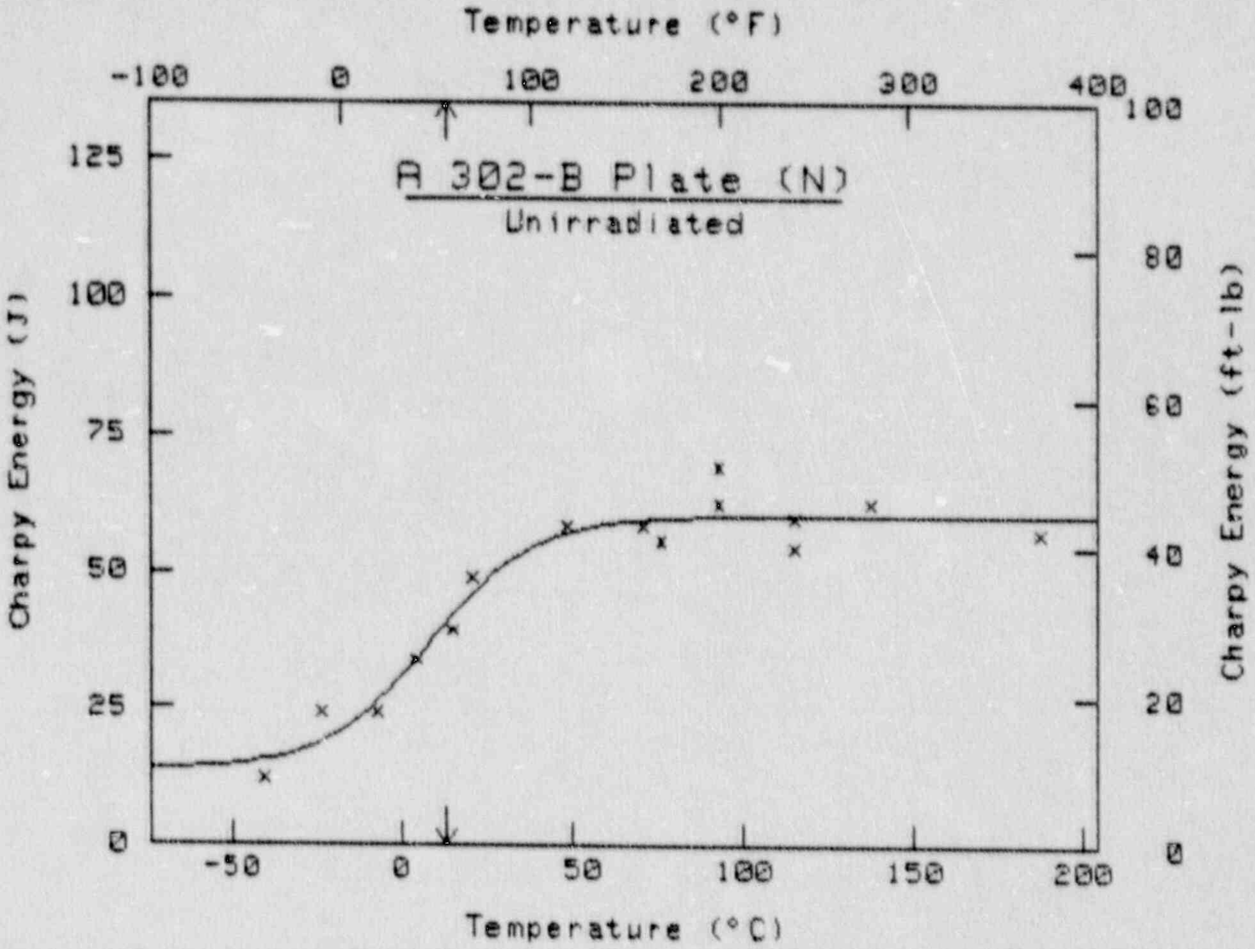
	English	Metric
A =	57.52 ft-lb	77.98 J
B =	39.87 ft-lb	54.05 J
C =	53.98 °F	29.99 °C
To =	88.61 °F	31.45 °C

Cv = 30 ft-lb (41 J) at T =	42.8 °F	6.0 °C
Upper Shelf Energy =	97.4 ft-lb	132.0 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-35	7.0
2	-20	24.0
3	20	27.0
4	30	33.0
5	40	34.0
6	70	30.0
7	70	38.0
8	80	56.0
9	100	74.0
10	115	78.0
11	150	84.0
12	300	97.0
13	400	93.0
14	400	104.0

0 = Fictitious Point Added * = Test Point Not Included

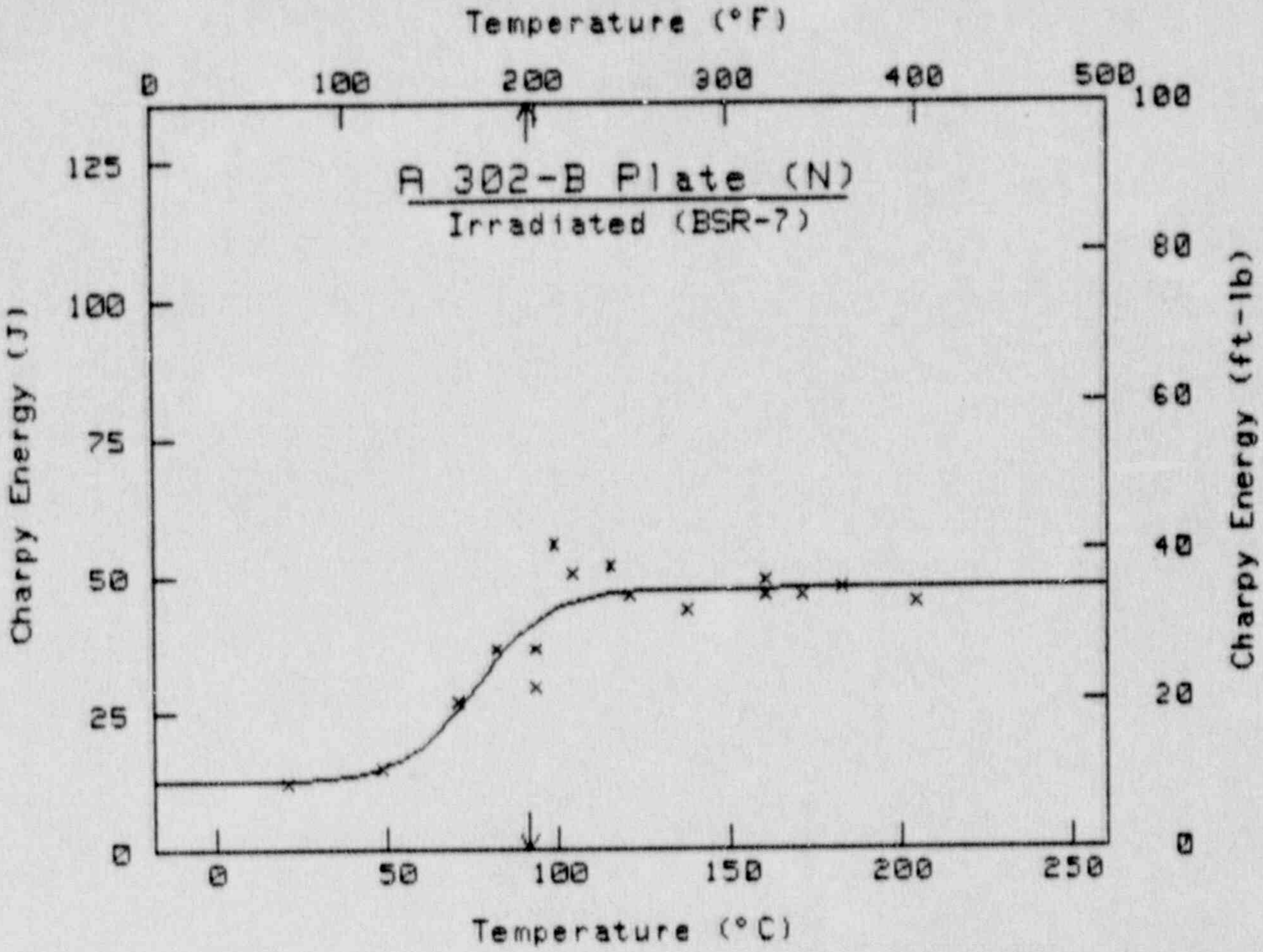


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	27.24 ft-lb	36.94 J
B =	17.18 ft-lb	23.29 J
C =	55.67 °F	30.93 °C
To =	47.26 °F	8.48 °C
Cv = 30 ft-lb (41 J) at T =	56.3 °F	13.5 °C
Upper Shelf Energy =	44.4 ft-lb	60.2 J

PT #	Temp (°F)	Energy (ft-lb)
1	-40	9.0
2	-10	18.0
3	20	18.0
4	40	25.0
5	60	29.0
6	70	36.0
7	120	43.0
8	160	43.0
9	170	41.0
10	200	46.0
11	200	51.0
12	240	40.0
13	240	44.0
14	280	46.0
15	370	42.0

O = Fictitious Point Added * = Test Point Not Included



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

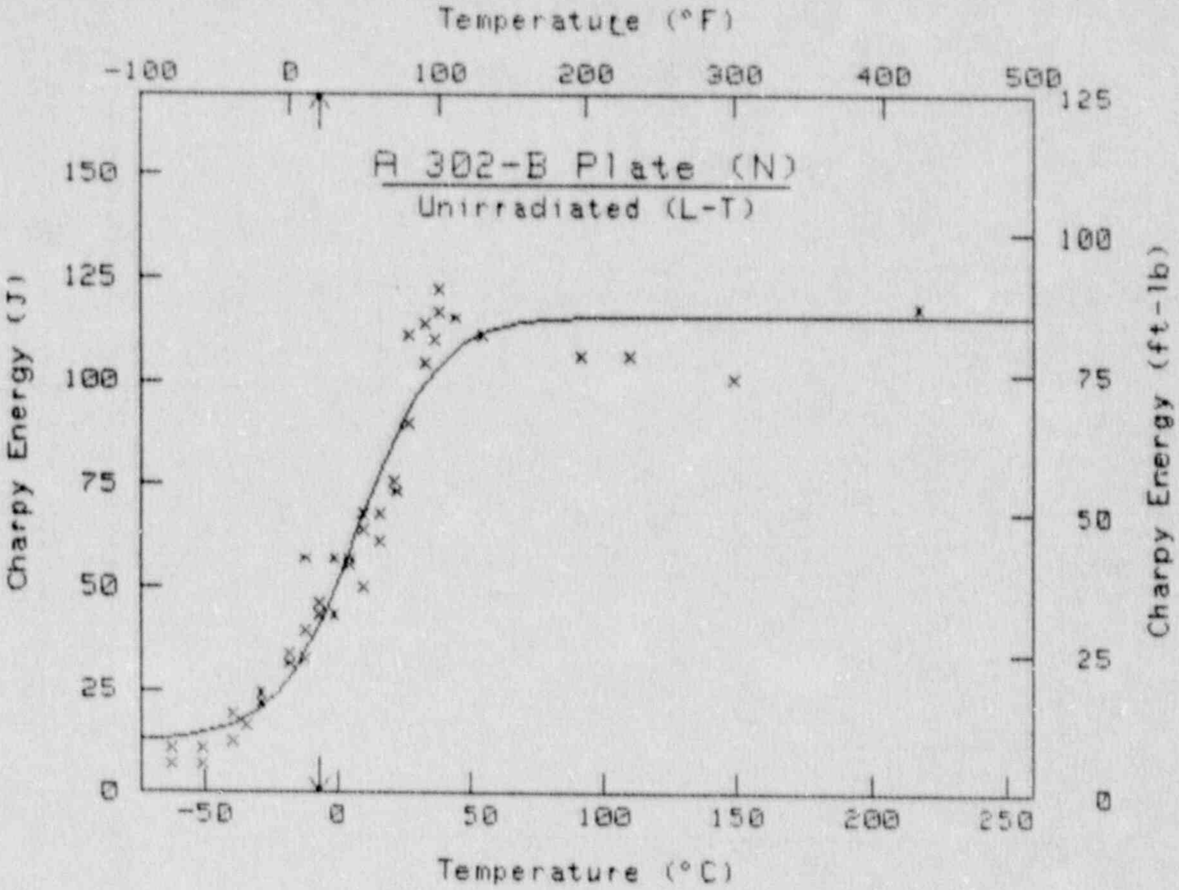
	English	Metric
A =	22.06 ft-lb	29.91 J
B =	12.88 ft-lb	17.46 J
C =	38.33 °F	21.29 °C
To =	169.27 °F	76.26 °C

Cv = 30 ft-lb (41 J) at T =	196.8 °F	91.6 °C
Upper Shelf Energy =	34.9 ft-lb	47.4 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	70	9.0	9	240	38.0
2	120	11.0	10	250	34.0
3	160	20.0	11	280	32.0
4	180	27.0	12	320	34.0
5	200	22.0	13	320	36.0
6	200	27.0	14	340	34.0
7	210	41.0	15	360	35.0
8	220	37.0	16	400	33.0

0 = Fictitious Point Added   * = Test Point Not Included



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

	English	Metric
A =	47.21 ft-lb	64.00 J
B =	38.08 ft-lb	51.63 J
C =	53.56 °F	29.75 °C
To =	45.79 °F	7.66 °C

Cv = 30 ft-lb (41 J) at T =	19.7 °F	-6.8 °C
Upper Shelf Energy =	85.3 ft-lb	115.6 J

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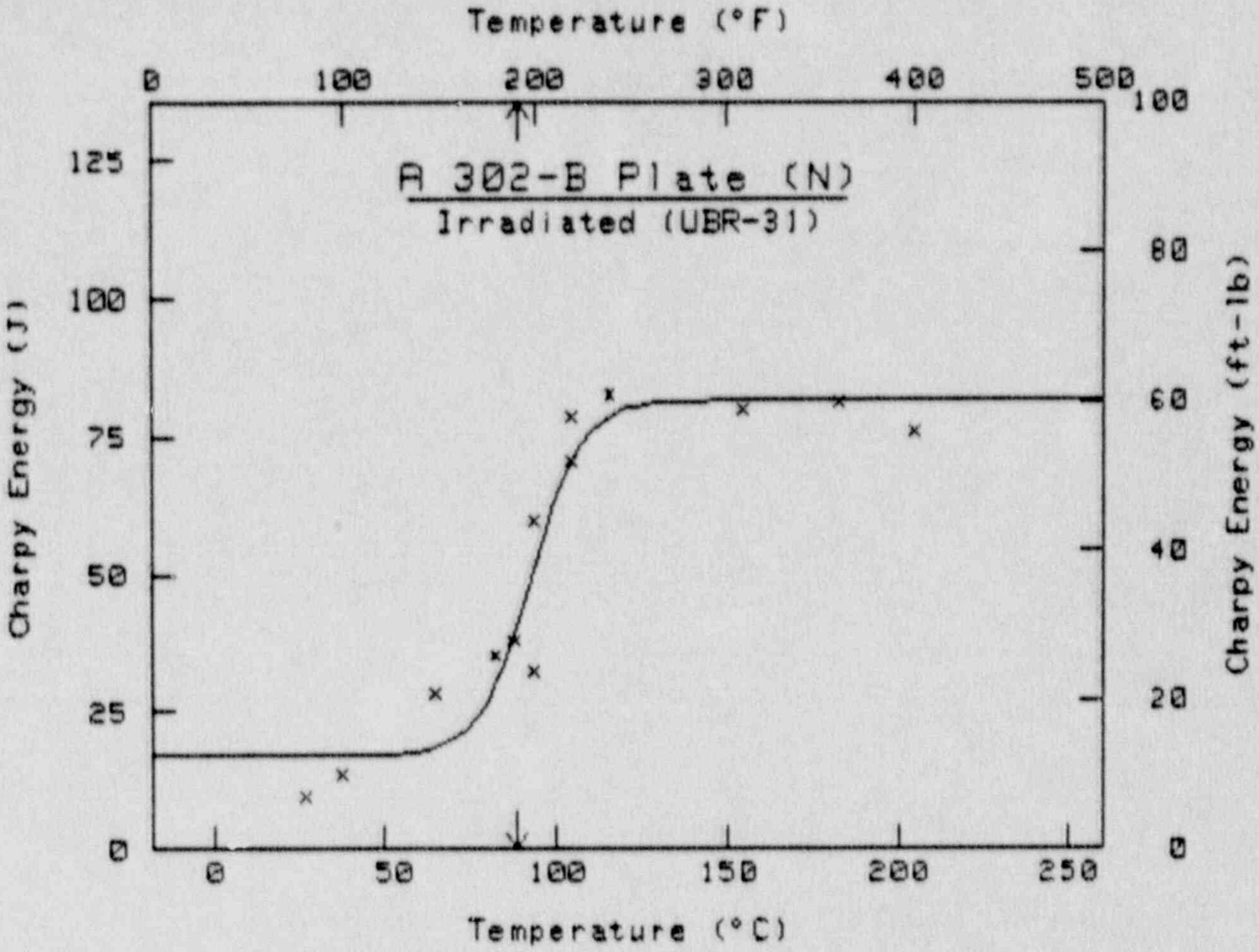
PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-80	5.0	21	50	37.0
2	-80	8.0	22	50	47.0
3	-60	5.0	23	50	50.0
4	-60	8.0	24	60	45.0
5	-40	9.0	25	60	50.0
6	-40	14.0	26	70	56.0
7	-30	12.0	27	72	54.0
8	-20	16.0	28	80	66.0
9	-20	18.0	29	80	82.0
10	0	23.0	30	90	77.0
11	0	25.0	31	90	84.0
12	10	24.0	32	96	81.0
13	10	42.0	33	100	86.0
14	10	29.0	34	100	90.0
15	20	32.0	35	110	85.0
16	20	34.0	36	130	82.0
17	30	32.0	37	196	78.0
18	30	42.0	38	230	78.0
19	40	41.0	39	300	74.0
20	40	42.0	40	424	87.0



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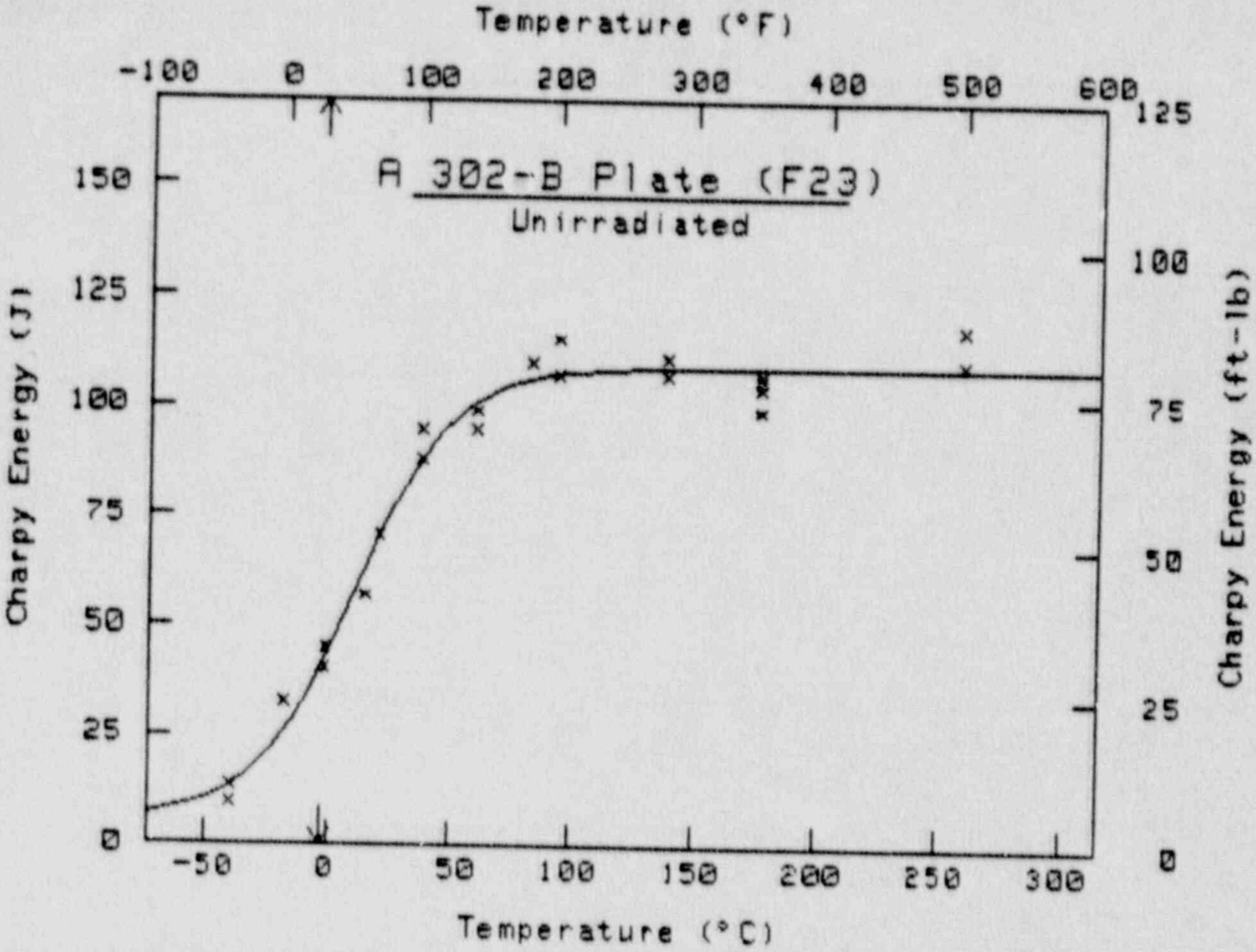
$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	36.28 ft-lb	49.19 J
B =	23.81 ft-lb	32.29 J
C =	26.89 °F	14.94 °C
To =	198.84 °F	92.69 °C
Cv = 30 ft-lb (41 J) at T =	191.6 °F	88.7 °C
Upper Shelf Energy =	60.1 ft-lb	81.5 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	80	7.0
2	100	10.0
3	150	21.0
4	180	26.0
5	190	28.0
6	200	24.0
7	200	44.0
8	220	52.0
9	220	58.0
10	240	61.0
11	310	59.0
12	360	60.0
13	400	56.0

0 = Fictitious Point Added   * = Test Point Not Included



****

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

	English	Metric
A =	42.17 ft-lb	57.17 J
B =	38.11 ft-lb	51.67 J
C =	72.62 °F	40.34 °C
To =	50.75 °F	10.42 °C

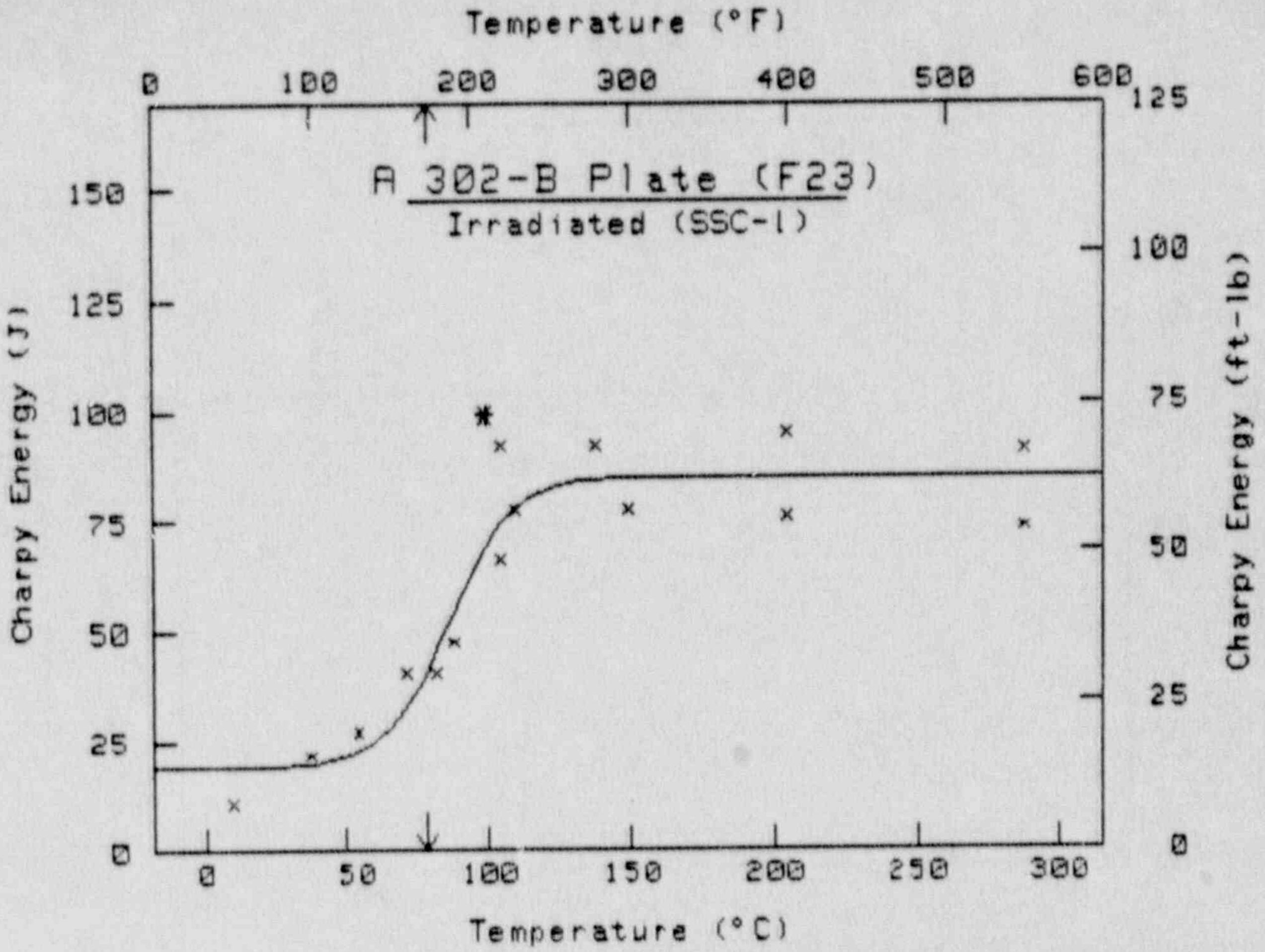
Cv = 30 ft-lb (41 J) at T = 26.7 °F -2.9 °C
Upper Shelf Energy = 80.3 ft-lb 108.8 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-40	7.0
2	-43	10.0
3	0	24.0
4	30	30.0
5	30	33.0
6	60	42.0
7	70	52.0
8	100	65.0
9	100	70.0
10	140	70.0
11	140	73.0

PT #	Temp (°F)	Energy (ft-lb)
12	180	81.0
13	200	85.0
14	200	79.0
15	280	79.0
16	280	82.0
17	350	73.0
18	350	78.0
19	350	77.0
20	350	79.0
21	500	81.0
22	500	87.0

0 = Fictitious Point Added * = Test Point Not Included



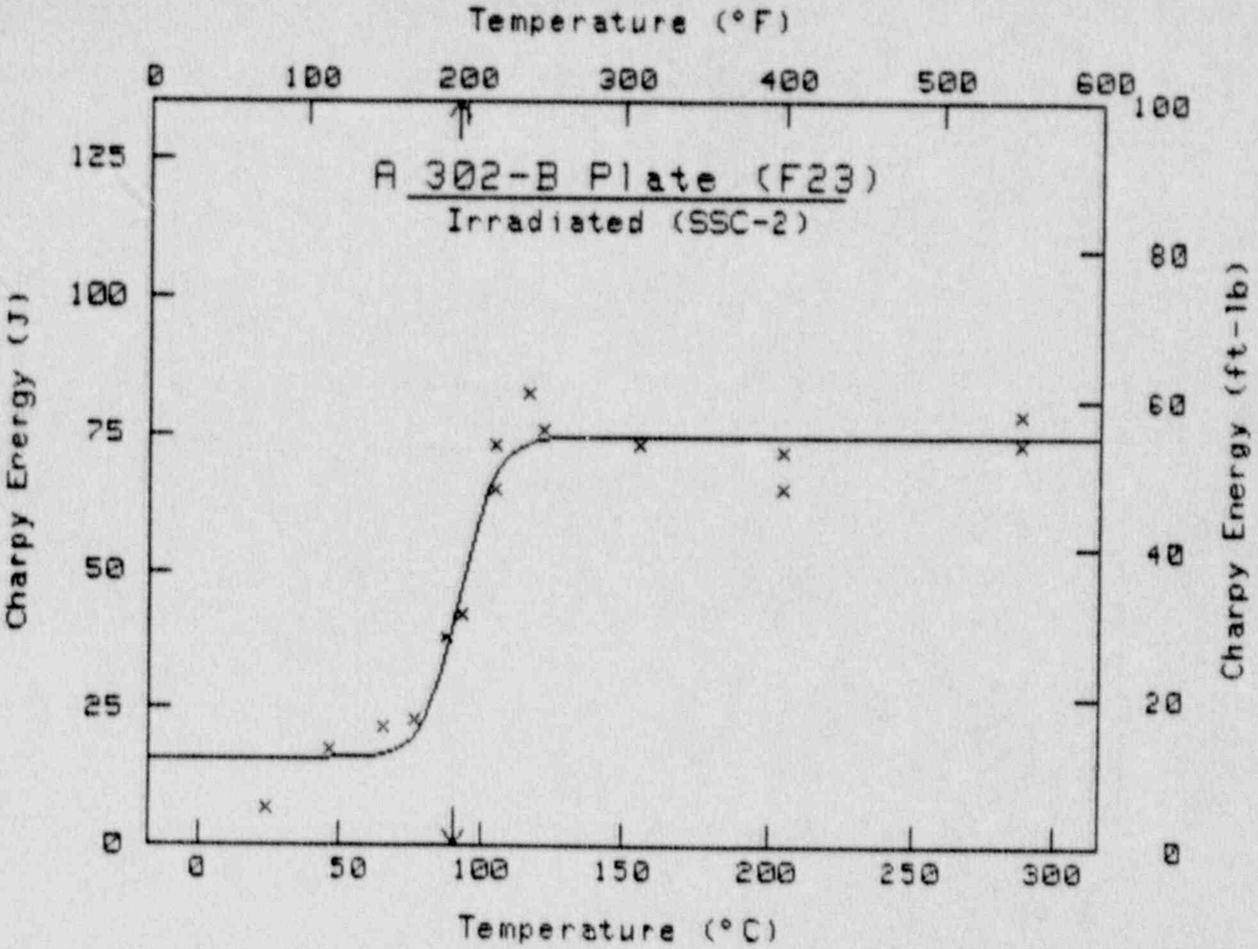
$Cv = A + B \tanh[(T - To)/C]$

		English	Metric
A	=	38.32 ft-lb	51.95 J
B	=	24.30 ft-lb	32.94 J
C	=	39.87 °F	22.15 °C
To	=	187.32 °F	86.29 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	173.1 °F	78.4 °C
Upper Shelf Energy =	62.6 ft-lb	84.9 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	50	8.0	9	220	49.0
2	100	16.0	10	230	57.0
3	130	20.0	11	280	68.0
4	160	30.0	12	300	57.0
5	180	30.0	13	400	70.0
6	190	35.0	14	400	56.0
7 *	210	73.0	15	550	54.0
8	220	68.0	16	550	67.0

O = Fictitious Point Added   * = Test Point Not Included



****

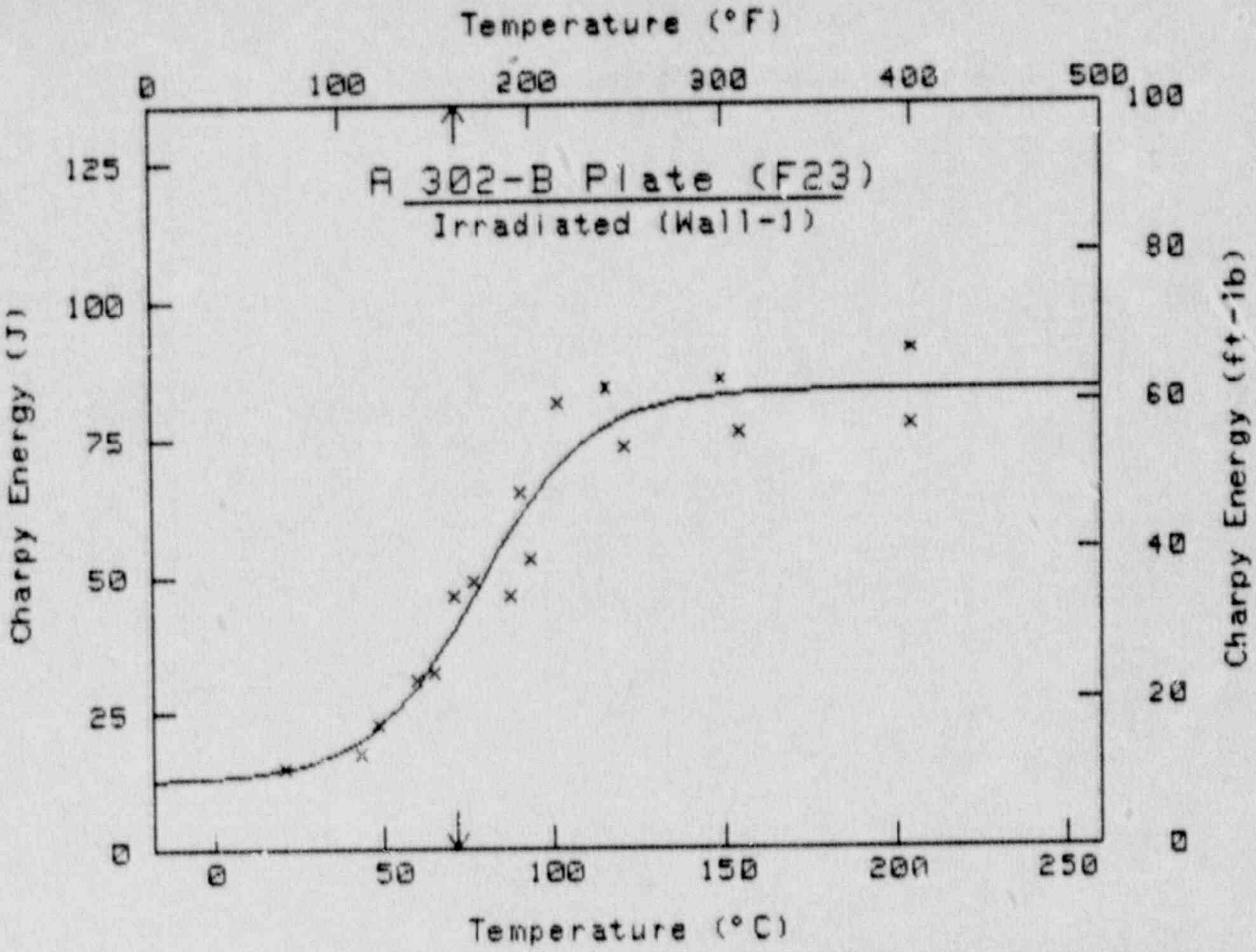
$Cv = A + B \tanh[(T - To)/C]$

		English	Metric
A	=	33.37 ft-lb	45.24 J
B	=	21.60 ft-lb	29.28 J
C	=	21.92 °F	12.18 °C
To	=	198.02 °F	92.23 °C
Cv = 30 ft-lb (41 J) at T	=	194.6 °F	90.3 °C
Upper Shelf Energy	=	55.0 ft-lb	74.5 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	75	5.0	9	240	61.0
2	115	13.0	10	250	56.0
3	150	16.0	11	310	54.0
4	170	17.0	12	310	54.0
5	190	28.0	13	400	48.0
6	200	31.0	14	400	53.0
7	220	54.0	15	550	54.0
8	220	48.0	16	550	58.0

0 = Fictitious Point Added * = Test Point Not Included



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

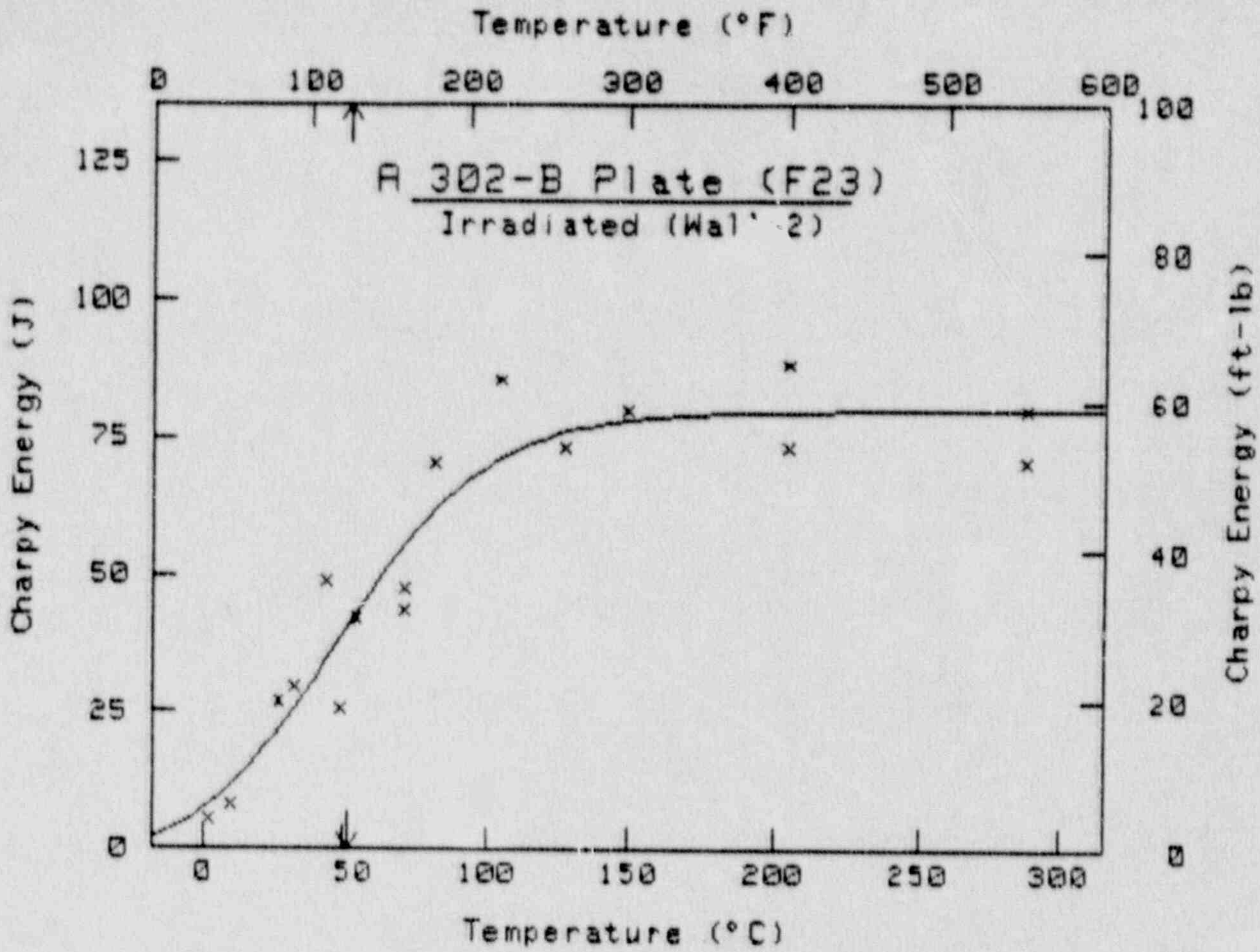
		English	Metric
A	=	35.41 ft-lb	48.01 J
B	=	26.09 ft-lb	35.38 J
C	=	58.71 °F	32.62 °C
To	=	173.24 °F	78.47 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	160.9 °F	71.6 °C
Upper Shelf Energy =	61.5 ft-lb	83.4 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	70	11.0	10	200	39.0
2	110	13.0	11	215	60.0
3	120	17.0	12	240	62.0
4	140	23.0	13	250	54.0
5	150	24.0	14	300	63.0
6	160	34.0	15	310	56.0
7	170	36.0	16	400	67.0
8	190	34.0	17	400	57.0
9	195	48.0			

0 = Fictitious Point Added   * = Test Point Not Included



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

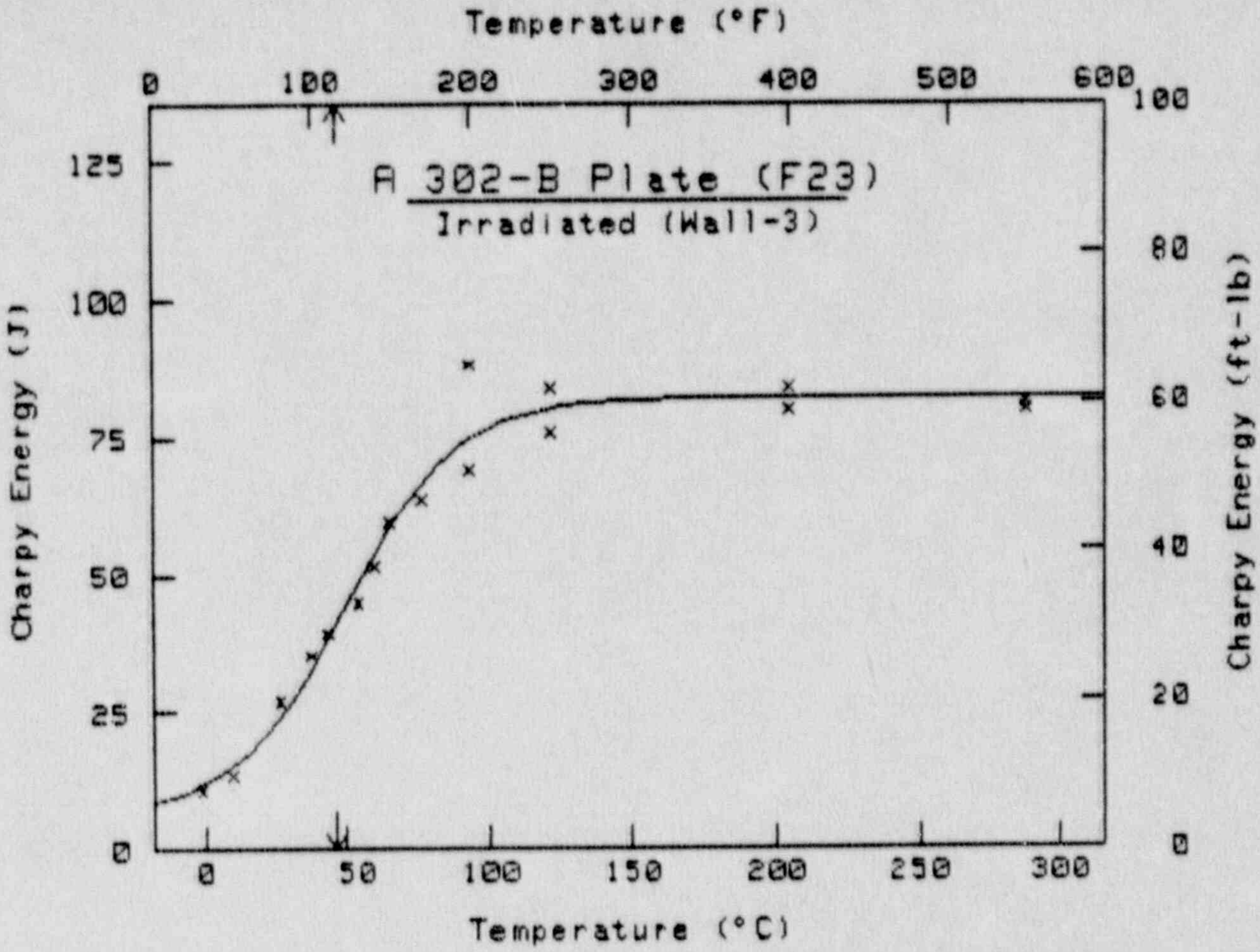
		English	Metric
A	=	27.72 ft-lb	37.59 J
B	=	31.09 ft-lb	42.15 J
C	=	94.56 °F	52.53 °C
To	=	117.59 °F	47.55 °C

Cv = 30 ft-lb (41 J) at T = 124.5 °F 51.4 °C

Upper Shelf Energy = 58.8 ft-lb 79.7 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	35	4.0	10	180	52.0
2	50	6.0	11	220	63.0
3	80	20.0	12	260	54.0
4	90	22.0	13	300	59.0
5	110	36.0	14	400	65.0
6	120	19.0	15	400	54.0
7	130	31.0	16	550	52.0
8	160	32.0	17	550	59.0
9	160	35.0			

0 = Fictitious Point Added * = Test Point Not Included



****

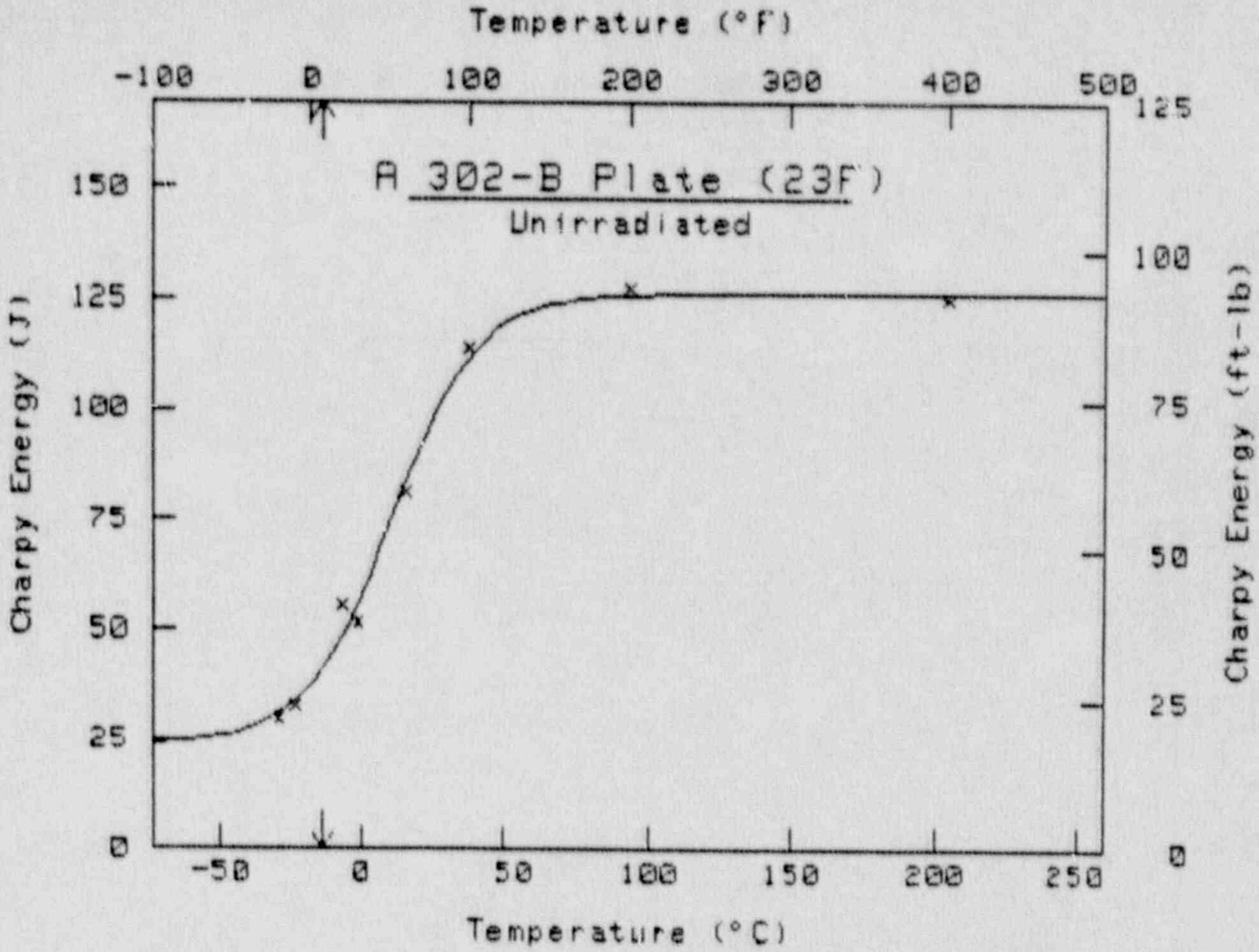
$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	32.61 ft-lb	44.21 J
B =	27.98 ft-lb	37.94 J
C =	71.01 °F	39.45 °C
To =	121.54 °F	49.74 °C
Cv = 30 ft-lb (41 J) at T =	114.9 °F	46.1 °C
Upper Shelf Energy =	60.6 ft-lb	82.2 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	30	8.0	10	200	51.0
2	50	10.0	11	200	65.0
3	80	20.0	12	250	56.0
4	100	26.0	13	250	62.0
5	110	29.0	14	400	59.0
6	130	33.0	15	400	62.0
7	140	38.0	16	550	59.0
8	150	44.0	17	550	60.0
9	170	47.0			

O = Fictitious Point Added   * = Test Point Not Included



****

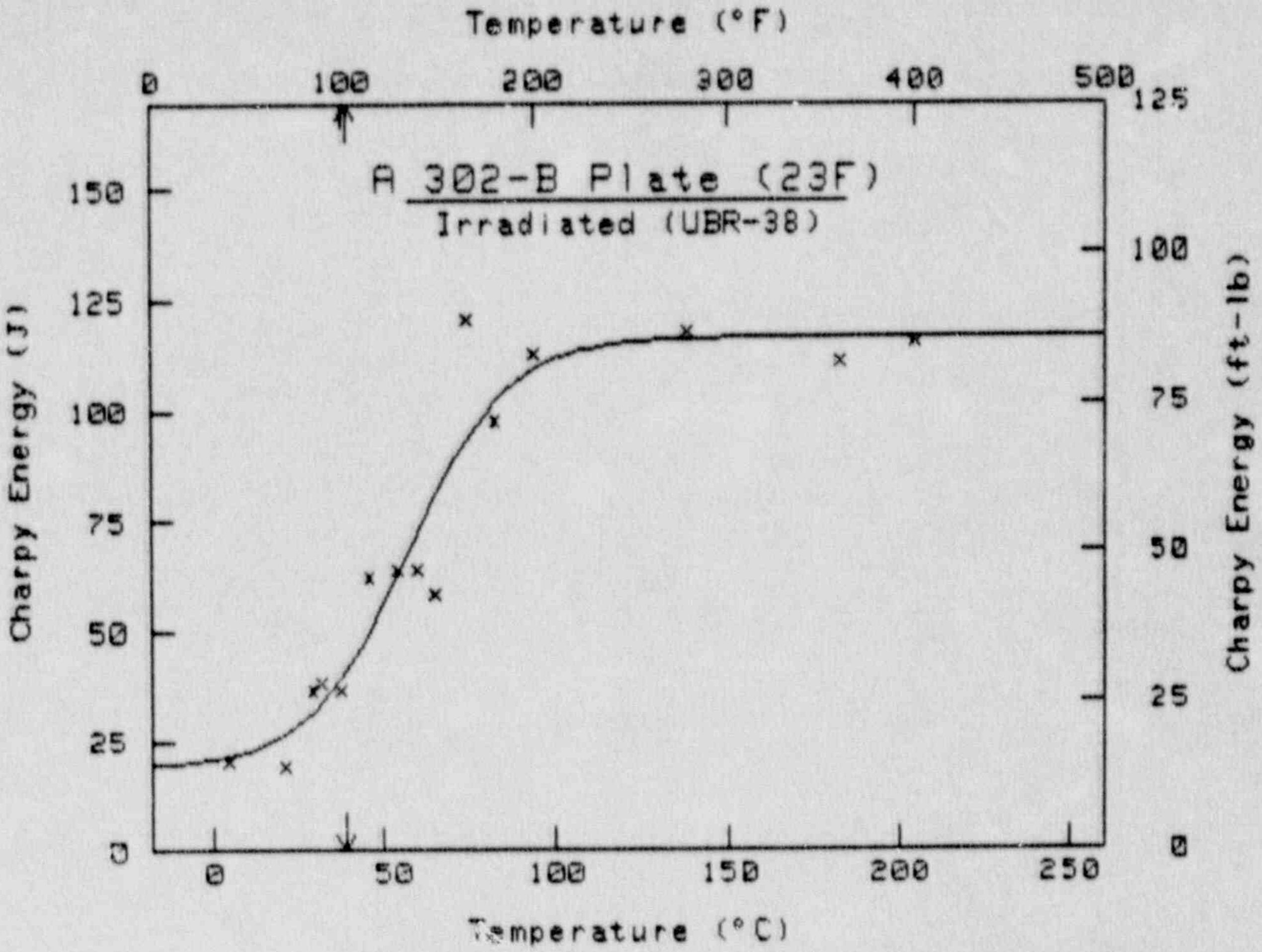
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	55.33 ft-lb	75.02 J
B =	37.67 ft-lb	51.08 J
C =	54.17 °F	30.09 °C
To =	51.21 °F	10.67 °C
Cv = 30 ft-lb (41 J) at T =	7.1 °F	-13.9 °C
Upper Shelf Energy =	93.0 ft-lb	126.1 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-20	22.0
2	-10	24.0
3	20	41.0
4	30	38.0
5	60	60.0
6	100	84.0
7	200	94.0
8	400	92.0
9	400	92.0

O = Fictitious Point Added * = Test Point Not Included



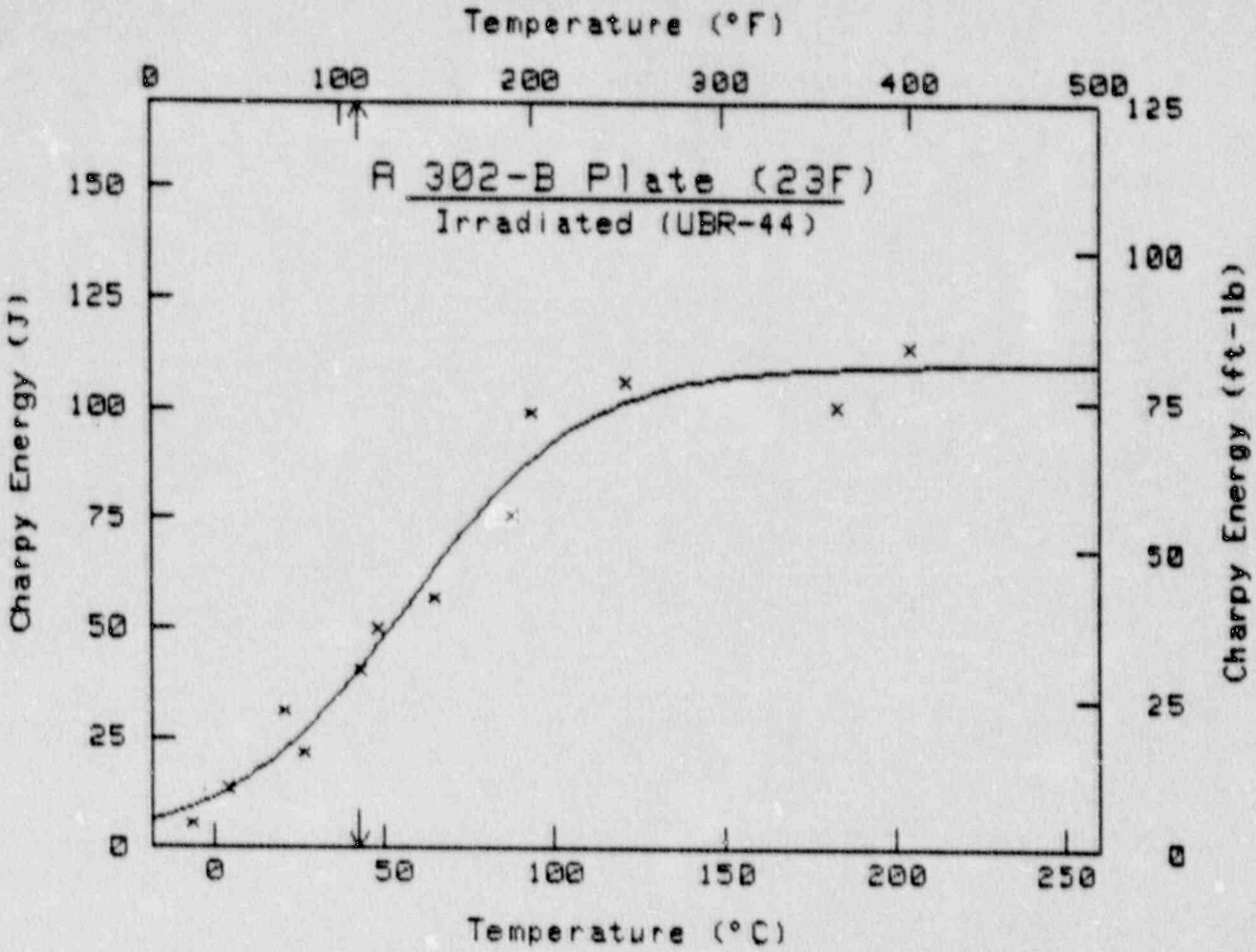
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	49.95 ft-lb	67.73 J
B	=	36.00 ft-lb	48.81 J
C	=	52.32 °F	29.07 °C
To	=	134.73 °F	57.07 °C

Cv = 30 ft-lb (41 J) at T	=	102.1 °F	38.9 °C
Upper Shelf Energy	=	86.0 ft-lb	116.5 J

PT #	Temp (°F)	Energy (ft-lb)
1	40	15.0
2	70	14.0
3	85	27.0
4	90	28.0
5	100	27.0
6	115	46.0
7	130	47.0
8	140	47.0
9	150	43.0
10	165	89.0
11	180	72.0
12	200	83.0
13	280	87.0
14	360	82.0
15	400	85.0

O = Fictitious Point Added   * = Test Point Not Included



****

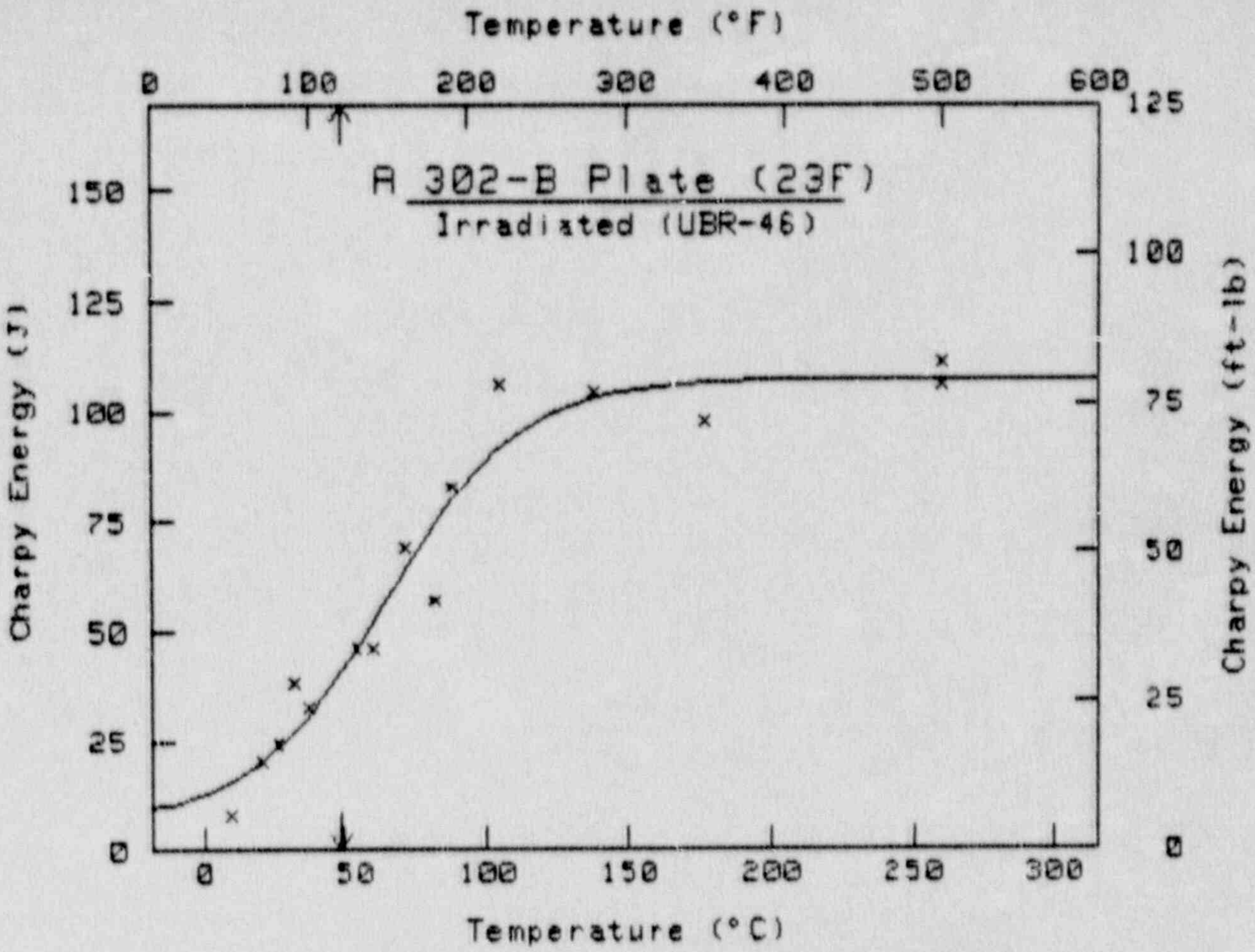
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	40.76 ft-lb	55.27 J
B =	40.30 ft-lb	54.64 J
C =	93.30 °F	51.83 °C
To =	135.11 °F	57.28 °C
Cv = 30 ft-lb (41 J) at T =	109.6 °F	43.1 °C
Upper Shelf Energy =	81.1 ft-lb	109.9 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	20	4.0
2	40	10.0
3	70	23.0
4	80	16.0
5	110	30.0
6	120	37.0
7	150	42.0
8	190	56.0
9	200	73.0
10	250	78.0
11	360	74.0
12	400	84.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

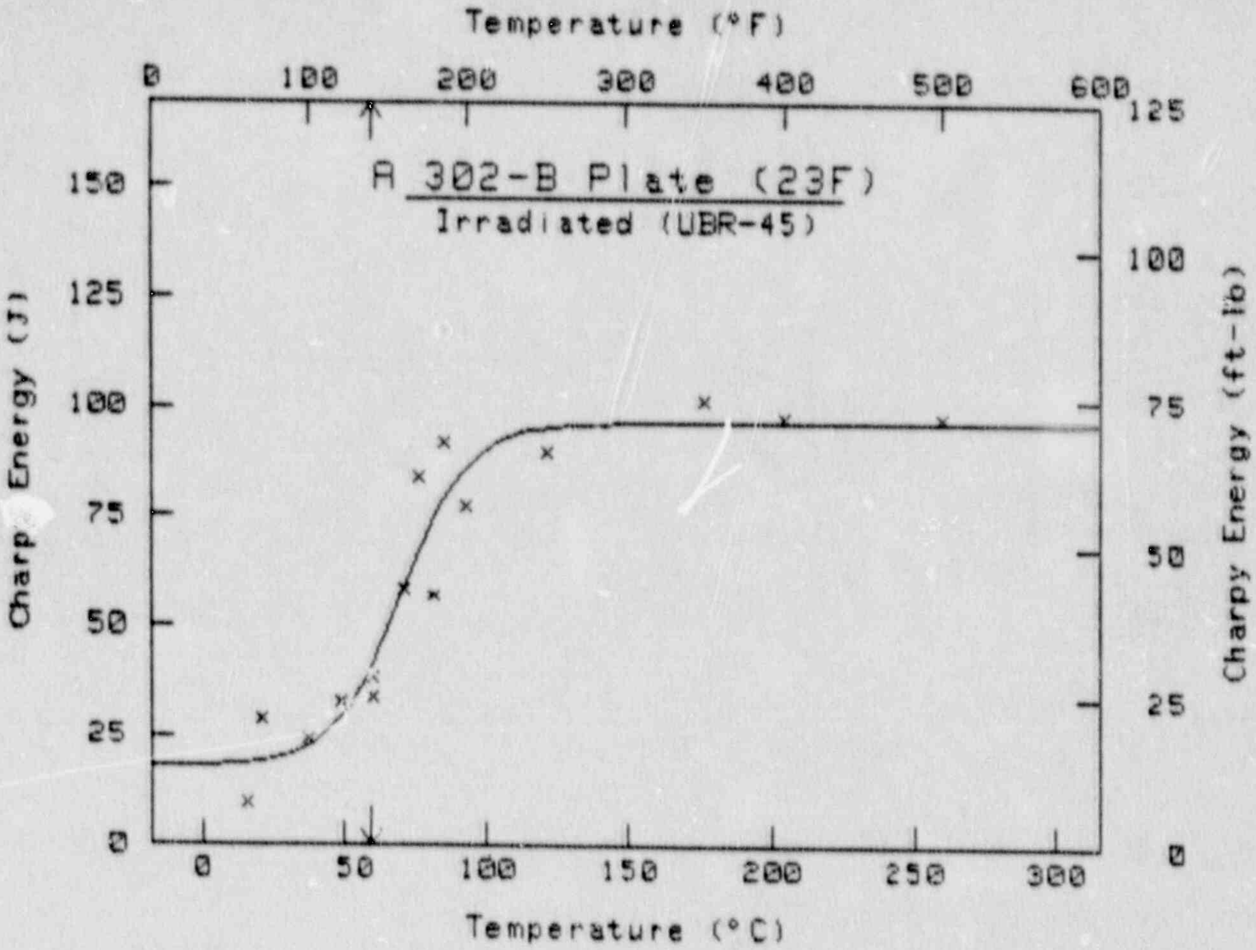
		English	Metric
A	=	41.92 ft-lb	56.84 J
B	=	37.21 ft-lb	50.45 J
C	=	85.81 °F	47.67 °C
To	=	148.24 °F	64.58 °C

		English	Metric
Cv = 30 ft-lb (41 J) at T	=	119.7 °F	48.7 °C
Upper Shelf Energy	=	79.1 ft-lb	107.3 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	50	6.0
2	70	15.0
3	80	18.0
4	90	28.0
5	100	24.0
6	130	34.0
7	140	34.0
8	160	51.0
9	180	42.0
10	190	61.0
11	220	78.0
12	280	77.0
13	350	72.0
14	500	82.0
15	500	78.0

0 = Fictitious Point Added   * = Test Point Not Included



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

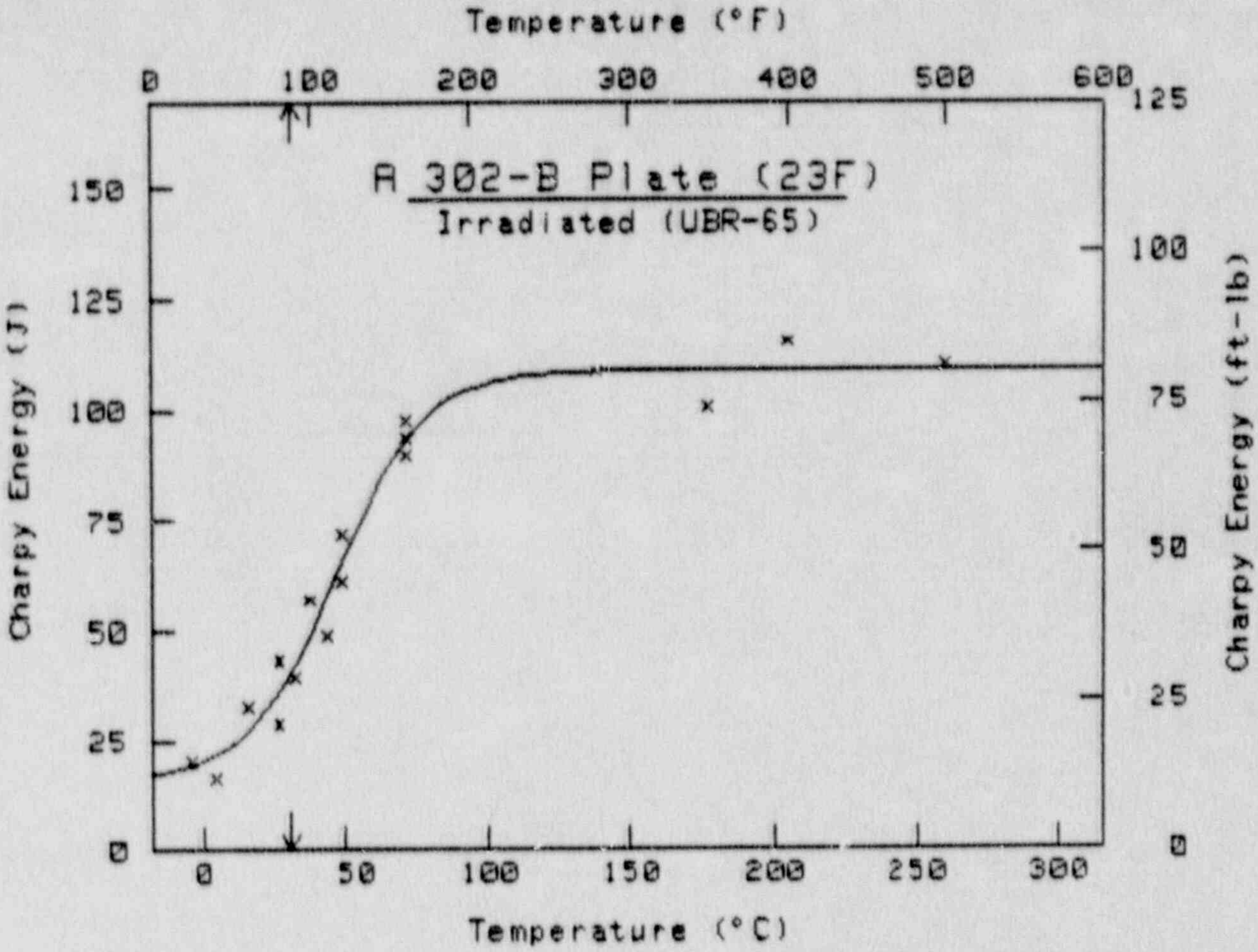
	English	Metric
A =	42.12 ft-lb	57.11 J
B =	28.95 ft-lb	39.25 J
C =	43.56 °F	24.20 °C
To =	158.59 °F	70.33 °C

Cv = 30 ft-lb (41 J) at T =	139.2 °F	59.5 °C
Upper Shelf Energy =	71.1 ft-lb	96.4 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	60	7.0
2	70	21.0
3	100	18.0
4	120	24.0
5	140	25.0
6	140	28.0
7	160	43.0
8	170	62.0
9	180	42.0
10	185	68.0
11	200	57.0
12	250	66.0
13	350	75.0
14	400	72.0
15	500	72.0

O = Fictitious Point Added * = Test Point Not Included



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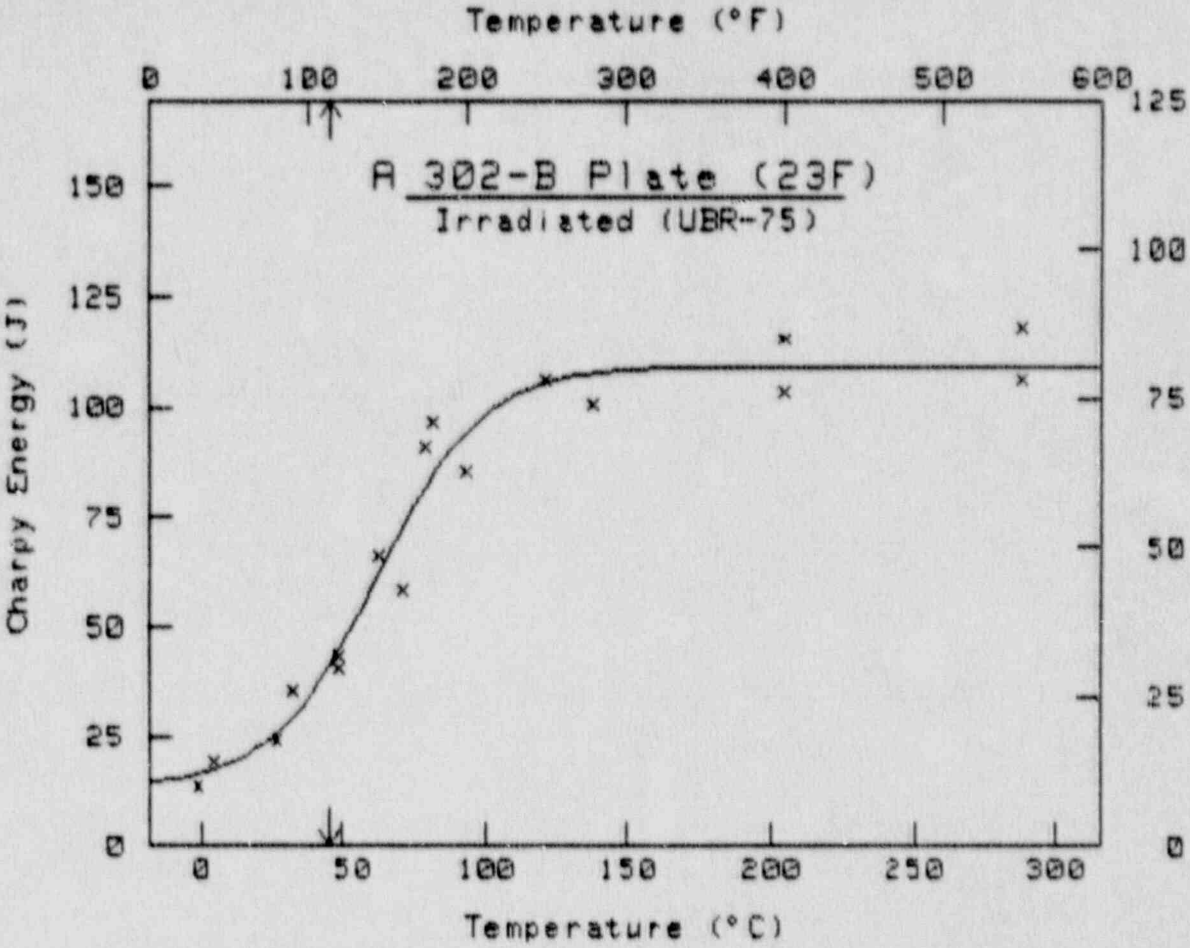
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	45.97 ft-lb	62.33 J
B =	34.24 ft-lb	46.42 J
C =	55.71 °F	30.95 °C
To =	115.95 °F	46.64 °C
Cv = 30 ft-lb (41 J) at T =	87.8 °F	31.0 °C
Upper Shelf Energy =	80.2 ft-lb	108.7 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	25	15.0	10	120	45.0
2	40	12.0	11	160	66.0
3	60	24.0	12	160	72.0
4	80	32.0	13	160	69.0
5	80	21.0	14	200	80.0
6	90	29.0	15	350	74.0
7	100	42.0	16	400	85.0
8	110	36.0	17	500	81.0
9	120	53.0			

0 = Fictitious Point Added * = Test Point Not Included



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

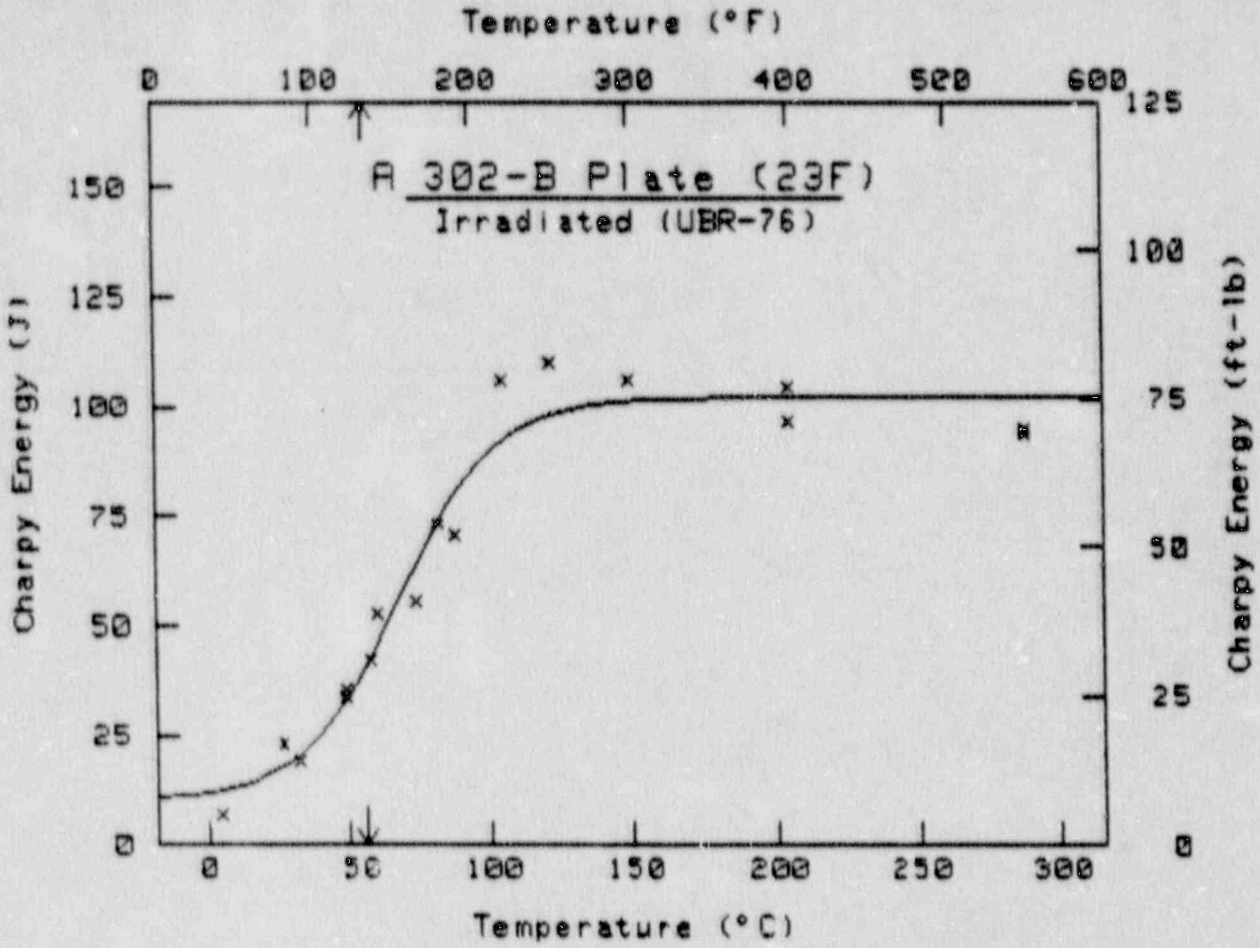
		English	Metric
A	=	45.07 ft-lb	61.10 J
B	=	35.33 ft-lb	47.91 J
C	=	66.98 °F	37.21 °C
To	=	143.78 °F	62.10 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	113.3 °F	45.2 °C
Upper Shelf Energy =	80.4 ft-lb	109.0 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	30	10.0	10	180	71.0
2	40	14.0	11	200	63.0
3	80	18.0	12	250	78.0
4	90	26.0	13	280	74.0
5	120	32.0	14	400	85.0
6	120	30.0	15	400	76.0
7	145	49.0	16	550	78.0
8	160	43.0	17	550	87.0
9	175	67.0			

0 = Fictitious Point Added   * = Test Point Not Included



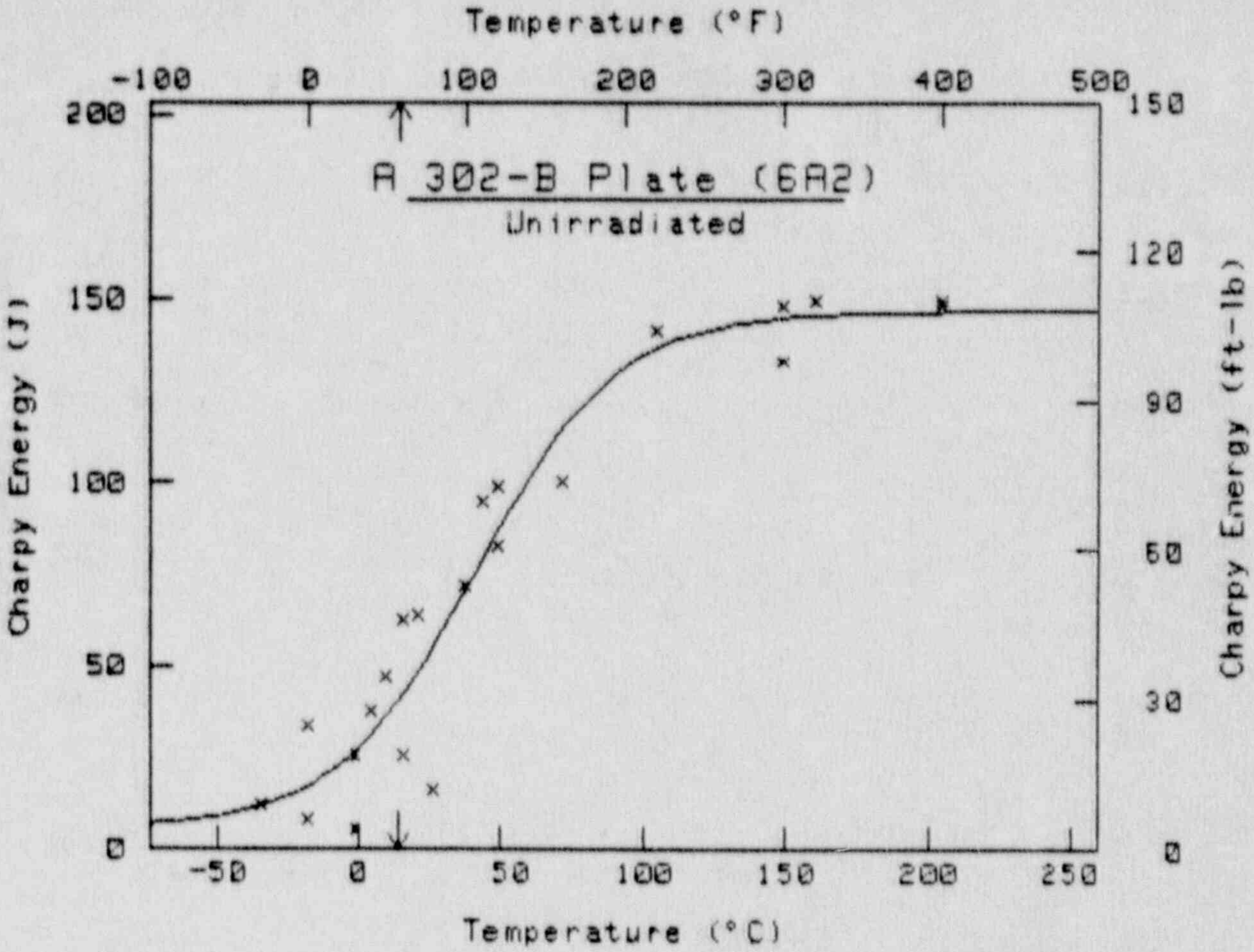
$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	41.32 ft-lb	56.03 J
B =	33.84 ft-lb	45.88 J
C =	61.93 °F	34.41 °C
To =	153.94 °F	67.75 °C

Cv = 30 ft-lb (41 J) at T =	132.4 °F	55.8 °C
Upper Shelf Energy =	75.2 ft-lb	101.9 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	40	5.0	10	190	52.0
2	80	17.0	11	220	78.0
3	90	14.0	12	250	81.0
4	120	26.0	13	300	78.0
5	120	25.0	14	400	71.0
6	135	31.0	15	400	77.0
7	140	39.0	16	550	70.0
8	165	41.0	17	550	69.0
9	180	54.0			

0 = Fictitious Point Added   * = Test Point Not Included



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

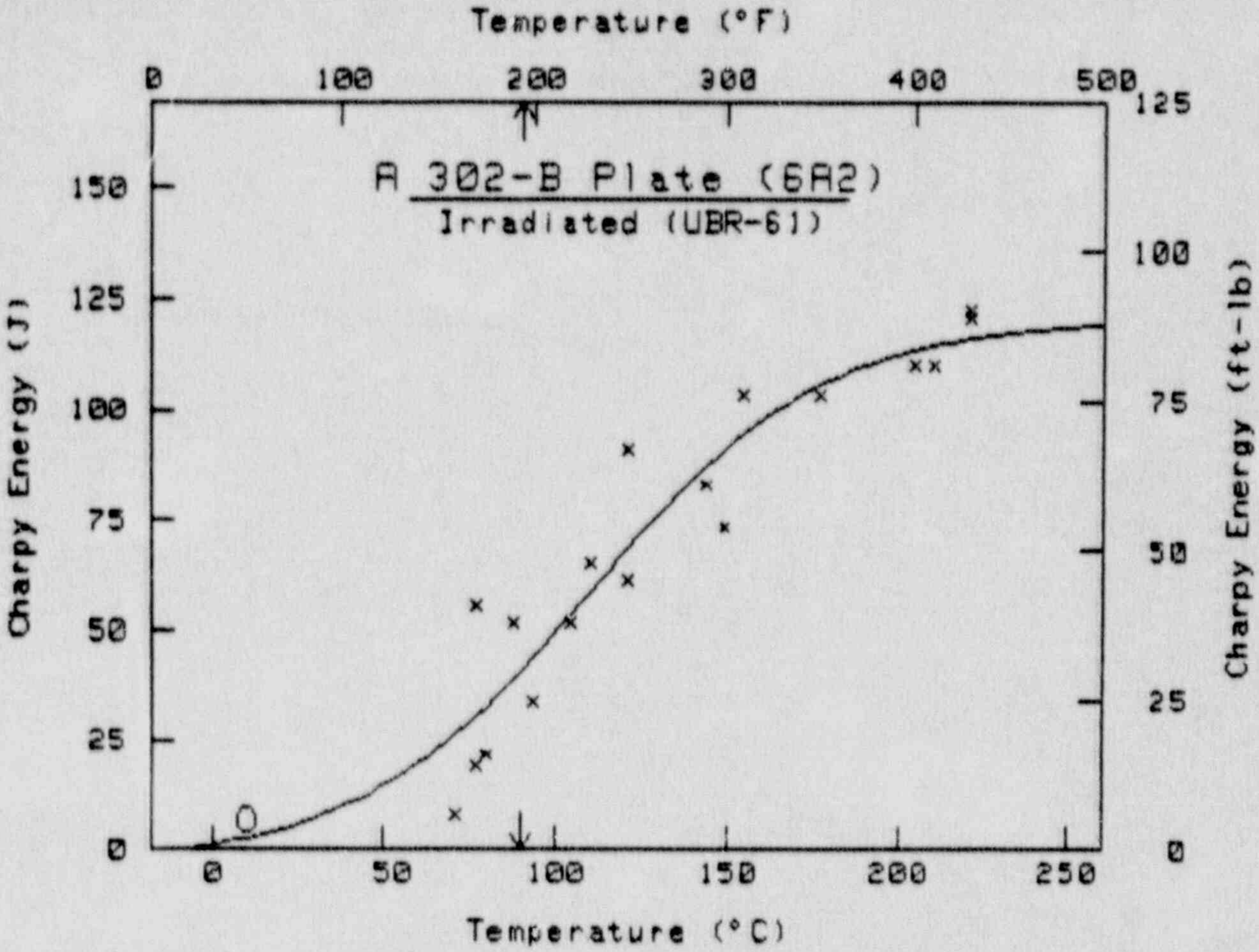
	English	Metric
A =	56.15 ft-lb	76.13 J
B =	51.89 ft-lb	70.36 J
C =	88.49 °F	49.16 °C
To =	106.86 °F	41.59 °C

Cv = 30 ft-lb (41 J) at T =	57.8 °F	14.3 °C
Upper Shelf Energy =	108.0 ft-lb	146.5 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-30	9.0	12	100	53.0
2	0	25.0	13	110	70.0
3	0	6.0	14	120	73.0
4	30	19.0	15	120	61.0
5	30	4.0	16	160	74.0
6	40	28.0	17	220	104.0
7	50	35.0	18	300	98.0
8	60	19.0	19	300	109.0
9	60	46.0	20	320	110.0
10	70	47.0	21	400	110.0
11	80	12.0	22	400	109.0

O = Fictitious Point Added   * = Test Point Not Included



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

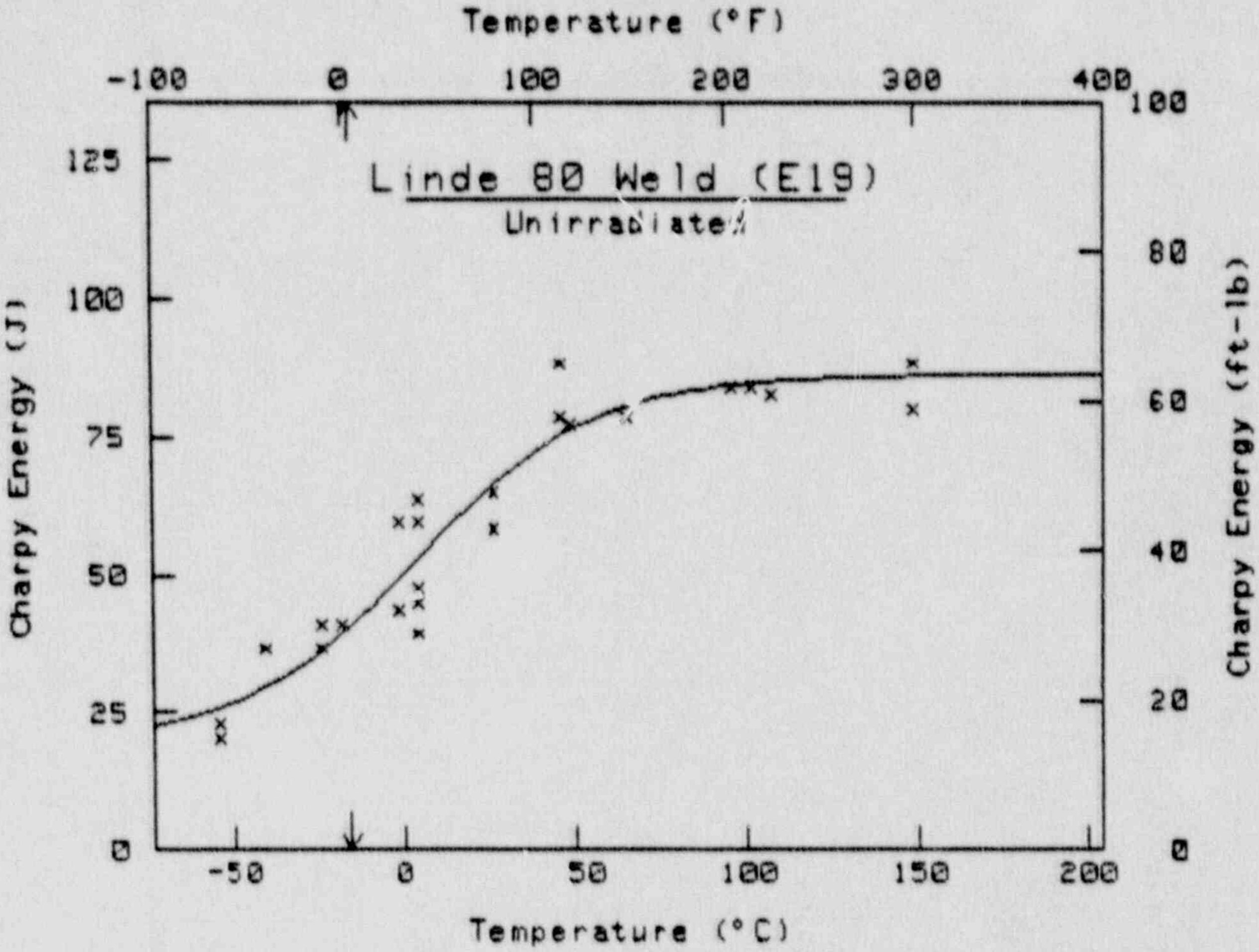
		English	Metric
A	=	43.04 ft-lb	58.36 J
B	=	45.66 ft-lb	61.91 J
C	=	121.38 °F	67.44 °C
To	=	229.62 °F	109.79 °C

Cv = 30 ft-lb (41 J) at T	=	194.0 °F	90.0 °C
Upper Shelf Energy	=	88.7 ft-lb	120.3 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	160	6.0	11	290	61.0
2	170	14.0	12	300	54.0
3	170	41.0	13	310	76.0
4	175	16.0	14	350	76.0
5	190	38.0	15	400	81.0
6	200	25.0	16	410	81.0
7	220	38.0	17	430	89.0
8	230	48.0	18	430	90.0
9	250	45.0	19 O	50	5.0
10	250	67.0			

O = Fictitious Point Added * = Test Point Not Included

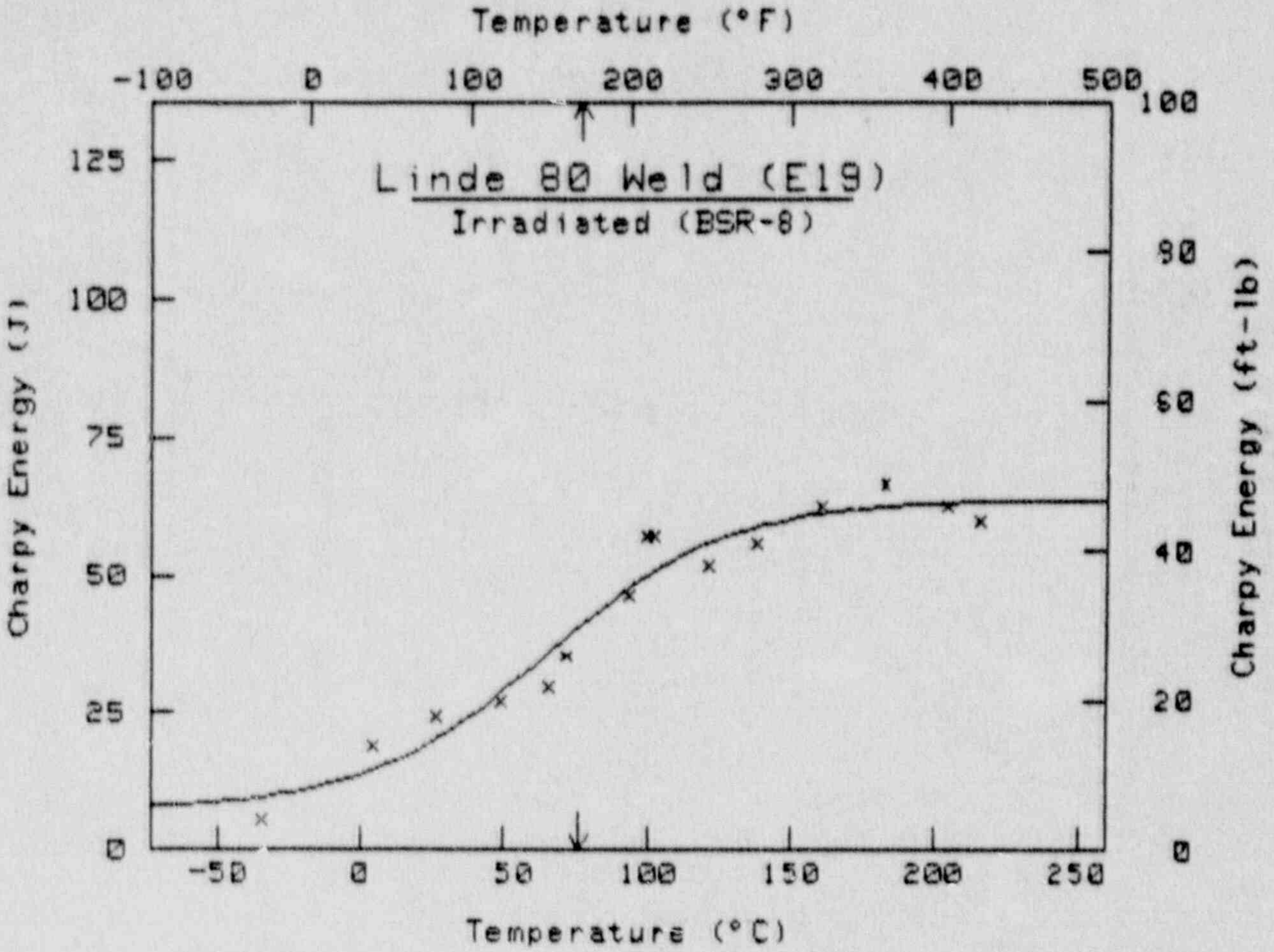


$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	38.96 ft-lb	52.83 J
B =	24.57 ft-lb	33.31 J
C =	92.55 °F	51.41 °C
To =	39.87 °F	4.37 °C
Cv = 30 ft-lb (41 J) at T =	4.5 °F	-15.3 °C
Upper Shelf Energy =	63.5 ft-lb	86.1 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-65	15.0	14	80	43.0
2	-65	17.0	15	80	48.0
3	-40	27.0	16	80	48.0
4	-10	27.0	17	115	58.0
5	-10	30.0	18	115	65.0
6	0	30.0	19	120	57.0
7	30	32.0	20	150	58.0
8	30	44.0	21	205	62.0
9	40	44.0	22	215	62.0
10	40	29.0	23	225	61.0
11	40	33.0	24	300	65.0
12	40	35.0	25	300	59.0
13	40	47.0	26	300	65.0

O = Fictitious Point Added * = Test Point Not Included



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

		English	Metric
A	=	26.16 ft-lb	35.47 J
B	=	20.73 ft-lb	28.11 J
C	=	111.93 °F	62.18 °C
To	=	148.11 °F	64.50 °C

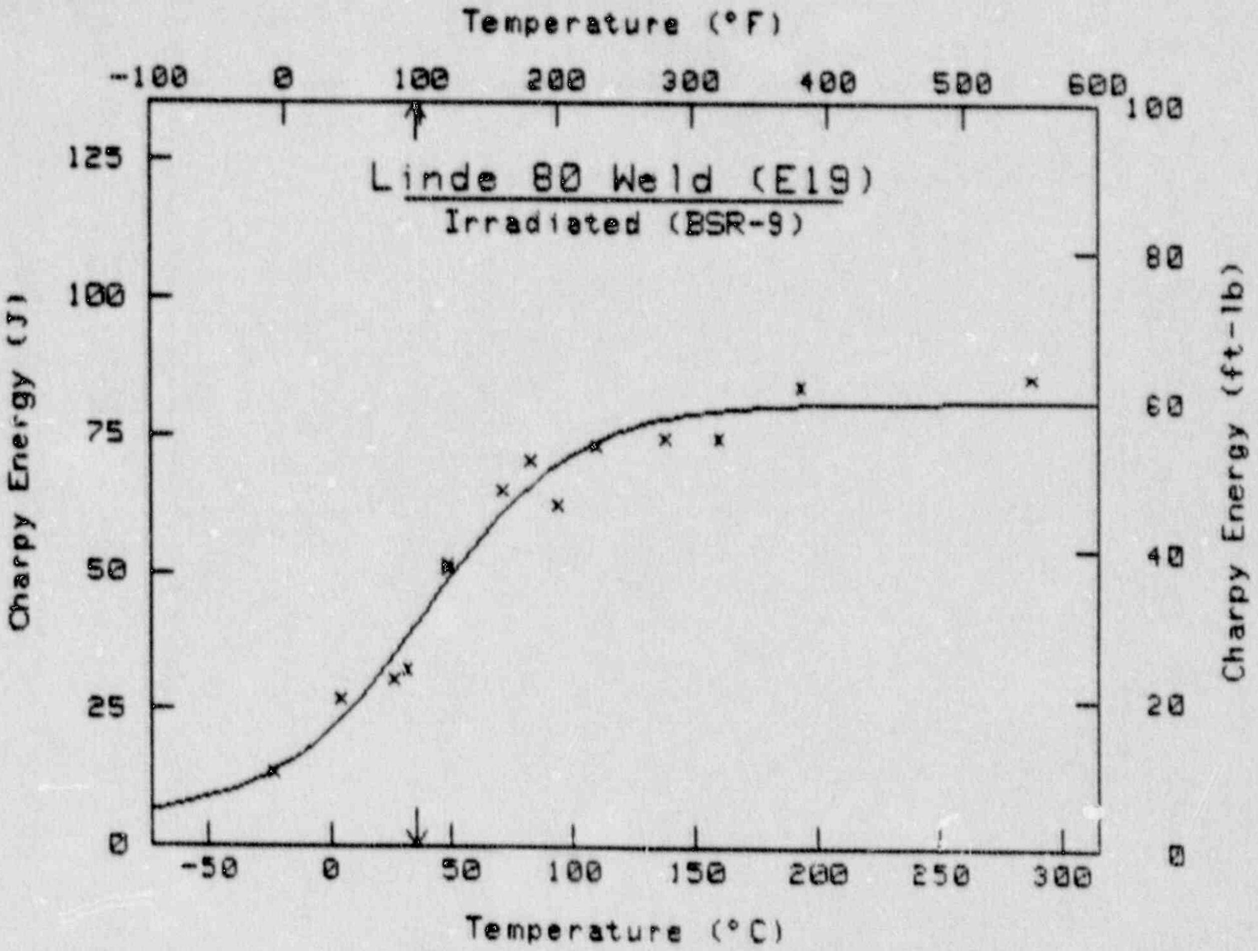
Cv = 30 ft-lb (41 J) at T = 169.1 °F 76.2 °C

Upper Shelf Energy = 46.9 ft-lb 63.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-30	4.0
2	40	14.0
3	80	18.0
4	120	20.0
5	150	22.0
6	160	26.0
7	200	34.0
8	210	42.0
9	215	42.0
10	250	38.0
11	280	41.0
12	320	46.0
13	360	49.0
14	400	46.0
15	420	44.0

0 = Fictitious Point Added * = Test Point Not Included



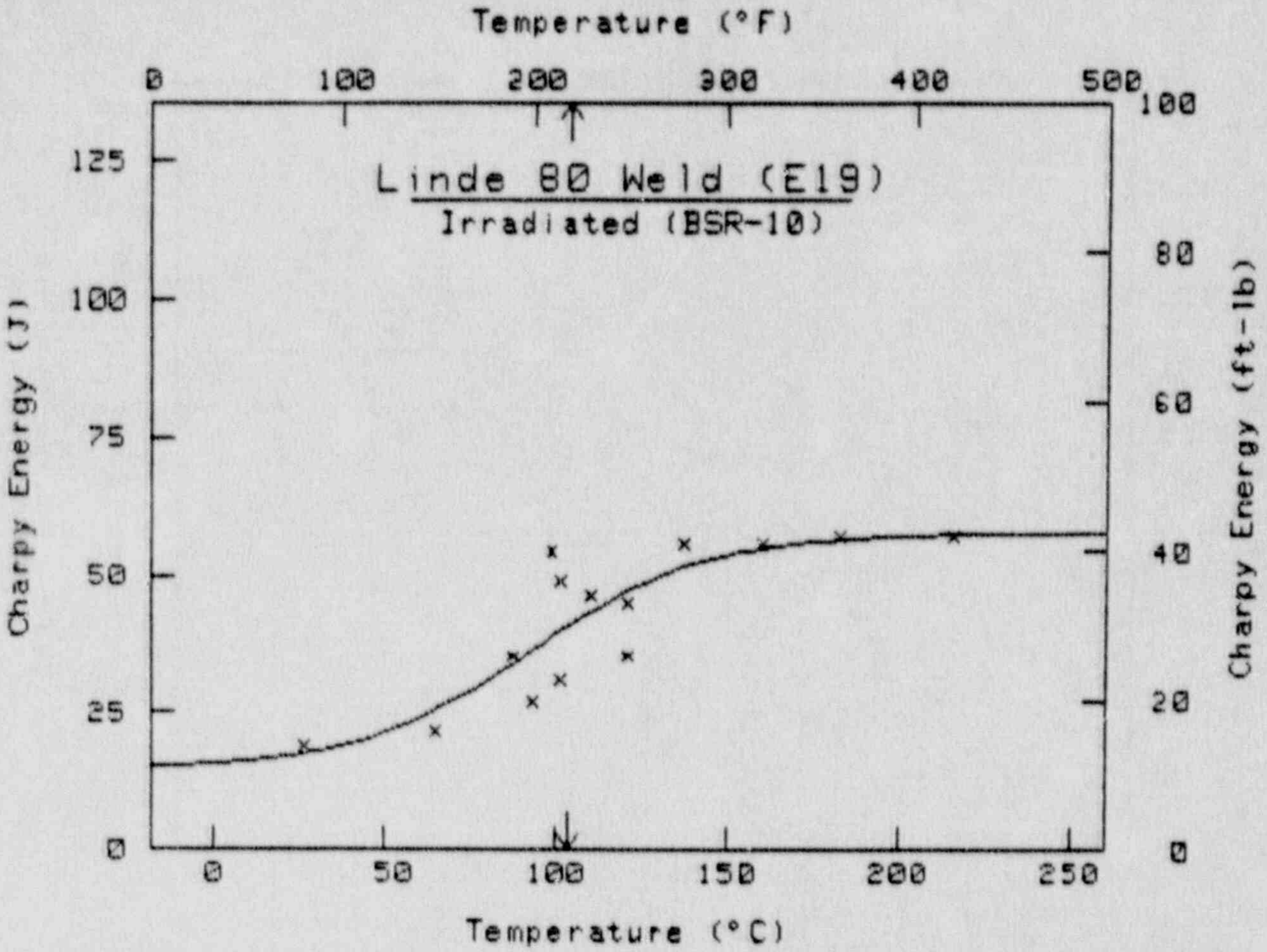
$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	31.68 ft-lb	42.95 J
B =	28.09 ft-lb	38.09 J
C =	111.55 °F	61.97 °C
To =	103.68 °F	39.82 °C

Cv = 30 ft-lb (41 J) at T =	97.0 °F	36.1 °C
Upper Shelf Energy =	59.8 ft-lb	81.0 J

PT #	Temp (°F)	Energy (ft-lb)
1	-10	10.0
2	40	20.0
3	80	22.5
4	90	24.0
5	120	37.5
6	120	38.0
7	160	48.0
8	180	52.0
9	200	46.0
10	230	54.0
11	280	55.0
12	320	55.0
13	380	62.0
14	550	63.0

O = Fictitious Point Added   * = Test Point Not Included



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

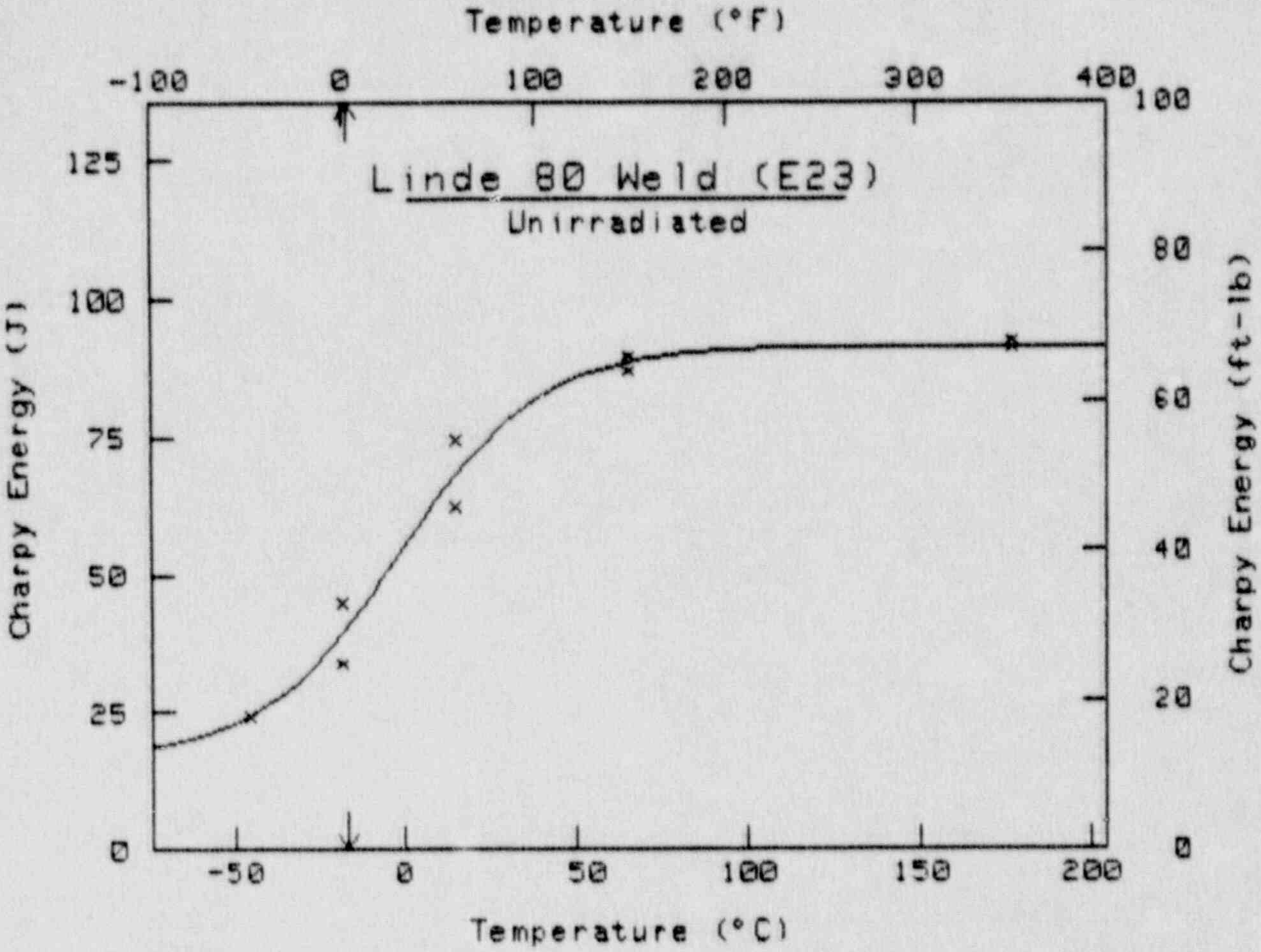
		English	Metric
A	=	26.65 ft-lb	36.13 J
B	=	15.83 ft-lb	21.46 J
C	=	90.44 °F	50.24 °C
To	=	199.41 °F	93.01 °C

Cv = 30 ft-lb (41 J) at T	=	218.9 °F	103.8 °C
Upper Shelf Energy	=	42.5 ft-lb	57.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	80	14.0
2	150	16.0
3	190	26.0
4	200	20.0
5	210	40.0
6	215	36.0
7	215	23.0
8	230	34.0
9	250	26.0
10	250	33.0
11	280	41.0
12	320	41.0
13	360	42.0
14	420	42.0

0 = Fictitious Point Added   * = Test Point Not Included



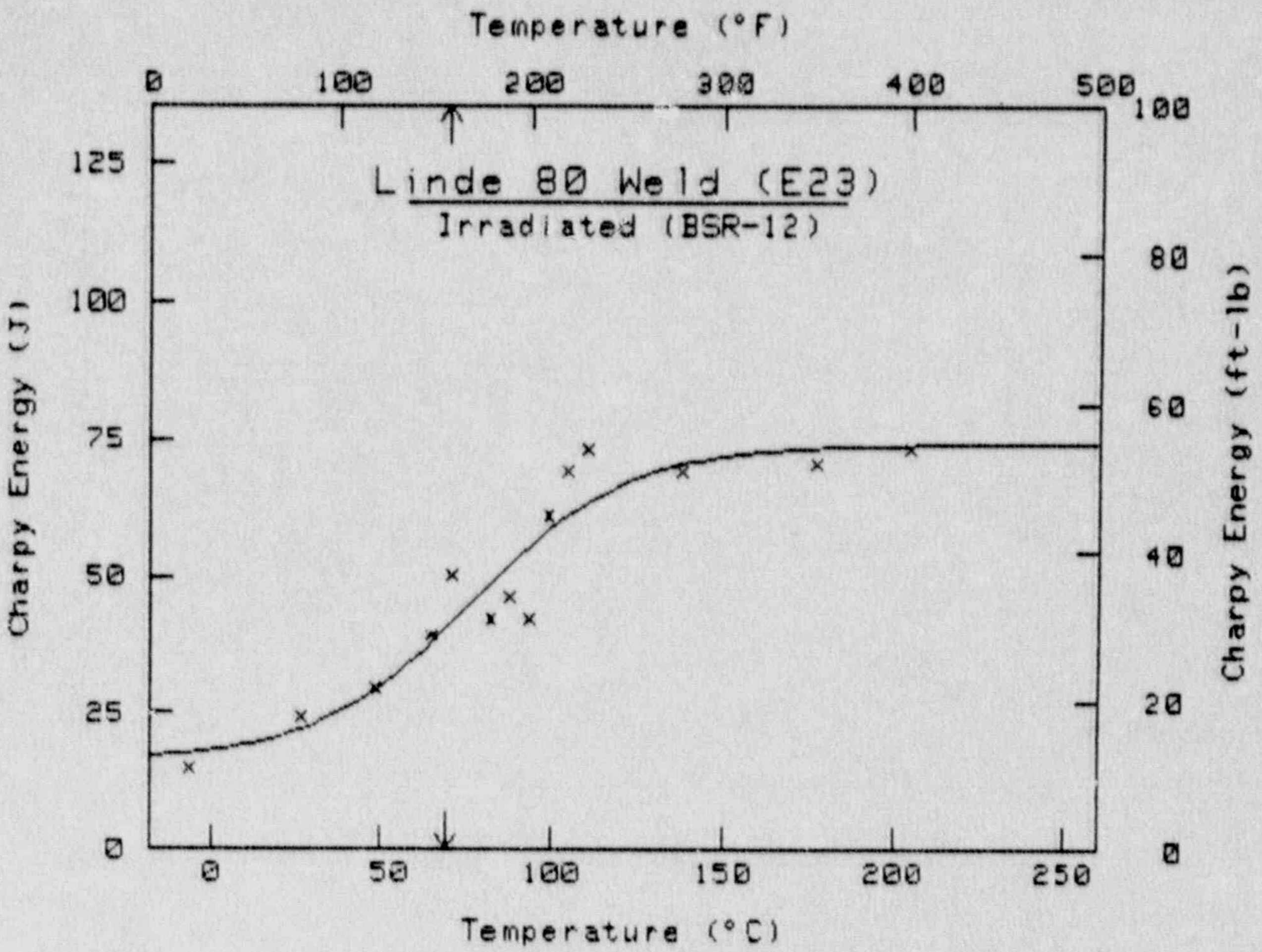
$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	39.82 ft-lb	53.99 J
B =	27.49 ft-lb	37.27 J
C =	73.52 °F	40.84 °C
To =	30.27 °F	-.96 °C

Cv = 30 ft-lb (41 J) at T =	2.8 °F	-16.2 °C
Upper Shelf Energy =	67.3 ft-lb	91.3 J

PT #	Temp (°F)	Energy (ft-lb)
1	-50	18.0
2	0	33.0
3	0	25.0
4	60	55.0
5	60	46.0
6	150	64.0
7	150	66.0
8	350	68.0
9	350	67.0

O = Fictitious Point Added   * = Test Point Not Included



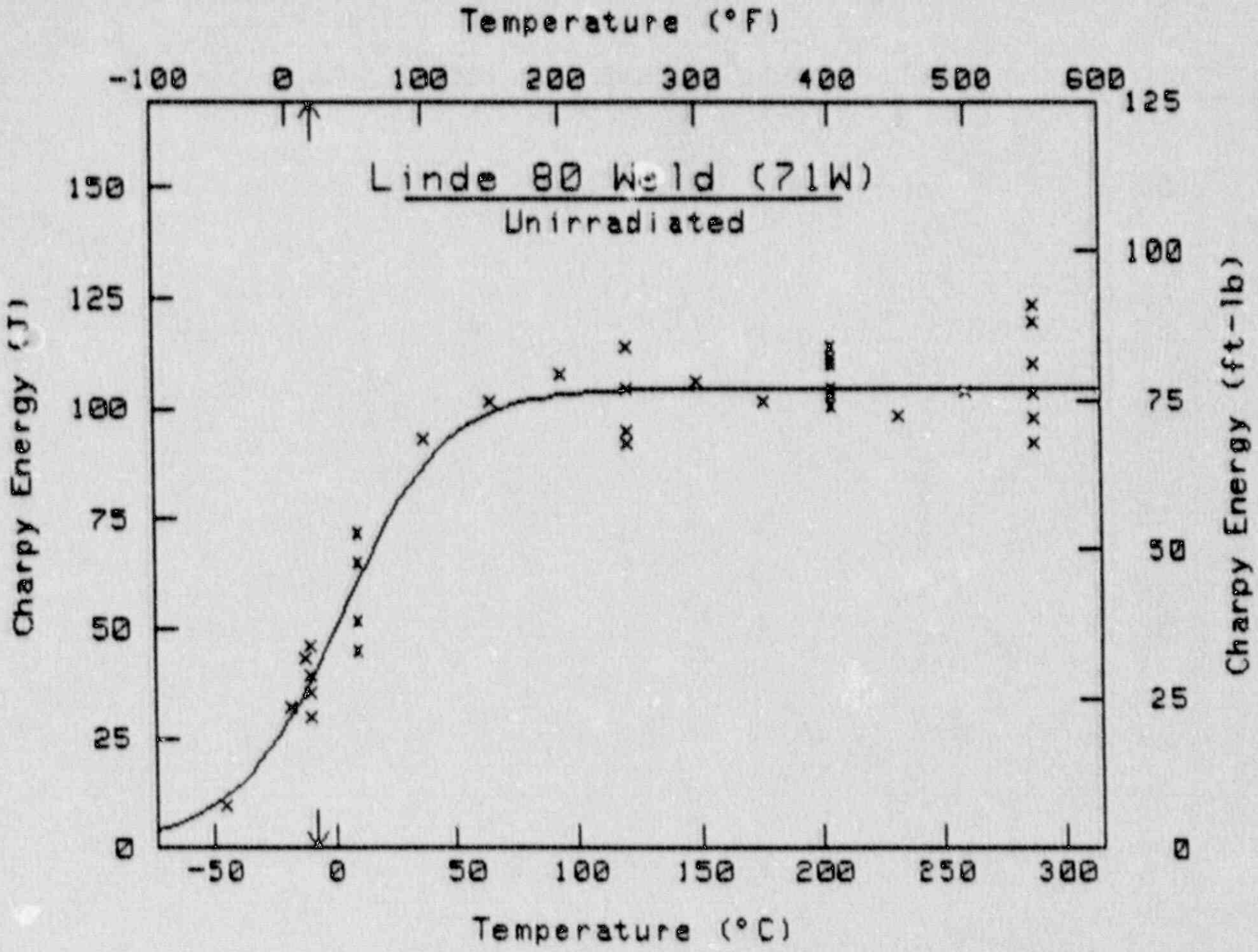
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	33.30 ft-lb	45.15 J
B	=	21.27 ft-lb	28.84 J
C	=	81.59 °F	45.33 °C
To	=	169.95 °F	76.64 °C

Cv = 30 ft-lb (41 J) at T	=	157.2 °F	69.5 °C
Upper Shelf Energy	=	54.6 ft-lb	74.0 J

PT #	Temp (°F)	Energy (ft-lb)
1	20	11.0
2	80	18.0
3	120	22.0
4	150	29.0
5	160	37.0
6	180	31.0
7	190	34.0
8	200	31.0
9	210	45.0
10	220	51.0
11	230	54.0
12	280	51.0
13	350	52.0
14	400	54.0

0 = Fictitious Point Added * = Test Point Not Included



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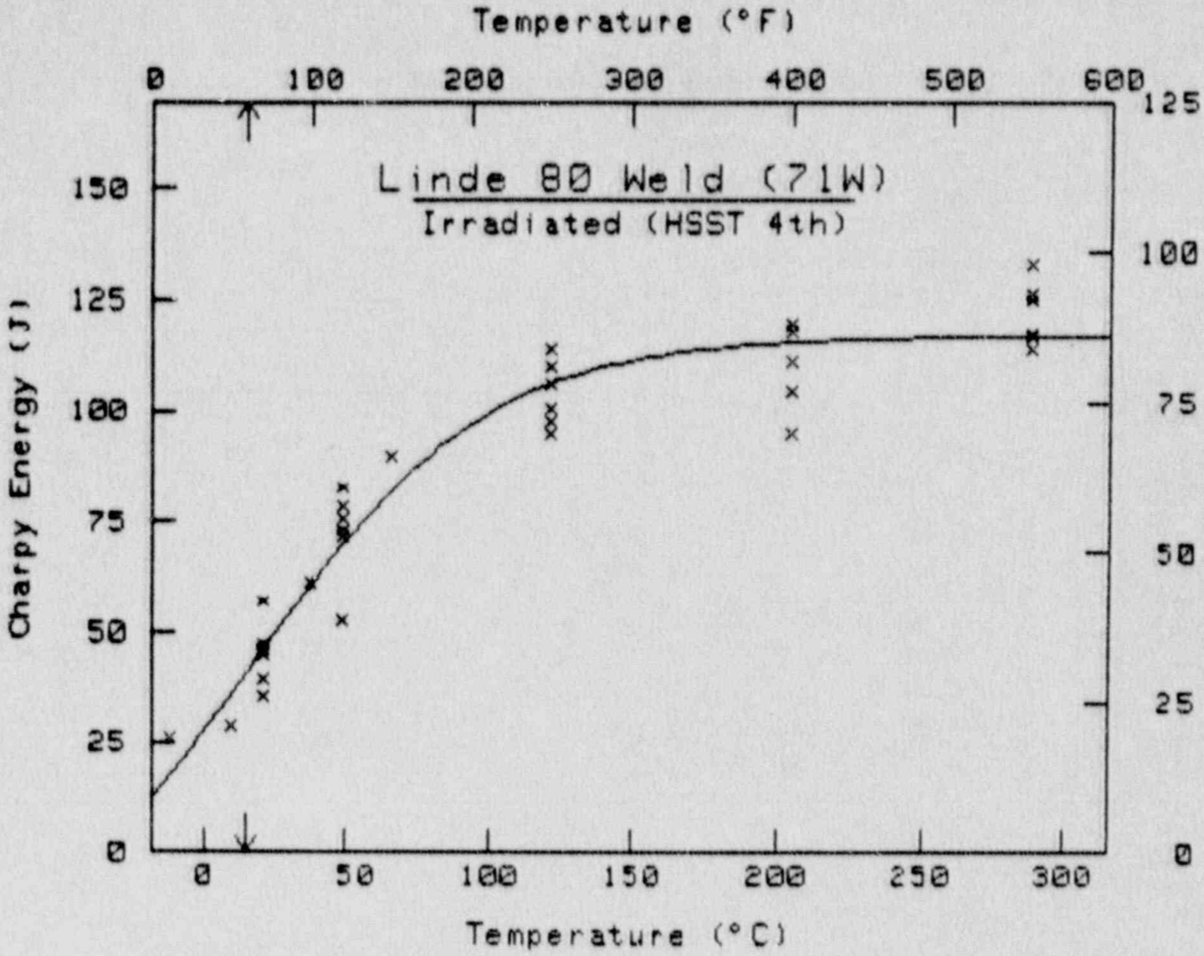
$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	38.91 ft-lb	52.76 J
B =	38.19 ft-lb	51.78 J
C =	79.07 °F	43.93 °C
To =	37.07 °F	2.82 °C
Cv = 30 ft-lb (41 J) at T =	18.3 °F	-7.6 °C
Upper Shelf Energy =	77.1 ft-lb	104.5 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-50	7.0	20	250	77.0
2	0	23.5	21	250	84.0
3	10	32.0	22	300	78.0
4	15	22.0	23	350	75.0
5	15	26.0	24	400	74.0
6	15	29.0	25	400	76.0
7	15	34.0	26	400	77.0
8	50	33.0	27	400	81.0
9	50	38.0	28	400	82.0
10	50	48.0	29	400	84.0
11	50	48.0	30	450	72.5
12	50	53.0	31	500	76.5
13	100	68.5	32	550	68.0
14	150	75.0	33	550	72.0
15	200	79.5	34	550	76.0
16	250	68.0	35	550	81.0
17	250	68.0	36	550	88.0
18	250	68.0	37	550	91.0
19	250	70.0			



****

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

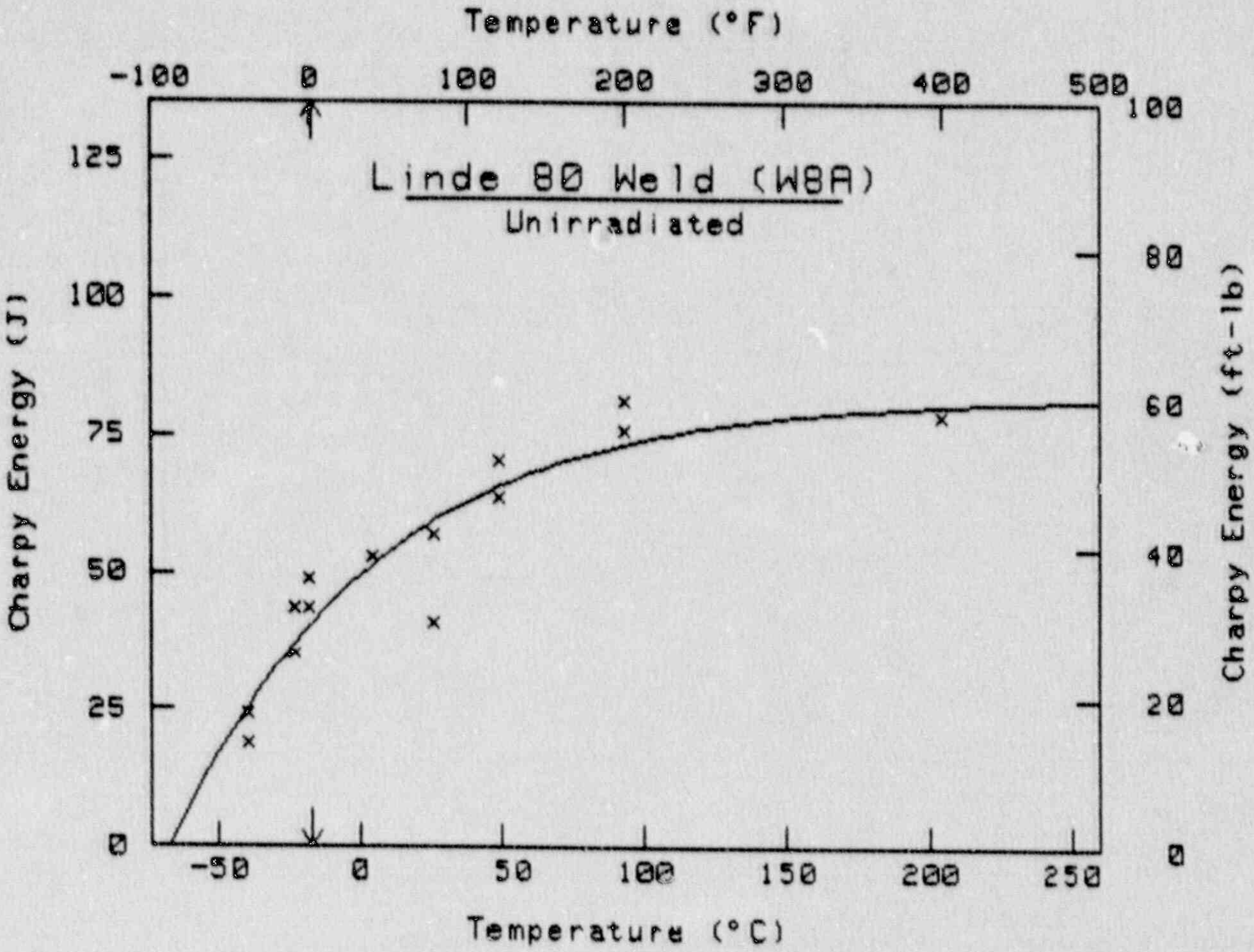
		English	Metric
A	=	31.63 ft-lb	42.89 J
B	=	54.55 ft-lb	73.95 J
C	=	146.78 °F	81.54 °C
To	=	63.68 °F	17.60 °C

Cv = 30 ft-lb (41 J) at T = 59.3 °F 15.2 °C

Upper Shelf Energy = 86.2 ft-lb 116.8 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	10	19.0	20	250	74.0
2	50	21.0	21	250	70.0
3	70	34.0	22	250	72.0
4	70	29.0	23	250	78.0
5	70	26.0	24	250	78.0
6	70	26.0	25	250	81.0
7	70	35.0	26	400	70.0
8	70	33.0	27	400	87.0
9	70	42.0	28	400	77.0
10	100	45.0	29	400	88.0
11	120	54.0	30	400	82.0
12	120	61.0	31	400	88.0
13	120	58.0	32	550	84.0
14	120	54.0	33	550	98.0
15	120	56.0	34	550	84.0
16	120	53.0	35	550	92.0
17	120	39.0	36	550	86.5
18	150	66.0	37	550	93.0
19	250	84.0	38	550	86.0



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

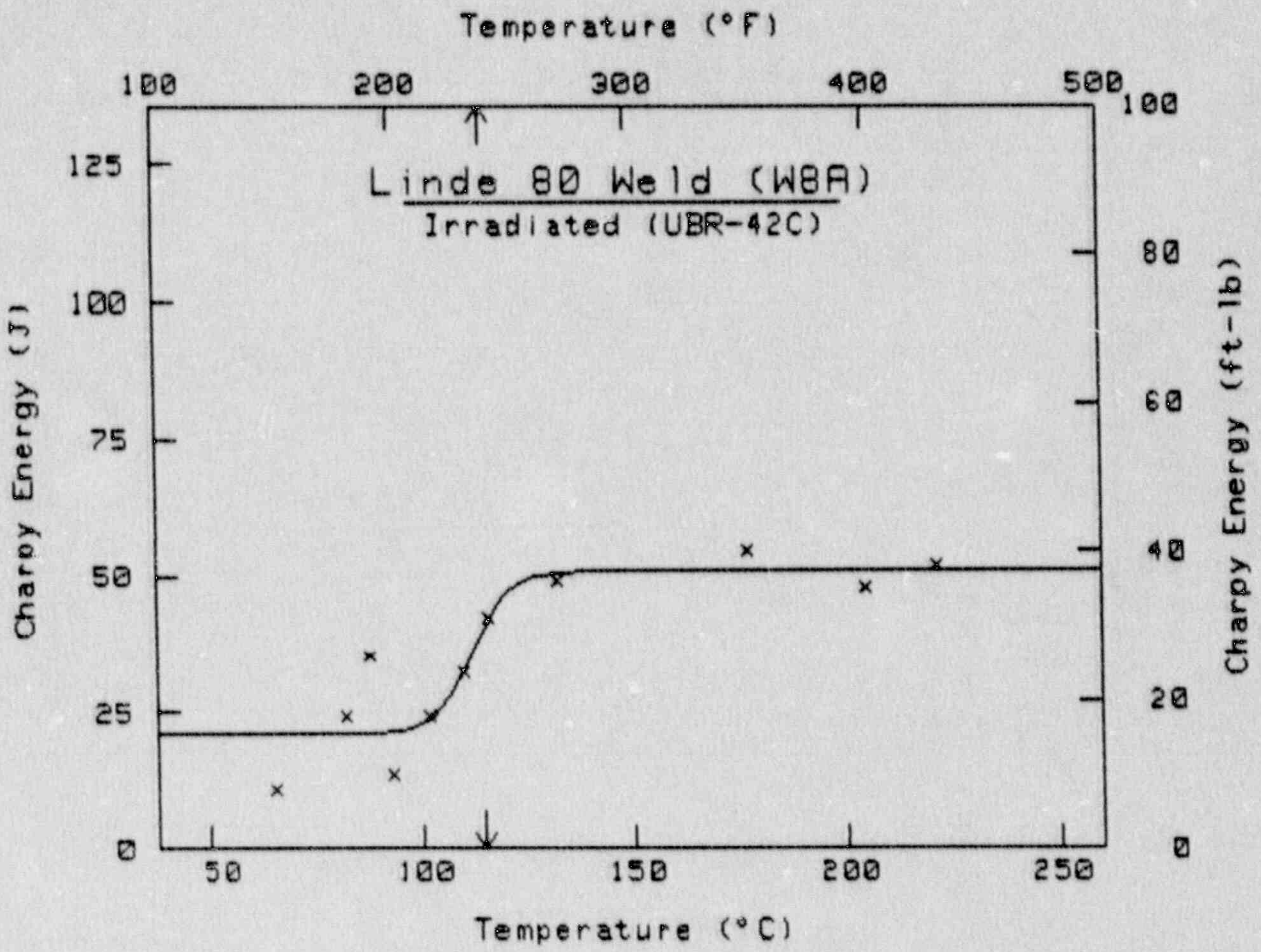
	English	Metric
A =	-355.03 ft-lb	-481.36 J
B =	415.53 ft-lb	563.39 J
C =	251.15 °F	139.53 °C
To =	-408.93 °F	-244.96 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	1.4 °F	-17.0 °C
Upper Shelf Energy =	60.5 ft-lb	82.0 J

PT #	Temp (°F)	Energy (ft-lb)
1	-40	14.0
2	-40	18.0
3	-10	26.0
4	-10	32.0
5	0	32.0
6	0	36.0
7	40	39.0
8	80	42.0
9	80	30.0
10	120	52.0
11	120	47.0
12	200	60.0
13	200	56.0
14	400	58.0
15	400	58.0

0 = Fictitious Point Added

* = Test Point Not Included



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

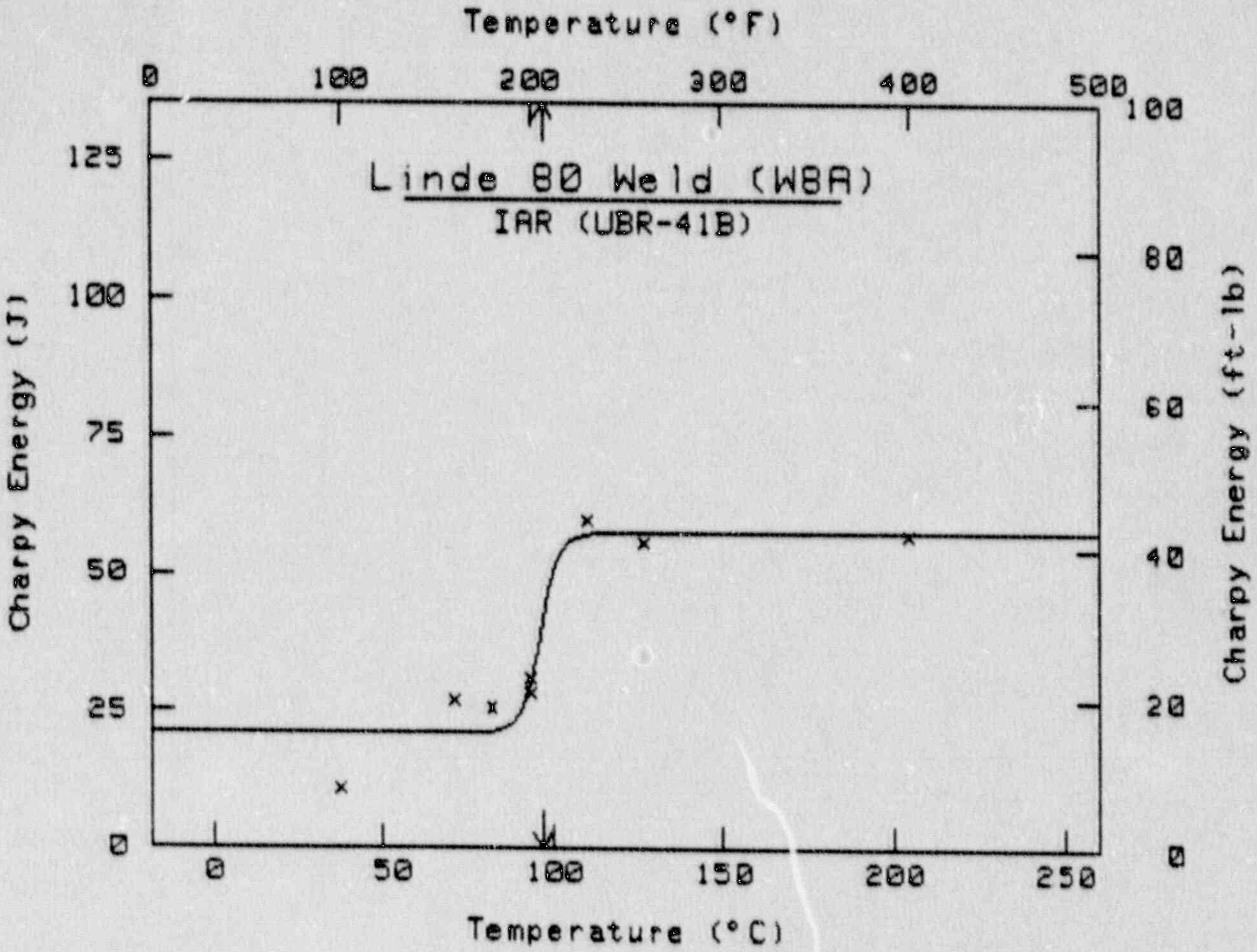
	English	Metric
A =	26.42 ft-lb	35.82 J
B =	10.91 ft-lb	14.79 J
C =	15.74 °F	8.74 °C
To =	233.31 °F	111.84 °C

Cv = 30 ft-lb (41 J) at T =	238.7 °F	114.8 °C
Upper Shelf Energy =	37.3 ft-lb	50.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	150	8.0
2	180	18.0
3	190	26.0
4	200	10.0
5	215	18.0
6	230	24.0
7	240	31.0
8	270	36.0
9	350	40.0
10	400	35.0
11	430	38.0

O = Fictitious Point Added   * = Test Point Not Included



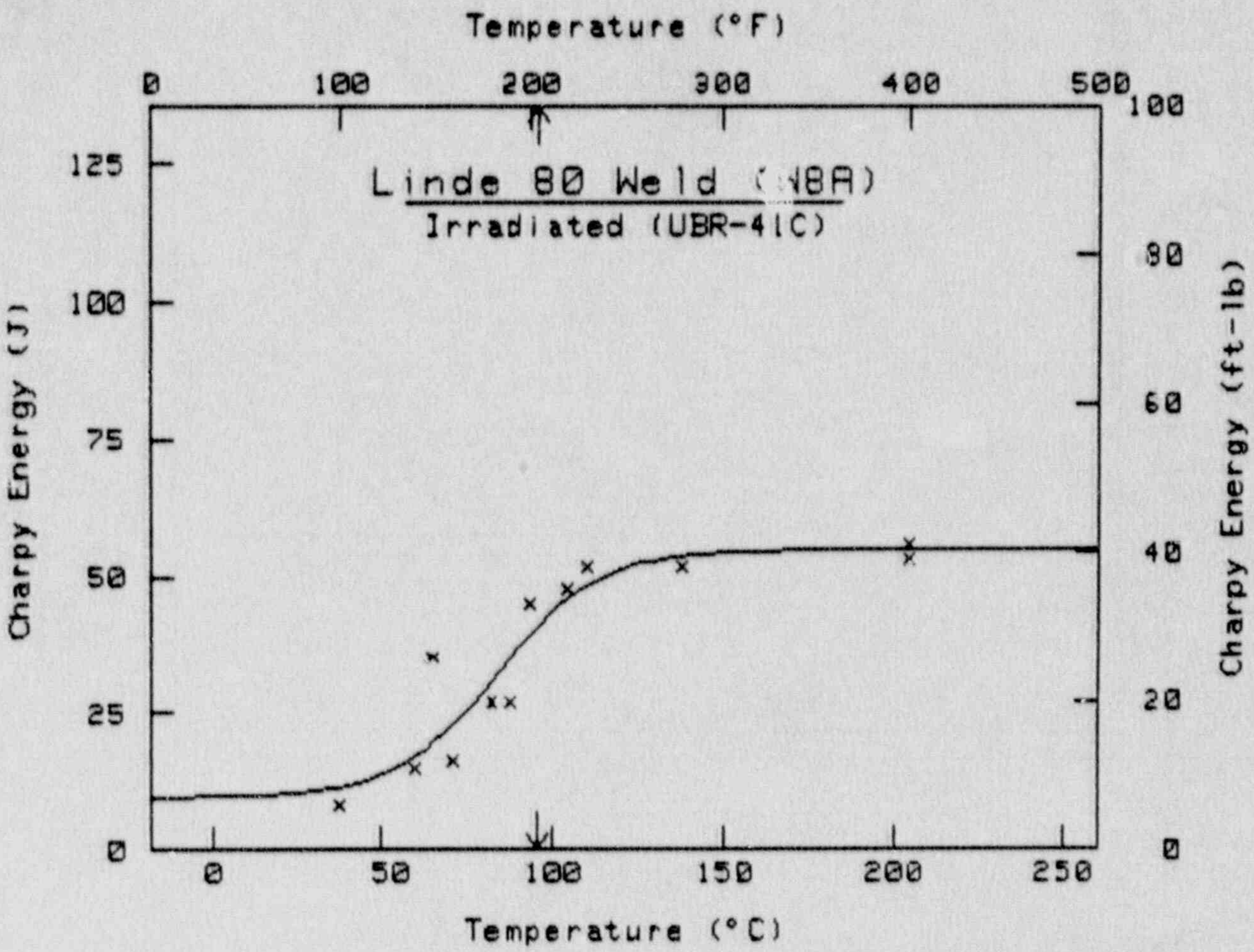
$$C_v = A + B \tanh[(T - T_o)/C]$$

		English	Metric
A	=	28.93 ft-lb	39.23 J
B	=	13.35 ft-lb	18.10 J
C	=	9.52 °F	5.29 °C
To	=	205.40 °F	96.34 °C

Cv = 30 ft-lb (41 J) at T	=	206.2 °F	96.8 °C
Upper Shelf Energy	=	42.3 ft-lb	57.3 J

PT #	Temp (°F)	Energy (ft-lb)
1	100	8.0
2	160	20.0
3	180	19.0
4	200	21.0
5	200	23.0
6	230	44.0
7	260	41.0
8	400	42.0
9	400	42.0

0 = Fictitious Point Added * = Test Point Not Included



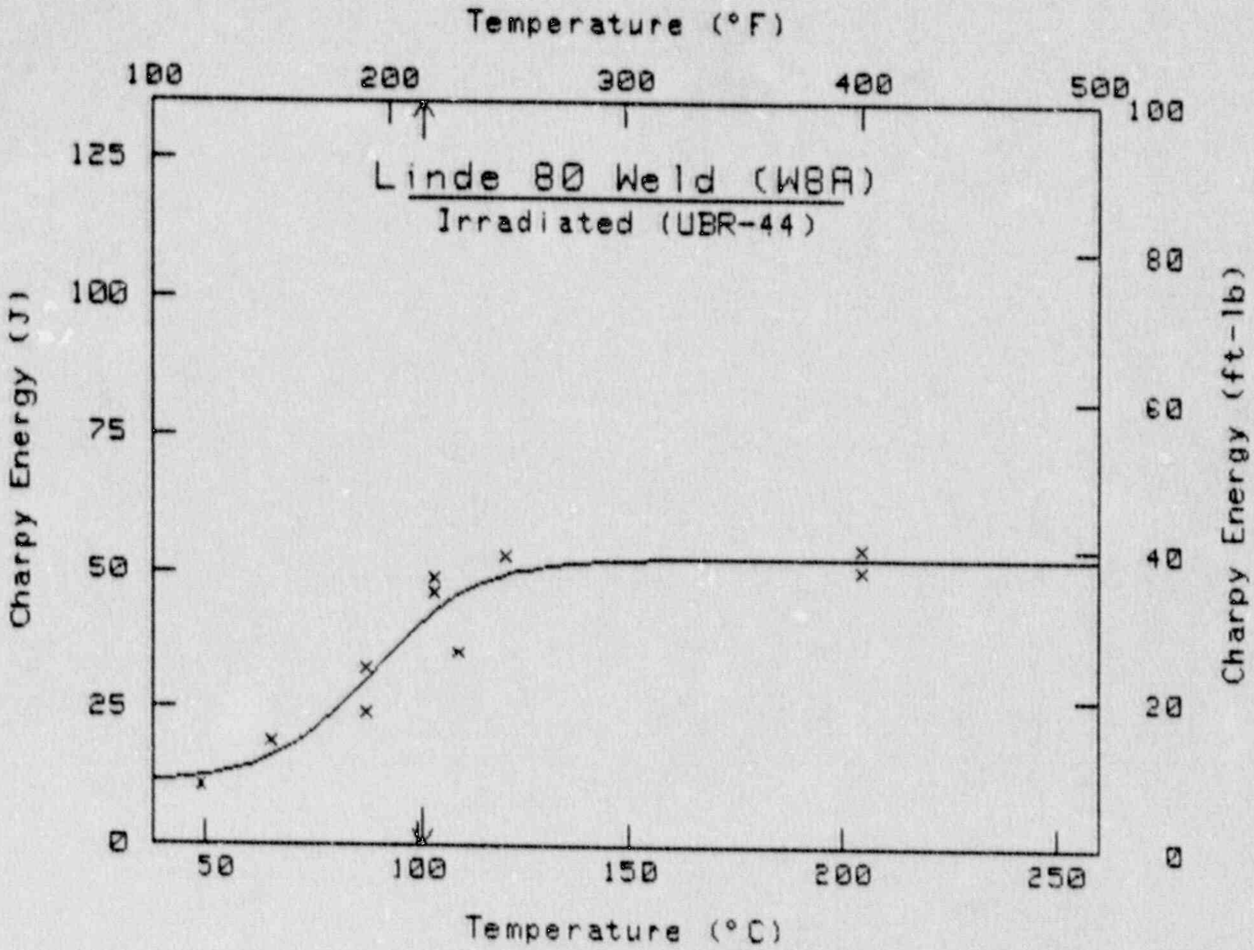
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	23.71 ft-lb	32.15 J
B	=	16.61 ft-lb	22.52 J
C	=	52.71 °F	29.28 °C
To	=	183.21 °F	84.00 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	204.2 °F	95.7 °C
Upper Shelf Energy =	40.3 ft-lb	54.7 J

PT #	Temp (°F)	Energy (ft-lb)
1	100	6.0
2	140	11.0
3	150	26.0
4	160	12.0
5	180	20.0
6	190	20.0
7	200	33.0
8	220	35.0
9	230	38.0
10	280	38.0
11	400	39.0
12	400	41.0

0 = Fictitious Point Added   * = Test Point Not Included



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

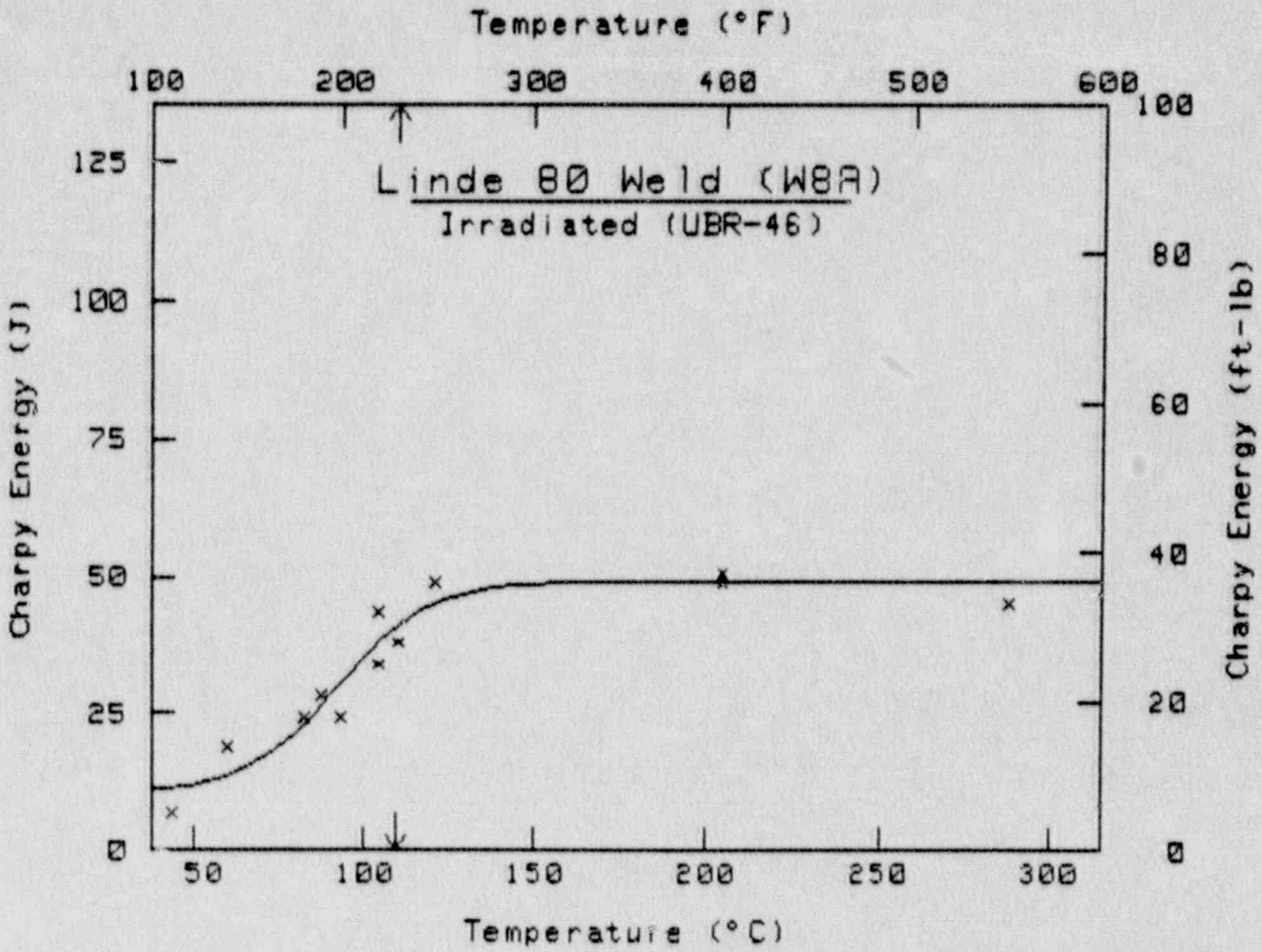
		English	Metric
A	=	23.42 ft-lb	31.76 J
B	=	15.32 ft-lb	20.77 J
C	=	44.82 °F	24.90 °C
To	=	193.74 °F	89.86 °C

Cv = 30 ft-lb (41 J) at T	=	214.3 °F	101.3 °C
Upper Shelf Energy	=	38.7 ft-lb	52.5 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	120	8.0
2	150	14.0
3	190	18.0
4	190	24.0
5	220	36.0
6	220	34.0
7	230	26.0
8	250	39.0
9	400	40.0
10	400	37.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

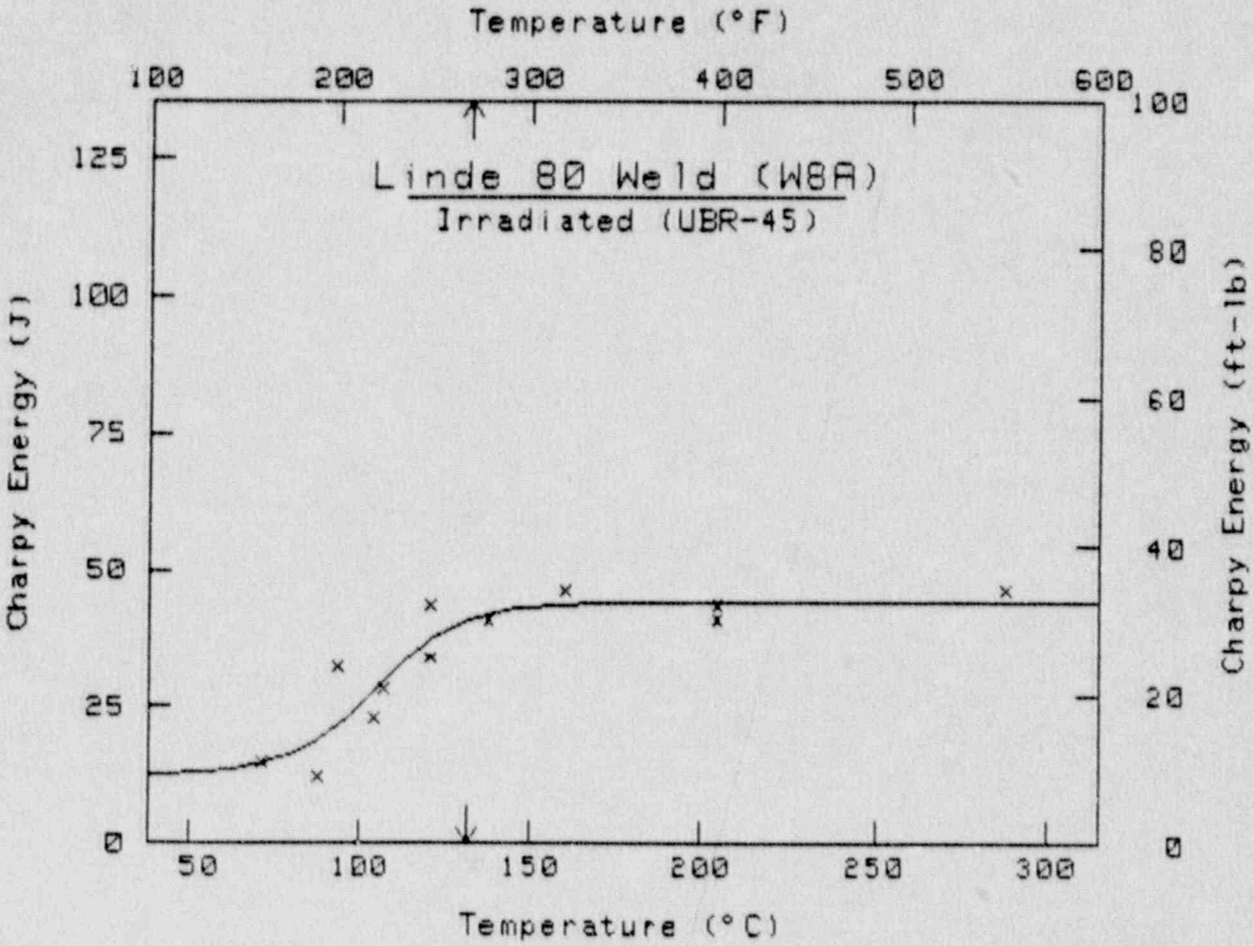
		English	Metric
A	=	21.98 ft-lb	29.80 J
B	=	14.24 ft-lb	19.30 J
C	=	48.14 °F	26.75 °C
To	=	198.10 °F	92.28 °C

Cv = 30 ft-lb (41 J) at T	=	228.8 °F	109.3 °C
Upper Shelf Energy	=	36.2 ft-lb	49.1 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	110	5.0
2	140	14.0
3	180	18.0
4	190	21.0
5	200	18.0
6	220	25.0
7	220	32.0
8	230	28.0
9	250	36.0
10	250	36.0
11	400	37.0
12	400	36.0
13	550	33.0

0 = Fictitious Point Added   * = Test Point Not Included



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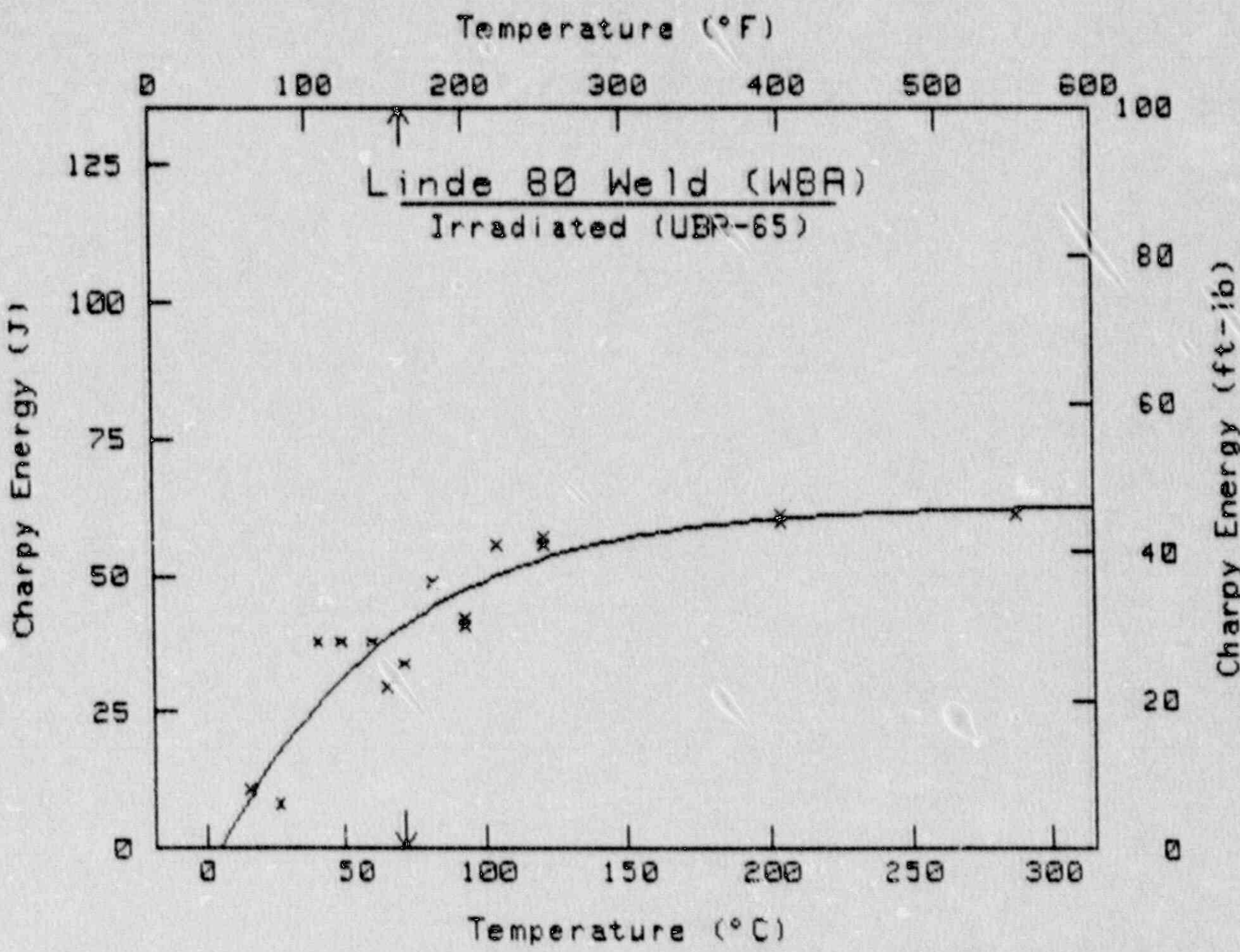
$$Cv = A + B \tanh[(T - To)/C]$$

	English	Metric
A =	20.89 ft-lb	28.32 J
B =	11.64 ft-lb	15.78 J
C =	46.05 °F	25.58 °C
To =	220.79 °F	104.89 °C
Cv = 30 ft-lb (41 J) at T =	269.2 °F	131.8 °C
Upper Shelf Energy =	32.5 ft-lb	44.1 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	160	11.0
2	190	9.0
3	200	24.0
4	220	17.0
5	225	21.0
6	250	32.0
7	250	25.0
8	280	30.0
9	320	34.0
10	400	30.0
11	400	32.0
12	550	34.0

0 = Fictitious Point Added   * = Test Point Not Included



`****************************************************************************`

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

		English	Metric
A	=	-192.93 ft-lb	-261.58 J
B	=	239.22 ft-lb	324.34 J
C	=	214.24 °F	119.02 °C
To	=	-198.09 °F	-127.83 °C

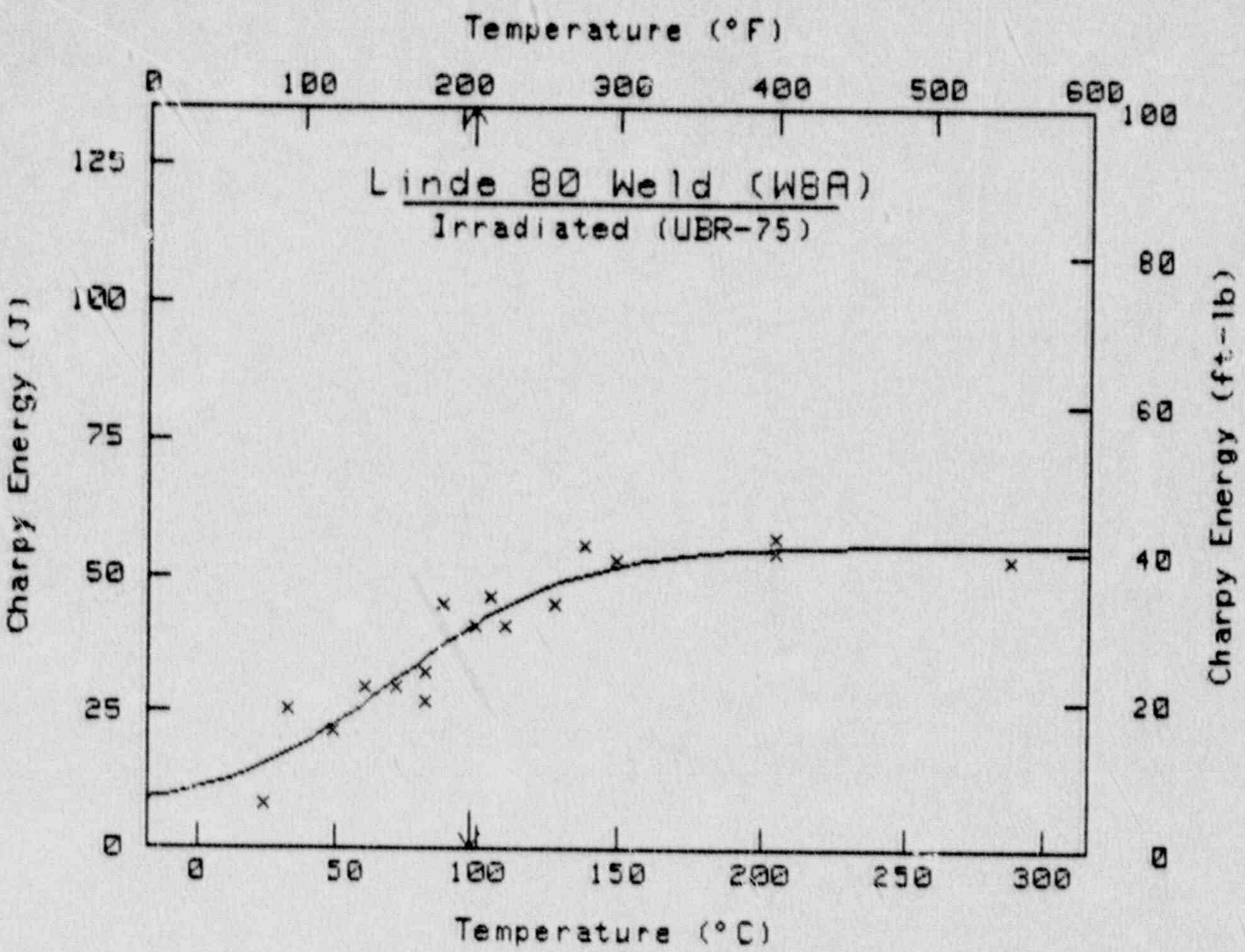
Cv = 30 ft-lb (41 J) at T = 160.3 °F 71.3 °C

Upper Shelf Energy = 46.3 ft-lb 62.8 J

`****************************************************************************`

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	60	8.0	9	200	30.0
2	80	6.0	10	200	31.0
3	105	28.0	11	220	41.0
4	120	28.0	12	250	41.0
5	140	28.0	13	250	42.0
6	150	22.0	14	400	45.0
7	160	25.0	15	400	44.0
8	180	36.0	16	550	45.0

O = Fictitious Point Added * = Test Point Not Included



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

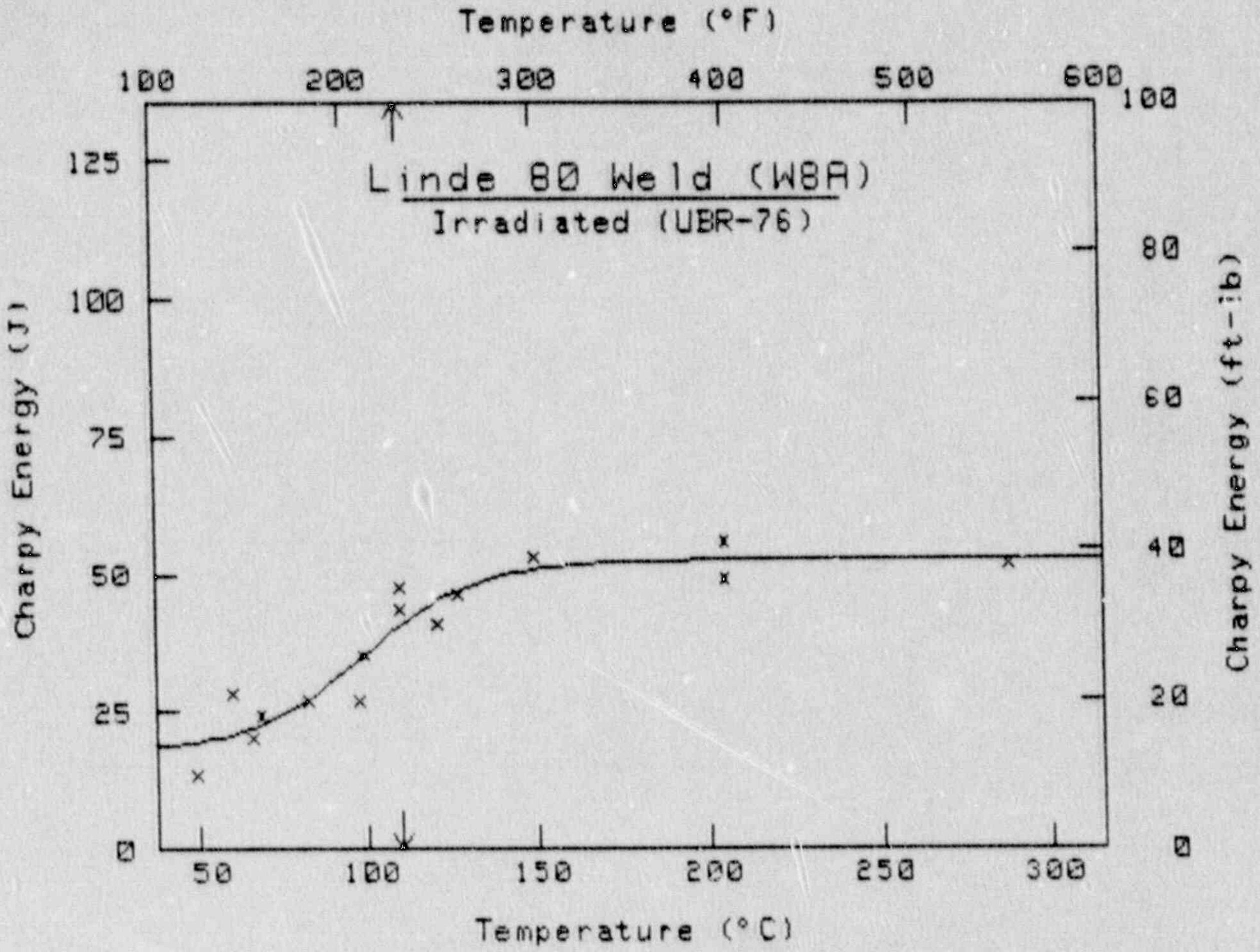
	English	Metric
A =	22.84 ft-lb	30.96 J
B =	18.27 ft-lb	24.77 J
C =	114.29 °F	63.50 °C
To =	160.55 °F	71.41 °C

Cv = 30 ft-lb (41 J) at T =	207.9 °F	97.7 °C
Upper Shelf Energy =	41.1 ft-lb	55.7 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	75	6.0	10	220	34.0
2	90	19.0	11	230	30.0
3	120	16.0	12	260	33.0
4	140	22.0	13	280	41.0
5	160	22.0	14	300	39.0
6	180	20.0	15	400	40.0
7	180	24.0	16	400	42.0
8	190	33.0	17	550	39.0
9	210	30.0			

0 = Fictitious Point Added   * = Test Point Not Included



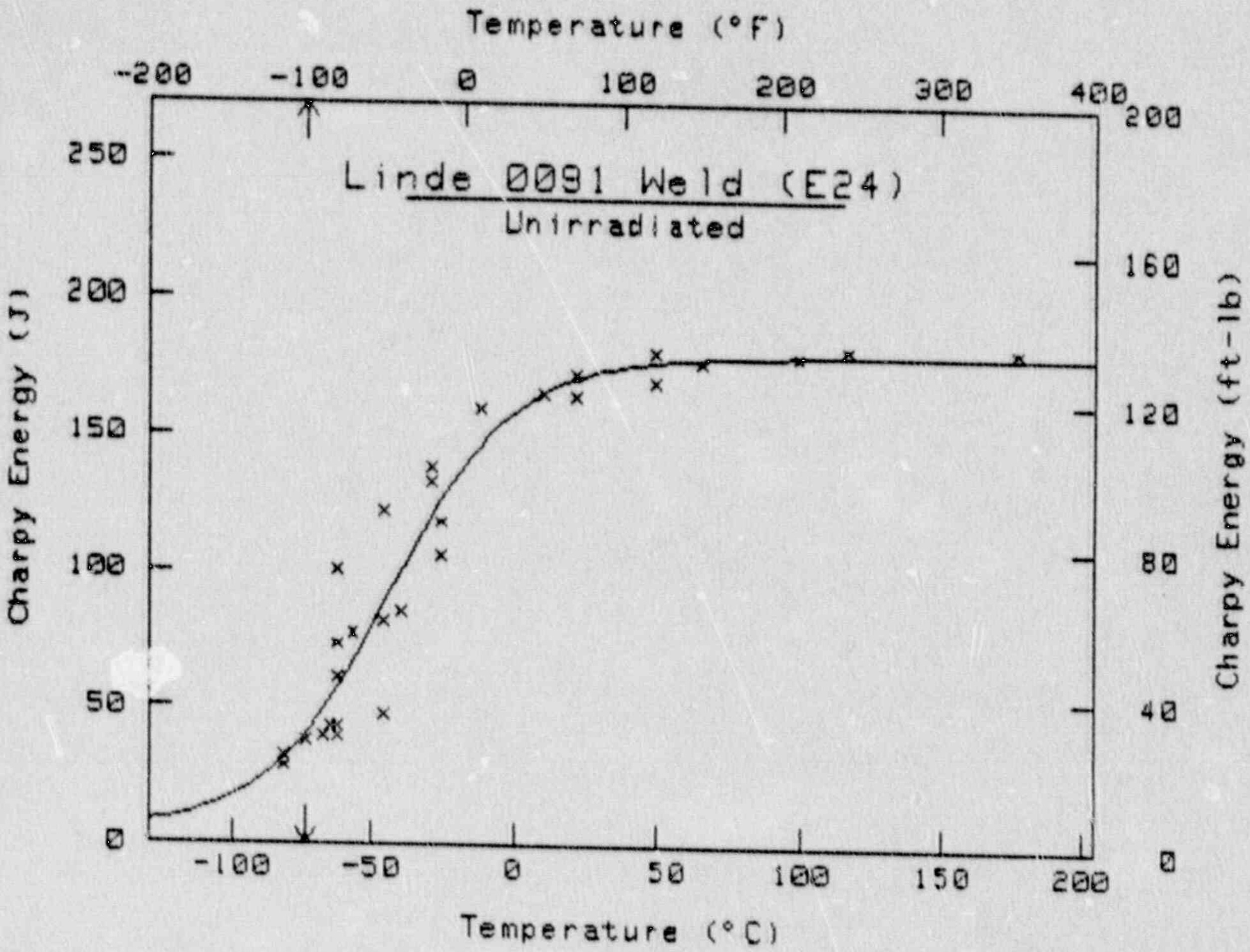
$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	25.90 ft-lb	35.11 J
B	=	12.75 ft-lb	17.29 J
C	=	60.17 °F	33.43 °C
To	=	210.12 °F	98.95 °C

Cv = 30 ft-lb (41 J) at T	=	230.2 °F	110.1 °C
Upper Shelf Energy	=	38.6 ft-lb	52.4 J

PT #	Temp (°F)	Energy (ft-lb)
1	120	10.0
2	140	21.0
3	150	15.0
4	155	18.0
5	180	20.0
6	208	20.0
7	210	26.0
8	230	35.0
9	230	32.0
10	250	30.0
11	260	34.0
12	300	39.0
13	400	36.0
14	400	41.0
15	550	38.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

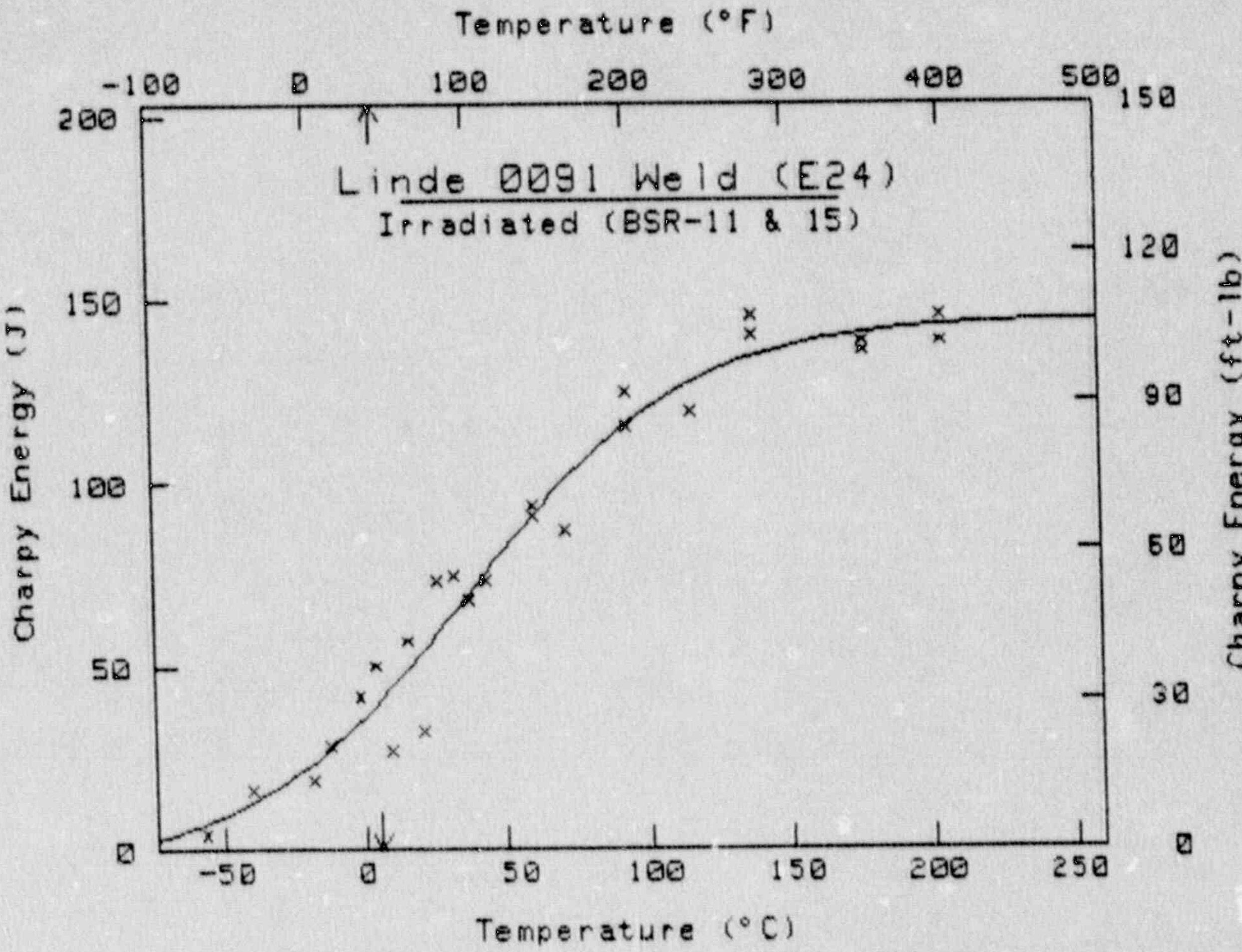
		English	Metric
A	=	67.79 ft-lb	91.91 J
B	=	64.44 ft-lb	87.37 J
C	=	79.36 °F	44.09 °C
To	=	-46.95 °F	-43.86 °C

Cv = 30 ft-lb (41 J) at T	=	-100.3 °F	-73.5 °C
Upper Shelf Energy	=	132.2 ft-lb	179.3 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-115	21.0	16	-20	98.0
2	-115	24.0	17	-20	102.0
3	-100	28.0	18	-15	78.0
4	-90	29.0	19	-15	87.0
5	-85	32.0	20	10	118.0
6	-80	74.0	21	50	122.0
7	-80	54.0	22	70	121.0
8	-80	29.0	23	70	127.0
9	-80	32.0	24	120	125.0
10	-80	45.0	25	120	133.0
11	-70	57.0	26	150	130.0
12	-50	60.0	27	210	132.0
13	-50	90.0	28	210	132.0
14	-50	35.0	29	240	134.0
15	-40	63.0	30	350	134.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

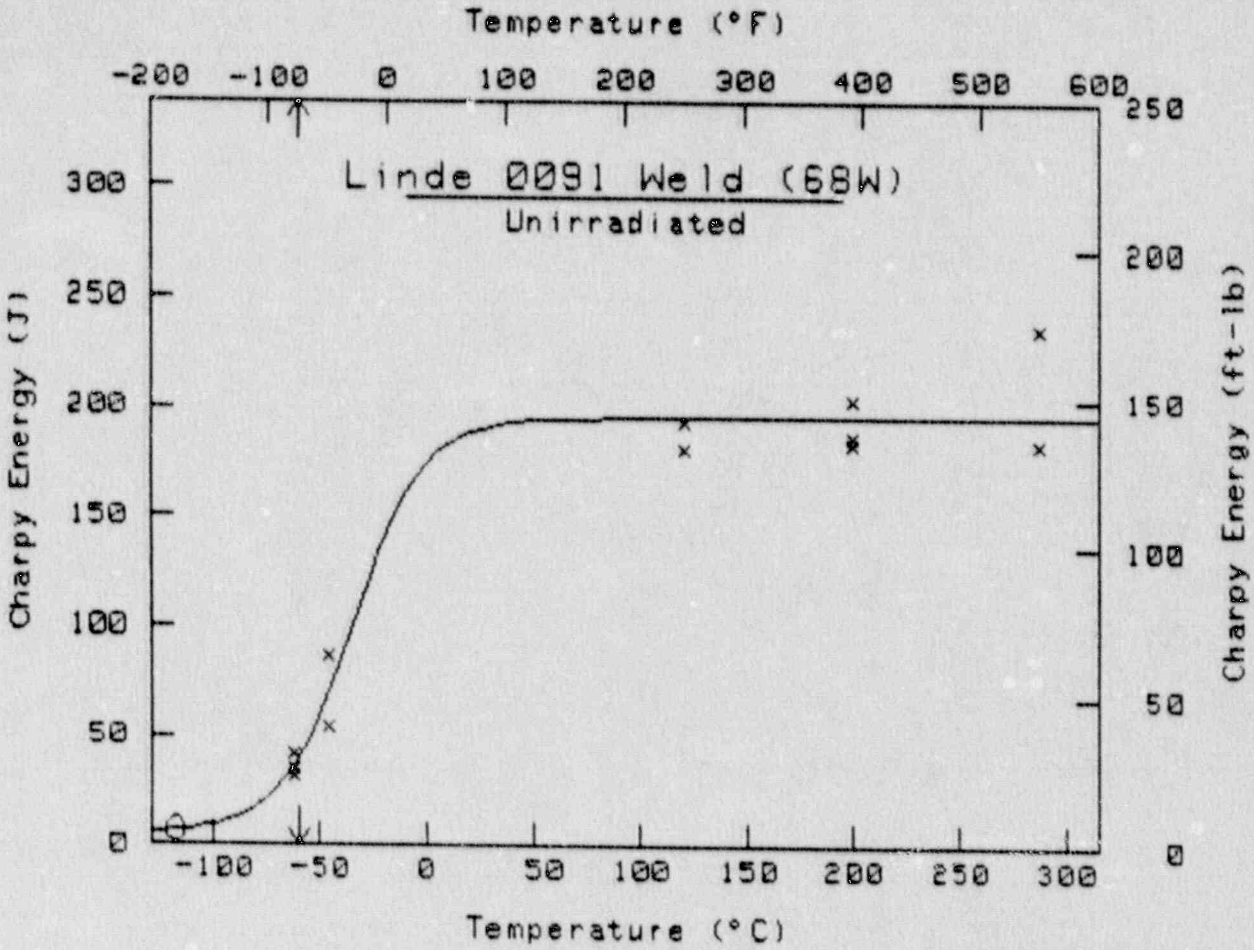
	English	Metric
A =	51.50 ft-lb	69.83 J
B =	55.16 ft-lb	74.78 J
C =	139.35 °F	77.42 °C
To =	99.78 °F	37.66 °C

Cv = 30 ft-lb (41 J) at T =	42.4 °F	5.8 °C
Upper Shelf Energy =	106.7 ft-lb	144.6 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-70	3.0	14	140	69.0
2	-40	12.0	15	140	67.0
3	0	14.0	16	160	64.0
4	10	21.0	17	200	85.0
5	30	31.0	18	200	92.0
6	40	37.0	19	240	88.0
7	50	20.0	20	280	103.0
8	60	42.0	21	280	107.0
9	70	24.0	22	350	102.0
10	80	54.0	23	350	100.0
11	90	55.0	24	400	107.0
12	100	50.0	25	400	102.0
13	110	54.0			

0 = Fictitious Point Added   * = Test Point Not Included



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

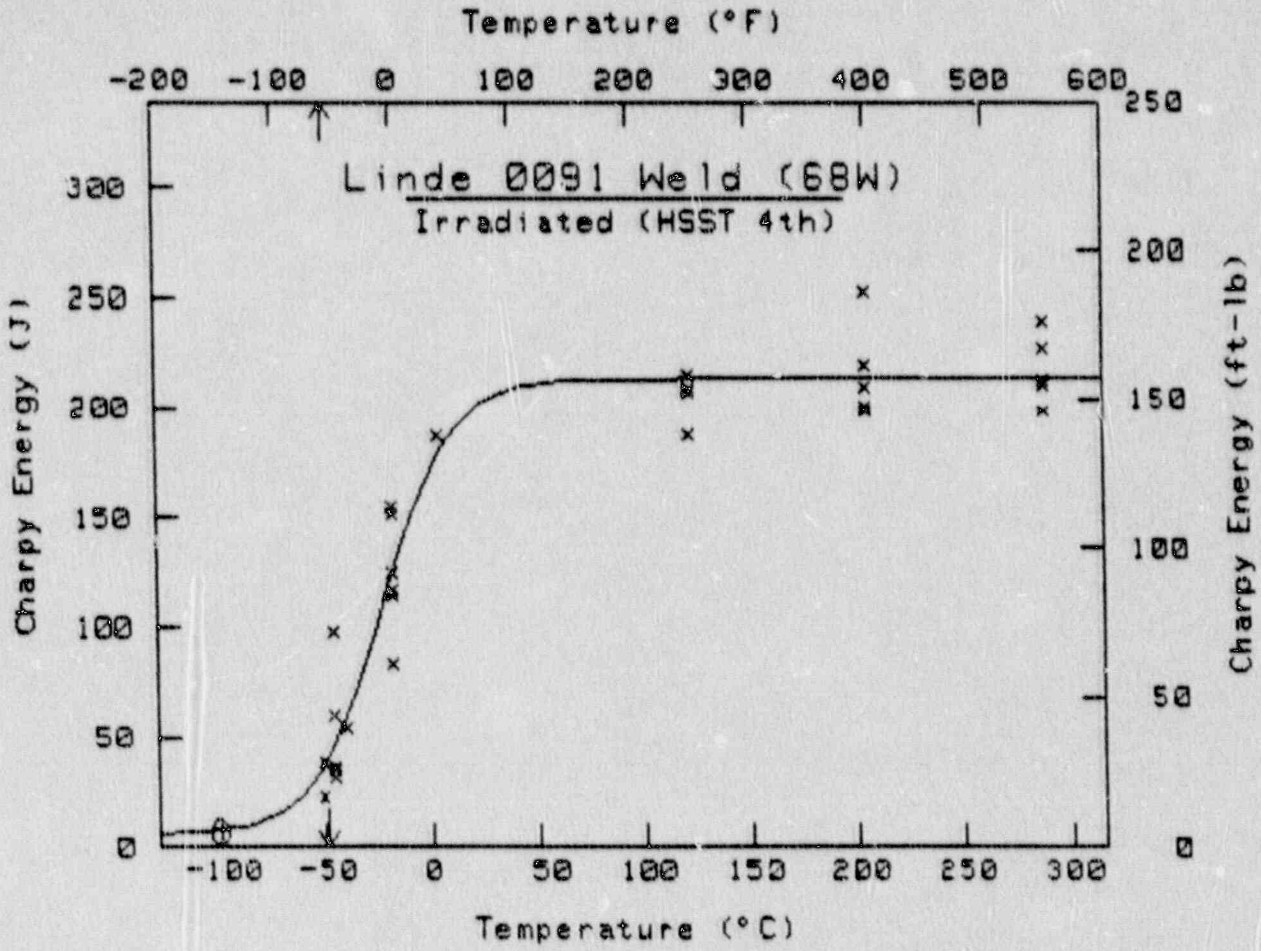
	English	Metric
A =	73.81 ft-lb	100.07 J
B =	69.84 ft-lb	94.69 J
C =	60.55 °F	33.64 °C
To =	-30.41 °F	-34.67 °C

Cv = 30 ft-lb (41 J) at T =	-75.0 °F	-59.5 °C
Upper Shelf Energy =	143.6 ft-lb	194.8 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-80	31.0
2	-80	26.0
3	-80	23.0
4	-50	40.0
5	-50	64.0
6	250	142.0
7	250	133.0
8	392	137.0
9	392	149.5
10	392	135.0
11	550	174.0
12	550	135.0
13 O	-180	5.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

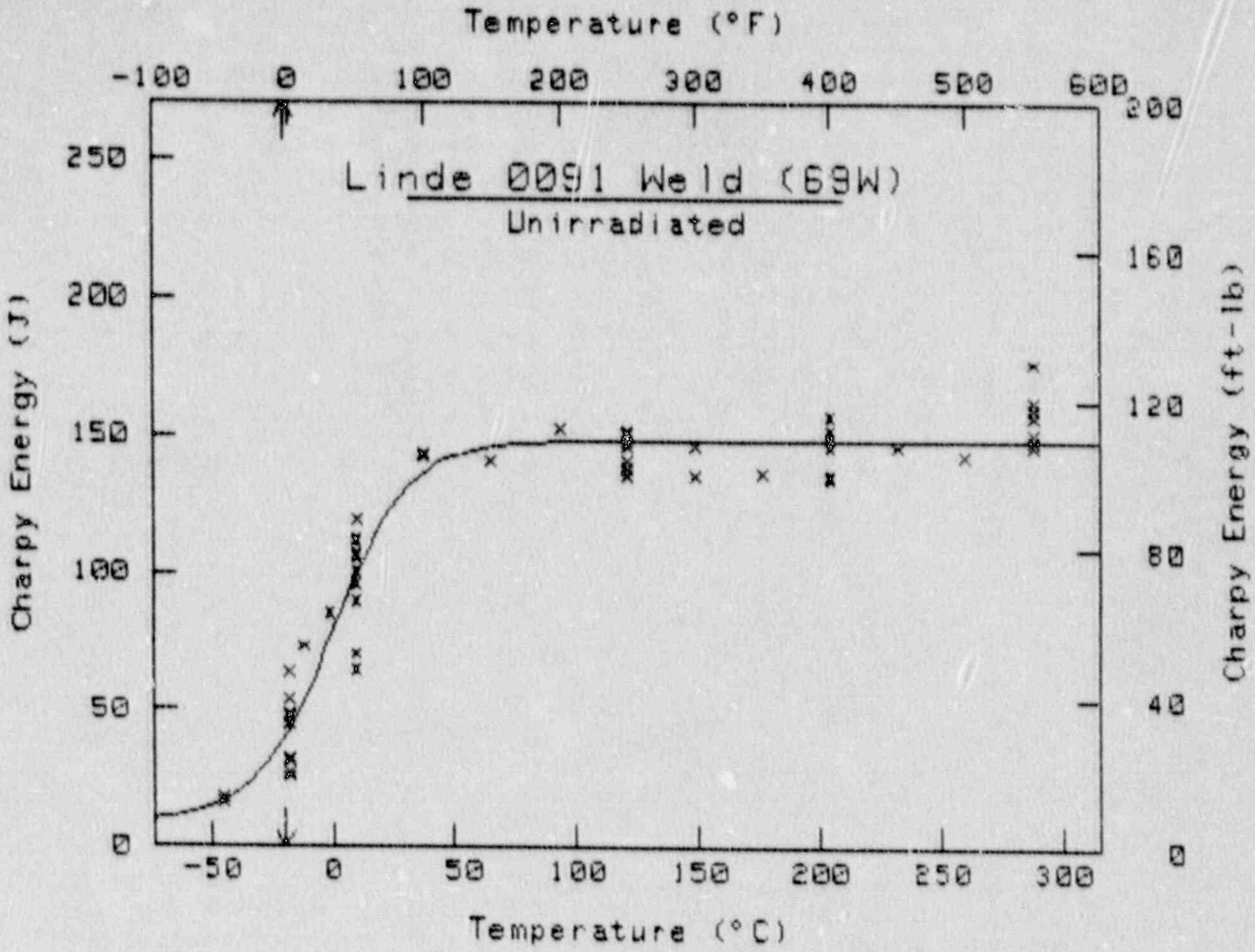
		English	Metric
A	=	80.55 ft-lb	109.21 J
B	=	76.20 ft-lb	103.31 J
C	=	59.00 °F	32.78 °C
To	=	-9.28 °F	-22.93 °C

Cv = 30 ft-lb (41 J) at T	=	-56.4 °F	-49.1 °C
Upper Shelf Energy	=	156.7 ft-lb	212.5 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-60	17.0	17	250	158.0
2	-60	28.0	18	250	152.0
3	-50	72.0	19	250	153.0
4	-50	26.0	20	250	154.0
5	-50	44.0	21	400	147.0
6	-50	23.0	22	400	161.0
7	-50	27.0	23	400	186.0
8	-40	40.0	24	400	146.0
9	0	84.0	25	400	154.0
10	0	114.0	26	550	167.0
11	0	61.0	27	550	155.0
12	0	86.0	28	550	146.0
13	0	112.0	29	550	176.0
14	0	92.0	30	550	156.0
15	40	138.0	31 O	-150	5.0
16	250	138.0			

O = Fictitious Point Added * = Test Point Not Included



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

	English	Metric
A =	57.98 ft-lb	78.61 J
B =	51.29 ft-lb	69.54 J
C =	57.06 °F	31.70 °C
To =	31.88 °F	-.07 °C
Cv = 30 ft-lb (41 J) at T =	-3.0 °F	-19.5 °C
Upper Shelf Energy =	109.3 ft-lb	148.1 J

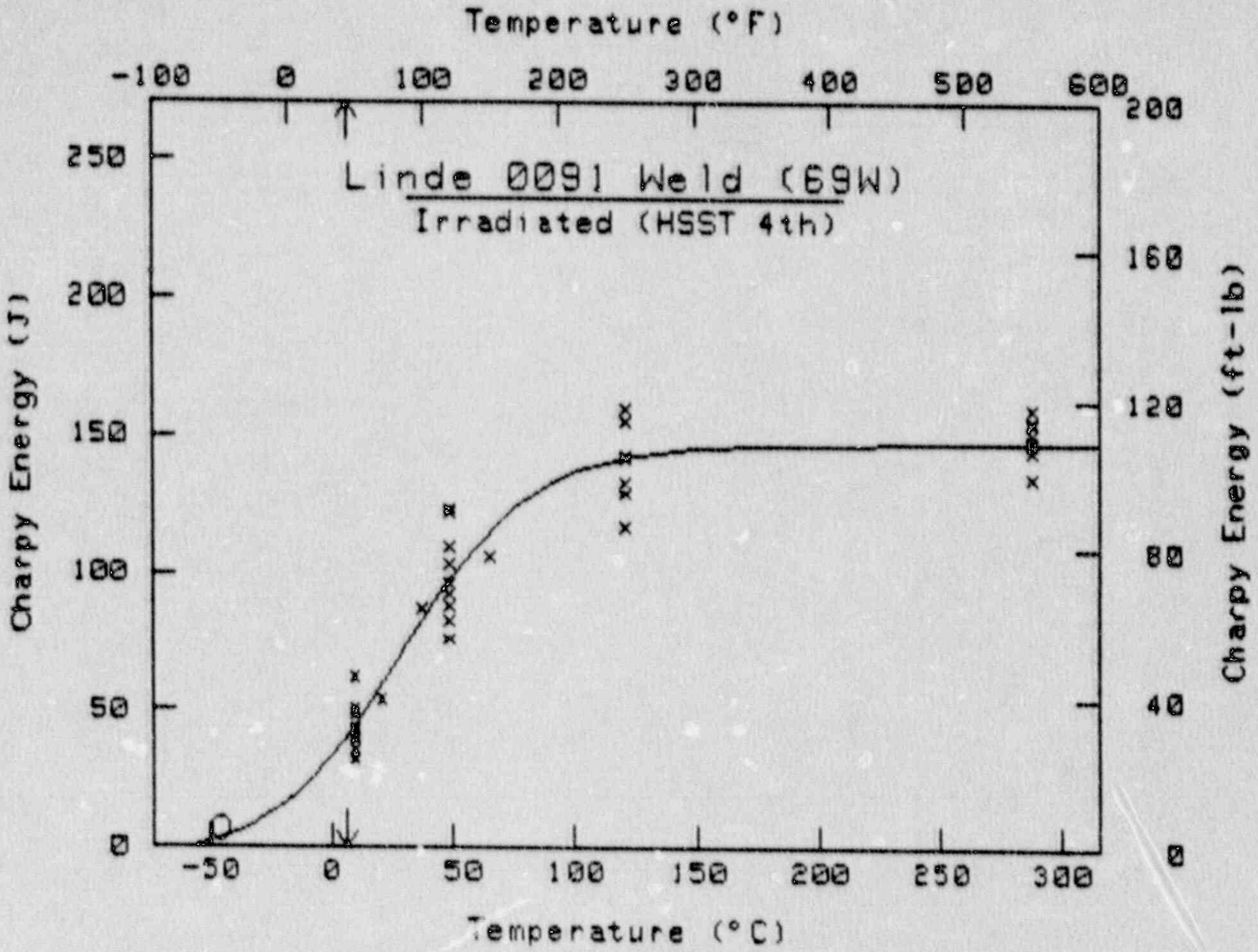
PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-50	13.5	33	250	104.0
2	-50	12.0	34	250	108.0
3	0	24.0	35	250	109.0
4	0	36.0	36	250	100.0
5	0	33.0	37	250	112.0
6	0	20.0	38	250	112.0
7	0	36.0	39	250	102.0
8	0	23.5	40	300	108.0
9	0	47.0	41	300	100.0
10	0	40.0	42	350	100.5
11	0	24.0	43	400	112.0
12	0	19.0	44	400	112.0
13	0	35.0	45	400	108.0
14	10	54.0	46	400	99.5
15	30	63.0	47	400	100.0
16	50	78.0	48	400	116.0
17	50	71.0	49	400	108.0
18	50	79.0	50	400	108.0
19	50	78.0	51	400	110.0

20	50	83.0
21	50	52.0
22	50	48.0
23	50	66.0
24	50	82.0
25	50	74.0
26	51	88.0
27	100	106.0
28	100	105.0
29	150	104.0
30	200	112.5
31	250	108.0
32	250	111.0

52	450	107.5
53	500	105.0
54	550	109.0
55	550	130.0
56	550	111.0
57	550	116.0
58	550	120.0
59	550	109.0
60	550	108.0
61	550	108.0
62	550	118.0
63	550	111.0

O = Fictitious Point Added

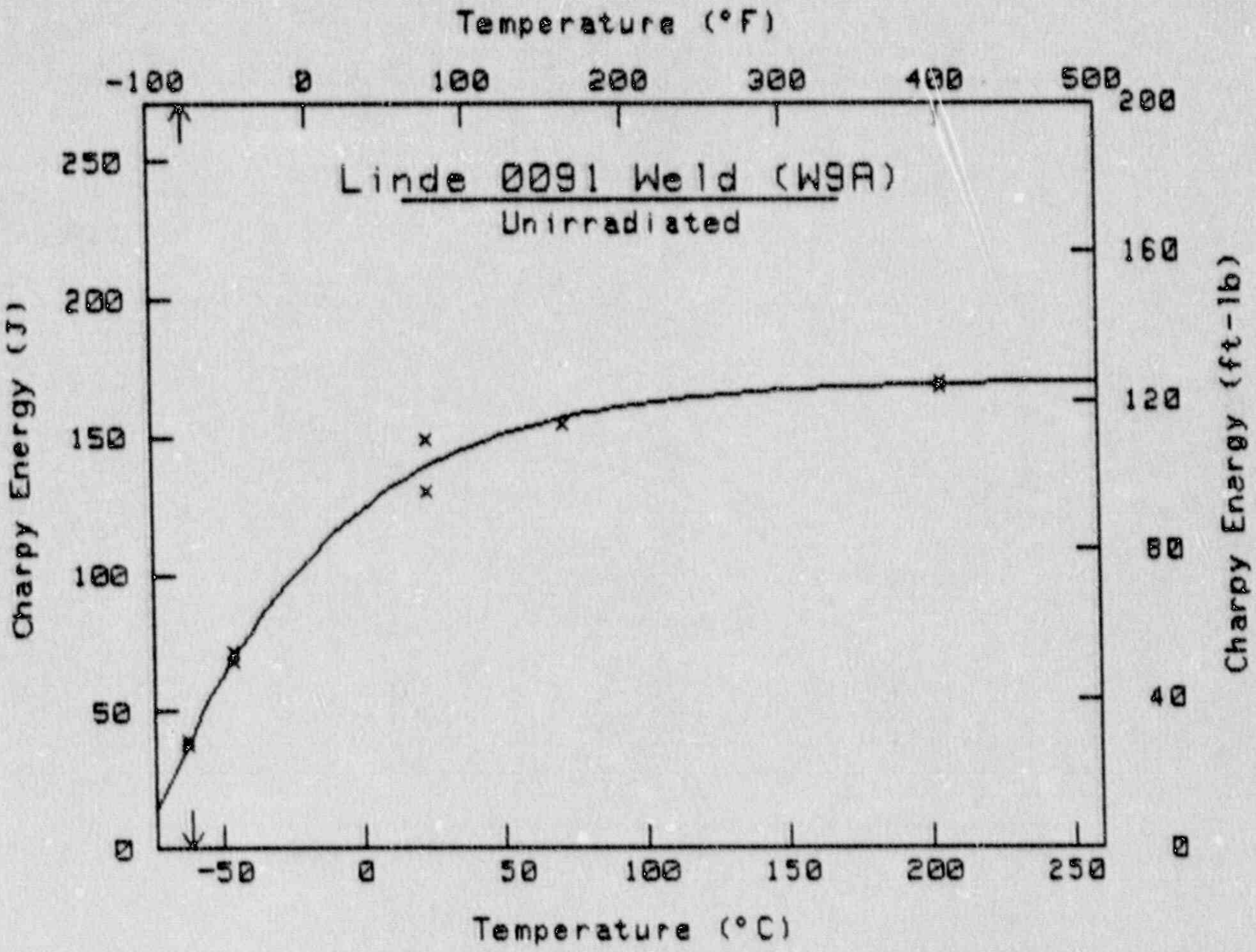
* = Test Point Not Included



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

	English	Metric
A =	51.89 ft-lb	70.36 J
B =	56.38 ft-lb	76.44 J
C =	98.01 °F	54.45 °C
To =	84.12 °F	28.96 °C
Cv = 30 ft-lb (41 J) at T =	44.0 °F	6.6 °C
Upper Shelf Energy =	108.3 ft-lb	146.8 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	50	26.0	20	120	81.0
2	50	30.0	21	150	78.0
3	50	32.0	22	250	86.0
4	50	24.0	23	250	104.5
5	50	31.0	24	250	98.0
6	50	37.0	25	250	114.5
7	50	36.0	26	250	98.0
8	50	29.0	27	250	118.0
9	50	46.0	28	250	105.5
10	70	40.0	29	250	95.0
11	100	64.0	30	550	118.0
12	120	76.0	31	550	111.0
13	120	61.0	32	550	109.0
14	120	56.0	33	550	106.5
15	120	65.0	34	550	99.0
16	120	68.0	35	550	114.0
17	120	90.0	36	550	108.5
18	120	91.0	37	550	114.5
19	120	71.0	38 O	-50	5.0

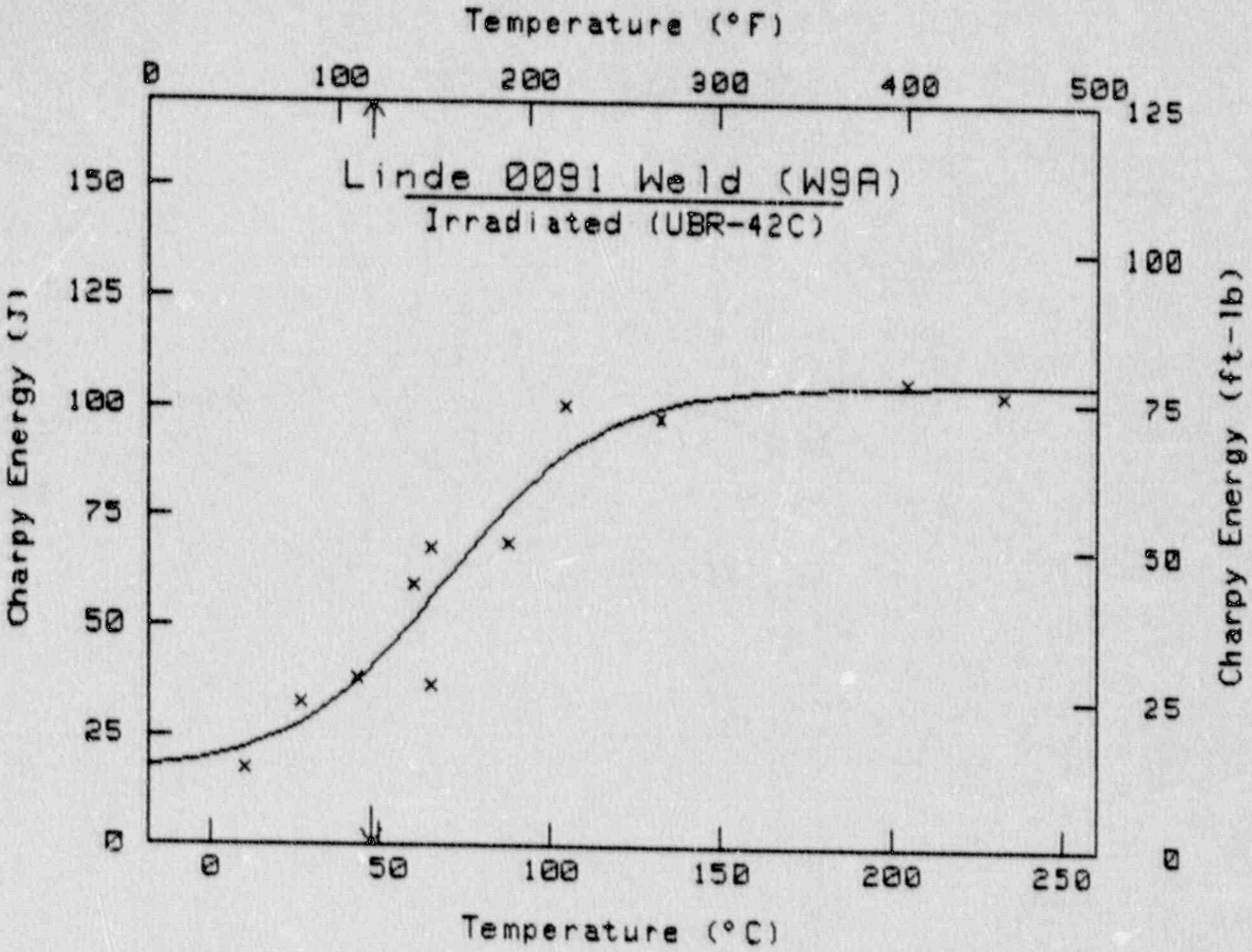


$$C_v = A + B \tanh[(T - T_o)/C]$$

	English	Metric
A =	-395.47 ft-lb	-536.18 J
B =	520.90 ft-lb	706.25 J
C =	204.01 °F	113.34 °C
To =	-312.32 °F	-191.29 °C
Cv = 30 ft-lb (41 J) at T =	-78.3 °F	-61.3 °C
Upper Shelf Energy =	125.4 ft-lb	170.1 J

PT #	Temp (°F)	Energy (ft-lb)
1	-80	29.0
2	-80	28.0
3	-50	53.0
4	-50	50.0
5	75	110.0
6	75	96.0
7	160	114.0
8	400	125.0
9	400	125.0
10	400	124.0

0 = Fictitious Point Added * = Test Point Not Included



****

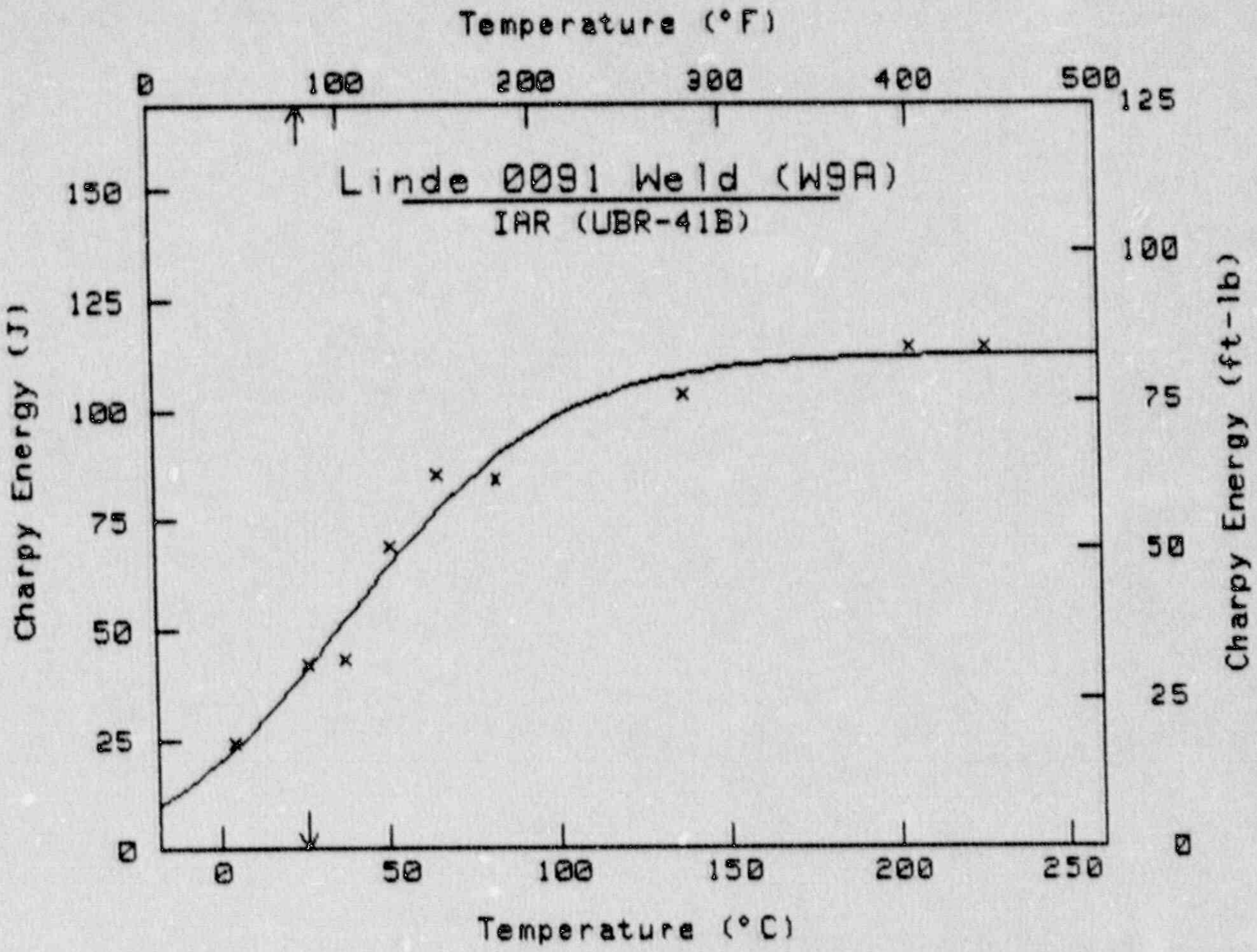
Cv = A + B tanh[(T - To)/C]

	English	Metric
A =	44.70 ft-lb	60.61 J
B =	32.97 ft-lb	44.71 J
C =	82.97 °F	46.10 °C
To =	157.59 °F	69.77 °C
Cv = 30 ft-lb (41 J) at T =	117.8 °F	47.7 °C
Upper Shelf Energy =	77.7 ft-lb	105.3 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	50	13.0
2	80	24.0
3	110	28.0
4	140	44.0
5	150	27.0
6	150	50.0
7	190	51.0
8	220	74.0
9	270	72.0
10	400	78.0
11	450	76.0

0 = Fictitious Point Added   * = Test Point Not Included



****

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

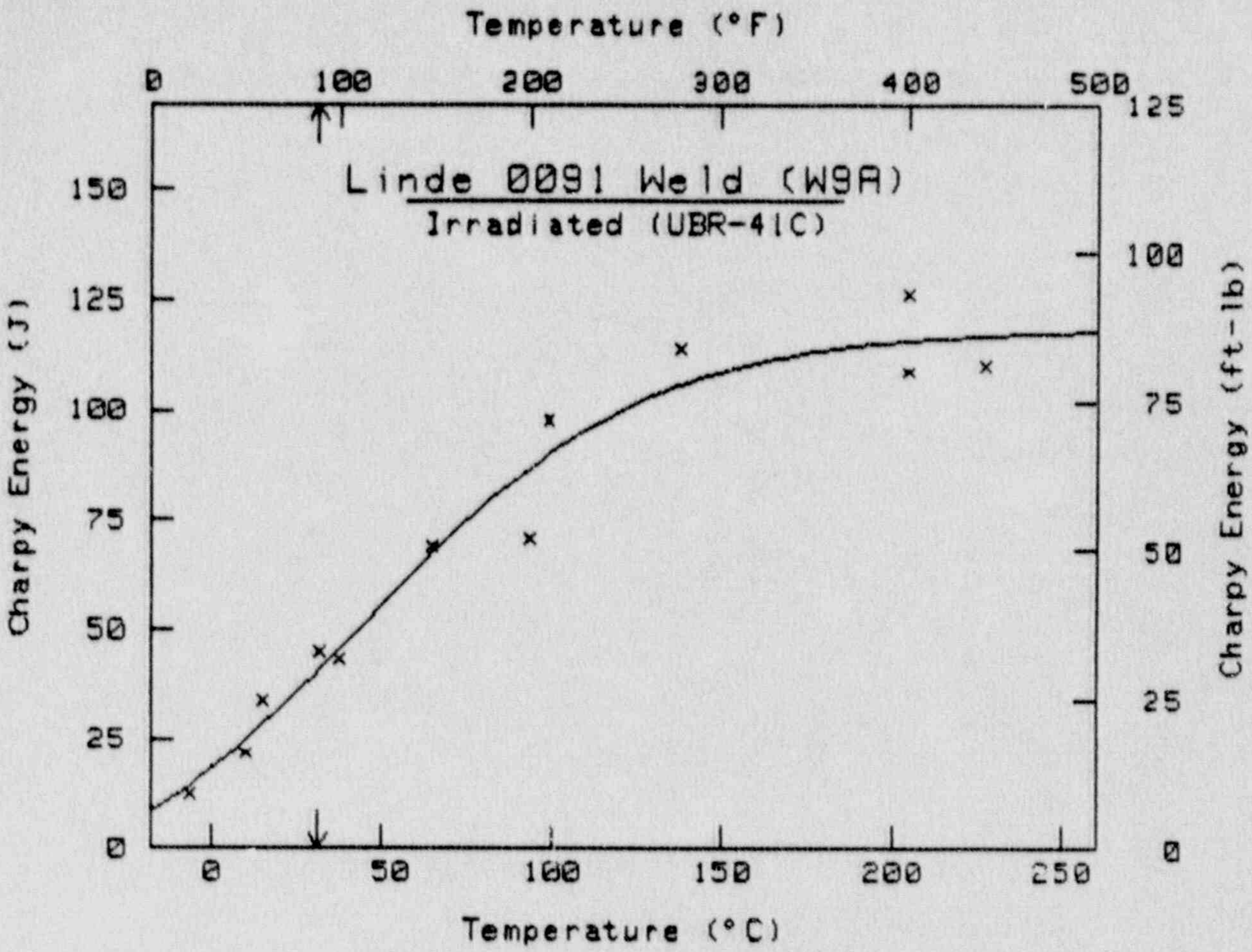
	English	Metric
A =	39.04 ft-lb	52.93 J
B =	43.81 ft-lb	59.39 J
C =	110.96 °F	61.65 °C
To =	101.80 °F	38.78 °C

Cv = 30 ft-lb (41 J) at T =	78.6 °F	25.9 °C
Upper Shelf Energy =	82.9 ft-lb	112.3 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	40	18.0
2	80	31.0
3	100	32.0
4	125	51.0
5	150	63.0
6	180	62.0
7	280	76.0
8	400	84.0
9	440	84.0

O = Fictitious Point Added   * = Test Point Not Included



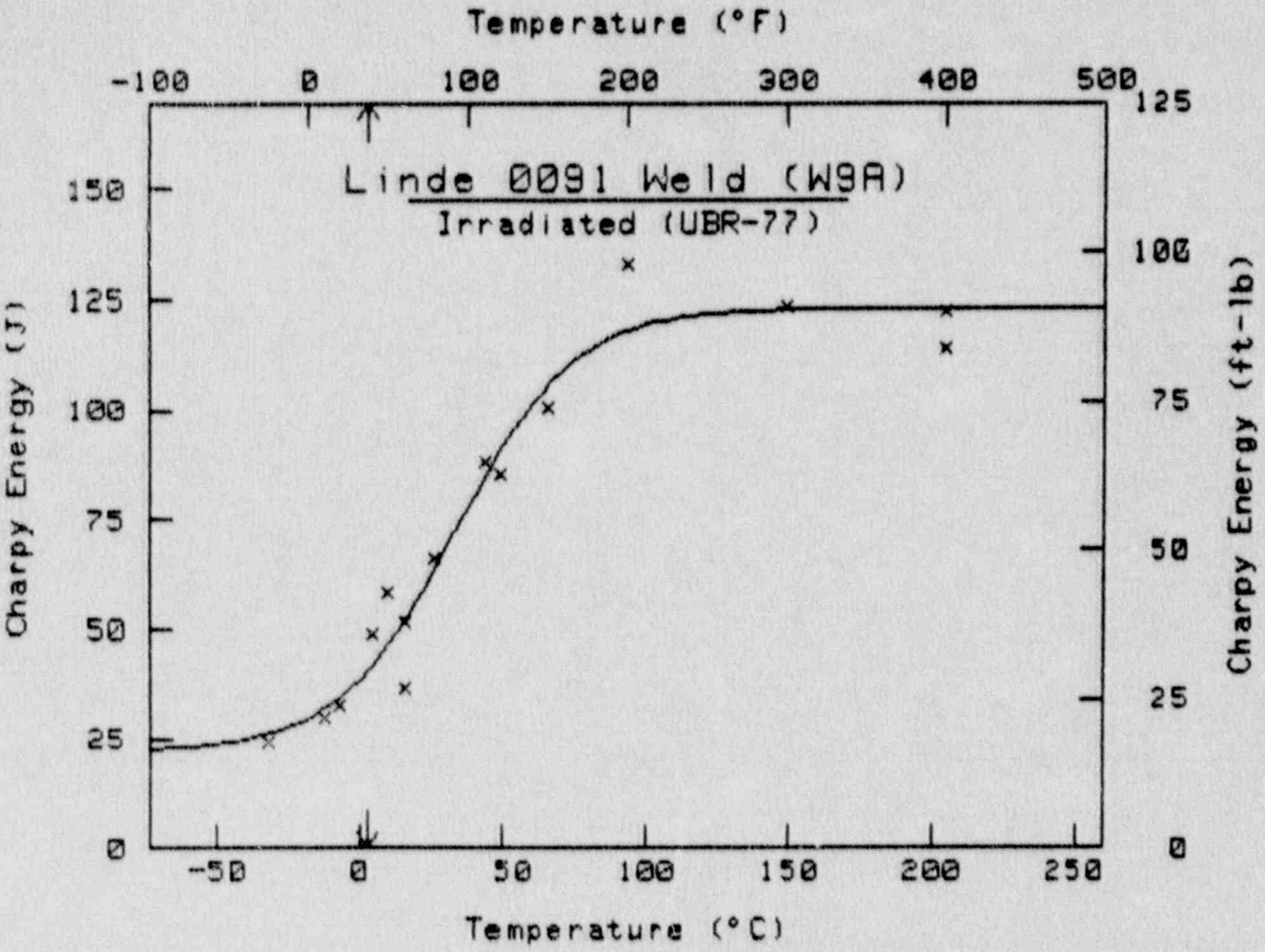
$$C_v = A + B \tanh[(T - T_o)/C]$$

		English	Metric
A	=	37.74 ft-lb	51.16 J
B	=	49.53 ft-lb	67.16 J
C	=	149.34 °F	82.97 °C
To	=	112.37 °F	44.65 °C

Cv = 30 ft-lb (41 J) at T	=	88.8 °F	31.6 °C
Upper Shelf Energy	=	87.3 ft-lb	118.3 J

PT #	Temp (°F)	Energy (ft-lb)
1	20	9.0
2	50	16.0
3	60	25.0
4	90	33.0
5	100	32.0
6	150	51.0
7	200	52.0
8	210	72.0
9	280	84.0
10	400	80.0
11	400	93.0
12	440	81.0

0 = Fictitious Point Added * = Test Point Not Included



****

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

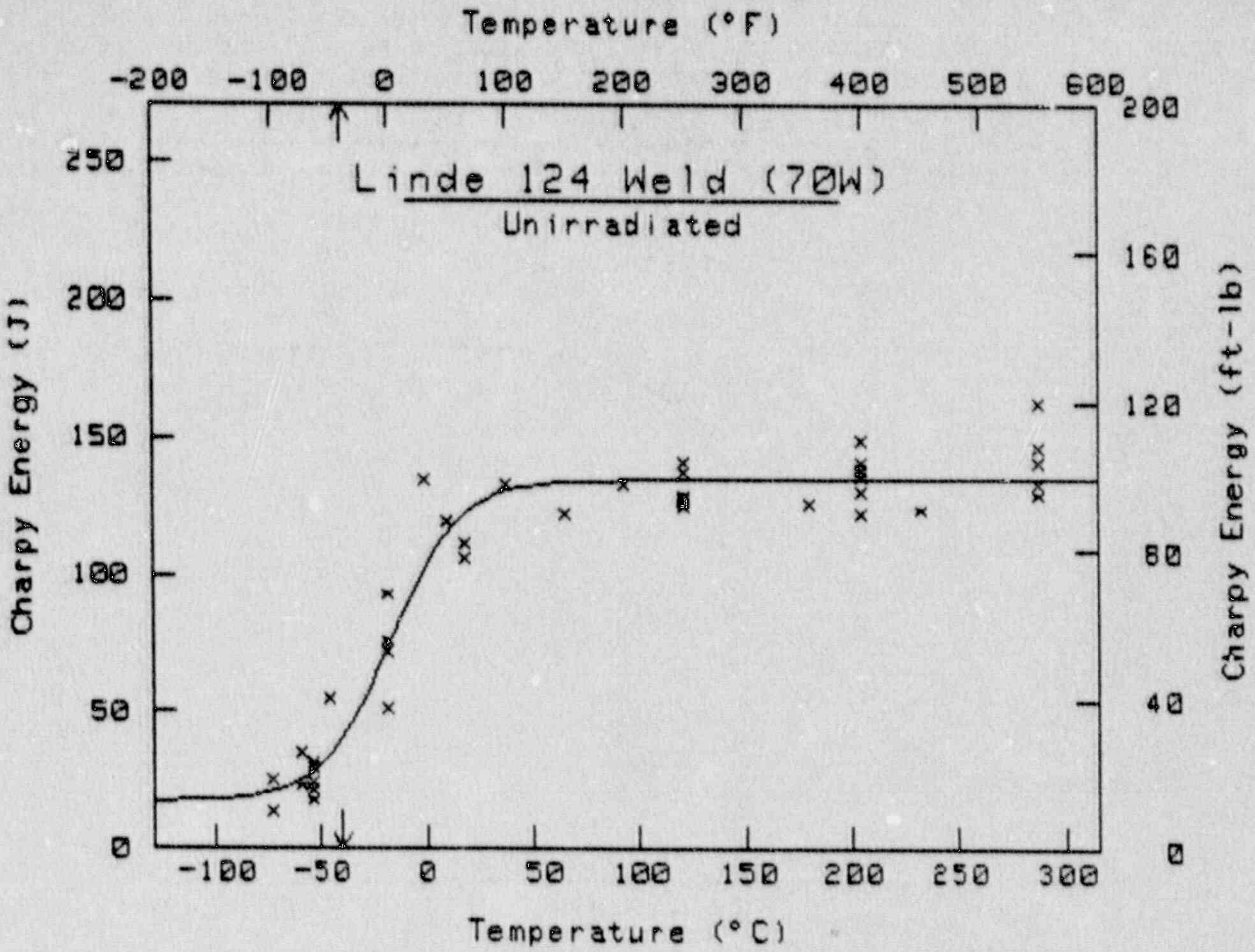
	English	Metric
A =	53.47 ft-lb	72.49 J
B =	37.20 ft-lb	50.44 J
C =	73.66 °F	40.92 °C
To =	92.33 °F	33.52 °C

Cv = 30 ft-lb (41 J) at T =	37.6 °F	3.1 °C
Upper Shelf Energy =	90.7 ft-lb	122.9 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-25	18.0
2	10	22.0
3	20	24.0
4	40	36.0
5	50	43.0
6	60	27.0
7	60	38.0
8	80	49.0
9	110	65.0
10	120	63.0
11	150	74.0
12	200	98.0
13	300	91.0
14	400	84.0
15	400	90.0

0 = Fictitious Point Added　　　* = Test Point Not Included



****

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

	English	Metric
A =	55.96 ft-lb	75.87 J
B =	43.10 ft-lb	58.44 J
C =	58.85 °F	32.70 °C
To =	1.87 °F	-16.74 °C

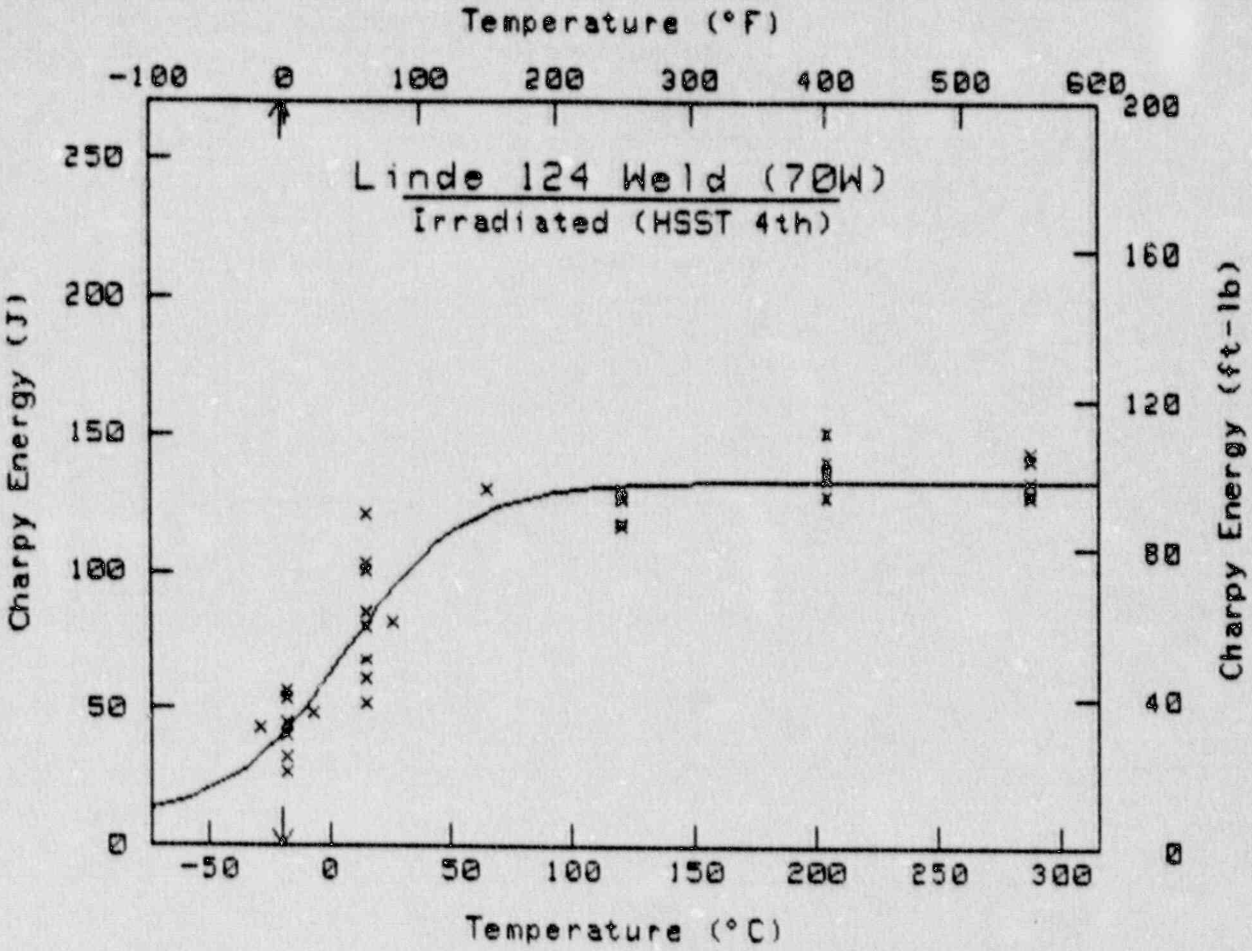
Cv = 30 ft-lb (41 J) at T =	-39.1 °F	-39.5 °C
Upper Shelf Energy =	99.1 ft-lb	134.3 J

****

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-100	10.0	23	200	98.0
2	-100	18.5	24	250	92.0
3	-75	17.0	25	250	93.0
4	-75	26.0	26	250	94.0
5	-65	13.0	27	250	95.0
6	-65	16.0	28	250	101.0
7	-65	22.0	29	250	104.0
8	-65	23.0	30	356	92.5
9	-65	18.0	31	400	90.0
10	-50	40.5	32	400	96.0
11	0	38.0	33	400	100.0
12	0	38.0	34	400	102.0
13	0	56.0	35	400	104.0
14	0	56.0	36	400	110.0
15	0	68.5	37	450	91.0
16	0	53.0	38	550	95.0
17	30	99.5	39	550	98.0
18	50	88.0	40	550	104.0
19	64	78.0	41	550	104.0

20	64	82.0	42	550	108.0
21	100	98.0	43	550	120.0
22	150	90.0			

O = Fictitious Point Added   * = Test Point Not Included

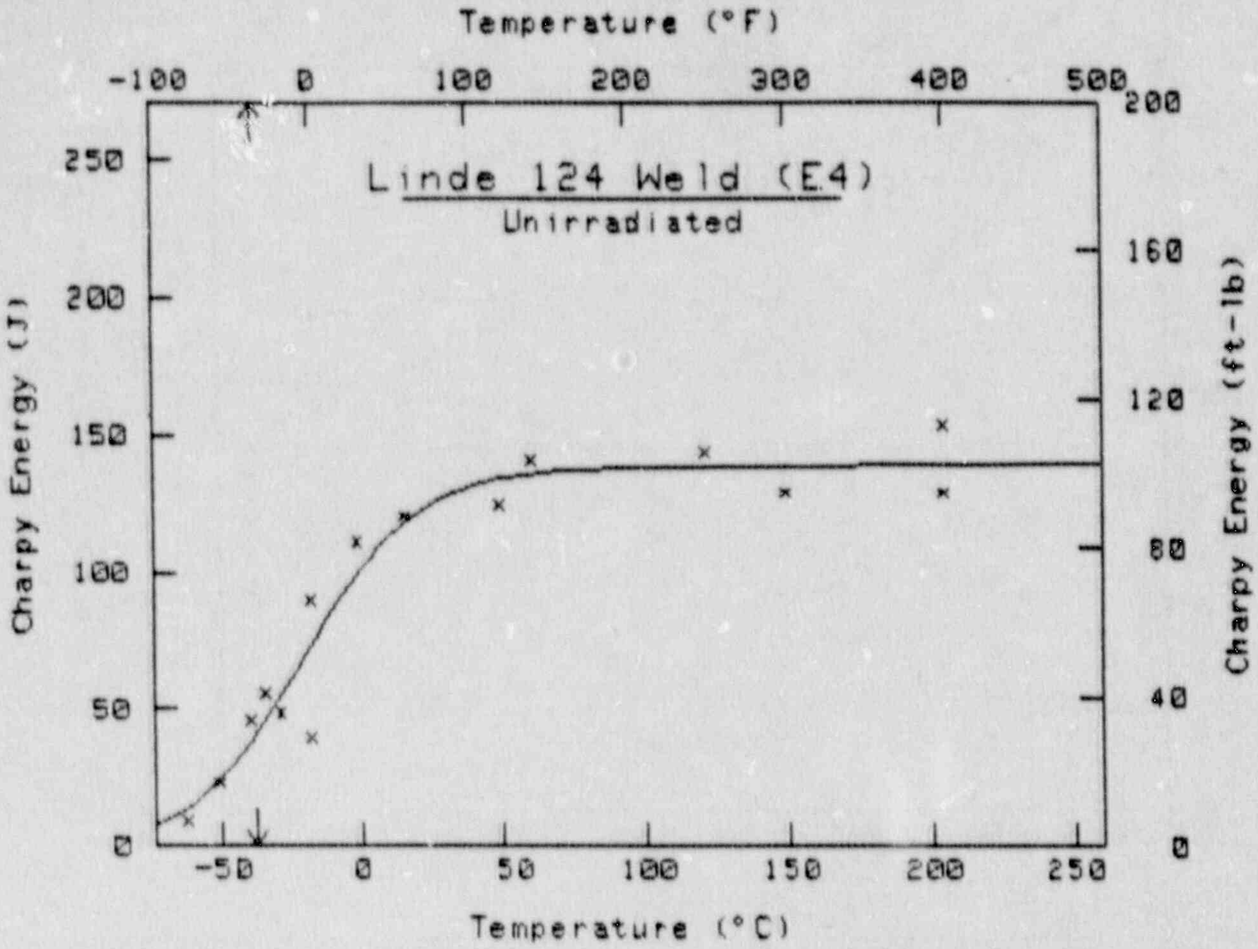


$$Cv = A + B \tanh[(T - To)/C]$$

		English	Metric
A	=	52.06 ft-lb	70.58 J
B	=	45.88 ft-lb	62.21 J
C	=	91.11 °F	50.62 °C
To	=	43.86 °F	6.59 °C

	English	Metric
Cv = 30 ft-lb (41 J) at T =	-3.9 °F	-19.9 °C
Upper Shelf Energy =	97.9 ft-lb	132.8 J

PT #	Temp (°F)	Energy (ft-lb)	PT #	Temp (°F)	Energy (ft-lb)
1	-20	32.0	20	150	96.0
2	0	24.0	21	250	93.0
3	0	30.0	22	250	96.0
4	0	33.0	23	250	94.0
5	0	30.0	24	250	87.0
6	0	40.0	25	250	96.0
7	0	42.0	26	250	86.0
8	0	24.0	27	400	111.0
9	0	20.0	28	400	100.0
10	20	36.0	29	400	98.5
11	60	63.0	30	400	101.0
12	60	38.5	31	400	103.0
13	60	74.0	32	400	94.0
14	60	89.5	33	550	95.0
15	60	59.0	34	550	94.0
16	60	76.0	35	550	104.0
17	60	50.0	36	550	95.0
18	60	45.0	37	550	98.0
19	80	60.0	38	550	106.0



****

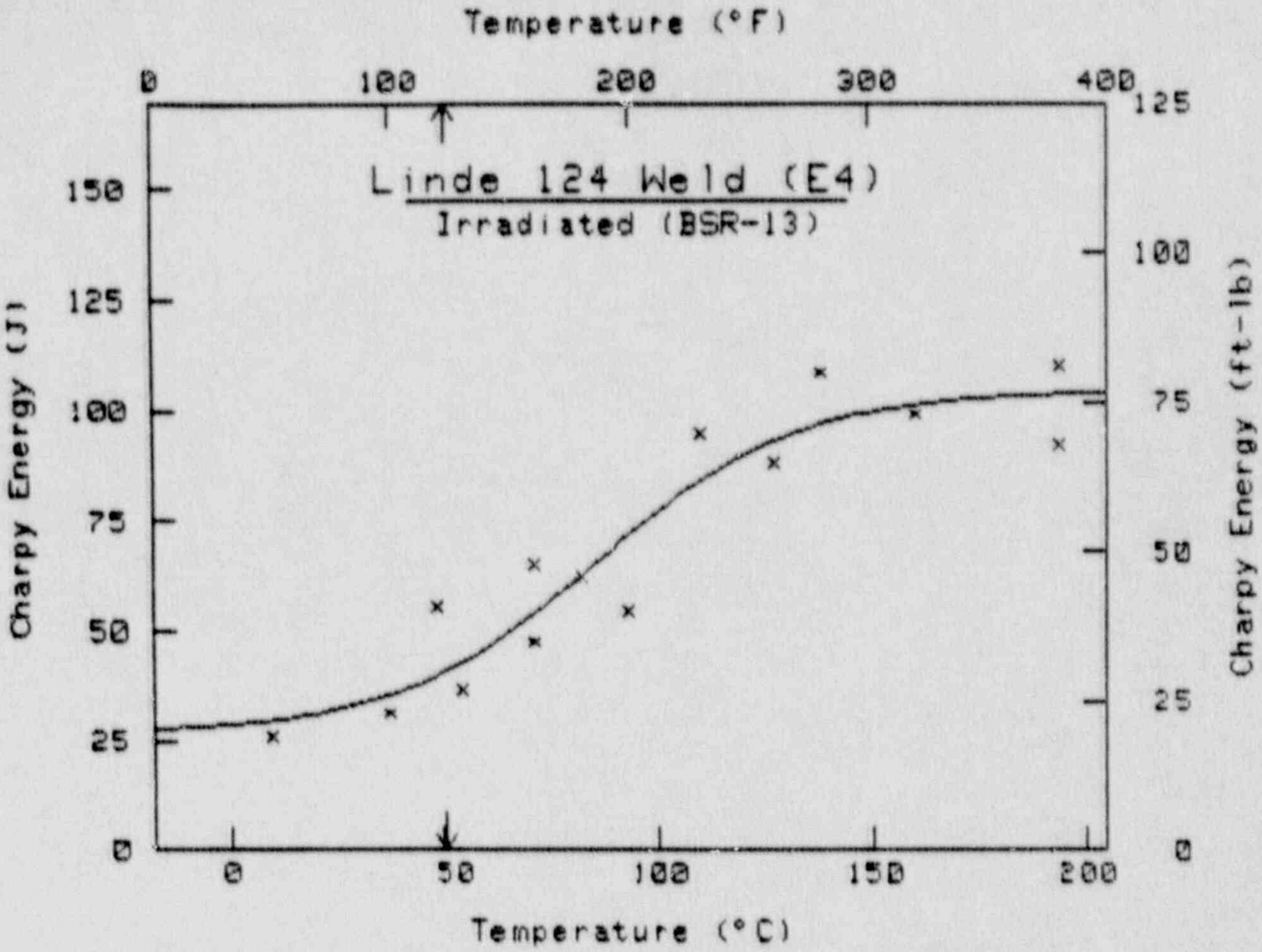
$Cv = A + B \tanh[(T - To)/C]$

	English	Metric
A =	49.83 ft-lb	67.56 J
B =	52.42 ft-lb	71.07 J
C =	74.62 °F	41.46 °C
To =	-6.23 °F	-21.24 °C
Cv = 30 ft-lb (41 J) at T =	-35.9 °F	-37.7 °C
Upper Shelf Energy =	102.3 ft-lb	138.6 J

****

PT #	Temp (°F)	Energy (ft-lb)
1	-80	7.0
2	-60	17.0
3	-40	34.0
4	-30	41.0
5	-20	36.0
6	0	29.0
7	0	66.0
8	30	82.0
9	60	89.0
10	120	92.0
11	140	104.0
12	250	106.0
13	300	95.0
14	400	95.0
15	400	113.0

O = Fictitious Point Added   * = Test Point Not Included



****

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

		English	Metric
A	=	48.30 ft-lb	65.49 J
B	=	28.61 ft-lb	38.78 J
C	=	83.79 °F	46.55 °C
To	=	186.51 °F	85.84 °C

Cv = 30 ft-lb (41 J) at T =	123.0 °F	50.6 °C
Upper Shelf Energy =	76.9 ft-lb	104.3 J

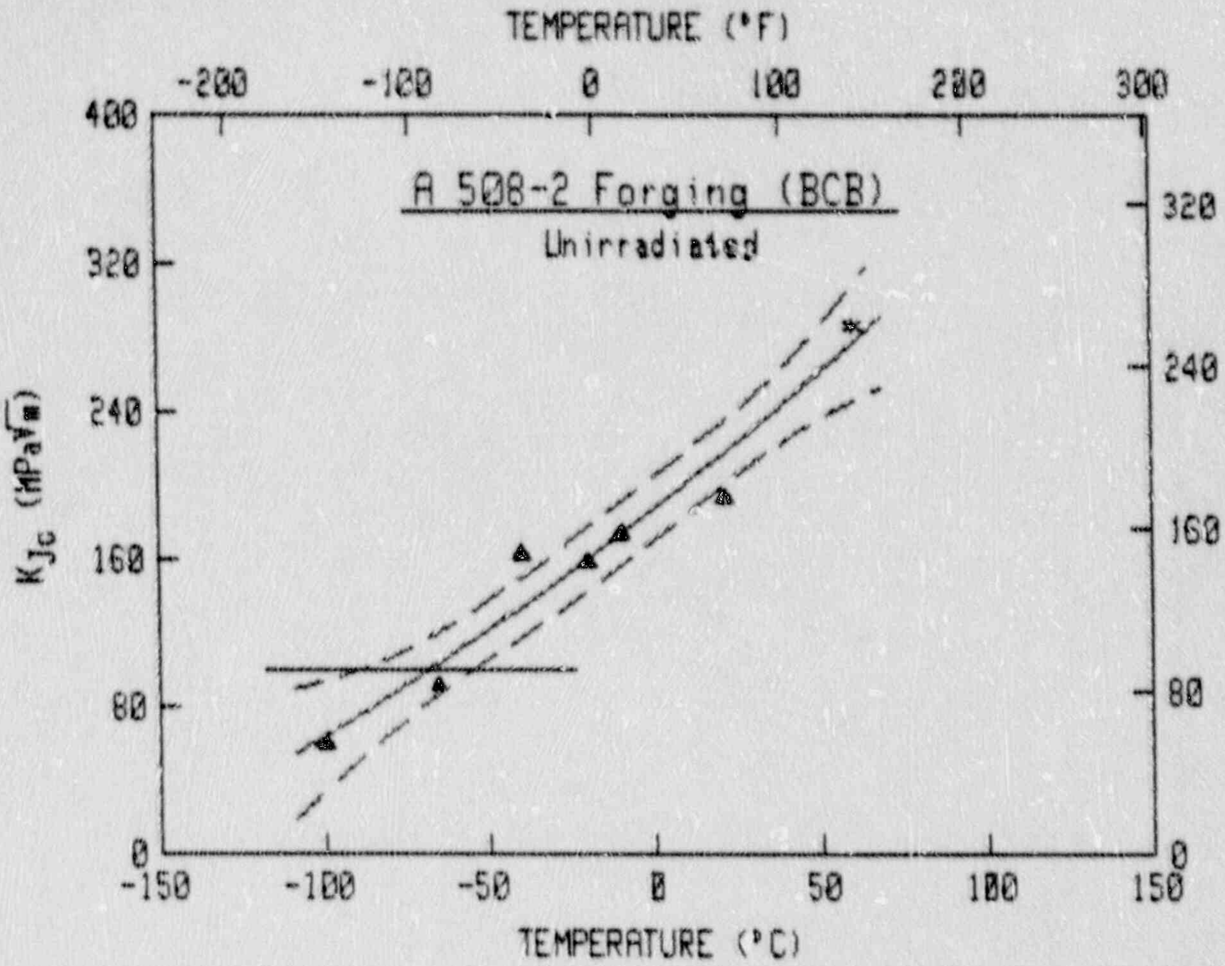
****

PT #	Temp (°F)	Energy (ft-lb)
1	50	19.0
2	100	23.0
3	120	41.0
4	130	27.0
5	160	35.0
6	160	48.0
7	180	46.0
8	200	40.0
9	230	70.0
10	260	65.0
11	280	80.0
12	320	73.0
13	380	81.0
14	380	68.0

O = Fictitious Point Added   * = Test Point Not Included

APPENDIX B

Curve-Fit Results for the Transition Regime
Fracture Toughness Data



****

Kjc = A + B exp [(T-To)/C)]

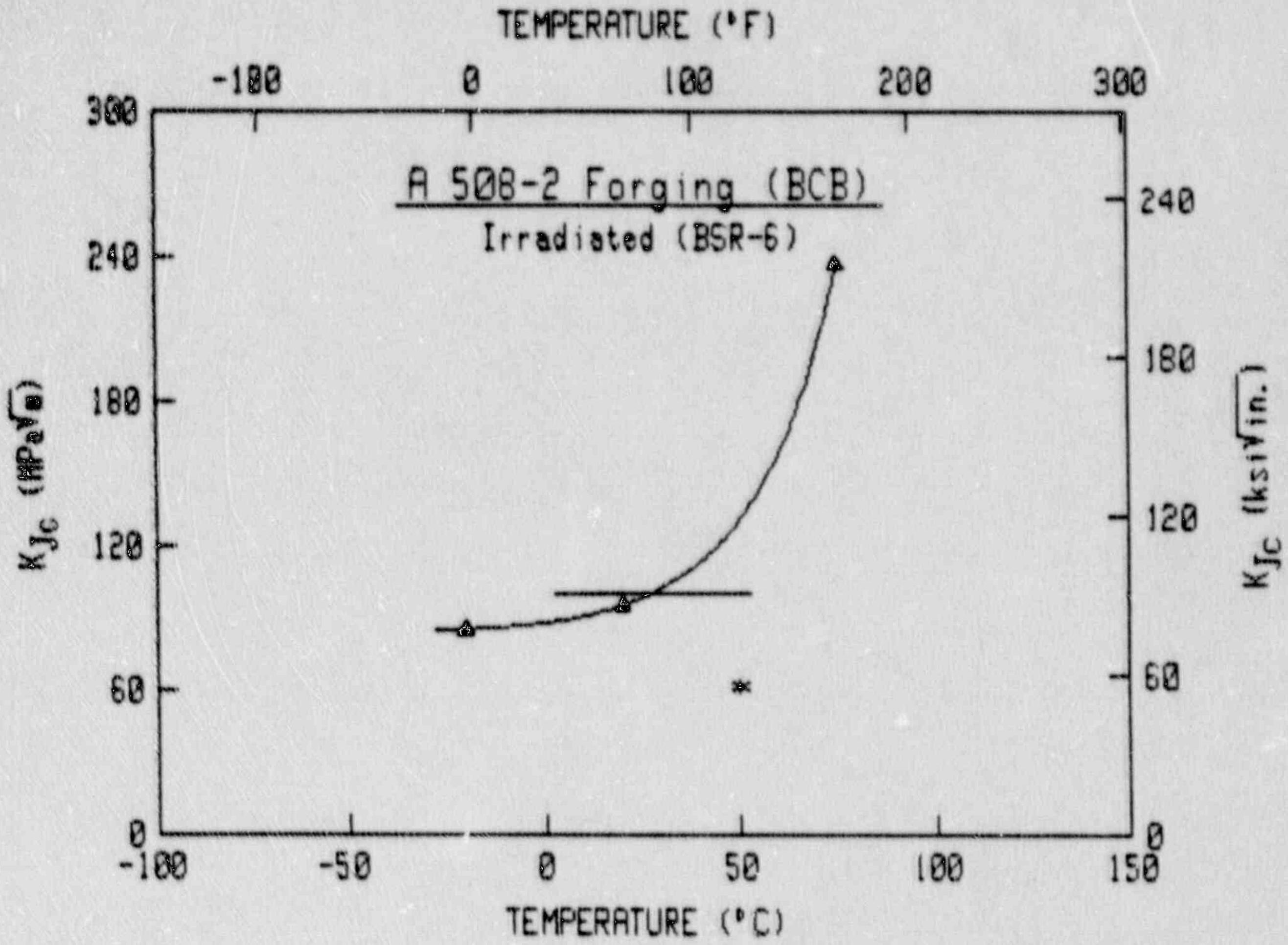
	Metric	English
A =	-372.73 MPa√m	-339.21 ksi√in
B =	559.44 MPa√m	509.12 ksi√in
C =	402.05°C	723.68°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-88°C	-126°F
Mean Curve =	-68°C	-90°F
Lower Bound =	-54°C	-65°F

****

Pt #	Temperature	Kjc
1	-100	60.3
2	-65	91.6
3	-40	163.1
4	-20	158.2
5	-10	173.6
6	21	193.2
7 *	60	286.4

* = Upper Shelf Data Point



****

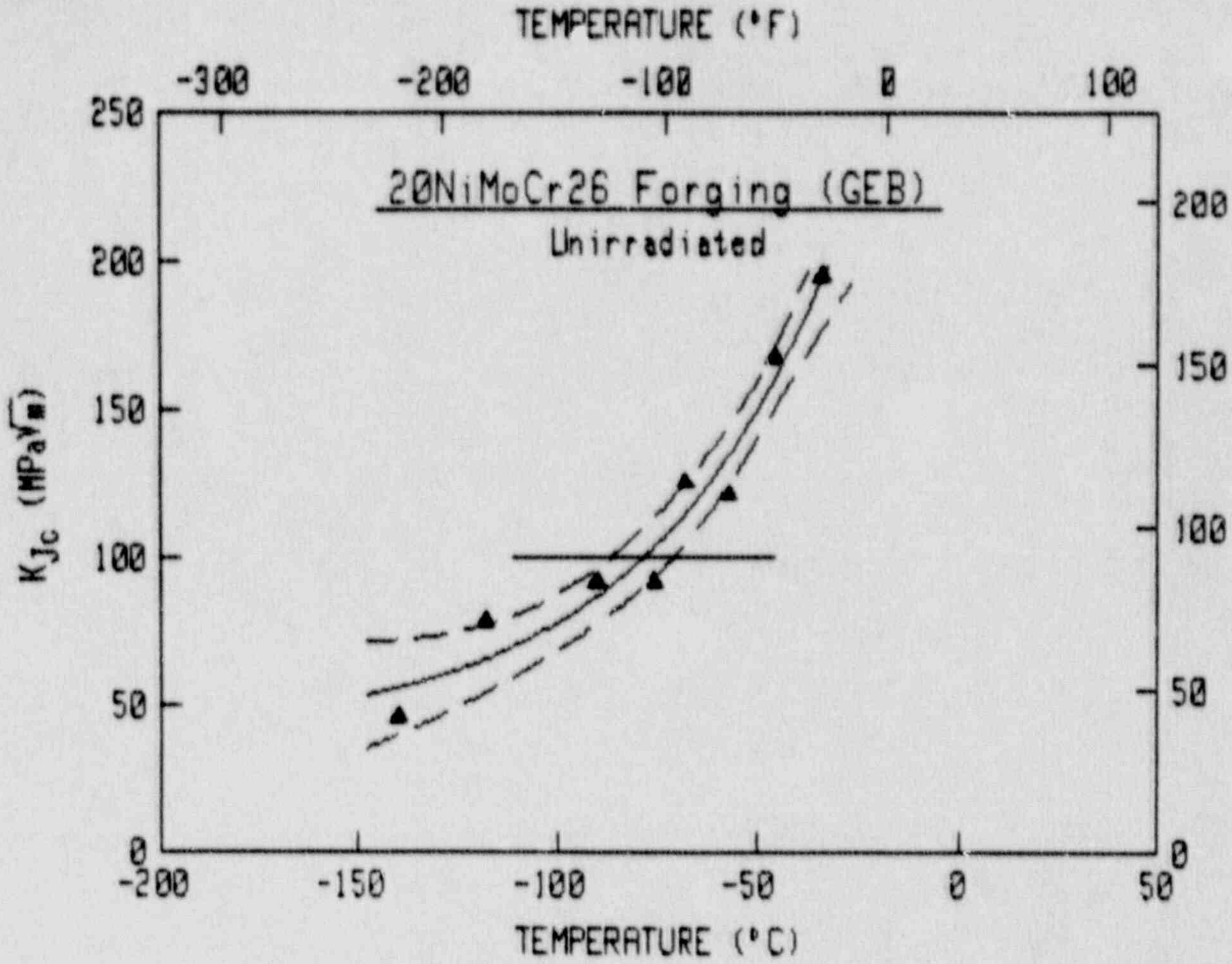
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	83.47 MPa√m	75.96 ksi√in
B =	4.45 MPa√m	4.05 ksi√in
C =	21.20°C	38.15°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Mean Curve =	28°C	82°F

****

Pt #	Temperature	Kjc
1	-20	85.2
2	20	94.9
3 *	50	61.4
4	75	236.6



****

Kjc = A + B exp [(T-To)/C)]

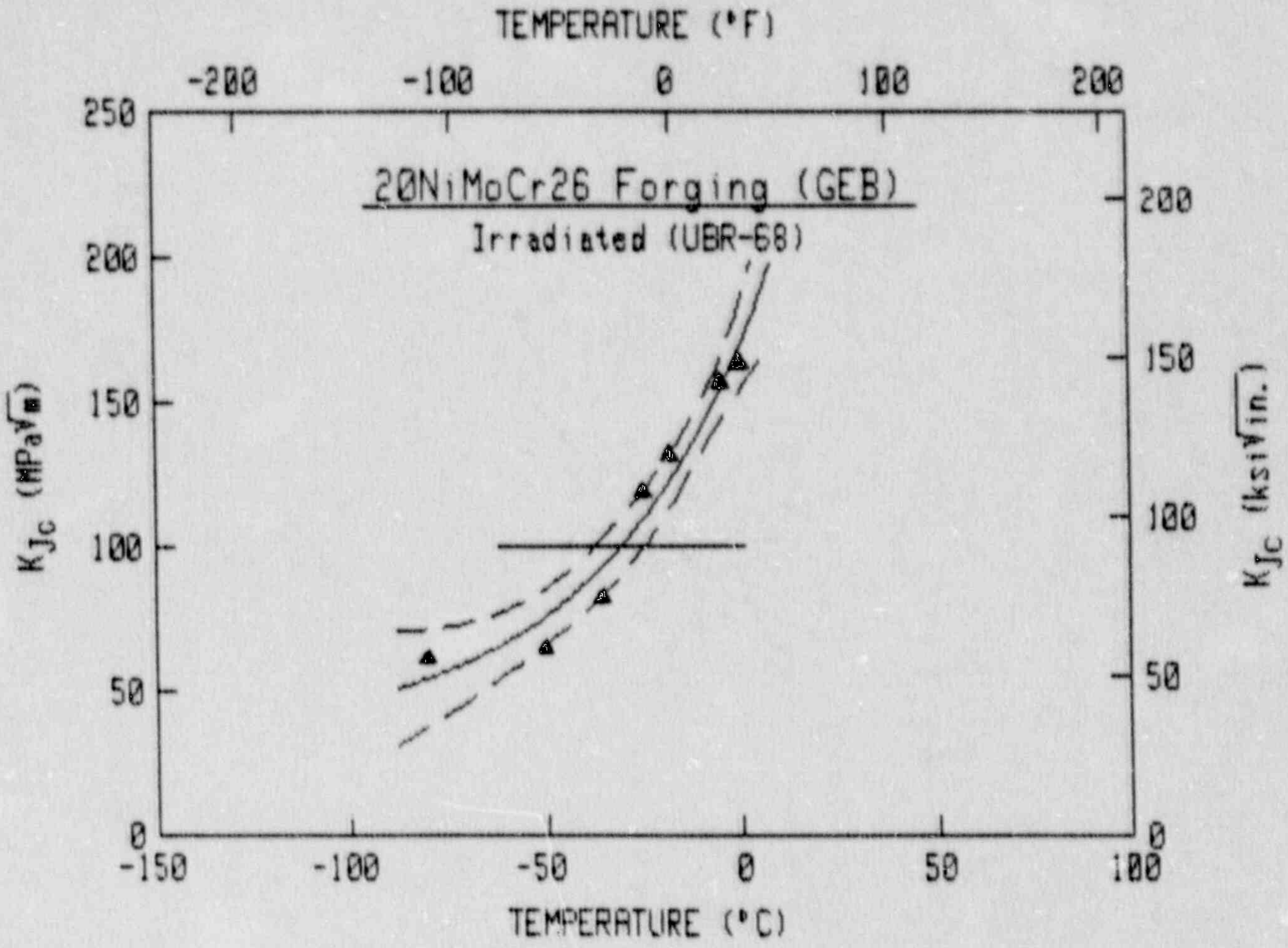
		Metric	English
A	=	39.61 MPa√m	36.04 ksi√in
B	=	321.80 MPa√m	292.85 ksi√in
C	=	46.90°C	84.41°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-86°C	-123°F
Mean Curve	=	-78°C	-109°F
Lower Bound	=	-71°C	-96°F

****

Pt #	Temperature	Kjc
1	-140	46.0
2	-118	78.2
3	-90	91.8
4	-76	91.7
5	-68	125.4
6	-57	121.5
7	-46	167.5
8	-34	195.3

O = Extra Point Added * = Point Deleted from Fit

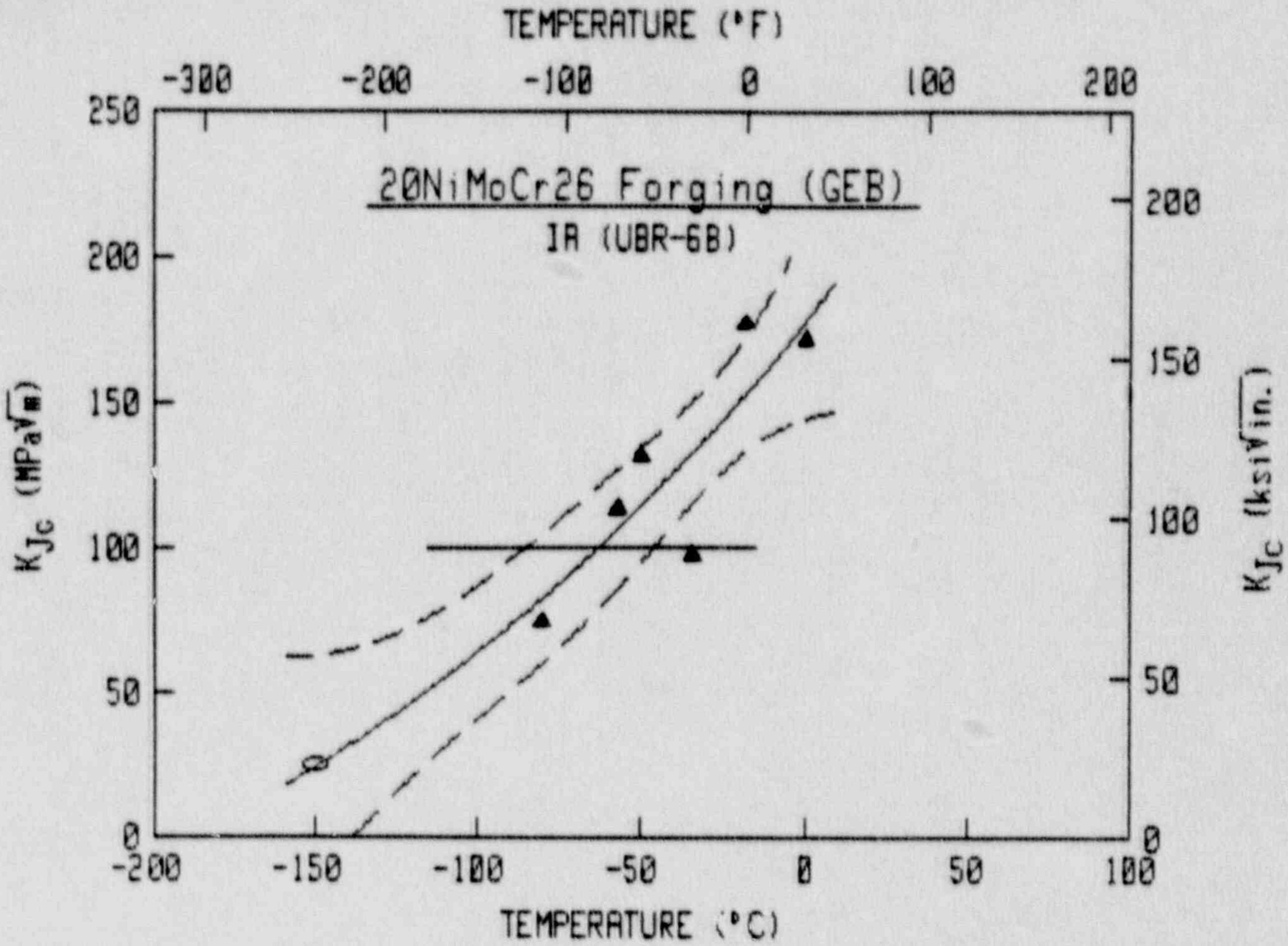


$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	33.26 MPa√m	30.27 ksi√in
B =	136.23 MPa√m	123.98 ksi√in
C =	42.71°C	76.89°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-37°C	-35°F
Mean Curve =	-30°C	-23°F
Lower Bound =	-24°C	-11°F

Pt #	Temperature	Kjc
1	-80	61.3
2	-50	64.7
3	-35	82.3
4	-25	118.7
5	-18	131.7
6	-5	156.6
7	0	163.4



****

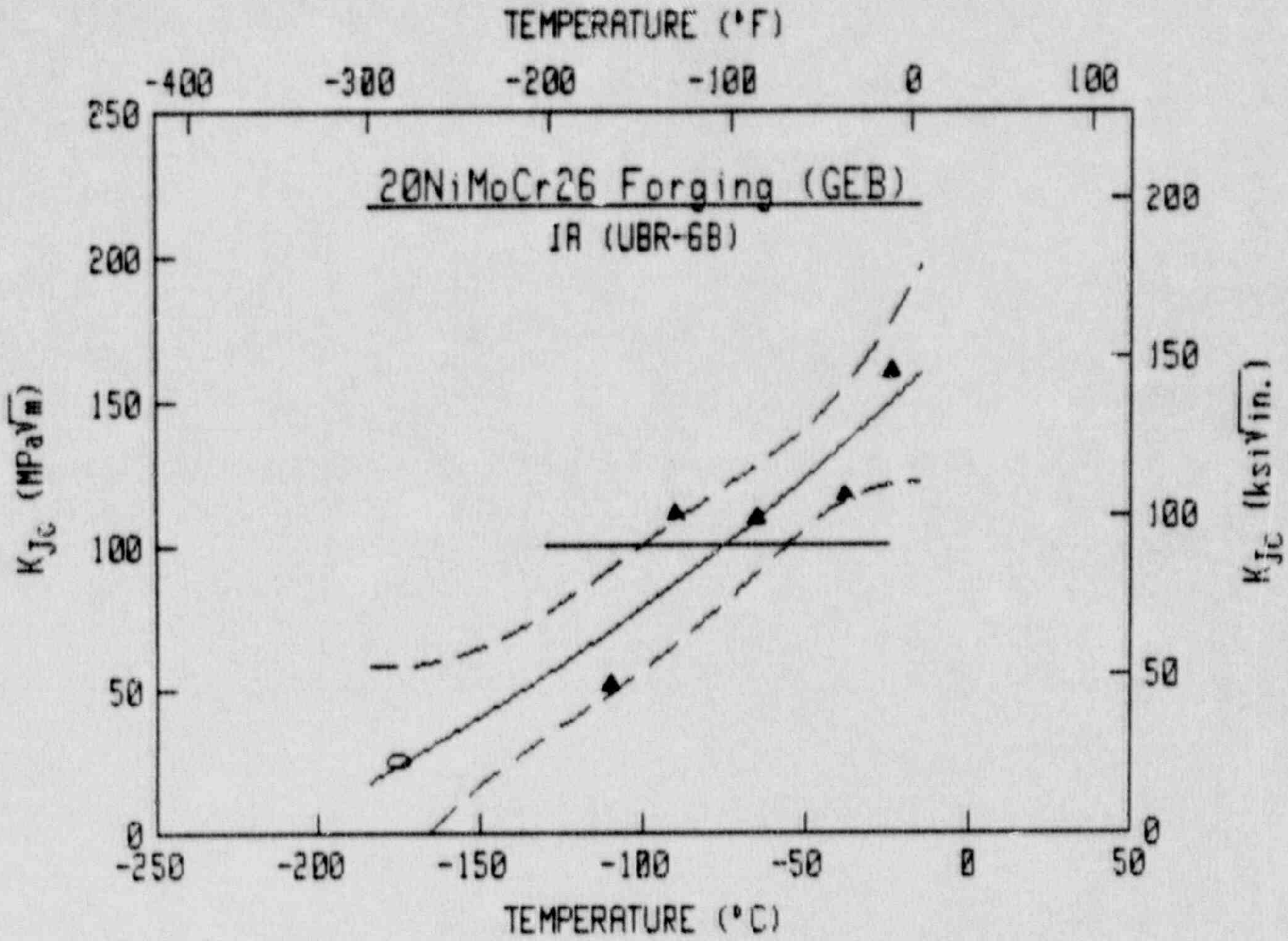
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	-122.84 MPa√m	-111.79 ksi√in
B	=	300.90 MPa√m	273.83 ksi√in
C	=	209.33°C	376.79°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-85°C	-121°F
Mean Curve	=	-63°C	-81°F
Lower Bound	=	-45°C	-49°F

****

Pt #	Temperature	Kjc
1	-80	74.5
2	-57	113.5
3	-50	131.6
4	-34	97.4
5	-18	177.4
6	0	171.9
7 O	-150	25.0



****

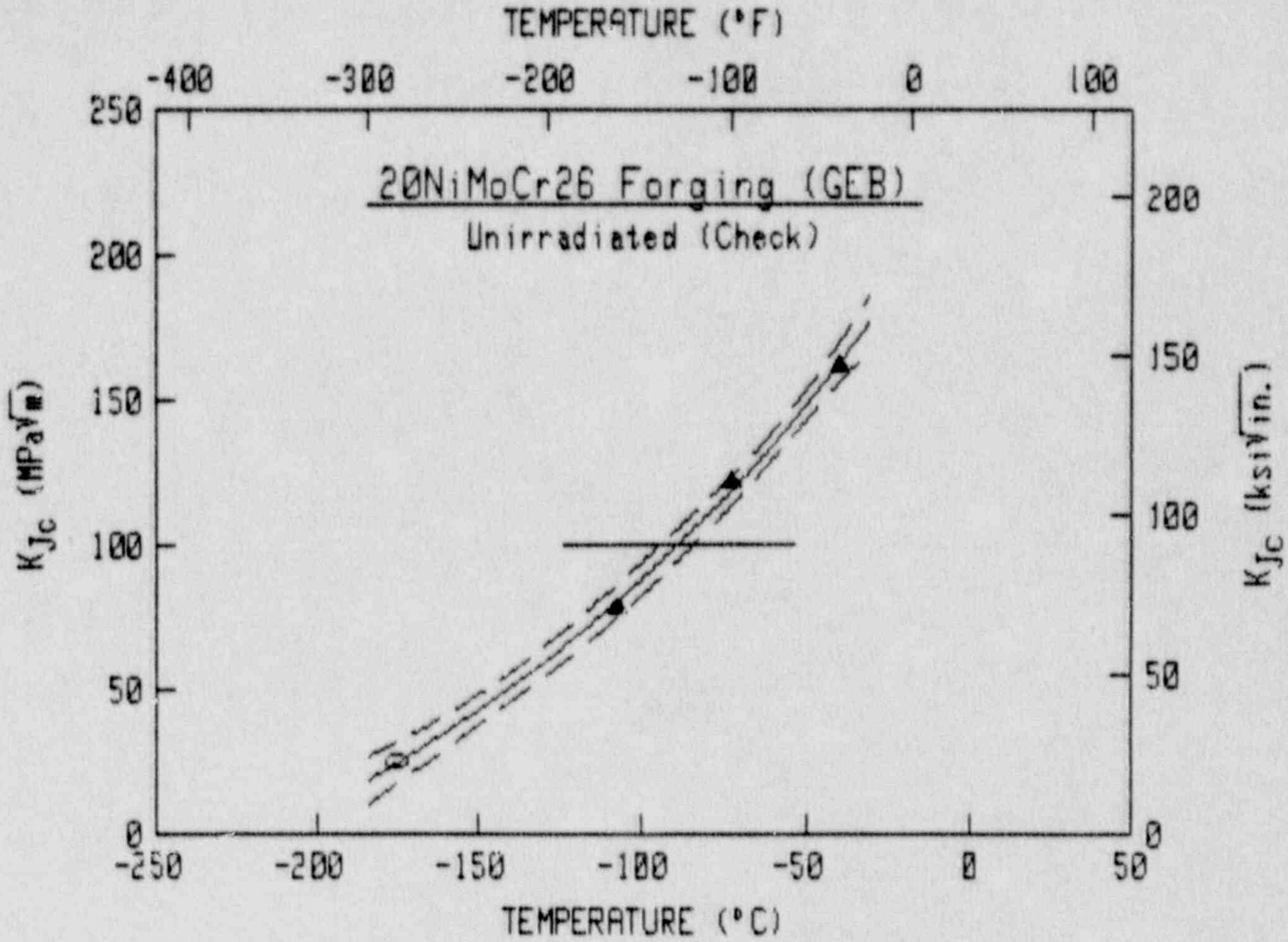
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-169.74 MPa√m	-154.47 ksi√in
B =	345.97 MPa√m	314.85 ksi√in
C =	300.41°C	540.74°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-100°C	-148°F
Mean Curve =	-75°C	-103°F
Lower Bound =	-55°C	-67°F

****

Pt #	Temperature	Kjc
1	-110	51.6
2	-90	110.9
3	-65	109.4
4	-38	117.0
5	-24	160.1
6 O	-175	25.0



****

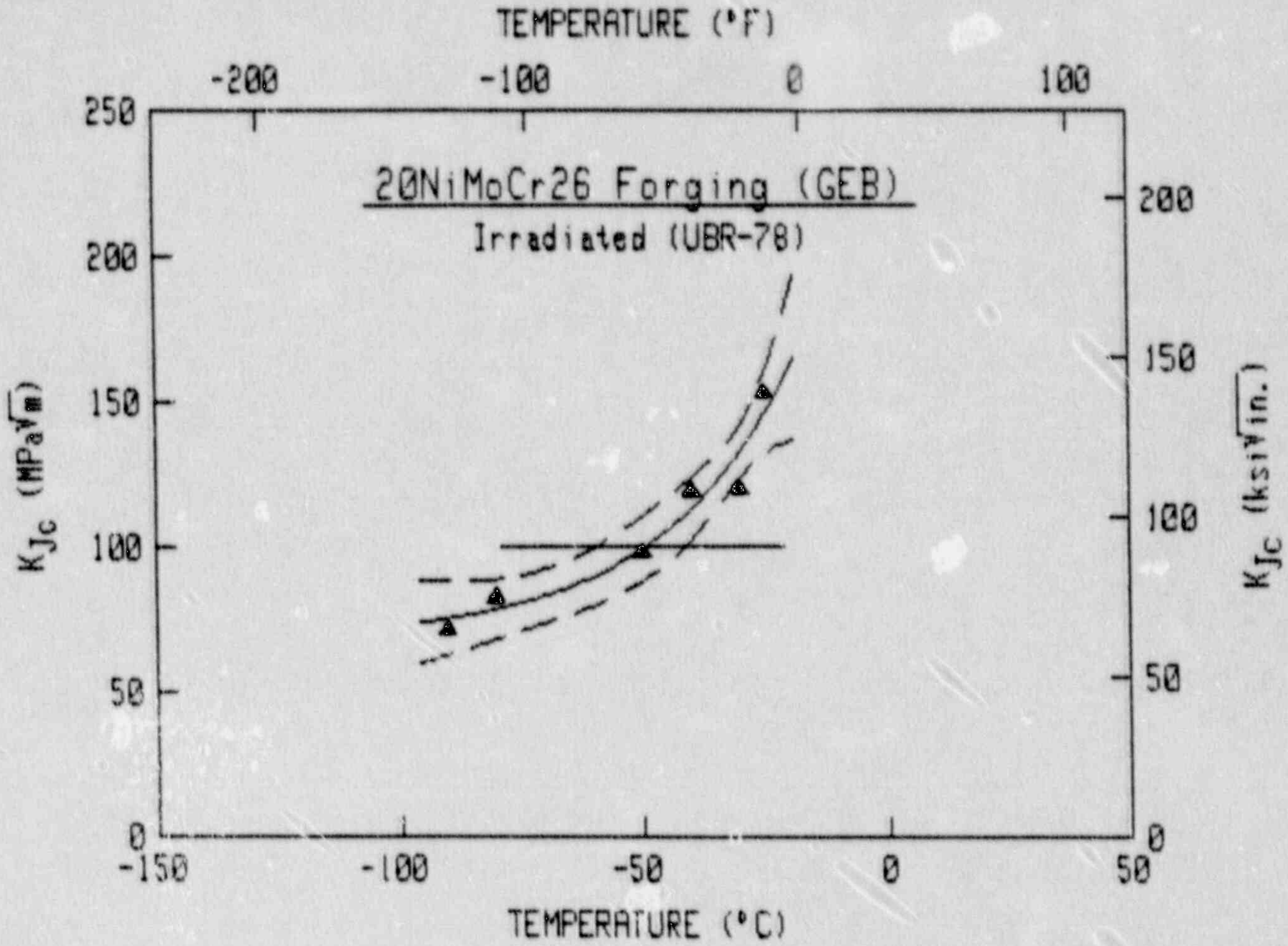
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	-92.57 MPa√m	-84.24 ksi√in
B	=	322.13 MPa√m	293.16 ksi√in
C	=	172.76°C	310.97°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-94°C	-137°F
Mean Curve =	-89°C	-128°F
Lower Bound =	-84°C	-119°F

****

Pt #	Temperature	Kjc
1	-107	78.1
2	-73	121.8
3	-40	161.9
4 O	-175	25.0



****

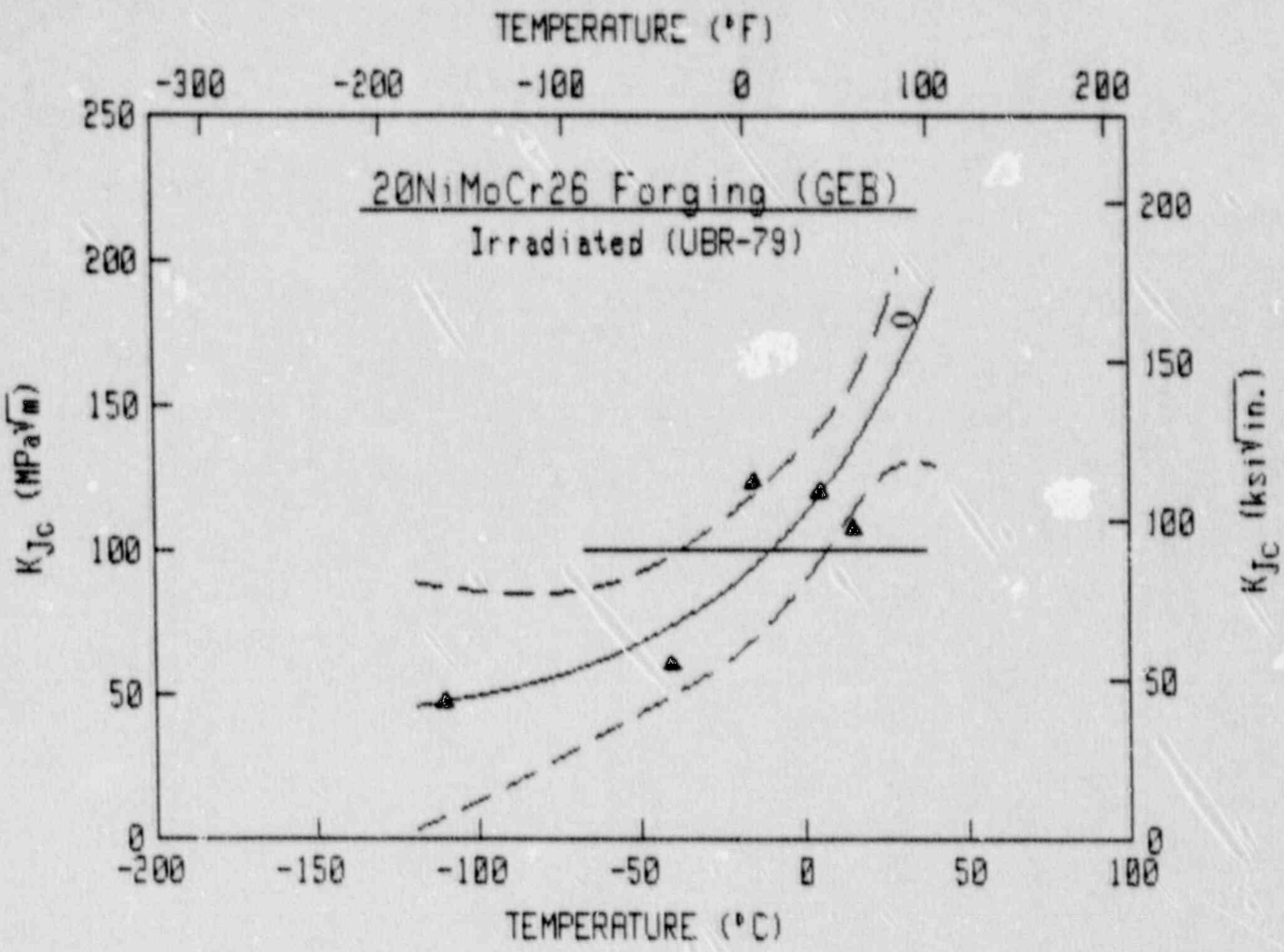
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	68.25 MPa√m	62.11 ksi√in
B	=	195.75 MPa√m	178.14 ksi√in
C	=	27.00°C	48.60°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-59°C	-74°F
Mean Curve =	-49°C	-56°F
Lower Bound =	-41°C	-42°F

****

Pt #	Temperature	Kjc
1	-90	71.3
2	-80	82.4
3	-50	98.0
4	-40	119.4
5	-30	119.8
6	-25	152.9



****

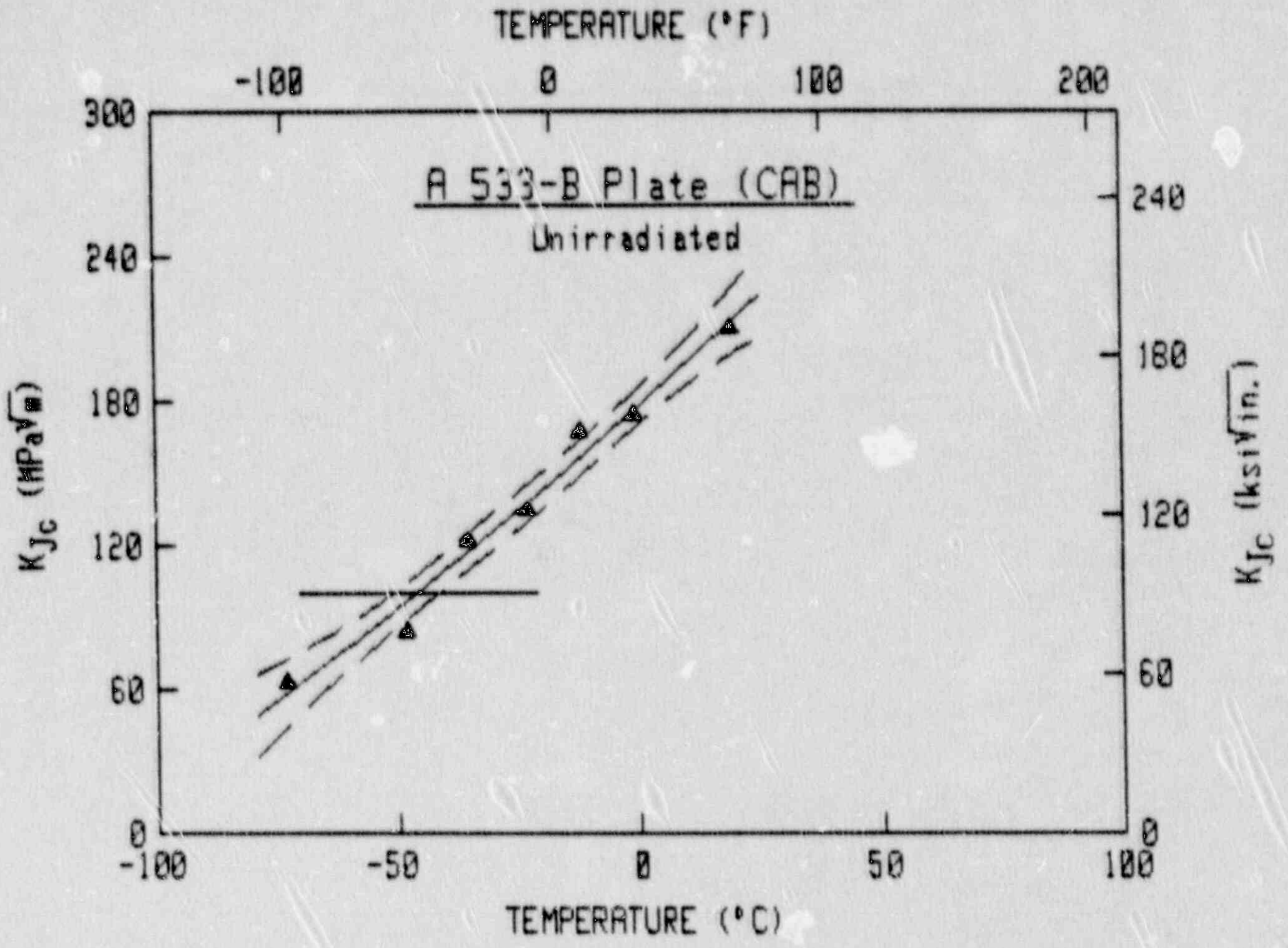
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	37.05 MPa√m	33.72 ksi√in
B =	75.18 MPa√m	68.42 ksi√in
C =	55.73°C	100.31°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-37°C	-35°F
Mean Curve =	-10°C	14°F
Lower Bound =	7°C	45°F

****

Pt #	Temperature	Kjc
1	-110	47.3
2	-40	60.5
3	-15	123.6
4	5	120.2
5	15	107.4
6 O	31	179.6



****

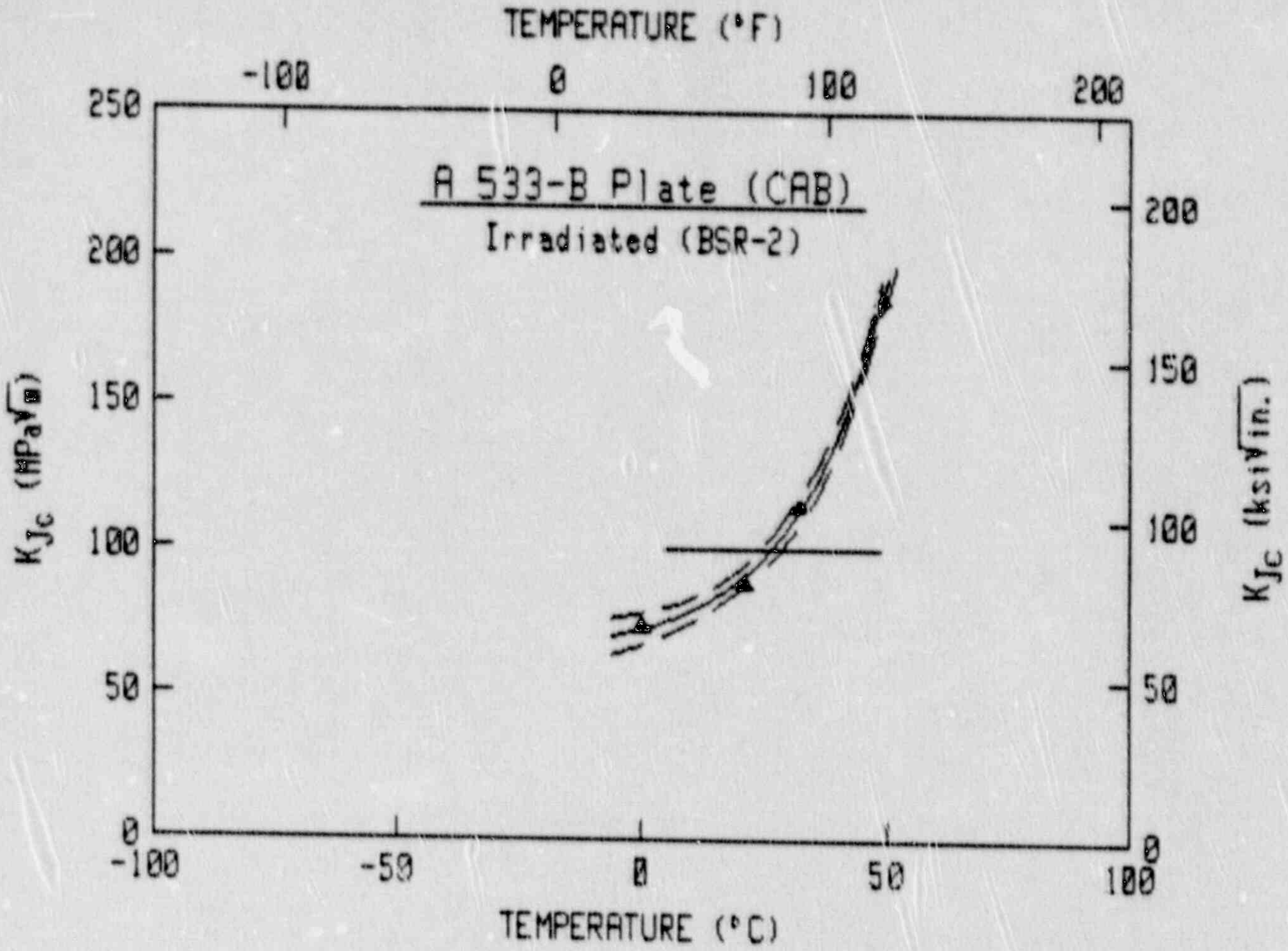
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-557.95 MPa√m	-507.76 ksi√in
B =	735.41 MPa√m	669.25 ksi√in
C =	412.40°C	742.31°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-50°C	-58°F
Mean Curve =	-46°C	-51°F
Lower Bound =	-41°C	-42°F

****

Pt #	Temperature	Kjc
1	-73	63.0
2	-48	84.1
3	-35	121.8
4	-23	134.5
5	-12	167.0
6	-1	174.2
7	19	209.6

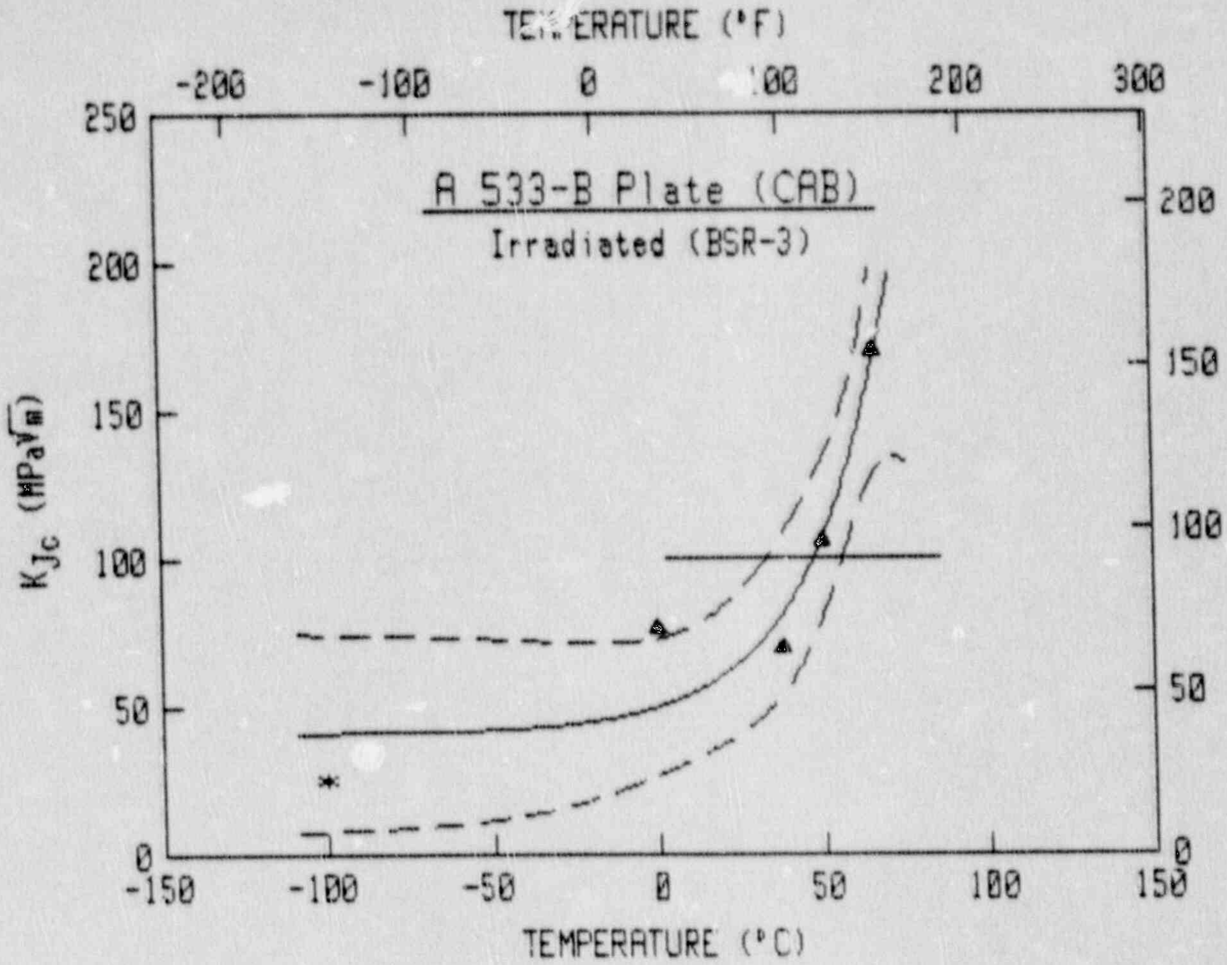


$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	63.55 MPa√m	57.83 ksi√in
B =	8.63 MPa√m	7.85 ksi√in
C =	18.42°C	33.16°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	25°C	77°F
Mean Curve =	27°C	80°F
Lower Bound =	29°C	84°F

Pt #	Temperature	Kjc
1	0	73.2
2	21	87.8
3	32	114.5
4	49	186.6



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Kjc = A + B exp [(T-To)/C)]

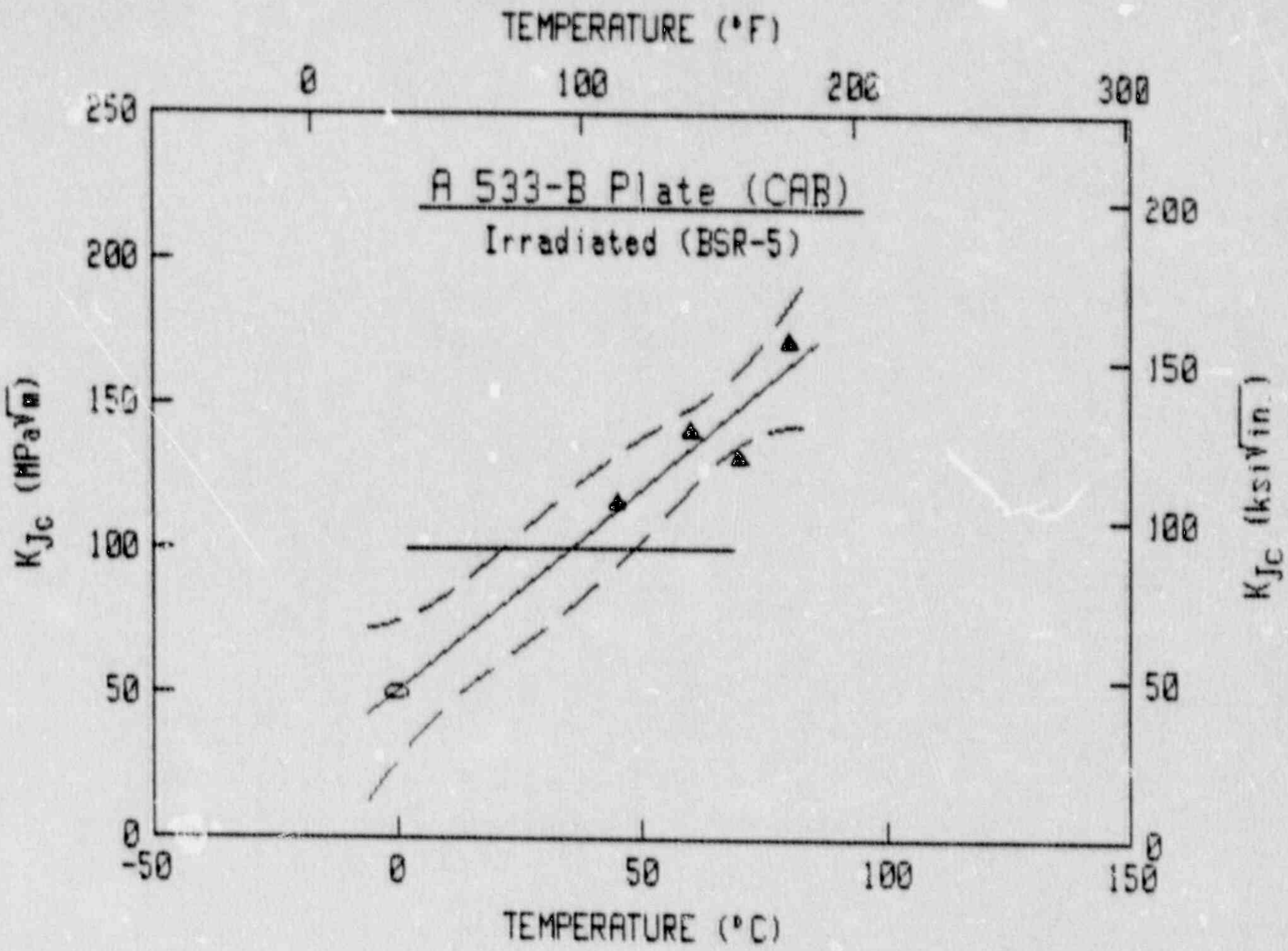
		Metric	English
A	=	40.98 MPa√m	37.30 ksi√in
B	=	8.70 MPa√m	7.92 ksi√in
C	=	24.65°C	44.38°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	33°C	91°F
Mean Curve	=	47°C	117°F
Lower Bound	=	56°C	133°F

****

Pt #	Temperature	Kjc
1	0	76.3
2	38	69.6
3	50	106.0
4	66	170.1
5 *	-100	25.0

* = Upper Shelf Data Point



****

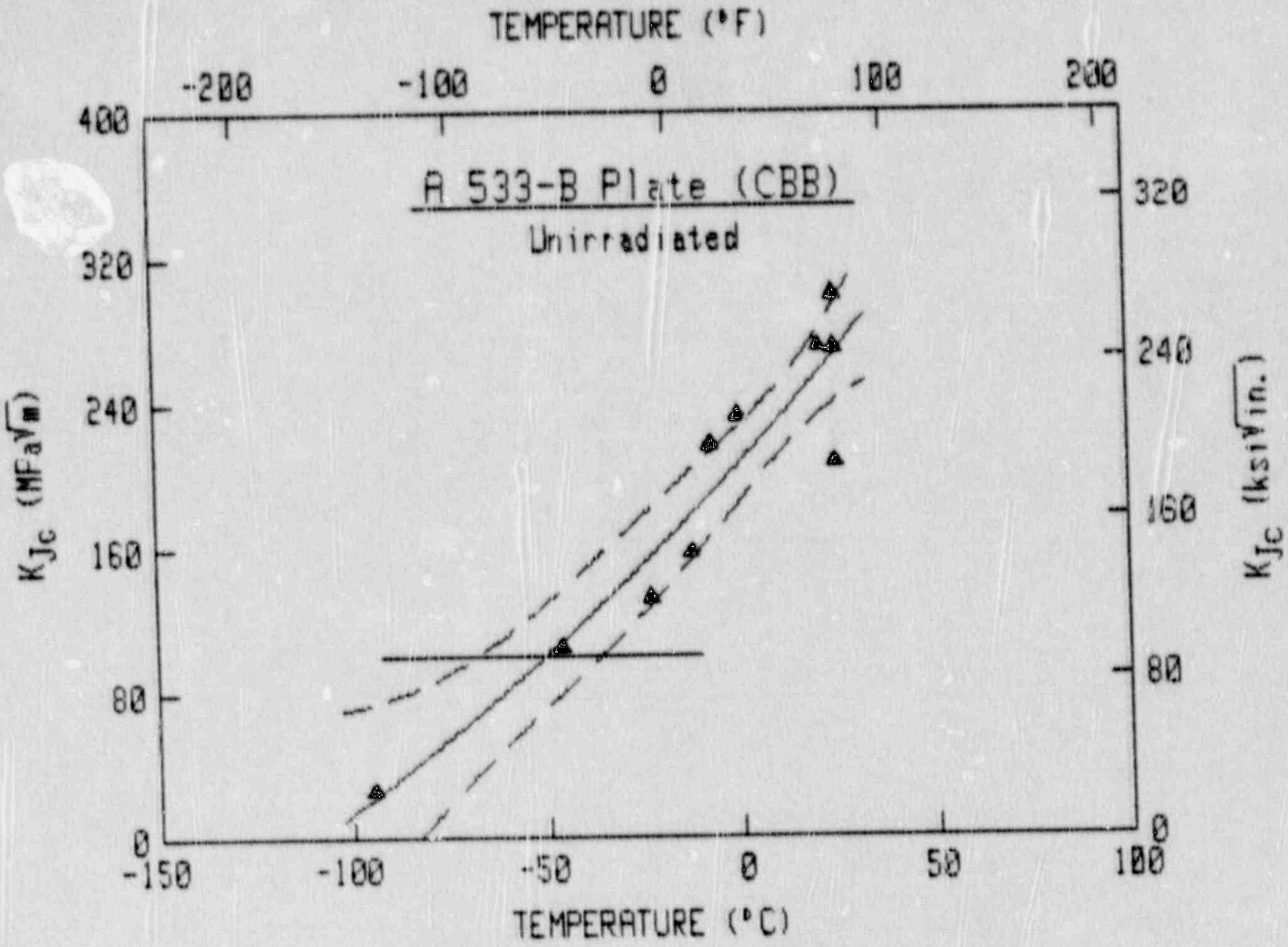
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	-2304.77 MPa√m	-2097.45 ksi√in
B	=	2355.45 MPa√m	2143.57 ksi√in
C	=	1715.82°C	3088.47°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	22°C	72°F
Mean Curve =	36°C	96°F
Lower Bound =	49°C	120°F

****

Pt #	Temperature	Kjc
1	45	116.0
2	60	141.1
3	70	131.4
4	80	171.8
5 O	0	50.0

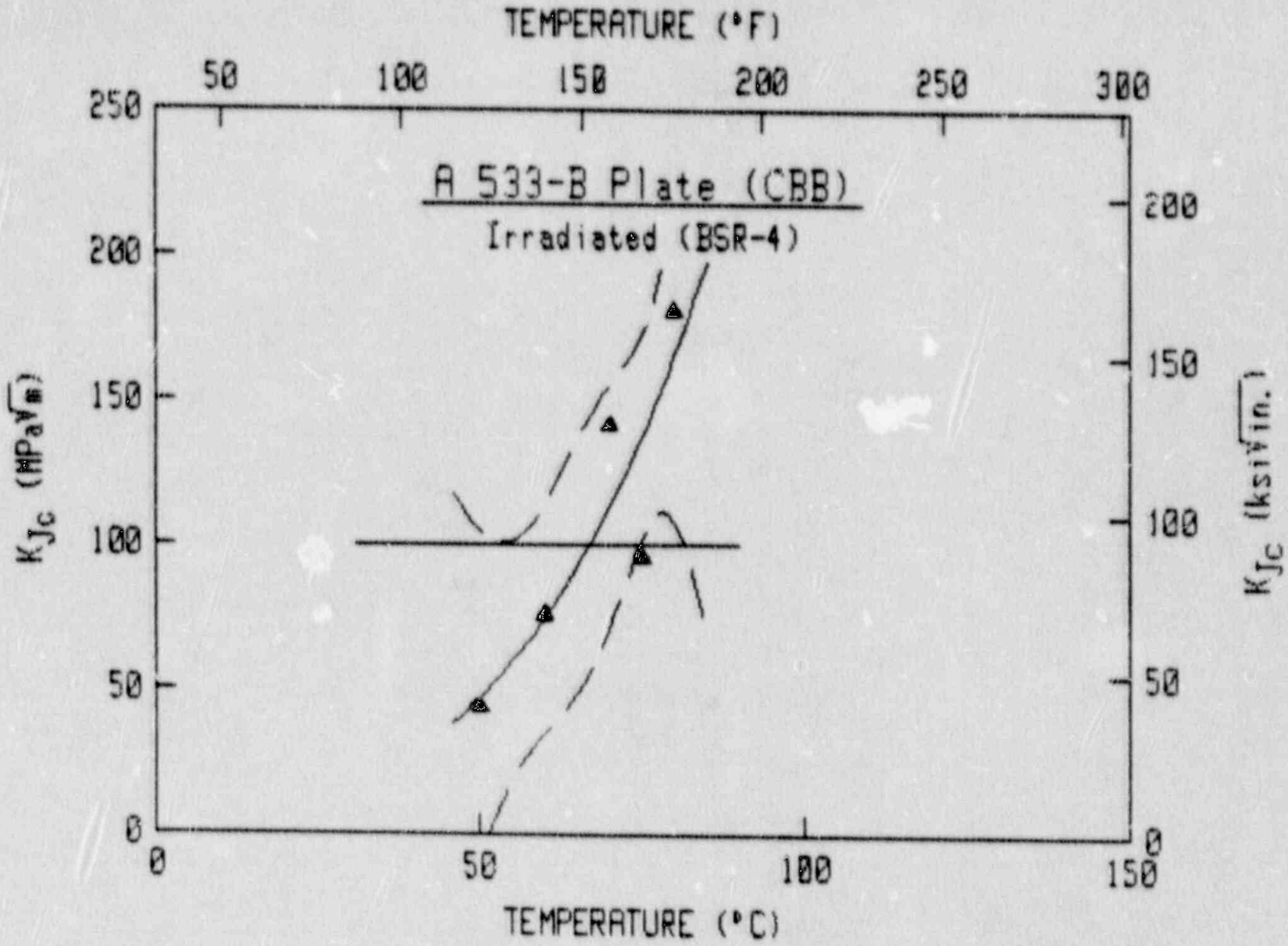


$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	-372.59 MPa√m	-339.08 ksi√in
B =	577.99 MPa√m	526.00 ksi√in
C =	248.50°C	447.29°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-67°C	-89°F
Mean Curve =	-50°C	-58°F
Lower Bound =	-35°C	-31°F

Pt #	Temperature	Kjc
1	-95	25.9
2	-46	104.6
3	-23	131.8
4	-12	157.0
5	-7	216.3
6	0	232.4
7	21	270.3
8	25	298.8
9	25	206.0
10	25	269.6



****

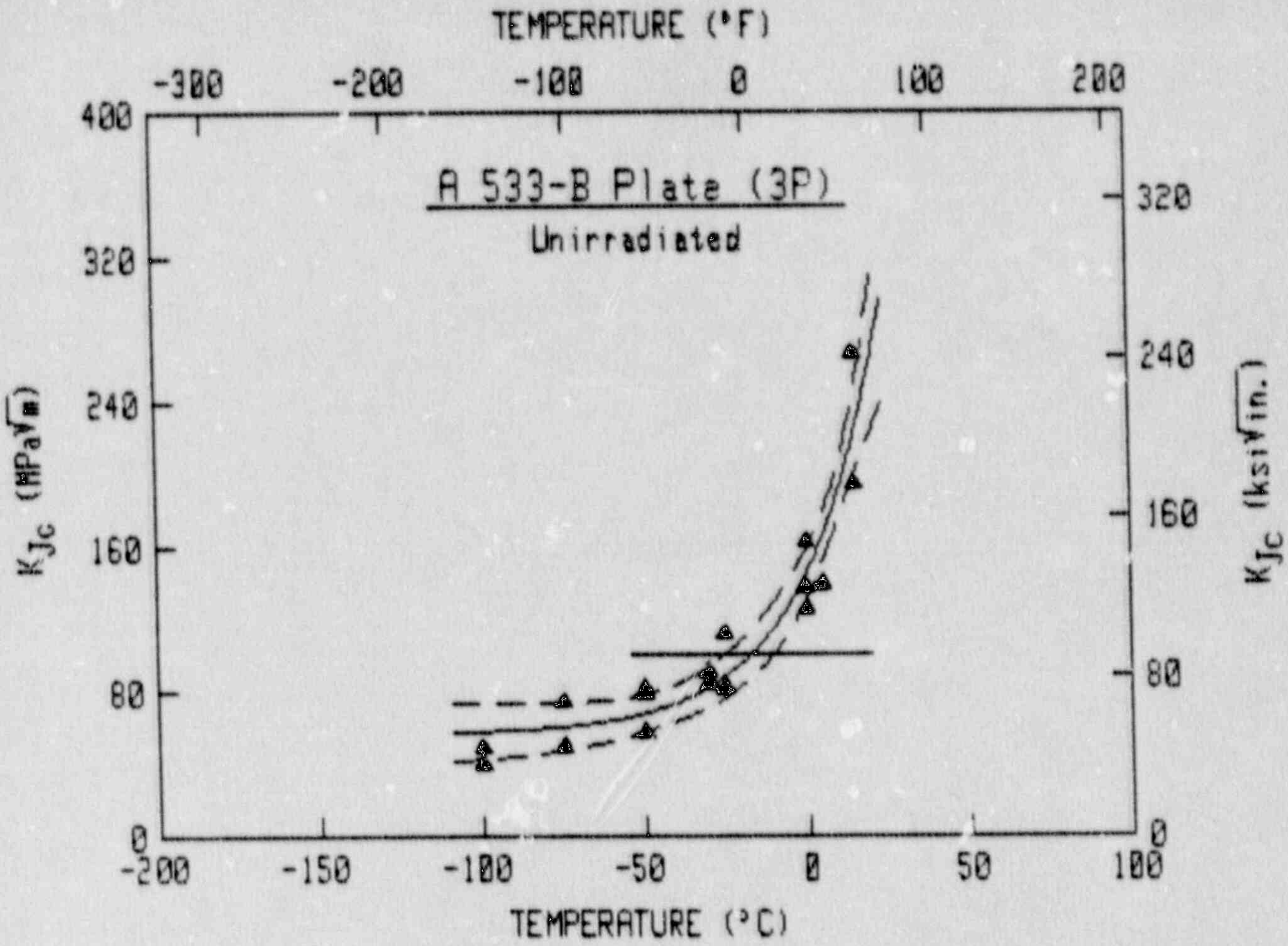
$Kjc = A + B \exp[(T-To)/C)]$

	Metric	English
A =	-30.86 MPa√m	-28.08 ksi√in
B =	16.69 MPa√m	15.19 ksi√in
C =	32.48°C	58.46°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	46°C	115°F
Mean Curve =	67°C	152°F
Lower Bound =	75°C	167°F

****

Pt #	Temperature	Kjc
1	50	43.8
2	60	75.8
3	70	141.3
4	75	95.7
5	80	180.8



****

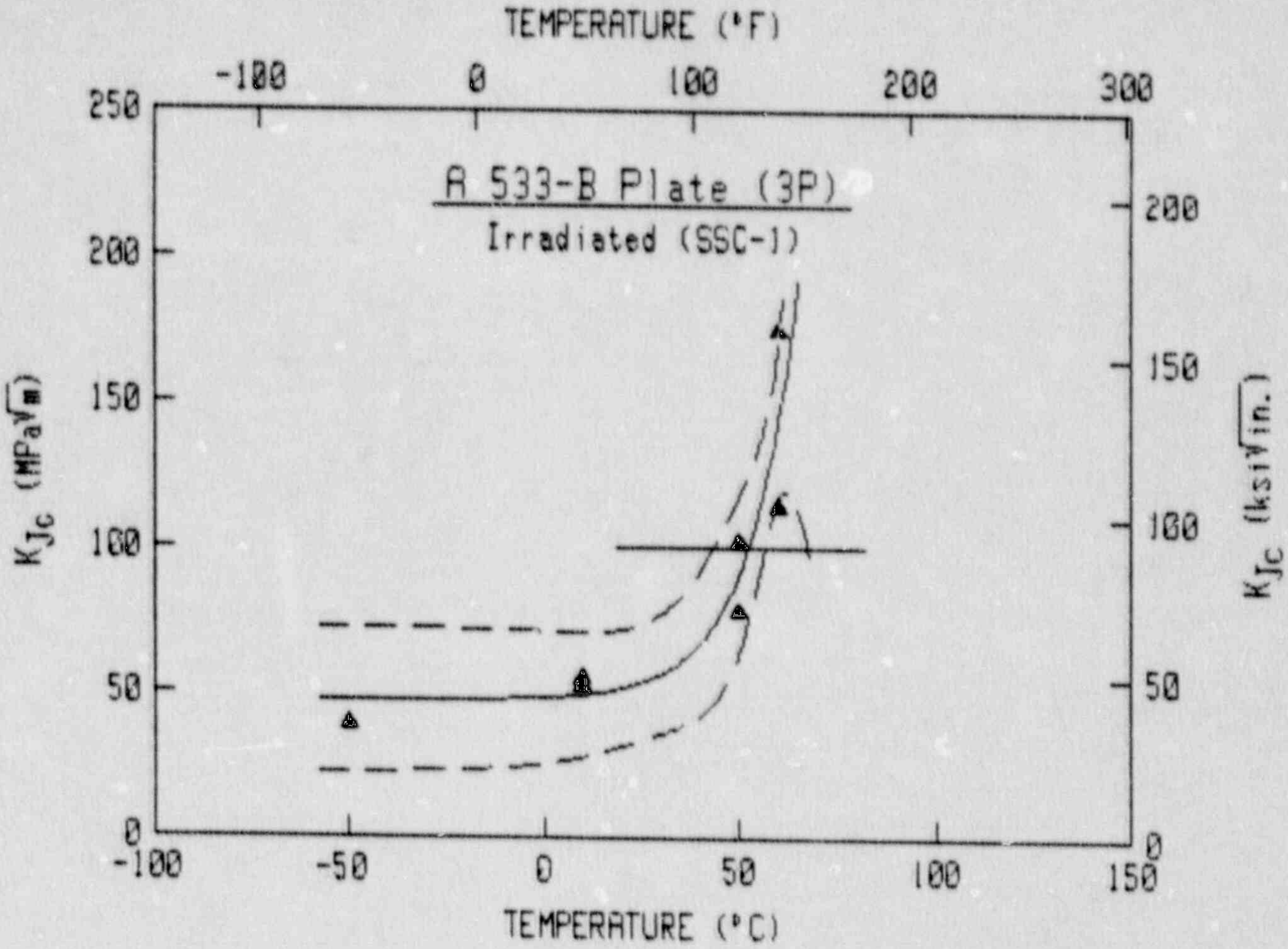
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	56.21 MPa√m	51.15 ksi√in
B	=	88.68 MPa√m	80.70 ksi√in
C	=	24.08°C	43.34°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-24°C	-11°F
Mean Curve =	-17°C	1°F
Lower Bound =	-10°C	14°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-100	40.1	10	-25	111.2
2	-100	48.7	11	-25	81.4
3	-75	49.0	12	0	136.5
4	-75	73.7	13	0	162.4
5	-50	57.4	14	0	125.6
6	-50	78.4	15	5	138.9
7	-50	81.1	16	15	266.0
8	-30	84.0	17	15	194.1
9	-30	90.7			



****

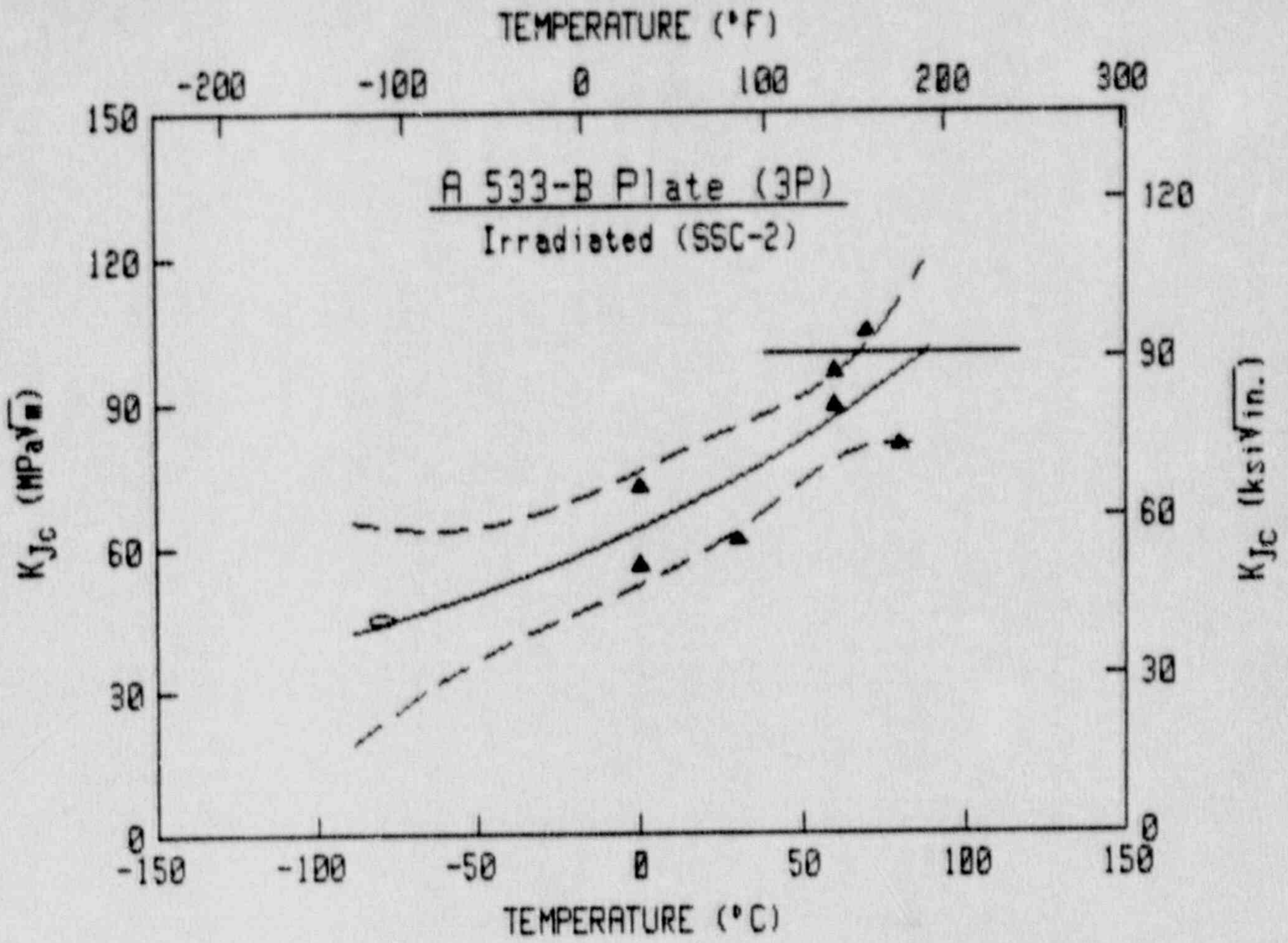
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	47.46 MPa√m	43.19 ksi√in
B =	.79 MPa√m	.71 ksi√in
C =	12.46°C	22.43°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	44°C	111°F
Mean Curve =	52°C	126°F
Lower Bound =	57°C	135°F

****

Pt #	Temperature	Kjc
1	-50	39.3
2	10	52.7
3	10	55.1
4	50	102.0
5	50	77.8
6	60	174.8
7	60	114.3



****

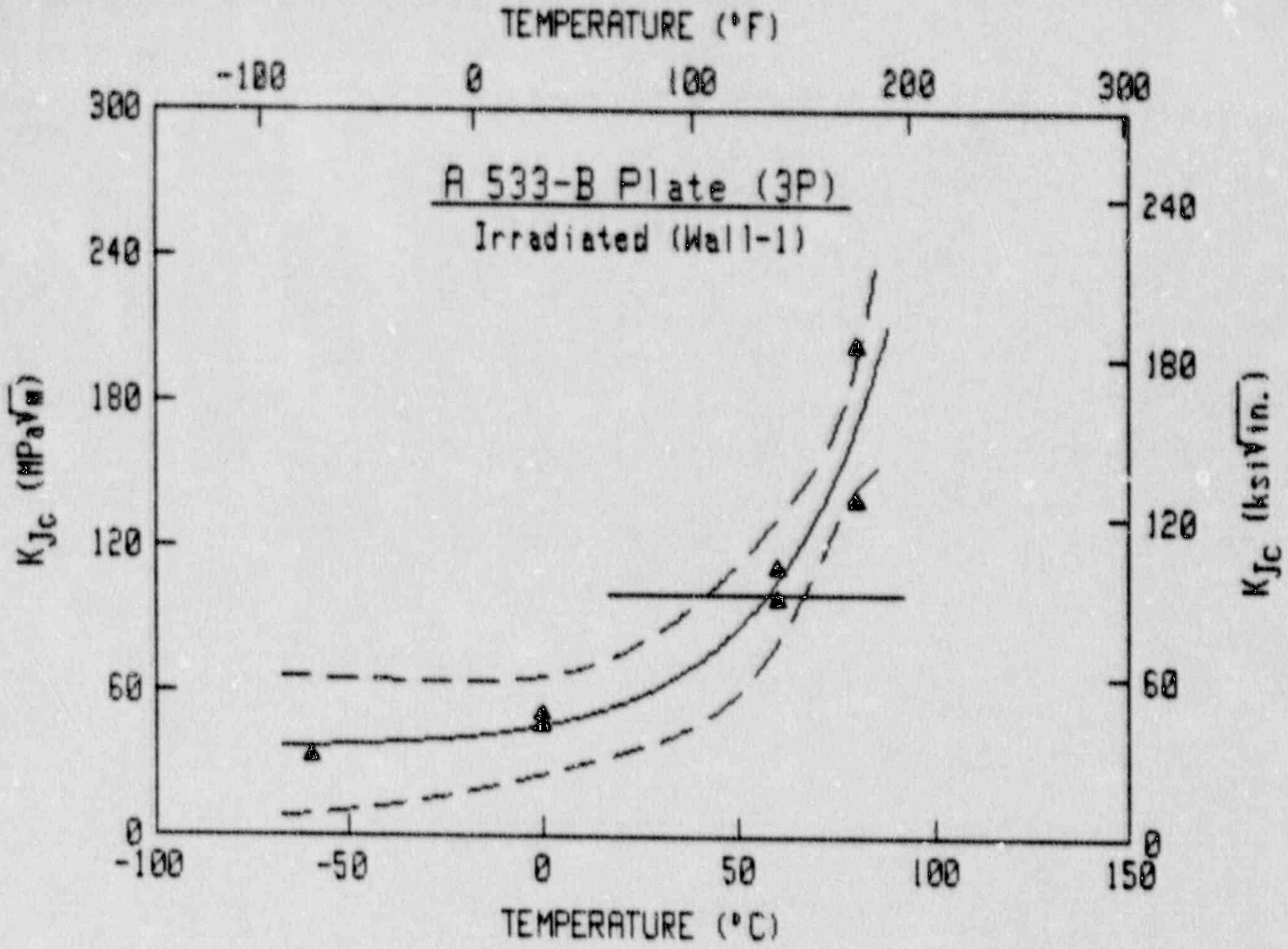
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	13.61 MPa√m	12.38 ksi√in
B =	50.00 MPa√m	45.50 ksi√in
C =	159.76°C	287.57°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	68°C	154°F
Mean Curve =	87°C	189°F

****

Pt #	Temperature	Kjc
1	0	72.4
2	0	55.9
3	30	61.3
4	60	89.0
5	60	96.2
6	70	104.4
7	80	80.8
8 O	-80	45.0



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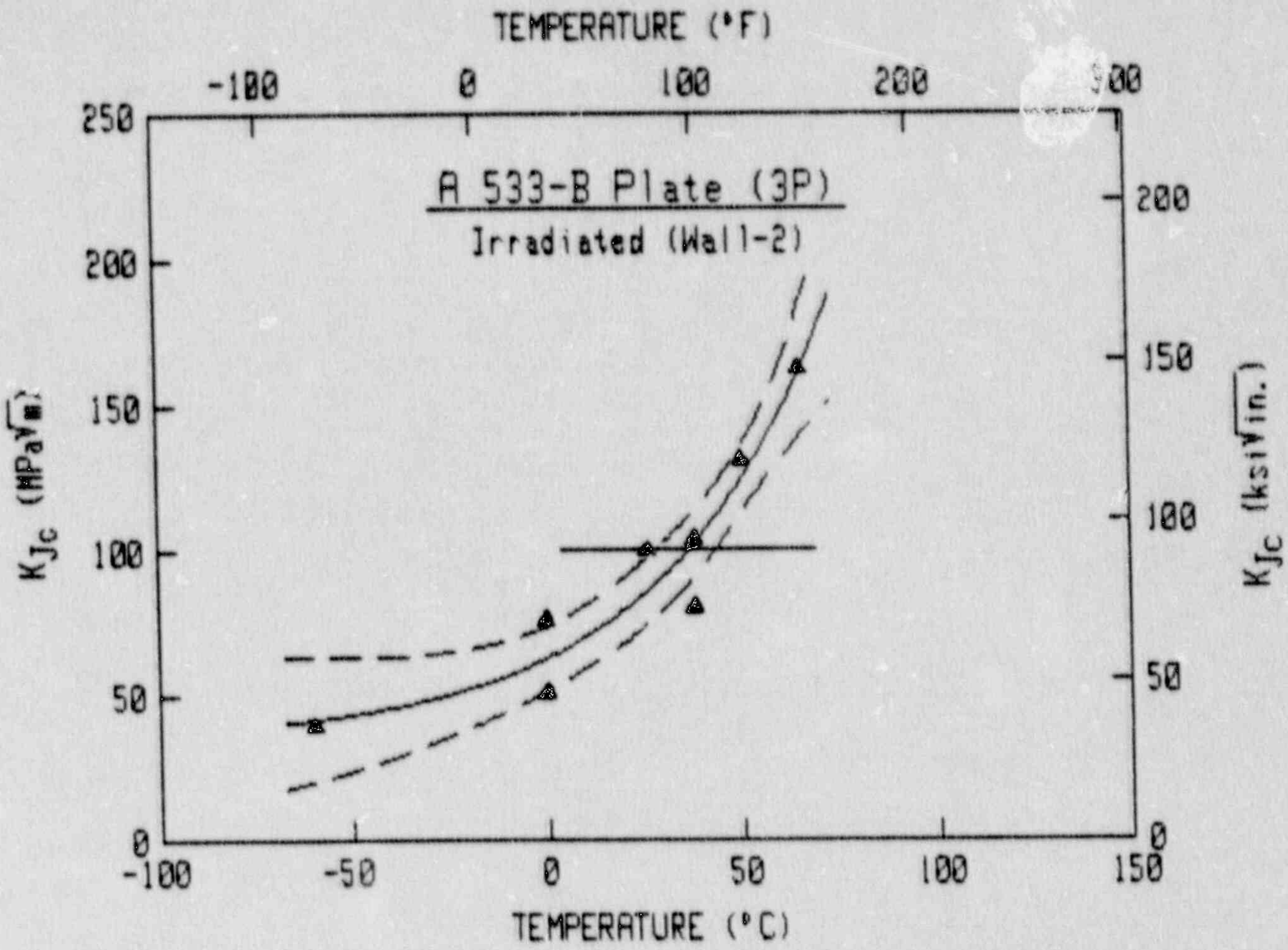
$$K_{jc} = A + B \exp[(T - T_o)/C]$$

	Metric	English
A =	35.75 MPa√m	32.54 ksi√in
B =	9.81 MPa√m	8.93 ksi√in
C =	30.53°C	54.95°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	42°C	108°F
Mean Curve =	57°C	135°F
Lower Bound =	67°C	153°F

****

Pt #	Temperature	Kjc
1	-60	33.1
2	0	50.7
3	0	46.1
4	60	98.1
5	60	110.9
6	80	139.2
7	80	203.1



****

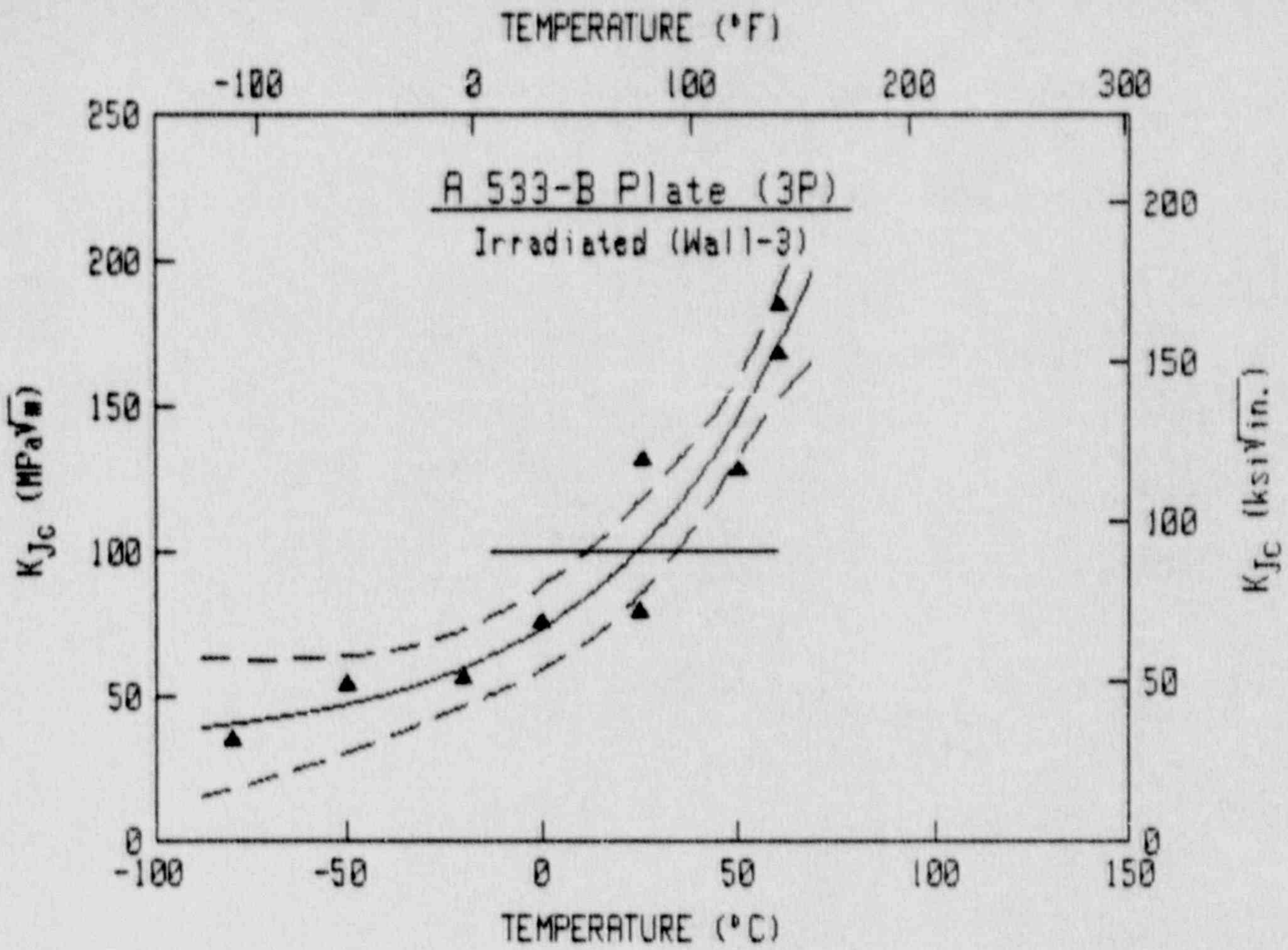
$K_{jc} = A + B \exp[(T-T_o)/C]$

	Metric	English
A =	34.82 MPa√m	31.69 ksi√in
B =	27.65 MPa√m	25.16 ksi√in
C =	42.65°C	76.76°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	29°C	84°F
Mean Curve =	37°C	98°F
Lower Bound =	44°C	111°F

****

Pt #	Temperature	Kjc
1	-60	39.6
2	0	50.7
3	0	75.9
4	26	99.8
5	38	103.5
6	38	79.9
7	50	130.8
8	65	162.3



****

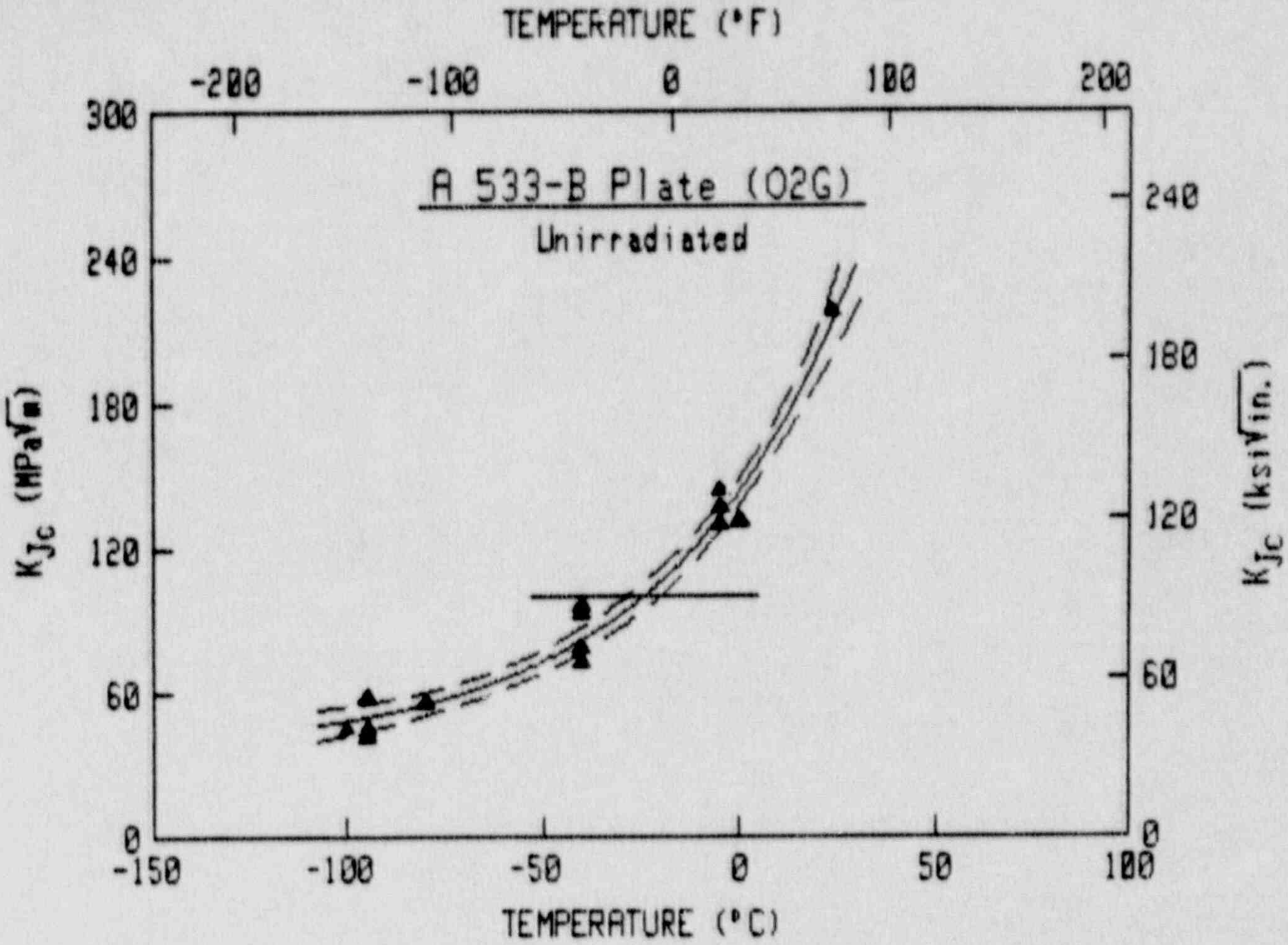
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	32.29 MPa√m	29.39 ksi√in
B	=	41.19 MPa√m	37.49 ksi√in
C	=	49.29°C	88.73°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	12°C	54°F
Mean Curve =	24°C	76°F
Lower Bound =	35°C	95°F

****

Pt #	Temperature	Kjc
1	-80	34.9
2	-50	54.3
3	-20	56.3
4	0	75.3
5	25	79.0
6	26	131.5
7	50	128.2
8	60	184.7
9	60	168.2



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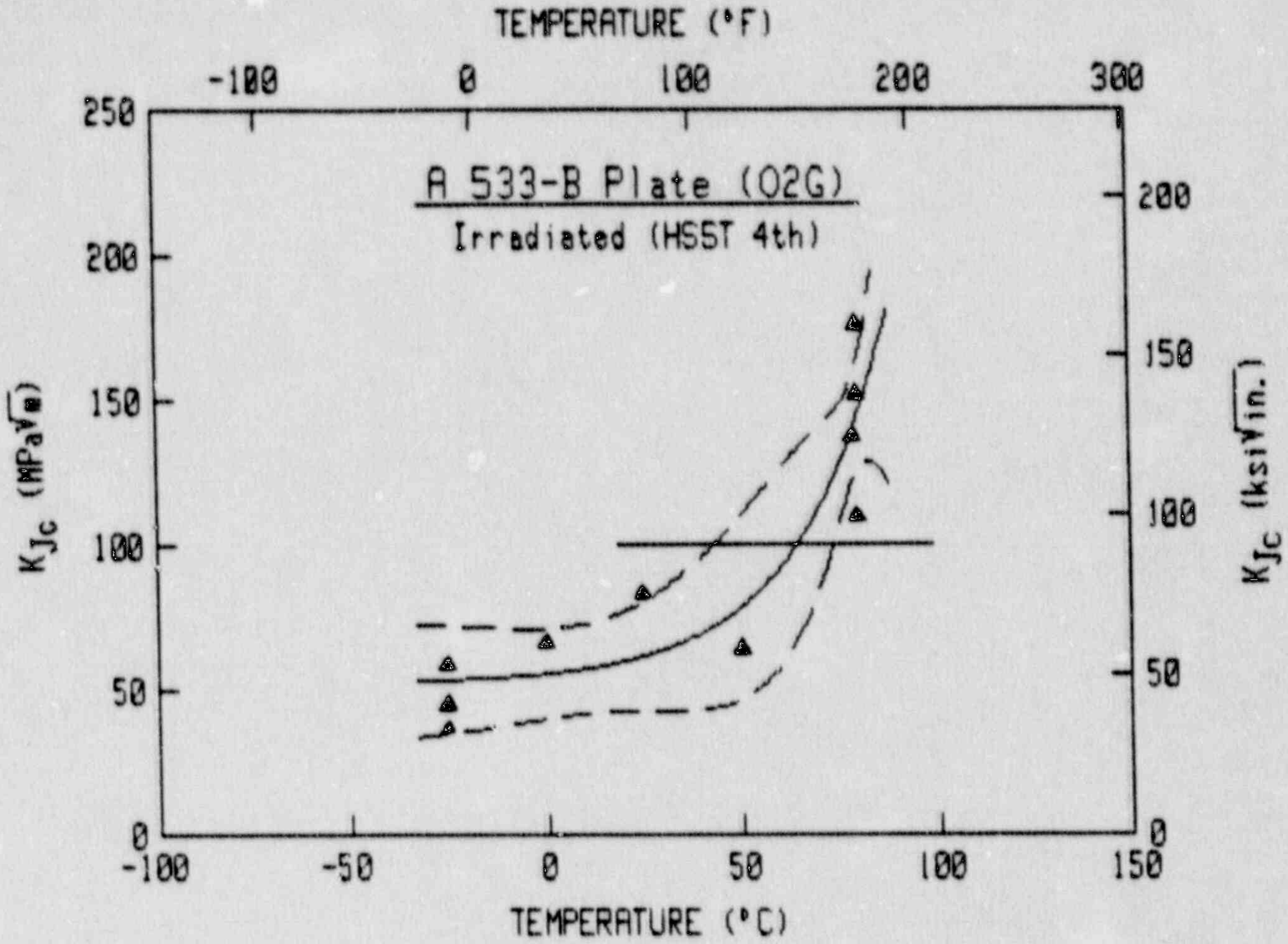
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	35.87 MPa√m	32.64 ksi√in
B	=	107.86 MPa√m	98.15 ksi√in
C	=	46.72°C	84.09°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-28°C	-18°F
Mean Curve	=	-24°C	-12°F
Lower Bound	=	-20°C	-4°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-100	44.4	10	-40	78.3
2	-95	44.4	11	-40	72.4
3	-95	58.7	12	-5	136.6
4	-95	45.2	13	-5	130.1
5	-95	42.0	14	-5	143.8
6	-95	57.3	15	0	131.6
7	-80	55.8	16	0	131.1
8	-40	93.1	17	23	217.8
9	-40	96.0			

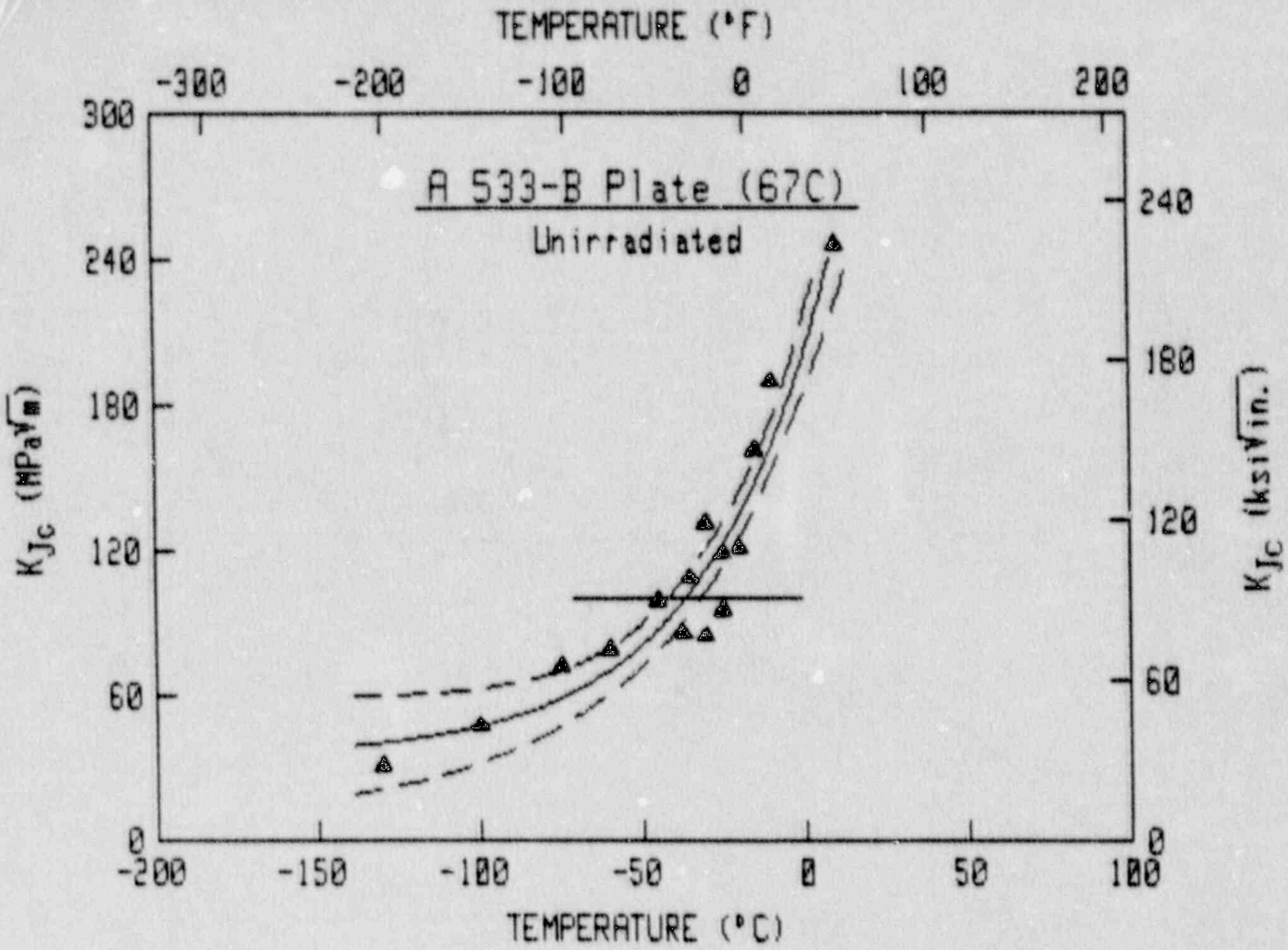


$$Kjc = A + B \exp[(T-To)/C)]$$

	Metric	English
A =	52.38 MPa√m	47.67 ksi√in
B =	3.12 MPa√m	2.84 ksi√in
C =	23.65°C	42.57°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	44°C	111°F
Mean Curve =	64°C	148°F
Lower Bound =	74°C	165°F

Pt #	Temperature	Kjc
1	-25	36.2
2	-25	45.1
3	-25	58.9
4	0	66.5
5	25	83.1
6	50	64.2
7	79	137.3
8	80	176.2
9	80	109.8
10	80	151.8



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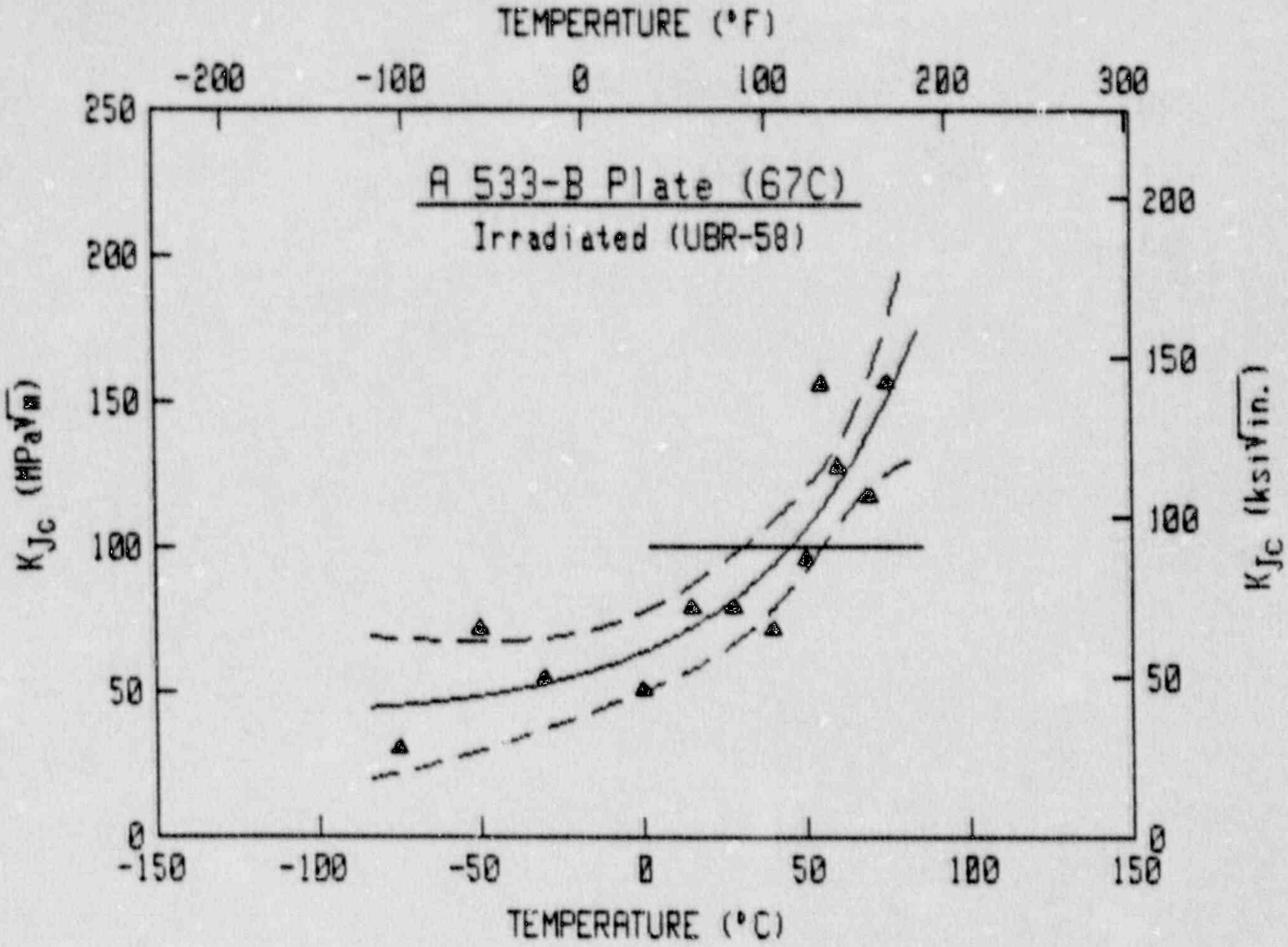
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	34.68 MPa√m	31.56 ksi√in
B =	166.83 MPa√m	151.82 ksi√in
C =	38.79°C	69.83°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-41°C	-42°F
Mean Curve =	-36°C	-33°F
Lower Bound =	-31°C	-24°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-130	30.7	9	-30	84.5
2	-100	47.7	10	-25	118.6
3	-75	72.0	11	-25	95.2
4	-60	79.2	12	-20	120.9
5	-45	99.0	13	-15	160.9
6	-37	85.4	14	-10	189.7
7	-35	108.6	15	10	246.1
8	-30	131.0			



****

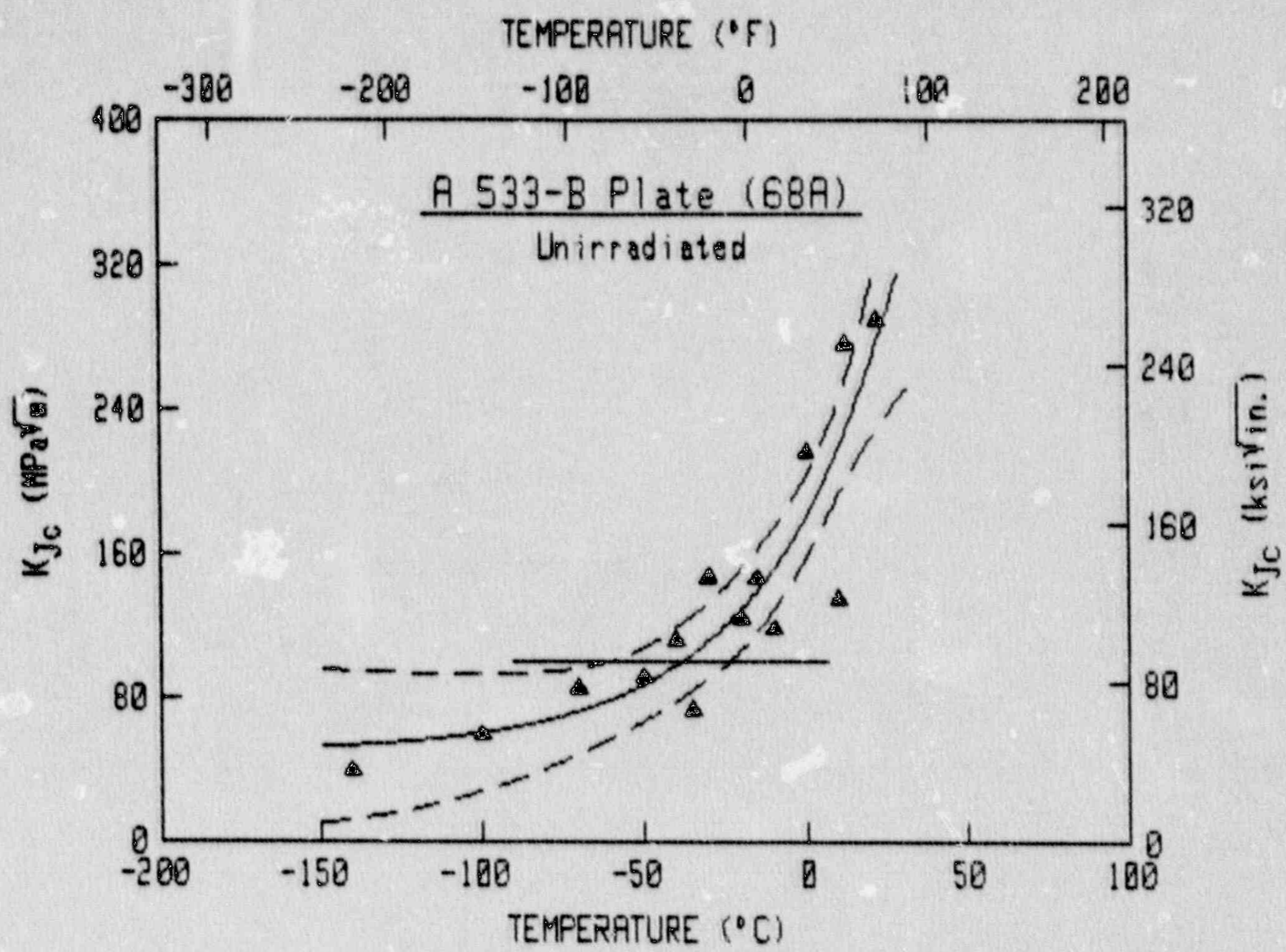
$$Kjc = A + B \exp[(T-To)/C]$$

	Metric	English
A =	40.33 MPa√m	36.71 ksi√in
B =	23.13 MPa√m	21.05 ksi√in
C =	47.90°C	86.22°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	32°C	90°F
Mean Curve =	45°C	114°F
Lower Bound =	56°C	133°F

****

Pt #	Temperature	Kjc
1	-75	30.3
2	-50	71.7
3	-30	54.7
4	0	50.4
5	15	78.9
6	28	78.6
7	40	71.4
8	50	95.7
9	55	156.1
10	60	127.8
11	70	117.0
12	75	156.4



****

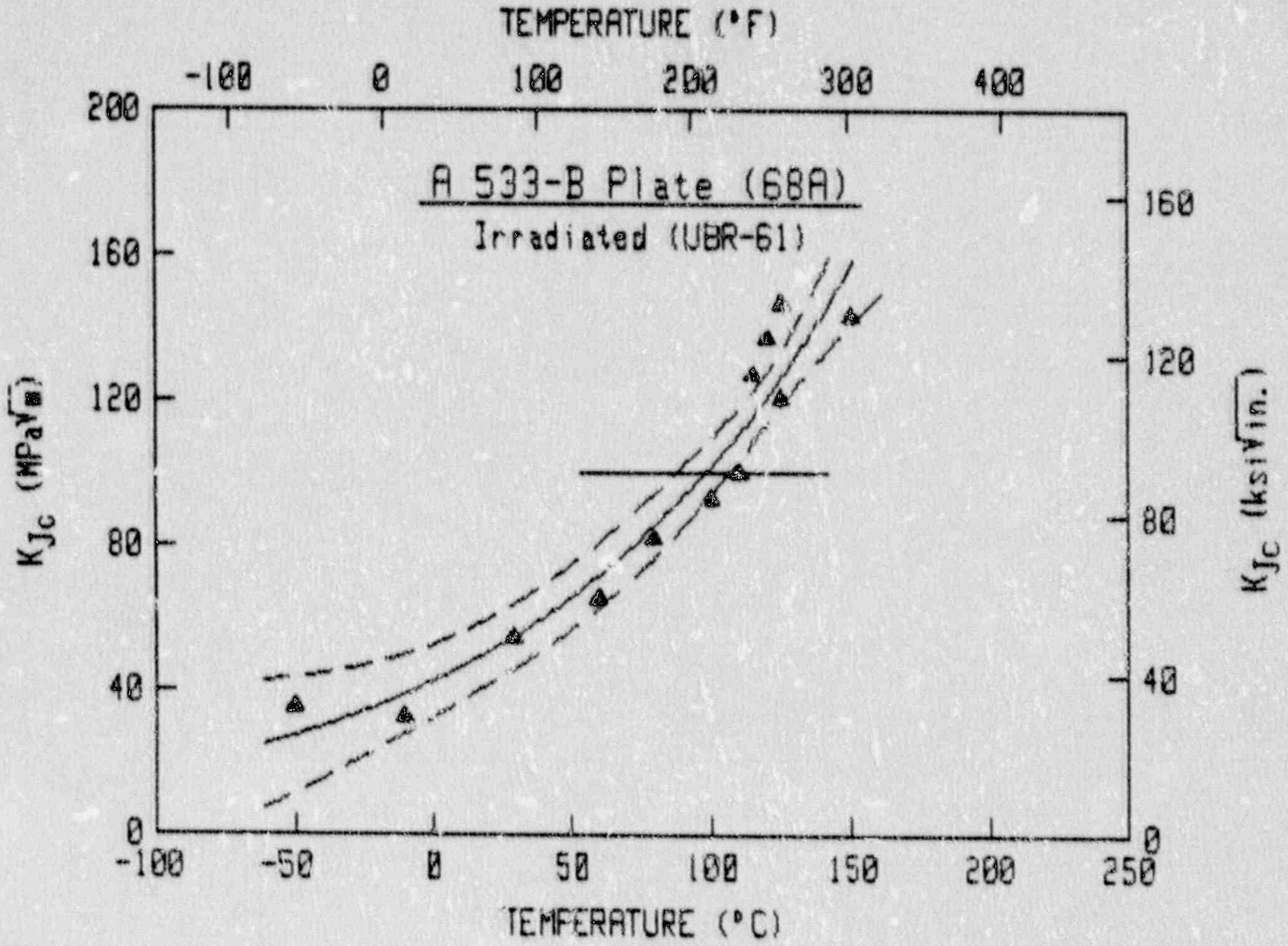
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	49.67 MPa√m	45.20 ksi√in
B =	131.48 MPa√m	119.65 ksi√in
C =	39.80°C	71.64°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-60°C	-76°F
Mean Curve =	-38°C	-37°F
Lower Bound =	-23°C	-9°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-140	39.4	8	-20	124.2
2	-100	59.6	9	-15	146.3
3	-70	85.6	10	-10	118.3
4	-50	91.3	11	0	216.2
5	-40	112.2	12	10	134.6
6	-35	73.0	13	12	276.2
7	-30	146.7	14	22	289.7

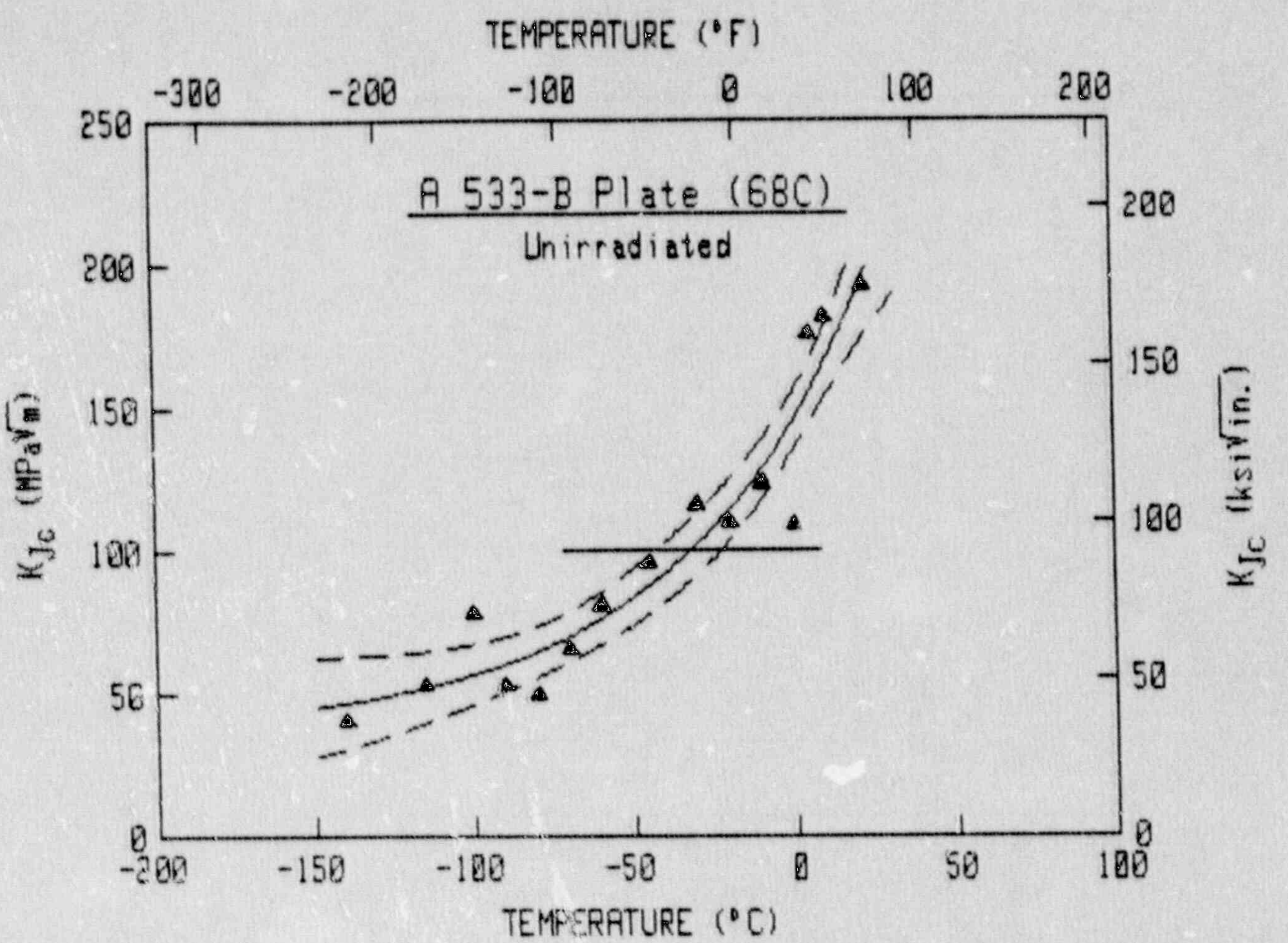


$$Kjc = A + B \exp [(T-To)/C)]$$

		Metric	English
A	=	-.11 MPa√m	-.10 ksi√in
B	=	42.46 MPa√m	38.64 ksi√in
C	=	114.45°C	206.01°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	88°C	190°F
Mean Curve =	98°C	209°F
Lower Bound =	107°C	225°F

Pt #	Temperature	Kjc
1	-50	35.2
2	-10	32.6
3	29	54.6
4	60	65.4
5	80	81.6
6	100	92.9
7	110	100.1
8	115	127.2
9	120	137.1
10	125	146.7
11	125	120.7
12	150	143.3



****

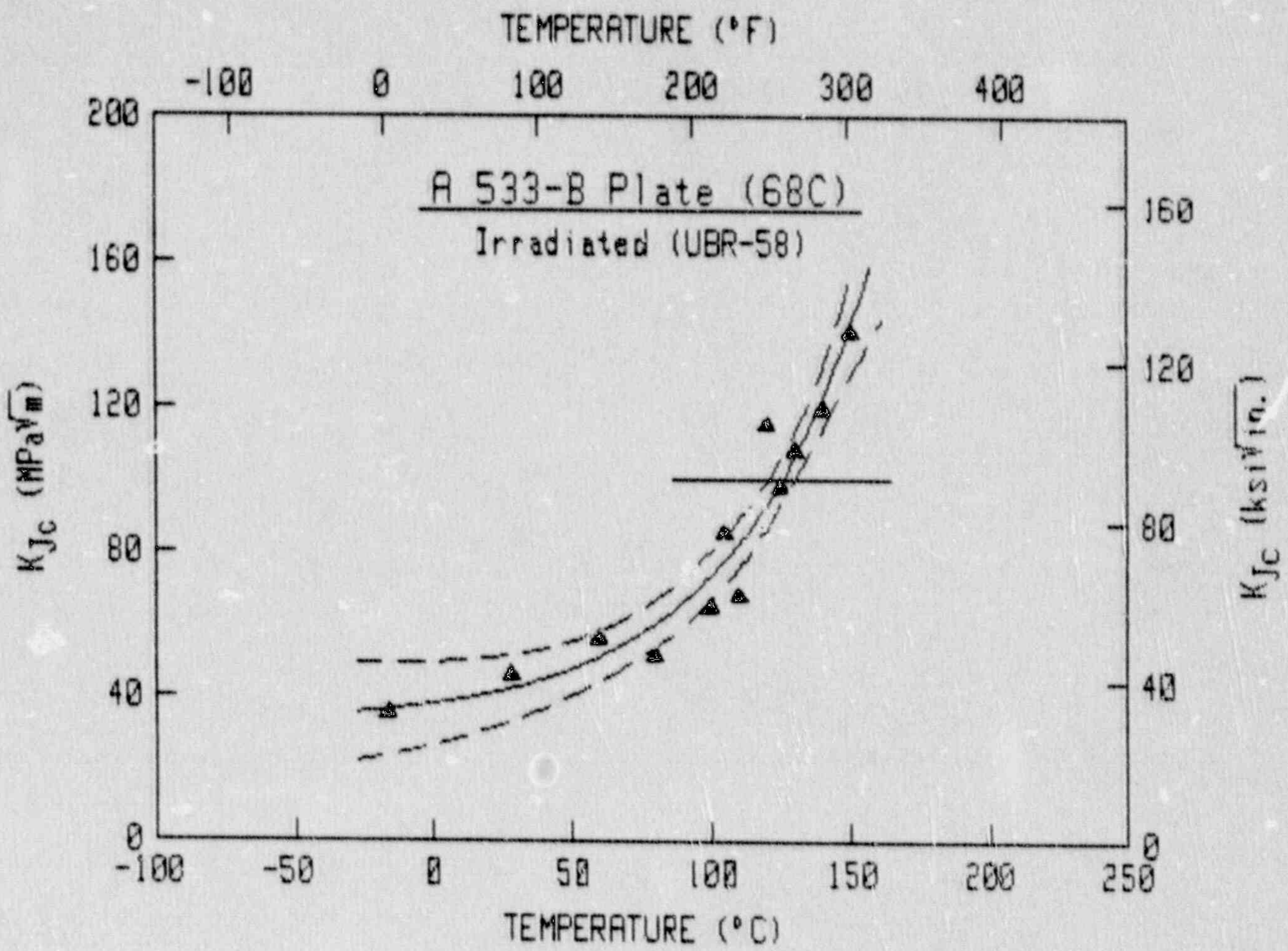
$$K_{jc} = A + B \exp[(T-T_o)/C]$$

		Metric	English
A	=	36.77 MPa√m	33.47 ksi√in
B	=	109.24 MPa√m	99.41 ksi√in
C	=	58.51°C	105.31°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-42°C	-44°F
Mean Curve =	-32°C	-26°F
Lower Bound =	-22°C	-8°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-140	40.4	9	-30	116.0
2	-115	52.9	10	-20	109.6
3	-100	77.8	11	-10	123.6
4	-90	53.0	12	0	108.9
5	-80	49.5	13	5	175.5
6	-70	65.5	14	10	181.3
7	-60	80.0	15	22	192.7
8	-45	95.3			

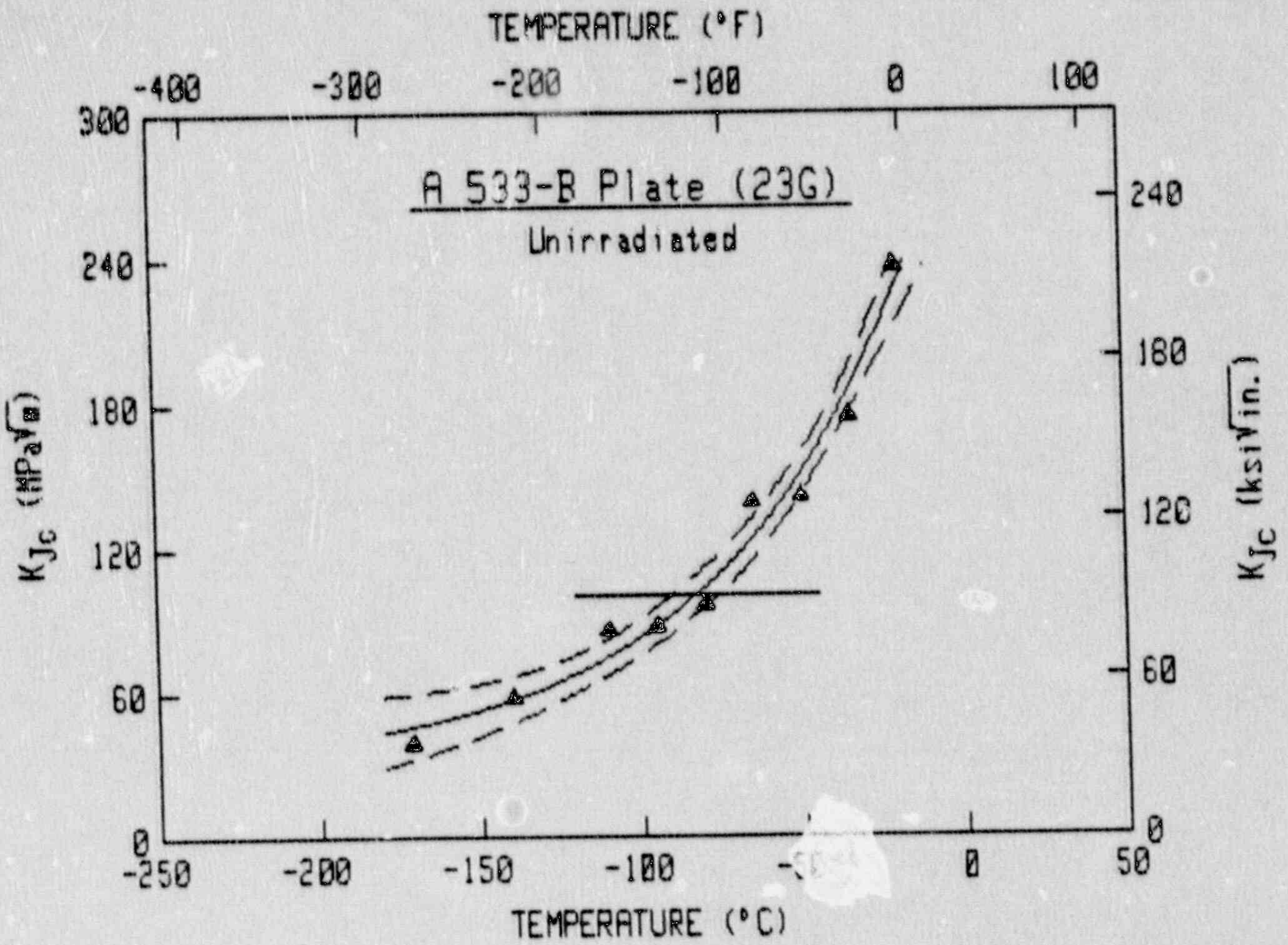


$$K_{jc} = A + B \exp[(T-T_o)/C)]$$

		Metric	English
A	=	32.12 MPa√m	29.23 ksi√in
B	=	5.76 MPa√m	5.24 ksi√in
C	=	50.81°C	91.45°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	121°C	250°F
Mean Curve =	125°C	258°F
Lower Bound =	130°C	266°F

Pt #	Temperature	Kjc
1	-15	35.2
2	28	45.9
3	60	55.9
4	80	51.1
5	100	64.7
6	105	85.1
7	110	67.7
8	120	115.0
9	125	97.9
10	130	108.2
11	140	119.4
12	150	140.8

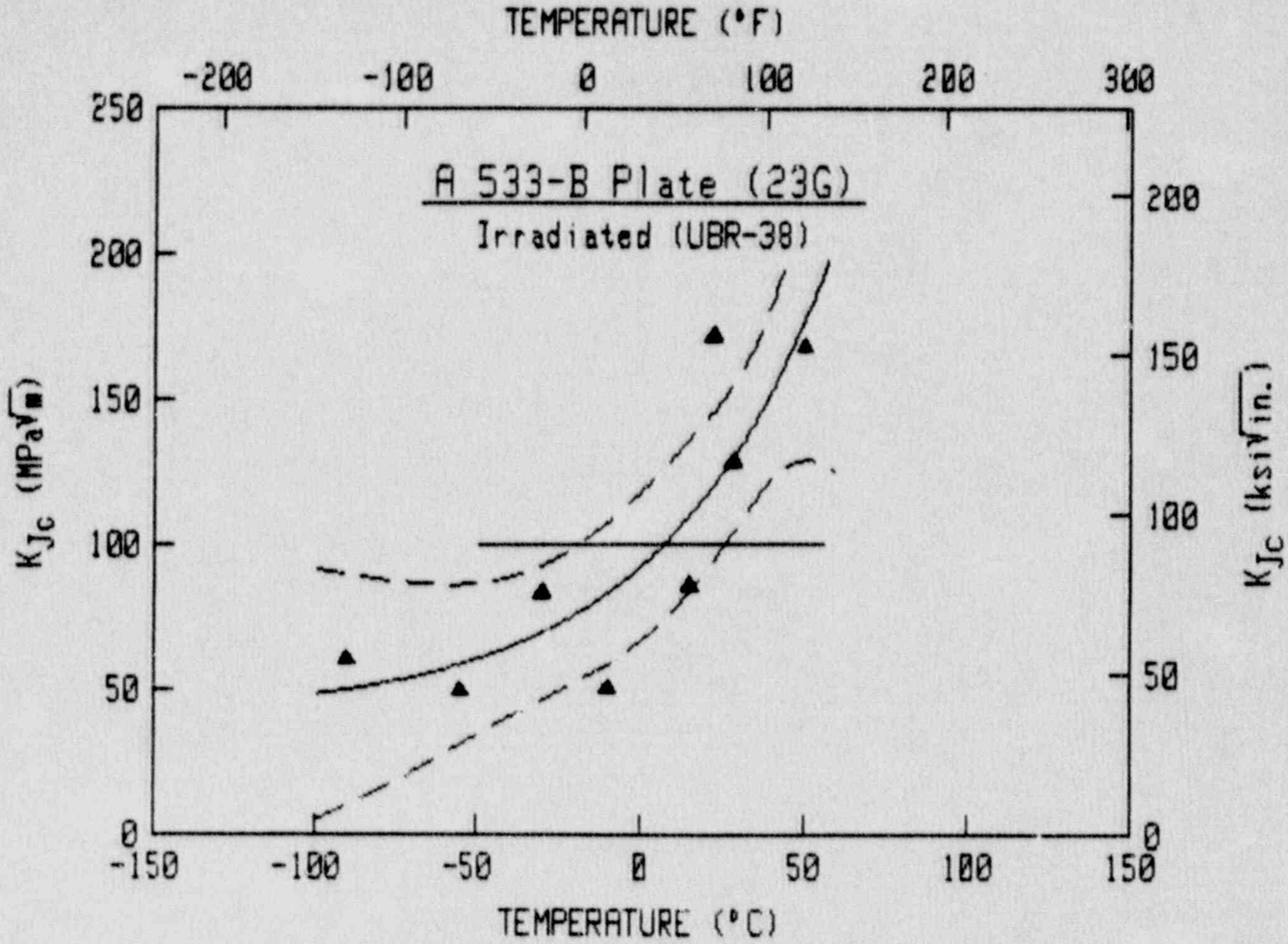


$$K_{jc} = A + B \exp[(T-T_o)/C]$$

		Metric	English
A	=	29.21 MPa√m	26.59 ksi√in
B	=	276.59 MPa√m	251.71 ksi√in
C	=	60.83°C	109.49°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-90°C	-130°F
Mean Curve =	-83°C	-117°F
Lower Bound =	-75°C	-103°F

Pt #	Temperature	Kjc
1	-171	39.0
2	-140	58.0
3	-110	85.7
4	-95	87.2
5	-80	96.0
6	-65	138.5
7	-50	141.1
8	-35	174.4
9	-20	236.2



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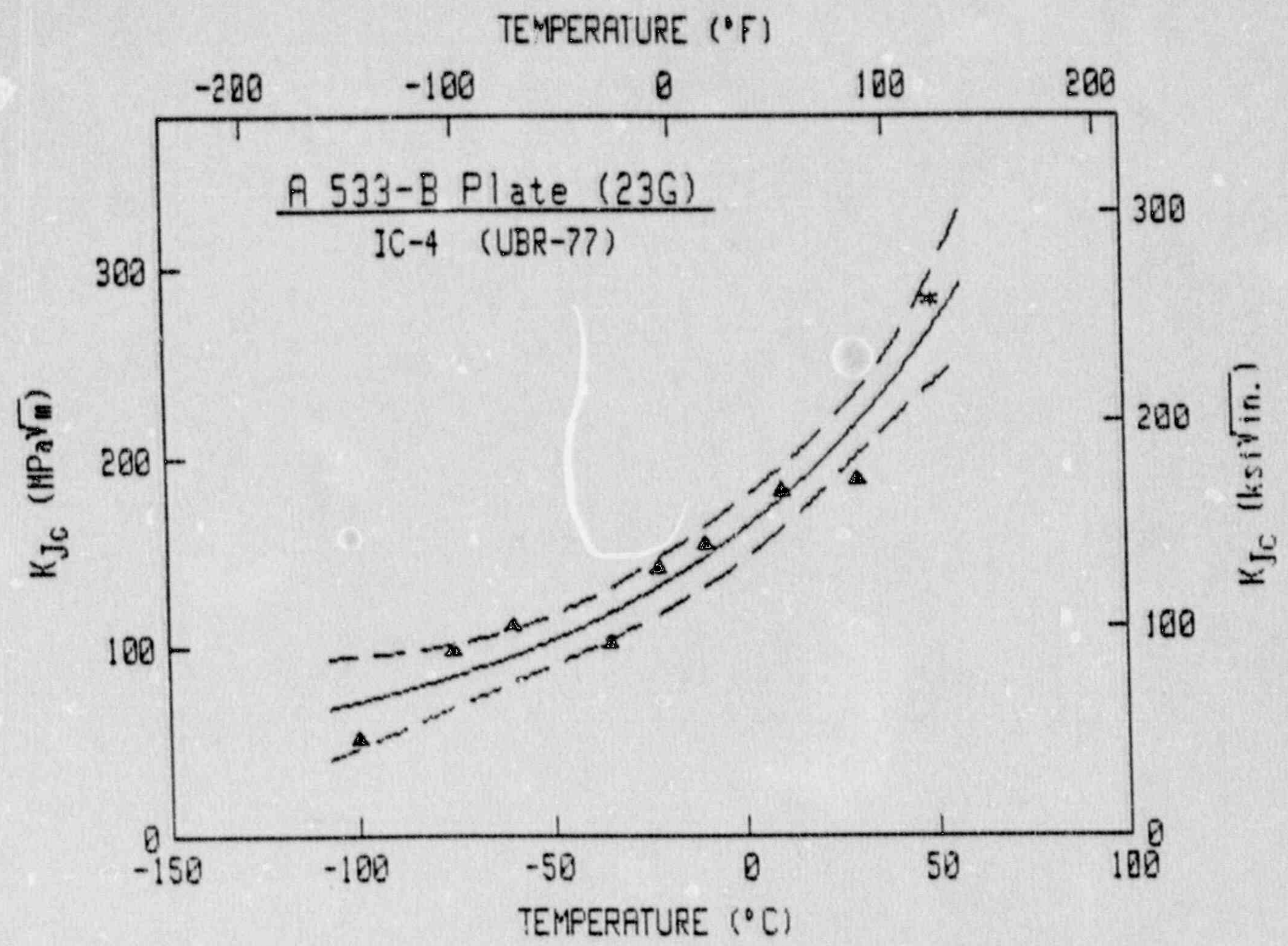
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	41.25 MPa√m	37.54 ksi√in
B =	51.03 MPa√m	46.44 ksi√in
C =	50.92°C	91.65°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-19°C	-2°F
Mean Curve =	7°C	45°F
Lower Bound =	26°C	79°F

****

Pt #	Temperature	Kjc
1	-90	60.5
2	-55	49.7
3	-30	83.4
4	-10	50.3
5	15	85.9
6	22	171.9
7	28	128.4
8	50	168.0



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$$Kjc = A + B \exp[(T-To)/C)]$$

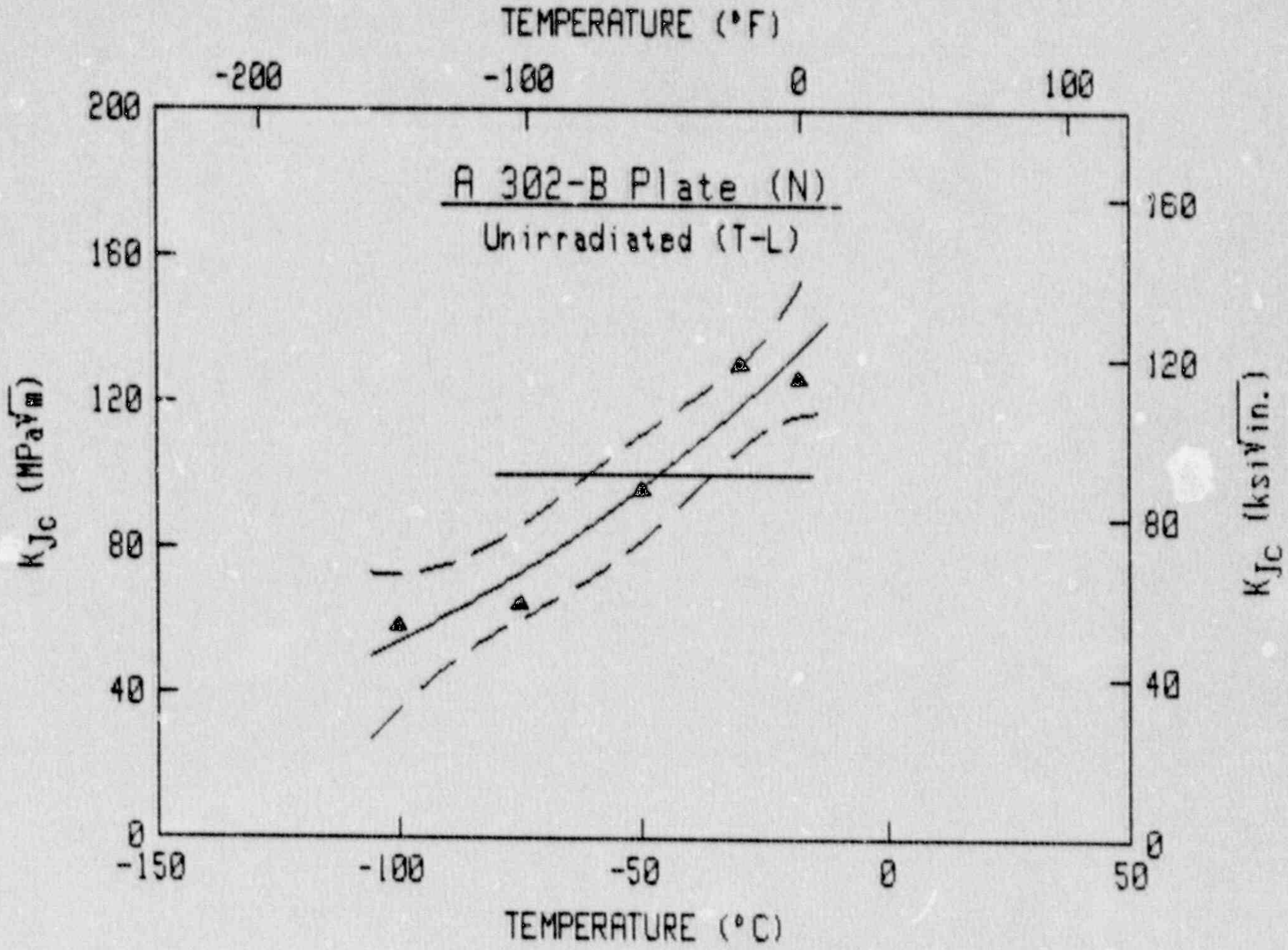
		Metric	English
A	=	30.60 MPa$\sqrt{m}$	27.85 ksi$\sqrt{in}$
B	=	131.34 MPa$\sqrt{m}$	119.53 ksi$\sqrt{in}$
C	=	84.53°C	152.16°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa$\sqrt{m}$	
Upper Bound =	-78°C	-108°F
Mean Curve =	-54°C	-65°F
Lower Bound =	-36°C	-36°F

****

Pt #	Temperature	Kjc
1	-100	51.5
2	-75	98.1
[illegible]	-60	110.9
4	-35	101.9
5	-22	141.2
[illegible]	-10	153.9
[illegible]	10	182.8
8	30	188.2
9 *	50	283.0

* = Upper Shelf Data Point



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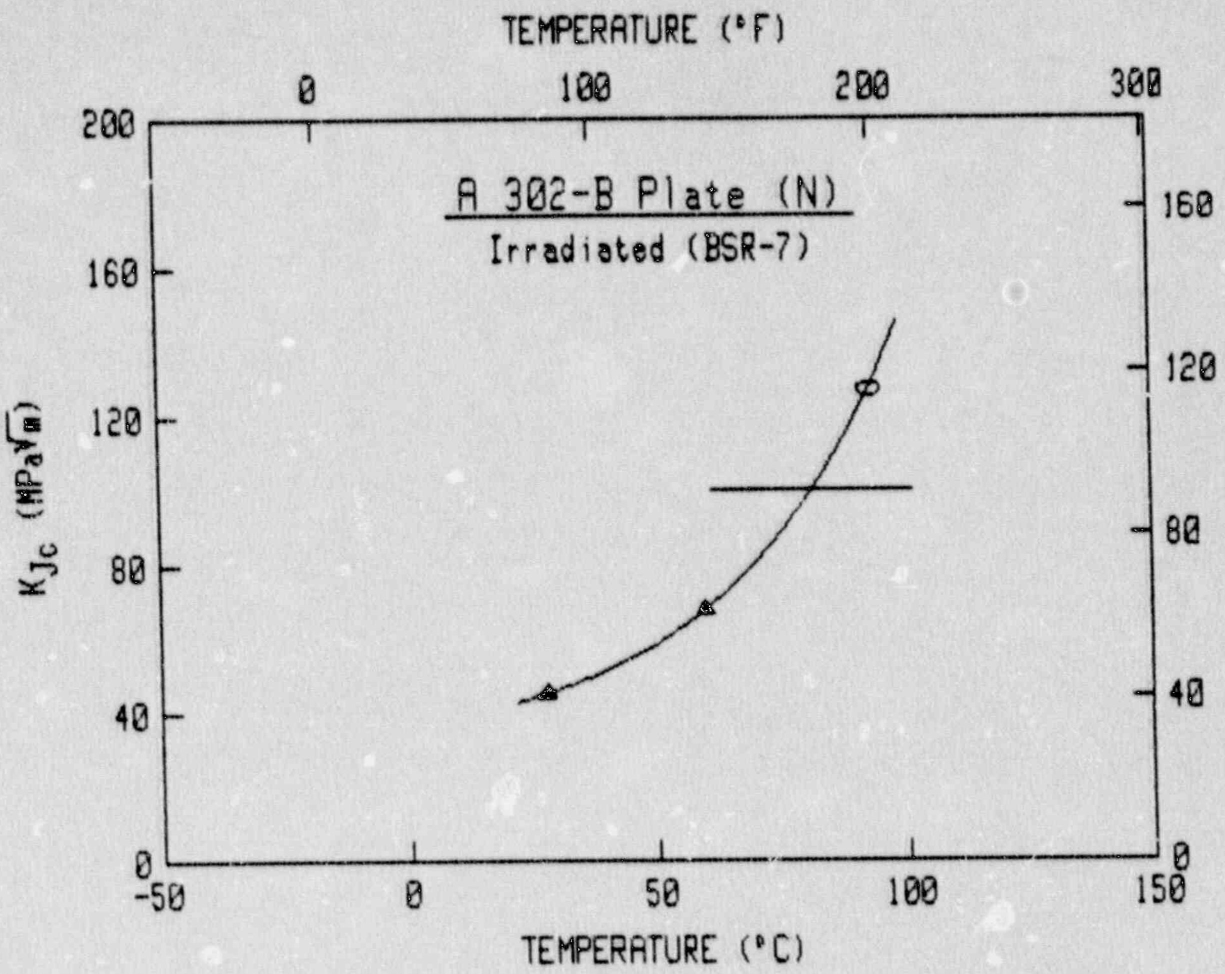
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-26.32 MPa√m	-23.95 ksi√in
B =	186.58 MPa√m	169.80 ksi√in
C =	118.79°C	213.83°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-60°C	-76°F
Mean Curve =	-46°C	-51°F
Lower Bound =	-35°C	-31°F

****

Pt #	Temperature	Kjc
1	-100	58.5
2	-75	64.4
3	-50	95.7
4	-30	130.6
5	-18	126.6



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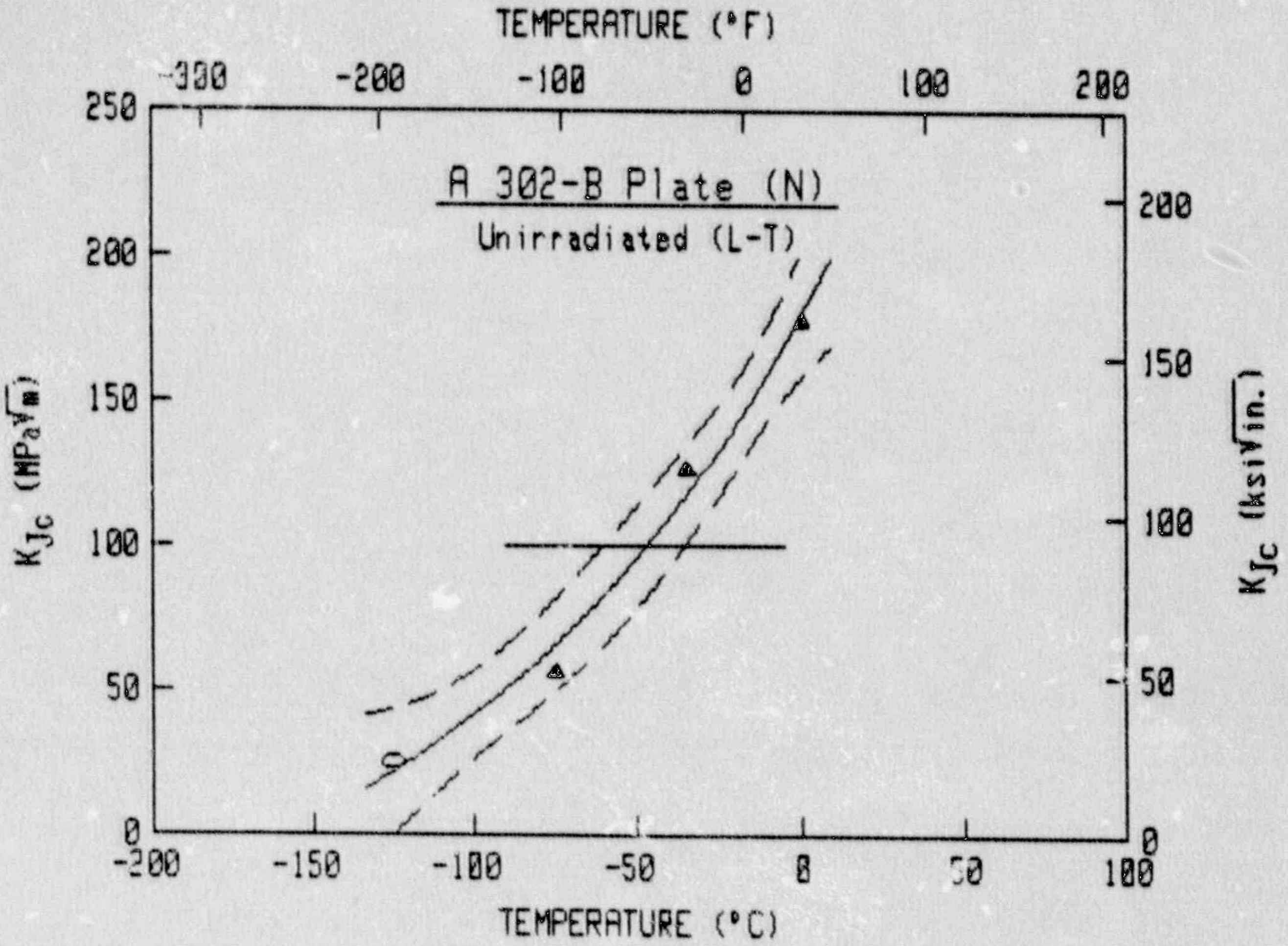
$$K_{jc} = A + B \exp[(T - T_o)/C]$$

	Metric	English
A =	30.63 MPa√m	27.87 ksi√in
B =	6.45 MPa√m	5.87 ksi√in
C =	34.37°C	61.87°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Mean Curve =	82°C	179°F

****

Pt #	Temperature	Kjc
1	28	45.2
2	60	67.6
3 O	93	127.2



****

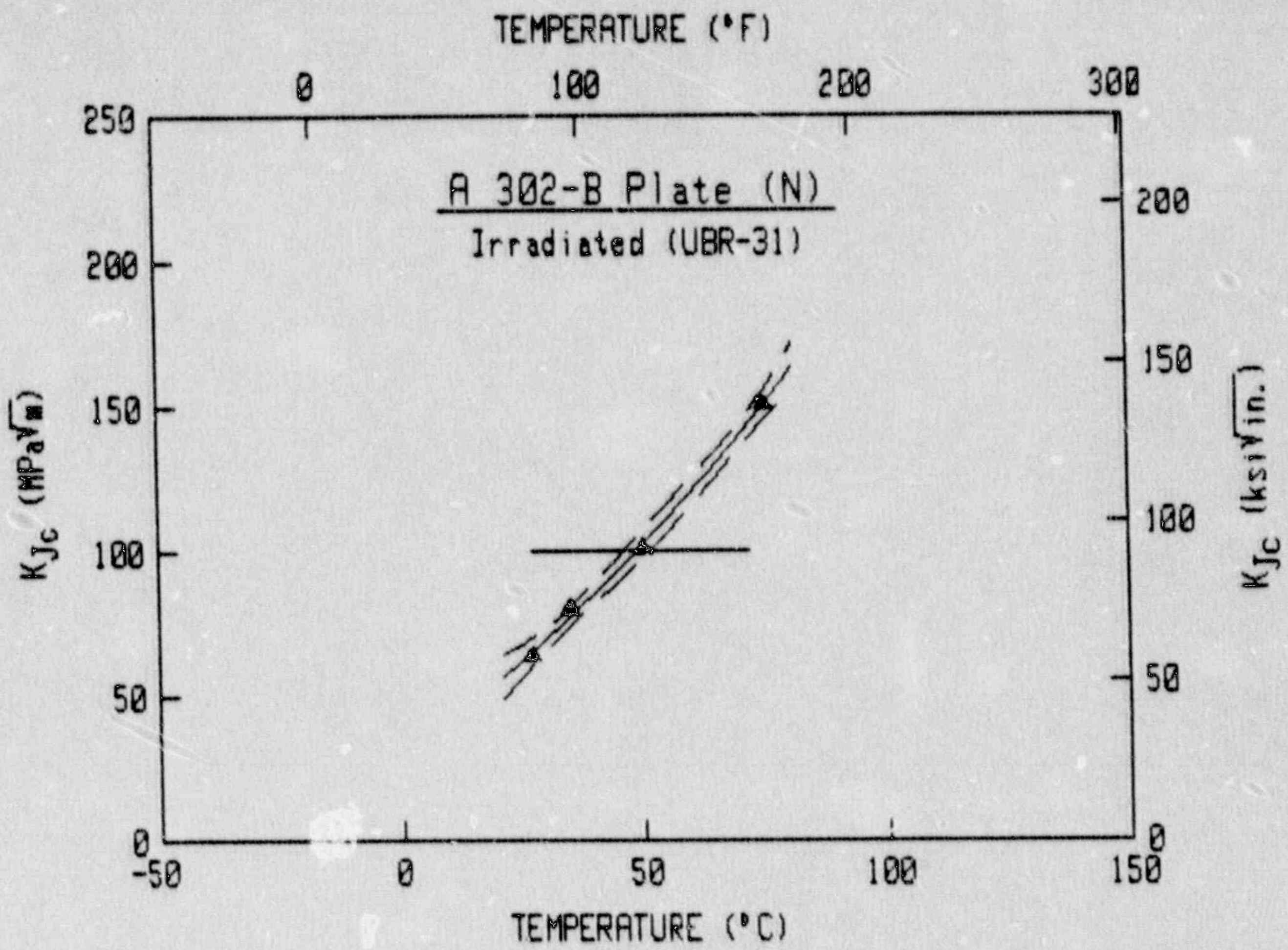
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-59.99 MPa√m	-54.59 ksi√in
B =	240.24 MPa√m	218.63 ksi√in
C =	115.90°C	208.62°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-60°C	-76°F
Mean Curve =	-47°C	-53°F
Lower Bound =	-35°C	-31°F

****

Pt #	Temperature	Kjc
1	-75	56.4
2	-35	126.5
3	0	177.5
4 O	-125	25.0

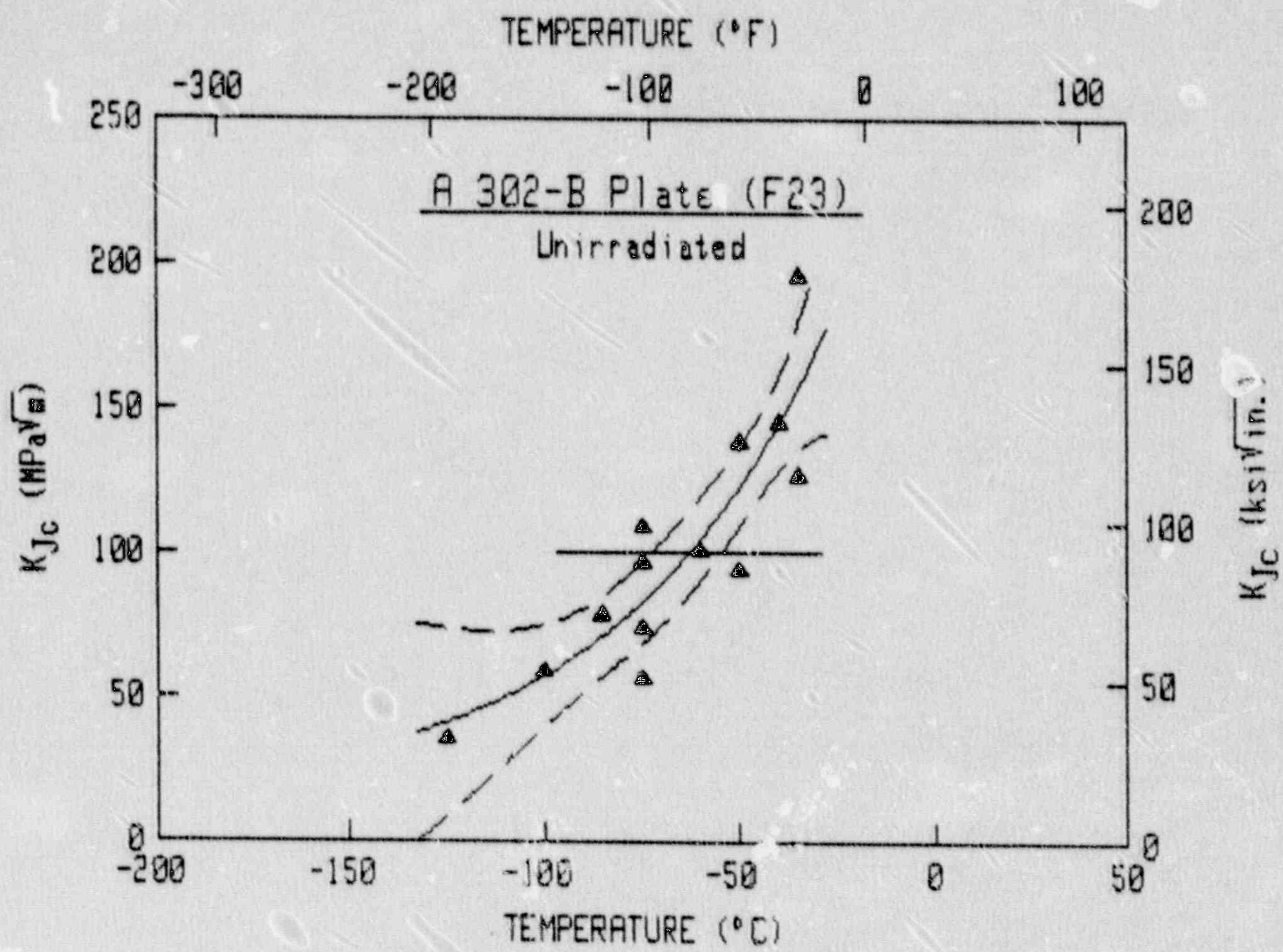


$$K_{jc} = A + B \exp [(T - T_o)/C]$$

	Metric	English
A =	-128.70 MPa√m	-117.12 ksi√in
B =	158.10 MPa√m	143.88 ksi√in
C =	132.14°C	237.84°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	47°C	117°F
Mean Curve =	49°C	120°F
Lower Bound =	52°C	126°F

Pt #	Temperature	Kjc
1	27	63.8
2	35	79.9
3	50	100.8
4	75	150.4



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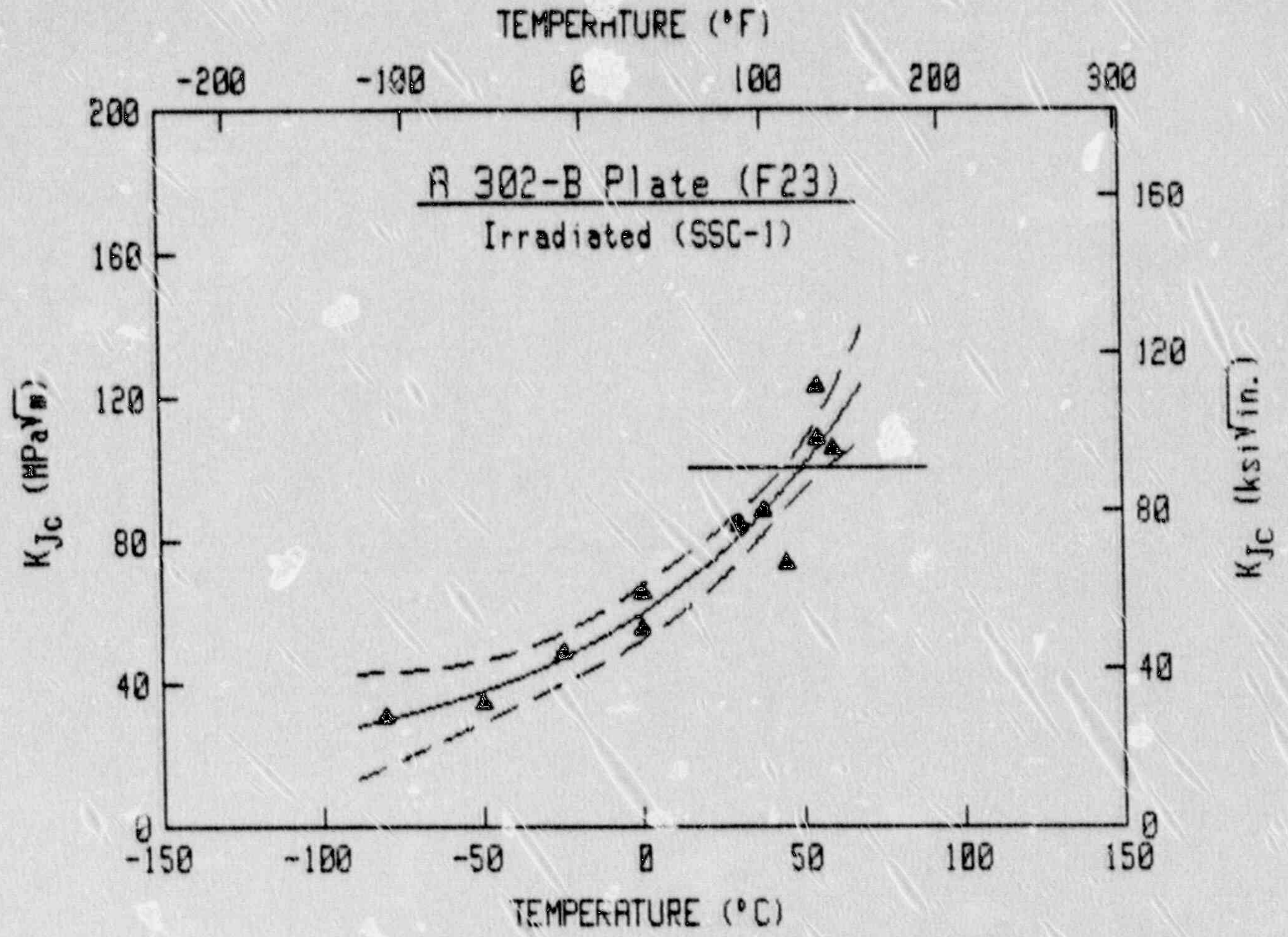
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	13.82 MPa√m	[illegible]2.50 [illegible]
B	=	275.26 MPa√m	250.50 [illegible]
C	=	54.00°C	97.20°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-72°C	-98°F
Mean Curve	=	-63°C	-81°F
Lower Bound	=	-54°C	-65°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-125	35.5	8	-60	101.0
2	-100	58.9	9	-50	138.4
3	-85	78.3	10	-50	93.9
4	-75	96.9	11	-40	145.0
5	-75	73.7	12	-35	196.0
6	-75	56.4	13	-35	126.6
7	-75	109.0			



****

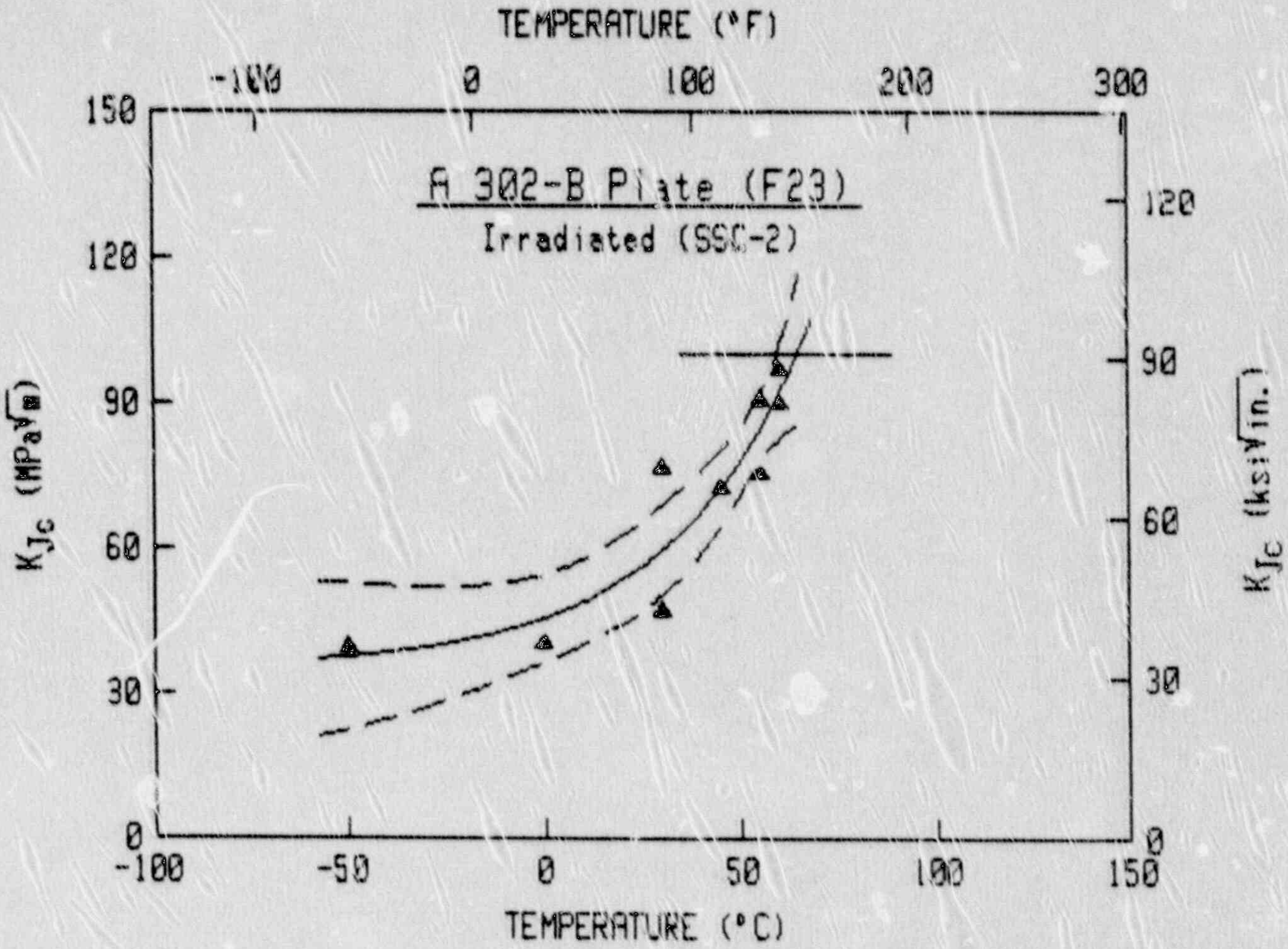
$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	12.42 MPa√m	11.31 ksi√in
B =	47.12 MPa√m	42.88 ksi√in
C =	80.67°C	145.21°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	45°C	113°F
Mean Curve =	50°C	122°F
Lower Bound =	59°C	138°F

****

Pt #	Temperature	Kjc
1	-80	30.8
2	-50	34.5
3	-25	48.6
4	0	65.2
5	0	53.4
6	30	83.9
7	30	85.2
8	[illegible]	87.9
9	[illegible]	73.2
10	55	122.6
11	55	108.0
12	60	105.4



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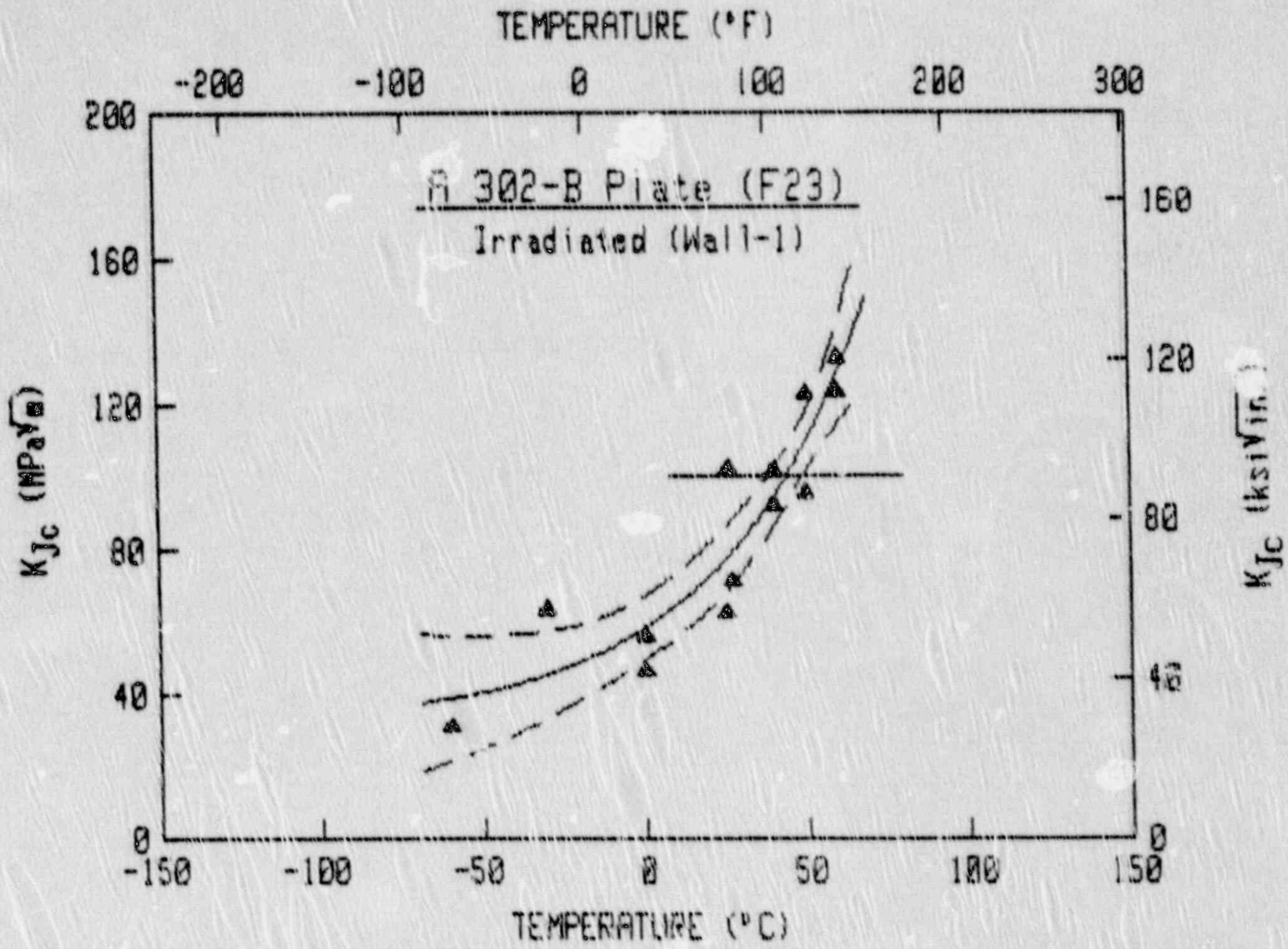
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	35.09 MPa√m	31.94 ksi√in
B =	10.28 MPa√m	9.35 ksi√in
C =	34.92°C	62.85°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	60°C	140°F
Mean Curve =	64°C	148°F

****

Pt #	Temperature	Kjc
1	-50	38.5
2	0	40.3
3	30	76.6
4	30	47.0
5	45	72.2
6	55	90.7
7	55	75.4
8	60	96.8
9	60	89.8



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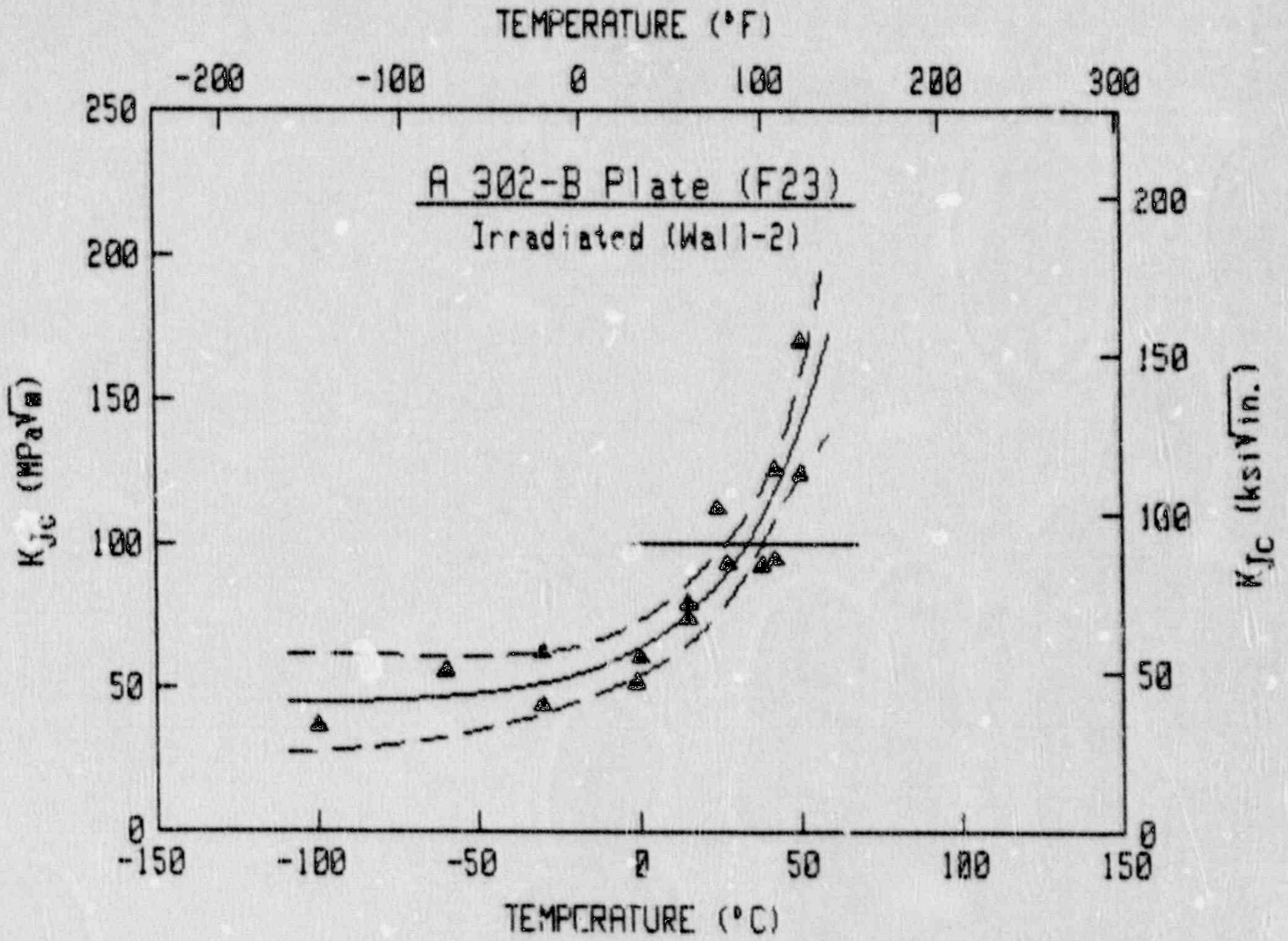
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	31.44 MPa√m	28.62 ksi√in
B	=	26.62 MPa√m	24.22 ksi√in
C	=	46.36°C	83.46°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	38°C	100°F
Mean Curve =	44°C	111°F
Lower Bound =	50°C	122°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-60	31.1	8	40	101.6
2	-30	63.2	9	40	91.7
3	0	46.2	10	50	95.5
4	0	56.0	11	50	122.8
5	25	62.4	12	60	123.4
6	26	102.2	13	60	132.9
7	27	71.0			



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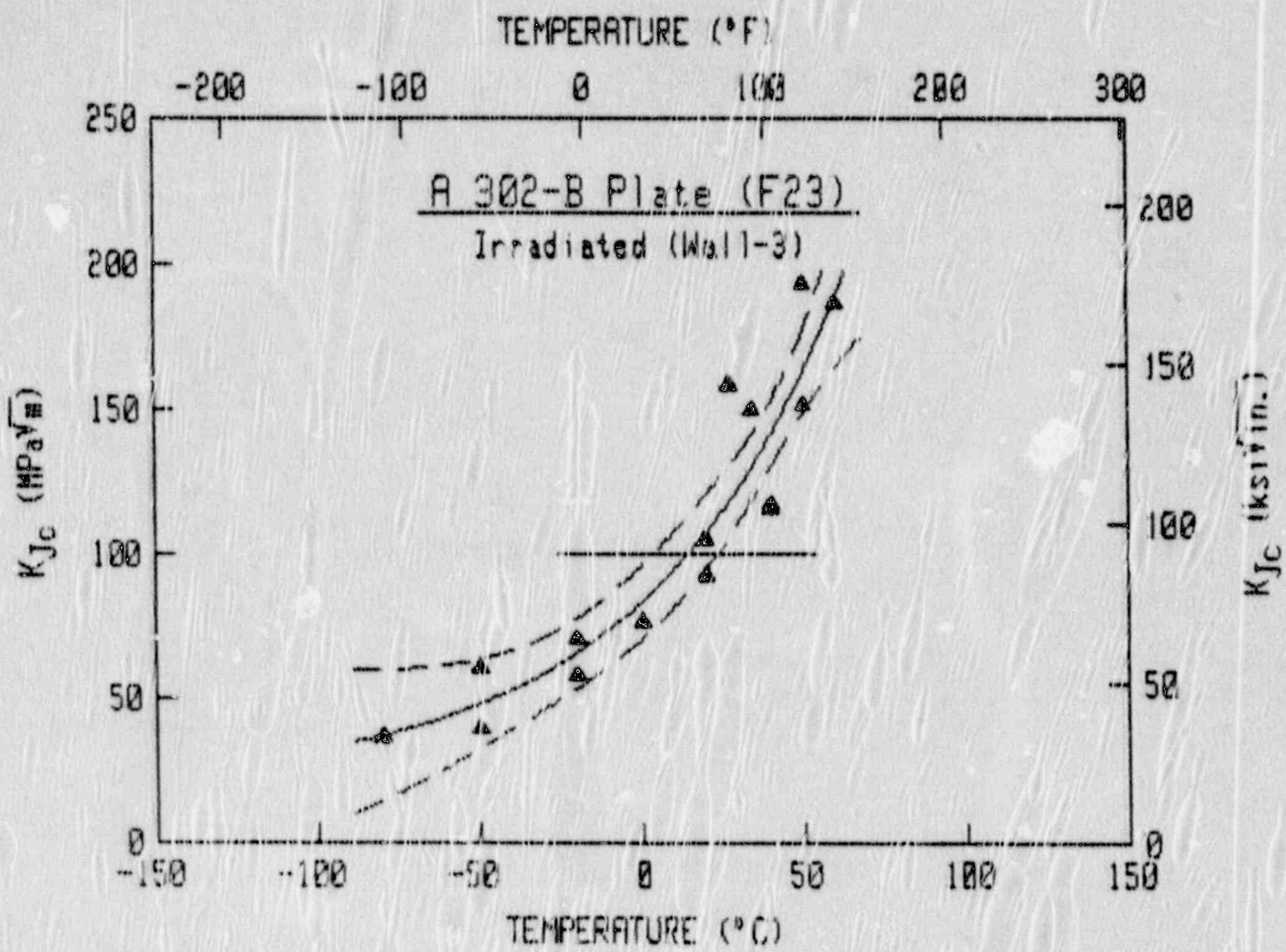
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	43.92 MPa√m	39.97 ksi√in
B	=	19.64 MPa√m	17.87 ksi√in
C	=	31.42°C	56.55°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	27°C	81°F
Mean Curve =	33°C	91°F
Lower Bound =	33°C	103°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-100	36.7	9	24	112.2
2	-60	55.7	10	27	92.9
3	-30	62.1	11	38	92.6
4	-30	43.6	12	42	125.9
5	-1	51.5	13	42	94.8
6	0	60.3	14	50	170.1
7	15	79.4	15	50	124.2
8	15	74.3			



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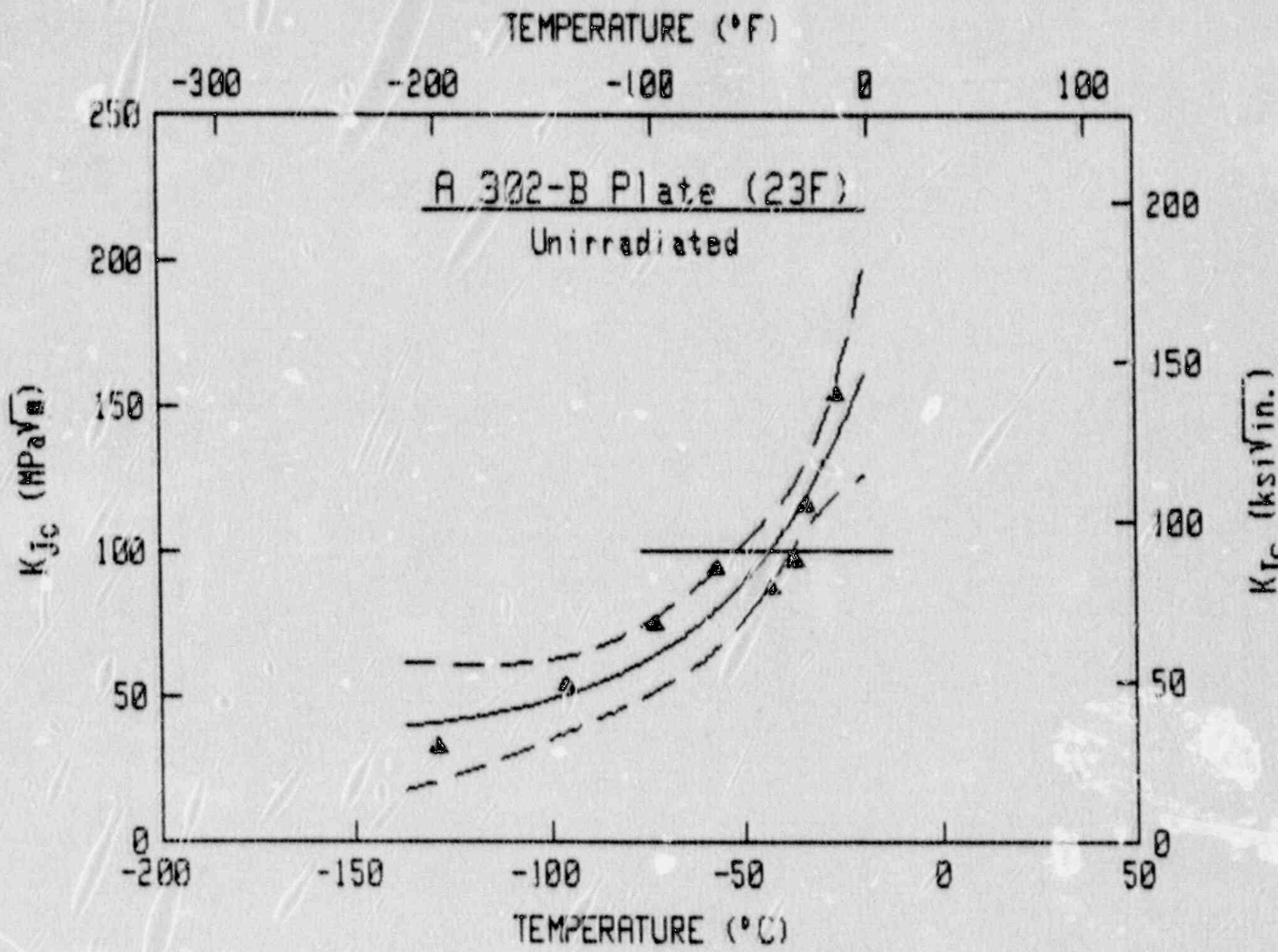
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	20.17 MPa√m	18.36 ksi√in
B =	63.19 MPa√m	57.51 ksi√in
C =	61.10°C	109.98°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	4°C	39°F
Mean Curve =	14°C	58°F
Lower Bound =	24°C	75°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-80	36.5	9	27	158.6
2	-50	60.8	10	34	149.7
3	-50	39.7	11	40	117.2
4	-20	58.0	12	40	115.8
5	-20	70.5	13	50	193.2
6	0	76.9	14	50	151.2
7	20	104.8	15	60	186.5
8	20	92.6			



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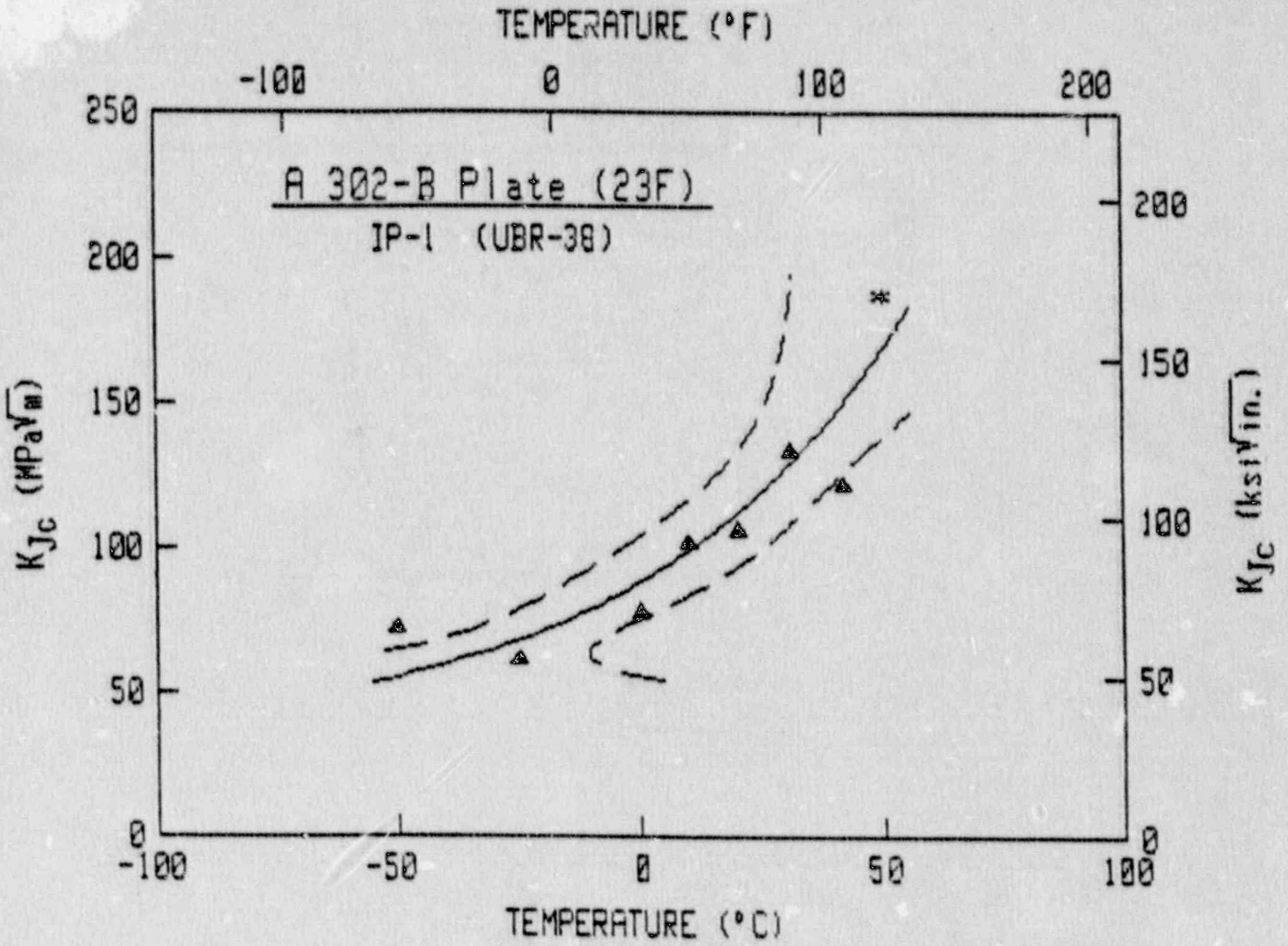
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	34.31 MPa√m	31.23 ksi√in
B	=	211.21 MPa√m	192.21 ksi√in
C	=	37.31°C	67.16°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-51°C	-60°F
Mean Curve =	-44°C	-46°F
Lower Bound =	-37°C	-35°F

****

Pt #	Temperature	Kjc
1	-129	32.4
2	-96	53.6
3	-73	74.5
4	-57	93.9
5	-43	87.1
6	-37	96.6
7	-34	116.1
8	-26	154.0



****

Kjc = A + B exp [(T-To)/C)]

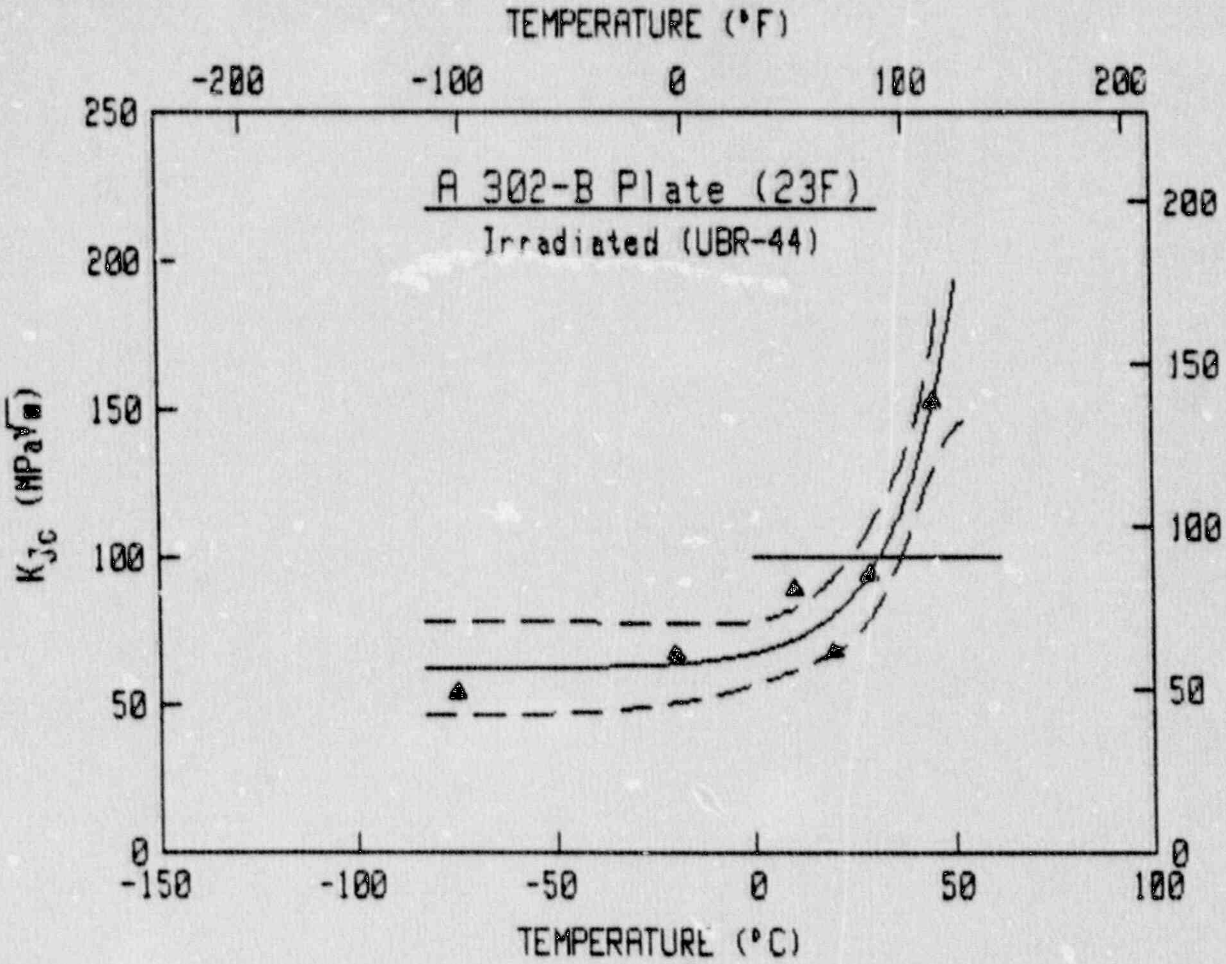
	Metric	English
A =	33.34 MPa√m	30.34 ksi√in
B =	54.49 MPa√m	49.59 ksi√in
C =	55.01°C	99.02°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-3°C	26°F
Mean Curve =	11°C	52°F
Lower Bound =	25°C	78°F

****

Pt #	Temperature	Kjc
1	-50	72.2
2	-25	61.4
3	0	77.4
4	10	101.4
5	20	105.8
6	31	133.3
7	42	121.6
8 *	50	186.9

* = Upper Shelf Data Point

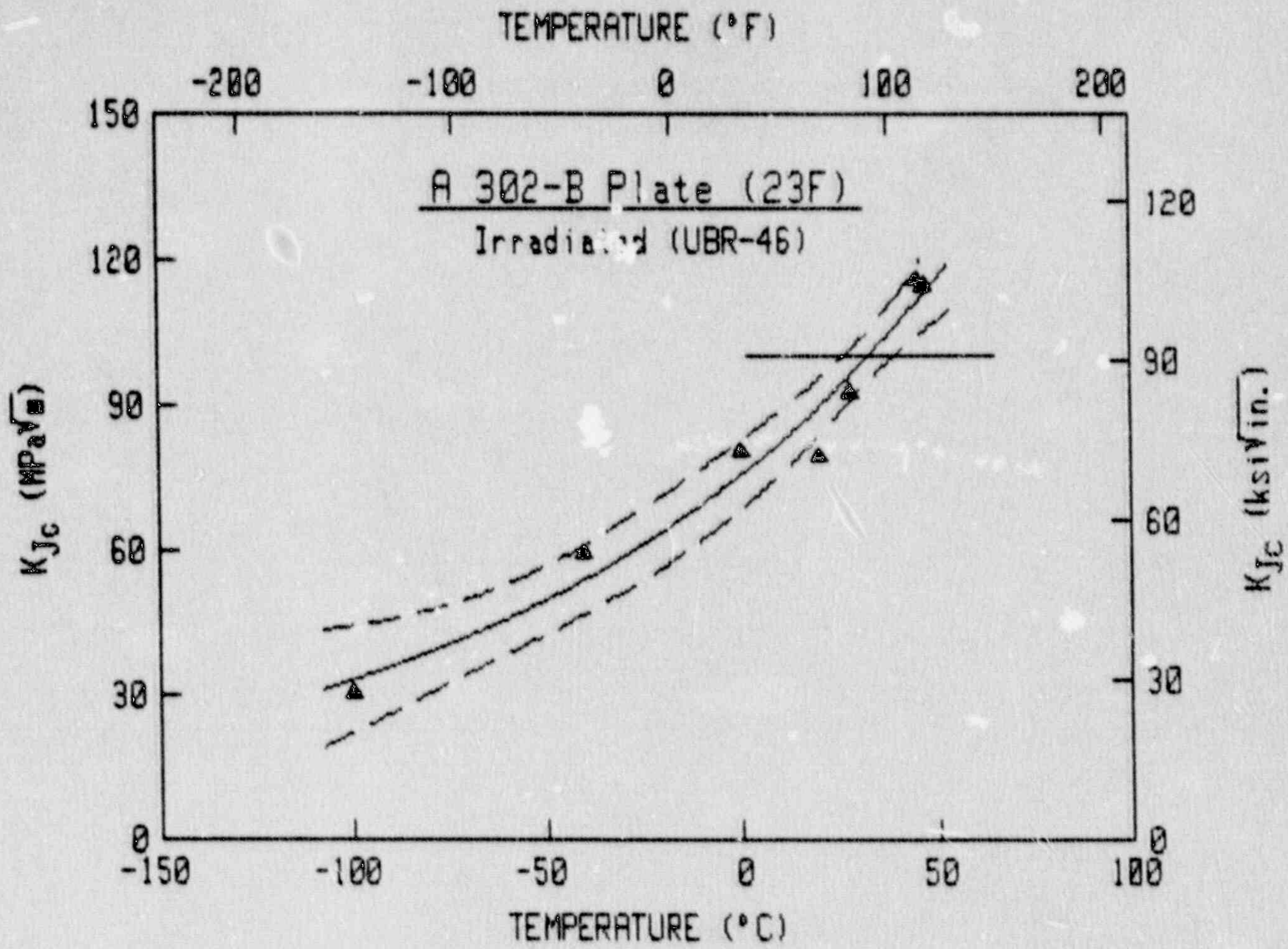


$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	62.37 MPa√m	56.76 ksi√in
B =	5.06 MPa√m	4.61 ksi√in
C =	15.66°C	28.19°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	25°C	77°F
Mean Curve =	31°C	89°F
Lower Bound =	37°C	99°F

Pt #	Temperature	Kjc
1	-73	54.3
2	-20	67.1
3	10	89.0
4	20	68.0
5	29	94.0
6	45	152.8



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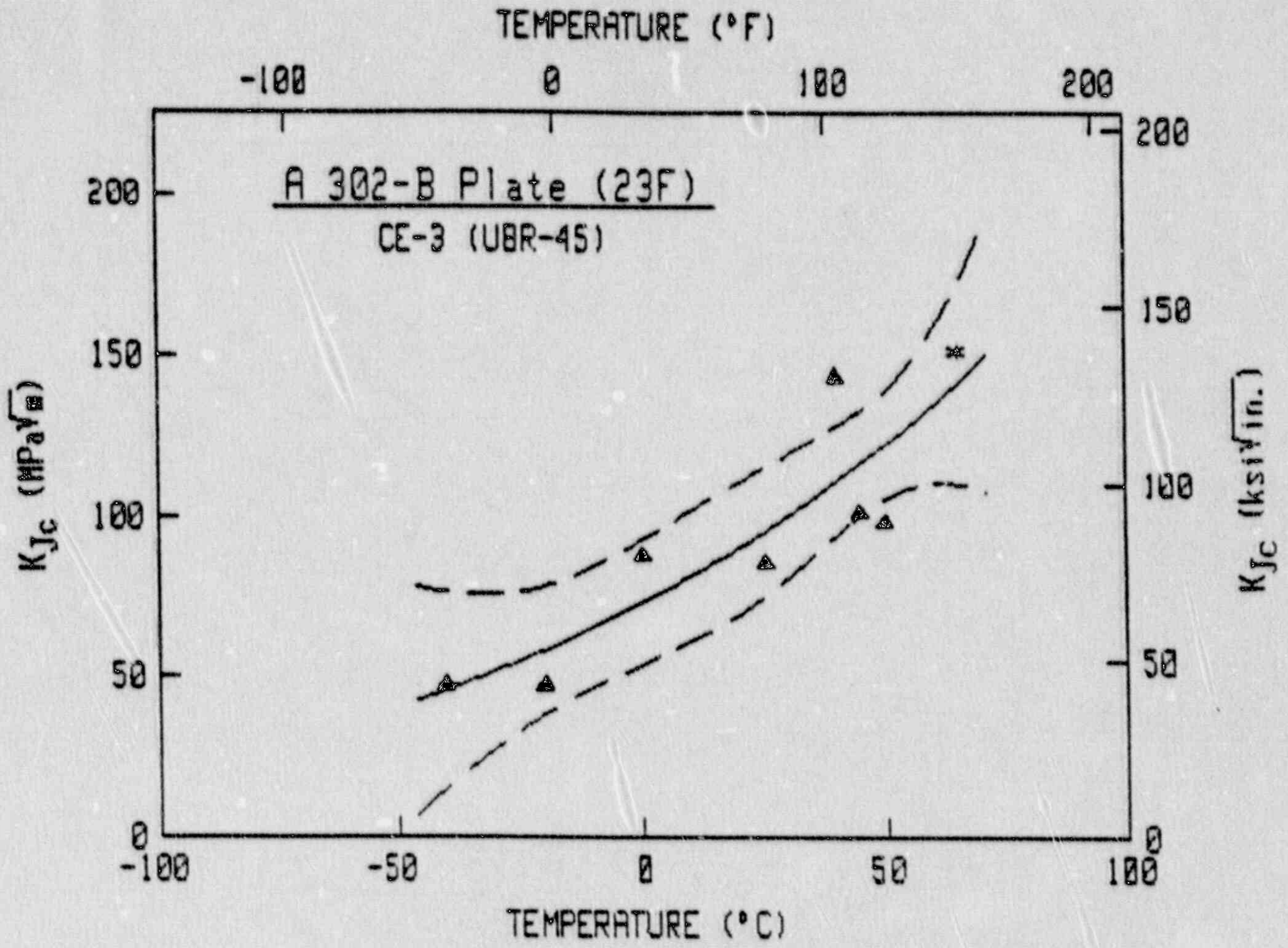
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	4.90 MPa√m	4.46 ksi√in
B =	70.51 MPa√m	64.17 ksi√in
C =	109.48°C	197.06°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	27°C	81°F
Mean Curve =	33°C	91°F
Lower Bound =	40°C	104°F

****

Pt #	Temperature	Kjc
1	-100	30.4
2	-40	59.4
3	0	80.2
4	20	79.4
5	28	92.6
6	45	115.9
7	47	114.5



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Kjc = A + B exp [(T-To)/C)]

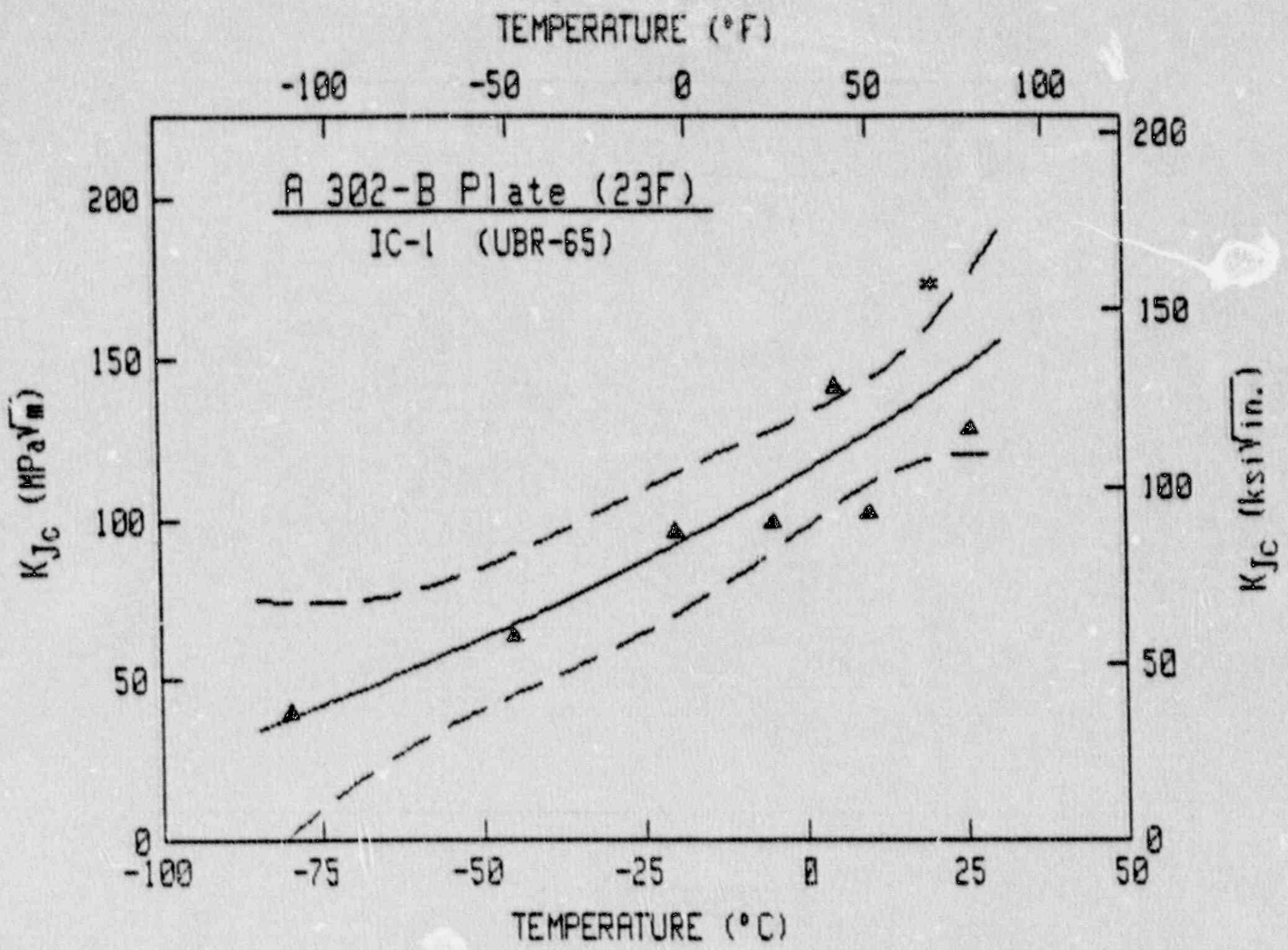
	Metric	English
A =	-21.45 MPa√m	-19.52 ksi√in
B =	94.06 MPa√m	85.60 ksi√in
C =	118.56°C	213.41°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	9°C	48°F
Mean Curve =	30°C	87°F
Lower Bound =	46°C	115°F

****

Pt #	Temperature	Kjc
1	-40	47.3
2	-20	47.2
3	0	87.4
4	25	85.0
5	40	143.5
6	45	100.9
7	50	98.0
8 *	65	151.3

* = Upper Shelf Data Point



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Kjc = A + B exp [(T-To)/C)]

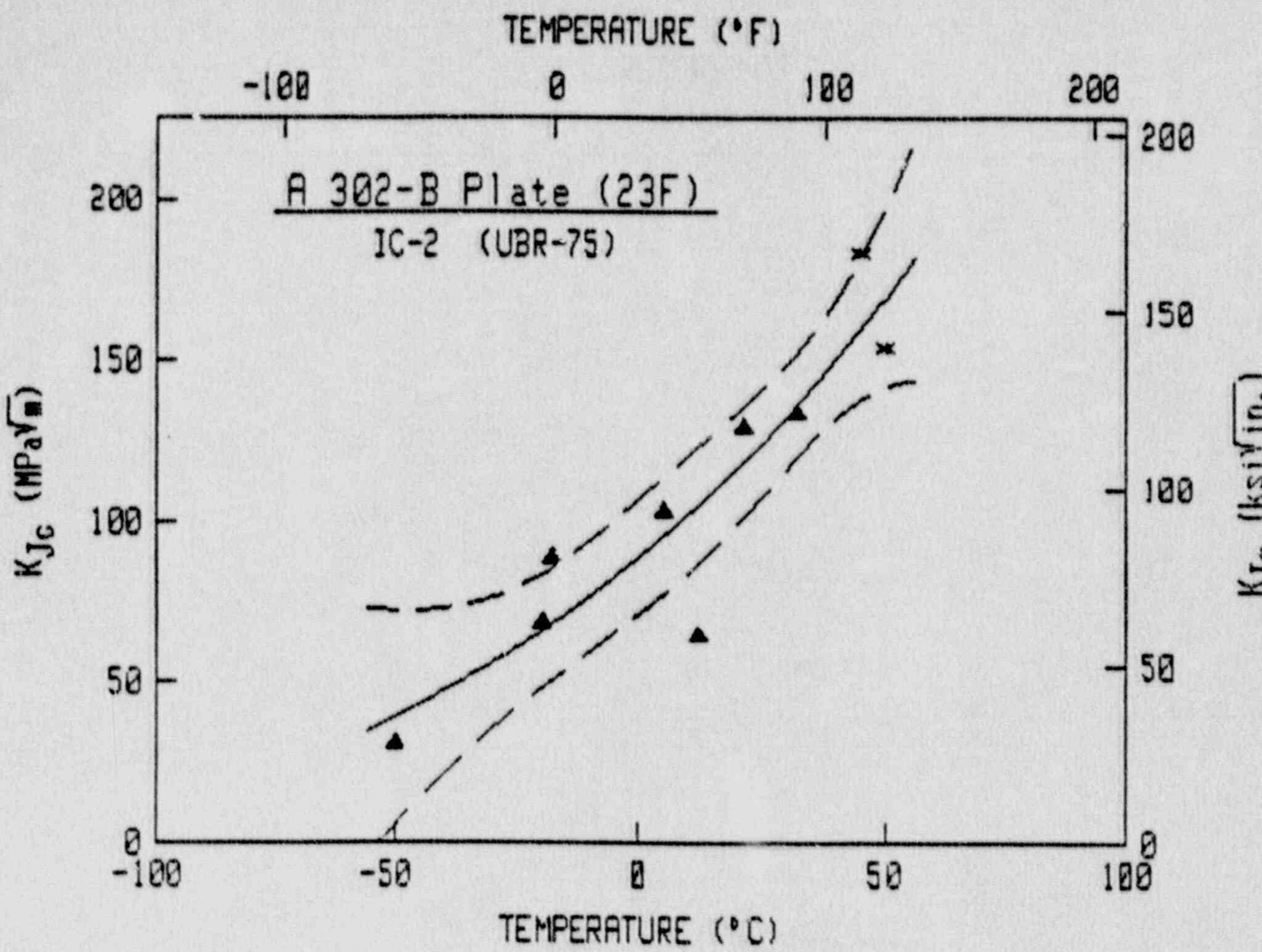
	Metric	English
A =	-94.80 MPa√m	-86.27 ksi√in
B =	209.40 MPa√m	190.56 ksi√in
C =	175.56°C	316.01°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-34°C	-29°F
Mean Curve =	-13°C	9°F
Lower Bound =	2°C	36°F

****

Pt #	Temperature	Kjc
1	-80	39.7
2	-45	63.4
3	-20	95.9
4	-5	98.7
5	5	141.1
6	10	101.7
7	26	127.8
8 *	20	173.1

* = Upper Shelf Data Point



****

Kjc = A + B exp [(T-To)/C)]

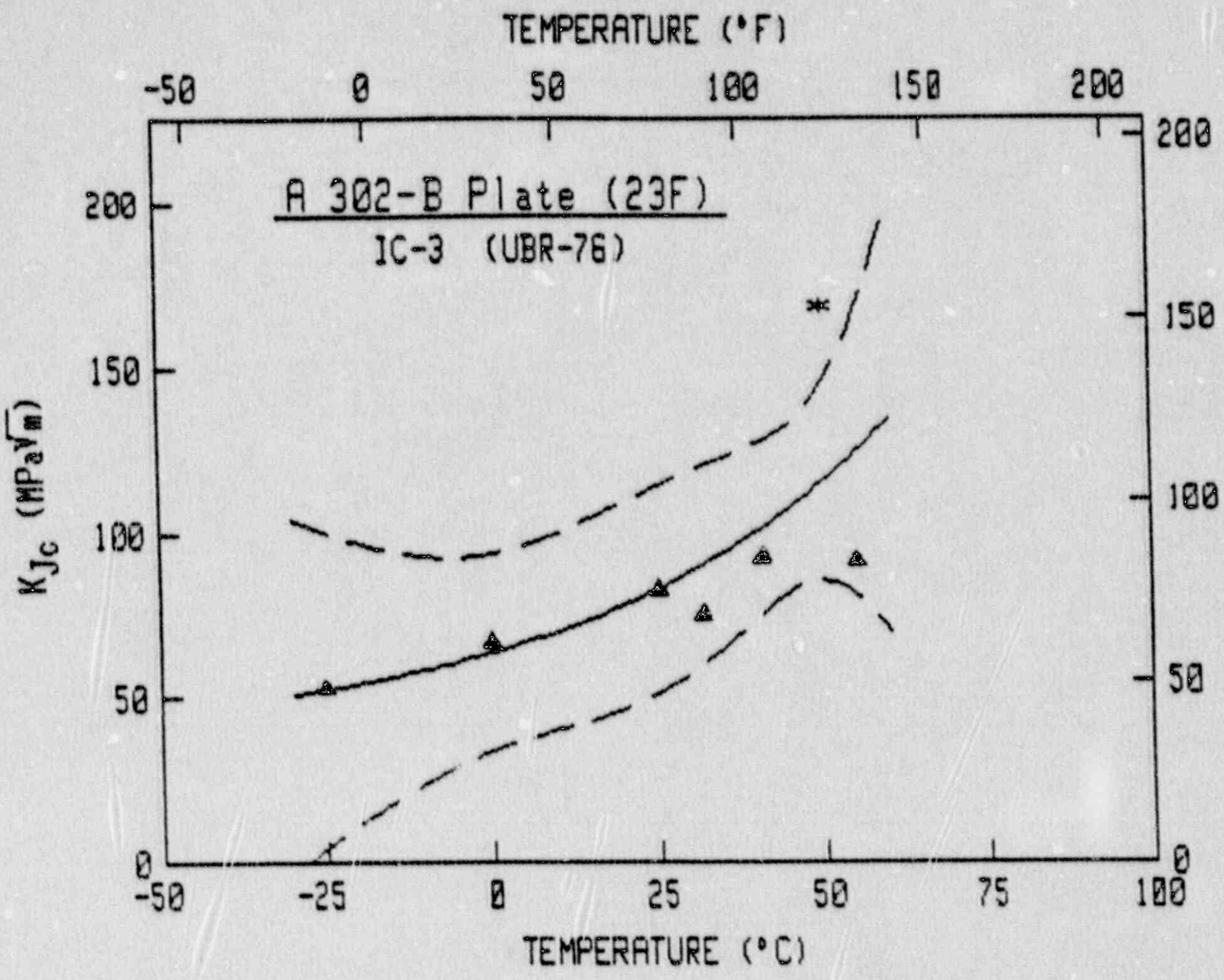
	Metric	English
A =	-41.11 MPa√m	-37.41 ksi√in
B =	129.66 MPa√m	118.00 ksi√in
C =	103.43°C	186.17°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-4°C	25°F
Mean Curve =	9°C	48°F
Lower Bound =	21°C	70°F

****

Pt #	Temperature	Kjc
1	-50	30.6
2	12	64.2
3	-18	88.4
4	32	133.1
5	21	129.1
6	-20	68.3
7	5	103.0
8 *	45	183.1
9 *	50	153.8

* = Upper Shelf Data Point



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

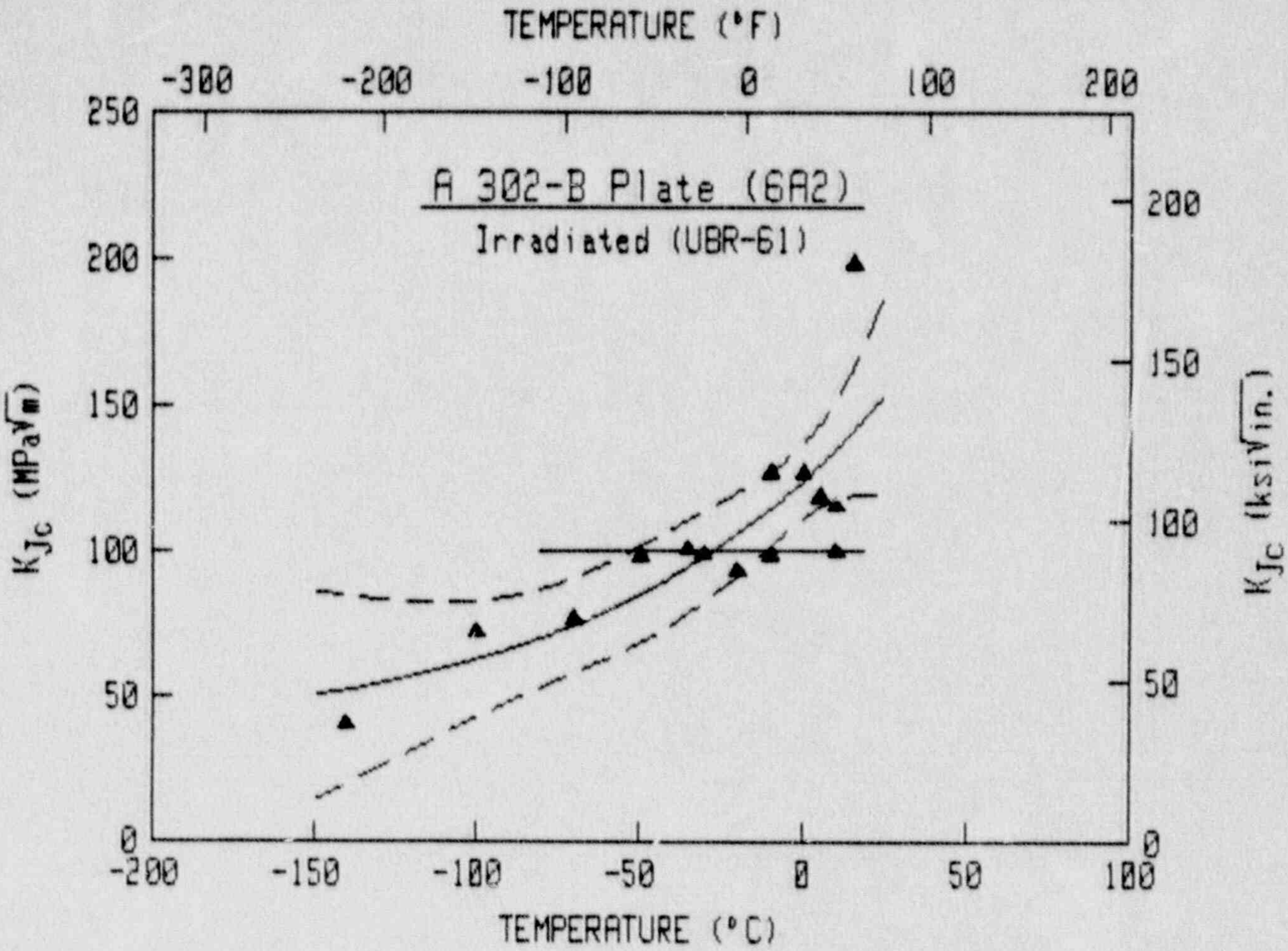
	Metric	English
A =	37.03 MPa√m	33.70 ksi√in
B =	26.47 MPa√m	24.09 ksi√in
C =	46.09°C	82.97°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-30°C	-22°F
Mean Curve =	40°C	104°F

****

Pt #	Temperature	Kjc
1	-25	52.9
2	0	66.9
3	25	82.5
4	32	75.2
5	41	92.4
6	55	91.3
7 *	50	168.4

* = Upper Shelf Data Point

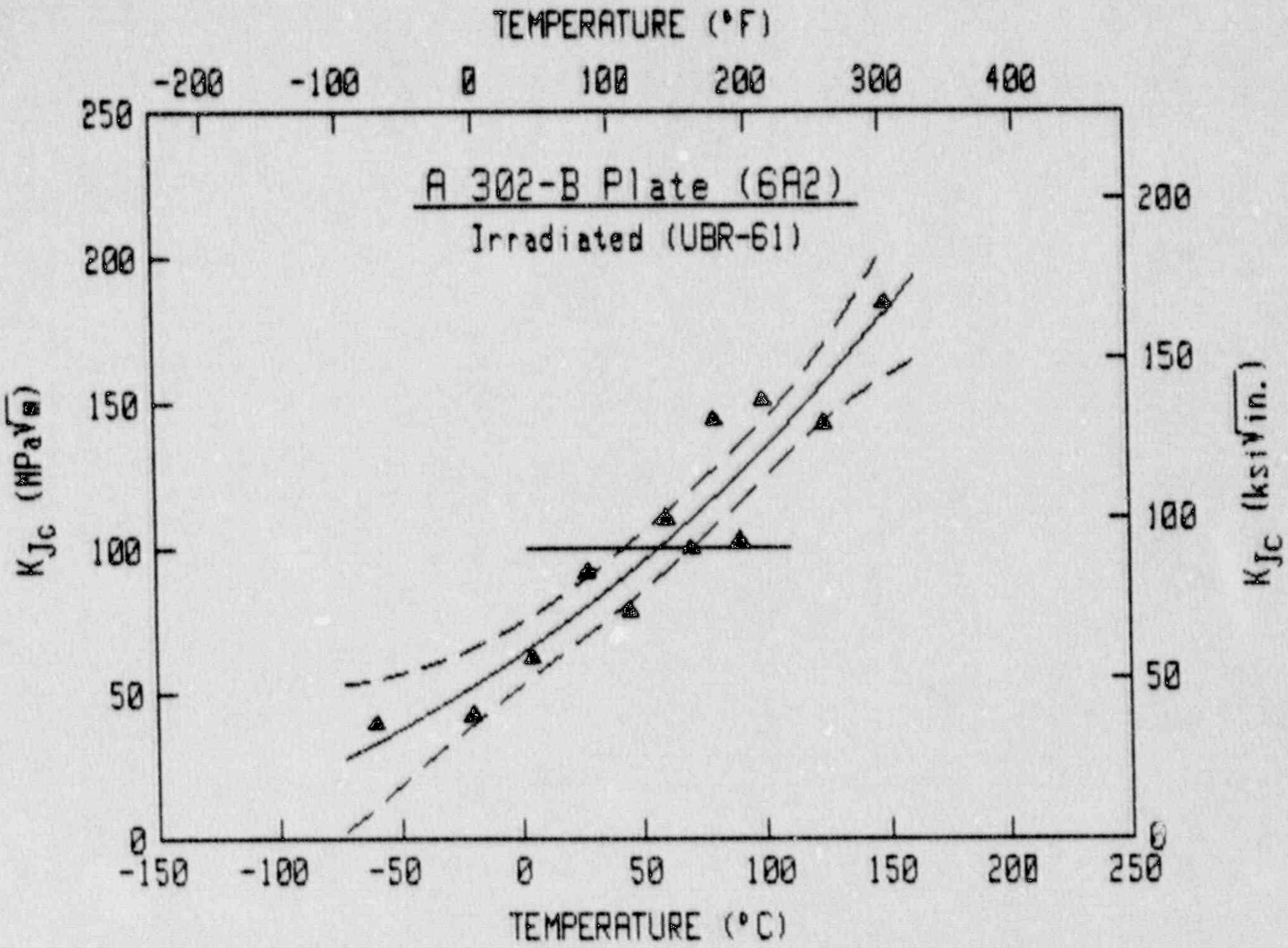


$$K_{jc} = A + B \exp[(T - T_o)/C)]$$

		Metric	English
A	=	34.48 MPa√m	31.38 ksi√in
B	=	89.47 MPa√m	81.42 ksi√in
C	=	86.45°C	155.62°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-51°C	-60°F
Mean Curve =	-27°C	-16°F
Lower Bound =	-11°C	12°F

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-140	40.2	8	-10	126.6
2	-100	72.2	9	-10	98.5
3	-70	76.6	10	0	126.8
4	-50	98.2	11	5	118.3
5	-35	100.5	12	10	115.6
6	-30	98.7	13	10	99.7
7	-20	92.9	14	15	198.7



****

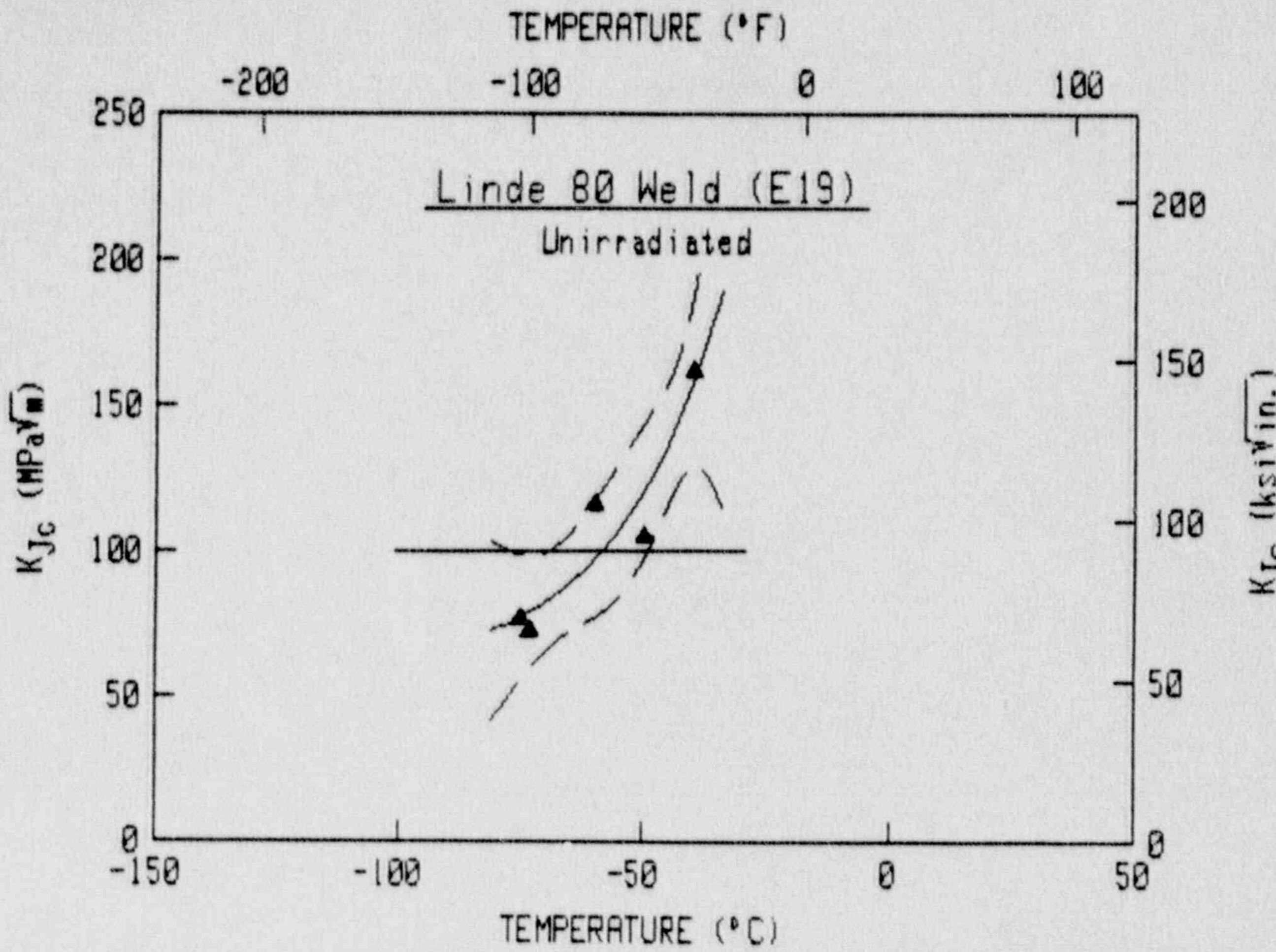
$$K_{jc} = A + B \exp[(T-T_o)/C)]$$

	Metric	English
A =	-79.12 MPa√m	-72.00 ksi√in
B =	142.53 MPa√m	129.71 ksi√in
C =	250.21°C	450.39°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	43°C	109°F
Mean Curve =	57°C	135°F
Lower Bound =	71°C	160°F

****

Pt #	Temperature	Kjc
1	-60	39.5
2	-20	42.3
3	5	62.1
4	28	91.8
5	45	78.2
6	60	110.1
7	70	99.5
8	80	143.9
9	90	102.6
10	100	150.5
11	125	142.5
12	150	183.9



****

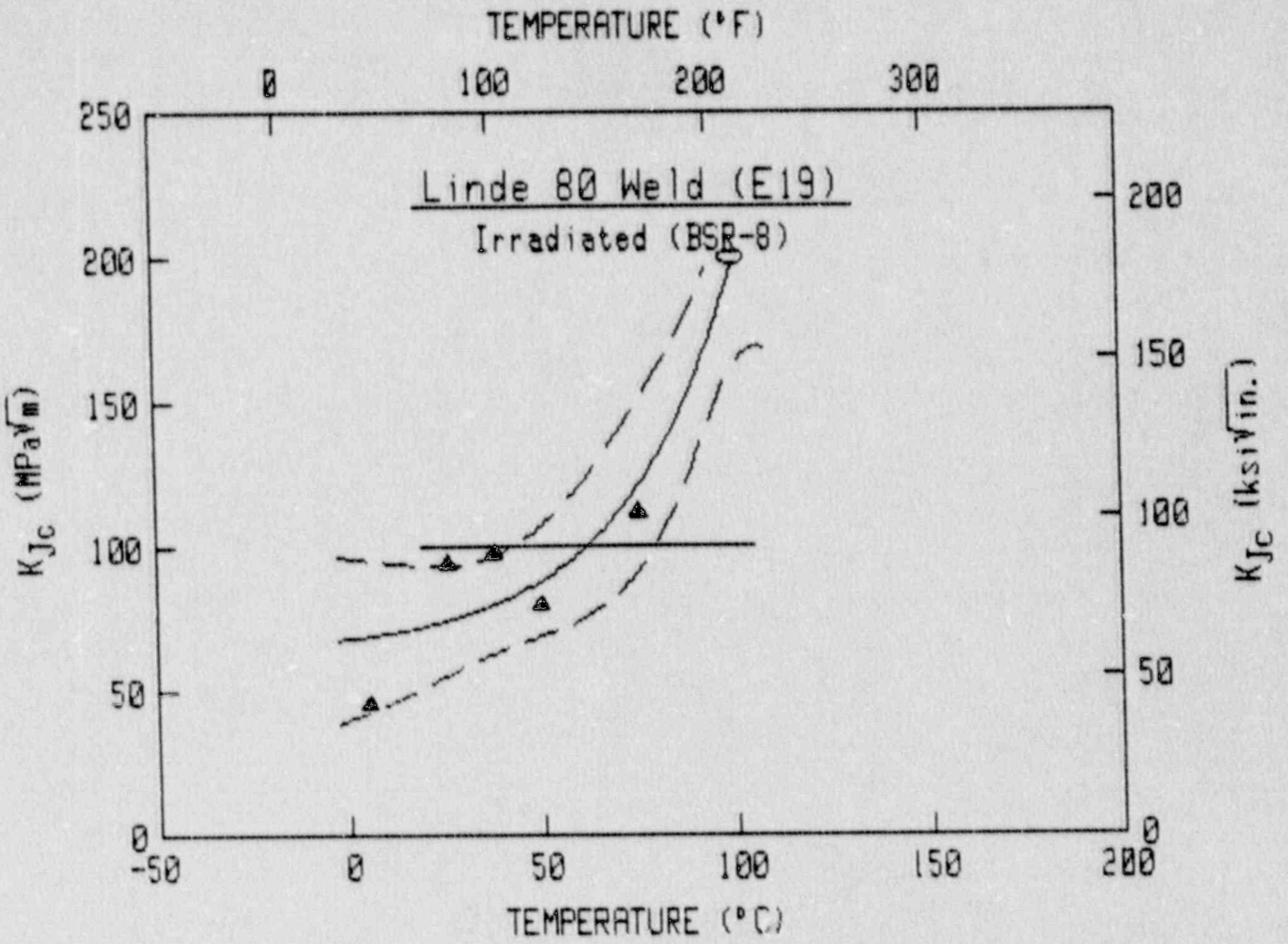
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	56.76 MPa√m	51.66 ksi√in
B =	630.12 MPa√m	573.44 ksi√in
C =	21.85°C	39.33°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-81°C	-114°F
Mean Curve =	-59°C	-73°F
Lower Bound =	-49°C	-56°F

****

Pt #	Temperature	Kjc
1	-75	76.7
2	-73	72.4
3	-60	116.0
4	-50	105.0
5	-40	161.7



****

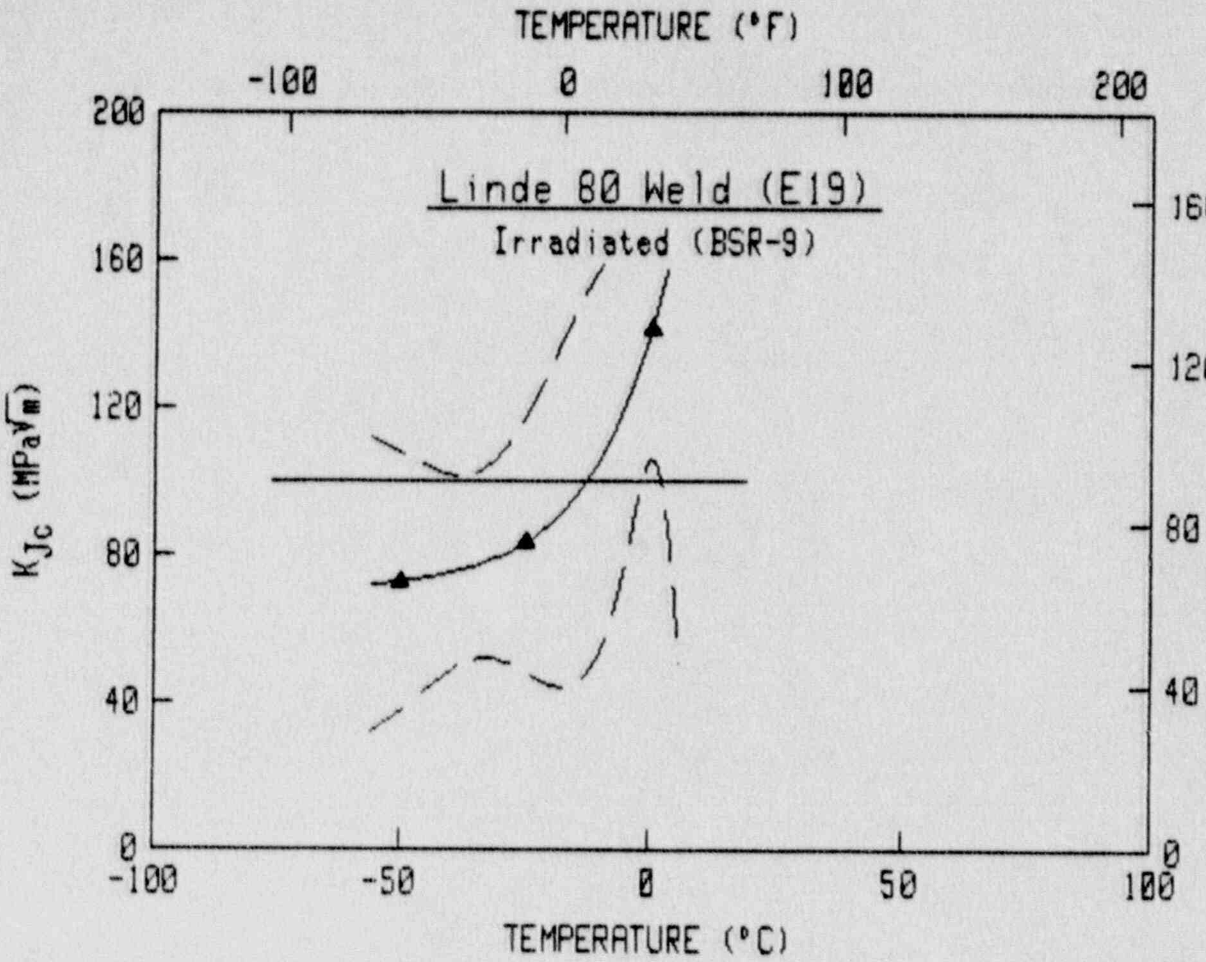
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	63.75 MPa√m	58.01 ksi√in
B =	4.30 MPa√m	3.91 ksi√in
C =	29.08°C	52.34°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	44°C	111°F
Mean Curve =	62°C	144°F
Lower Bound =	80°C	176°F

****

Pt #	Temperature	Kjc
1	5	45.3
2	26	94.3
3	38	97.4
4	50	79.8
5	75	111.9
6 O	100	200.0



****

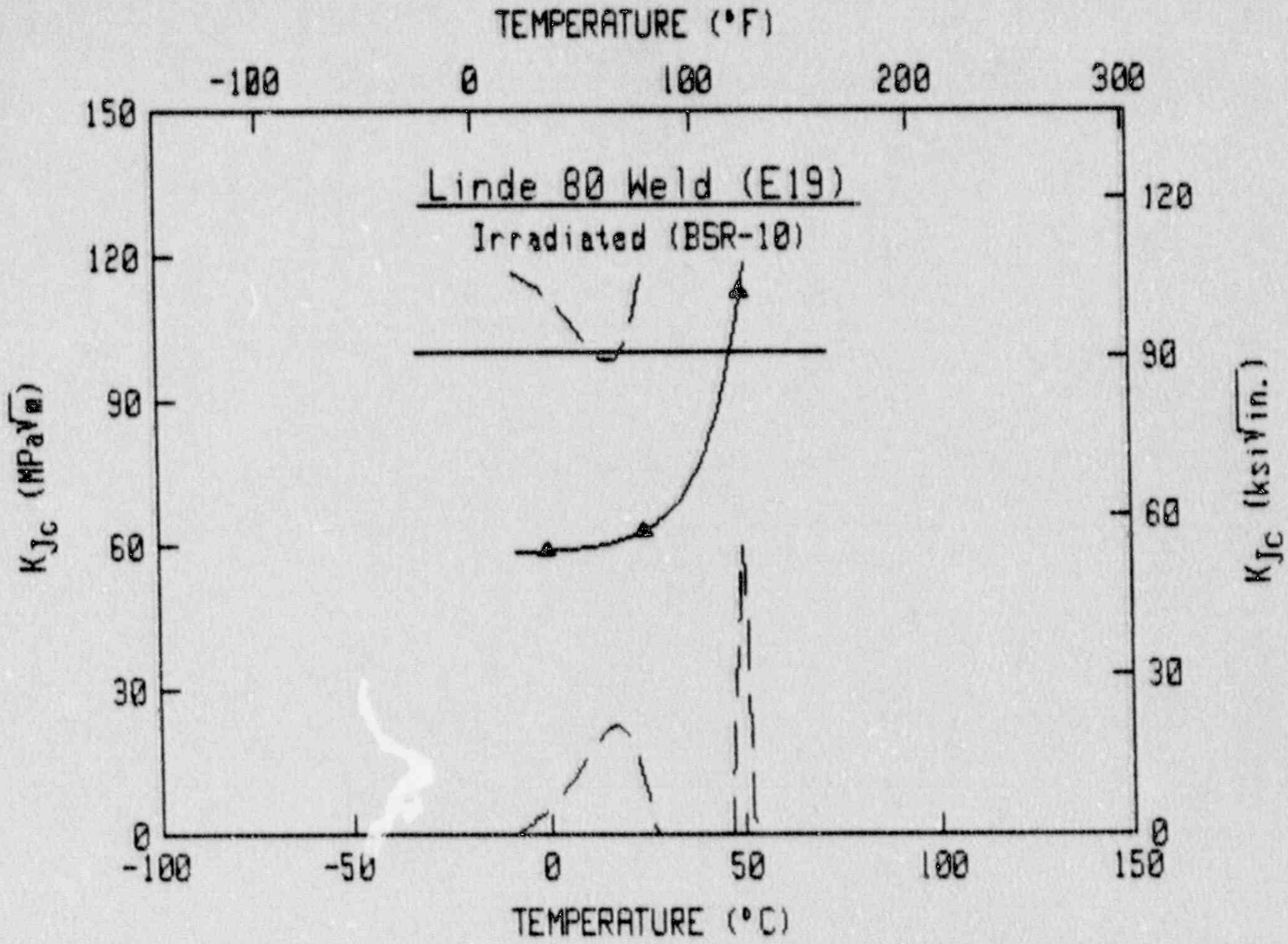
$$Kjc = A + B \exp[(T-To)/C)]$$

	Metric	English
A =	70.28 MPa√m	63.96 ksi√in
B =	71.22 MPa√m	64.81 ksi√in
C =	14.78°C	26.60°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-56°C	-69°F
Mean Curve =	-13°C	9°F
Lower Bound =	-1°C	30°F

****

Pt #	Temperature	Kjc
1	-50	72.7
2	-25	83.4
3	0	141.5



****

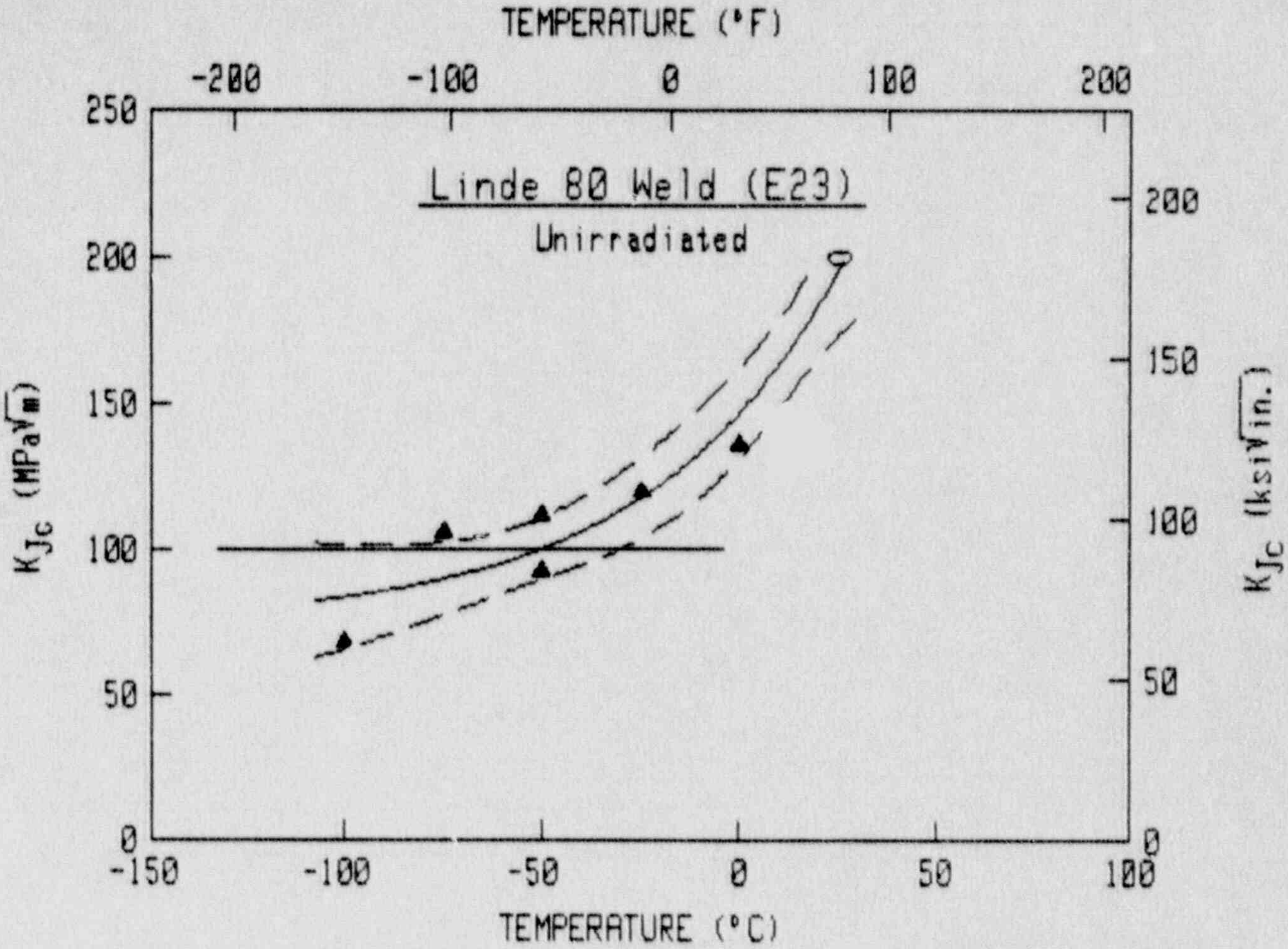
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	58.47 MPa√m	53.21 ksi√in
B	=	.33 MPa√m	.30 ksi√in
C	=	9.81°C	17.65°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-8°C	18°F
Mean Curve	=	47°C	117°F

****

Pt #	Temperature	Kjc
1	0	58.8
2	25	62.7
3	50	112.6



****

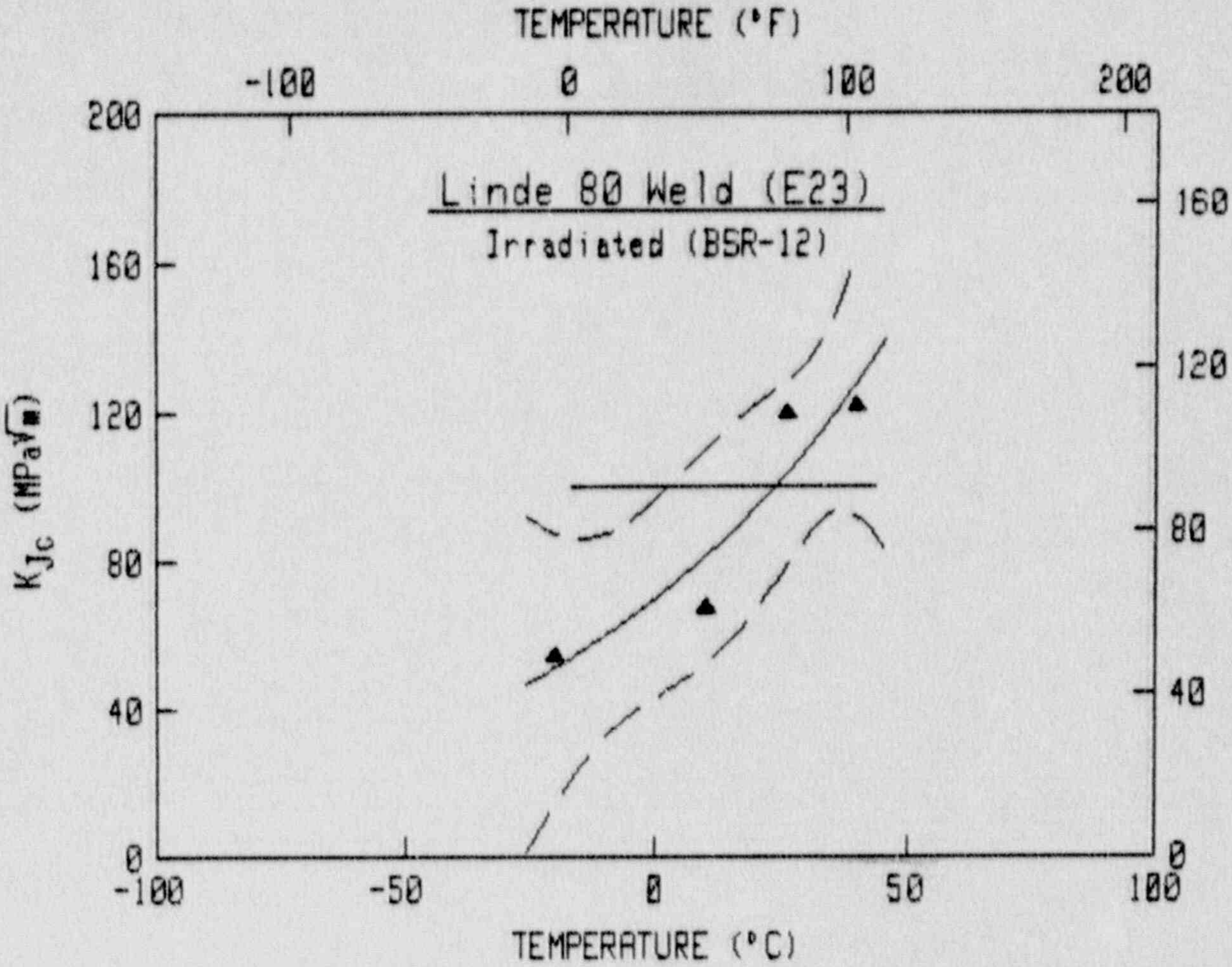
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	74.92 MPa√m	68.18 ksi√in
B =	71.72 MPa√m	65.27 ksi√in
C =	47.66°C	85.80°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-108°C	-162°F
Mean Curve =	-50°C	-58°F
Lower Bound =	-29°C	-20°F

****

Pt #	Temperature	Kjc
1	-100	68.2
2	-75	105.8
3	-50	111.7
4	-50	92.6
5	-25	119.5
6	0	135.9
7 O	25	200.0



****

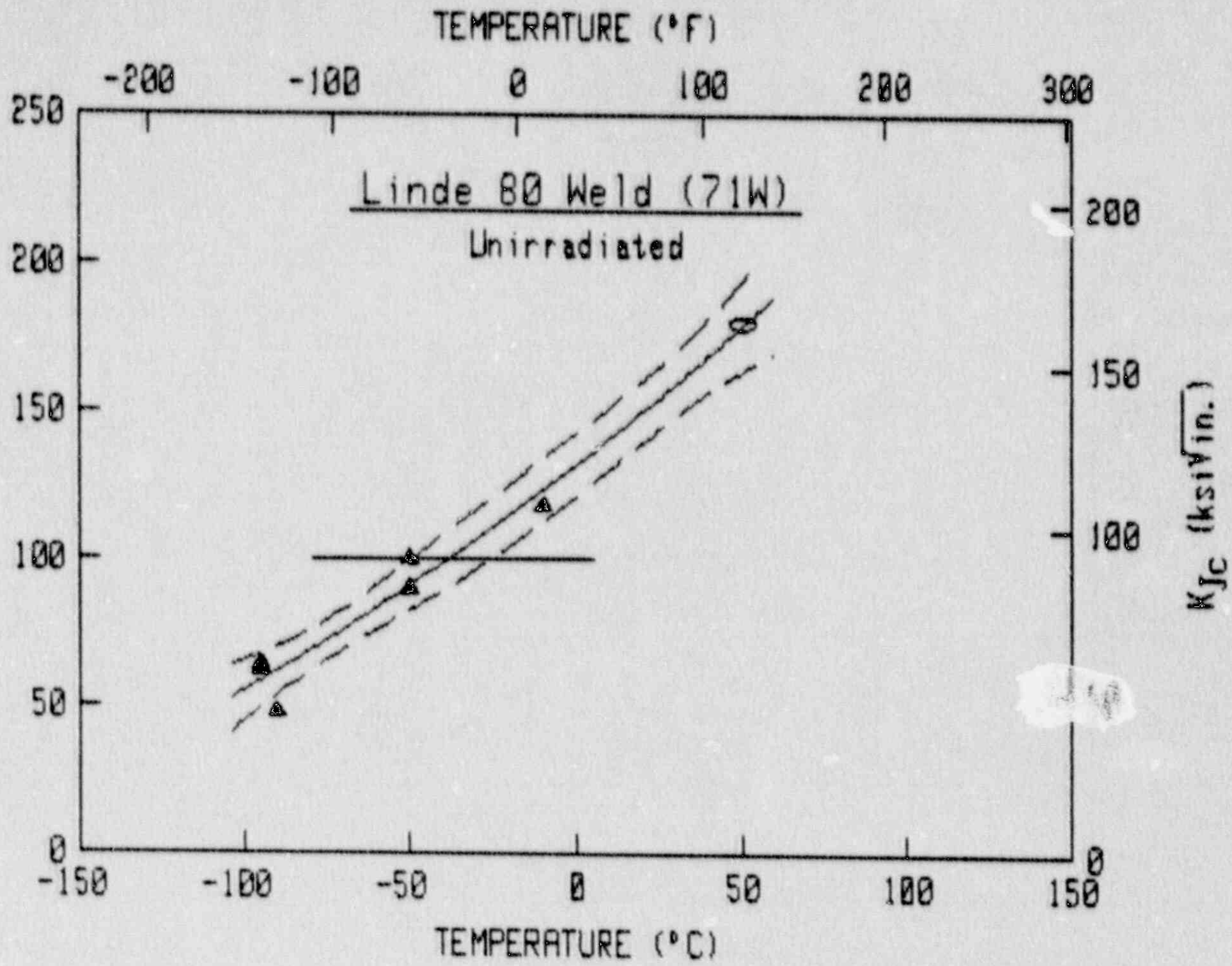
$$Kjc = A + B \exp [(T-To)/C)]$$

	Metric	English
A =	-3.12 MPa√m	-2.84 ksi√in
B =	72.76 MPa√m	66.21 ksi√in
C =	68.18°C	122.72°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	3°C	37°F
Mean Curve =	24°C	75°F

****

Pt #	Temperature	Kjc
1	-20	54.3
2	10	67.4
3	26	119.8
4	40	121.9



****

Kjc = A + B exp [(T-To)/C)]

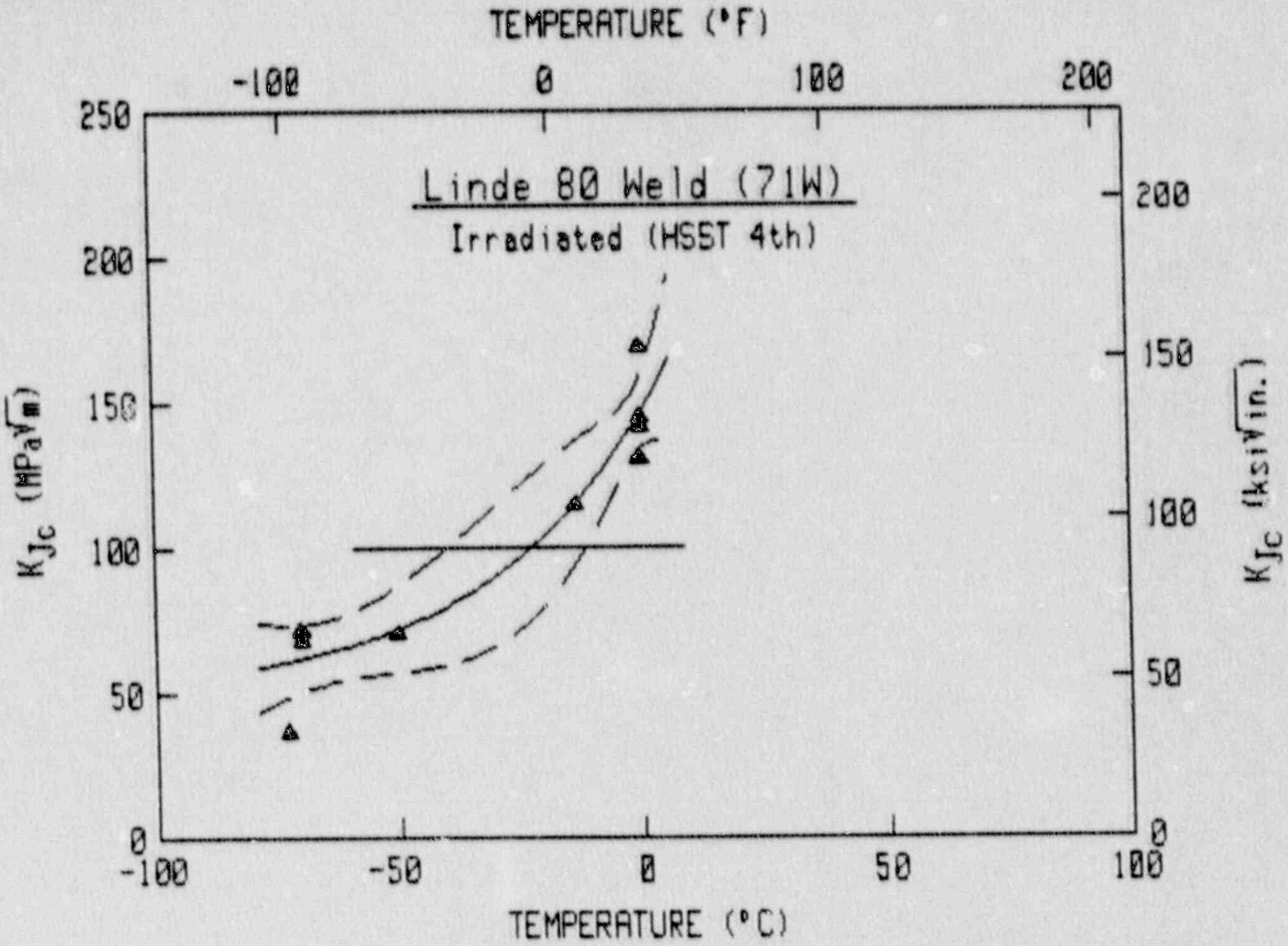
		Metric	English
A	=	-180.65 MPa√m	-164.40 ksi√in
B	=	312.49 MPa√m	284.38 ksi√in
C	=	355.28°C	639.50°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-49°C	-56°F
Mean Curve =	-38°C	-37°F
Lower Bound =	-25°C	-13°F

****

Pt #	Temperature	Kjc
1	-95	64.4
2	-95	62.7
3	-90	47.8
4	-50	89.9
5	-50	100.1
6	-10	118.0
7 O	50	180.0

O = Extra Point Added   * = Point Deleted from Fit



****

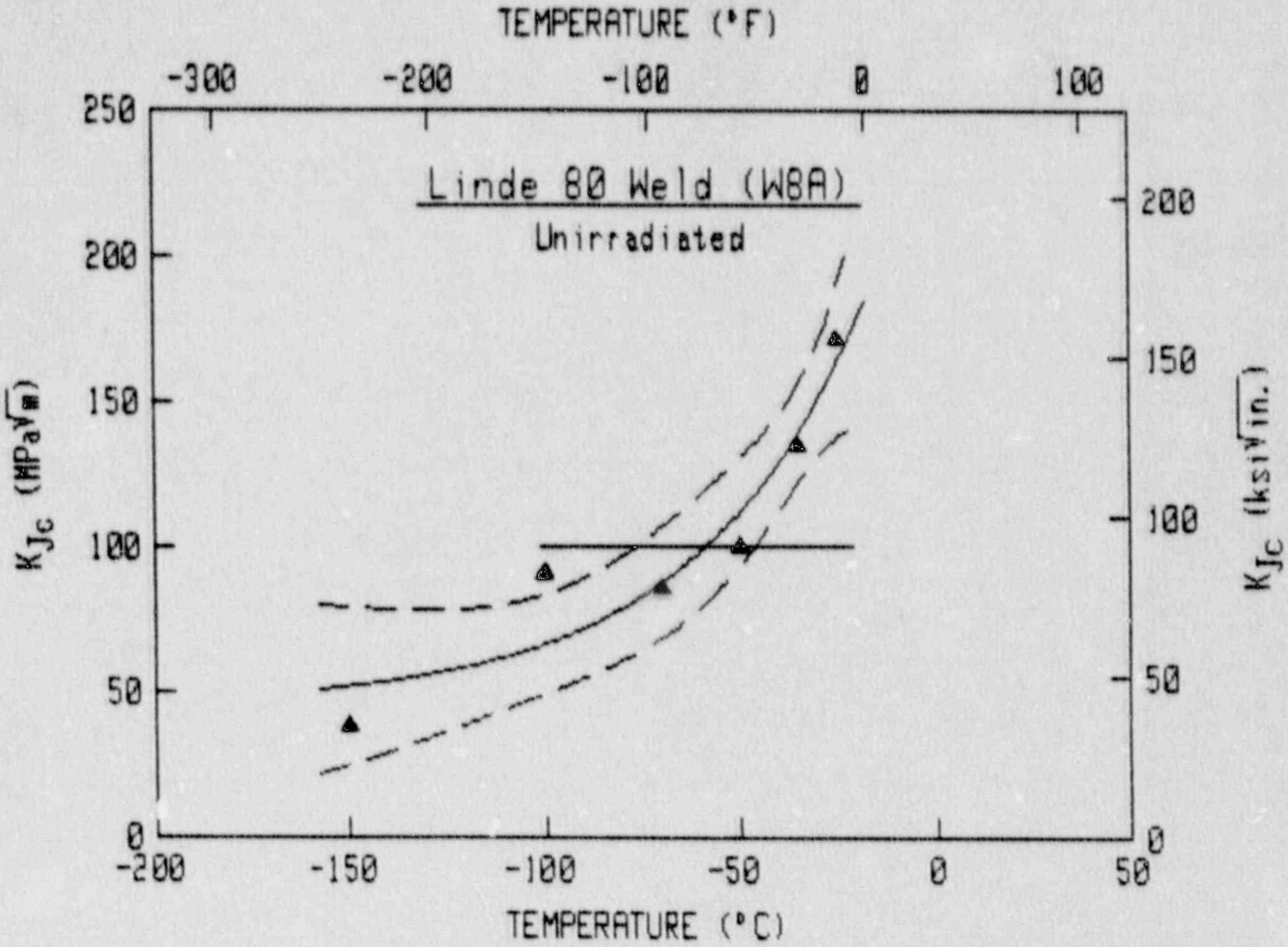
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	48.94 MPa√m	44.54 ksi√in
B =	97.36 MPa√m	88.60 ksi√in
C =	34.55°C	62.19°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-39°C	-38°F
Mean Curve =	-22°C	-8°F
Lower Bound =	-11°C	12°F

****

Pt #	Temperature	Kjc
1	-73	36.6
2	-70	71.2
3	-70	68.5
4	-70	71.9
5	-50	70.3
6	-13	114.5
7	0	169.0
8	0	130.6
9	0	141.6
10	0	144.7



****

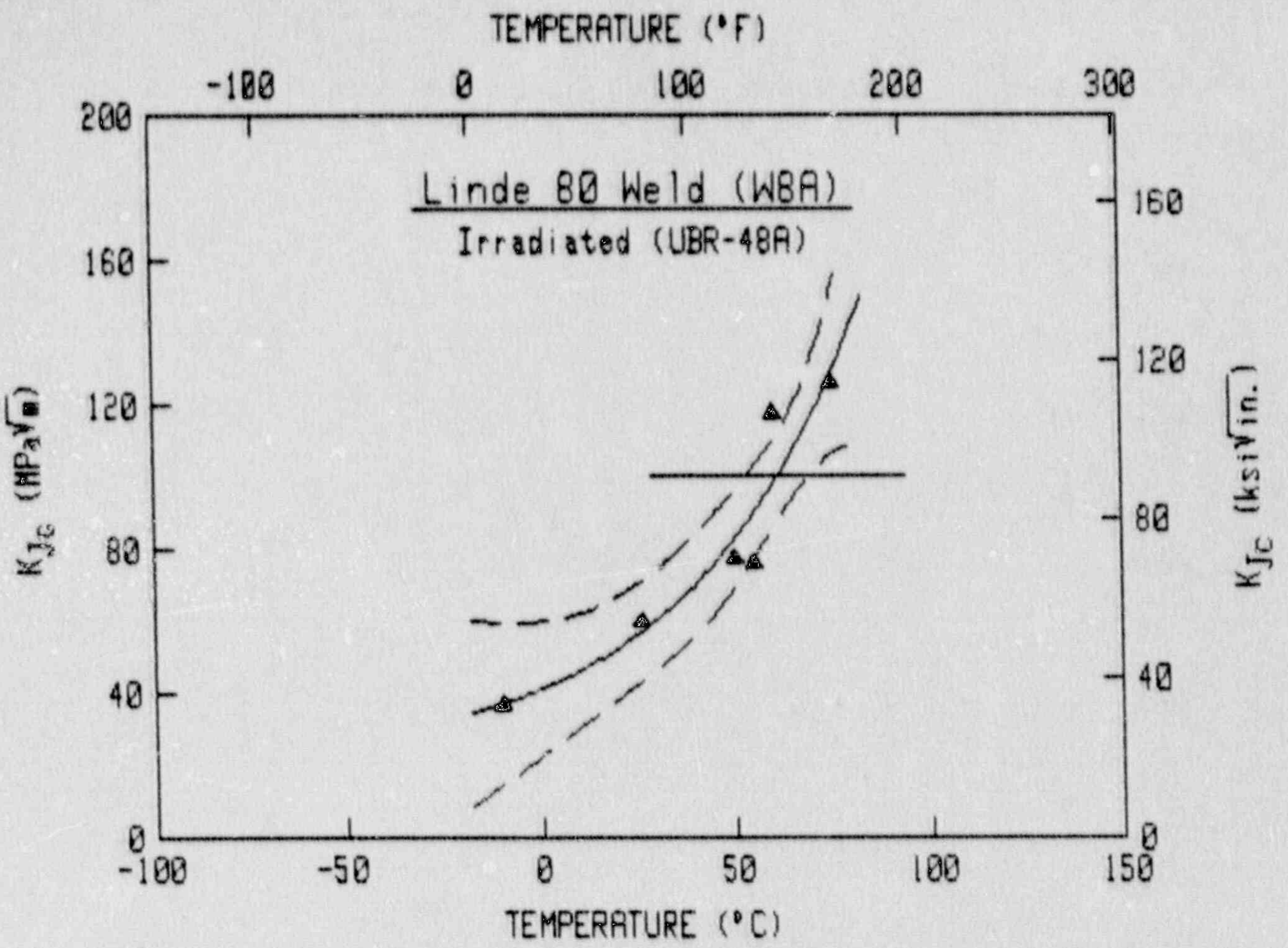
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	45.18 MPa√m	41.11 ksi√in
B =	210.89 MPa√m	191.92 ksi√in
C =	43.47°C	78.24°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-76°C	-105°F
Mean Curve =	-59°C	-73°F
Lower Bound =	-46°C	-51°F

****

Pt #	Temperature	Kjc
1	-150	38.2
2	-100	90.9
3	-70	85.5
4	-50	100.2
5	-35	134.5
6	-25	171.4



****

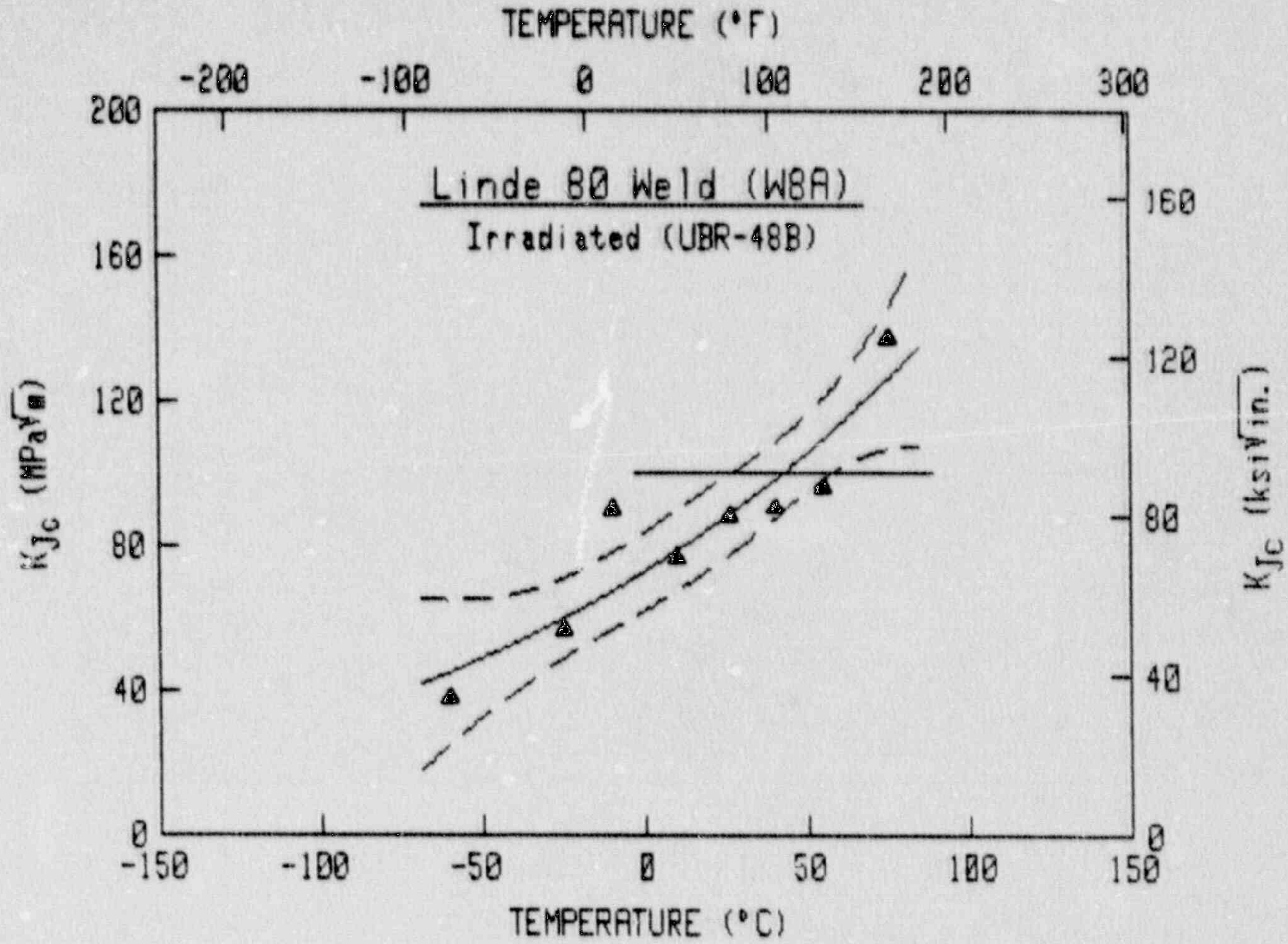
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	21.16 MPa√m	19.26 ksi√in
B =	19.82 MPa√m	18.03 ksi√in
C =	44.29°C	79.71°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	54°C	129°F
Mean Curve =	61°C	142°F
Lower Bound =	69°C	156°F

****

Pt #	Temperature	Kjc
1	-10	36.7
2	26	59.8
3	50	77.2
4	55	75.6
5	60	117.6
6	75	126.0



****

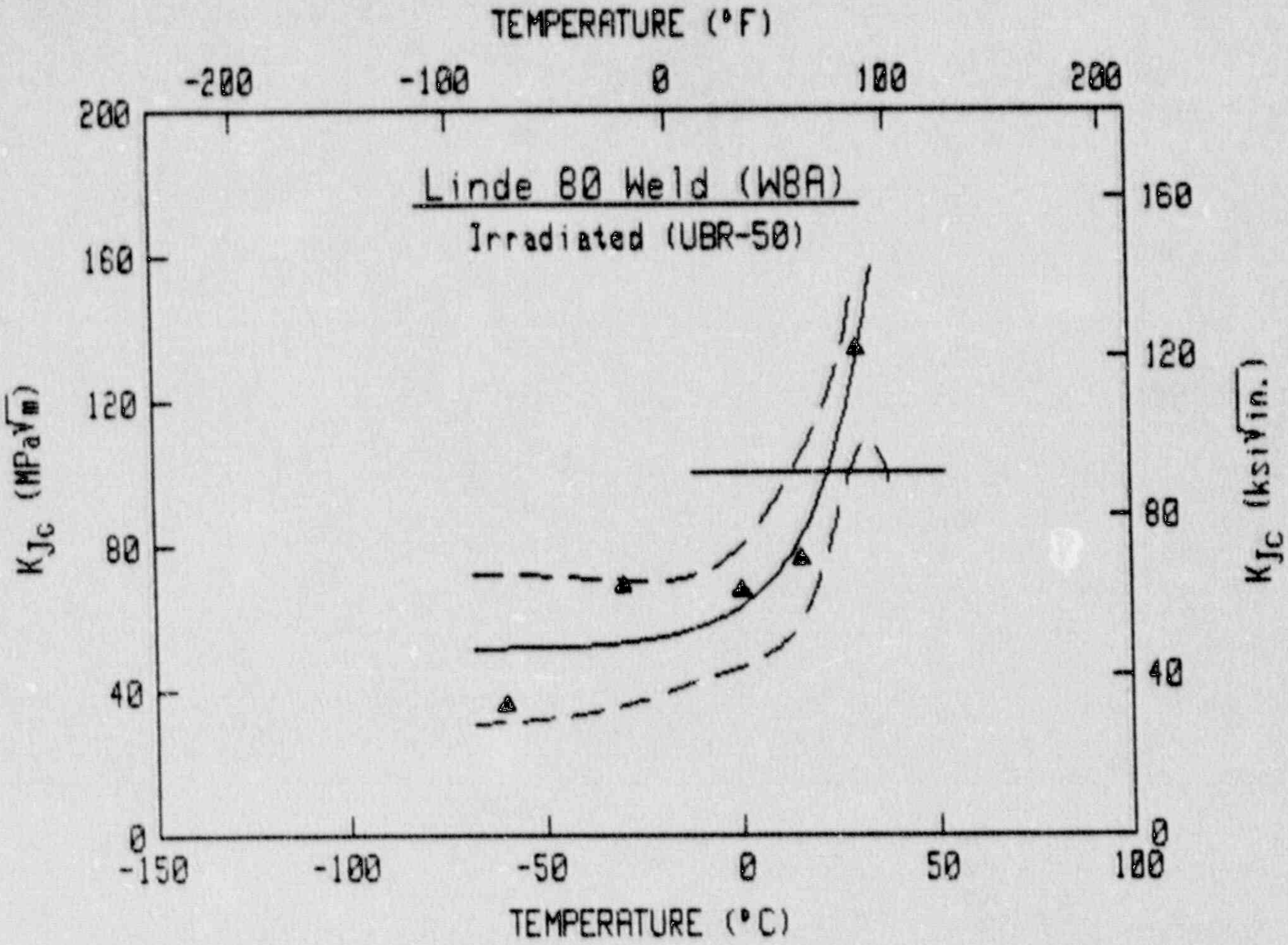
$$K_{jc} = A + B \exp[(T-T_o)/C]$$

	Metric	English
A =	-14.89 MPa√m	-13.55 ksi√in
B =	87.63 MPa√m	79.75 ksi√in
C =	157.30°C	283.14°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	27°C	81°F
Mean Curve =	43°C	109°F
Lower Bound =	59°C	138°F

****

Pt #	Temperature	Kjc
1	-60	37.9
2	-25	56.7
3	-10	89.9
4	10	76.8
5	26	87.9
6	40	90.3
7	55	96.1
8	75	137.3



****

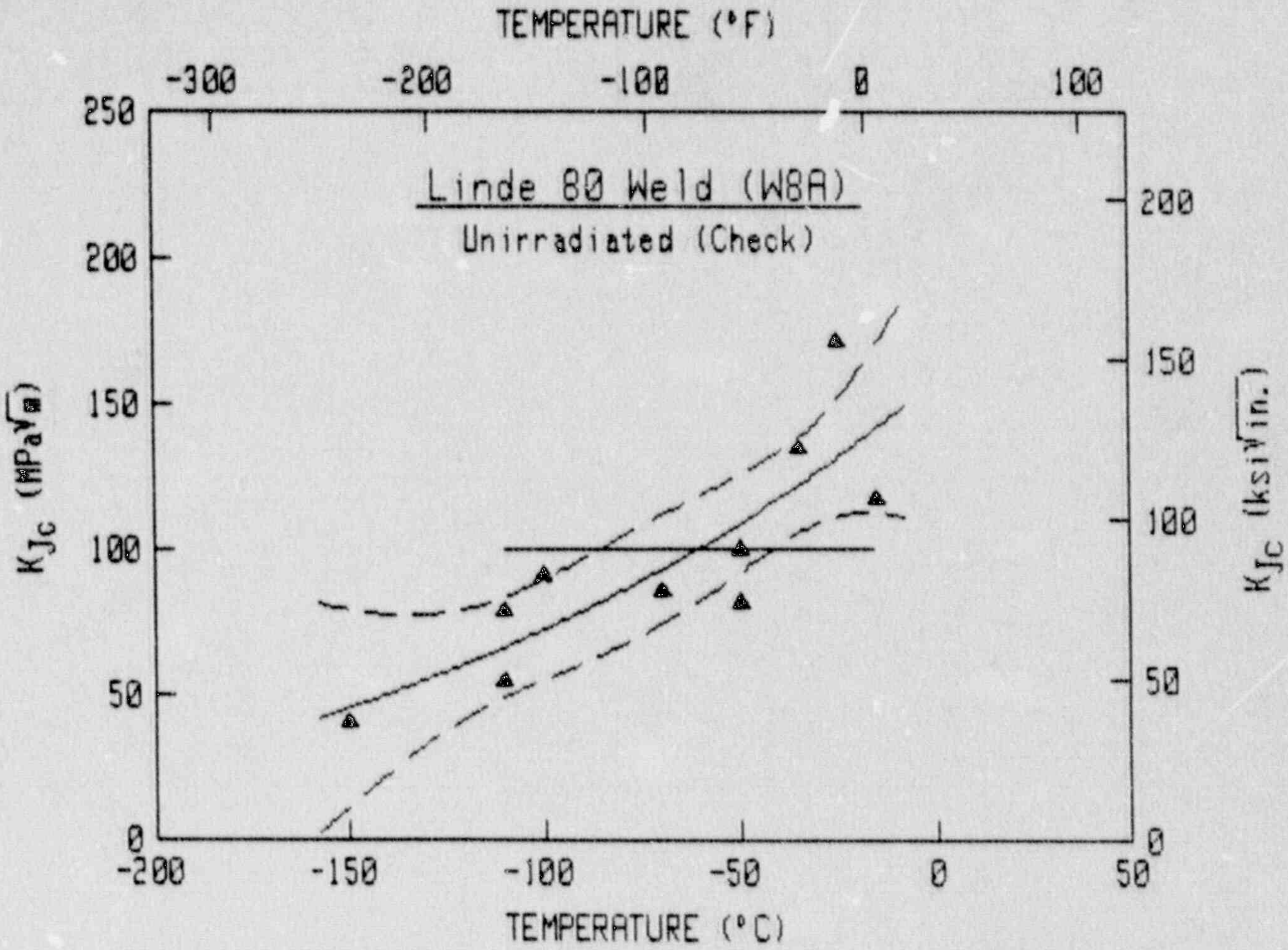
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	51.38 MPa√m	46.75 ksi√in
B =	11.55 MPa√m	10.51 ksi√in
C =	15.36°C	27.65°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	13°C	55°F
Mean Curve =	22°C	72°F
Lower Bound =	28°C	82°F

****

Pt #	Temperature	Kjc
1	-60	36.0
2	-30	68.8
3	0	67.5
4	15	75.9
5	30	134.2



****

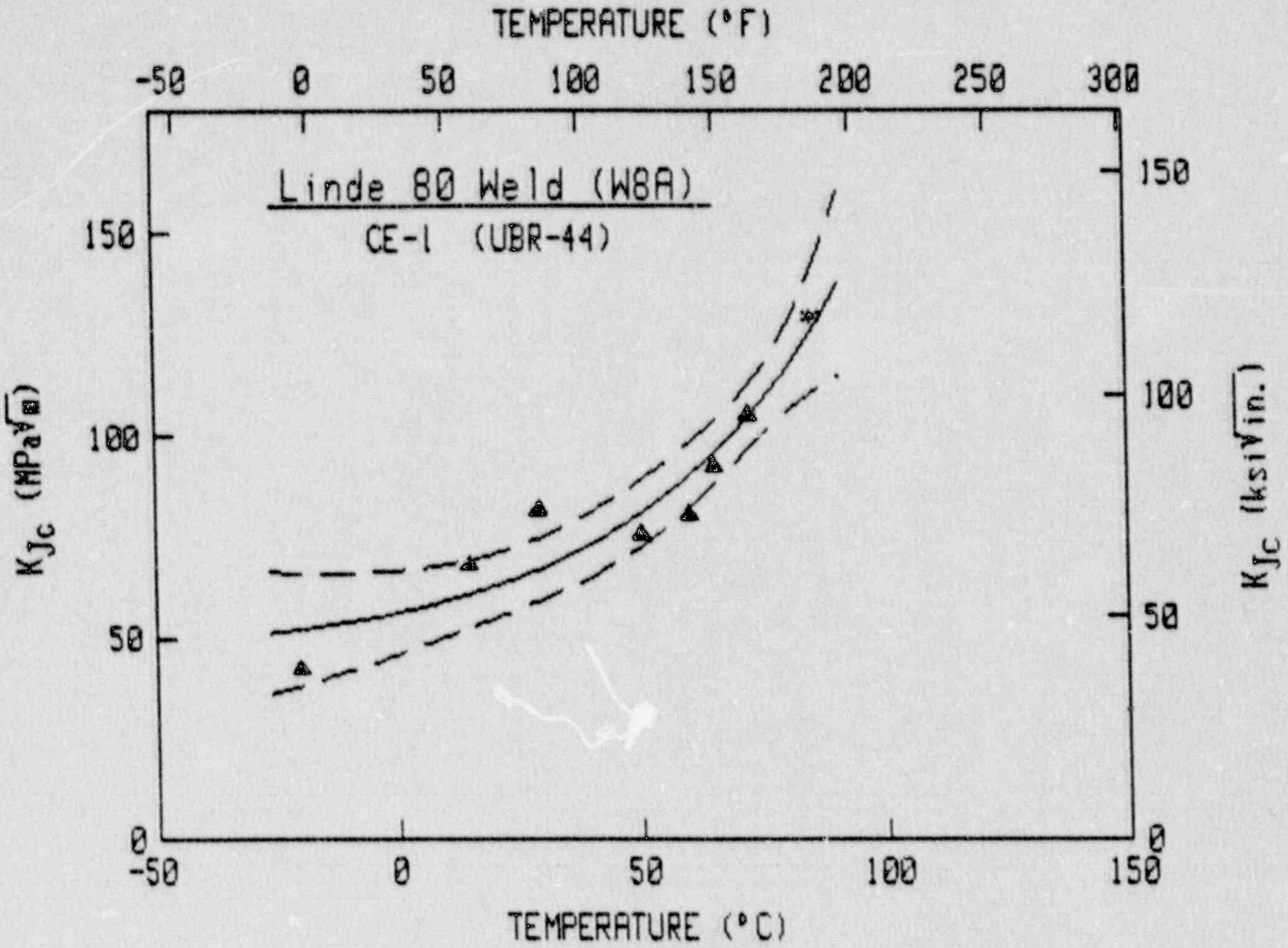
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	-30.21 MPa√m	-27.50 ksi√in
B	=	188.13 MPa√m	171.21 ksi√in
C	=	164.52°C	296.13°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-85°C	-121°F
Mean Curve	=	-61°C	-77°F
Lower Bound	=	-41°C	-42°F

****

Pt #	Temperature	Kjc
1	-150	40.3
2	-110	78.6
3	-110	54.6
4	-100	90.9
5	-70	85.5
6	-50	81.5
7	-50	100.2
8	-35	134.5
9	-25	171.4
10	-15	117.2



****

$$Kjc = A + B \exp[(T-To)/C)]$$

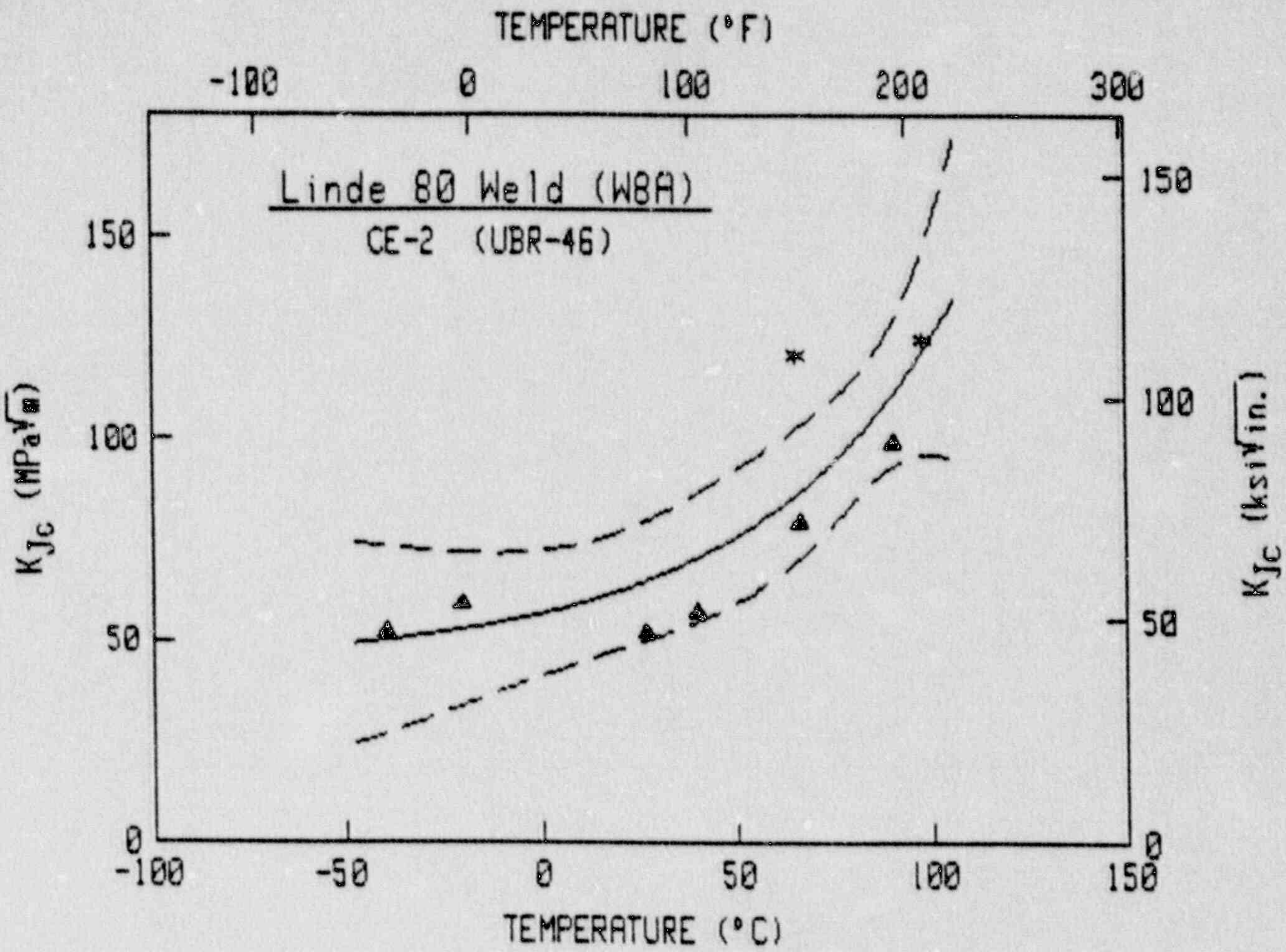
	Metric	English
A =	45.32 MPa√m	41.25 ksi√in
B =	10.88 MPa√m	9.90 ksi√in
C =	42.56°C	76.61°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	63°C	145°F
Mean Curve =	69°C	156°F
Lower Bound =	75°C	167°F

****

Pt #	Temperature	Kjc
1	-20	42.4
2	15	68.0
3	29	81.7
4	50	75.6
5	60	80.6
6	65	92.4
7	72	105.2
8 *	85	129.5

* = Upper Shelf Data Point



****

$Kjc = A + B \exp[(T-To)/C]$

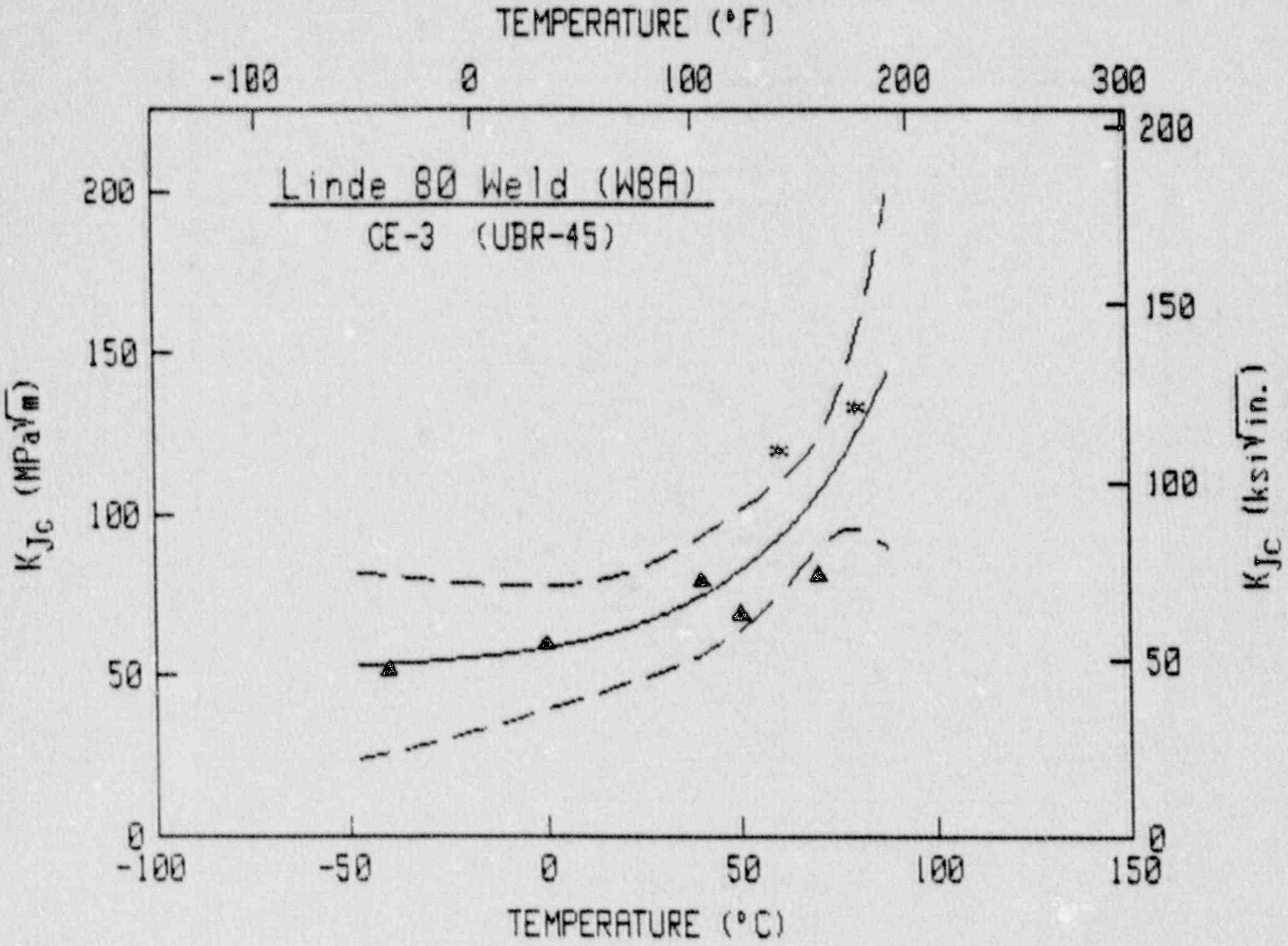
	Metric	English
A =	44.49 MPa√m	40.48 ksi√in
B =	12.18 MPa√m	11.08 ksi√in
C =	52.99°C	95.38°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	62°C	144°F
Mean Curve =	80°C	177°F

****

Pt #	Temperature	Kjc
1	-40	52.3
2	-20	59.0
3	27	51.8
4	40	57.1
5	66	79.3
6	90	99.1
7 *	65	120.6
8 *	98	124.7

* = Upper Shelf Data Point



****

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

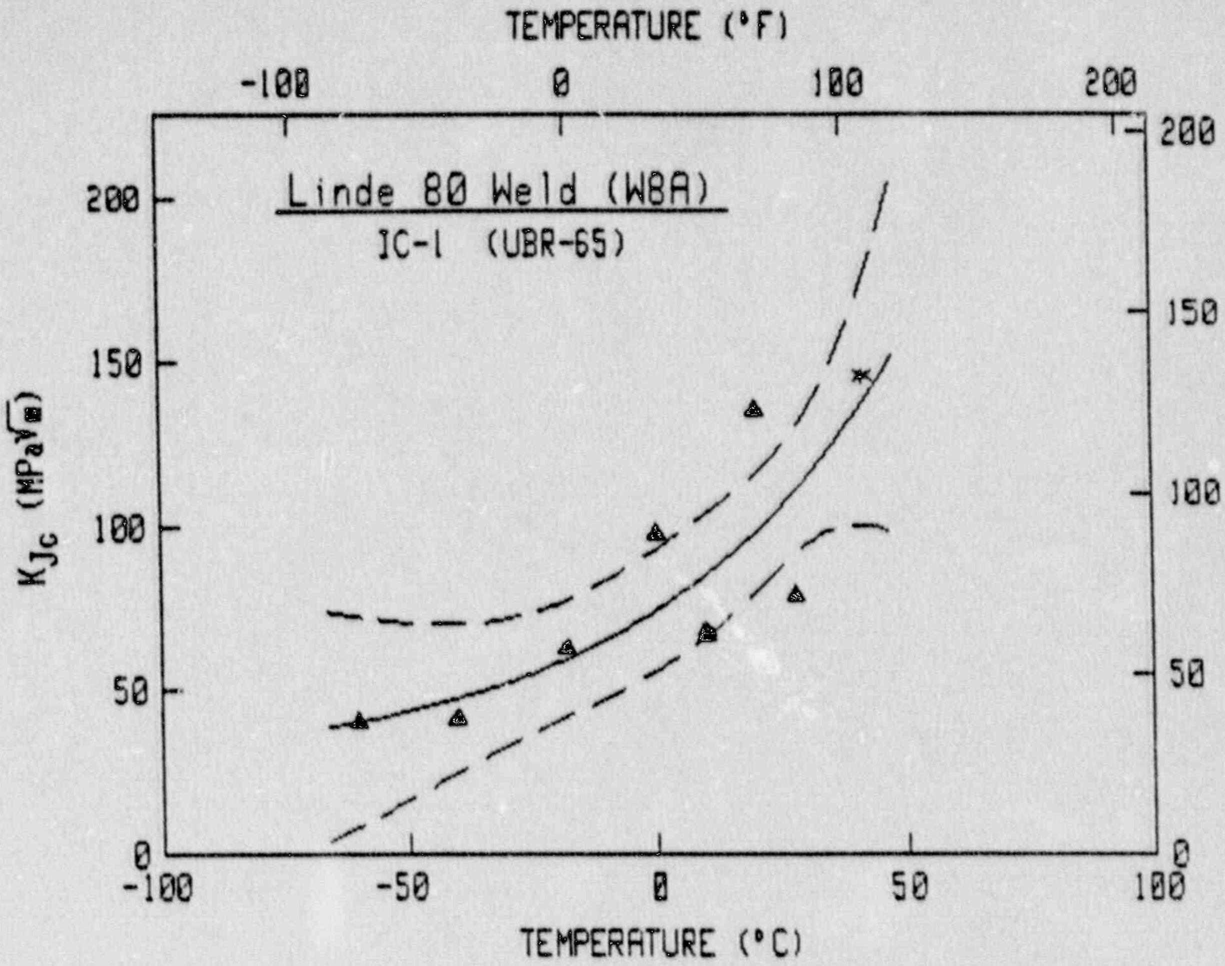
	Metric	English
A =	51.10 MPa√m	46.50 ksi√in
B =	7.49 MPa√m	6.82 ksi√in
C =	34.96°C	62.92°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	49°C	120°F
Mean Curve =	66°C	150°F

****

Pt #	Temperature	Kjc
1	-40	51.7
2	0	59.8
3	40	79.0
4	50	69.2
5	70	81.1
6 *	60	119.4
7 *	80	133.2

* = Upper Shelf Data Point



****

Kjc = A + B exp [(T-To)/C)]

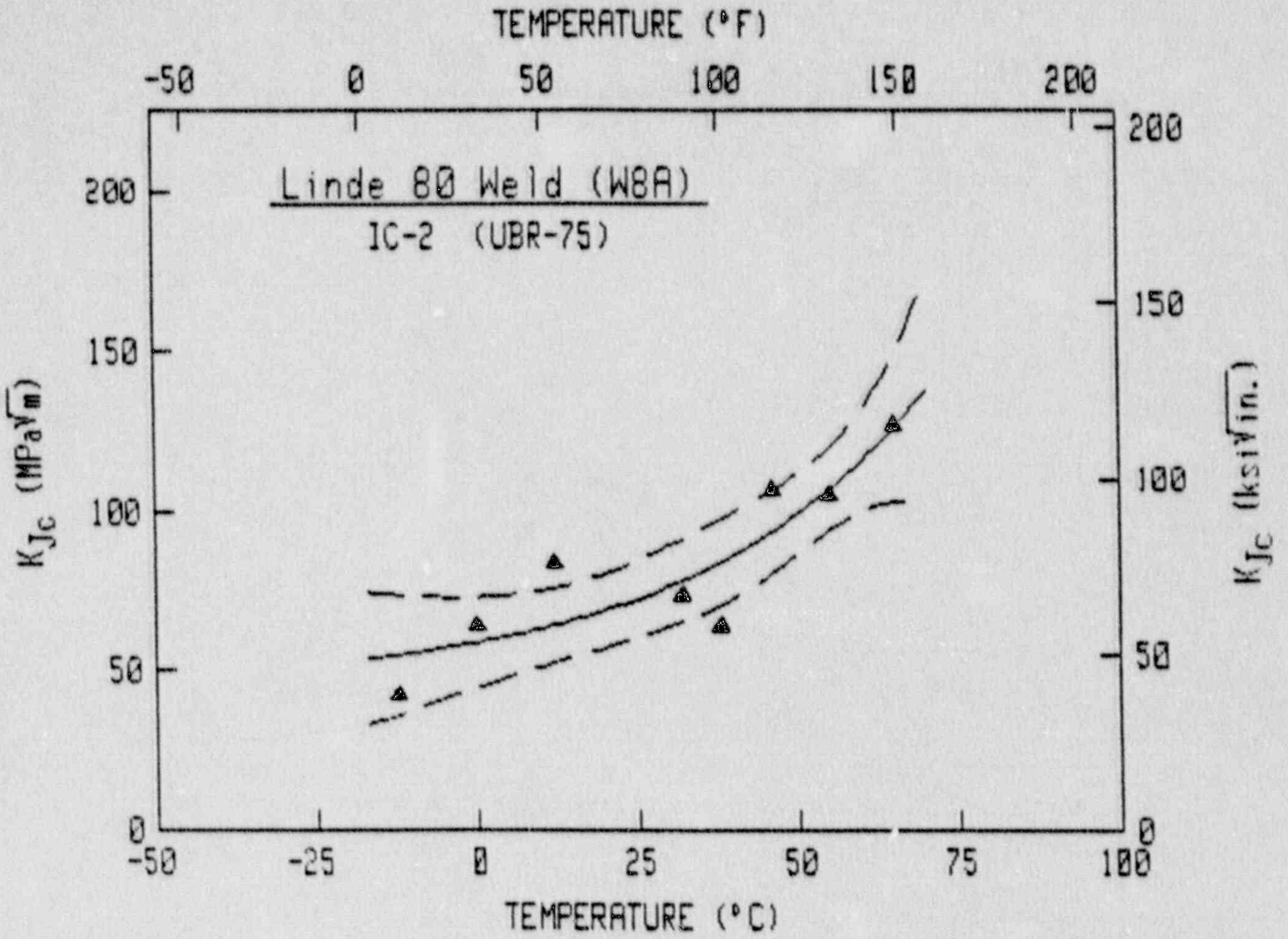
	Metric	English
A =	25.58 MPa√m	23.28 ksi√in
B =	48.46 MPa√m	44.10 ksi√in
C =	50.23°C	90.41°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	7°C	45°F
Mean Curve =	22°C	71°F
Lower Bound =	40°C	104°F

****

Pt #	Temperature	Kjc
1	-60	40.5
2	-40	41.1
3	-18	62.7
4	0	97.7
5	10	68.0
6	10	66.6
7	20	135.3
8	28	78.6
9 *	42	145.5

* = Upper Shelf Data Point



****

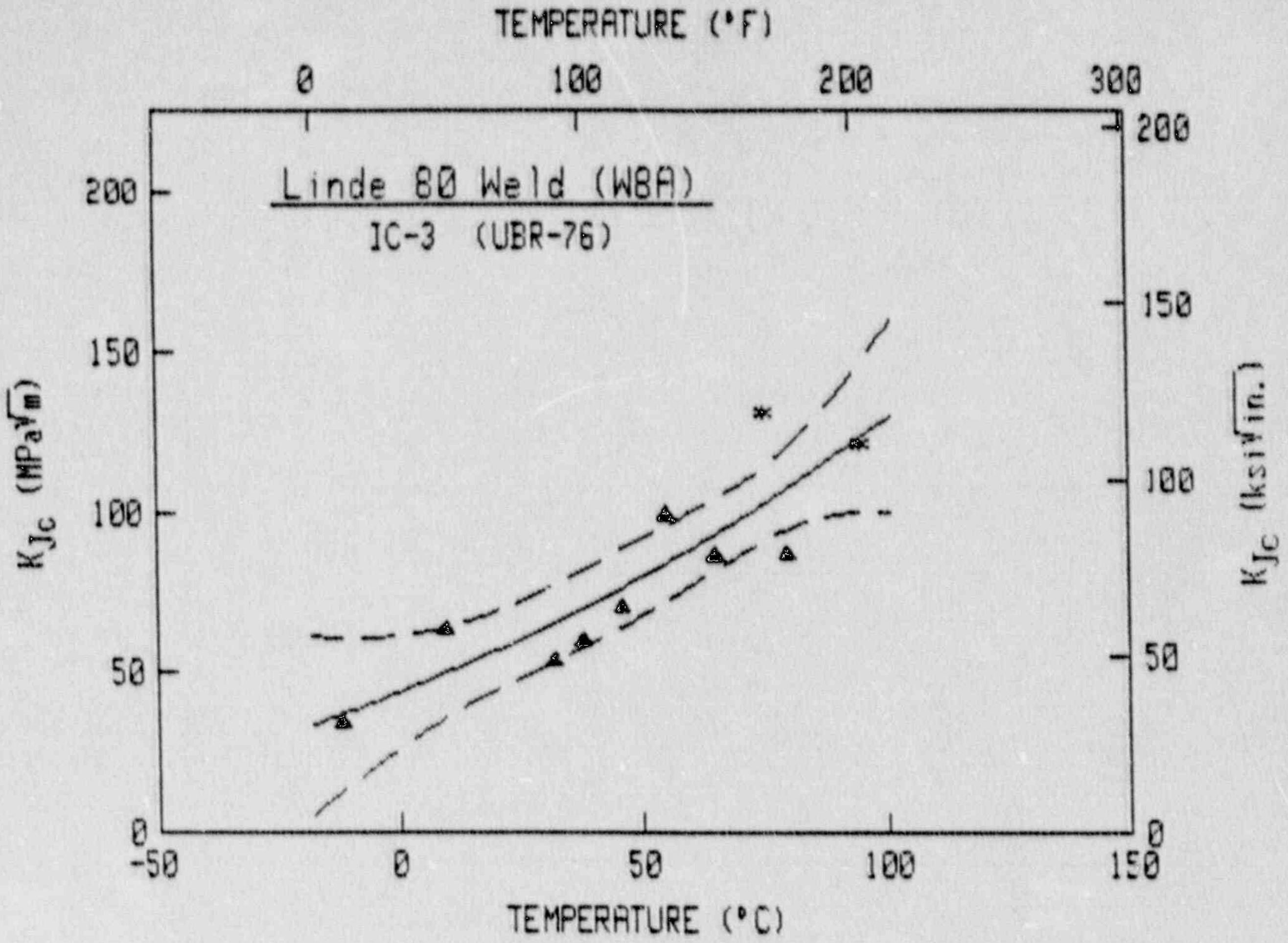
$$Kjc = A + B \exp[(T-To)/C]$$

	Metric	English
A =	44.93 MPa$\sqrt{m}$	40.89 ksi$\sqrt{in}$
B =	13.89 MPa$\sqrt{m}$	12.64 ksi$\sqrt{in}$
C =	36.91°C	66.44°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa$\sqrt{m}$	
Upper Bound =	41°C	106°F
Mean Curve =	51°C	124°F
Lower Bound =	61°C	142°F

****

Pt #	Temperature	Kjc
1	-12	42.2
2	0	64.2
3	12	83.7
4	32	73.5
5	38	63.6
6	46	106.7
7	55	104.7
8	65	126.7



****

Kjc = A + B exp [(T-To)/C)]

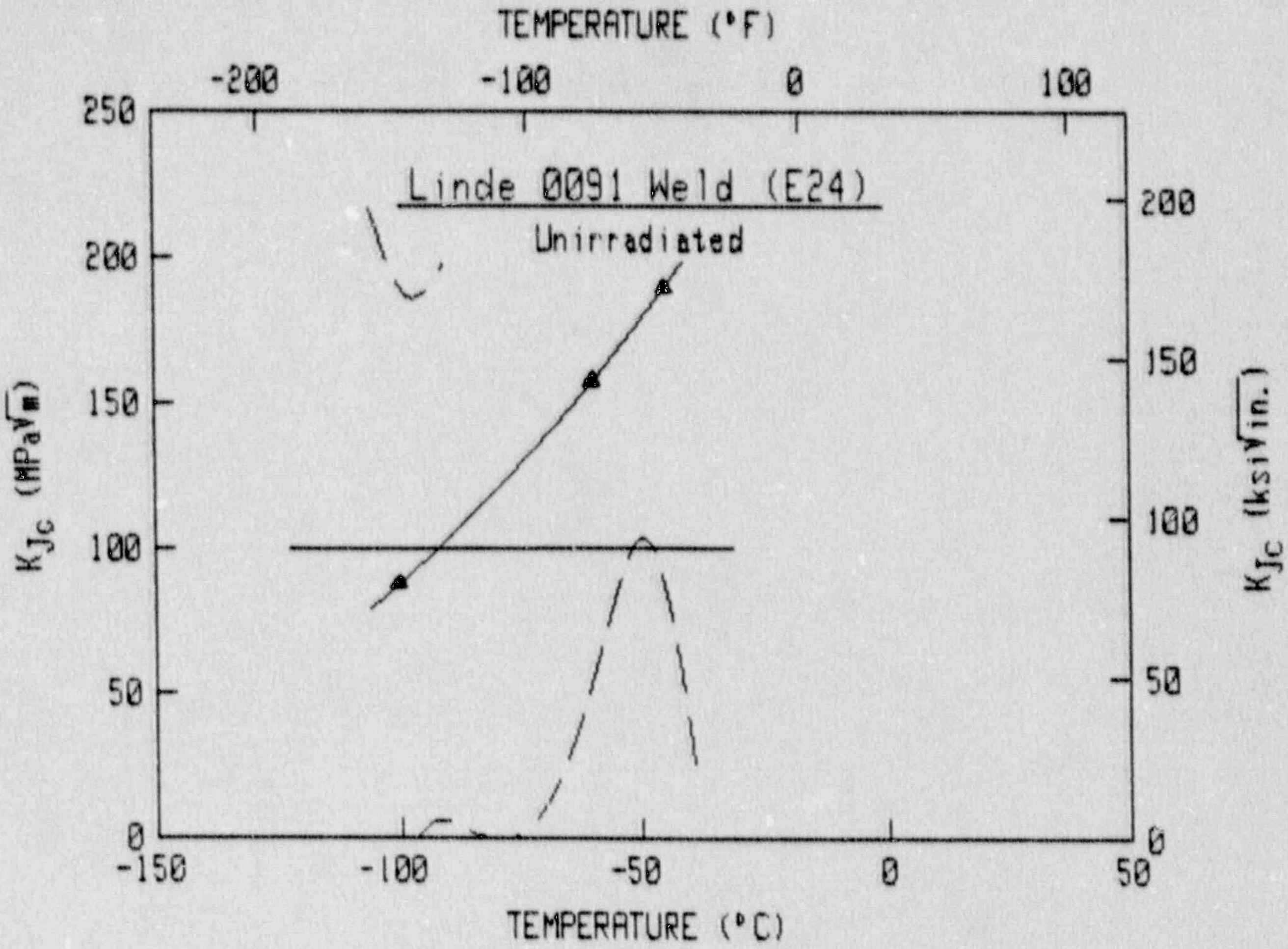
	Metric	English
A =	-49.78 MPa√m	-45.30 ksi√in
B =	93.48 MPa√m	85.07 ksi√in
C =	154.78°C	278.60°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	61°C	142°F
Mean Curve =	73°C	163°F
Lower Bound =	97°C	207°F

****

Pt #	Temperature	Kjc
1	-12	34.3
2	10	63.3
3	32	53.7
4	38	59.6
5	46	70.1
6	55	99.2
7	65	86.3
8	80	86.8
9 *	75	131.2
10 *	95	121.1

* = Upper Shelf Data Point



****

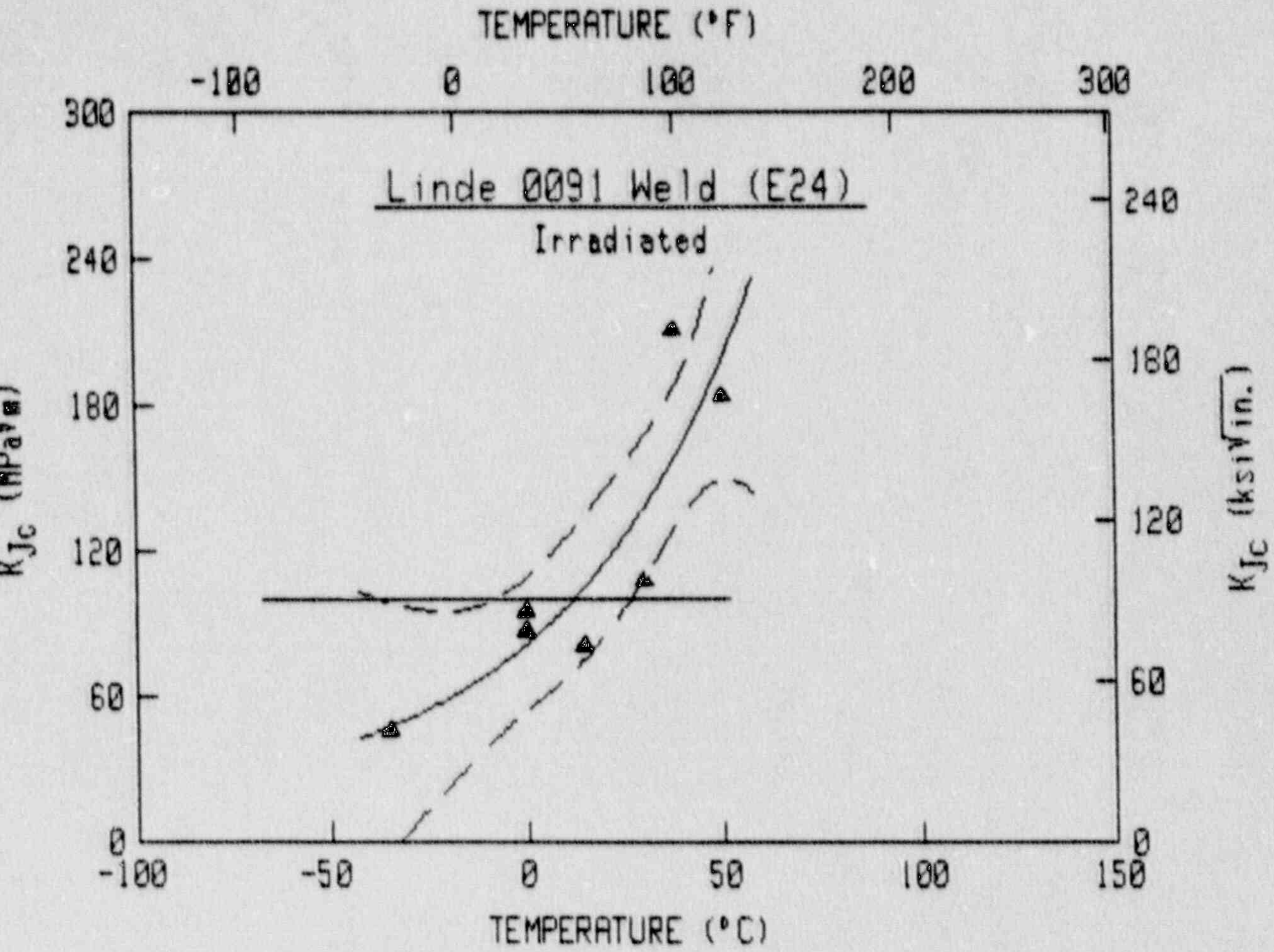
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-108.62 MPa√m	-98.85 ksi√in
B =	419.68 MPa√m	381.93 ksi√in
C =	131.71°C	237.09°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-102°C	-152°F
Mean Curve =	-92°C	-134°F
Lower Bound =	-51°C	-60°F

****

Pt #	Temperature	Kjc
1	-100	87.8
2	-60	157.5
3	-45	189.6



****

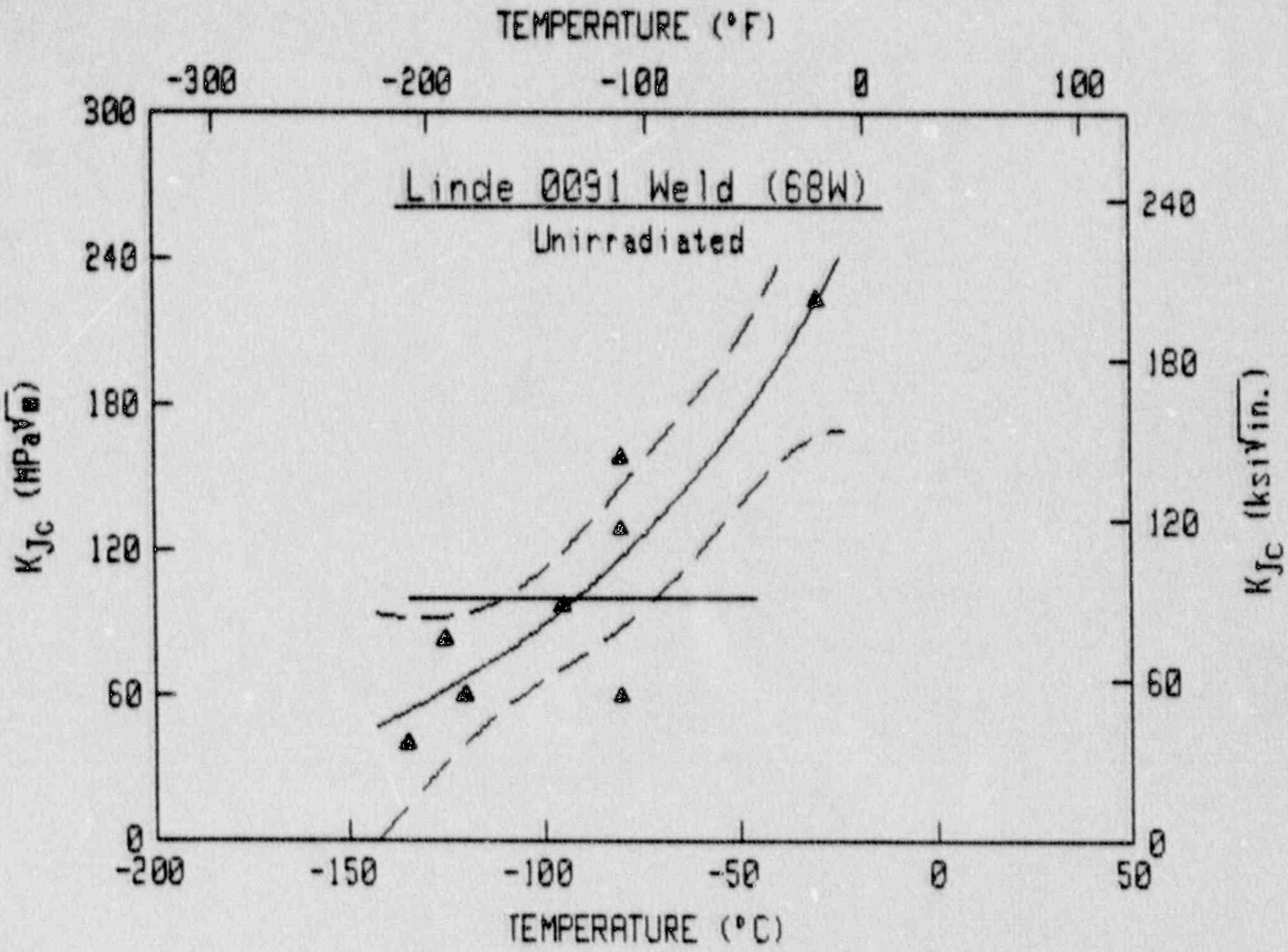
$$K_{jc} = A + B \exp [(T - T_o)/C]$$

	Metric	English
A =	14.64 MPa√m	13.32 ksi√in
B =	66.72 MPa√m	60.72 ksi√in
C =	49.15°C	88.48°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-43°C	-45°F
Mean Curve =	12°C	54°F
Lower Bound =	27°C	81°F

****

Pt #	Temperature	Kjc
1	-35	45.8
2	0	87.2
3	0	94.9
4	15	81.2
5	30	107.5
6	38	210.7
7	50	183.8



****

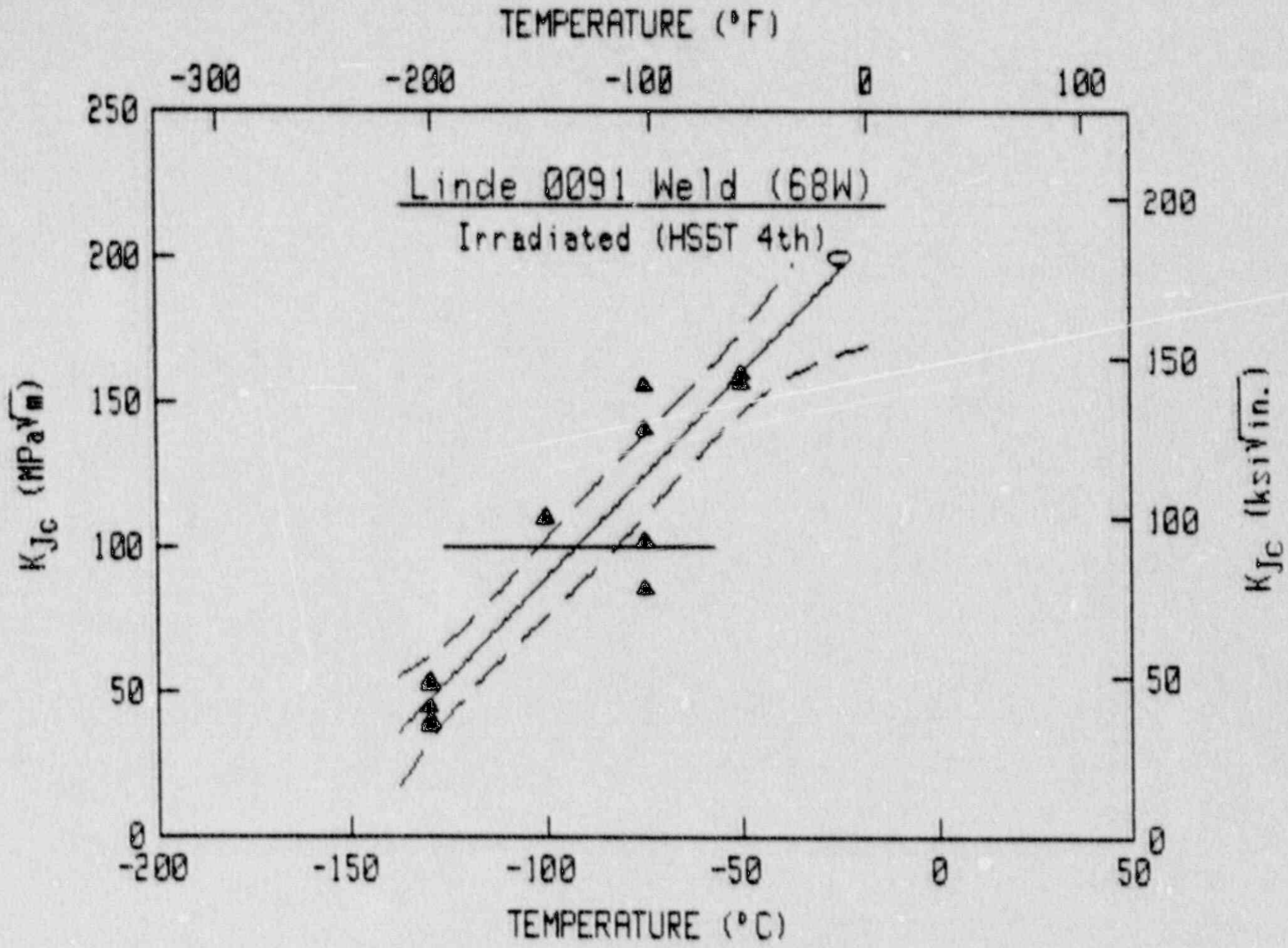
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	-19.51 MPa√m	-17.75 ksi√in
B	=	341.54 MPa√m	310.82 ksi√in
C	=	87.07°C	156.73°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-109°C	-164°F
Mean Curve =	-91°C	-133°F
Lower Bound =	-71°C	-96°F

****

Pt #	Temperature	Kjc
1	-135	40.2
2	-125	83.2
3	-120	59.8
4	-95	97.0
5	-80	128.4
6	-80	59.5
7	-80	158.1
8	-30	223.1



****

Kjc = A + B exp [(T-To)/C)]

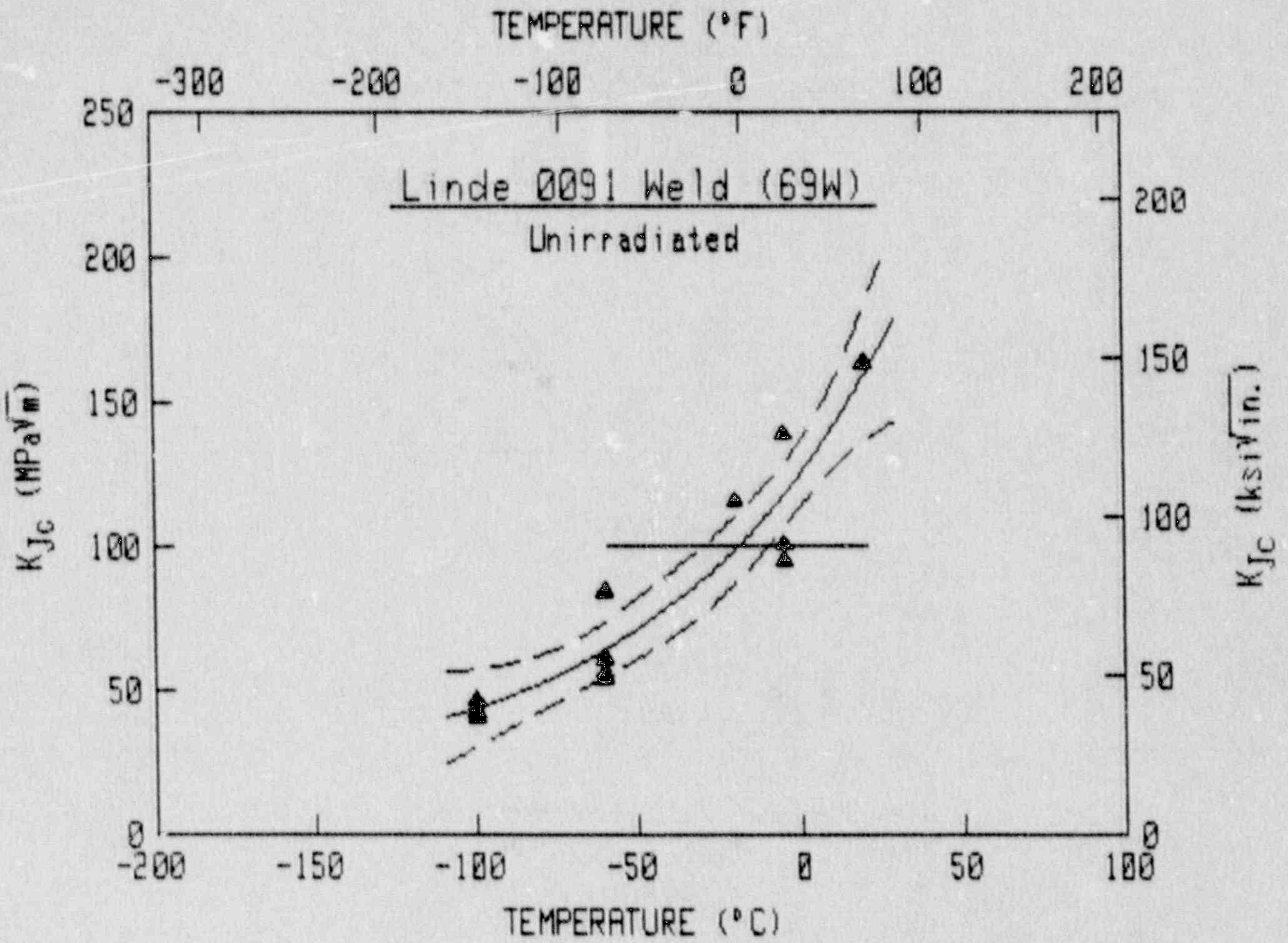
		Metric	English
A	=	-5247.39 MPa√m	-4775.37 ksi√in
B	=	5478.95 MPa√m	4986.11 ksi√in
C	=	3798.68°C	6837.62°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-101°C	-150°F
Mean Curve	=	-92°C	-134°F
Lower Bound	=	-82°C	-116°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-130	39.8	8	-75	85.3
2	-130	52.5	9	-75	102.0
3	-130	38.5	10	-75	155.7
4	-130	53.6	11	-50	156.3
5	-130	44.5	12	-50	159.8
6	-100	110.2	13 *	-25	200.0
7	-75	140.4			

O = Extra Point Added   * = Point Deleted from Fit



****

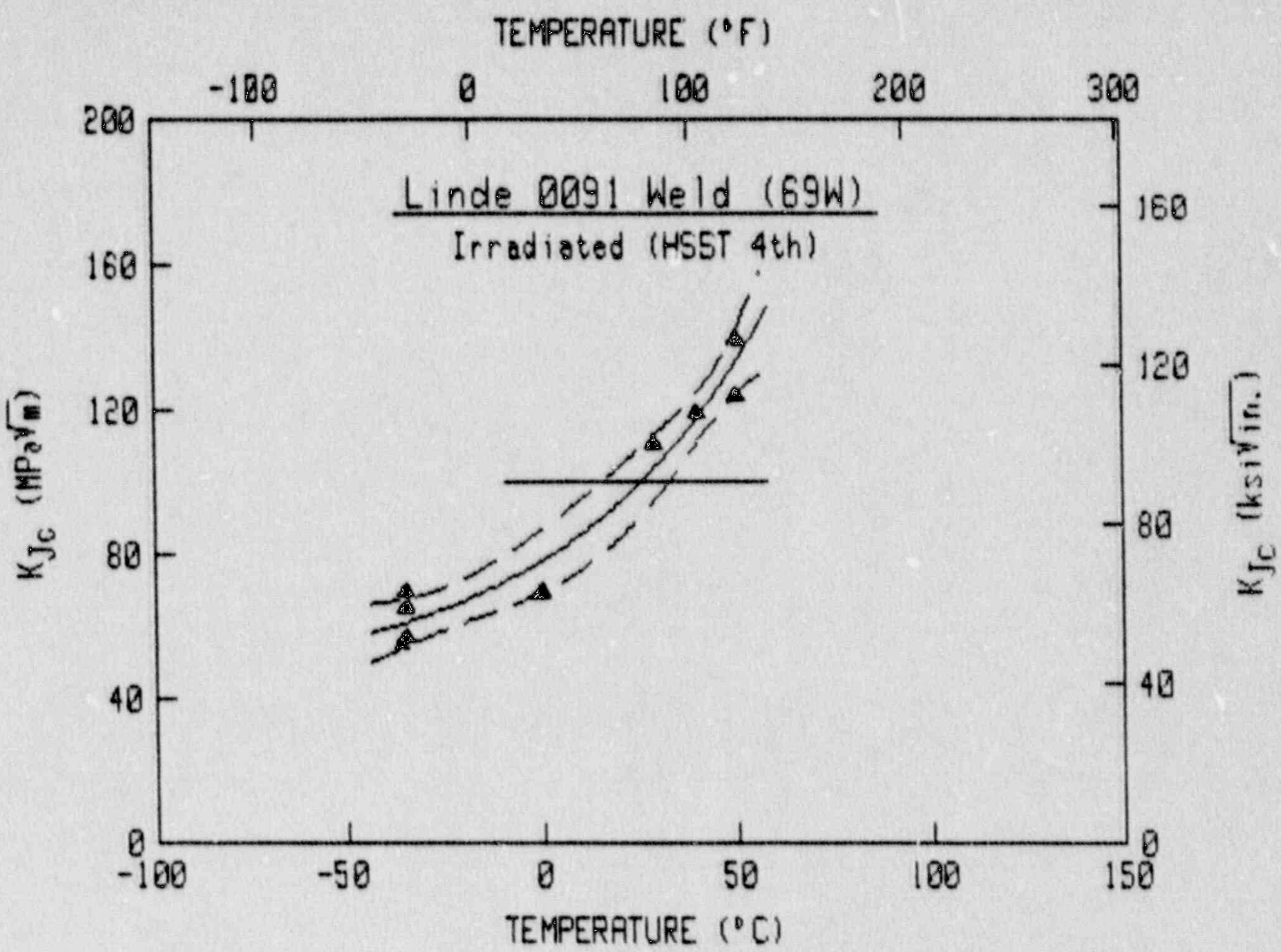
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	16.08 MPa√m	14.64 ksi√in
B =	108.85 MPa√m	99.06 ksi√in
C =	72.96°C	131.32°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-29°C	-20°F
Mean Curve =	-19°C	-2°F
Lower Bound =	-9°C	16°F

****

Pt #	Temperature	Kjc
1	-100	40.7
2	-100	46.6
3	-100	42.4
4	-60	56.1
5	-60	60.8
6	-60	84.2
7	-60	54.1
8	-20	115.4
9	-5	94.9
10	-5	100.5
11	-5	138.8
12	20	163.6



****

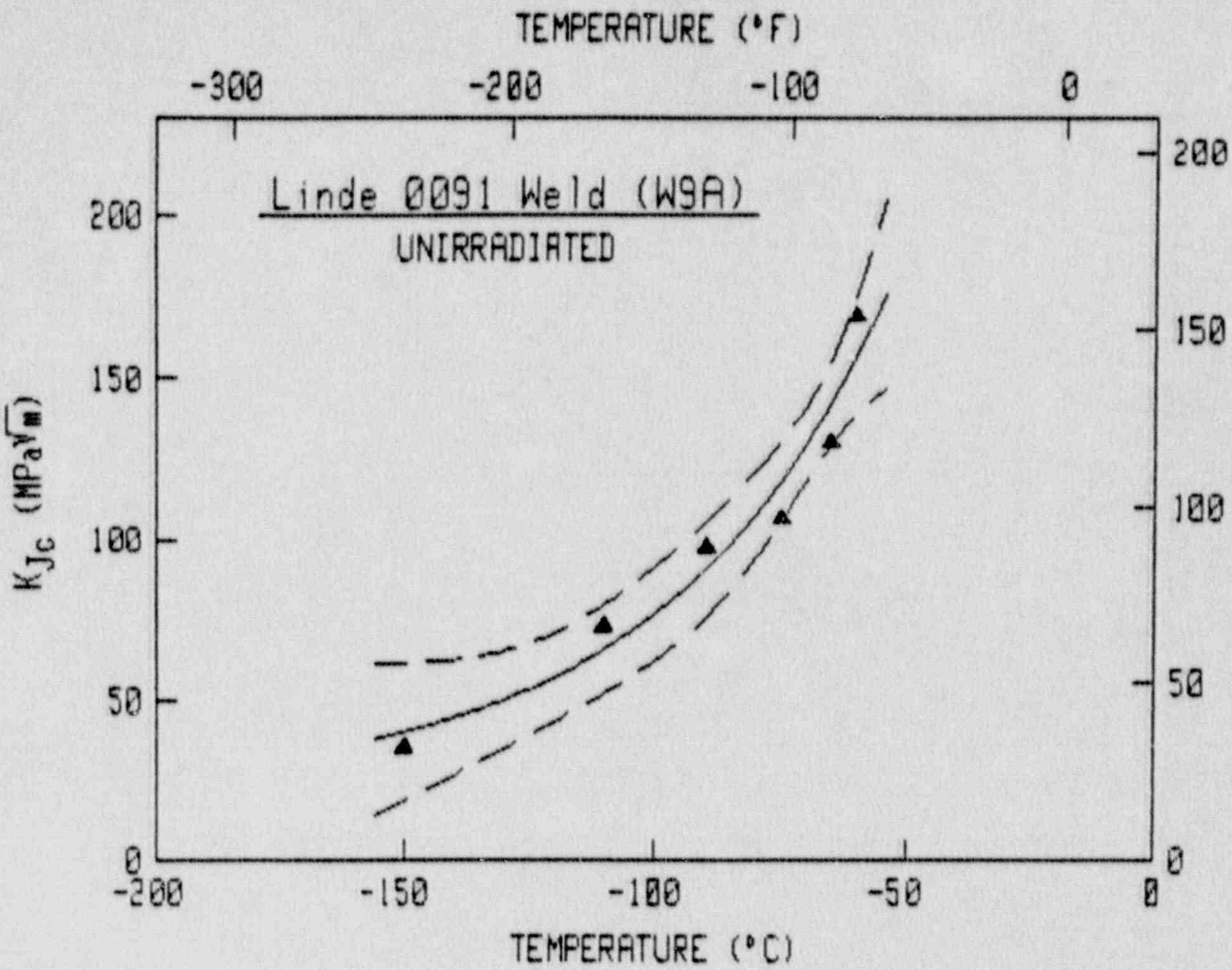
$K_{jc} = A + B \exp[(T-T_o)/C]$

	Metric	English
A =	42.50 MPa√m	38.68 ksi√in
B =	35.57 MPa√m	32.37 ksi√in
C =	53.40°C	96.11°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	16°C	61°F
Mean Curve =	26°C	78°F
Lower Bound =	33°C	91°F

****

Pt #	Temperature	Kjc
1	-36	55.0
2	-35	69.8
3	-35	57.0
4	-35	65.4
5	0	69.2
6	29	110.6
7	40	119.2
8	50	139.4
9	50	123.9



****

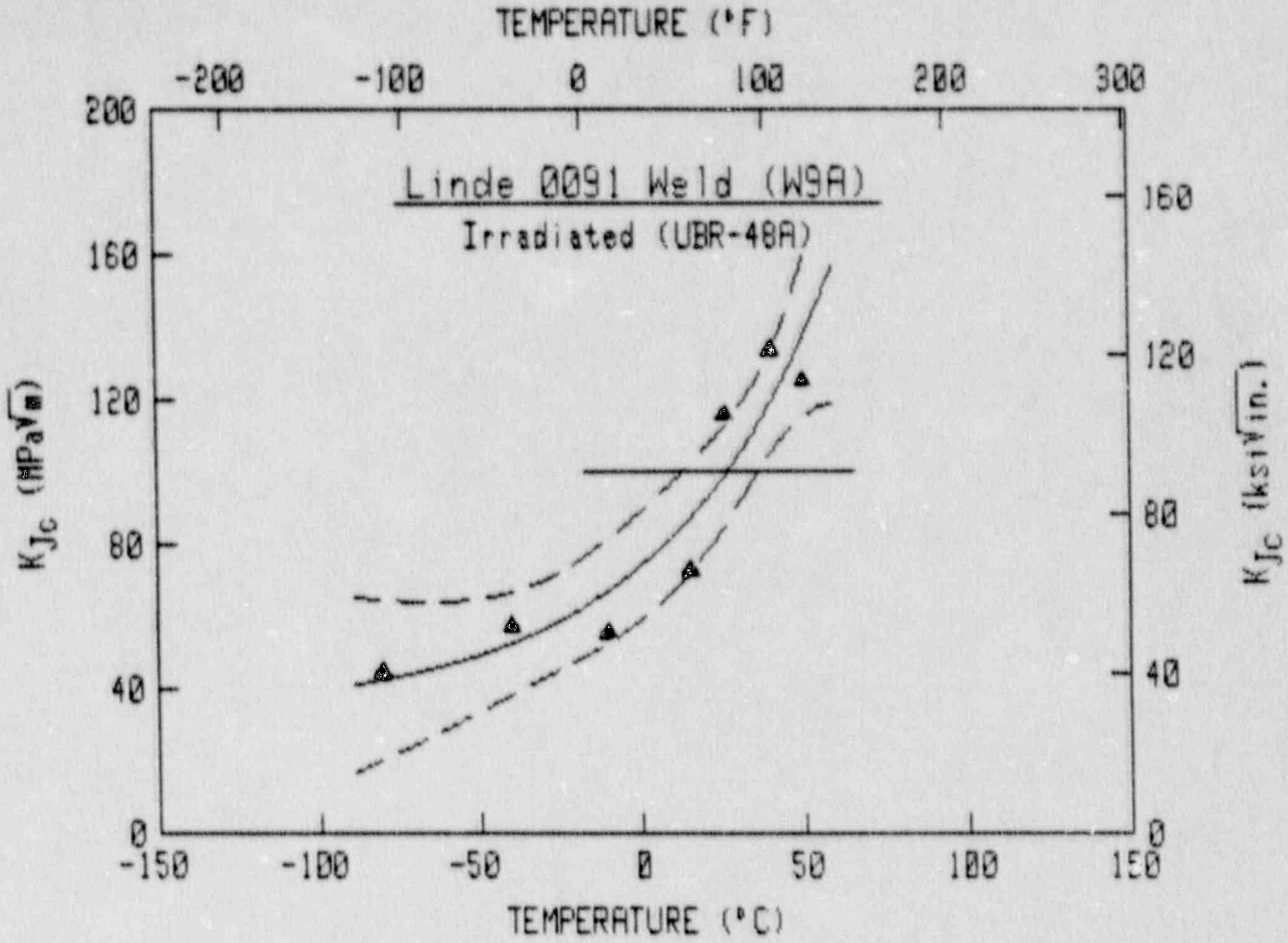
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	22.40 MPa√m	20.38 ksi√in
B	=	519.22 MPa√m	472.51 ksi√in
C	=	44.24°C	79.63°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-93°C	-135°F
Mean Curve =	-84°C	-119°F
Lower Bound =	-77°C	-107°F

****

Pt #	Temperature	Kjc
1	-150	35.4
2	-110	72.7
3	-90	97.6
4	-75	106.4
5	-60	169.3
6	-65	130.1



****

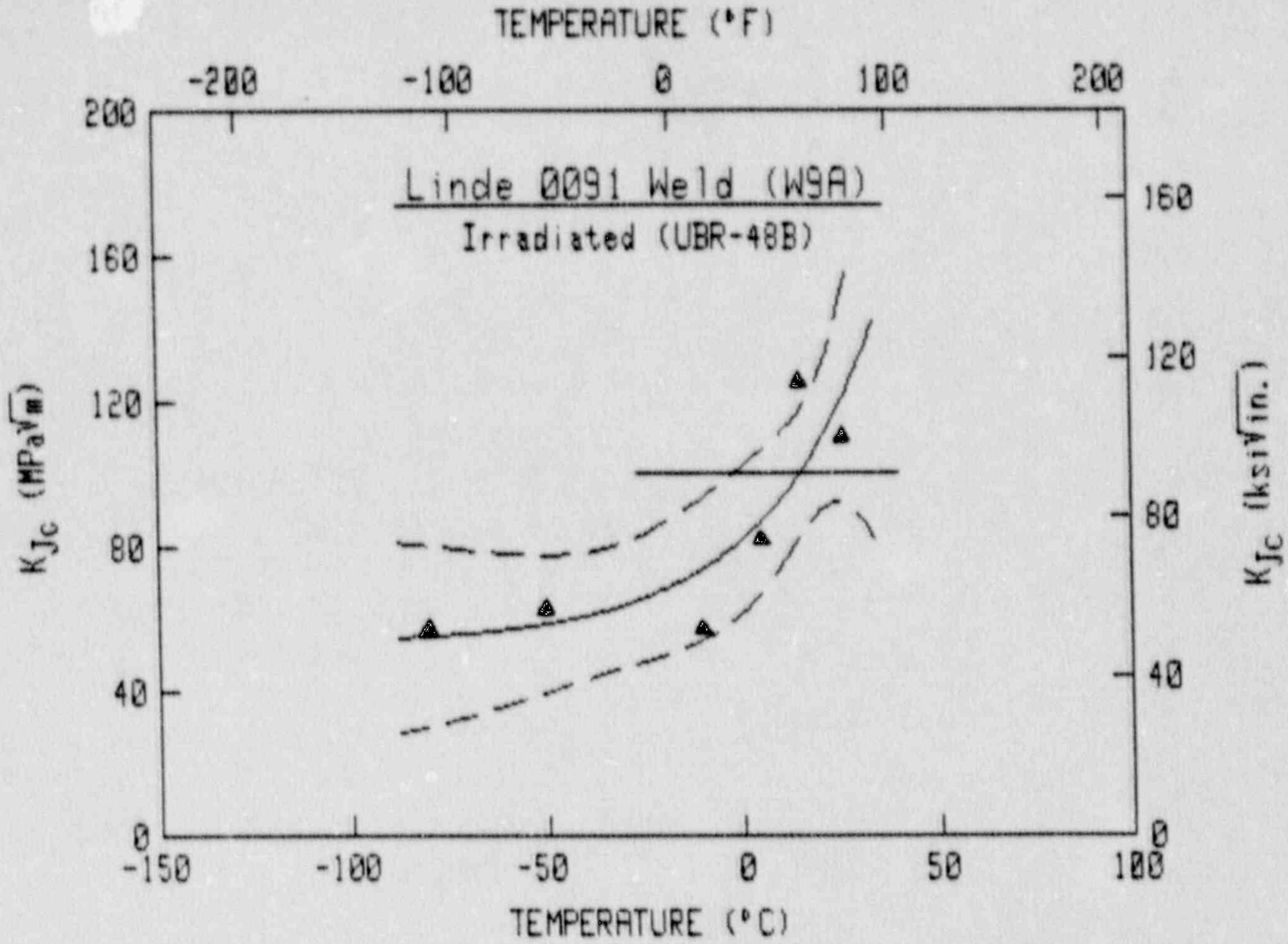
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	33.66 MPa√m	30.64 ksi√in
B =	40.10 MPa√m	36.49 ksi√in
C =	52.66°C	94.79°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	13°C	55°F
Mean Curve =	27°C	80°F
Lower Bound =	36°C	97°F

****

Pt #	Temperature	Kjc
1	-80	44.7
2	-40	57.4
3	-10	55.5
4	15	72.7
5	26	115.9
6	40	133.5
7	50	125.0



****

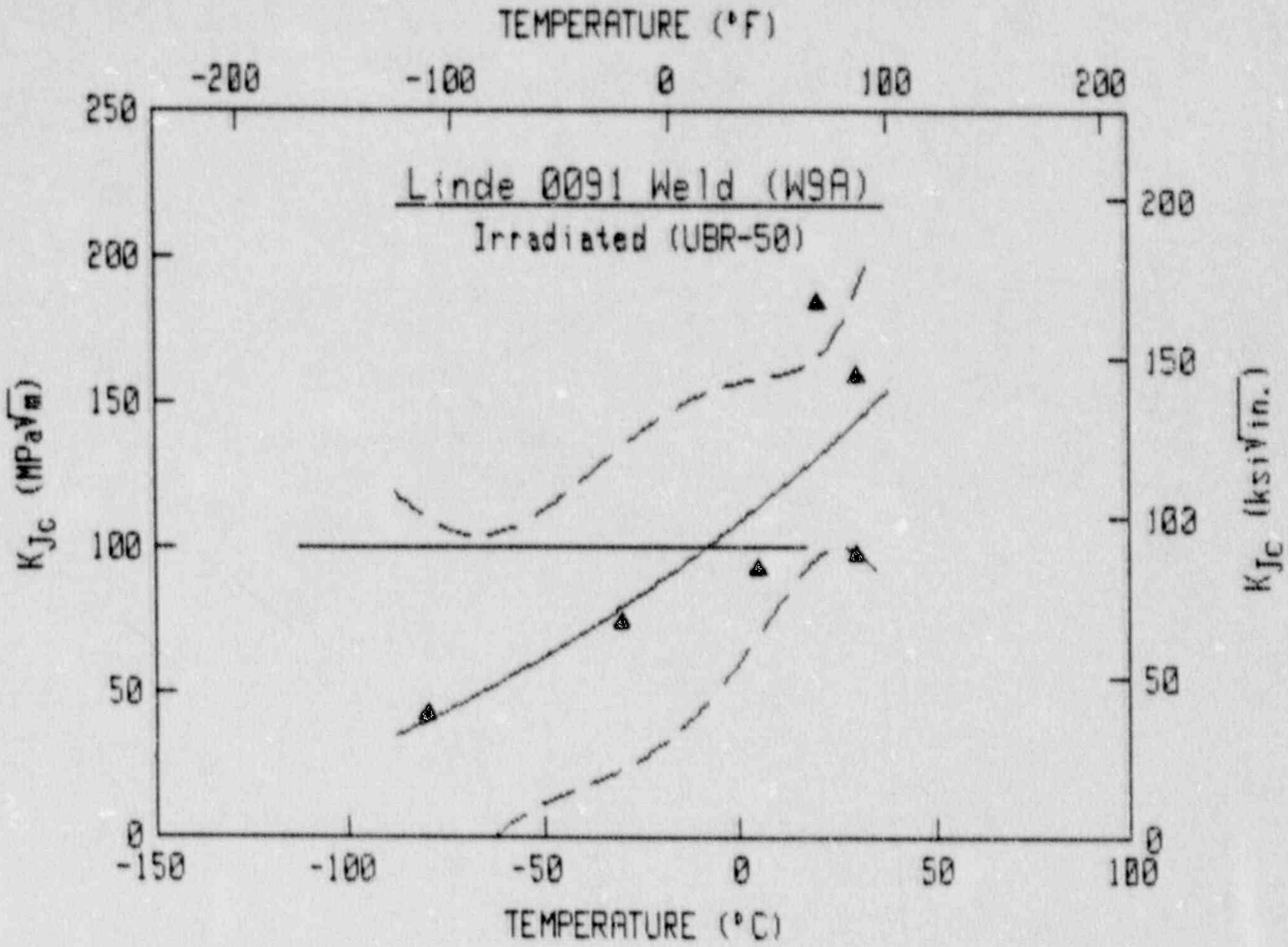
Kjc = A + B exp [(T-To)/C)]

		Metric	English
A	=	53.32 MPa√m	48.52 ksi√in
B	=	28.14 MPa√m	25.61 ksi√in
C	=	29.63°C	53.33°F
To	=	0.00°C	32.00°F

		Temperature at 100 MPa√m	
Upper Bound	=	-1°C	30°F
Mean Curve	=	15°C	59°F

****

Pt #	Temperature	Kjc
1	-80	57.5
2	-50	62.6
3	-10	57.1
4	5	81.8
5	15	125.6
6	26	110.2



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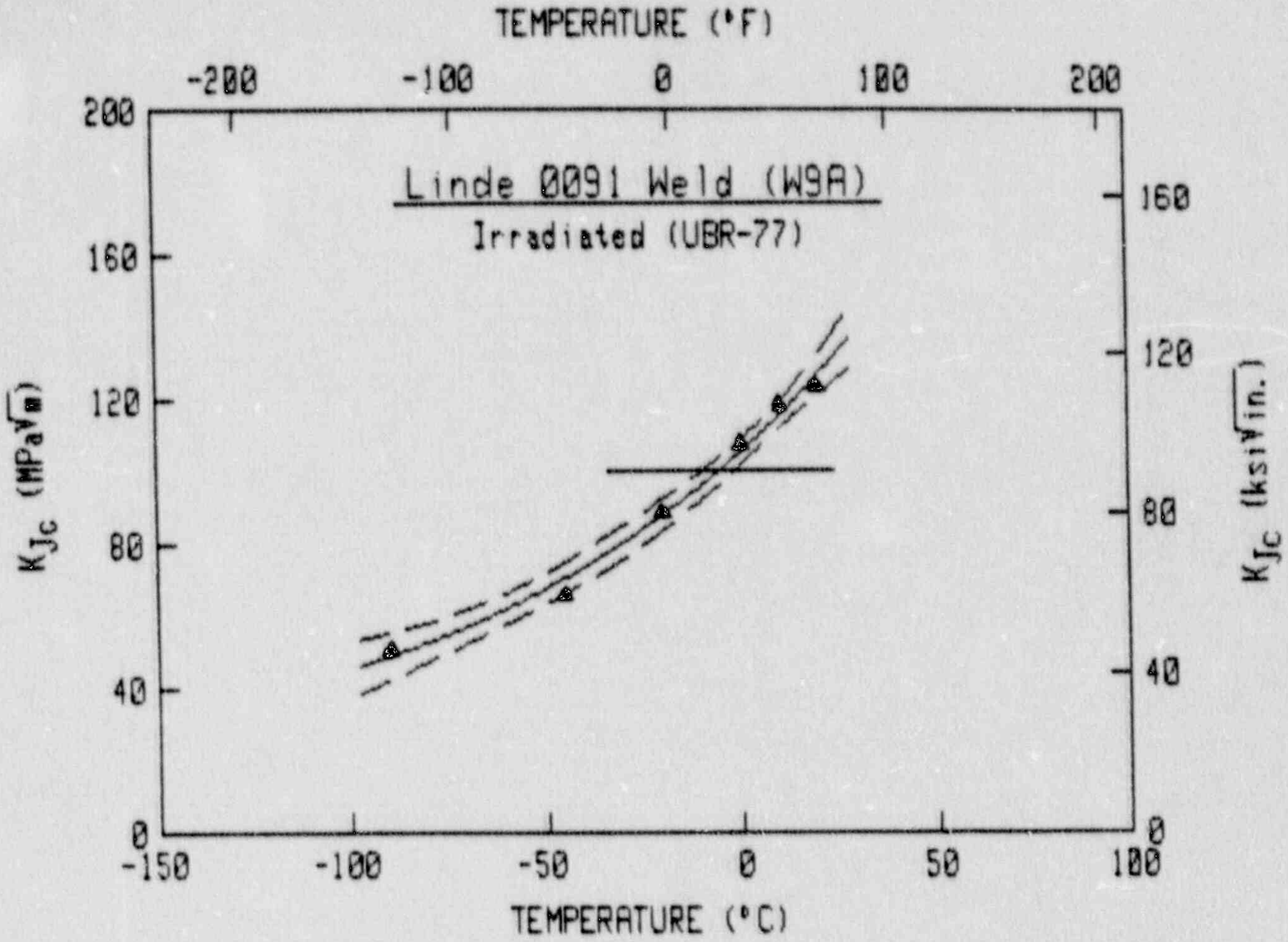
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-70.52 MPa√m	-64.18 ksi√in
B =	178.82 MPa√m	162.74 ksi√in
C =	166.31°C	299.35°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-88°C	-126°F
Mean Curve =	-8°C	18°F

****

Pt #	Temperature	Kjc
1	-80	42.5
2	-30	74.3
3	5	92.6
4	20	184.4
5	30	159.5
6	30	97.7

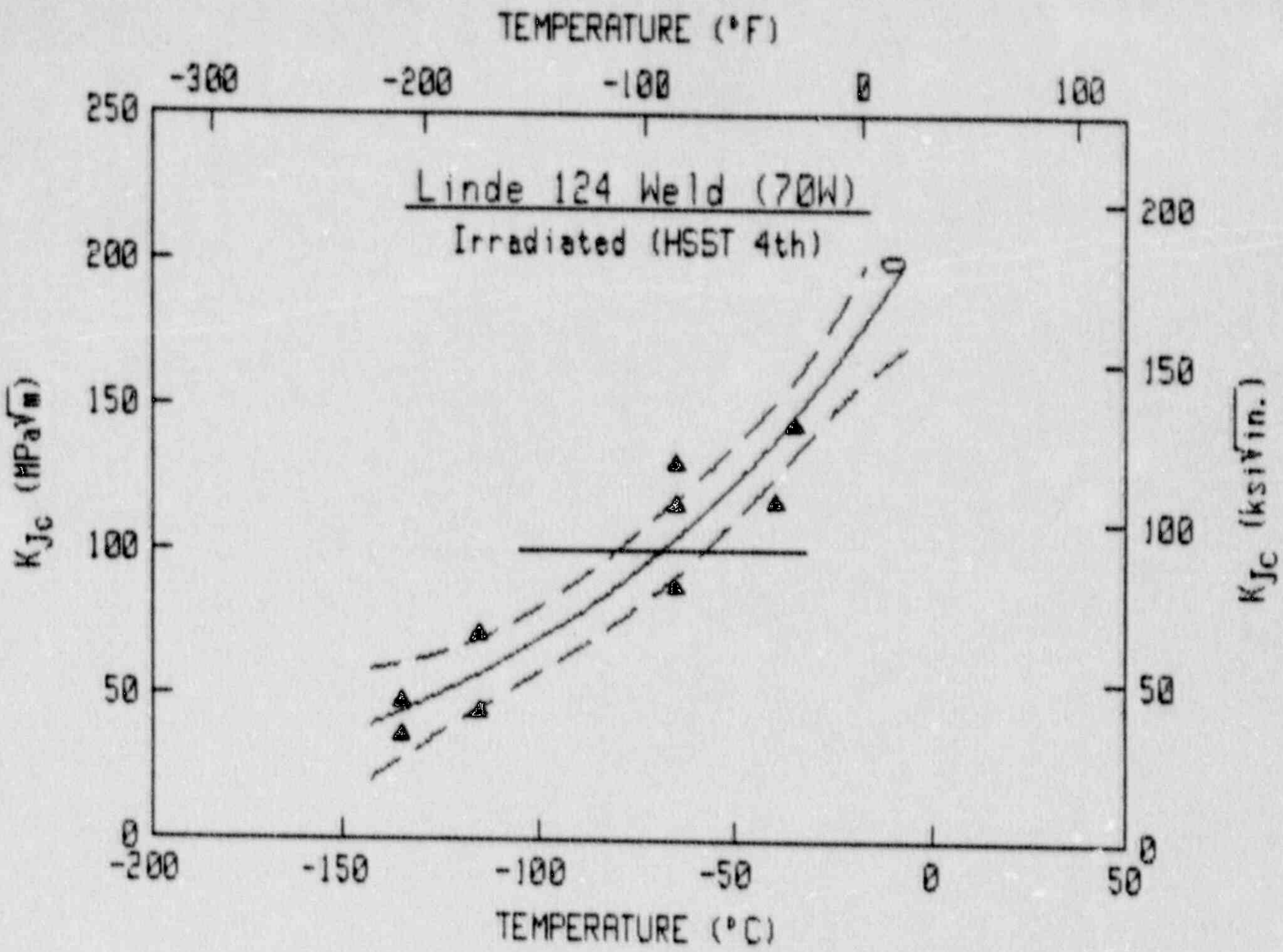


$$K_{jc} = A + B \exp[(T - T_o)/C]$$

		Metric	English
A	=	13.69 MPa√m	12.45 ksi√in
B	=	91.27 MPa√m	83.06 ksi√in
C	=	94.29°C	169.72°F
To	=	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-9°C	16°F
Mean Curve =	-5°C	23°F
Lower Bound =	-1°C	30°F

Pt #	Temperature	Kjc
1	-90	50.6
2	-45	65.7
3	-20	88.4
4	0	107.5
5	10	118.0
6	20	123.1

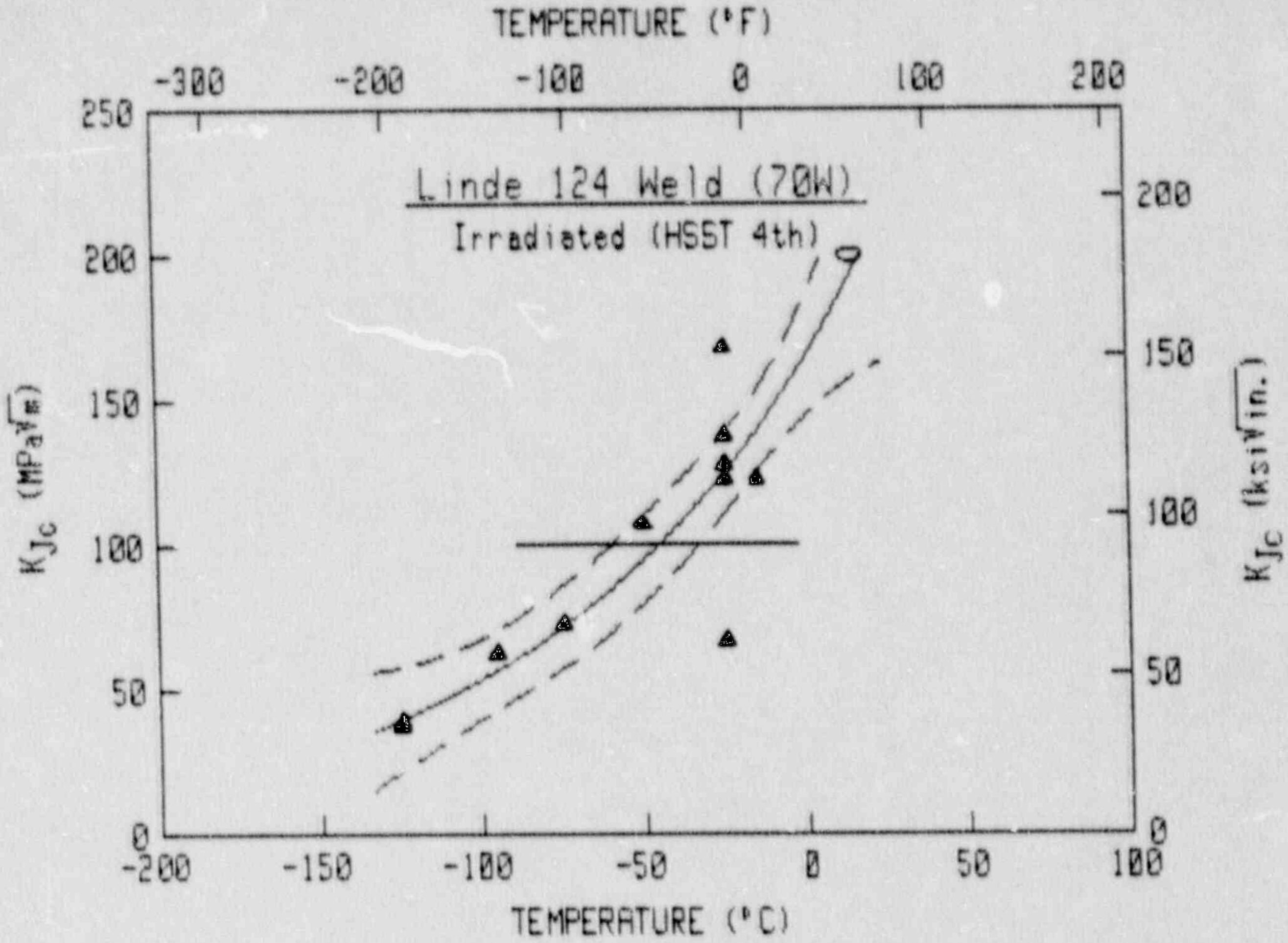


$$Kjc = A + B \exp[(T - To)/C)]$$

	Metric	English
A =	-13.91 MPa√m	-12.66 ksi√in
B =	228.96 MPa√m	208.37 ksi√in
C =	98.13°C	176.64°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-80°C	-112°F
Mean Curve =	-69°C	-91°F
Lower Bound =	-57°C	-71°F

Pt #	Temperature	Kjc
1	-135	47.3
2	-135	35.9
3	-115	71.1
4	-115	44.1
5	-65	116.0
6	-65	87.2
7	-65	130.1
8	-40	116.8
9	-35	143.5
10 O	-10	200.0



****

Kjc = A + B exp [(T-To)/C)]

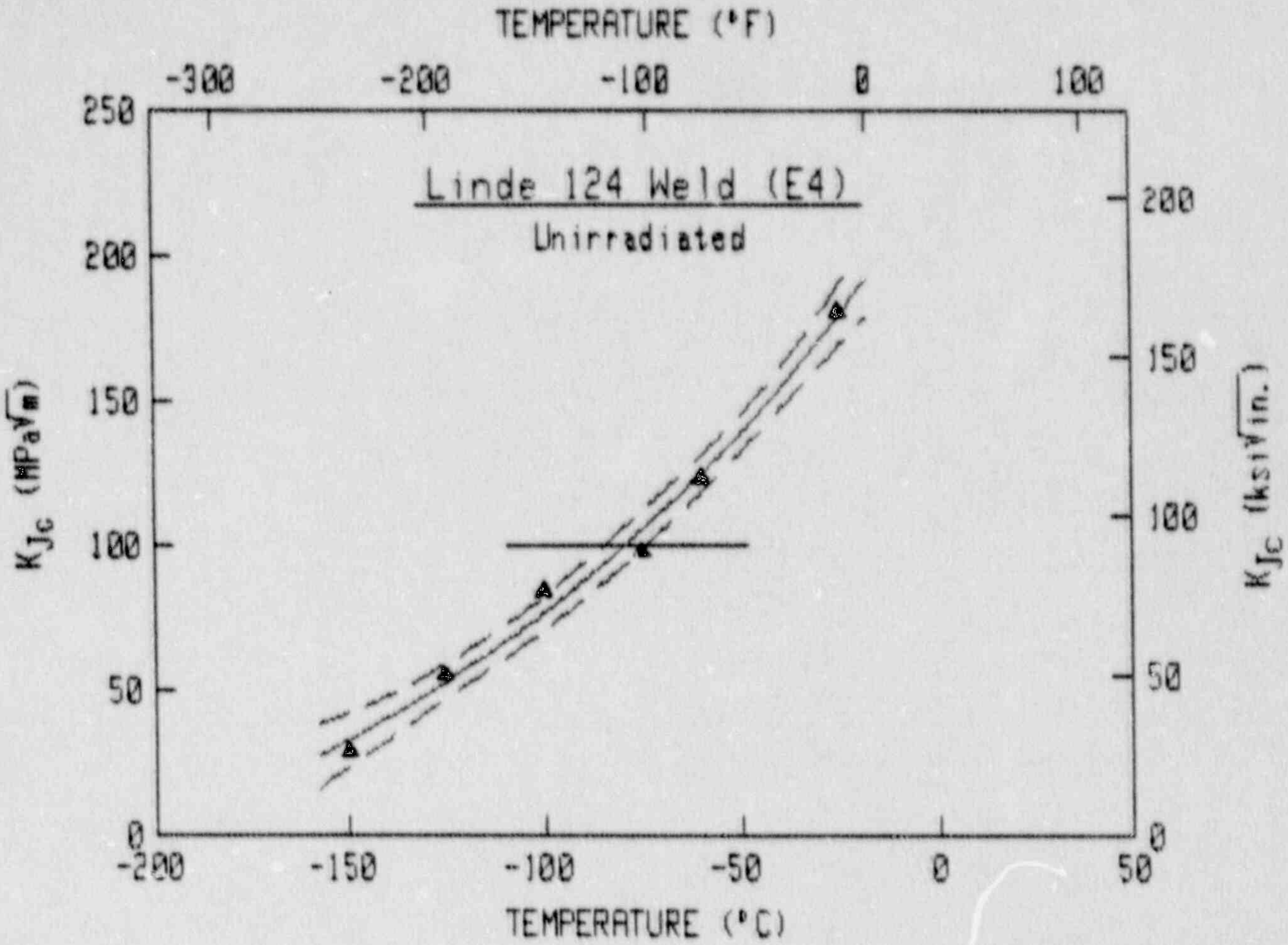
	Metric	English
A =	-5.93 MPa√m	-5.40 ksi√in
B =	170.28 MPa√m	154.96 ksi√in
C =	94.85°C	170.74°F
To =	0.00°C	32.00°F

Temperature at 100 MPa√m		
Upper Bound =	-59°C	-74°F
Mean Curve =	-45°C	-49°F
Lower Bound =	-32°C	-26°F

****

Pt #	Temp.	Kjc	Pt #	Temp.	Kjc
1	-125	36.9	8	-25	168.1
2	-125	37.9	9	-25	137.6
3	-125	37.3	10	-25	127.6
4	-125	39.0	11	-25	66.7
5	-95	62.5	12	-25	122.6
6	-75	72.4	13	-15	122.8
7	-50	107.2	14 *	15	200.0

0 = Extra Point Added * = Point Deleted from Fit



****

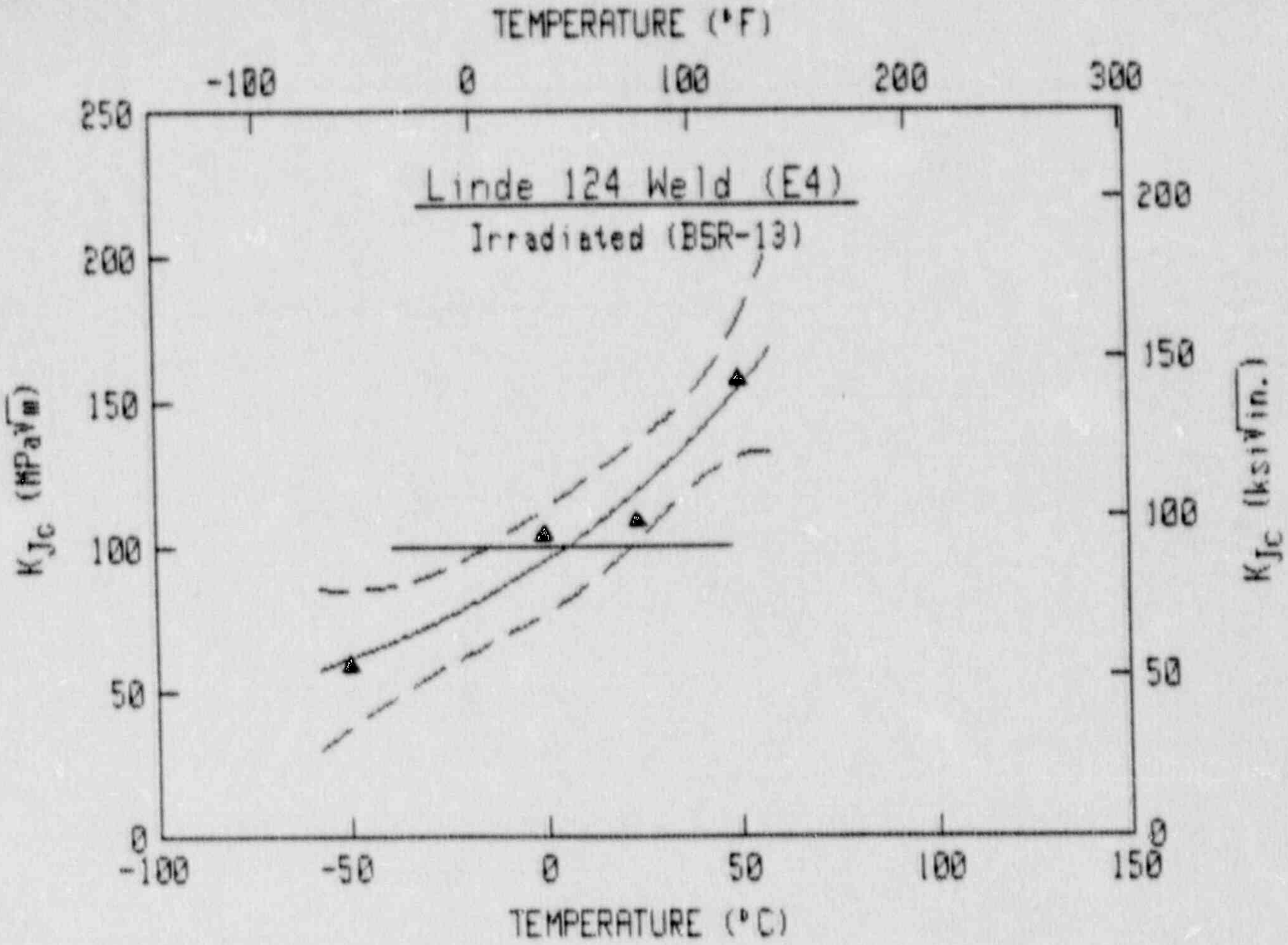
Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	-70.51 MPa√m	-64.17 ksi√in
B =	298.26 MPa√m	271.43 ksi√in
C =	141.49°C	254.67°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-84°C	-119°F
Mean Curve =	-79°C	-110°F
Lower Bound =	-73°C	-99°F

****

Pt #	Temperature	Kjc
1	-150	29.3
2	-125	55.3
3	-100	84.2
4	-75	97.9
5	-60	123.6
6	-25	181.0



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Kjc = A + B exp [(T-To)/C)]

	Metric	English
A =	19.55 MPa√m	17.79 ksi√in
B =	75.18 MPa√m	68.42 ksi√in
C =	85.22°C	153.40°F
To =	0.00°C	32.00°F

	Temperature at 100 MPa√m	
Upper Bound =	-14°C	7°F
Mean Curve =	6°C	42°F
Lower Bound =	23°C	73°F

****

Pt #	Temperature	Kjc
1	-50	59.1
2	0	104.4
3	24	108.8
4	50	157.7

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Reactor pressure vessel (RPV) surveillance capsules contain Charpy-V (C_v) specimens, but many do not contain fracture toughness specimens; accordingly, the radiation-induced shift (increase) in the brittle-to-ductile transition region (ΔT) is based upon the ΔT determined from notch ductility (C_v) tests. Since the ASME K_{Ic} and K_{IR} reference fracture toughness curves are shifted by the ΔT from C_v, assurance that this ΔT does not underestimate ΔT associated with the actual irradiated fracture toughness is required to provide confidence that safety margins do not fall below assumed levels.

To assess this behavior, comparisons of ΔT's defined by elastic-plastic fracture toughness and C_v tests have been made using data from RPV base and weld metals in which irradiations were made under test reactor conditions.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)
Notch ductility, fracture toughness, radiation embrittlement, nuclear pressure vessel steels and welds, test method correlations, fluence rate effects

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