DATE ISSUED JAN 20 1979

[redacted]

Fast Breeder Reactors

POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

ORNL/Sub-4291/1
TR-MCD-015

A PROGRAM FOR THE DEVELOPMENT OF ADVANCED FERRITIC ALLOYS FOR LMFBR STRUCTURAL APPLICATION

Approved by: P. E. C. Bryant
Director
Materials and Chemistry Development

Date: September 20, 1977

ORNL/Sub-4291/1
TR-MCD-015

A PROGRAM FOR THE DEVELOPMENT OF ADVANCED FERRITIC ALLOYS FOR LMFBR STRUCTURAL APPLICATION

Topical Report

September, 1977

by

G. C. Bodine, Jr.*
B. Chakravarti*
C. M. Owens
B. W. Roberts*
D. M. Vandergriff*
C. T. Ward*

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Prepared for Oak Ridge National Laboratory operated by Union Carbide Corporation for the U. S. Energy Research and Development Administration.

Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095

*Metallurgical and Materials Laboratory, Chattanooga, Tenn.

LEGAL NOTICE

This report was prepared by Combustion Engineering, Inc., as an account of work sponsored by Union Carbide-Nuclear Division. Neither Union Carbide, members of Union Carbide, nor Combustion Engineering, Inc., nor any person acting on behalf of either:

a. Makes any warranty or representation, express or implied including the warranties of fitness for a particular purpose of merchantability with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

b. Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

TABLE OF CONTENTS

		Page
I.	ABSTRACT	5
II.	INTRODUCTION	6
III.	BASE METAL DEVELOPMENT	8
	A. Introduction	12
	B. Experimental Procedure	17
	C. Results and Discussion	18
IV.	MELTING AND CONSOLIDATION PRACTICE	60
	A. Experimental Heats	63
	B. Consolidation Practice	63
	C. Hardware Manufacturing - Tubing	64
V.	WELD FILLER METAL DEVELOPMENT	71
	A. Introduction	75
	B. Experimental Procedure	76
	C. Results and Discussion	80
VI.	CREEP AND STRESS RUPTURE	156
	A. Introduction	162
	B. Experimental Procedure	162
	C. Results and Discussion	163
VI.A	CODE CASE 1592 ALLOWABLE DESIGN STRESSES	170
	A. Derivation	170
	B. Definition and Discussion	170
	1. S_o - Maximum Allowable Value Of General Primary Membrane Stress Intensity	170
	2. S_m - Time Independent Design Stress Intensity	172
	3. S_y - Yield Strength Of A Material At A Given Temperature	172
	4. S_t - Time Dependent Design Stress Intensity	172
	5. S_{mt} - General Membrane Stress Intensity	173
		249

TABLE OF CONTENTS (cont.'d)

		Page
VII.	SUMMARY	249
VIII.	ACKNOWLEDGEMENT	260
IX.	APPENDIX	261

I. ABSTRACT

The development program described was initiated to provide an alternate code-approved advanced ferritic alloy for LMFBR structural use. Appproximately thirty (30) laboratory heats were melted of the type 9Cr-1Mo-Nb-V. The elevated temperature properties of the experimental alloys are superior to code-approved and commercial candidate steels. Code Case 1592 allowable stress intensities have been calculated and are compared to other candidates. Improvements realized in weldability, toughness, and elevated temperature performance are discussed.

II. INTRODUCTION

Advanced stabilized 9% chromium-molybdenum ferritic steels are particularly attractive when compared with existing ASME Code-approved alloys. These advanced ferritics provide significantly higher strength and stability relative to 2-1/4 Cr-1 Mo (Grade 22). This advantage reduces much of the need for inelastic design analysis and increases safety margins related to accident conditions. Data to date indicate that the 10^5-hr stress to rupture strength should be at least twice that of Grade 22 in the temperature range 500 to 600° C. Properties of the advanced ferritics are also particularly impressive when their estimated S_o values (by ASME criteria) are contrasted with established S_o values for austenitic alloys and ferritic Grade 22 from ASME Case 1592-7.

Additional benefits of the advanced ferritic alloys over Grade 22 include: increased carbon stability, improved resistance to thermal shock, and enhanced corrosion resistance. The characteristic higher yield strength, lower thermal expansion, higher thermal diffusivity, and improved resistance to caustic and chloride stress corrosion cracking render the advanced ferritics superior to austenitic candidates for the intended service. Also the advanced ferritics may resist both radiation-induced swelling and helium embrittlement as necessary for incore applications.

Although some of the commercial ferritics might be classified as advanced, apparently none exhibited a completely optimum combination of desired stability toughness, and weldability. This report describes

development of an advanced stabilized ferritic alloy with composition optimized to enhance elevated temperature strength, stability, weldability, and toughness.

Included is a candidate alloy selection phase, to be followed by a comprehensive effort related to water/steam-side corrosion, sodium compatibility, and fabrication technology. The end objective is to provide the extensive mechanical property test matrix necessary for ASME Code approval. Candidate alloy evaluation is in progress, and final selection will be completed in late 1978.

SECTION III

BASE METAL DEVELOPMENT

B. Chakravarti

LIST OF TABLES

Table No.		Page
1	Comparison of Charpy Properties for all Heats in the Normalized and Tempered Condition and Normalized, tempered and Aged Condition	27
2	Comparison of Charpy Properties of Modified 9Cr-1Mo Alloys Versus 2-1/4Cr-1Mo and HT9 Alloys	29
3	Atomic Absorption Analyses of Trace Elements in 9Cr-1Mo Modified Alloys	30
4	Transformation Temperatures of Modified 9Cr-1Mo Alloys	32

LIST OF FIGURES

		Page
1(a-d)	Constitution diagrams for Cr-Mo-V alloys, showing equilibrium carbide phase fields	33
2.	SEM photographs of Charpy sample of ESR XA 3171, aged 2000 hours, at 950° F and broken at -80° F, showing cleavage fracture	34
3.	SEM photograph of Charpy sample of ESR HT 91887, aged 2000 hours, 950° F, and broken at 0° F, showing cleavage fracture	35
4.	Optical micrographs of unaged and aged samples of ESR XA 3177	36
5.	Optical micrographs of unaged and aged samples of ESR XA 3178	37
6.	Optical micrographs of unaged and aged samples of ESR XA 3181	38
7.	Optical micrographs of unaged and aged samples of ESR HT 91887	39
8.	Plot of percent nickel versus shift in 50 ft-lb values after aging	40
9.	Plot of percent silicon versus shift in 50 ft-lb values after aging	41
10.	Plot of percent nitrogen versus shift in 50 ft-lb values after aging	42
11(a-b)	Nomarski micrographs of ESR XA 3177 after normalizing and after normalizing and tempering	43
12(a-b)	Nomarski micrograph of ESR HT 91887 after normalizing and after normalizing and tempering	44
13.	Optical micrographs of unaged samples of ESR XA 3186	45
14.	Optical micrographs of unaged samples of ESR XA 3187	46
15.	Optical micrographs of unaged samples of ESR XA 3217	47
16(a-c)	Extraction replica showing distribution of carbides after normalizing and tempering ESR XA 3187	48
17.	Extraction replicas showing differences of carbide size and distribution between Heats ESR XA 3177 and ESR HT 91887	49
18.	Extraction replica showing distribution of fine matrix carbides in normalizing and tempering ESR HT 91887	50

		Page
19.	TEM micrograph of normalized ESR XA 3177 showing lath martensitic structure	51
20(a-b)	TEM micrographs of normalized and tempered ESR HT 91887, showing tempered lath martensitic structure	52
21.	TEM micrograph of ESR HT 91887, showing fine matrix carbides inhibiting recovery and precipitating on dislocations	53
22.	Photograph of ESR HT 91887, 5000 lb ingot	54
23.	Macrostructures of as-cost ESR HT 91887 ingot, top and bottom sections	55
24.	Microstructure of as-rolled and normalized plate of ESR HT 91887, showing distribution of inclusion	56
25(a-b)	Microstructures of hot worked and heat treated samples from top and bottom of ESR HT 91887	57
26.	Plot of Charpy curves of ESR HT 91887, showing effect of hot working finishing temperatures	58
27.	Microstructures of ESR HT 91887 after hot working and finishing at different temperatures	59

III. BASE METAL DEVELOPMENT - B. Chakravarti

A. Introduction

It is known that when the 9Cr-Mo alloy is properly balanced with respect to ferrite and austenite formers, no free δ-ferrite remains in the microstructure in the normalized and tempered condition. Free δ-ferrite is undesirable because it reduces both strength and toughness, especially in the transverse properties. Several attempts (1-3) have been made previously at calculating chromium equivalency. A formula developed by Newhouse, et al, (3), and expanded by C-E was used in this work and is as follows:

Chromium equivalent -

%Cr + 6%Si + 4%Mo + 1.5%W + 11% V + 5% Nb + 8%Ti + 12%Al - 40%C - 30%N - 4%Ni - 2% Mn - %Cu

Through use of this formula, the influence of alloy modifications on microstructure and properties was evaluated. The object was to obtain 100% martensite on normalizing. Results from the initial trials indicated that a chromium equivalent of approximately 10.00 was necessary to avoid formation of the free δ-ferrite.

A nominal 9% chromium was maintained in all experimental alloys. There is no strength advantage in adding larger quantitites, since chromium contributes little to the strengthening of the iron base (4,5). Larger amounts in fact degrade toughness by forming twin martensites (4), and unbalance the 100% martensitic structure. The internal defect structure of martensite (twinned or dislocated) while not directly relatable to the deformation mode during fracture, is indirectly relatable to toughness through factors such as dislocation pinning and the inability of partial twinning dislocations to cross slip and so blunt an advancing crack tip. On the practical side,

9% chromium would be a significant improvement over the reference alloy 2-1/4Cr-1Mo in making the alloy resist rusting, thus significantly facilitating field and shop fabrication of large components for a clean sodium system.

The heavily dislocated substructure produced by the martensitic reaction on normalizing and air cooling the Fe-Cr-Mo-C alloy provides an excellent substructure for good creep strength if it can be stabilized by precipitation. Creep strength of the bcc solid solution has been explained by Argent, et al, (5), in terms of influence of alloying on the recovery of the 3-dimensional dislocation substructure present in the material. This is characterized by differences in interaction energies due to atomic size and compressibility and the order of effectiveness for Fe base solid solution is then Nb, Al, W, Mo, V, Si, Mn, Cr, and Ni. He shows that molybdenum is a very effective strengthening element which appears to saturate the dislocation networks in ferritic steels at approximately 1%. Further additions of molybdenum does not produce an increase in strength. For vanadium containing alloys, vandium-carbom atom groupings apparently form on dislocations (5) and confer considerable creep strength. The carbides of chromium and vanadium are effective only for a limited time, for when they grow,interparticle spacing becomes larger than the elements of the 3-dimensional dislocation network. Niobium carbides on the other hand grow more slowly and thus a fine dispersion can confer considerable creep strength. This is because of either a reduced coarsening rate of MX carbide or an increase in the number of VC pairs available to pin dislocations.

On the other hand, Baird, et al, (6), suggest that molybdenum imparts marked creep strength in solid solution provided appreciable amounts of carbon and/or nitrogen are also present. He showed that 1% Mo added to interstitial free iron produces a limited amount of creep strengthening, and adding 0.01% C or N to the binary alloy produced a large increase in initial creep strength due to interaction solid solution strenthening. Thus, in the substitutional-interstitial alloys, precipitation of alloy carbides and nitrides occurs during creep on dislocations and in the grain boundaries. This depletes the solid solution of interstititals and thus reduces the magnitude of the interaction solid solution strengthening. The high long-term creep strength of the C-E experimental alloys is attributed to the fine dispersion of the precipitate particles on dislocations generated during creep, or to the dislocation substructure produced by this process.

In the nominal 9Cr-1Mo alloy the carbide precipitate is $M_{23}C_6$ and M_7C. Matrix structure is an important variable in determining coarsening rate. Fine grain size and dislocation substructure inherited from martensite cause a significant increase in coarsening rate. It has been shown by Van Niekerk, et at, (10), that molybdenum does not affect the coarsening rate of $M_{23}C_6$ as it retards for M_3C and accelerates for M_7C_6 in chrome-molybdenum steels. This is rather fortunate since molybdenum is known to have a pronounced effect on the recovery of iron, which would tend to favor the coarsening process. The absence of the effect may be explained by the fact that $M_{23}C_6$ is associated with high chromium steels, where easy access to chromium is always available to the growing carbides. Thus, the influence of molybdenum in improving the creep strength of ferritic steels containing $M_{23}C_6$ cannot be explained by the effects of this element on the coarsening rate of the carbides

but by solid solution or interaction solid solution strengthening. The nature of the carbides and their coarsening rate determine to an extent (being one factor only) the stability of the alloy and its behavior to high temperature creep. Thus, the 2-1/4 Cr-1Mo alloy which has large amounts of Mo_2C precipitated, show comparable creep properties when compared to the 9Cr-1Mo (T9) alloy, even though the latter has much higher alloying content.

The coarsening rate for the equilibrium carbide in 9Cr-1Mo alloy can be reduced by introducing vanadium to the alloy, such that vanadium enters the $M_{23}C_6$ carbide. The amount of vanadium addition required has to be selected properly so that no transitionary carbides form. The constitution diagrams of Andrews, et al, (11), help in selecting the amounts of alloying additions to make. Figures 1 (a-d) are sections showing the equilibrium carbide fields present. In comparing Figures 1a and b, we see that adding V to the Fe-Cr-Mo alloy severely restricts the $M_{23}C_6$ carbide field, and at 0.5%V, Mo content has to be restricted to 0.8% or less if a singular $M_{23}C_6$ carbide is to form. Figure 1c shows similar results, i.e., with Fe-9Cr-1Mo alloy $M_{23}C_6$ forms, while Figure 1d shows that with increasing Mo to 2%, there exists no possibility of avoiding the formation of M_6C. Thus, by restricting the additions of Mo and V together the formation of M_6C, which generally forms in a massive manner at grain boundaries, can be avoided.

Truly the most remarkable alloying effects are due to minute additions of boron, for it supposedly increases elongation,rupture stress, and 'n', (the stress dependence of creep rate), when added in the proper amounts. It is widely agreed that boron serves at the grain boundaries because of its odd atomic size. In molybdenum containing steels boron increases the amount of $M_{23}C_6$ (12) carbide and

suppresses, if any tendency exists,the formation of a Fe_2MoC and M_6C. Boron is also recognized to retard the evolution of depleted zone at the grain boundaries and thus sharply effect 'n'.

To make the alloy resistant to temper and other embrittlement, it is necessary that the formation of transitionary carbides be avoided and that the equilibrium carbide ($M_{23}C_6$) forms initially (13). This is achieved by tempering the alloy as high as possible to the Ac_1 and controlling the composition so that only a singular equilibrium carbide forms.

Additions of nickel were kept at a minimum to avoid embrittlement problems. Nickel is known to reduce the solubilities of embrittling elements (e.g., Sb) in the matrix as shown by Nageswararao, et al, (14), which results in embrittlement at the grain boundaries. Marrison and Hogg (15), examined the effect of nickel on 12Cr-Mo-V-Nb steels and showed that nickel has a marked effect on the stability ofthe $M_{23}C_6$ carbide , by accelerating its coarsening rate. Thus, alloys containing high nickel content contained unstable carbide structures and low creep strength, while those containing low nickel content were associated with high creep strength.

Additions of Nb was restricted so as not to form Fe-Nb eutectics by segregation, which causes severe decrease in toughness properties. The Nb forms Nb (CN), which precipitates in austenite during hot rolling and refines the austenitic grain size. This refinement is primarily responsible for the excellent room temperature Charpy properties observed. These Nb (CN) precipitates are not affected by the normalizing and tempering heat treatment. The fine precipitate it forms stabilizes the substructure that forms, and since its coarsening rate is low, the effect on creep strength of the material is, therefore, substantial.

Based on this, a series of alloys were made with controlled compositions described in the next section.

B. Experimental Procedure

The 1/2" thick plate obtained from processing each experimental heat was evaluated using a standard screening procedure. The screening involved Charpy testing of transverse samples from each heat in the normalized and tempered condition. Since the number of samples per heat was limited (eight per heat), careful attention was paid in selecting each test temperature so as to define the transition temperature region and the upper energy shelf. The data was plotted by a computer, using Oldfield's statistical fit procedure. The 50 ft-lb value was used as a measure of the material's characteristic transition temperature.

Samples from each experimental heat were given an aging treatment of 2000 hours at 950° F. Aging was performed by taking the Charpy samples, encapsulating in vacuo and aging in a salt bath. The shifts in the 50 ft-lb value and the change in the upper energy shelf was noted. The Charpy plot for each heat of material in the unaged and aged condition is attached in Appendix 1.

Samples from each heat of material were tension tested at room temperature and elevated temperatures viz, 900° F, 1000° F, and 1100° F. Tests were conducted on .252" samples, using extensometry to 1% elongation. Yield and tensile strength, percent elongation, and reduction in area were calculated.

Limited metallography has been performed on these alloys. Bulk extraction, using a 6N HCℓ solution has been performed to identify and characterize the carbides present in a few of the heats at various

conditions. A limited amount of transmission electron microscopy has also been performed. Thin foils were prepared, using an acetic-perchloric electrolyte and single-stage carbon replicas. Replicas were extracted with a bromine-methanol solution after deep etching in a HCℓ-picral solution.

On the basis of data generated from Charpy and mechanical property testing, a few of the heats were selected for creep rupture evaluation both in air and argon. Details of the test procedure are described in a later section.

Samples have been sent out to various laboratories for inclusion in sodium loops, steam loops, etc., to evaluate the materials behavior with respect to carburization/decarburization in sodium as well as scaling and oxidation losses in steam. Some foil samples have also been sent for irradiation experiments. Material from a few heats are presently being given a 10,000 hour aging at different temperatures, which will be evaluated later. None of the results from these samples are available as yet.

C. Results and Discussions

The pertinent data from the Charpy curves in Appendix 1 are presented in Table 1, where the 50 ft-lb values and the upper energy shelf values for all heats tested are shown, both before and after the aging treatment. The shift in those values on aging are also tabulated. Since the Charpy curves were drawn using a limited number of points, the upper energy shelf values are not exact, though the magnitudes are correct. Therefore, the shifts recorded in the upper energy shelf values, which are all small anyway, can for the most part be neglected.

The shift in the 50 ft-lb value shows a significant variation from one heat to another. The earlier heats,starting from 3154, all have a shift in the 50 ft-lb value in the range of 50-90 degrees. The later heats have a smaller shift in the 50 ft-lb value and in certain cases the shift is nearly zero. ESR XA 3177 is one heat that has a shift of nearly zero, and is an alloy containing .5% Tungsten and 0.8% molybdenum. The other alloys only contain molybdenum.

Such a shift in the 50 ft-lb value is not unusual, as seen in Table 2, which shows the shifts for a similar aging treatment given to the commercial 2-1/4 Cr-1Mo alloy and Sandvik HT-9 alloy. For the 2-1/4 Cr-1Mo alloy, the shift is substantial and worse after quenching and tempering. Sandvik HT-9, which is also a molybdenum-Tungsten bearing alloy, has a larger shift than ESR XA 3177, a similar alloy, as mentioned earlier. Table 2 contains data from three (3) heats of experimental alloys which show a minimal shift of the 50 ft-lb value on aging.

The shift in the Charpy 50 ft-lb value can arise from a number of factors. To evaluate if embrittlement of the prior austenite grain boundaries was a factor, a few heats of material were analyzed for trace elements. Table 3 shows that the embrittling elements present are in negligible quantitites, as is expected, since all the heats were melted from pure melting stock. Further evidence is seen in Figures 2 and 3, which are SEM fractographs of aged Charpy samples of heat ESR XA 3181 and 91887, tested at lower energy shelf temperatures,showing only cleavage fractures. No intergranular fracture was observed on any of the samples examined, which would have been expected if embrittlement had occurred.

The increase in the 50 ft-lb value cannot be explained by an increase in grain size of the alloys. Figures 4-7 show micrographs of heats ESR XA 3177, 3178, 3181, and 91887 both in the unaged and aged conditions. There is no noticeable change in grain size in any of the cases and any change, if any, in carbide precipitation is not observable in these optical micrographs. This is so for all, except heat ESR XA 3178 (Figure 5), which has free δ-ferrite in the structure and shows precipitation has occurred within the δ-ferrite areas on aging. Thus, to explain the aging shift, structural evaluation is necessary to document in detail the submicroscopic structure and carbide precipitates.

Finally, an attempt was made to relate the shift to the presence or absence of certain alloying elements. It is known, as discussed previously, that nickel can have a detrimental effect on aging embrittlement for ferritic steels. Figure 8 shows a plot of the 50 ft-lb shift value versus percentage nickel in the various alloys. While the band of alloys containing less than 0.2% nickel is not explainable, the plot does show that alloys containing nickel greater than 0.2% has a positive effect on the shift of the 50 ft-lb value. Thus, eliminating or reducing nickel content in the experimental alloys was established as mandatory. The value of this is seen in comparing the compositions of the earlier heats with the later heats, which have small amounts of nickel and a negligible shift in their 50 ft-lb values. Similar plots were made with % Si and % nitrogen (Figures 9,10), these showed no clear cut tendency in explaining the 50 ft-lb shifts observed.

Microstructural evaluation of the modified alloys has begun on a few selected alloys. In general, the microstructure, after normalizing and tempering, is a fully tempered martensite. With the extended austenite bay that these alloys possess, they invariably transform to martensite on cooling after normalizing, irrespective

of the cooling rate used. The typical normalized structure is as shown in Figures 11a and 12a for heats 3177 and 91887. The Normarski micrographs, clearly show the lath packets of the martensite that formed on cooling. Heat 3177 also shows the presence of large TiN particles distributed in the matrix, which are unaffected by the normalizing treatment. Dilatometric scans made on the modified alloys show that on heating the Ac_1 ranges from 1525 - 1550° F; and Ac_3 from 1640 - 1670° F; and on cooling the M_s is around 720 - 770° F, and M_f around 500° F, depending on the alloy (see Table 4).

Figures 11b, 12b, 13, and 14 show typical microstructures obtained after heat treating ESR XA 3186 and 3187. The microstructure is 100% tempered martensite. Note the absence of free δ-ferrite. The final grain size of the modified alloys is small, especially when compared to similarly processed 9Cr-1Mo unmodified alloy ESR XA 3217, Figure 15. The grain refinement of the modified alloy is due to precipitation of NbCN during hot working of the austenite, which allows recrystallization to proceed but inhibits grain growth. The fine grain size produced by normal processing of the alloy is primarily responsible for the excellent Charpy properties observed. The NbCN precipitated during hot working is unaffected by the normalizing treatment since its solubility product at 1900° F is small, but the chromium carbides are taken into solution. This was verified by performing bulk extraction of the carbides and identifying them by x-ray diffraction.

The carbide present after normalizing was identified, using EDAX analyses as niobium rich Nb(CN), containing small amounts of titanium, vanadium, and chromium, Figure 16b. On tempering the alloy, the singular $M_{23}C_6$ carbide precipitate is principally chromium rich and contains molybdenum, iron, and vanadium.

Bulk extraction analysis of carbides from alloys aged 2000 hours at 950° F showed that no other carbides formed in the alloy. Thus, the design aspect of the alloy is met in eliminating the formation of M_6C in the initial structure as well as in the microstructure at 2000 hours aging. The general distribution of the carbides is shown in Figure 16a for ESR XA 3187 after normalizing and tempering.

The carbide size and distribution in the different alloys are not exactly similar as can be seen in Figure 17, where the carbide distribution and size can be compared for ESR XA 3177 (Figure 17a) and ESR heat 91887 (Figure 17b).

The $M_{23}C_6$ carbide in both cases has precipitated at the lath and grain boundaries and is approximately 5000 Å average size. In addition, heat 91887 (Figures 18a and 18b) has a very fine matrix precipitate which has been tentatively identified as NbCN. The particles are too small for selected area diffraction and are unresolvable by EDAX analysis. However, these particles are approximately the same size as the particles observed after normalizing, which were identified by bulk extraction as NbCN. Heat 3177 also has a matrix precipitate but the sizes involved are larger and their strengthening component much smaller.

Transmission electron microscopy was used to characterize the tempered lath martensitic structure of the heat treated alloy, as shown in Figures 19-20. The substructure is heavily dislocated from the martensite reaction, and lath and grain boundaries contain carbides. Also observed is the distribution of fine NbCN precipitates throughout the matrix, and some are clearly observed to inhibit recovery,as seen at the arrow in Figure 21. Some even finer precipitates are observed on the dislocations themselves, which would inhibit their motion.

Evaluation of Large 5000 Lb ESR Heat

A 5000 lb ESR ingot was ordered to the following target composition, utilizing high purity melting stock.

C	Mn	Si	Cr	Mo	V	Ni	Nb	Ti	B	Zr	N	Al
0.09	0.4	0.1	9.0	1.0	0.2	0.1	0.12	0.02	0.004	.004	.05	low as possible

The ESR ingot manufactured by Cartech Corporation had a nominal 17" Ø finished size, a photograph of which is shown in Figure 22. Two slabs 1 (one) inch thick were cut from the top and bottom surfaces of the ingot for evaluation. They were macroetched; Figure 23, which shows no unusual structures like banding or macrosegregation. Samples were cut from both the surface and center areas for chemical analysis and metallography. A complete chemical analysis of both the edge and center sections of both top and bottom position of the ingot is presented in the following table (see next page).

The comparisons show good chemical homogeneity, suggesting that manufacture of such large sizes may not represent production problems with respect to segregation, etc. The only difference of note is that the Cartech supplied analysis shows boron to be present as 30 ppm, whereas repeated attempts at C-E failed for confirm this value. The heat was clean as expected, except for areas near the circumference where the inclusion content was high (Figure 24). The inclusions were entrapped slag/oxide particles and were mainly Fe, Cr, Mn aluminates and silicates as analyzed by EDAX, Figure 24. Microstructures of the top and bottom sections show equivalent tempered martensitic structures, Figure 25.

CHEMICAL COMPOSITION FOR FIRST 5000 LB ESR HEAT

CARTECH HEAT NO. 91887

Heat No. 91887	LOC	C	Mn	Si	S	P	Cr	Nb	V	W	Cb	Ti	Ni	N_2	Al	Cu	B	Zr	Sb	O_2
Cartech Analysis	Top	.090	.33	.13	.004	.006	8.92	.99	.25		.18	<.03	.11	.039	.012		.003	<.01		
C-E Analysis	TOP	.086	.38	.01	.005	.005	9.09	1.03	.22	<.01	.16	<.01	.07	.041	.010	.01	<.001	<.001	<.001	.015
Edge of Ingot	BOT	.083	.39	.05	.004	.008	8.85	.94	.20	<.01	.18	<.01	.10	.040		.02		<.001	.002	
C-E Analysis	TOP	.097	.38	.08	.005	.007	9.22	1.01	.22	<.01	.15	<.01	.08	.038			<.001	<.001		
Center of Ingot	BOT	.083	.39	.13	.004	.007	8.99	.99	.21	<.01	.17	<.01	.09	.037			<.001	<.001		

A five (5) inch slice was cut from the top of the ingot and sections were hot worked to 1/2" plate for mechanical property evaluations. Samples for unaged and aged Charpies, room and elevated temperature tension tests, and creep rupture samples were all manufactured from the material in batches, the results of which are presented in a later section.

Since all the samples did not come from the same processed material, an experiment was run to evaluate the sensitivity of Charpy properties to the hot working finishing temperatures. Samples from this heat were hot worked exactly the same until the plate was 1" thick, and then cooled to room temperature. They were reheated and then given some reduction in area and finished at 1600° F, 1800° F, and at 1900° F.

Charpy tests were run to evaluate the effect of finishing temperature. The results are plotted in Figure 26. The transition temperature, as measured by the 50 ft-lb value, remains nearly the same, as does the upper energy shelf. The microstructures, Figure 27, show that the grain size in each case is comparable and that finishing at 1600° F has not retarded the recrystallization to any appreciable extent.

REFERENCES

1. R. D. Thielman, Proc., ASTM, 40, 1940, pg. 788

2. C. B. Post and W. S. Eberly, ASTM Trans., 43, 1951, pg. 243

3. D. L. Newhouse, C. J. Boyle, and R. M. Curran, ASTM 68th Annual Meeting, 1965, Purdue University

4. J. A. McMahon and G. Thomas, The Microstructure and Design of Alloys, Proc. of Third International Conference on Strength of Metals, 1973, Vol. 1, pg. 180

5. B. B. Argent, M. N. Van Niekerk, and G. A. Redfern, JISI, 208, 1970, pg. 830

6. J. D. Baird and A. Jamieson, JISI, 210, 1972, pg. 847

7. W. Crafts and J. L. Lamont, Trans. AIME, 188, 1950, pg. 561

8. K. Kuo, JISI, 184, 1956, pg. 258

9. T. Mukerjee, W. E. Stumpf, C. M. Sellars, and W. J. McG. Tegart, JISI, 207, 1969, pg. 621

10. M. N. Van Niekerk and B. B. Argent, JISI, 208, 1970, pg. 781

11. K. W. Andrews , H. Hughes, and D. J. Dyson, JISI, 210, 1972, pg. 337

12. M. Alden, S. Asplund, and B. Aronsson, JISI, 207, 1969, pg. 235

13. J. R. Rellick and C. J. McMahon, Jr., Met. Trans., 5, 1974, pg. 2439

14. M. Nageswararao, C. J. McMahon, and H. Herman, Met. Trans., 5, 1974, pg. 1061

15. T. Marrison and A. Hogg, Creep Strength in Steel and High Temperature Alloys", Metal Soc. Publ. 151, 1972, pg. 242

TABLE 1

COMPARISON OF CHARPY PROPERTIES FOR ALL HEATS IN THE NORMALIZED AND TEMPERED CONDITION, AND NORMALIZED, TEMPERED AND AGED CONDITION

THREE PARAMETER FIT

Heat No.	Processing	50 Ft-lb Value Temp. Unaged	Aged*	Shift	Upper Energy Shelf Unaged	Aged*	Shift
ESR XA 3090 OP	HP&HF&HR to 1/2" PL	154	212	58	90	70	- 20
ESR XA 3154 BNT	HP & Tube Red. 3-1/2x.600"	- 37	57	94	109	105	- 4
ESR XA 3155 OS	HR 2-1/2" to .600", 1900°F Final	- 49	26	75	139	122	- 17
ESR XA 3158 TC	HR from 2-3/4" Slice (Trans.) to 1/2" PL	45	111	66	105	112	- 7
ESR XA 3159 OT	H Forged at Cartech to 1/2" PL	8	69	61	110	98	12
ESR XA 3160 OW	H Forged at Cartech to 1/2" PL	44	105	62	124	124	0
ESR XA 3161 OV	H Forged at Cartech to 1/2" PL	22	69	47	108	118	10
ESR XA 3161 SZ	H Forged to 1" at Cartech, HR to 1/2"	- 3	30	33	128	138	10
ESR XA 3162 OW	H Forged at Cartech to 1/2" PL	67	84	17	120	126	6
ESR XA 3162 TA	H Forged to 1" at Cartech, HR to 1/2"	- 35	- 21	14	158	156	- 2
ESR XA 3163 OX	H Forged at Cartech to 1/2" PL	34	26	- 8	120	116	- 4
ESR XA 3163 TB	H Forged to 1" at Cartech, HR to 1/2"	- 34	14	48	145	133	- 12
ESR XA 3175 SX	HR (Trans.) 2-3/4" to 1/2" PL	118	82	- 36	87	107	20
ESR XA 3176 DL	HR 3" Slice 3"x5" to 1/2" PL at 2150° F	7	40	33	111	107	- 4
ESR XA 3177 TD	HR 3" Slice to 1/2" PL	5	- 3	- 8	116	118	2
ESR XA 3178 TE	HR 3" Slice to 1/2" PL	4	22	18	119	100	- 18
ESR XA 3179 TF	HR 3" Slice to 1/2" PL	- 12	16	28	128	116	- 12
ESR XA 3180 AG	H Forged at Cartech to 1/2" PL	- 12	- 7	5	101	112	11
ESR XA 3181 TG	HR 3" Slice to 1/2" PL	- 35	- 15	20	116	112	- 4
ESR XA 3182 AH	H Forged at Cartech to 1/2" PL	- 3	6	9	109	123	14

- continued next page -

*Aged 2000 hours at 950° F

TABLE 1 (continued)

THREE PARAMETER FIT

Heat No.	Processing	50 Ft-Lb Value Temp. Unaged	Aged*	Shift	Upper Energy Shelf Unaged	Aged*	Shift
ESR XA 3183 AI	H Forged at Cartech to 1/2" PL	- 31	- 25	6	103	115	12
ESR XA 3184 AJ	H Forged at Cartech to 1/2" PL	- 36	- 41	- 5	124	131	7
ESR XA 3185 AK	H Forged at Cartech to 1/2" PL	65	61	- 4	136	125	- 11
ESR XA 3185 DM	HR 3" Slice 3"x5" to 1/2" PL at 2150° F	85	115	30	92	86	- 6
ESR XA 3186 AL	HR 3" Slice 3"x5" to 1/2" PL at 1900° F	- 35	- 20	15	109	124	15
ESR XA 3187 AM	HR 3" Slice 3"x5" to 1/2" PL at 1900° F	- 36	- 45	- 9	105	115	10
ESR XA 3217 CS	HR to 3-1/2"x1/2" PL at 2150°F	6	86	80	126	155	29
#9 1887 DN	HR to 3-1/2"x1/2" PL at 2150°F	31	106	75	114	90	- 24

*Aged 2000 hours at 950° F

TABLE 2

COMPARISON OF CHARPY PROPERTIES OF MODIFIED 9Cr-1Mo ALLOY VERSUS 2-1/4Cr-1Mo AND HT9 ALLOYS

Alloy Designation	68 Joule TT (°C)			Upper Energy Shelf** Joules		
	After Aging*	Before Aging	Shift on Aging	After Aging	Before Aging	Change on Aging
2-1/4 Cr, 1 Mo, N(955°C), T(704°C)	48	- 18	66	112.5	126.1	- 13.5
2-1/4 Cr, 1 Mo, Q(955°C), T(704°C)	23	- 55	78	108.5	116.6	- 8.1
0.2 C,12 Cr,1 Mo,0.3 V,.5 W,.5 Ni Sandvik HT-9	38	6	32	100.3	135.6	- 35.3
Experimental Alloys						
0.1 C,9 Cr,2 Mo,0.2 V,.45 Cb	100	68	32	94.9	103.0	- 8.1
0.1 C,9 Cr,1 Mo,0.2 V,.10 Cb,1.13 Ni	14	- 38	52	114.6	147.8	- 33.2
0.1 C,9 Cr,1 Mo, V, Cb,...Three Indidual Heats	- 43.0	- 38	- 5.0	155.9	142.4	13.5
	- 40.6	- 38	- 2.6	177.6	168.1	9.5
	- 31.5	- 35	3.5	155.9	139.6	16.2

*Aging for 2000 hours at 510° C
**Defined by FATT 100% Shear

TABLE 3

ATOMIC ABSORPTION ANALYSES OF TRACE ELEMENTS IN 9Cr - 1MO MODIFIED ALLOYS

HEAT NO.	LOCATION	DR BORON	WET BORON	ATOMIC ABSORPTION						
				Pb	Sb	As	Bi	Sn	Se	Cd
Cartech Ht 91887	3" from Circum. Top	<.001	<.001	<.0005	.0005	.0005	.0005	.0017	.0005	<.0001
Cartech Ht 91887	3" from Circum. Top	<.001								
ESR XA 3224	Center 3/4" Pl.	.003	<.001	<.0005	<.0005	.0020	<.0005	.0010	<.0005	<.0001
ESR XA 3224	Center 3/4" Pl.	.003								
ESR XA 3177	7" from Bottom	<.001	<.001	<.0005	<.0005	.0020	<.0005	.0012	.0007	<.0001
ESR XA 3177	7" from Bottom	<.001								
ESR XA 3178	7" from Bottom	<.001	<.001	<.0005	<.0005	.0025	<.0005	.0017	.0008	<.0001
ESR XA 3178	7" from Bottom	<.001								
ESR XA 3218	Top Billet	.002	.005	<.0005	<.0005	.0013	<.0005	.0010	.0006	<.0001
ESR XA 3218	Top Billet	.002								

- continued next page -

TABLE 3 (continued)

FOR AGED SAMPLES (2000 HRS AT 950° F)

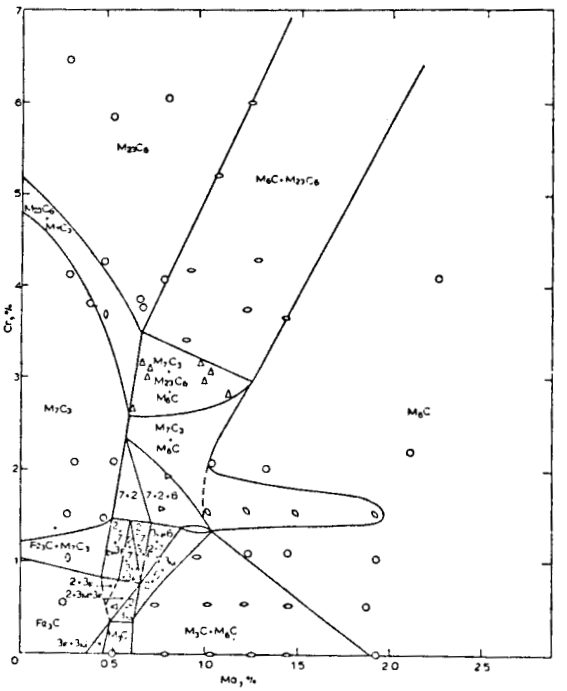
HEAT NUMBER	As	Bi	Sb %
ESR XA 3090	.0034	Not Detected	.0011
ESR XA 3154A	.0043	Not Detected	.0028
ESR XA 3154 B	.0029	Not Detected	.0028
ESR XA 3155	.0024	Not Detected	.0027
ESR XA 3156	.0032	Not Detected	.0022
ESR XA 3159	.0037	Not Detected	.0026
ESR XA 3160	.0031	Not Detected	.0021
ESR XA 3161	.0027	Not Detected	.0026
ESR XA 3162	.0027	Not Detected	.0030
ESR XA 3178	.0035	Not Detected	.0030
ESR XA 3179	.0031	Not Detected	.0030
ESR XA 3181	.0029	Not Detected	.0029

TABLE 4

TRANSFORMATION TEMPERATURES (° F)

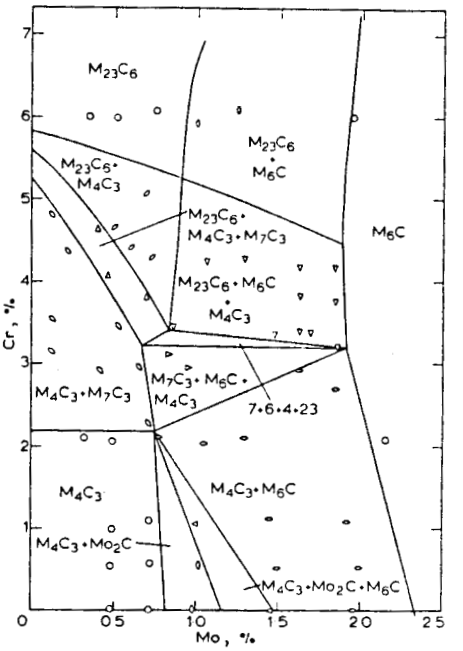
OF MODIFIED 9Cr-1 Mo ALLOYS

	Ac_1	Ar_1	Ac_3	Ar_3
ESR XA 3177 (TD)	1529	--	1641	724
	1536	498	1666	720
ESR Ht. 91887 (DP)	1552 1555	528 538	1666 1637	758 766



Constitution of steels after treatment for 1000 h at 700°C as a function of Cr and Mo content, 0%V

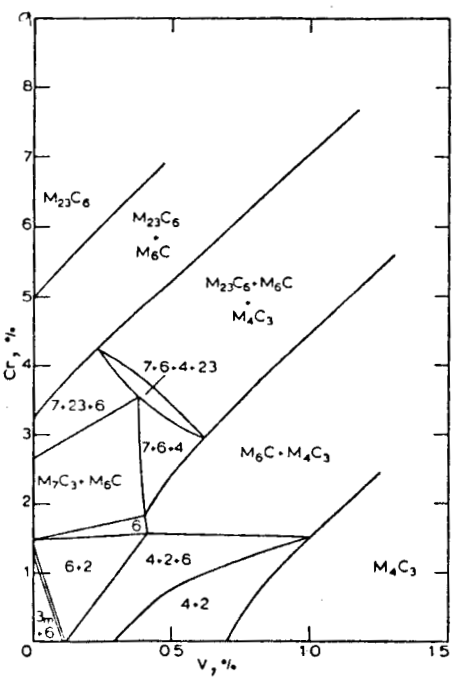
(a)



23=$M_{23}C_6$, 4=M_4C_3, 6=M_6C, 7=M_7C_3

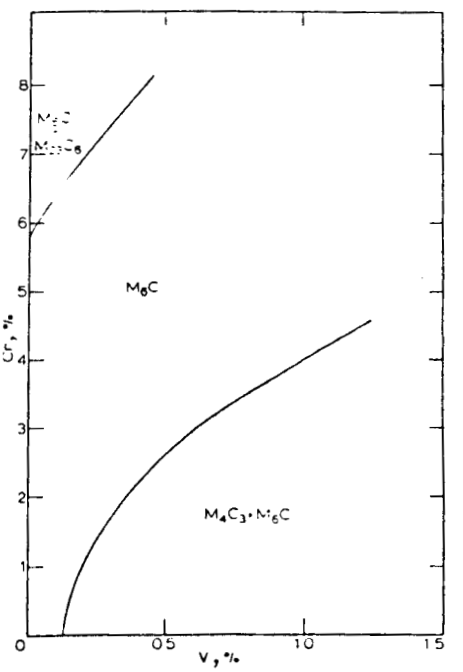
Constitution of steels after treatment for 1000 h at 700°C as a function of Cr and Mo content, 0·5%V

(b)



Constitution of steels after treatment for 1000 h at 700°C as a function of Cr and V content, 1%Mo

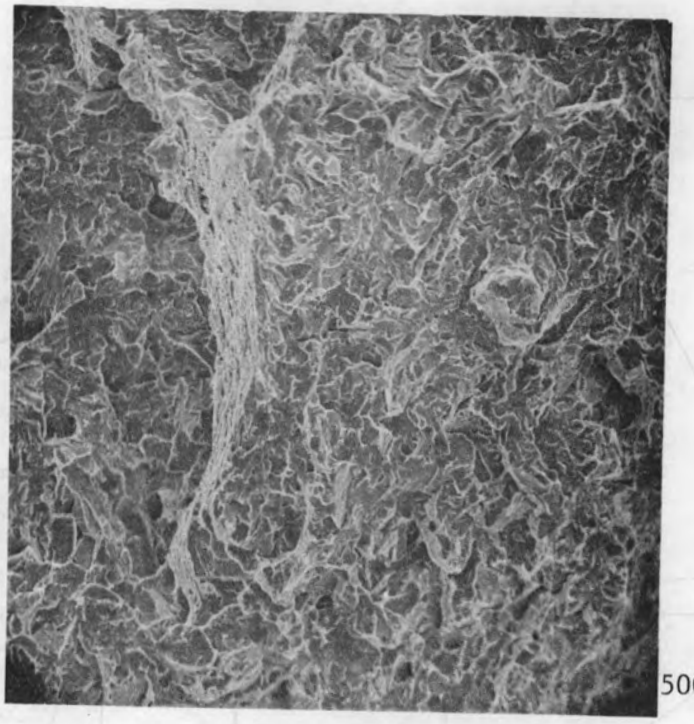
(c)



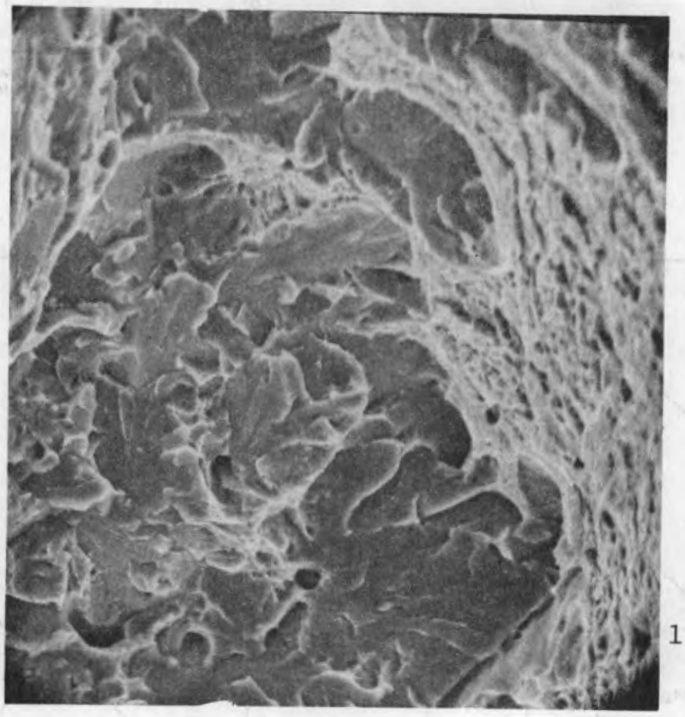
Constitution of steels after treatment for 1000 h at 700°C as a function of Cr and V, 2%Mo

(d)

Figure 1. Constitution diagrams for Fe-Cr-Mo-V alloys after Andrews et al (14). (a) Equilibrium carbide phase field for alloy containing 0%V and (b) containing 0.5%V. (c) Equilibrium carbide phase field plotted with increasing vanadium content at 1%Mo and (d) with 2%Mo.

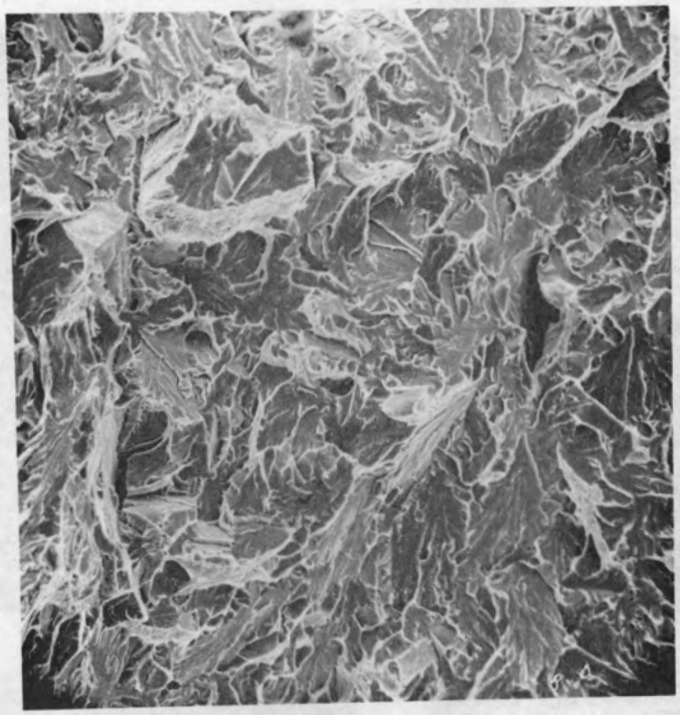


500X

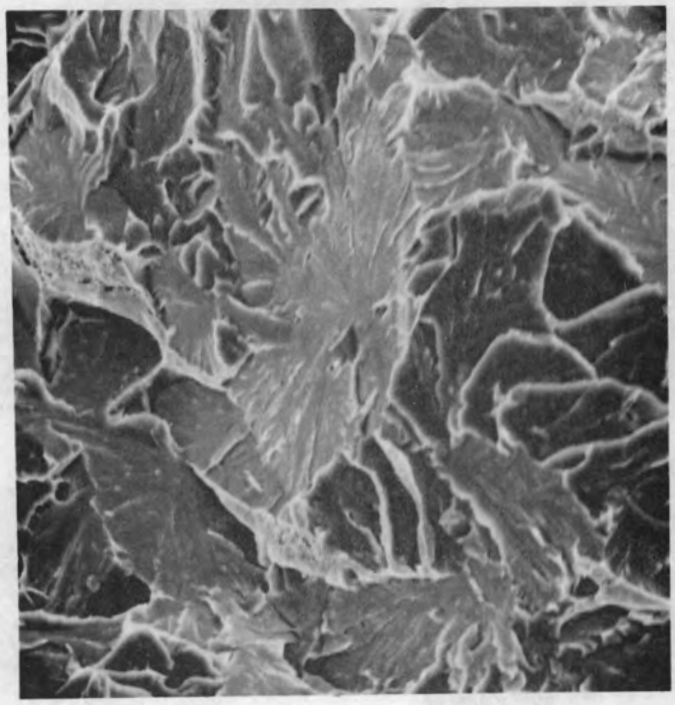


1500X

Figure 2. CHARPY FRACTURE SURFACE OF ESRXA 3181 AT - 80°F AFTER 2000 HOURS AGING AT 950°F.



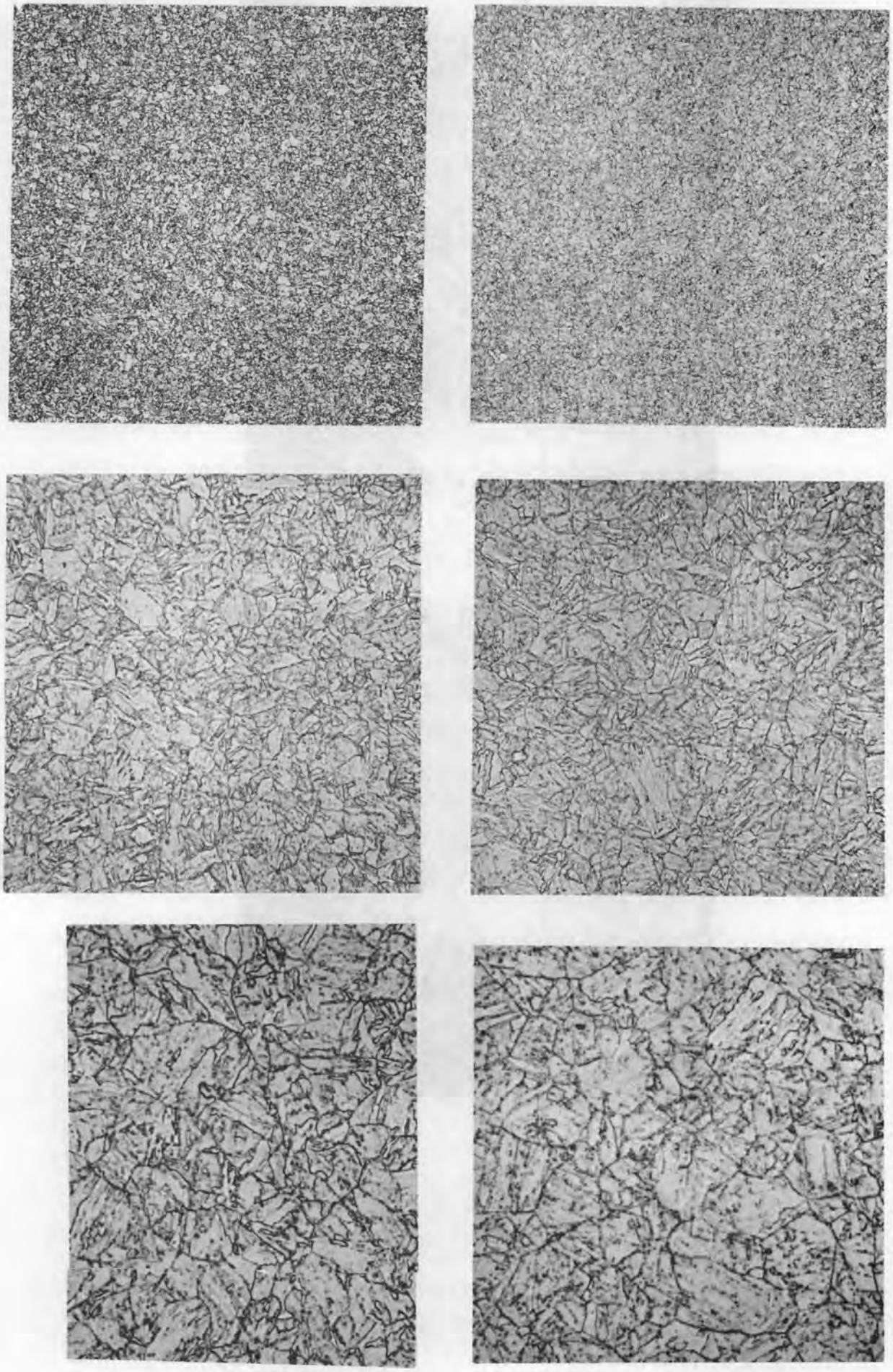
500X



1500X

Figure 3. CHARPY FRACTURE SURFACE OF ESR HT. 91887 AT 0°F AFTER 2000 HOURS AGING AT 950°F.

Figure 4. Optical migrographs of unaged and aged samples for ESR XA 3177.



ESR XA 3177
Charpy Samples
TD

100X

500X

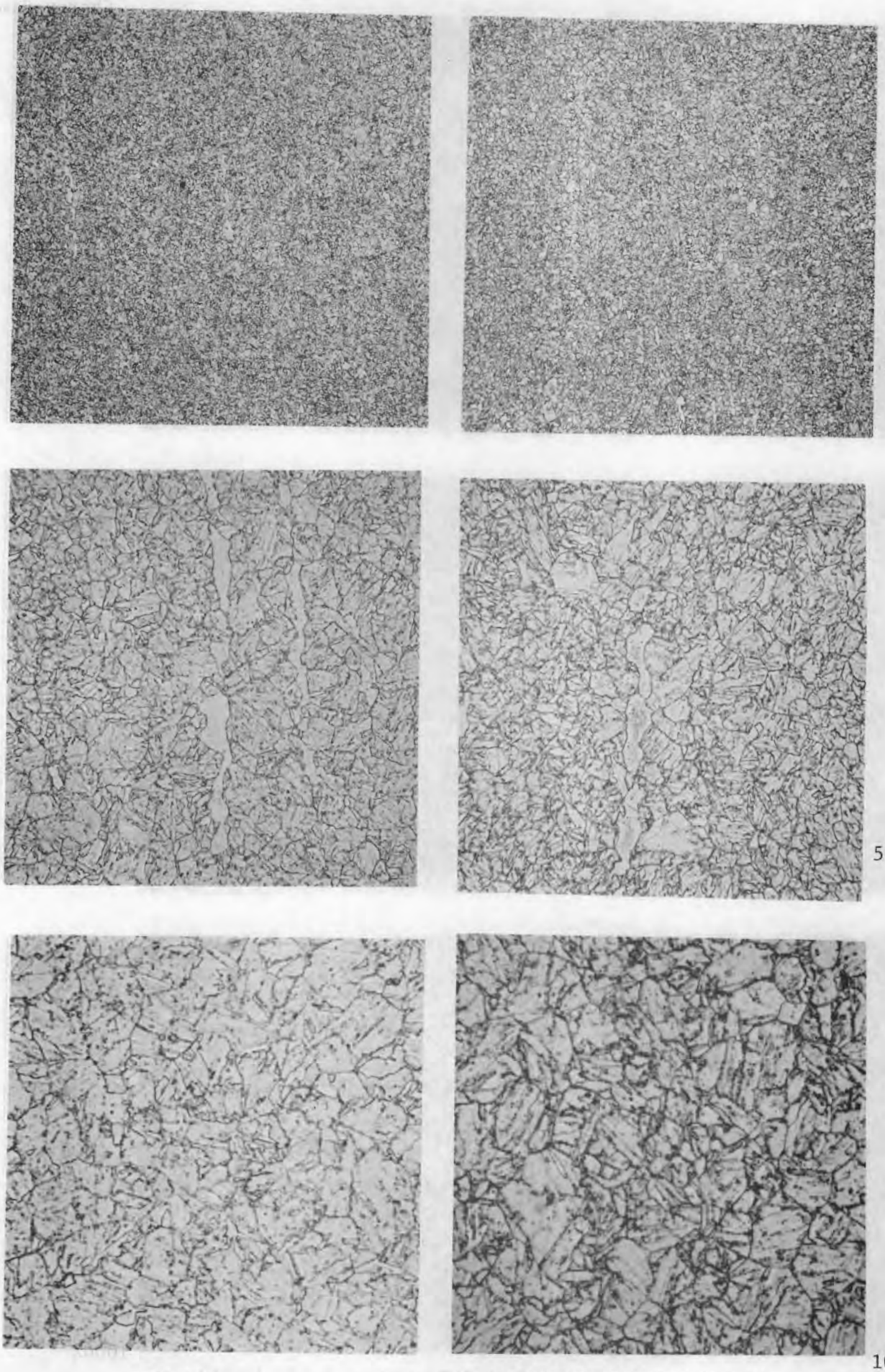
1000X

UNAGED

AGED 2000 HRS @ 950°F (TDIJ)

Figure 5. Optical micrographs of unaged and aged samples of ESR XA 3178.

ESR XA 3178
Charpy Sample
TE



100X

500X

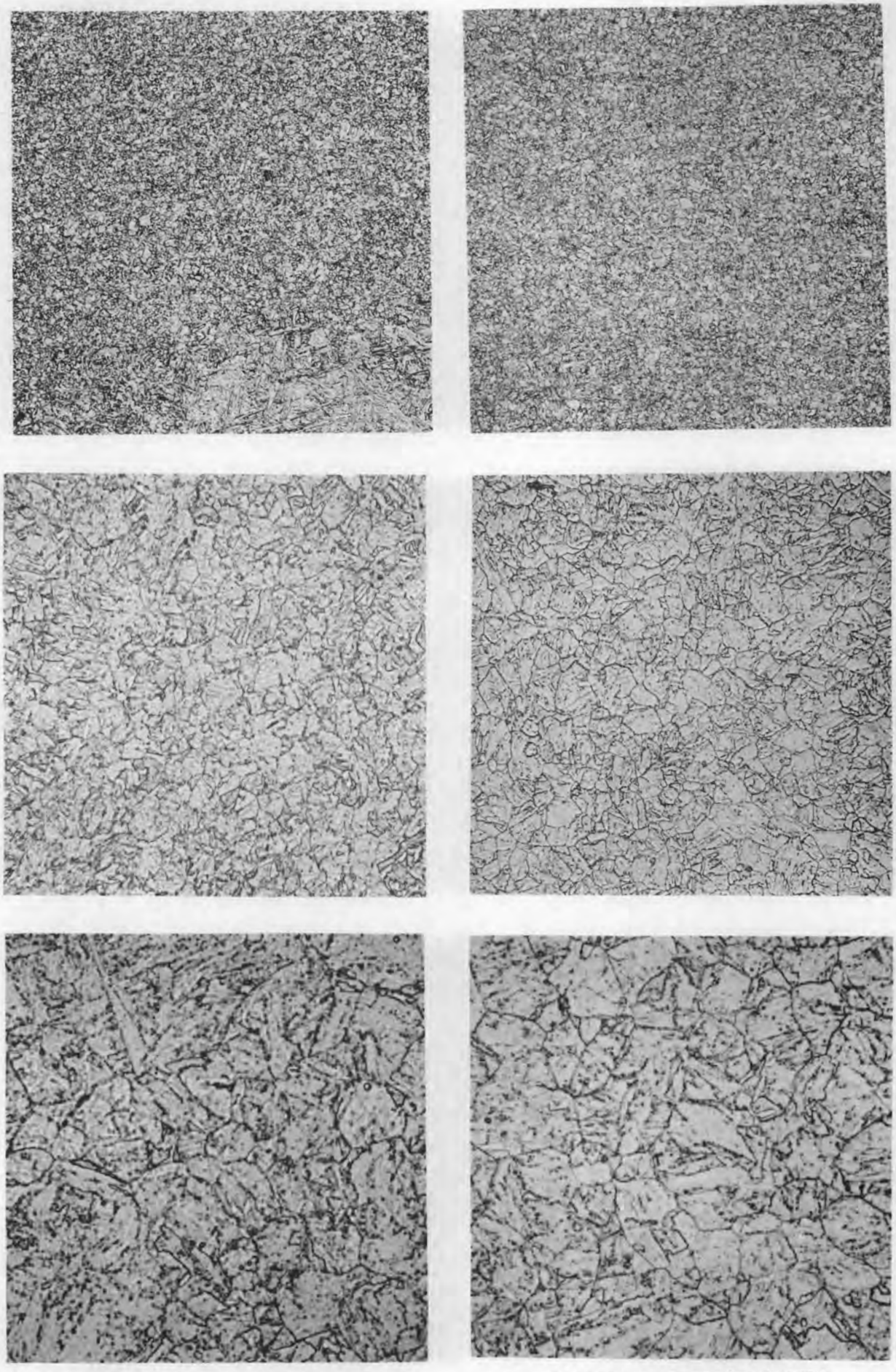
1000X

UNAGED

AGED 2000 HR @ 950°F, (TETN)

Figure 6. Optical micrographs of unaged and aged samples of ESR XA 3181.

ESR XA 3181
Charpy Sample
TG



100X

500X

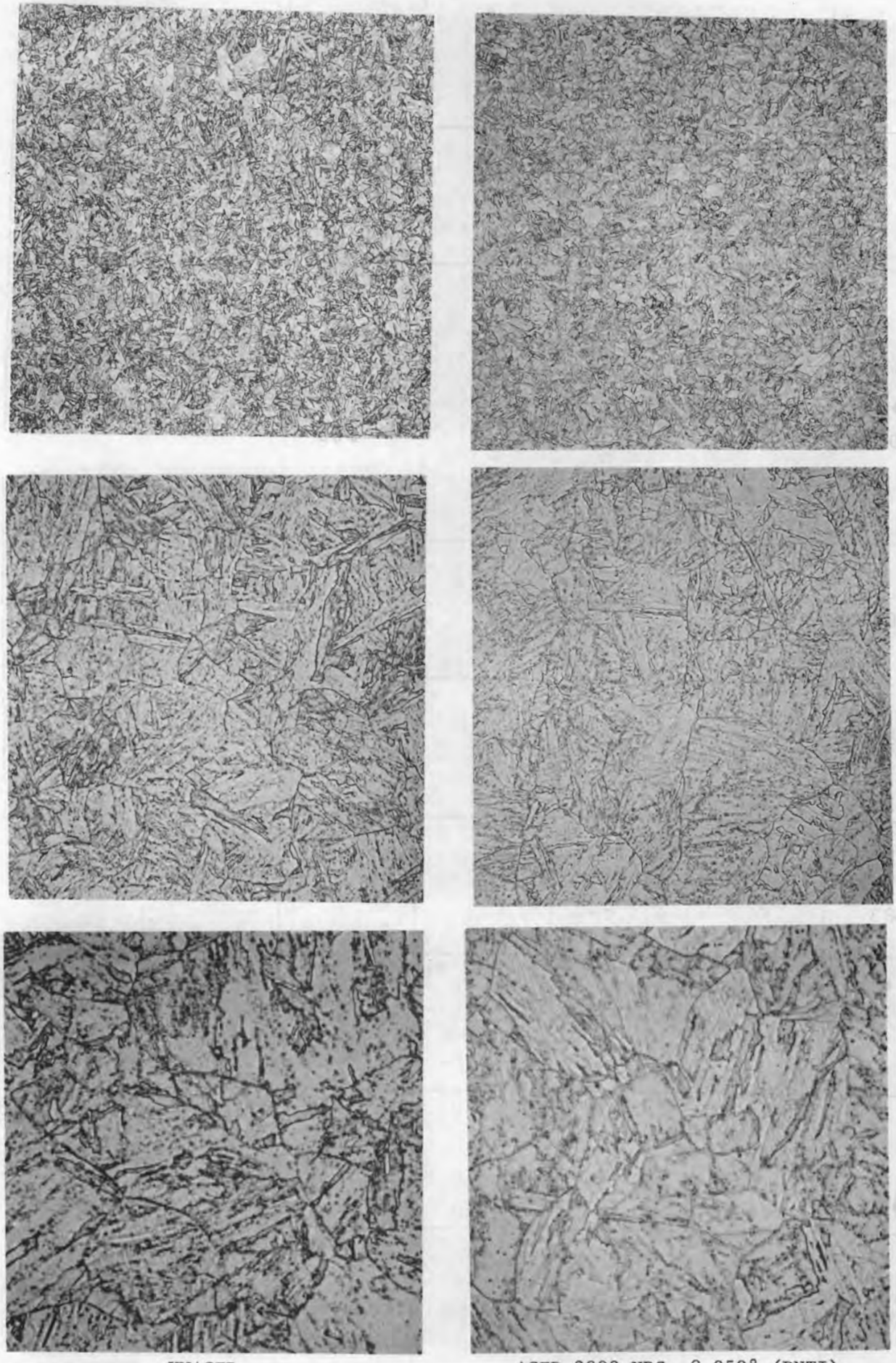
1000X

UNAGED

AGED 2000 HRS. @ 950°F (TGTL)

Figure 7. Optical micrograph of unaged and aged samples of ESR HT 91887.

ESR
HT 91887
Charpy Sample
DN



100X

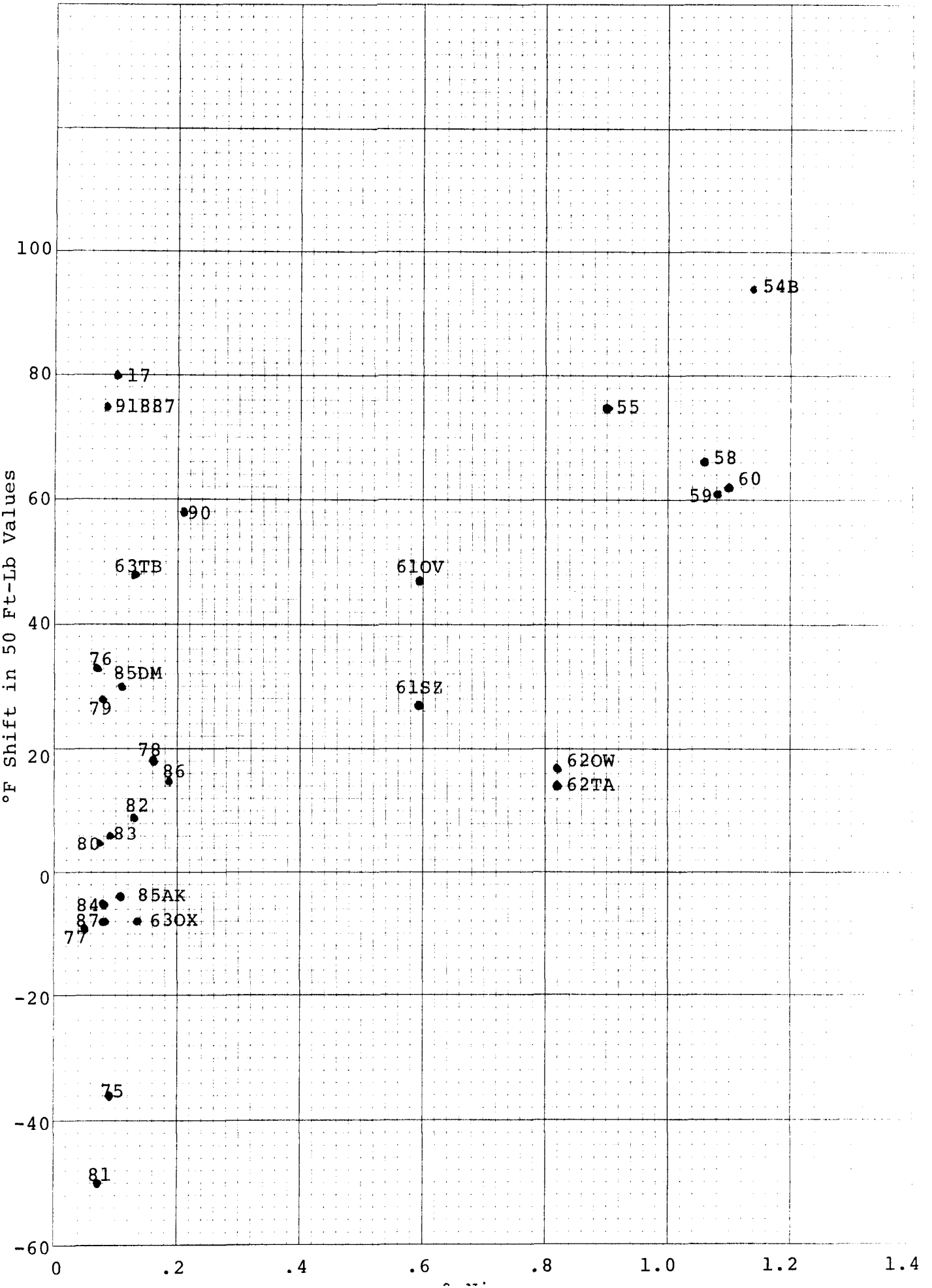
500X

1000X

UNAGED

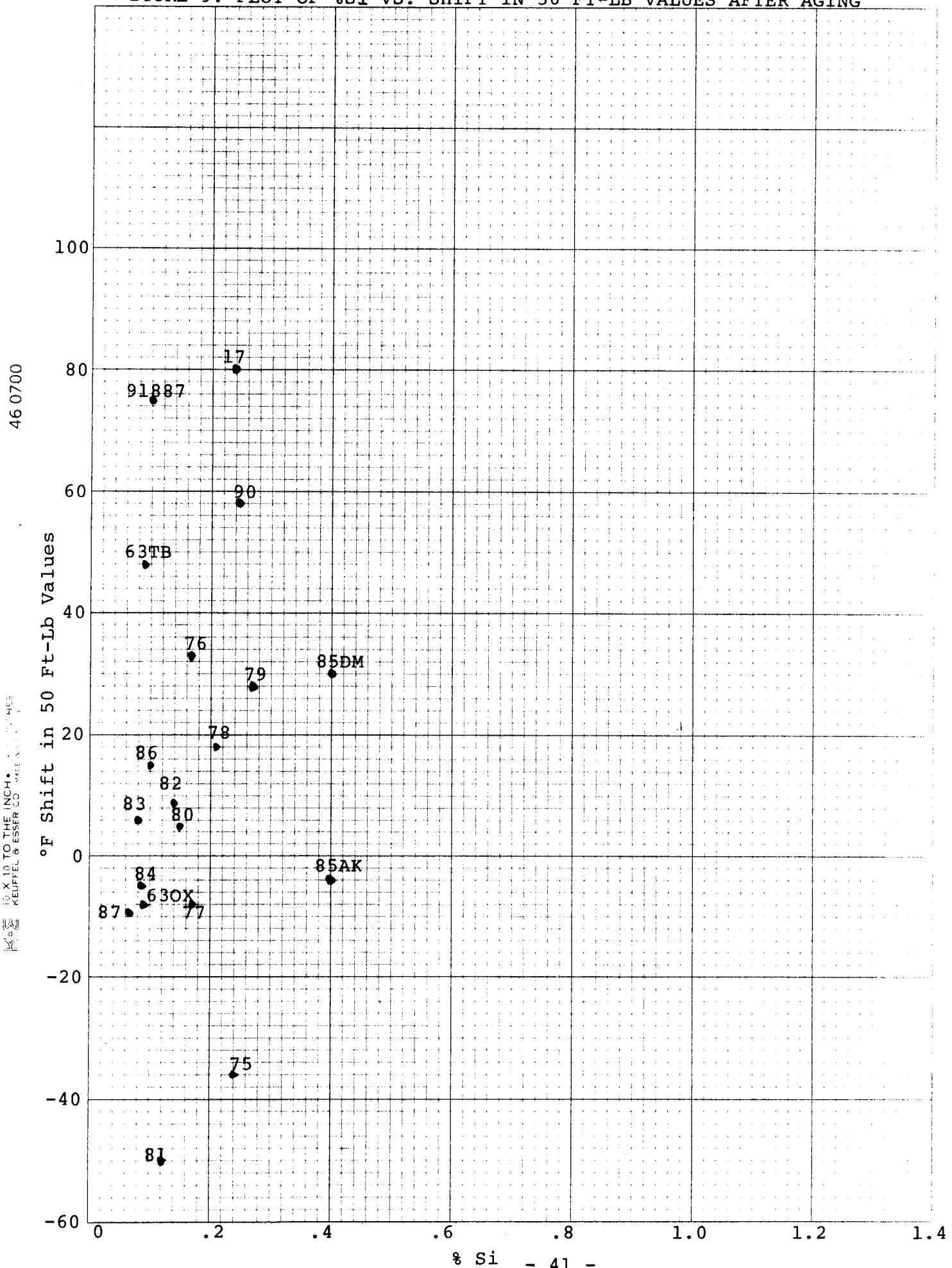
AGED 2000 HRS. @ 950° (DNTI)

FIGURE 8: PLOT OF %Ni VS. SHIFT IN 50 FT-LB VALUES AFTER AGING



46 0700

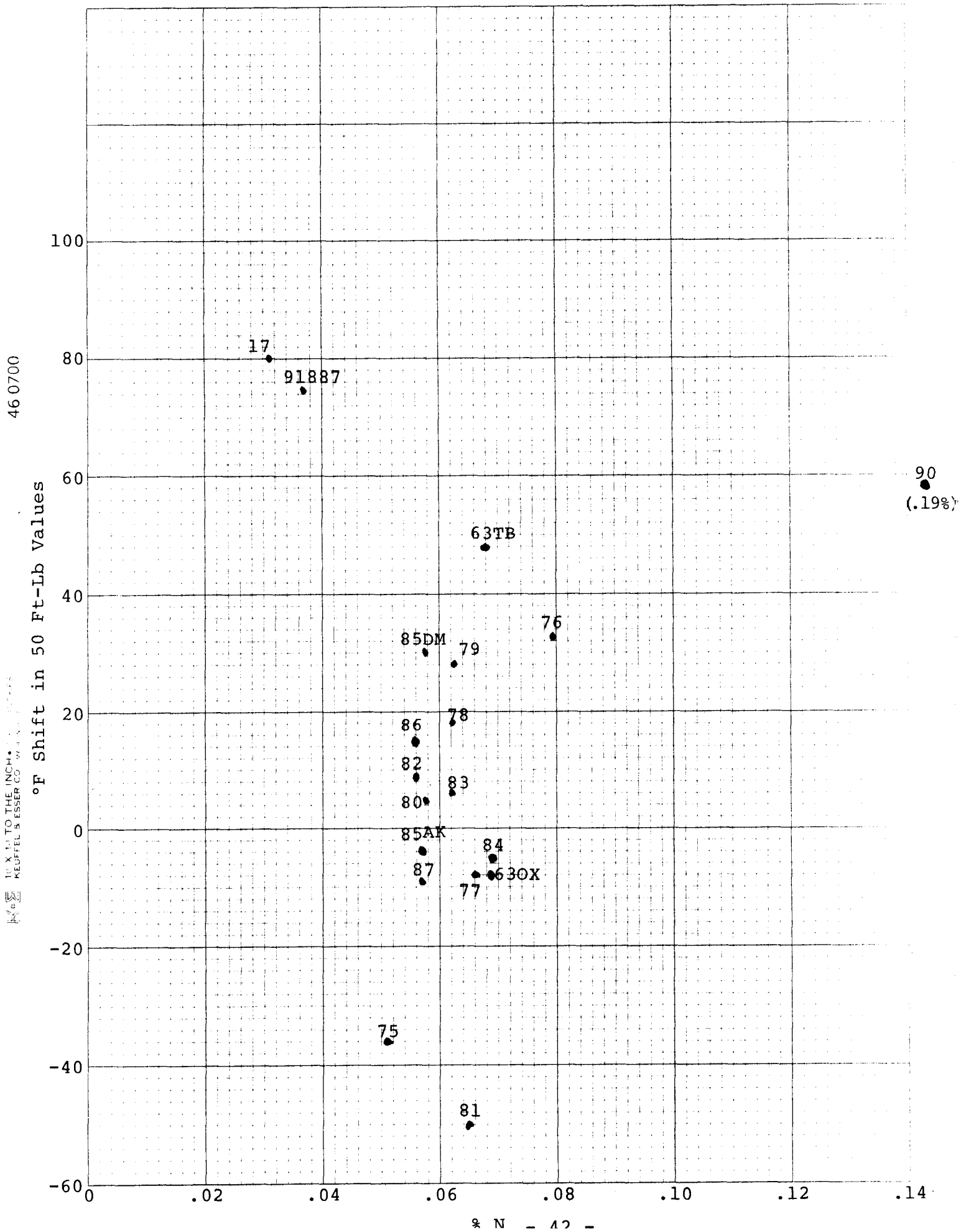
FIGURE 9: PLOT OF %Si VS. SHIFT IN 50 FT-LB VALUES AFTER AGING



460700

10 X 10 TO THE INCH
KEUFFEL & ESSER CO.

FIGURE 10: PLOT OF %N VS. SHIFT IN 50 FT-LB VALUES AFTER AGING



46 0700

10 X 10 TO THE INCH
KEUFFEL & ESSER CO.

(a)

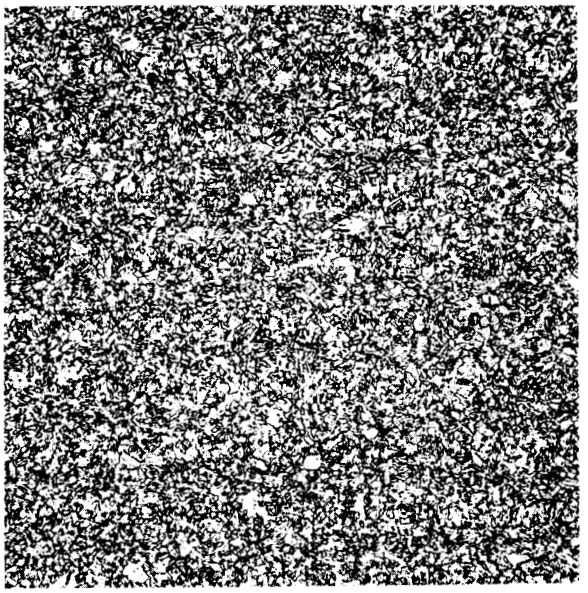
(b)

FIGURE 11: Normarski Micrographs of ESR XA 3177; (a) after normalizing at 1900°F for 1 hour and air cooling, and (b) after normalizing and tempering for 1 hour at 1400°F. HCl Picral Etch, 1500X.

(a)

(b)

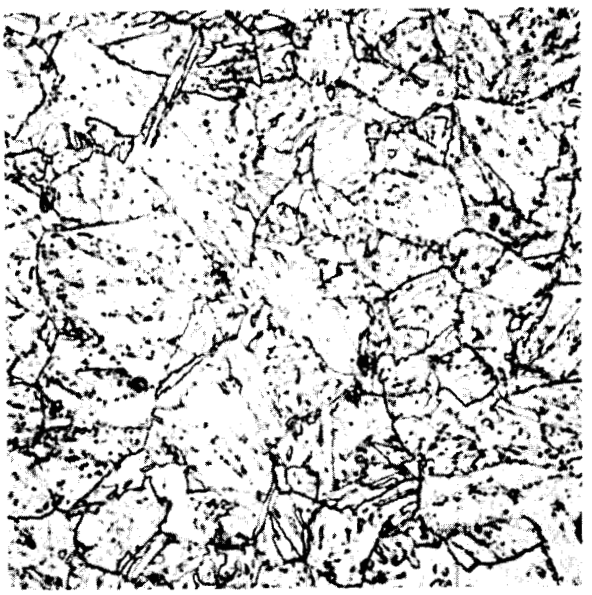
FIGURE 12: Normarski Micrographs of ESR HT. 91887; (a) after normalizing at 1900°F for 1 hour and air cooling, (b) after normalizing and tempering at 1400°F for 1 hour. HCl Picral Etch, 1500X.
Individual lath packets can be observed in the normalized microstructure, which on tempering shows interlath and grain boundary carbide precipitates.



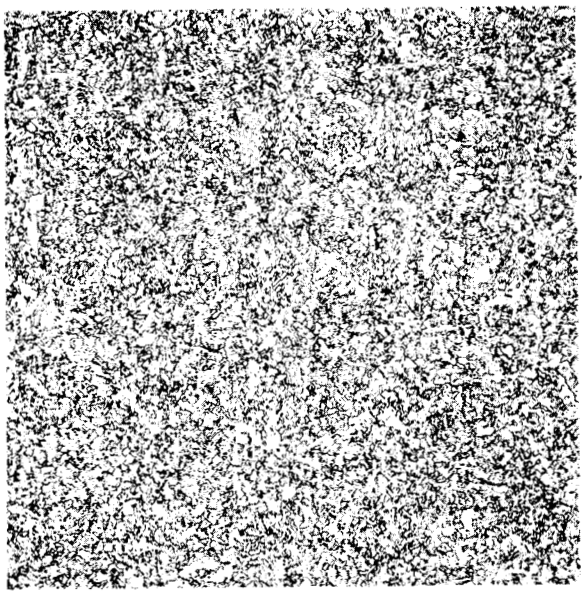
100X

FIGURE 13: Optical Micrograph of ESR XA 3186 from unaged charpy sample (AL). Normalized 1900°F, 1 Hr., AC and tempered 1400°F, 1 HR., AC. HCl Picral Etch

500X



1000X

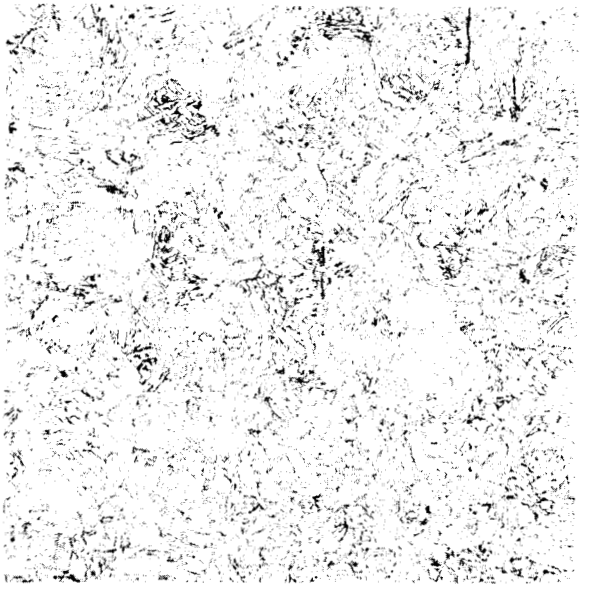


100X

FIGURE 14: Optical Micrographs of ESR XA 3187 from unaged charpy sample (AM). Normalized 1900°F, 1 HR, AC and tempered 1400°F, 1 HR, AC. HCl Picral Etch

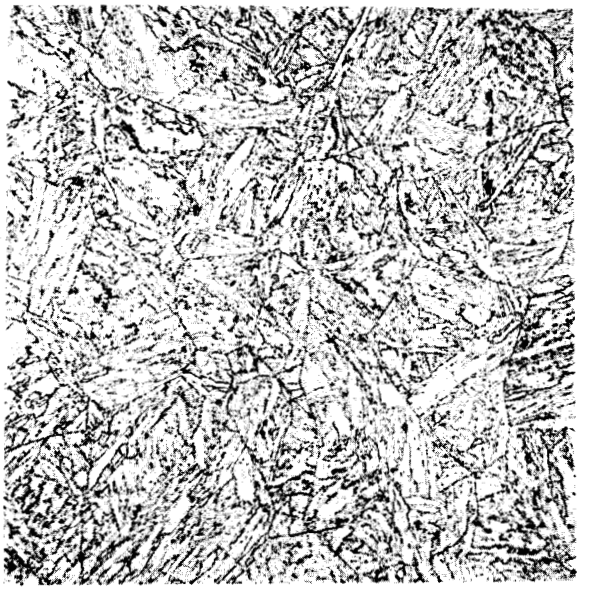
500X

1000X



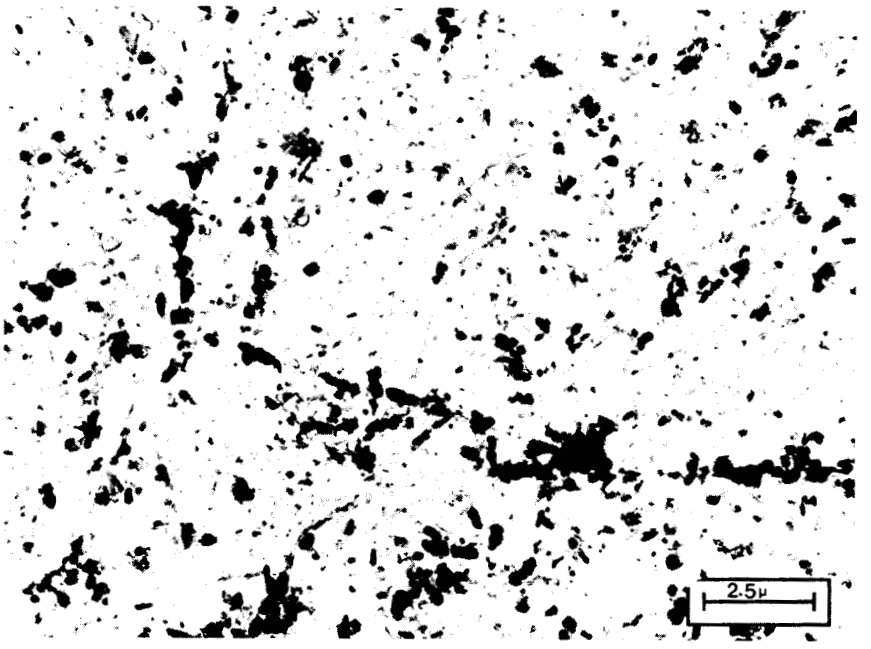
100X

FIGURE 15: Optical Micrographs of ESR XA 3217 from unaged charpy sample (CS). Normalized 1900°F, 1 Hr., AC and tempered 1400°F, 1 Hr., AC. HCl Picral Etch.

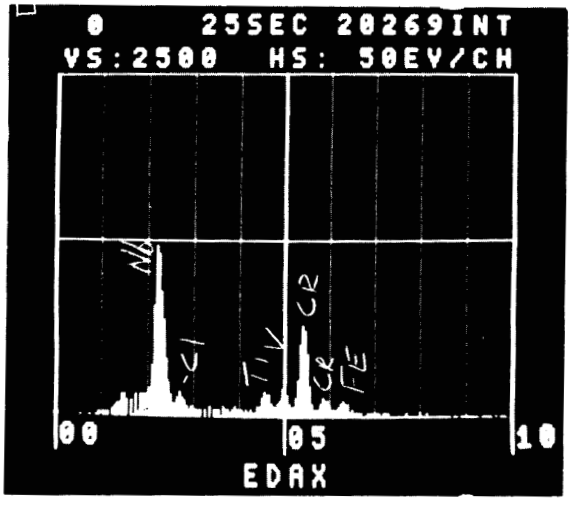


500X

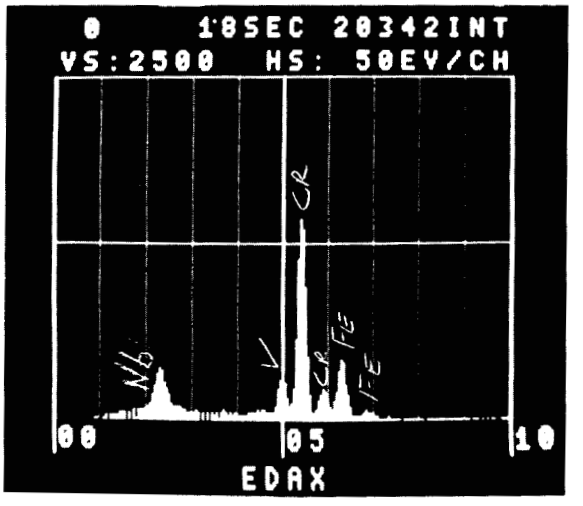
1000X



(a)



(b)

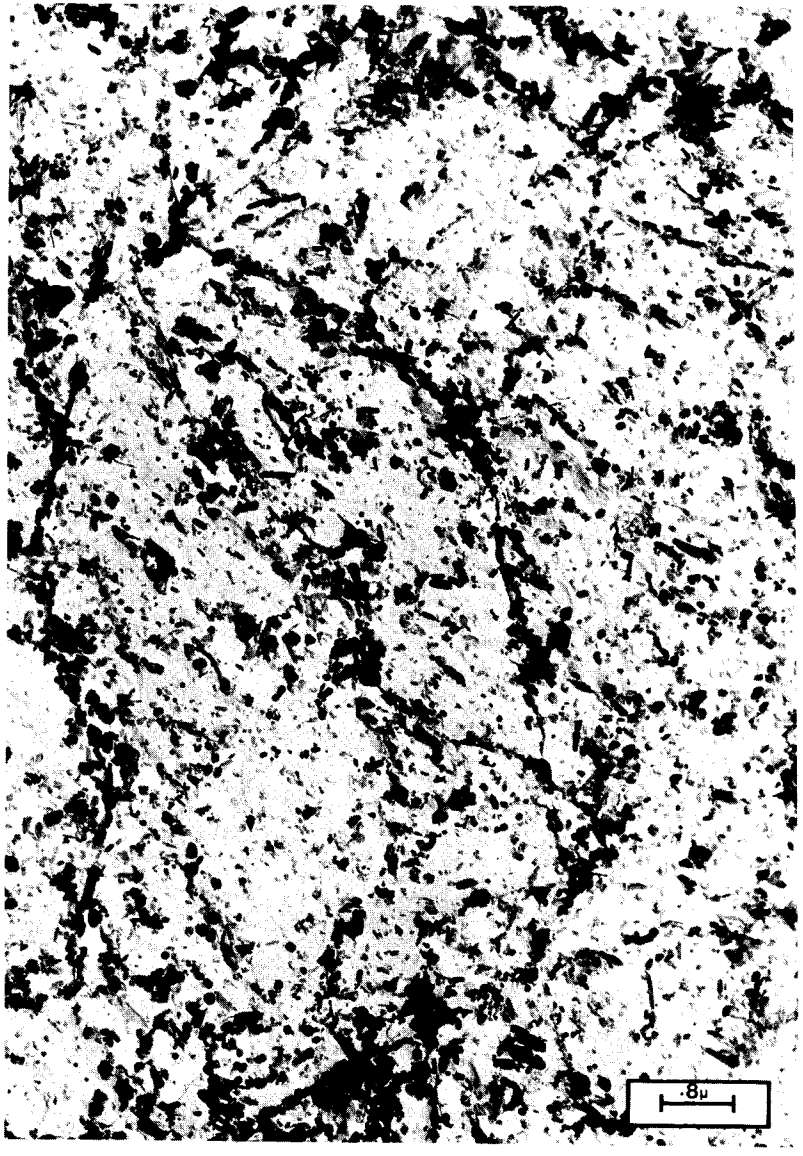


(c)

FIGURE 16: (a) Carbide Extraction Replica showing grain boundary $M_{23}C_6$ carbides and uniform distribution of MX within matrix after normalizing and tempering. ESR XA 3187.

(b) EDAX analysis of bulk extraction residue after normalizing showing composition of NbCN containing small amounts of vanadium and titanium

(c) EDAX analysis of bulk extraction residue after normalizing and tempering showing composition of M_{23} C_6 and MX.



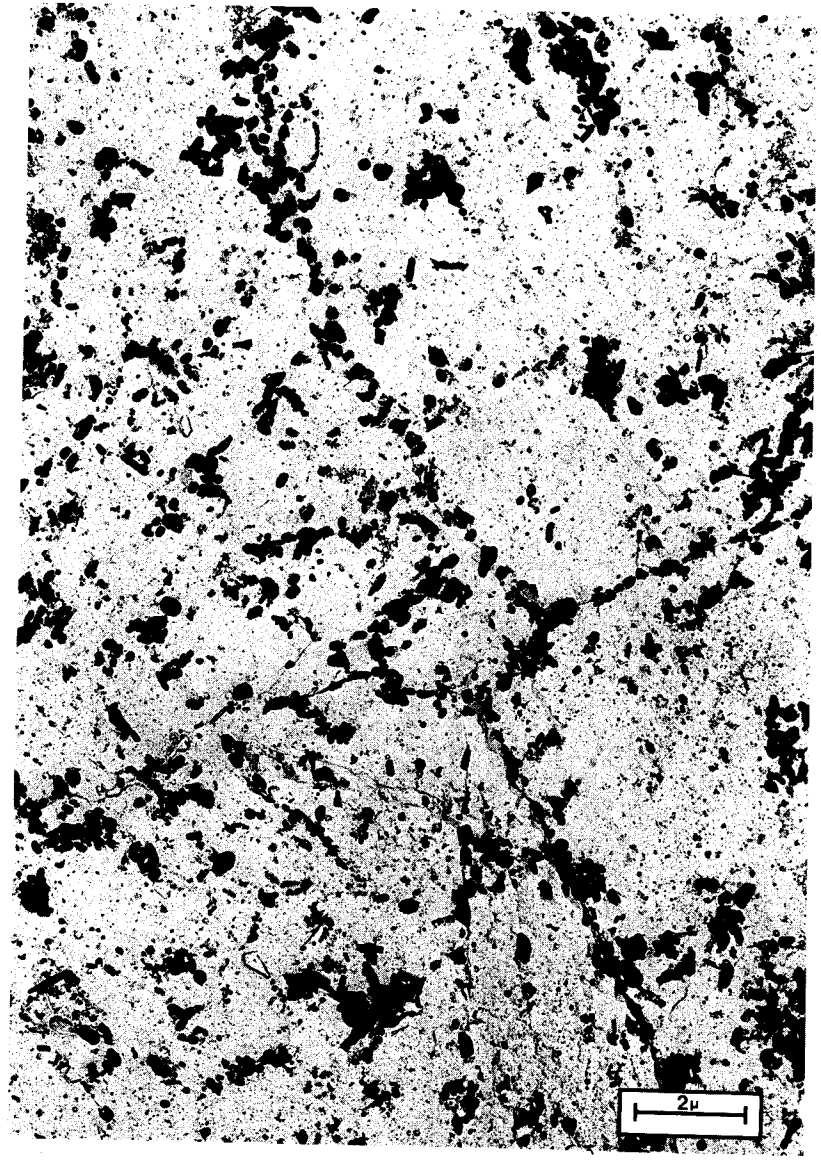


FIGURE 17: Electron Replicas showing carbide size and distribution differences between ESR XA 3177 (a) and ESR HT. 91887 after normalizing and tempering.

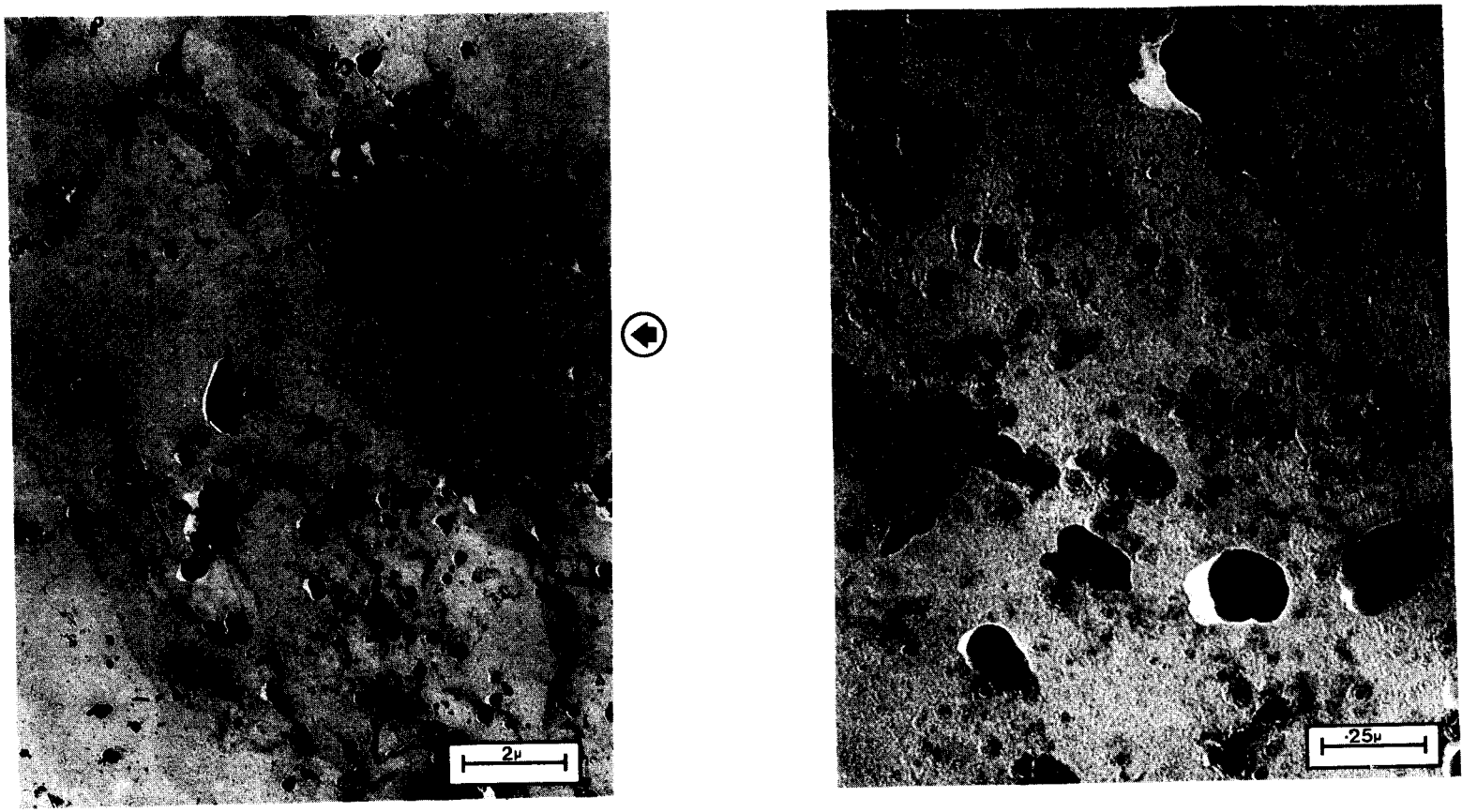
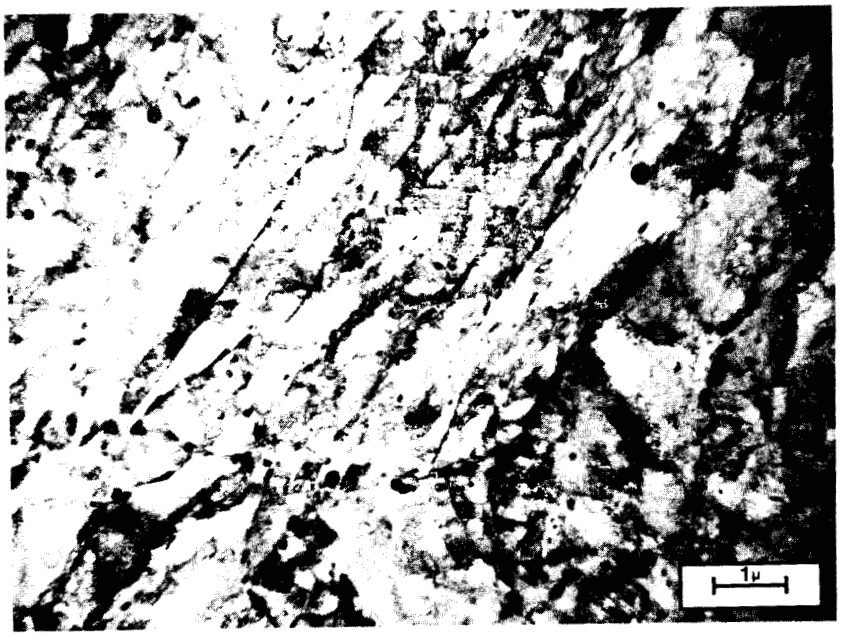


FIGURE 18: Electron Replica of ESR HT 91887 after normalizing and tempering, (a) showing $M_{23}C_6$ at grain boundaries and fine NbCN precipitated within the matrix, (b) enlarged view of area marked by arrow showing fine matrix carbides.

FIGURE 19: TEM micrograph of ESR XA 3177 after normalizing at 1900°F for 1 hour and air cooling, showing lath martensitic structure.



(a)

(b)

FIGURE 20: TEM micrographs of normalized and tempered ESR HT. 91887 showing tempered lath martensitic structure.

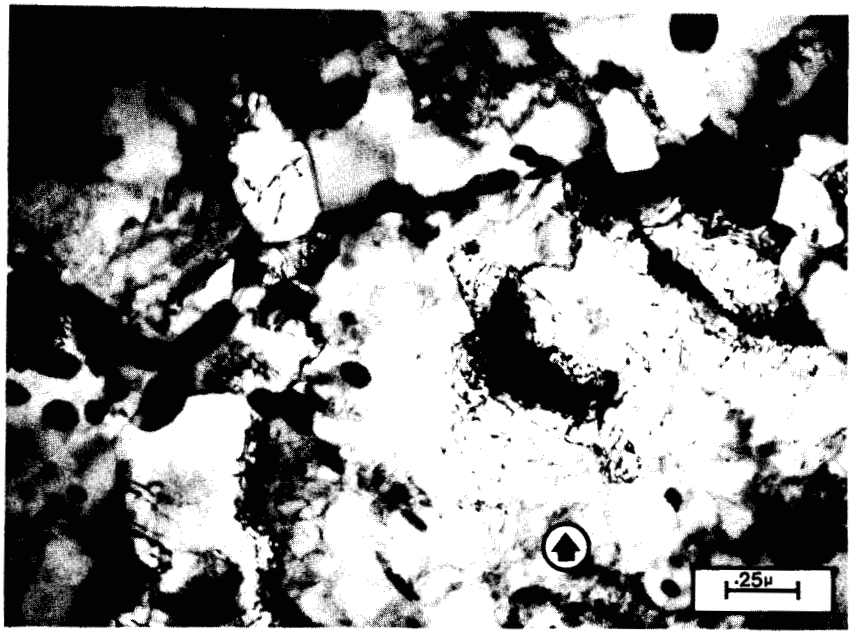


FIGURE 21: TEM micrograph of ESR HT. 91287, showing fine matrix carbides inhibiting recovery and precitating on dislocations.

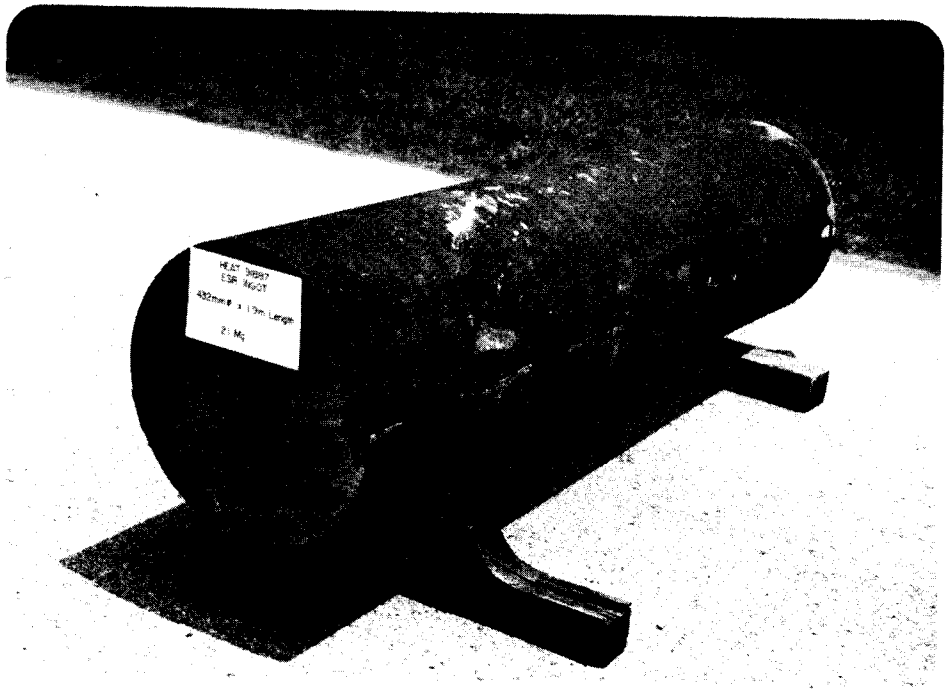
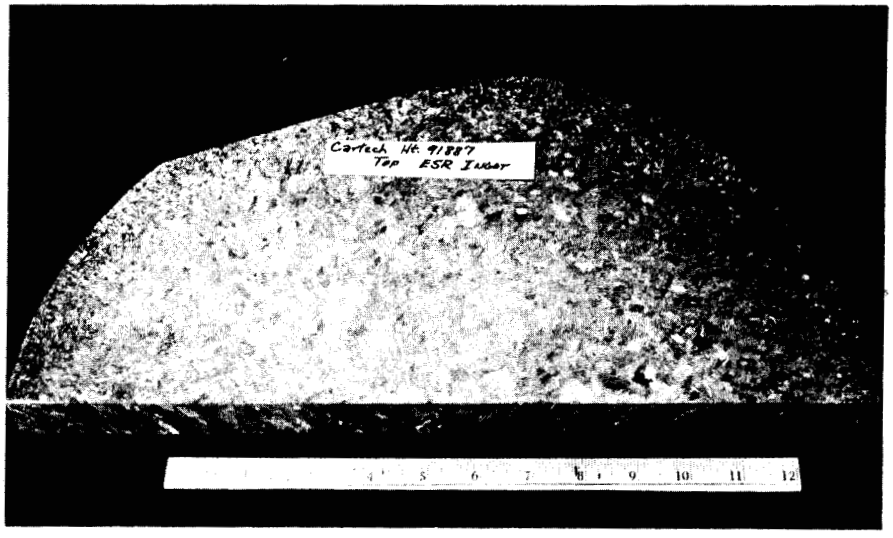


FIGURE 22: PHOTOGRAPH OF 5000 # HEAT ESR INGOT OF MODIFIED 9 Cr-1 Mo ALLOY. (SURFACE RUSTING FROM FREE IRON LEFT BY SURFACE GRINDING OPERATION).



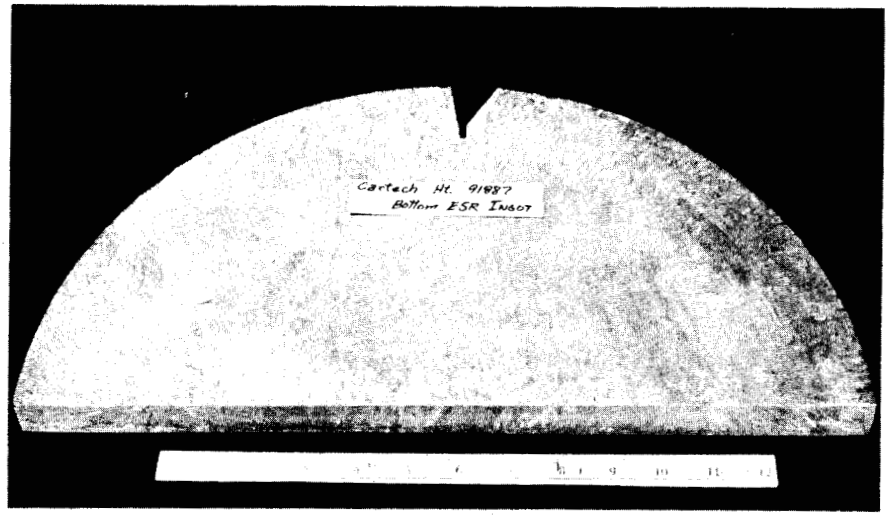
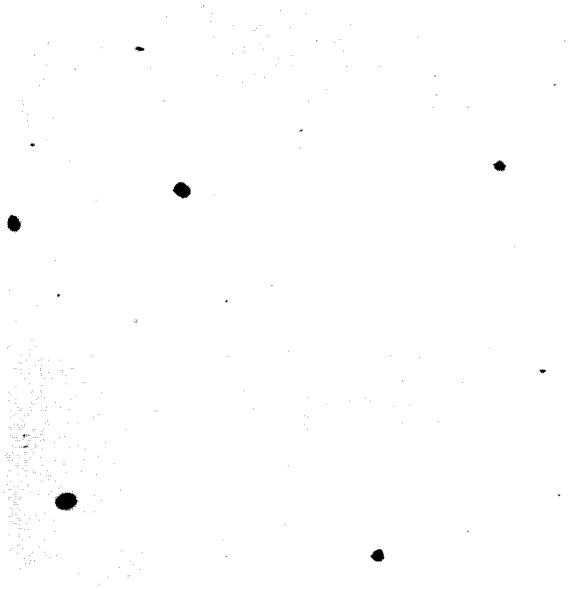
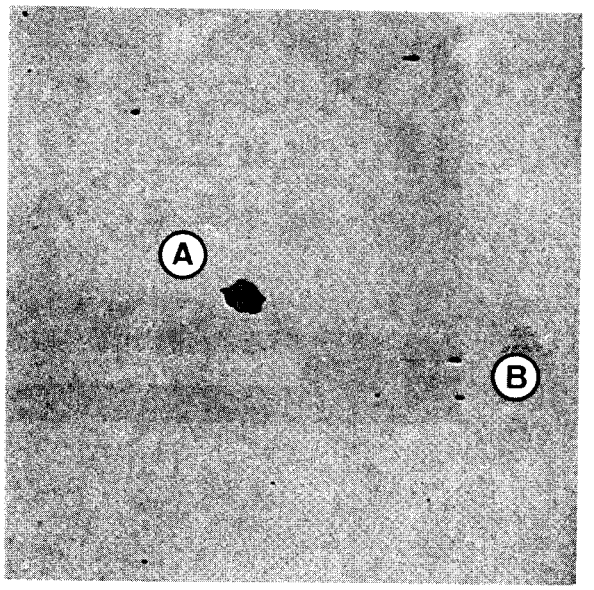


FIGURE 23: MACROSTRUCTURE OF AS CAST ESR INGOT TOP AND BOTTOM OF 5000 LB. HEAT 91887.

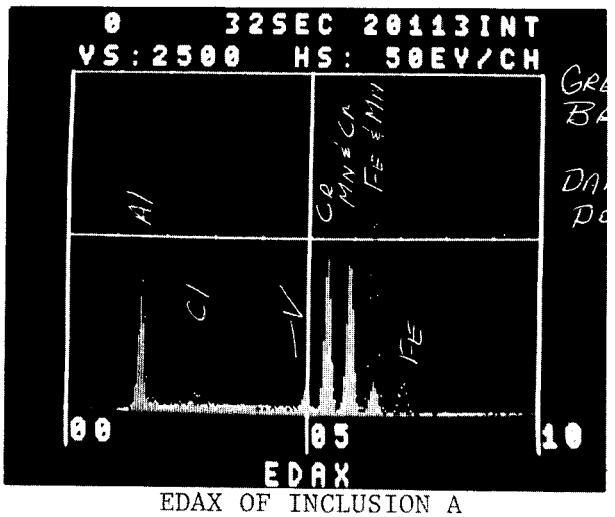
FIGURE 24: MICROSTRUCTURE OF HT. 91887, AS ROLLED PLATE AFTER NORMALIZING @ 1900°F, 1 HR AC. SHOWING INCLUSIONS ON SAMPLES NEAR CIRCUMFERENCE. INCLUSIONS ARE MAINLY Fe, Cr, Mn ALUMINATES, SILICATES, FROM ESR SLAG.



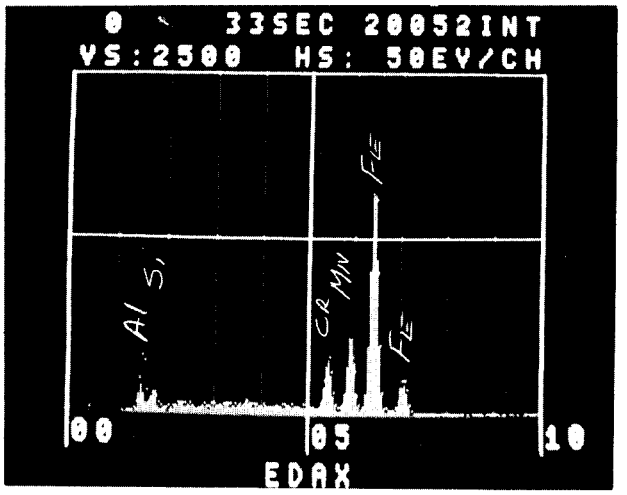
200X, UNETCHED



800X, SEM MICROGRAPH



EDAX OF INCLUSION A
GREY BARS, DARK DOTS.



EDAX COMPARISON OF TWO INCLUSIONS
MARKED B. DOTS LOWER INCLUSION

FIGURE 4(a) TOP

FIGURE 4(b) BOTTOM

FIGURE 25 a&b: MICROSTRUCTURE OF HOT WORKED AND HEAT TREATED SAMPLES FROM TOP AND BOTTOM OF THE FIRST 5000 LB. ESR HEAT (HT. 91887). HEAT TREATMENT 1900°F, 1 HR., AC, + 1400°F, 1 HR., AC. (200X).

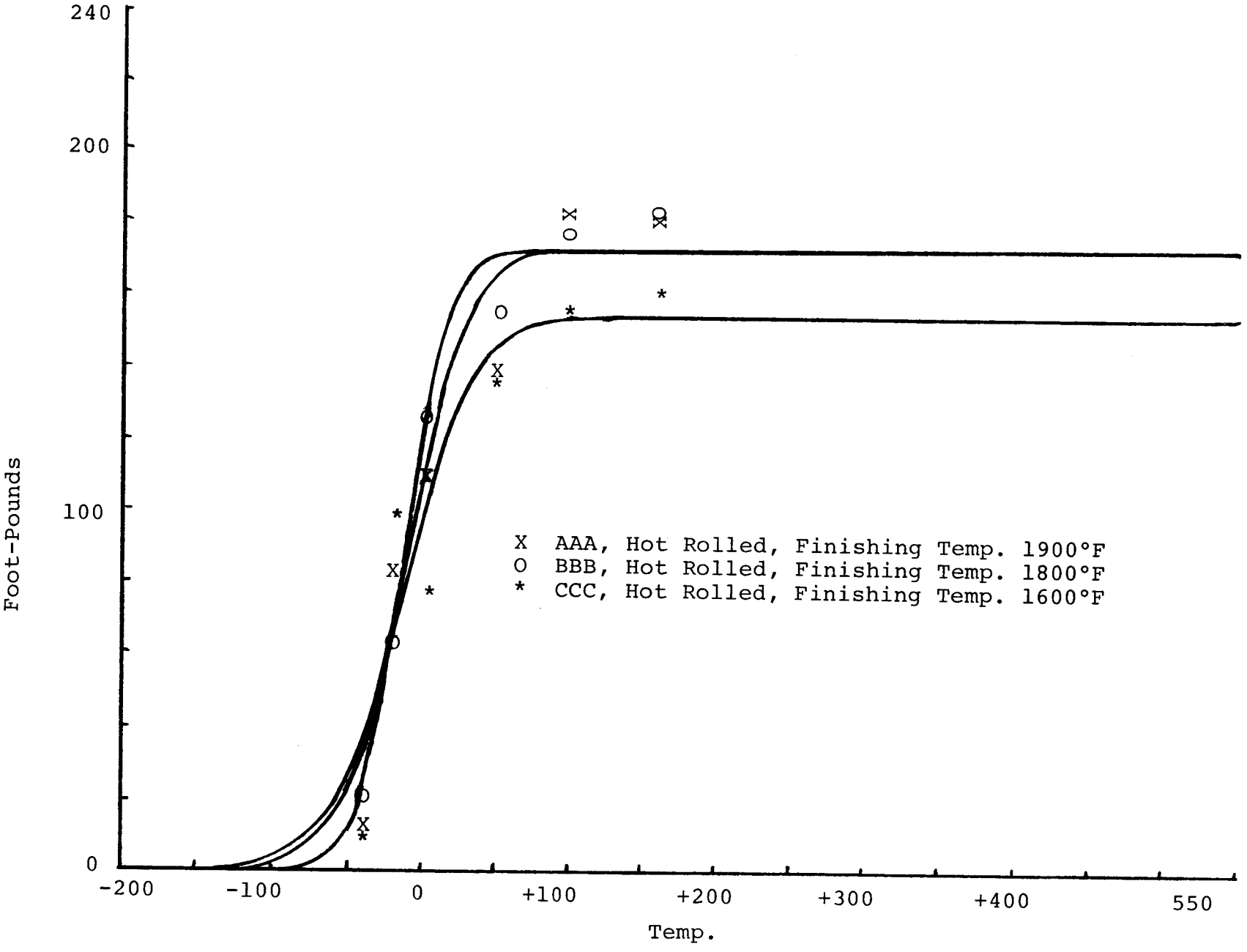
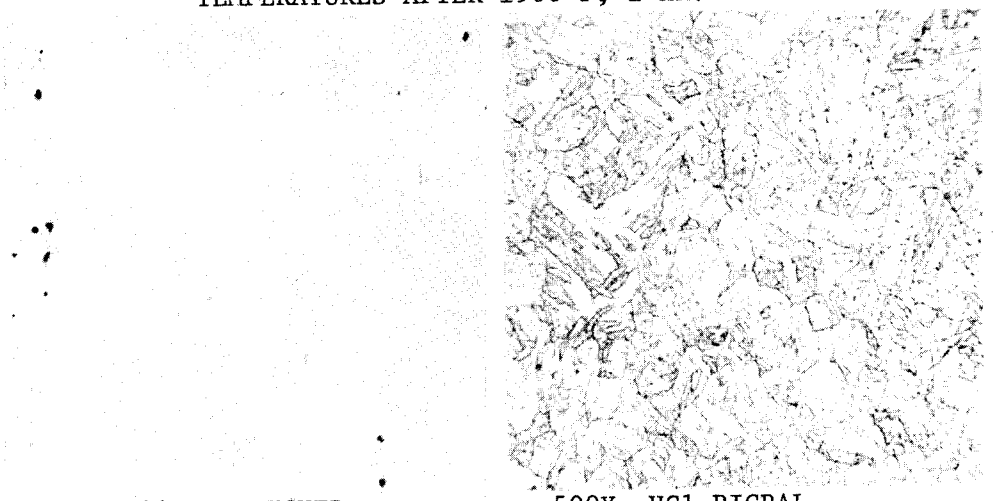


FIGURE 26: Plot of Charpy Curves of Heat 91887 Hot Rolled and Finished at 1600°F, 1800°F, and 1900°F. Charpy Test Run After Normalizing and Tempering.

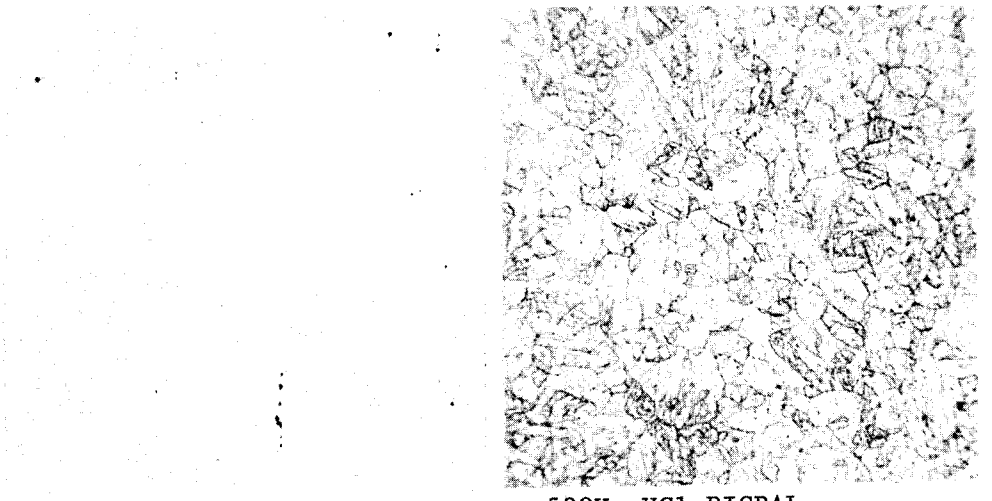
FIGURE 27: MICROSTRUCTURES OF HT. 91887 AFTER HOT FINISHING AT DIFFERENT TEMPERATURES AFTER 1900°F, 1 HR. NORMALIZE + 1400°F, 1 HR. TEMPER



100X, UNETCHED

500X, HC1 PICRAL

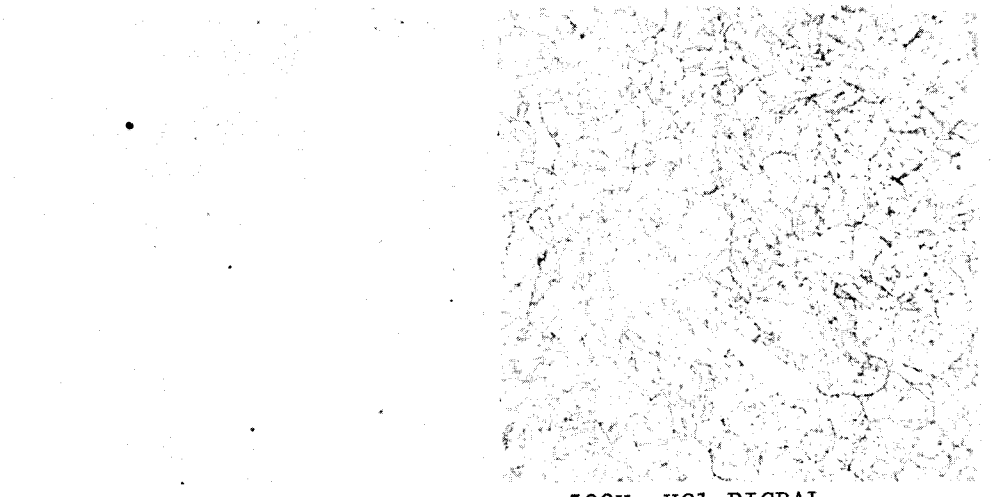
HOT FINISHED @ 1600°F LONGITUDINAL SECTION



100X, UNETCHED

500X, HC1 PICRAL

HOT FINISHED @ 1800°F LONGITUDINAL SECTION



100X, UNETCHED

500X, HC1 PICRAL

HOT FINISHED @ 1900°F LONGITUDINAL SECTION

SECTION IV

MELTING AND CONSOLIDATION PRACTICE

G. C. Bodine, Jr.

LIST OF FIGURES

Figure No.		Page
1	Processing Sequence for C-E/Sumitomo Tube Production Experiment	67

LIST OF TABLES

Table No.		Page
1	Chemical Analysis	68
2	Reduction Data on Controlled Rolling of Heat 91887	69
3	Check Analysis of Cold Drawn Tube	70

IV. MELTING AND CONSOLIDATION PRACTICE - G. C. Bodine, Jr.

A. Experimental Heats

Experimental alloys were prepared by air induction melting (AIM) followed by electroslag remelting (ESR). The duplex AIM-ESR laboratory heats ranged from 25 to 50 kg. Air induction melts were cast into nominal 102 mm diameter round electrodes which were then electroslag remelted and cast into nominal 127 mm diameter ingots. Approximately thirty (30) laboratory heats were made with the following alloying addition ranges as weight percent: 8.5-11.5 Cr, 0.1-2.1 Mo, 0-1.5 W, 0.04-0.33 V, 0.01-0.45 Nb, 0.04-1.2 Ni, 0.03-0.08 N, 0.2-1.3 Mn, 0.01-0.26 Si, and 0.05-0.14 C. Residual Ti content was between 0 and 0.05 weight percent. Levels of sulfur and phosphorus were within 0.005-0.014 and 0.010-0.014 weight percent, respectively. A few of the heats contained deliberate boron and zirconium additions.

Large ESR Ingot (Heat 91887)

A 2.2×10^4nx432mm diameter ESR ingot was produced by CARTECH to the Combustion Engineering Metallurgical and Materials Laboratory (MML) specified chemistry. The nominal analysis (as weight present) of the 432 mm diameter ESR ingot was: 0.09 C, 8.92 Cr, 0.99 Mo, 0.25 V, and 0.18 Nb. The chemical analyses for this ingot as well as for all the experimental laboratory heats is shown in Table 1.

B. Consolidation Practice

Sections of each ESR ingot were converted to 13 mm thick plate by various processing techniques including hot forging, hot rolling, and combinations of hot forging and rolling. A few sections were cold rolled directly to plate and some were also cold finished after hot forging and/or hot rolling. A series of

controlled hot rolling experiments was undertaken in order to characterize the effect of heating and rolling temperature upon final heat treated properties of plate. The experimental procedure included the attachment of thermocouples to the rolling stock and monitoring temperature during heating and rolling. Experimental rolling and temperature data are shown in Table 2. All finished rolled plate heat treatment consisted of a 1038° C one (1) hour) normalize followed by a 760° C (one (1) hour) temper.

Two laboratory AIM-ESR ingots were processed into tubular sections. One was converted by hot piercing the ingot, surface machining the pierced ingot bore and outside diameter, and cold pilgering (tube reducing) through three (3) passes to 38.1 mm OD x 5.1 mm wall. The other ingot was surface machined, bored and direct cold pilgered through two (2) passes to 60 mm OD x 7.6 mm wall. No difficulties were encountered during the tube conversion of either ingot. Interstage heat treatment between passes was at 760° C for one (1) hour and final heat treatment consisted of normalizing at 1038° C for one (1) hour followed by tempering at 760° C for one (1) hour.

C. Hardware Manufacturing - Tubing

Evaluation of the processing of experimental AIM-ESR ingot sections to plate and tube indicated that the advanced nine (9) chromium ferritic alloys possessed good workability and should be satisfactory for commercial production of seamless tubing.

In order to further demonstrate the potential of these alloys for seamless tubemaking, the Combustion Engineering Metallurgical and Materials Laboratory arranged with the Sumitomo Tube Works for the conversion of seven (7) AIM-ESR ingots to 152 mm diameter tubing.

Each of the ingots was hot extruded and cold drawn to a final tube size of 50.8 mm OD x 5.0 mm wall thickness. Chemical analysis of the material is shown in Table 3, and a flow sheet of the processing sequence is shown in Figure 1. The inclusion of a 12% chromium alloy was for reference purposes with respect to the comparative 9% chromium alloy processing characteristics. The mill reported that no difficulty was experienced during the processing of the alloys, but it was noted that the 12% chromium alloy showed a rougher surface after extrusion and was generally more difficult to process than the 9% chromium alloys. This observation was consistent with previous mill experience related to 12% chromium ferritic boiler tube alloys. The mill concluded that the advanced 9% alloys should not present any additional basic production considerations than that normally experienced with commercial ASME Type T-9, 9% chromium - 1% molybdenum alloy. However, the advanced 9% chromium alloys will probably require longer heat treatment and higher normalizing temperatures than the T-9 alloy. These requirements will not be ideally suited for most commercial continuous furnace installations. The higher temperature and longer time might also require some adjustments for scale removal when a protective atmosphere is not available. The hot extrusion of ESR ingots larger than the 152 mm diameter ingots is a possibility based upon the success with the experimental C-E ingots.

At some future time, consideration should be given

to alternate melting practices, i.e., electric furnace/AOD process. Other processes may provide material characteristics similar to that obtained in the AIM-ESR practice.

FIGURE 1

PROCESSING SEQUENCE FOR
C-E/SUMITOMO TUBE PRODUCTION EXPERIMENT

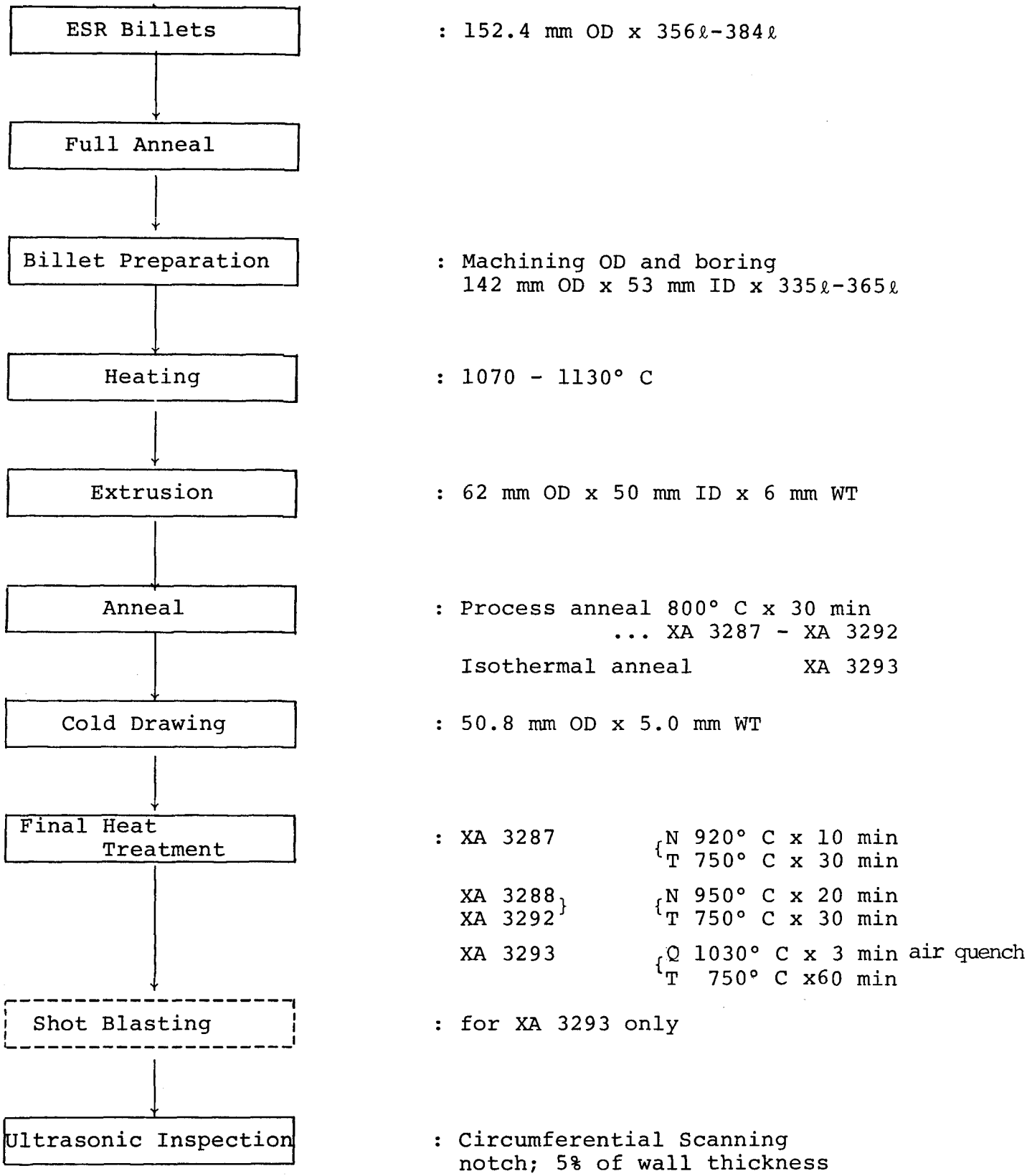


TABLE 1

Chemical Analysis

Heat	C	Mn	Si	S	P	Cr	Mo	V	W	Cb	Ti	Ni	N	Al
XA 3154A	.078	.50	.25	.011	.012	9.05	1.53	.27		.13	.05	1.13	.047	.024
XA 3154B	.078	.53	.26	.012	.012	9.16	1.54	.27		.13	.04	1.15	.049	.005
XA 3155	.092	.67	.14	.005	.012	8.48	2.12	.33	.01	.04	<.01	.90	.029	.003
XA 3156	.14	.59	.10	.005	.012	8.88	2.01	.31	.01	.05	<.01	.90	.031	.001
XA 3157	.21	.53	.17	.007	.008	11.47	1.03	.30	.54	.01	<.01	.55	.045	.002
XA 3158	.10	.70	.31	.007	.013	9.59	1.50	.32	<.01	.15	.05	1.09	.052	.017
XA 3159	.092	.57	.24	.007	.013	10.02	1.50	.31	<.01	.13	.04	1.11	.053	.014
XA 3160	.082	.61	.24	.007	.013	9.95	1.47	.31	<.01	.14	.03	1.17	.056	.014
XA 3161	.097	.49	.11	.009	.012	9.25	1.10	.25	<.01	.10	.04	.60	.042	.012
XA 3162	.090	.51	.12	.010	.012	9.24	1.08	.24	<.01	.11	.05	.82	.024	.010
XA 3163	.094	.50	.07	.011	.012	9.21	1.00	.24	<.01	.11	.02	.08	.067	.009
XA 3175	.072	.43	.23	.009	.012	9.90	1.07	.15	<.01	.14	.05	.09	.052	.010
XA 3176	.082	.43	.15	.011	.012	9.62	.75	.13	<.01	.09	.04	.07	.078	.011
XA 3177	.087	.44	.17	.010	.012	9.50	.78	.14	.48	.11	.04	.08	.065	.011
XA 3178	.094	.49	.20	.009	.013	9.42	1.55	.30	<.01	.14	.04	.16	.061	.010
XA 3179	.087	.43	.24	.009	.009	9.56	.76	.27	<.01	.10	.05	.08	.051	.009
XA 3180	.11	.46	.14	.009	.011	9.16	1.05	.26	<.01	.13	.05	.07	.058	.009
XA 3181	.09	.48	.10	.010	.011	9.10	.77	.26	.48	.09	.03	.07	.064	.008
XA 3182	.11	.48	.13	.010	.012	8.96	1.04	.26	<.01	.12	.05	.08	.055	.007
XA 3183	.096	.37	.06	.010	.014	8.55	1.05	.21	<.01	.12	.01	.08	.061	.007
XA 3184	.091	.50	.07	.010	.011	8.92	1.05	.20	<.01	.09	<.01	.08	.067	.003
XA 3185	.099	.66	.41	.008	.013	9.16	1.04	.22	<.01	.14	.03	.11	.057	.016
XA 3186	.087	.35	.07	.009	.012	8.59	1.05	.21	<.01	.10	.01	.07	.054	.007
XA 3187	.081	.33	.03	.014	.012	8.94	1.05	.21	<.01	.11	<.01	.04	.066	.007
XA 3188	.098	.31	.01	.010	.014	8.29	1.04	.20	1.47	.10	.01	.08	.050	.006
XA 3217	.082	.50	.24	.010	.014	9.18	1.03	.04	<.01	.01	<.01	.10	.028	.028
XA 3218	.078	.25	.06	.008	.014	8.73	1.04	.18	.45	.11	.02	.05	.071	.016
XA 3224	.050	.19	.12	.010	.013	8.47	.06	.21	.49	.13	.04	.06	.054	.015
XA 3271	.074	.37	.06	.007	.009	10.27	1.00	.14	.45	.09	.01	.21	.067	.004
XA 3272	.083	.33	.05	.008	.014	8.40	.76	.30	1.06	.12	.01	.08	.052	.005
XA 3273	.10	.32	.05	.007	.011	9.26	.80	.23	<.01	.13	<.01	.12	.037	.002
XA 3280	.075	.35	.09	.008	.013	9.26	.75	.13	.48	.10	.01	.05	.069	.002
91887	.097	.38	.08	.005	.007	9.22	1.00	.22	<.01	.15	<.01	.08	.038	.003

TABLE 2

REDUCTION DATA ON CONTROLLED ROLLING OF HEAT 91887

PIECE	PASS	% RED.	ENTER TEMP.	EXIT TEMP.
A	1	18	A 2177° F B 2180° F	A 2197° F B 2200° F(?)
	2	23	A 2070° F B 2021° F	A 2092° F B 2036° F
	3	24	A 1913° F B 1813° F	A 1932° F B 1831° F
	4	15	A 1814° F B 1813° F	A 1838° F B 1813° F
B	1	23	A 2104° F B 2114° F	A 2120° F(?) B 2127° F
	2	31	A 1927° F B 1898° F	A 1950° F(?) B 1934° F
C	1	24	A 2100° F B 2100° F	A 2125° F(?) B 2132° F
	2	21	A 1801° F B 1838° F	A 1838° F B 1861° F(?)
	3	20	A 1669° F B 1660° F	A 1697° F B 1692° F
	4	17	A 1553° F B 1562° F	A 1579° F B 1593° F

A - near edge, near center width and thickness
B - mid-length, near center width and thickness
? - denotes estimate

TABLE 3

CHECK ANALYSIS OF COLD DRAWN TUBE

Heat No.	C	Si	Mn	P	S	Ni	Cr	Mo	Nb	V	W	Ti	Sol Al	N
XA 3287	.085	.14	.55	.009	.003	.08	9.04	1.02	<.002	.022	<.01	<.005	.018	.0280
XA 3288	.071	.11	.53	.009	.004	.18	9.20	2.04	<.002	.022	<.01	--	.010	.0306
XA 3289	.056	.06	.83	.012	.010	.08	9.28	2.08	.31	.022	<.01	--	.001	.0229
XA 3290	.074	.01	.45	.009	.013	.06	8.26	1.02	.05	.19	<.01	--	.001	.0245
XA 3291	.075	.11	.54	.008	.010	.07	9.36	1.57	.11	.29	<.01	.010	.001	.0598
XA 3292	.077	.06	.48	.008	.008	.08	9.16	0.80	.09	.20	.41	.010	.001	.0598
XA 3293	.22	.11	.56	.009	.004	.54	11.40	1.80	.011	.30	.44	<.005	.005	.0305

SECTION V

WELD FILLER METAL DEVELOPMENT

D. M. Vandergriff

LIST OF FIGURES

Figure No.		Page
1	Test Plate Welding Procedure	86
2	Welding Procedure	87
3	Test Plate Welding Procedure	88
4	Charpy V-Notch Samples with Impact Strengths Greater than 240 ft-lbs	89
5	Charpy V-Notch Impacts Plates 206-B, 207-B, 215-B	90
6	Charpy V-Notch Impacts Plates 165-B, 167-B	91
7	Charpy V-Notch Impacts Plates 169-B, 176-B, 177-B, 180-B	92
8	Charpy V-Notch Impacts Plates 169-B, 178-B, 179-B	93
9	Charpy V-Notch Impacts Plates 101-A, 102-A, 103-A	94
10	Charpy V-Notch Impacts Plates 197-B, 199-B	95
11	Charpy V-Notch Impacts 195-B, 191-B, 204-B	96
12	Charpy V-Notch Impacts Plates 195-B, 219-B	97
13	Charpy V-Notch Impacts Plates 191-B, 208-B	98
14	Charpy V-Notch Impacts Plates 191-B, 220-B, 221-B	99
15	Charpy V-Notch Impacts Plates 191-B, 222-B, 223-B	100
16	Charpy V-Notch Impacts Plates 206-B, 207-B, 215-B	101
17	Charpy V-Notch Impacts Plates 165-B, 167-B	102
18	Charpy V-Notch Impacts Plates 169-B, 176-B, 177-B, 180-B	103
19	Charpy V-Notch Impacts Plates 169-B, 176-B, 179-B	104
20	Charpy V-Notch Impacts Plates 101-A, 102-A, 103-A	105
21	Charpy V-Notch Impacts Plates 197-B, 199-B	106
22	Charpy V-Notch Impacts Plates 195-B, 191-B, 204-B	107

LIST OF FIGURES (cont'd)

Figure No.		Page
23	Charpy V-Notch Impacts Plates 195-B, 219-B	108
24	Charpy V-Notch, Impacts Plates 191-B, 208-B	109
25	Charpy V-Notch Impacts Plates 191-B, 220-B, 221-B	110
26	Charpy V-Notch Impacts Plates 191-B, 222-B,223-B	111

LIST OF TABLES

Table No.		Page
I	Shielded Metal Arc Welding of 9Cr-1Mo-V-W Using High Frequency Pulsed Arc Power Supply	112
II	SMAW Test Plate Heat Treatments	113
III	Shielded Metal Arc Undiluted Weld Pads	117
IV	Chemical Composition - Wt %	119
V	Delta Ferrite Determinations in 9Cr SMA Weld Metal	124
VI	9% Cr Shielded Metal Arc Weld Deposits	125
VII	Summary of Charpy-V Notch Impact Results	150
VIII	Weld Metal Composition Ranges	154
IX	CVN Results for Lot 111	155

V. WELD FILLER METAL DEVELOPMENT - D. M. Vandergriff

A. Introduction

The Liquid Metal Fast Breeder Reactor (LMFBR) alternate structural materials development program was initiated to develop a stabilized 9-12 chromium ferritic steel aimed at ASME Code approval in five years. The inherent advantages of this class of steels and the specific development goals with respect to mechanical properties were stated earlier in this paper. A weld filler metal was to be developed simultaneously that would produce a weld joint that meets all the property objectives of the wrought base metal.

Due to C-E's vast experience in weld filler metal development, improving toughness in the weldment was identified as the crucial area of the development task. The major weld development effort was concentrated on improving the CVN impact strength of the Shielded Metal Arc (SMA) deposit while maintaining sufficient hot strength and carbide stability. Successful covered electrode formulation has permitted all alloying via the electrode coating without impairing the weld quality. This avoids the unacceptable delay and high cost of procuring multiple heats of prealloyed core wire.

An acceptable laboratory welding technique was recently developed to allow more emphasis on the Gas Tungsten Arc (GTA) process. Test results have shown that SMA deposited weld metal has better impact properties when refined by remelting each layer of deposit with the manual GTA process.

B. Experimental Procedure

In order to evaluate the wide combination of chemical compositions and fabrication conditions for this weld metal development, a total of 191 batches of SMA electrodes were made from 127 different coating formulations. One heat of solid filler wire was melted and reduced to two sizes for evaluation. This filler material was used to produce 127 3/4" thick butt weld test plates. Six of the test plates were manual Gas Tungsten Arc welded and 121 were Shielded Metal welded.

The test plates welded for evaluation during the initial portion of this development were 3/4" thick by 10" long butt weld coupons as illustrated in Figure 1. The base material was mild carbon steel with two layers of "buttering" with 9Cr-1Mo-V-W SMA Lot No. 1 on the backing bar and the edges of the test plate prior to fit up as shown in Figure 1. The 1" weld groove was then welded with 3/16" diameter SMA electrodes at 400° F minimum preheat and 600° F maximum interpass temperature. The twenty test plates that utilized the buttered base material in order to minimize unacceptable dilution in the weld deposit are designed as "A" series by the suffix after the plate number.

The remainder of the weld coupons were prepared, using a single heat of 3/4" thick Type 410 stainless steel plate as the base material. This base material eliminated the necessity for "buttering" prior to fit up since weld deposit dilution was minimal in the center of the deposit to be tested. The groove geometries and welding conditions for both the 3/16" and 1/4" diameter SMA electrodes are shown in Figure 2. This series of test plates is designated by the suffix "B".

Two test plates, 206-B and 207-B, were made in order to evaluate the use of solid alloyed filler wire with the manual GTA welding process. The 3/32" diameter core wire, R-4001 was reduced from an ESR ingot melted by C-E's Metallurgical and Materials Laboratory (MML), Metals Processing Section. The chemistry aim was the same as Lot No. 111 (9Cr-1Mo-.15V-.15W-.05Cb-.05N_2-.07C) which had the best impact properties of any SMA lot tested at that time. The ingot was processed by Carpenter Steel into a 1" double octagon and then swaged by the MML to 1/4" diameter rod stock. The 50 lbs of rod stock was then drawn by C-E's Atlanta Wire Plant to 3/32" (R-4001) and 3/16" (R-4002) diameter wire for welding.

The manual GTA welded test plates were prepared using the same weld groove for the "B" series SMA test plates (See Figure 2). The 3/32" diameter filler wire was welded using both 150 amps and 180 amps that gave heat inputs of 34 and 43 kj/inch, respectively, for the two test plates.

In order to reduce the delay and cost of procuring additional heats of alloyed filler wire for the GTA welding process, a laboratory welding technique was developed that allowed SMA deposited weld metal to be used as the filler metal for the GTA process. The SMA electrodes are easily and quickly manufactured to the exact chemistries desired and the very different thermal conditions and resultant microstructure of the GTA process are evaluated. The "B" series weld groove geometry is used and the first layer of SMA weld metal is deposited in the normal manner using three beads to fill the groove width (see Figure 3). This is followed by an autogeneous GTA remelt pass down the center of the weld groove. The previously deposited SMA weld metal is remelted in the area from which the V-notch of the Charpy impact specimens is machined. The tested weld deposit is therefore similar enough to a weld deposit

of solid alloyed filler wire made with the GTA process to allow evaluation of this process without unacceptable time delays and excessive cost.

The possibility of grain refinement of the SMA weld deposit,using pulsations of the welding arc to create forced thermal fluctuations which might alter the solidification pattern of the molten weld metal,was explored. In order to weld these test plates, a power supply was modified that would allow a high frequency pulsed arc current to be super-imposed on a constant background current from another power supply. A full range of frequencies were evaluated up to 20,000 Hz with the total of the average pulse current plus the background current held at a constant of 235 amps for all test plates. Table I shows the welding conditions evaluated for high frequency pulsed arc welding of SMA 9Cr-1Mo-V-W electrodes.

All of the weld metal test plates were given a post-weld heat treatment. Different heat treatments were explored aimed at improving the CVN impact properties. All plates were allowed to cool to room temperature and then heat treated according to the procedures listed in Table II. The HRB hardness values are listed also. Hardness was determined after post-weld heat treatment as measured in accordance with ASME E92-72 and then converted from the Vickers HV50 values, using the conversion tables in ASTM E140-72.

The chemical composition for the deposited weld metal was determined for each of the 127 test plates prepared. Standards were established for the x-ray fluorescence and optical emission spectrometers during the initial phase of the weld development so that the bulk of the analytical work was performed on these two instruments. The undiluted SMA weld pad chemical analysis used in this work are listed in Table III. Wet chemistry

and atomic absorption techniques were used as needed. The chemical compositions of the weld metal deposits are listed in Table IV.

In order to predict the possible presence of delta ferrite (δ) in the weld deposit, the following chromium equivalent formula developed by General Electric and revised using the Ti, Al, and Cu values from "Thielemann on Rupture Properties of Ferrous Alloys", ASTM Proceedings, Volume 40, 1940, was used:

$$\text{Cr Eq} = \%\,\text{Cr} + 6(\%\,\text{Si}) + 4(\%\,\text{Mo}) + 1.5\,(\%\text{W}) + 11\,(\%\text{V}) + 5\,(\%\,\text{Cb}) + 8\,(\%\,\text{Ti}) + 12\,(\%\,\text{Al soluble}) - 40\,(\%\,\text{C}) - 2\,(\%\,\text{Mn}) - 4\,(\%\,\text{Ni}) - 2\,(\%\,\text{Co}) - 30\,(\%\,\text{N}) - \%\,\text{Cu}$$

If the Cr Eq value is less than 10, then δ is usually not present. If the Cr Eq value is 10-12, then some δ may be present. For Cr Eq >12, δ will be present. Table V in the Appendix shows the correlation between δ ferrite, as determined metallographically for several lots of 9% Cr weld metal alloys and the value, as predicted from the above formula. The predictability of the Cr Eq formula appears satisfactory.

One hundred and twenty (120) of the plates were tested for CVN impact properties. Eight (8) standard 10x10 mm CVN specimens were prepared from each test plate and broken by the 240 ft-lb hammer at different test temperatures in order to establish the ductile-brittle transition curve. The CVN test data is tabulated in Table VI. From plots of the impact energy, mil lateral expansion, and fracture appearance versus test temperature, the transition temperature at 50 ft-lb, 35 mil lateral expansion, and 100% shear FATT plus the impact energy at the upper shelf were determined. These values are tabulated in Table VII.

Six test plates, Nos. 209-B to 214-B, were prepared for creep rupture and hot tensile testing. These were made from 9Cr-1Mo-V-W-N_2 SMA Lots 109 and 111, which had no columbium added and .05% Cb, respectively. No pulsing or GTA remelt was used for any of these six test plates. Results are reported in the section on creep rupture testing.

C. Results and Discussion

One-hundred and twenty-seven (127) different chemical compositions for weld filler metal have been evaluated. The minimum acceptable CVN impact properties have been achieved in two recent weld deposits - one welded with the laboratory GTA process and the other using SMA. Both welds were 9Cr-1Mo-.16V-.14W.04Cb, with the GTA having .044N, and the SMA .033N. The transition temperature at 50 ft-lbs was 40° F for both, with the upper energy shelf just over 100 ft-lbs. A summary of CVN impact properties for all test plates is shown in Table VIII. The CVN data is listed in Table VI.

The two best weld deposits tested have been the manual GTA weld deposits made with the solid alloyed filler wire (R-4001) reduced from an ESR ingot. The two test plates, Nos. 206-B and 207-B, were welded with the same filler wire at heat inputs of 34 KJ/in and 43 KJ/in, respectively. The upper energy shelf exceeded the 240 ft-lb capacity of the impact hammer and these CVN specimens were unbroken (see Figure 4). The 50 ft-lb transition temperatures were approximately 60° F,with the higher heat input showing slightly better CVN properties. Figure 5 shows the ductile-brittle transition curves for these GTA welds, as compared to a SMA deposit with the duplicate chemistry. Thus it appears that the improved properties are weld process dependent.

In order to evaluate the laboratory GTA technique, using SMA deposits as filler metal, two test plates were prepared using the same lot of SMA filler metal. Plate No. 165-B was prepared using the GTA remelt procedure described in the section on Test Procedures, and shown in Figure 3. Plate No. 167-B was prepared with the conventional SMA welding procedure. The transition curves are plotted in Figure 6. Both deposited chemical compositions were the same, but the ductile-brittle transition curve shifted over 100° with the GTA remelt procedure showing the improved properties over the SMA weld.

Many different chemical compositions were tried in order to obtain deposited weld metal impact properties that match the wrought base metal being developed. Table VIII gives the ranges of the alloying and minor element contents in the 126 weld metal compositions tested. Figure 7 shows the transition curves of four weld compositions that had alloying elements added for strength to a basic 9Cr-1Mo composition. As shown, the boron and zirconium additions were very detrimental to impact strength. Tungsten had no noticeable effect on the impact strength of the weld metal and the 0.05% nitrogen added to a 9Cr-1Mo composition for creep resistance produced only a slight decrease in impact strength. The vanadium additions of 0.17% with 0.08% carbon created an additional shift of approximately 20° F in the transition curve. Columbium additions greater than 0.05% were also detrimental to the CVN properties. Figure 8 shows 0.17% V plus 0.02% Cb shifting the transition curve more than just vanadium additions alone. Electrode diameter was varied in

order to determine the effect of heat input on the ductile-brittle transition temperature. Identical chemical compositions were made from 5/32", 3/16", and 1/4" diameter SMA electrodes. Also, the effects of preheat temperature and postweld heat treatment (tempering temperature) were investigated over a broad range. A consistent trend was not observed in the CVN data. The impact properties did not correlate with the weld hardness readings made after postweld heat treatment. Other more elusive factors appear dominant.

Notch toughness improvement in a Mn-Mo-V weld filler metal was reported by S. M. Silverstein, R. P. Sopher, and P. J. Rieppel in "Filler Wire for Welding Army Ordnance Armor", The Welding Journal Research Supplement, May, 1959, with additions of misch metal to the electrode coating. An investigation of misch metal (a mixture of rare earth metals) additions to the 9Cr-1Mo high strength weld metal was performed. Figure 9 shows the effect of misch metal treatment to the SMA weld deposit via additions to otherwise identical electrode coatings. The 0.5% misch metal additions show CVN impact strength improvement while 1.0% was detrimental as compared to no misch metal addition.

The Welding Institute and others reported that grain refinement was possible in the weld deposit by pulsing the welding arc in order to create forced thermal fluctuation, thereby altering the solidication pattern of the weld puddle. C-E explored the effect on CVN properties with SMA electrodes,using the technique of a high frequency pulsing current superimposed on a constant background,in order to generate dendrite fragmentation at the growing solid/liquid interface. It

was shown that certain frequencies were beneficial in the improvement of impact strength with the weld deposits tested. Table I lists the welding conditions explored in this investigation.

Figure 10 shows the improvement in the ductile-brittle transition curve with welding conditions of 40 amps pulse at 10kHz plus 195 amps of background current, using Lot 109 (9Cr-1Mo-V-W). The 50 ft-lb transition temperature shifted 50 degrees, as compared to no pulsing with the same filler metal.

Figures 11 and 12 show the effects of high frequency pulsing of SMA Lot 111, 9Cr-1Mo-V-W-Cb, with Cb added for improved creep rupture properties. A pulse current of 40 amps at 15 kHz created the most improvement in the CVN transition curve. Higher frequencies proved detrimental at the same current levels. Also, the CVN properties worsened when the pulsed current was increase from 40 amps to 100 amps at the same frequency as shown in Figure 12.

The use of pre-alloyed core wire with the SMA process was explored, using the same hat of wire that yielded the exceptionally high upper energy shelf, when deposited with GTA process (see Figure 5 for "hammer-stoppers"). As shown in the comparison in Figure 13, no significant advantage was evident in the use of costly pre-alloyed core wire versus alloying through the SMA electrode coating.

The nominal weld deposit composition of 9Cr-1Mo-.074C-.16V-.14W-.04Cb (Lot 111) has shown the best CVN impact properties of any compositions tested, which had sufficient alloying to provide adequate high temperature mechanical properties. The CVN results of all tests with Lot 111 are listed in Table IX. This

composition has been tested for creep rupture properties (see Creep Rupture Section) and has shown adequate matching properties to the wrought base material. The impact strength of this weld composition improves when the GTA process is used. Figure 14 shows the shift of the 50 ft-lb transition temperature down to 40° F when the GTA remelt procedure (see Figure 3) at a heat input of 61 KJ/in was used. Lower heat inputs show slightly less improvement over the SMA process.

Recently, the amount of nitrogen added to Lot 111 for improved creep rupture strength was investigated in order to correlate the nitrogen content of the weld metal as a function of CVN impact strength. The coating formulation was kept identical with changes made only in the alloying of nitrogen. Figure 15 shows the results of the CVN testing with 0.033% nitrogen in the deposit yielding a 40° F transition temperature at 50 ft-lb versus much higher transition temperatures for both lower and higher nitrogen contents. This 9Cr-1Mo-V-W-Cv weld metal with 0.033% N in the deposit exhibits the best CVN impact properties of any filler metal composition developed in this program for use with the SMA process.

The CVN transition curves for mil laterial expansion versus temperature for the weld deposits discussed in this section are shown in Figures 16 through 26.

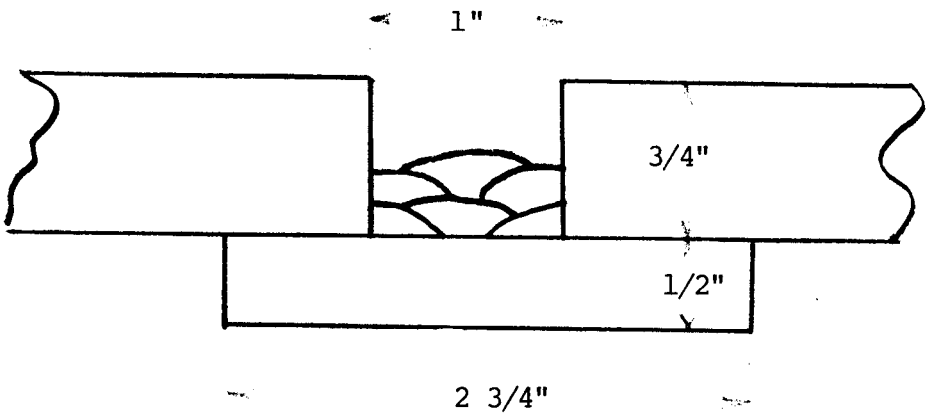
Additional developed of the best 9Cr-1M0-V-W-Cb weld filler metal composition is expected to yield additional improvement of low temperature fracture toughness and practical shop techniques to assure consistent fabrication applications. Concurrently, the weld composition will be refined in order to seek further improvement of the long-term creep rupture ductility and creep fatigue resistance.

Due to the recent work with the SMA nitrogen content, optimization of this alloying element will be given a high priority. Boron as well as rare earth treated weld compositions will be included in this assessment of the nitrogen content, which may be a successful path for obtaining improved creep ductility along with acceptable room temperature fracture toughness. The misch metal additions to the coating formulation will be optimized based on earlier work. Also, the slag system being used will be further developed with the goal of a more basic flux coating to improve the CVN properties.

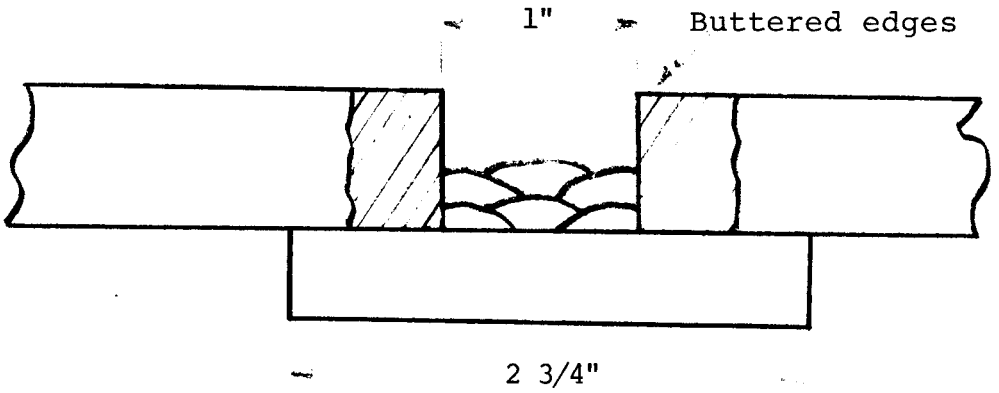
Further development of the welding techniques used will include automating the GTA remelt procedure for closer control of the welding conditions. This would incorporate the use of an arc voltage control. Additional work is planned with high frequency pulsing with both the SMA and GTA welding processes.

FIGURE 1

TEST PLATE WELDING PROCEDURE



Lot No. 1 used for buttering 2 layers on bar prior to fit-up

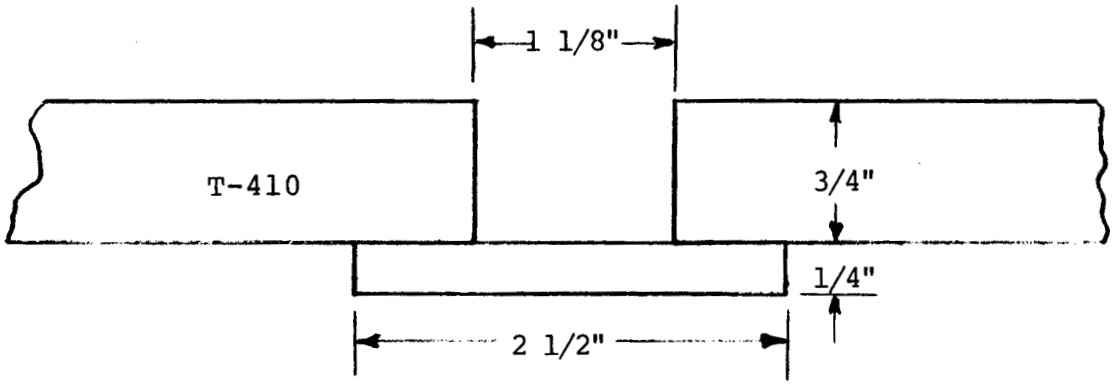


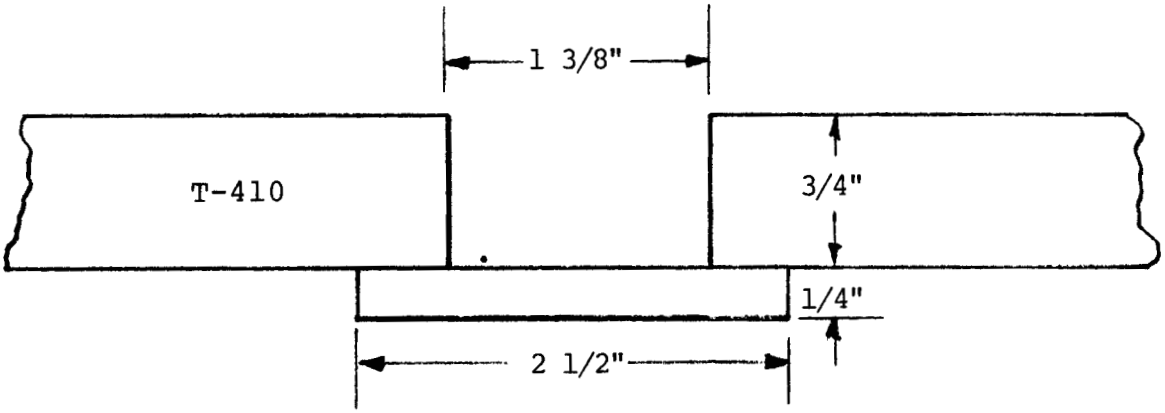
400-600° C preheat and interpass
235 amps DCPR 23-24 volts
travel speed 8-9 inches/minute
heat input 35-45 KJ/in

FIGURE 2

WELDING PROCEDURES

3/16" Dia. "B" Series SMA Weld Test Plates
400-600° F Preheat and Interpass
200 Amps DCRP 20-23 Volts
Travel Speed 8-9 Inches/Minute
Heat Input 25-35 KJ/In

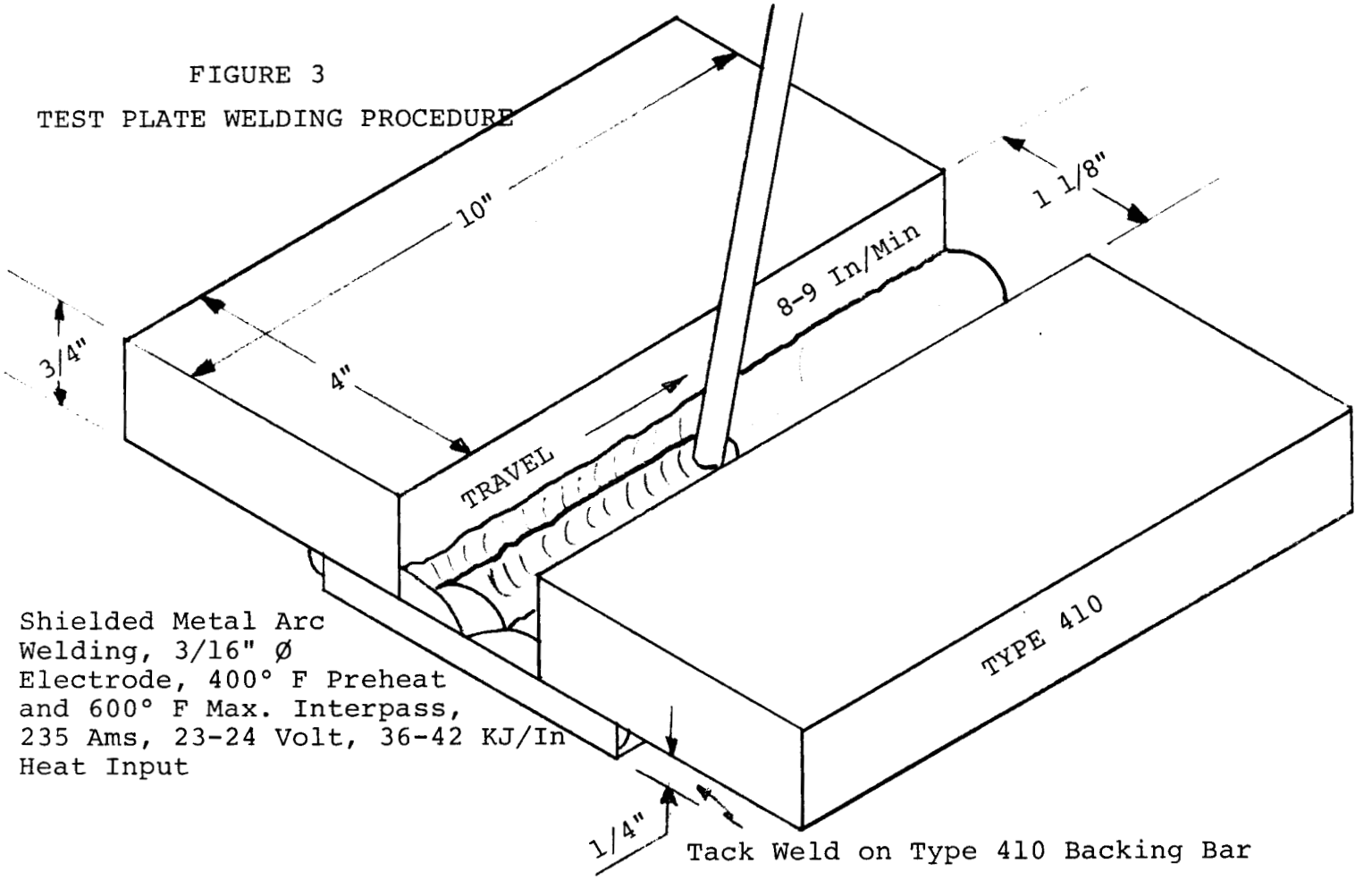




1/4" Dia. "B" Series SMA Weld Test Plates
400-600° F Preheat and Interpass
325 Amps DCRP 26 Volts
Travel Speed 6-7 Inches/Minute
Heat Input 78 KJ/In

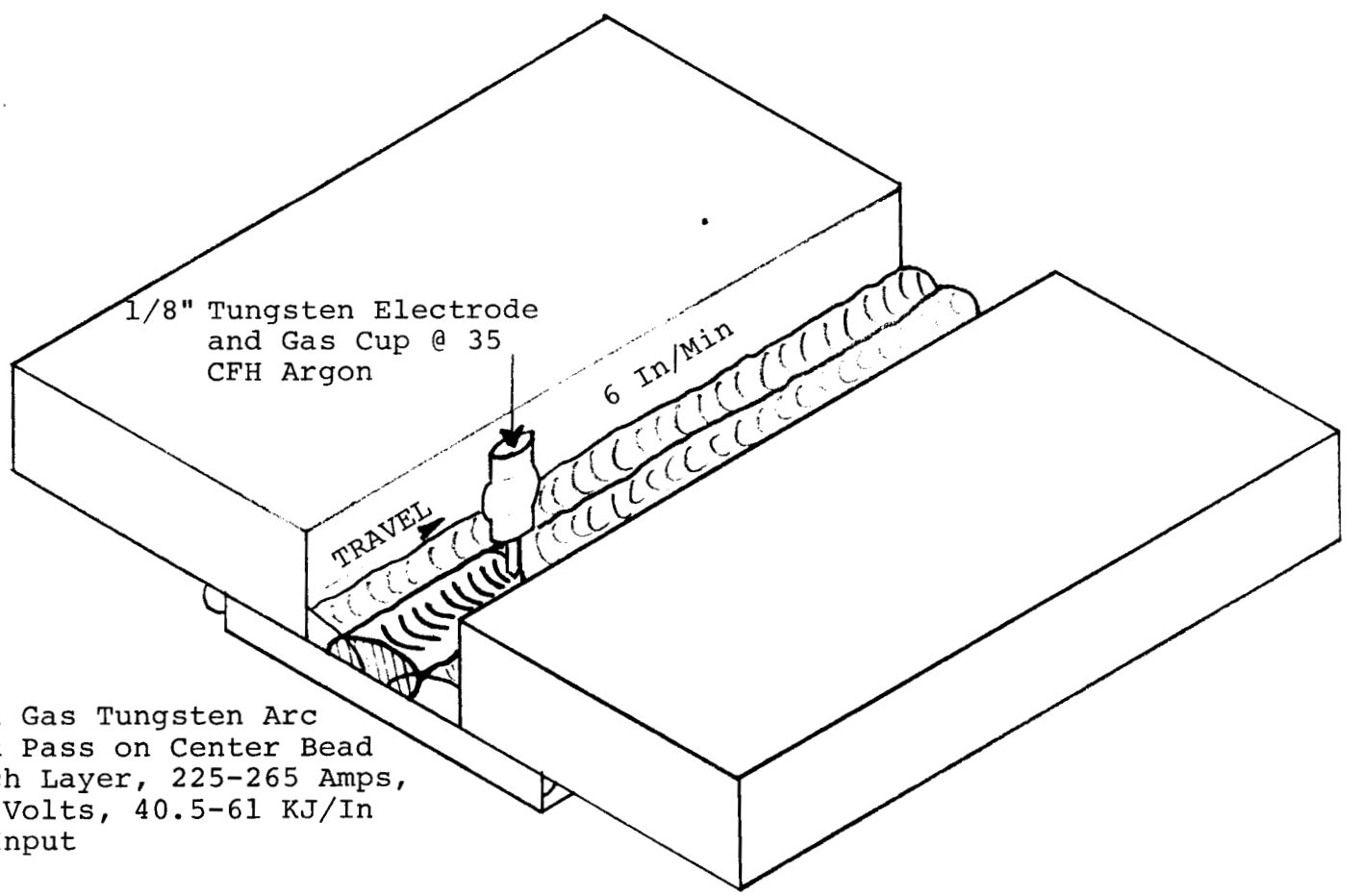
FIGURE 3

TEST PLATE WELDING PROCEDURE

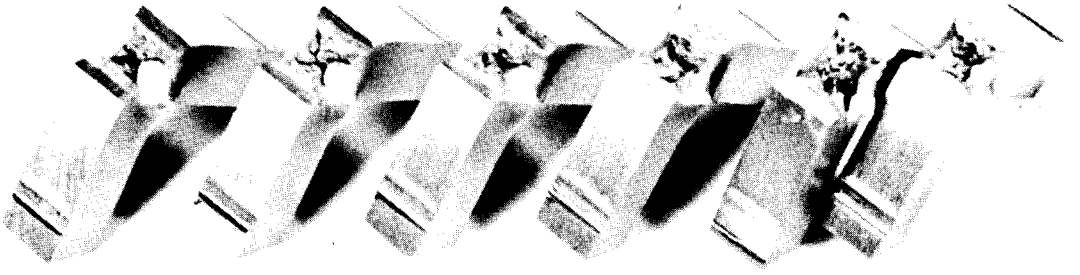


Shielded Metal Arc Welding, 3/16" Ø Electrode, 400° F Preheat and 600° F Max. Interpass, 235 Ams, 23-24 Volt, 36-42 KJ/In Heat Input

Tack Weld on Type 410 Backing Bar



Manual Gas Tungsten Arc Remelt Pass on Center Bead of Each Layer, 225-265 Amps, 18-23 Volts, 40.5-61 KJ/In Heat Input



60° F 70° F 80° F 100° F 160° F

"HAMMER STOPPER"
CVN's GTA 9Cr-1Mo-V-W-Cb Welds
>240 ft-lbs

FIGURE 4

Charpy V-Notch Samples with Impact Strengths Greater than 240 ft-lbs. Data Points are Plotted in Figure 5 for Plates 206-B and 207-B

FIGURE 5

CHARPY V-NOTCH IMPACTS

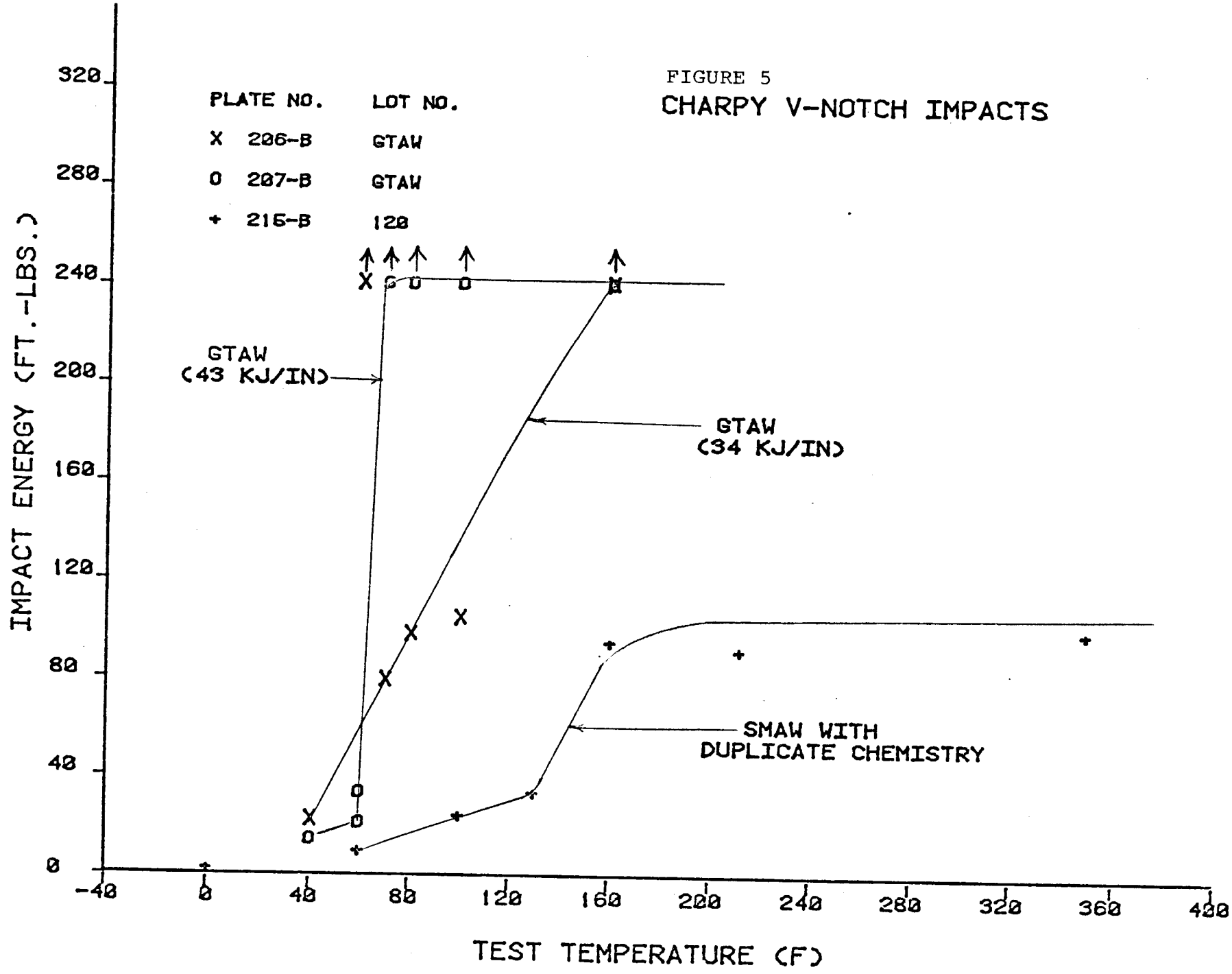


FIGURE 6

CHARPY V-NOTCH IMPACTS

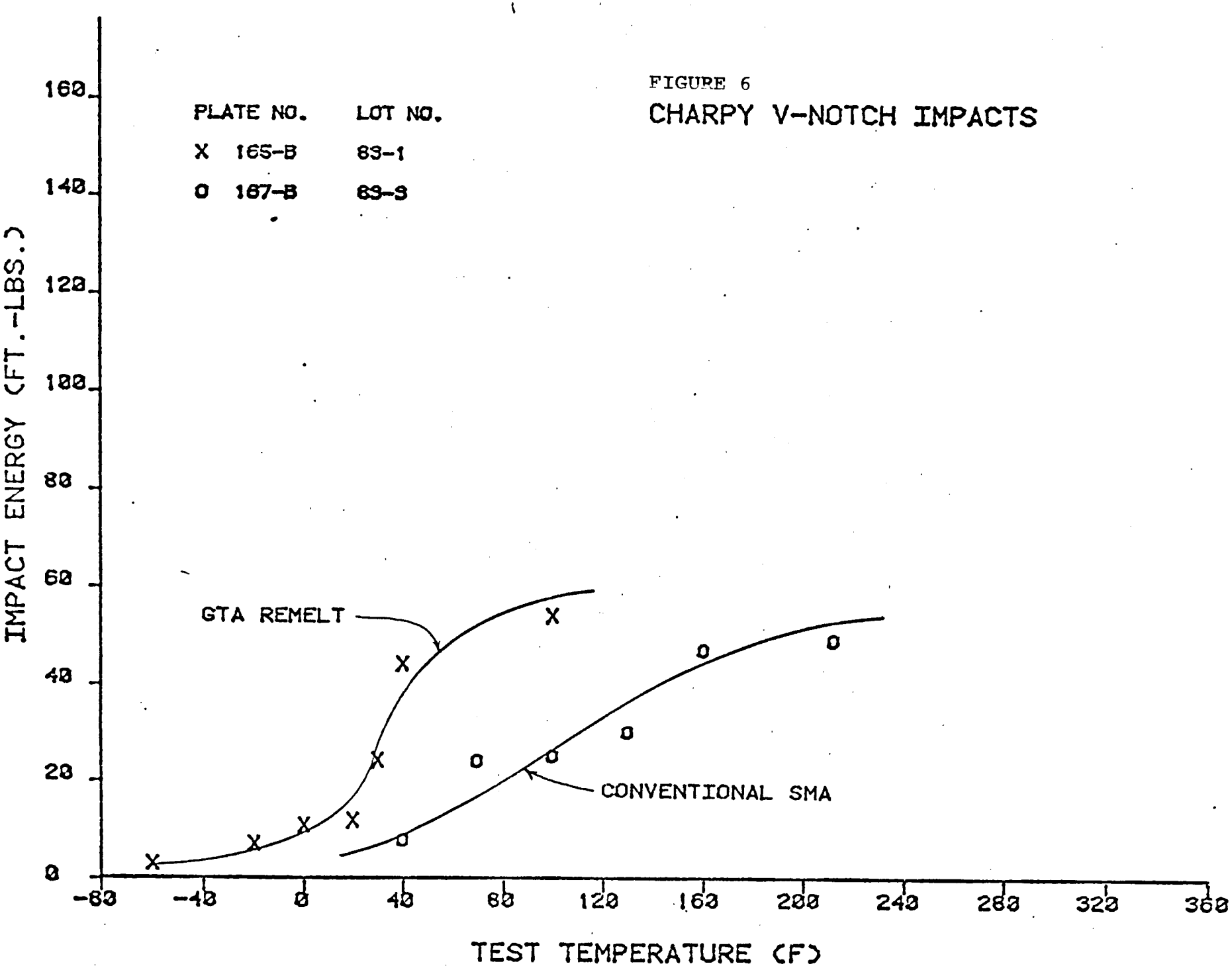


FIGURE 7
CHARPY V-NOTCH IMPACTS

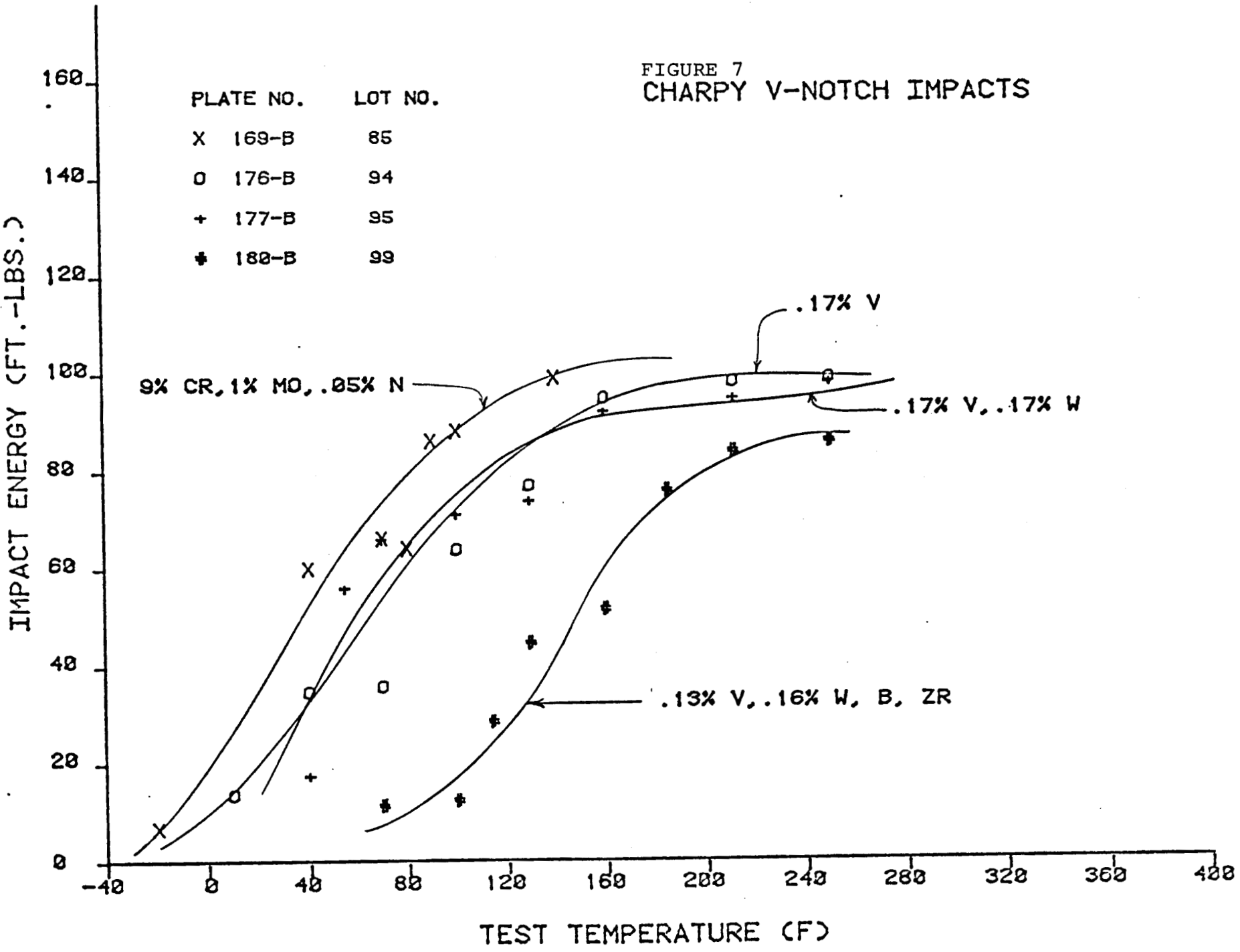


FIGURE 8

CHARPY V-NOTCH IMPACTS

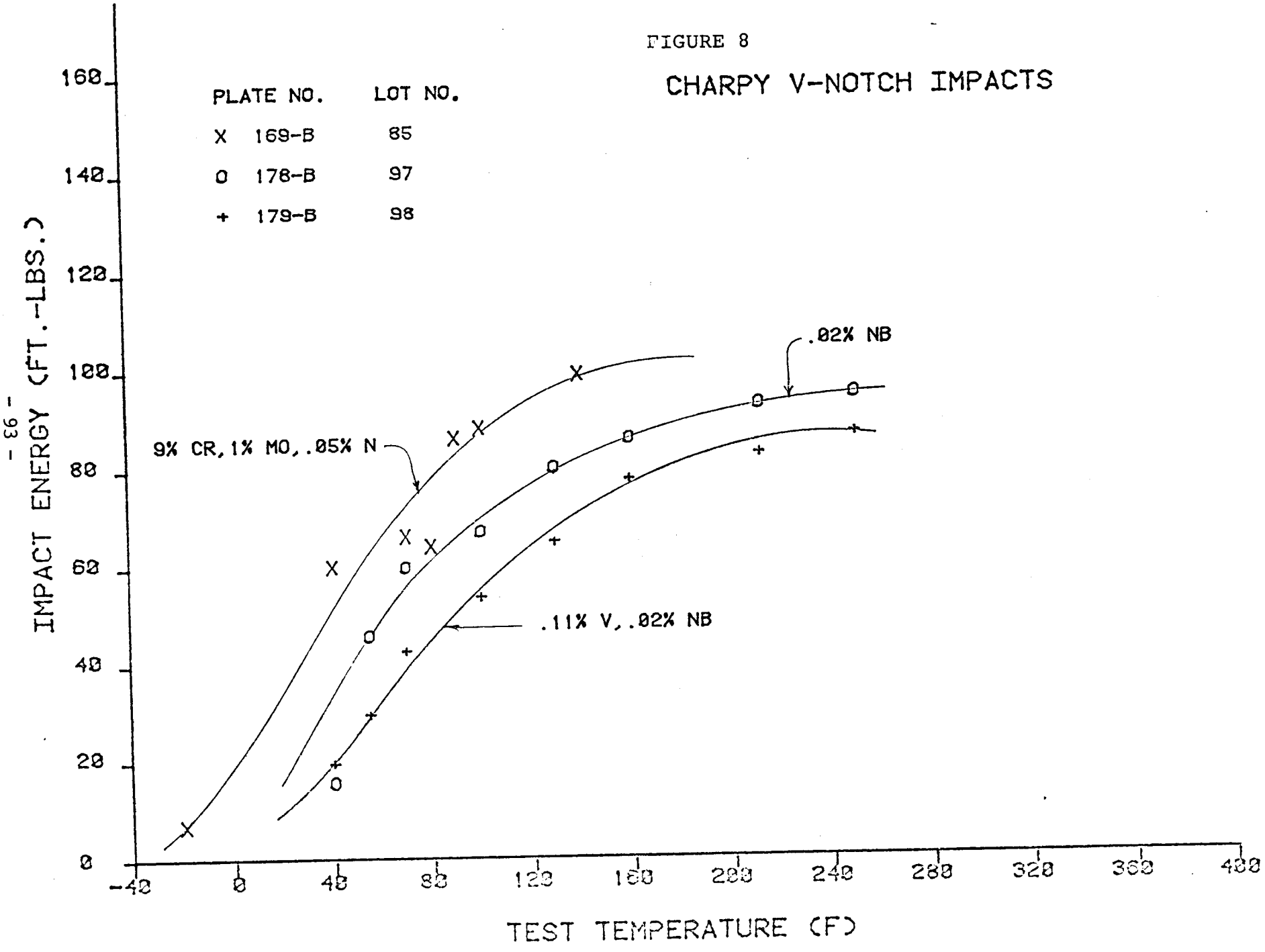


FIGURE 9

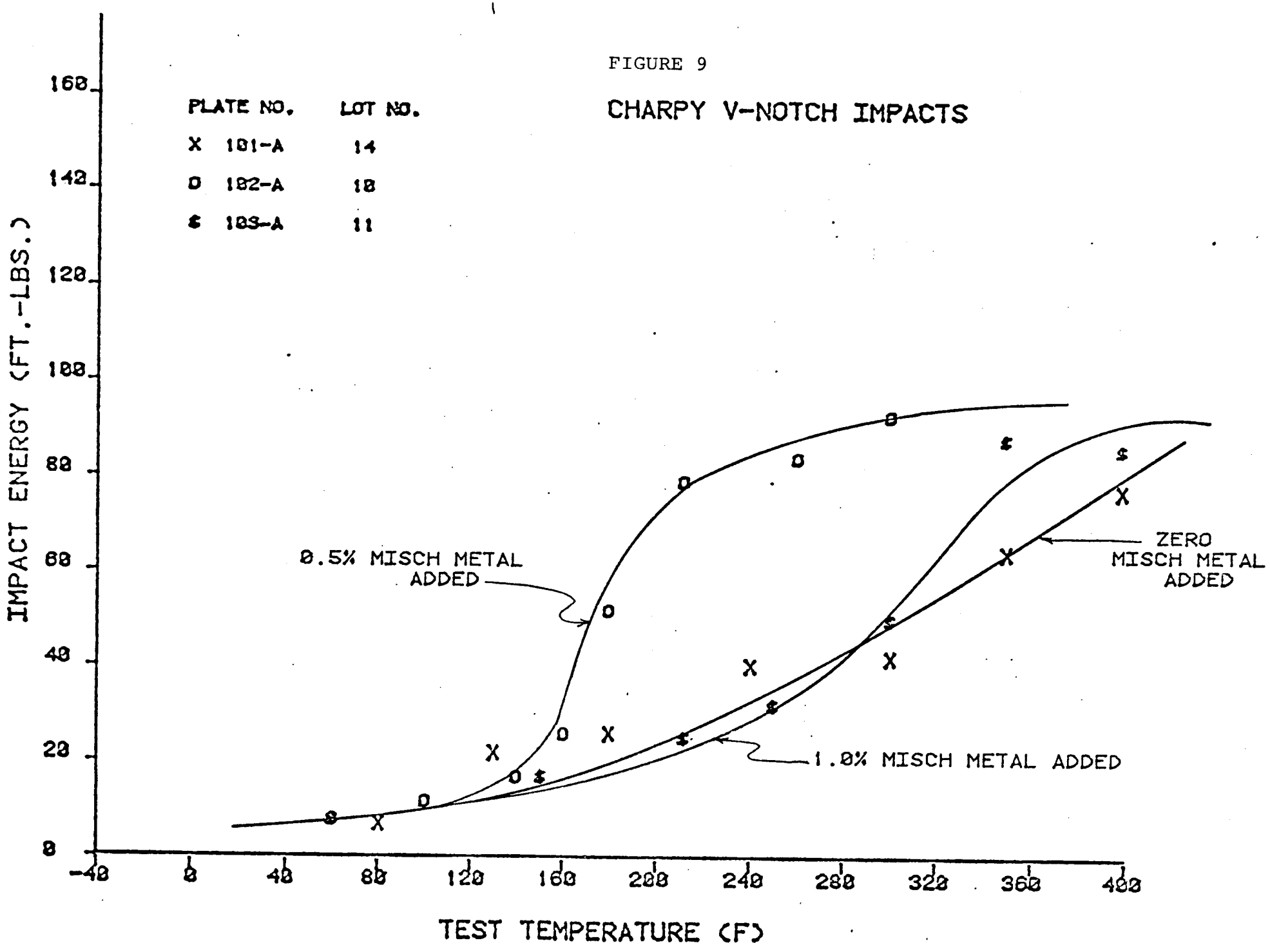

CHARPY V-NOTCH IMPACTS
PLATE NO. LOT NO.
X 101-A 14
O 102-A 10
$ 103-A 11
0.5% MISCH METAL ADDED
ZERO MISCH METAL ADDED
1.0% MISCH METAL ADDED
IMPACT ENERGY (FT.-LBS.)
TEST TEMPERATURE (F)
0
20
40
60
80
100
120
140
160
-40
0
40
80
120
160
200
240
280
320
360
400

FIGURE 10

CHARPY V-NOTCH IMPACTS

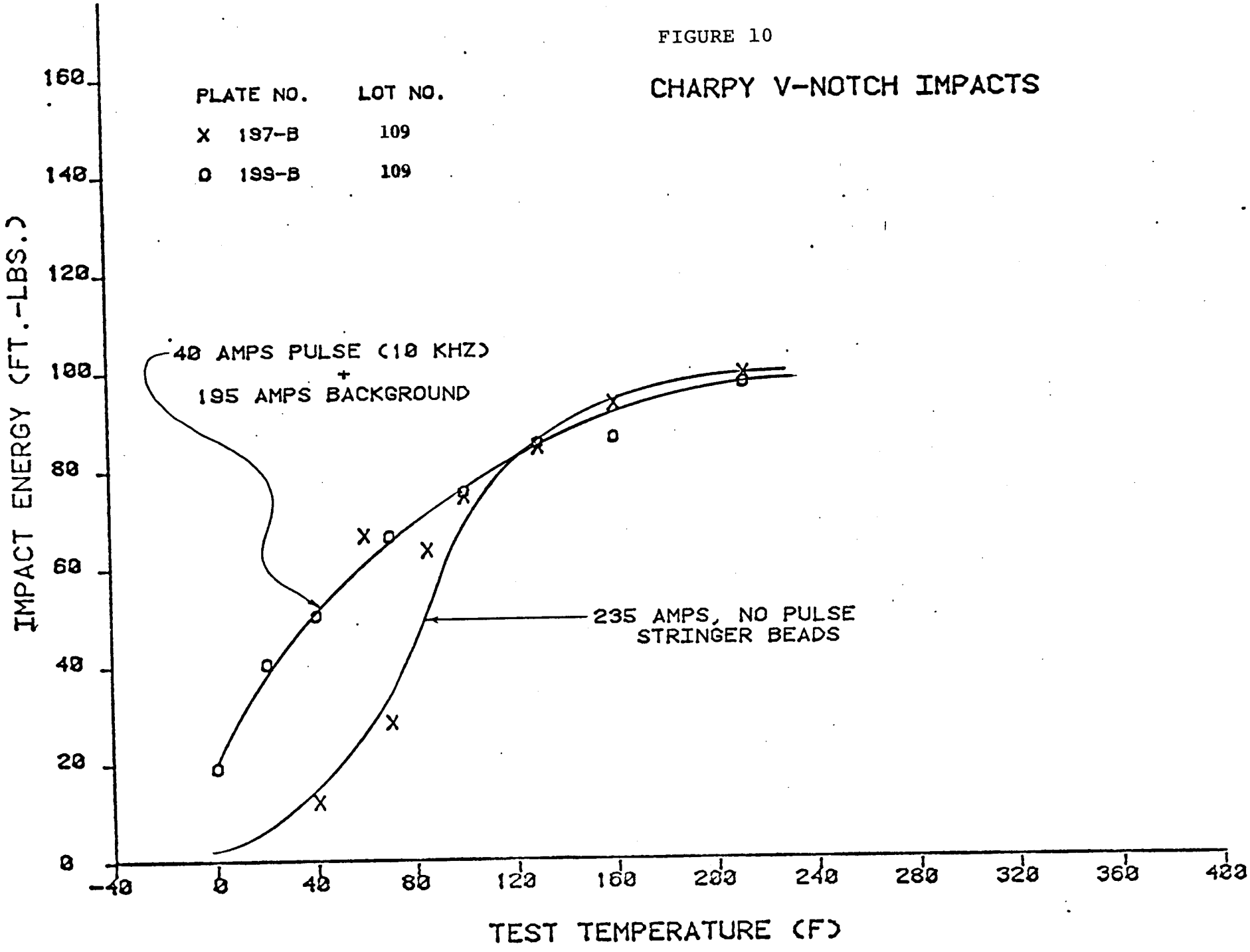


FIGURE 11

CHARPY V-NOTCH IMPACTS

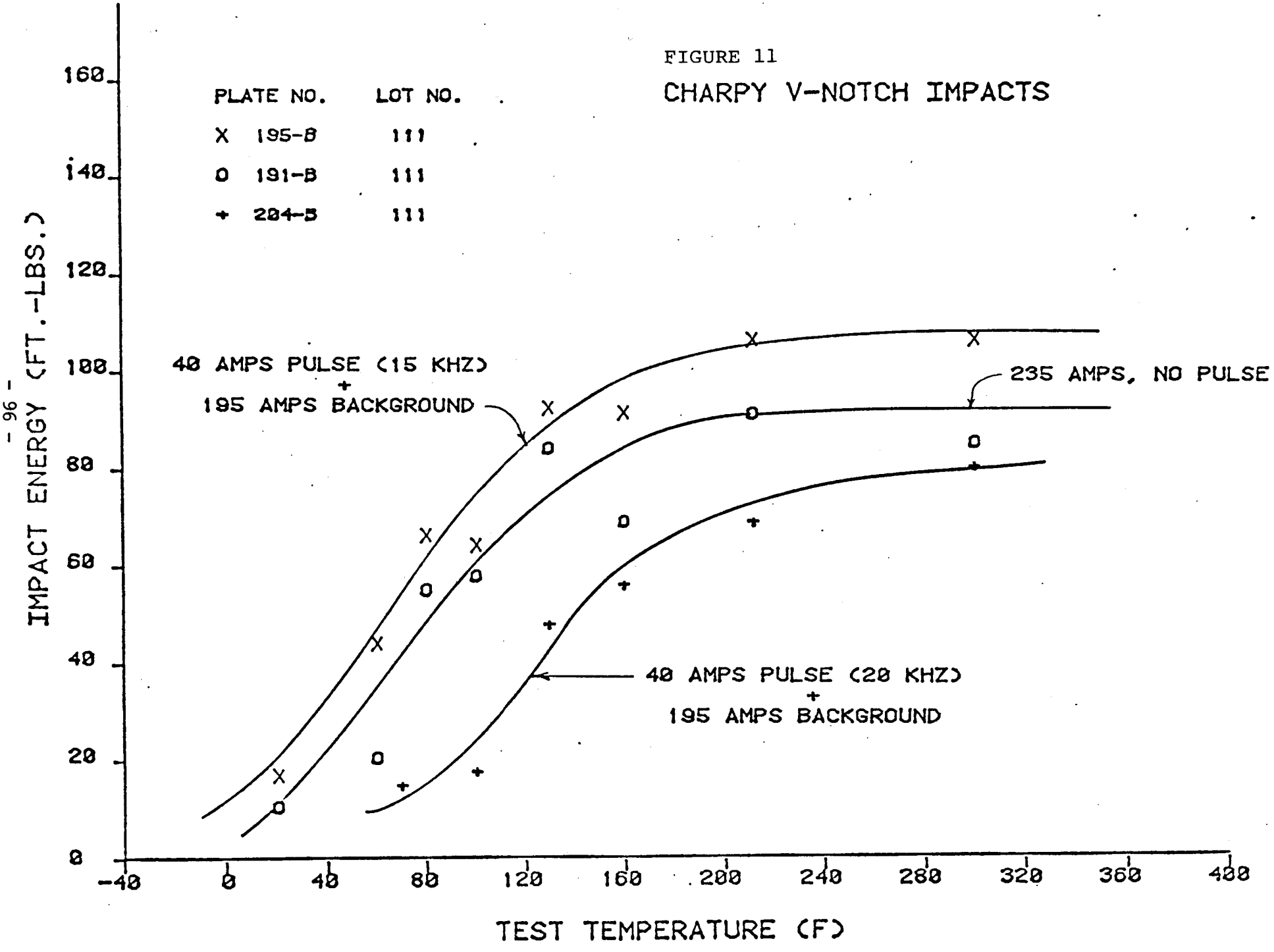


FIGURE 12

CHARPY V-NOTCH IMPACTS

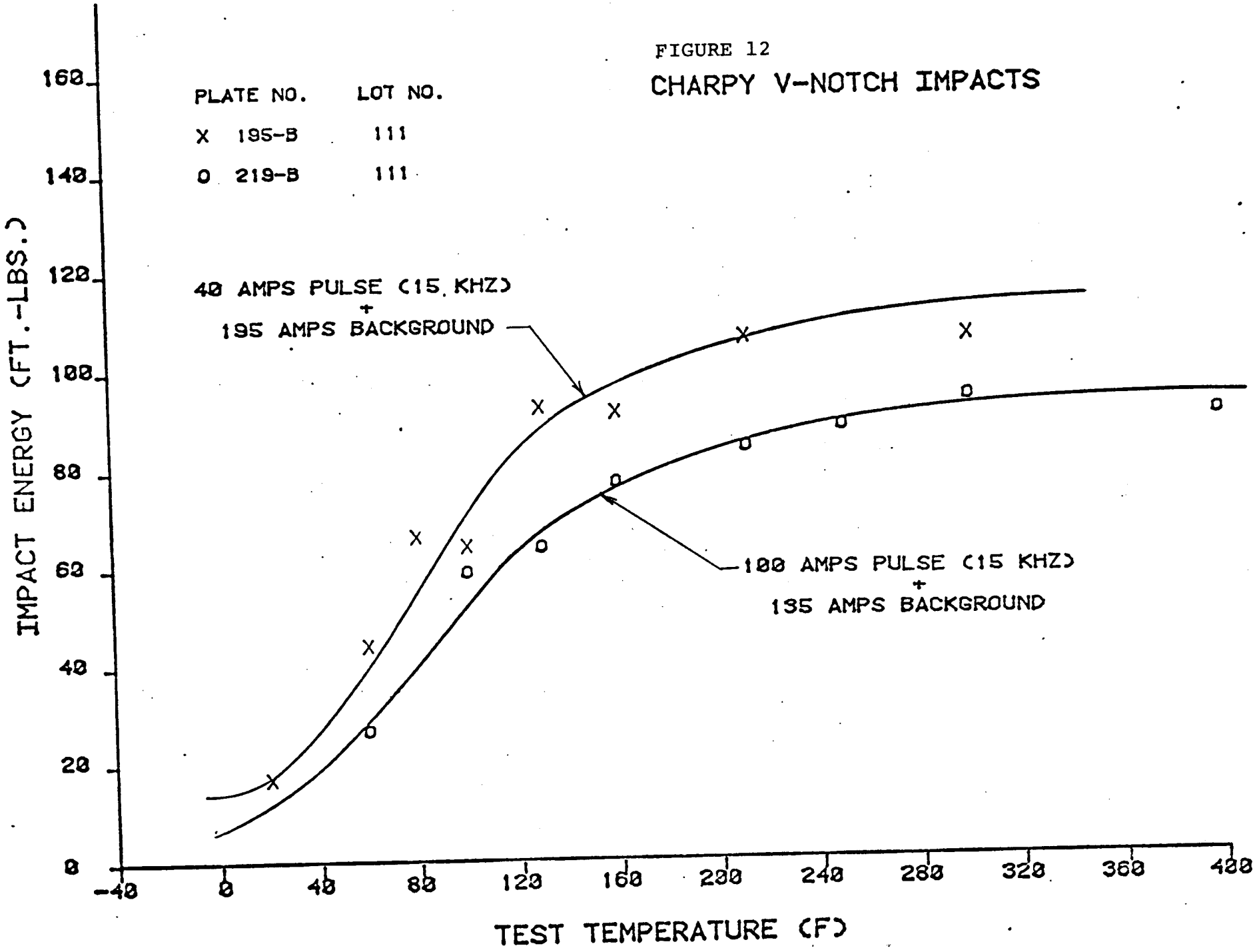


FIGURE 13

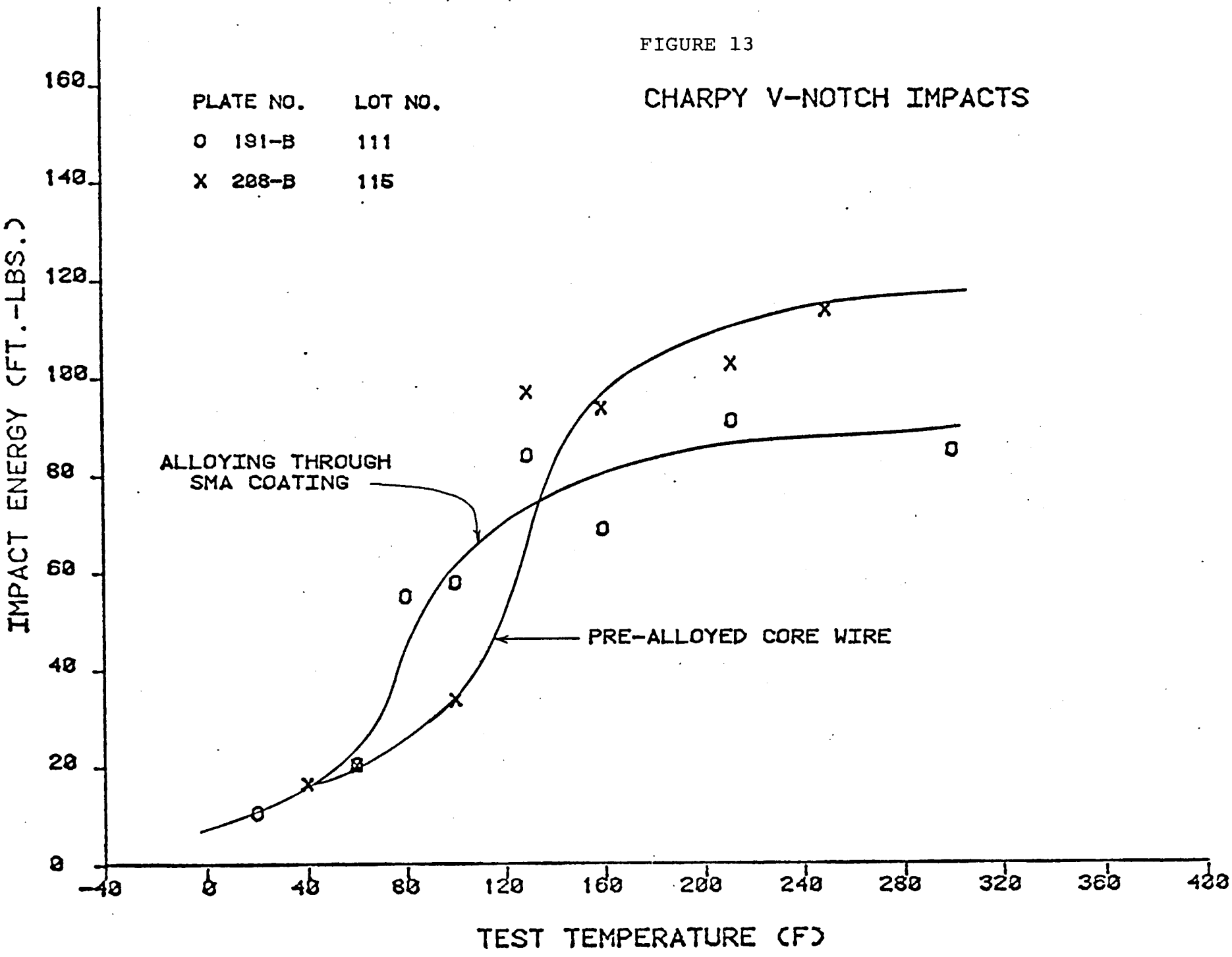

CHARPY V-NOTCH IMPACTS
PLATE NO. LOT NO.
O 191-B 111
X 208-B 115
ALLOYING THROUGH SMA COATING
PRE-ALLOYED CORE WIRE
IMPACT ENERGY (FT.-LBS.)
TEST TEMPERATURE (F)
0
20
40
60
80
100
120
140
160
-40
0
40
80
120
160
200
240
280
320
360
400

FIGURE 14

CHARPY V-NOTCH IMPACTS

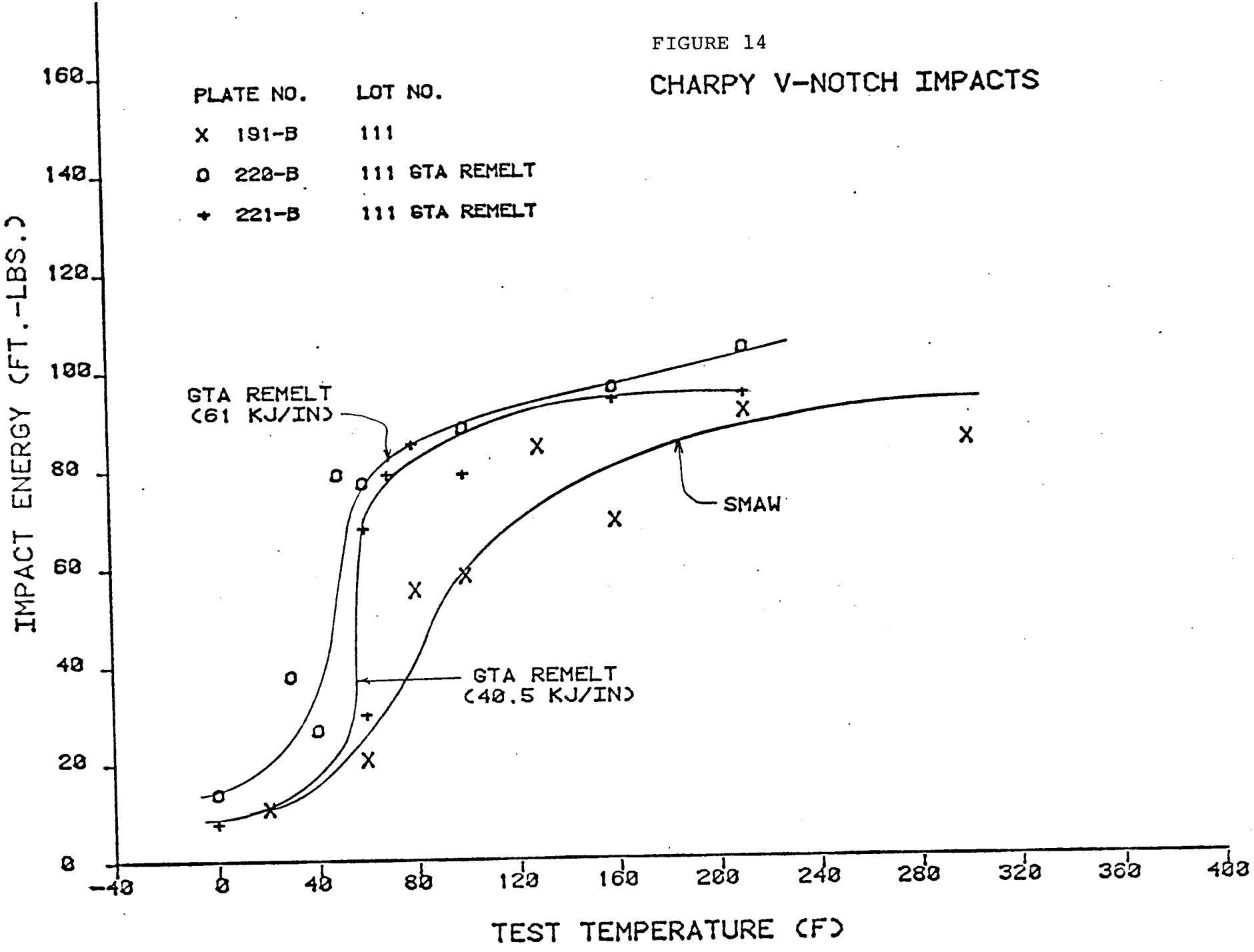


FIGURE 15

CHARPY V-NOTCH IMPACTS

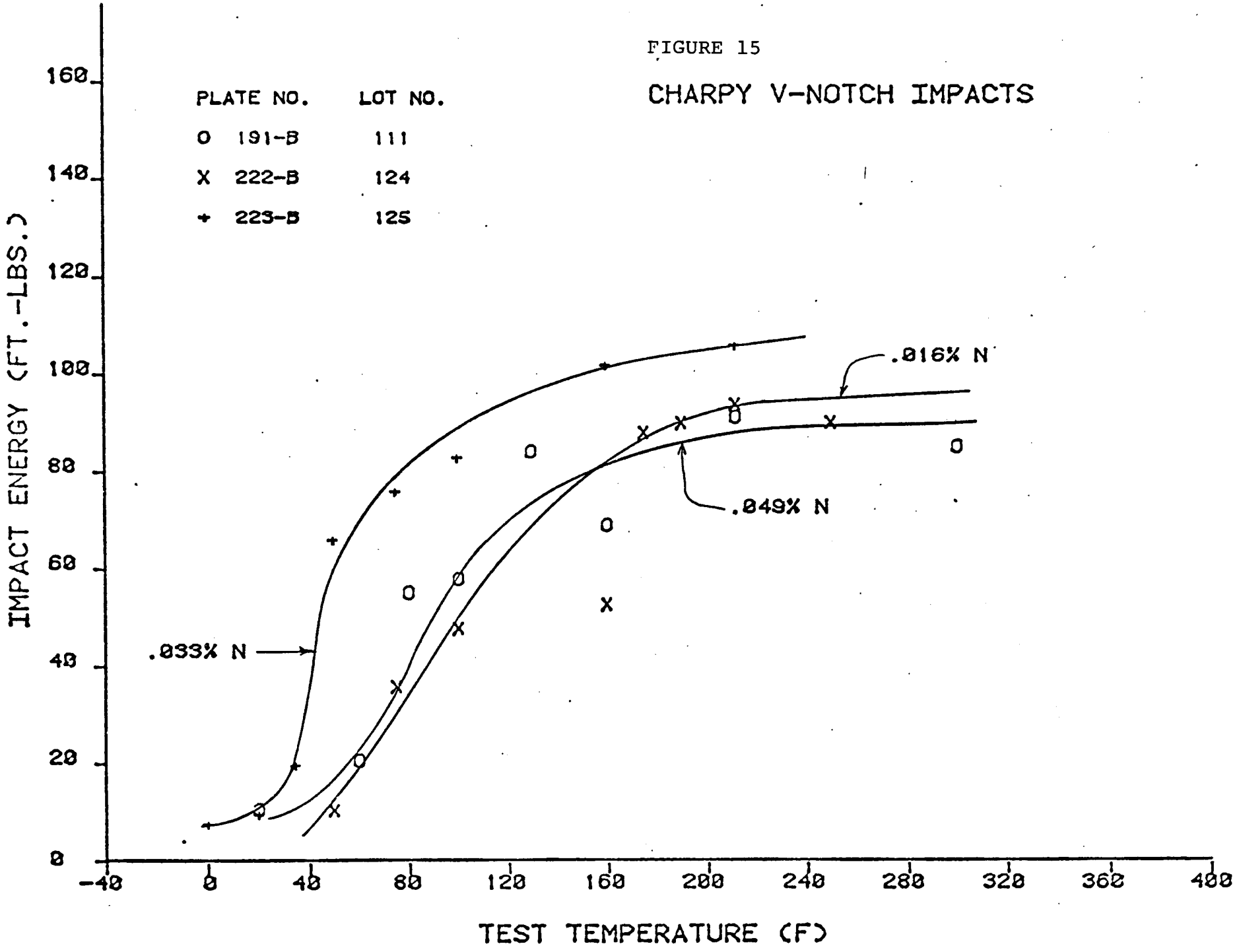


FIGURE 16

CHARPY V-NOTCH IMPACTS

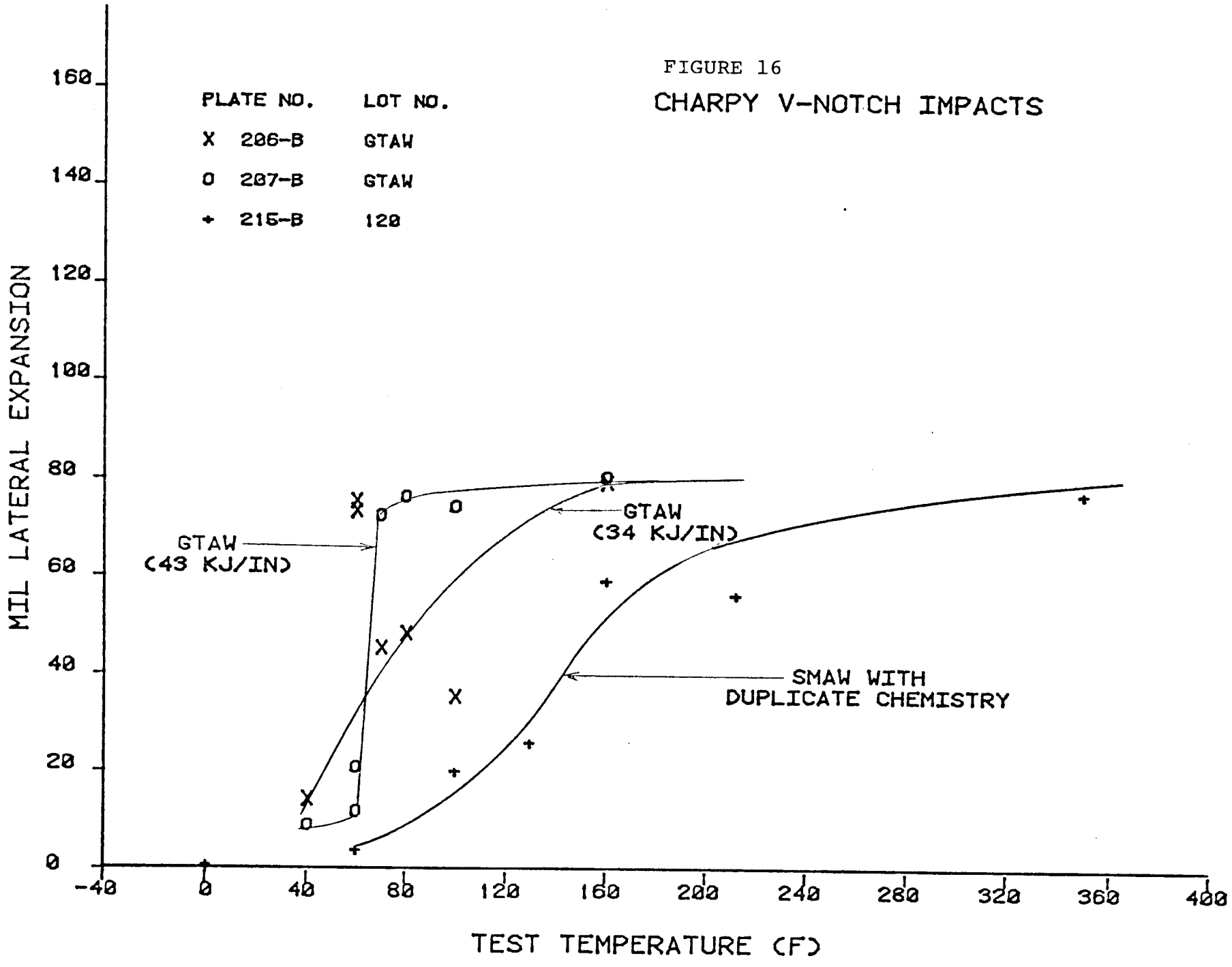


FIGURE 17

CHARPY V-NOTCH IMPACTS

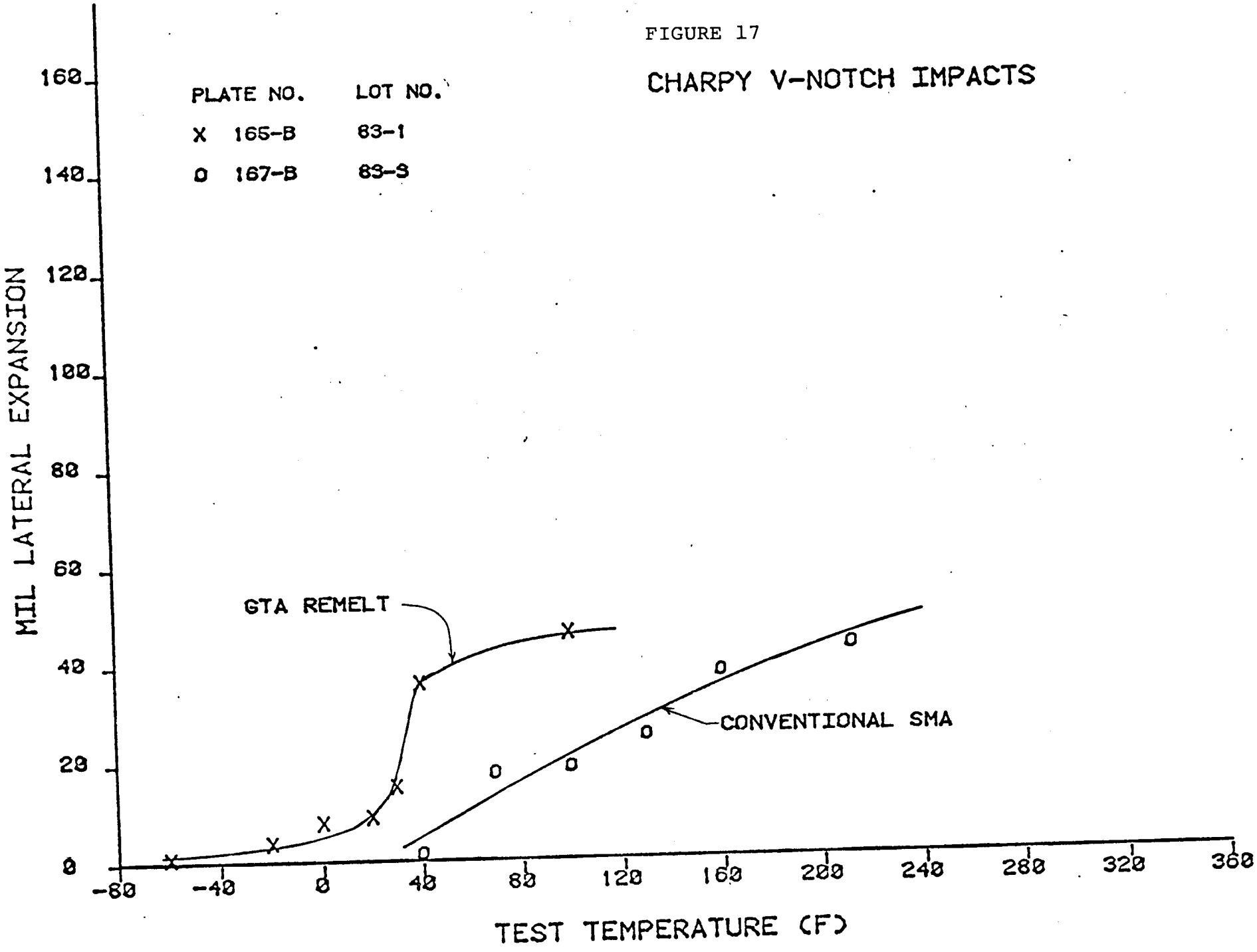


FIGURE 18

CHARPY V-NOTCH IMPACTS

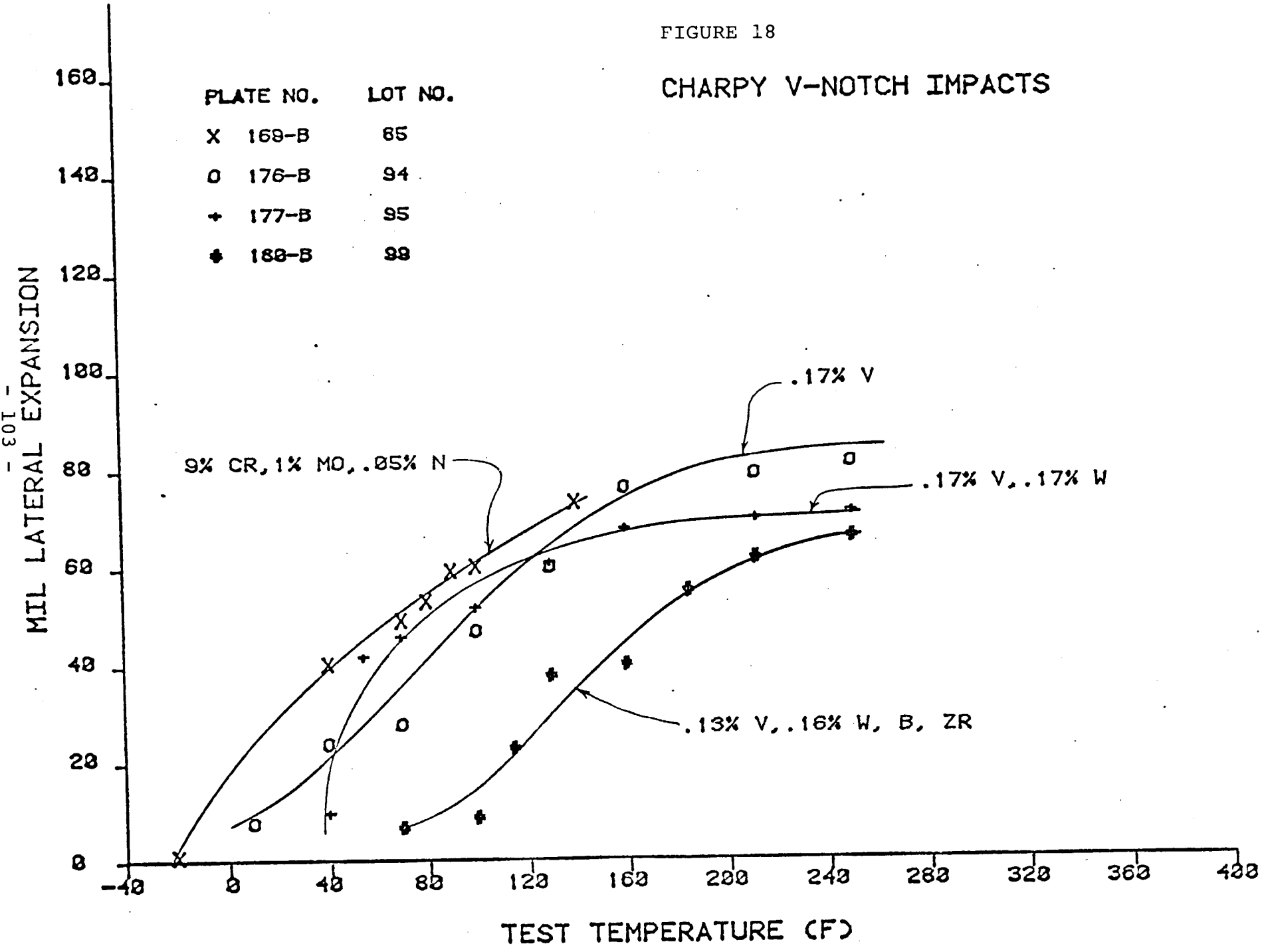


FIGURE 19

CHARPY V-NOTCH IMPACTS

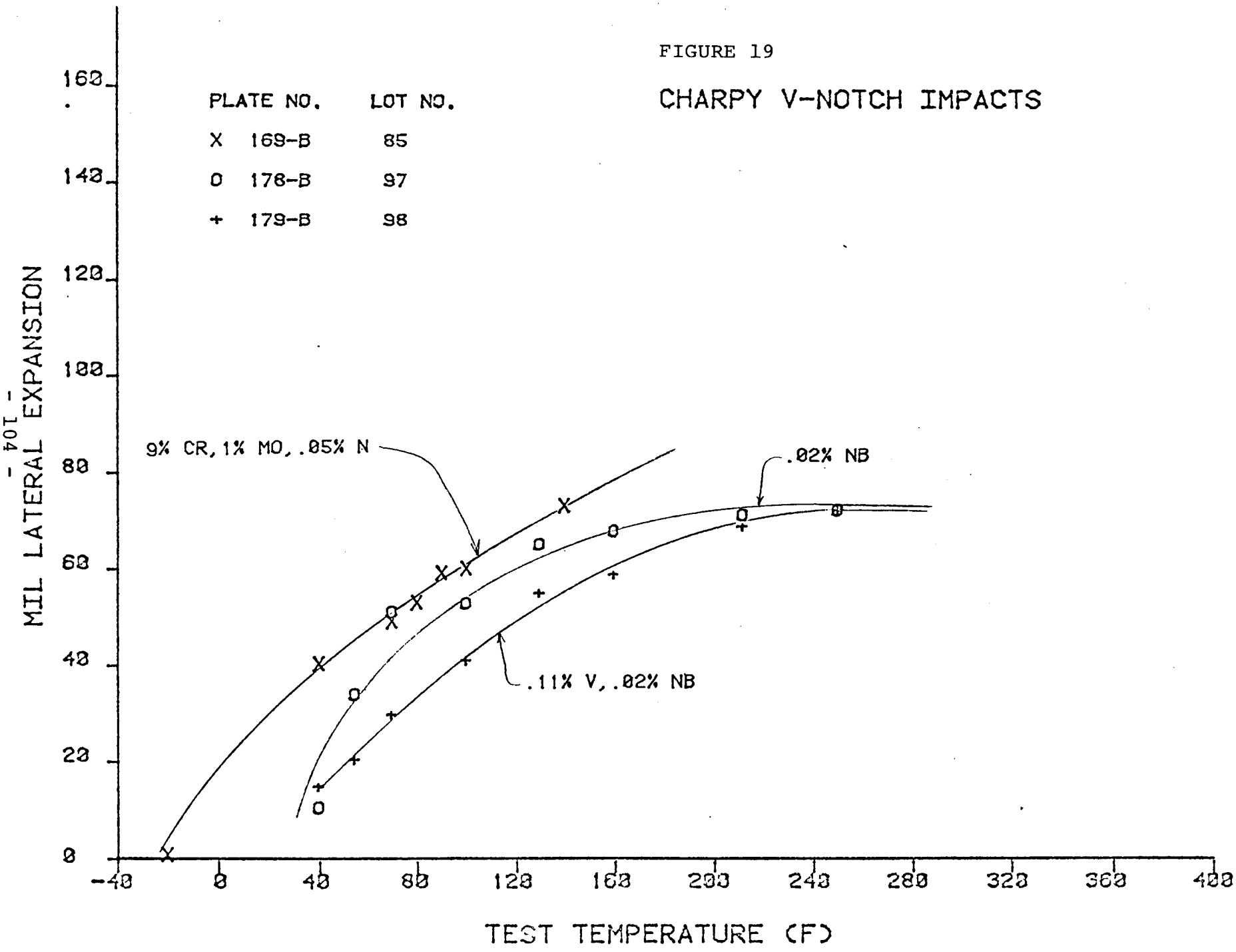


FIGURE 20

CHARPY V-NOTCH IMPACTS

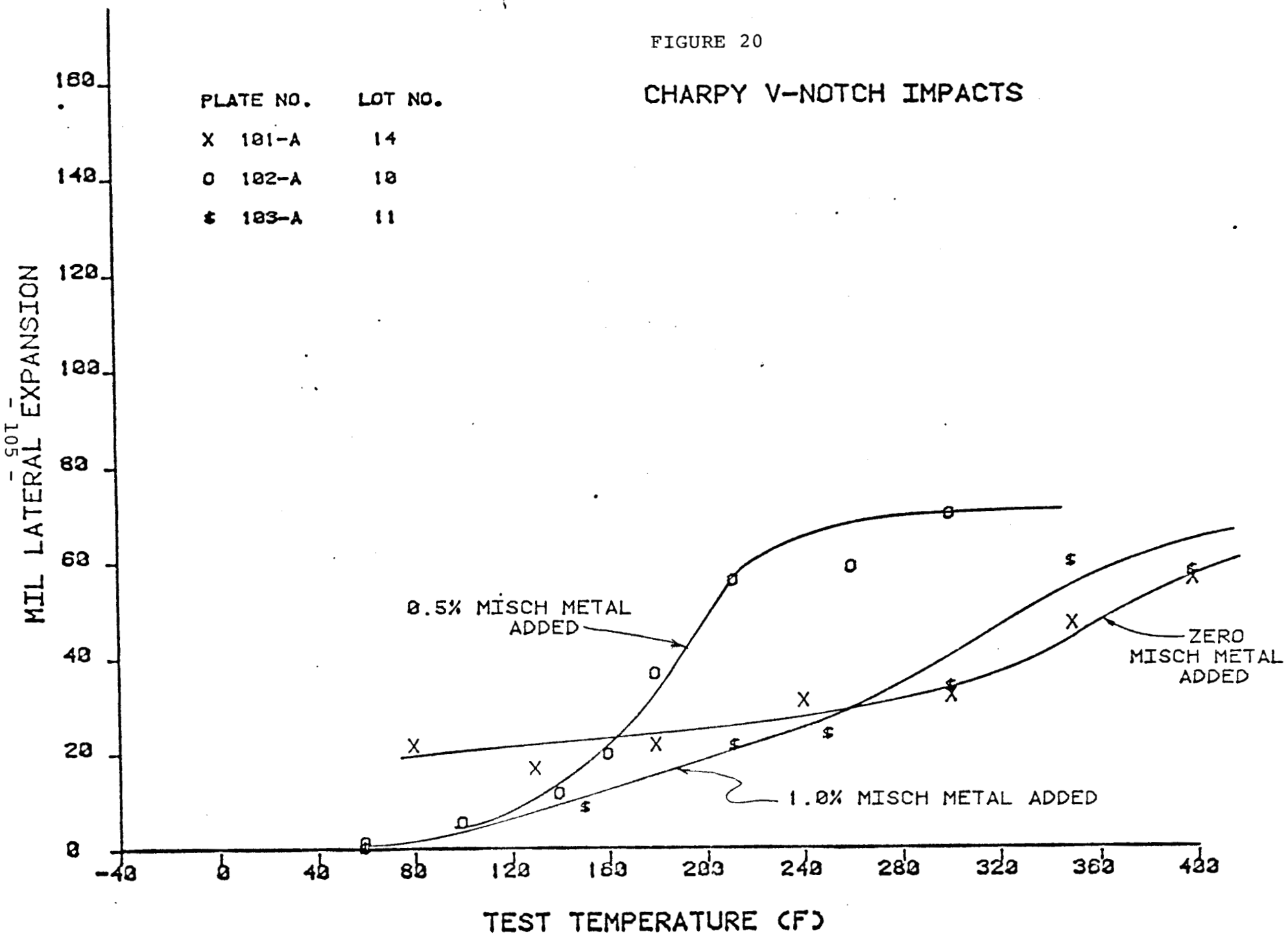


FIGURE 21

CHARPY V-NOTCH IMPACTS

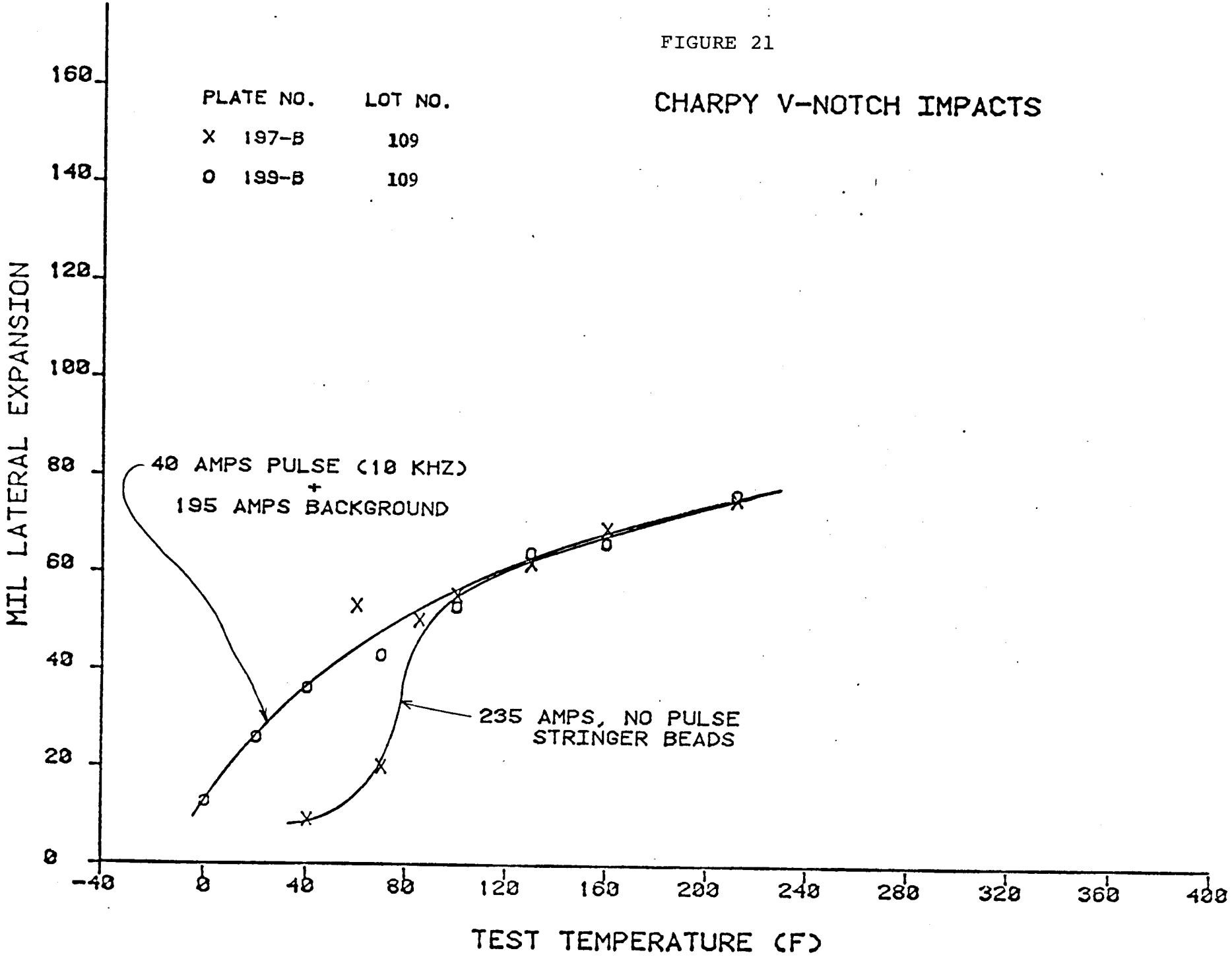


FIGURE 22

CHARPY V-NOTCH IMPACTS

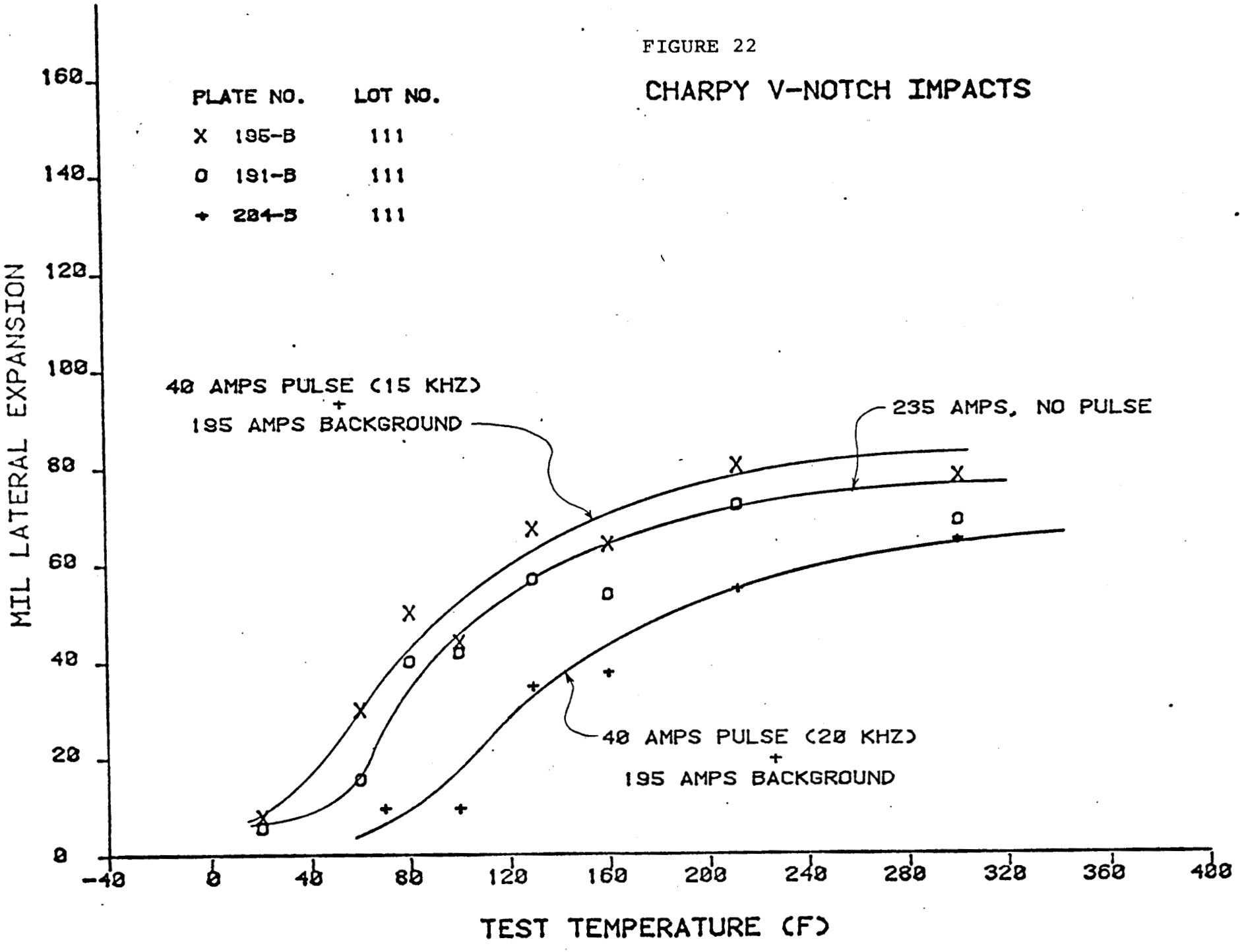


FIGURE 23

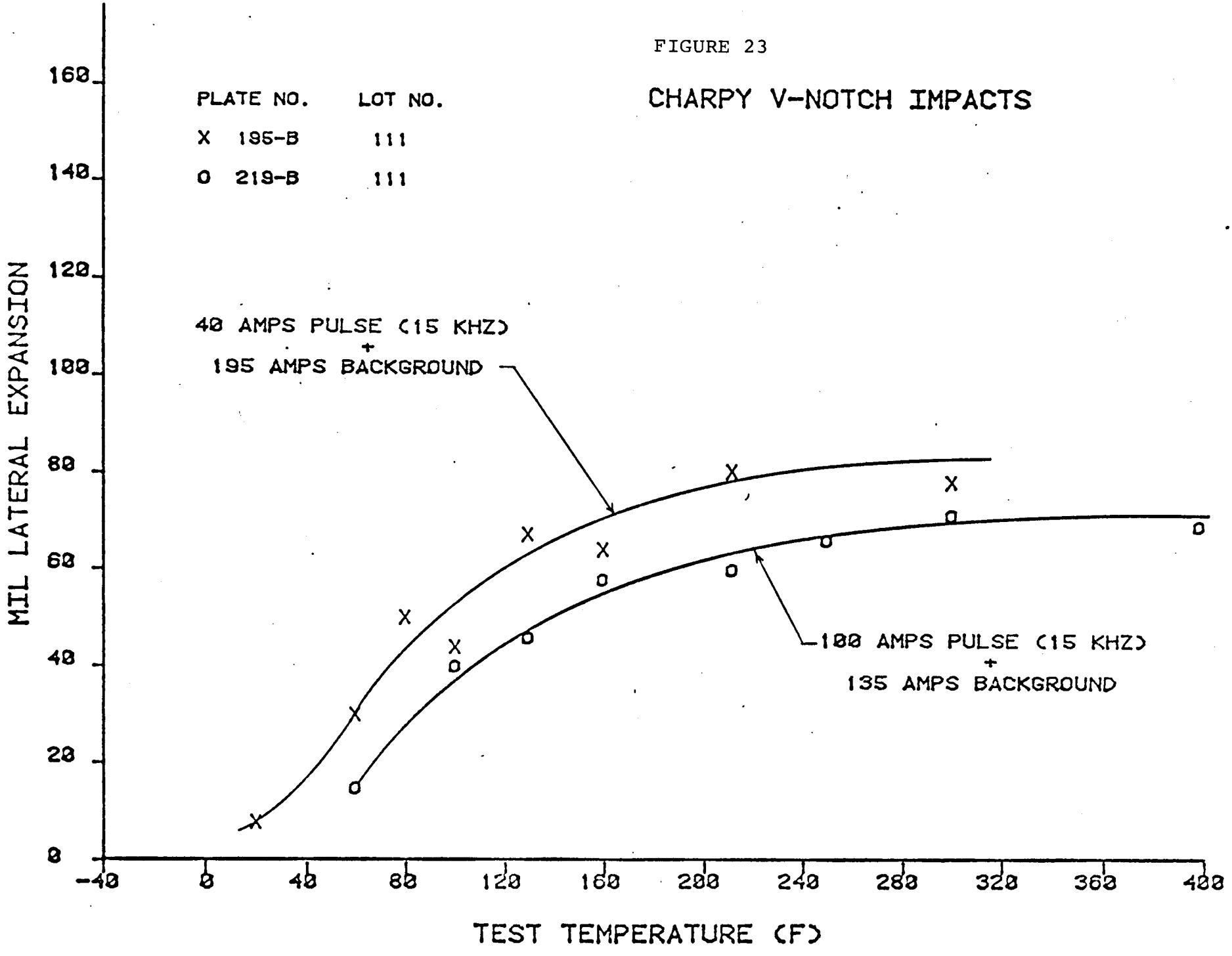

CHARPY V-NOTCH IMPACTS
PLATE NO. LOT NO.
X 195-B 111
O 219-B 111
40 AMPS PULSE (15 KHZ)
+
195 AMPS BACKGROUND
100 AMPS PULSE (15 KHZ)
+
135 AMPS BACKGROUND
MIL LATERAL EXPANSION
TEST TEMPERATURE (F)
0
20
40
60
80
100
120
140
160
-40
0
40
80
120
160
200
240
280
320
360
400

FIGURE 24

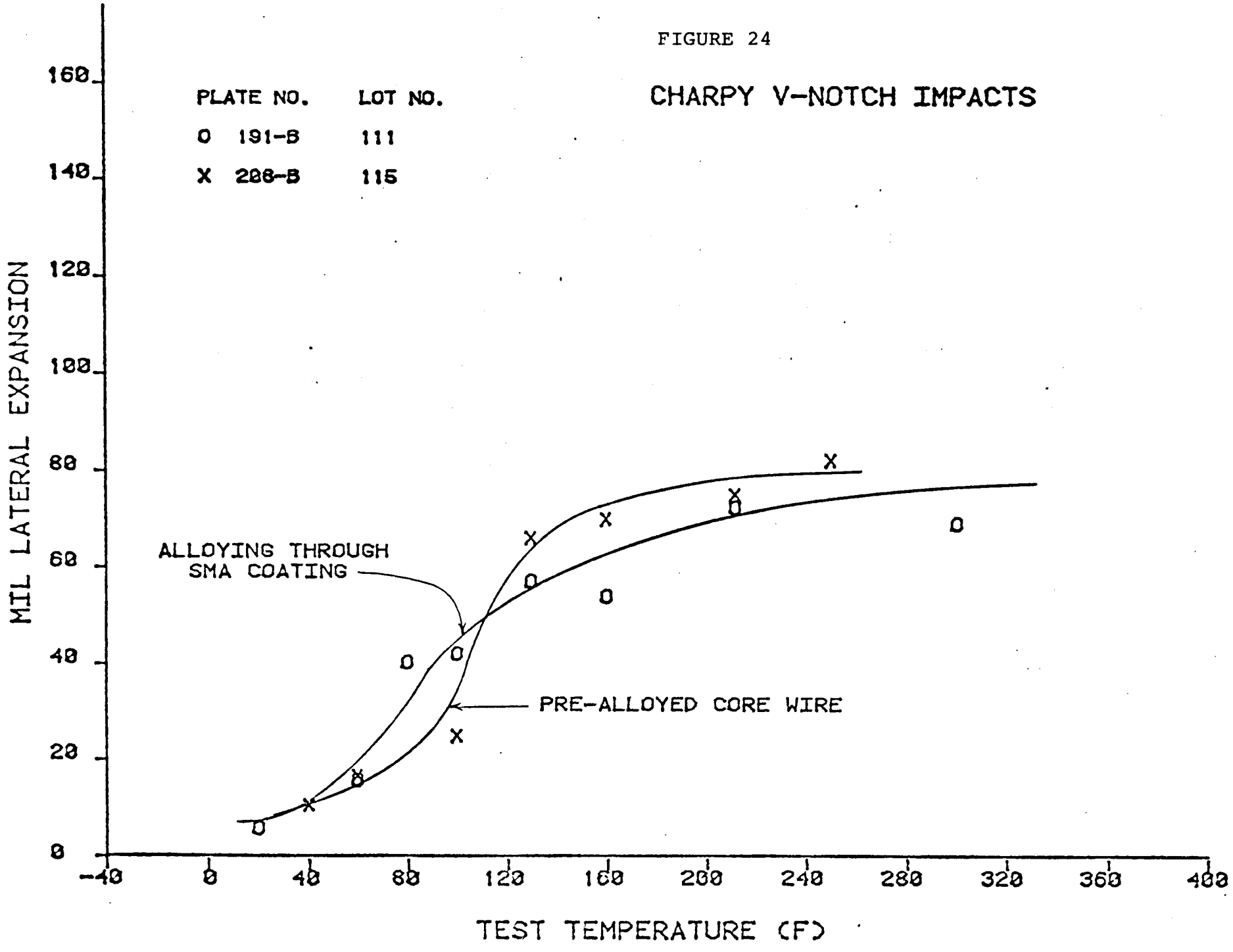

CHARPY V-NOTCH IMPACTS
PLATE NO. LOT NO.
O 191-B 111
X 208-B 115
ALLOYING THROUGH SMA COATING
PRE-ALLOYED CORE WIRE
MIL LATERAL EXPANSION
TEST TEMPERATURE (F)
0
20
40
60
80
100
120
140
160
-40
0
40
80
120
160
200
240
280
320
360
400

FIGURE 25

CHARPY V-NOTCH IMPACTS

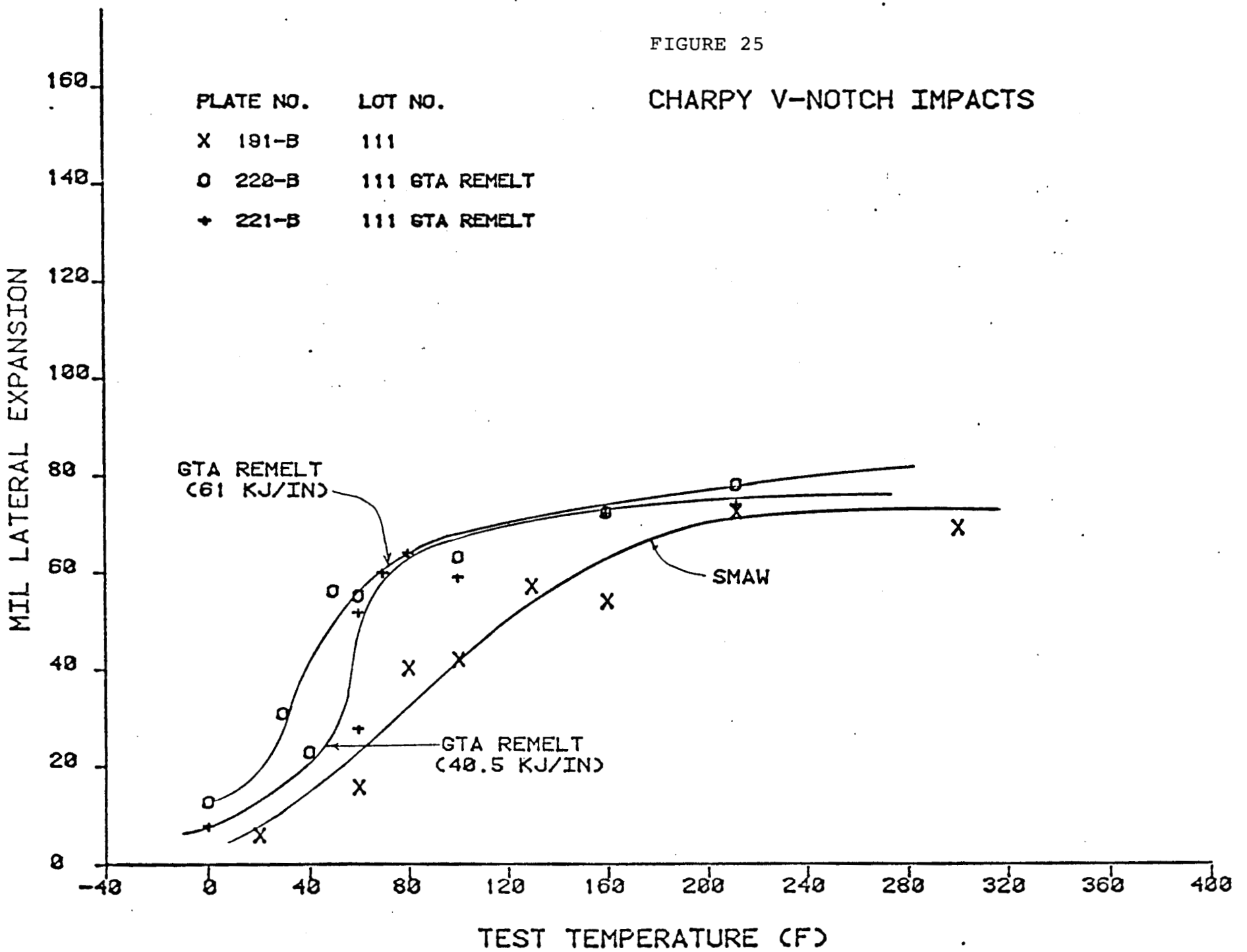


FIGURE 26

CHARPY V-NOTCH IMPACTS

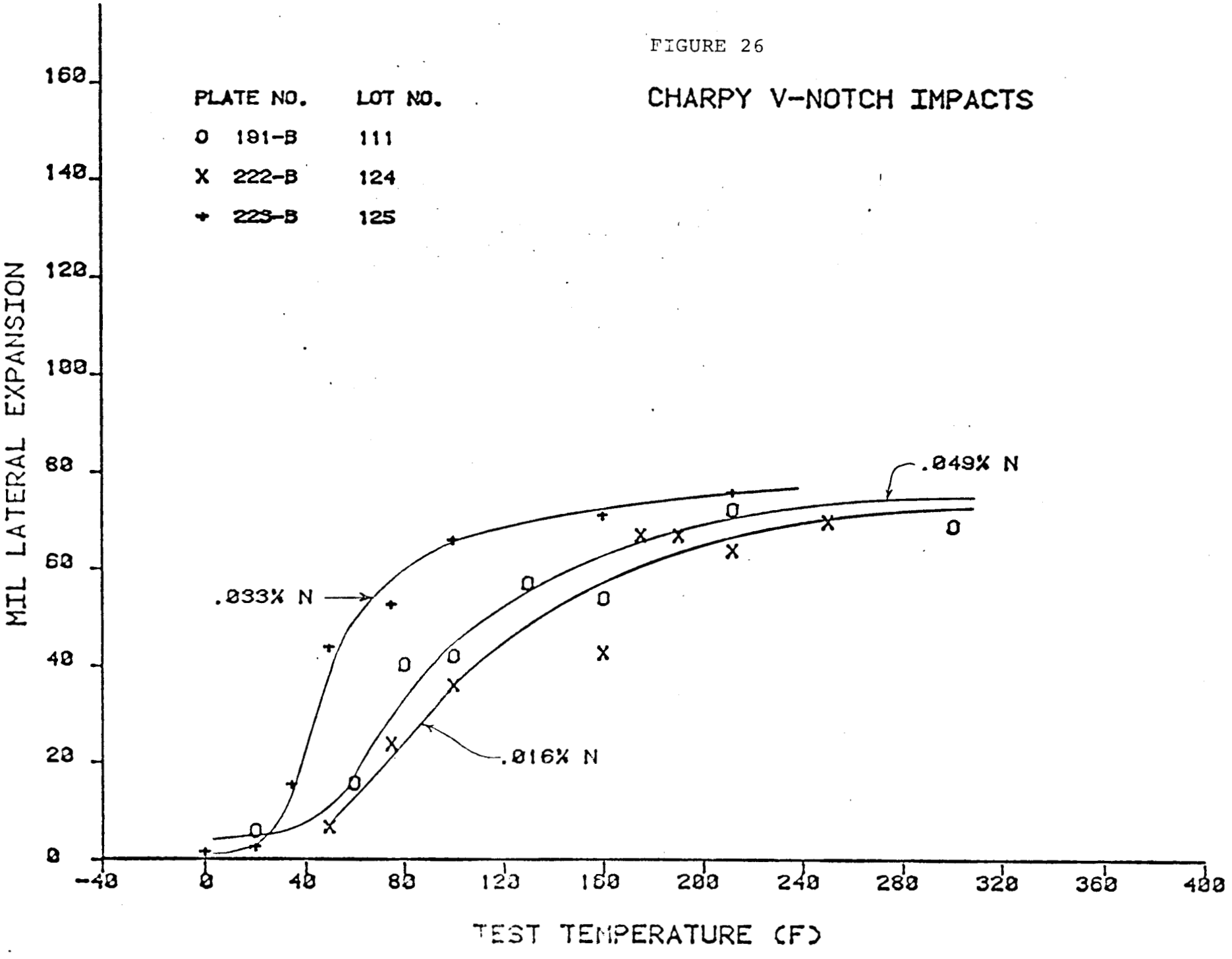


TABLE I

SHIELDED METAL ARC WELDING OF

9Cr-1Mo-V-W USING HIGH FREQUENCY PULSED ARC POWER SUPPLY

Plate No.	Lot No.	Weld Bead Type	Pulse Freq. Hz	Avg.Pulse Current (Amps)	Constant Background Current (Amps)
191-B	111	Weave		-	235
192-B	111	Stringer		-	235
193-B	111	Weave	5,000	40	195
194-B	111	Weave	10,000	40	195
195-B	111	Weave	15,000	40	195
196-B	109	Weave	-	-	235
197-B	109	Stringer	-	-	235
198-B	109	Weave	5,000	40	195
199-B	109	Weave	10,000	40	195
200-B	109	Weave	15,000	50	195
201-B	113	Weave	-	-	180
202-B	111	Weave	15,000	40	195
203-B	111	Weave	17,000	40	195
204-B	111	Weave	20,000	40	195
205-B	113	Stringer	-	-	180
217-B	111	Weave	10,000	115	120
219-B	111	Weave	15,000	100	135

TABLE II
SMAW TEST PLATE HEAT TREATMENTS

Code	Plate No.	Mix	Lot	Welder	Date	1 Hr., Air Cool After Each Tempering Heat Treatment - °F			Hardness (1) HRC	
GV	100-A	8842	1	OSJ	2/28/75	1400	-		23.7	
GW	101-A	8855	14	JHK	2/28/75	1400	-		25.4	
HR	102-A	8851	10	OSJ	3/10/75	1400	-		24.1	
HS	103-A	8852	11	JHK	3/10/75	1400	-		24.0	
HT	104-A	8856	15	OSJ	3/10/75	1400	-		24.8	
HU	105-A	8860	19	OSJ	3/10/75	1400	-		25.2	
HV	106-A	8861	20	JHK	3/10/75	1400	-		24.7	
HW	107-A	8862	21	JHK	3/10/75	1400	-		24.6	
IC	108-A	8864	23	JHK	3/13/75	1400	-		29.1	
ID	109-A	8865	24	OSJ	3/13/75	1400	-		27.5	
IE	110-A	8866	25	OSJ	3/13/75	1400	-		28.8	
IP	111-A	8869	28	OSJ	3/19/75	1400	-		27.7	
IR	112-A	8870	29	JHK	3/19/75	1400	-		28.1	
JI	113-A	8872	31	JFT	3/22/75	1400	-		21.3	
JJ	114-A	8872	31	JFT	3/22/75	1400	-		22.8	
JK	115-A	8864	23	JFT	3/22/75	1400	1400		23.8	
JL	116-A	8869	28	JFT	3/22/75	1400	-		25.7	
JM	117-A	8867	26	OSJ	3/24/75	1400	-		22.7	
JN	118-A	8868	27	JHK	3/24/75	1400	-		28.5	
JO	119-A	8873	32	OSJ	3/24/75	1400	-		29.4	
JS	120-B	8848	7	OSJ	3/25/77	1400	-		26.6	
JT	121-B	8849	8	JHK	3/25/75	1400	-		26.5	
-	122-B	8866	25	JHK	3/27/75	1400	-		26.7	
-	122-B	8866	25	JHK	3/27/75	1450	-		23.6	
-	122-B	8866	25	JHK	3/27/75	1475	-		22.2	
-	122-B	8866	25	JHK	3/27/75	1500	-		20.0	
KL	123-B	8880	39	OSJ	4/2/75	1500	1400		22.6	
KU	124-B	8881	40	OSJ	4/4/75	1475	-		23.9	
KV	125-B	8882	41	OSJ	4/4/75	1475	-		22.4	
KW	126-B	8883	42	JHK	4/4/75	1475	-		20.0	
KX	127-B	8884	43	JHK	4/4/75	1475	1400		20.9	
LU	128-B	8900	45	JHK	4/10/75	1475	1400		97.2	HRB
LZ	129-B	8851	10	JHK	4/15/75	1475	-		98.8	HRB
MA	130-B	8860	19	JHK	4/15/75	1475	1400		97.6	HRB
MB	131-B	8903	48	OSJ	4/15/75	1475	1400		98.5	HRB
ML	132-B	8908	53	OSJ	4/19/75	1150	1475	1400	24.1	

(1) Converted from Vickers hardness (HV50) with ASTM E140-72 after measuring in accordance with ASTM E92-72.

TABLE II
SMAW TEST PLATE HEAT TREATMENTS

Code	Plate No.	Mix	Lot	Welder	Date	1 Hr., Air Cool After Each Tempering Heat Treatment			Hardness HRB
MS	133-B	8906	51	JHK	4/28	1475°	1400°	-	94.7
MT	134-B	8907	52	OSJ	4/28	1475°	1400°	-	94.3
MU	135-B	8908	53	JHK	4/28	1475°	1400°	-	98.3
MV	136-B	8909	54	JHK	4/28	1475°	-	-	95.75
MW	137-B	8910	55	OSJ	4/28	1475°	-	-	96.47
MX	138-B	8924	56	OSJ	4/28	1475°	-	-	95.42
MY	139-B	8925	57	OSJ	4/28	1475°	-	-	95.1
NR	140-B	8926	58	JHK	5/1	1475°	-	-	94.9
NS	141-B	8927	59	OSJ	5/1	1475°	-	-	97.2
NU	142-B	8281	60	OSJ	5/2	1475°	-	-	91.3
NV	143-B	8281	61	JHK	5/2	1475°	-	-	92.3
NX	144-B	8928	62	JHK	5/6	1475°	1400°	-	98.4
NY	145-B	8929	63	JHK	5/6	1475°	1400°	-	98.0
NZ	146-B	8930	64	OSJ	5/6	1475°	1400°	1375°	23.0 HRC
OA	147-B	8931	65	OSJ	5/6	1475°	1400°	1375°	98.6
OB	148-B	8932	66	OSJ	5/6	1475°	1400°	1375°	99.2
PK	149-B	8884	43	OSJ	5/12	1900°	1400°	-	99.3
PL	150-B	8908	68	OSJ	5/19	1475°	1400°	-	98.0
PM	151-B	8860	69	OSJ	5/20	1475°	1400°	-	97.8
PN	152-B	8884	70	OSJ	5/20	1475°	1400°	-	98.7
PO	153-B	8929	71	JHK	5/20	1475°	1400°	-	97.6
PP	154-B	8932	72	JHK	5/20	1475°	1400°	-	23.0 HRC
RY	155-B	8940	73	JHK	5/29	1475°			94.5
RZ	156-B	8941	74	JHK	5/29	1475°			94.6
SA	157-B	8942	75	JFT	5/29	1475°			97.0
SB	158-B	8943	76	JFT	5/29	1475°			97.8
SC	159-B	8944	77	JHK	5/29	1475°			22.4 HRC
SD	160-B	8945	78	JFT	5/29	1475°			21.7 HRC
SE	161-B	8904	79	JFT	5/30	1475°	1400°		23.2 HRC
SF	162-B	8905	80	JFT	5/30	1475°	1400°		98.6
SG	163-B	8948	81	OSJ	6/2	1475°	1400°		98.2
SH	164-B	8949	82	OSJ	6/2	1475°	1400°		97.9
TJ	165-B	8961	83-1	OSJ	6/10	1450°			96.8
TK	166-B	8961	83-2	JHK	6/10	1475°			95.1
TL	167-B	8961	83-3	JHK	6/10	1450°			96.2
TM	168-B	8962	84	JFT	6/10	1450°			94.5
TN	169-B	8963	85	JFT	6/10	1450°			96.3

TABLE II
SMAW TEST PLATE HEAT TREATMENTS

Code	Plate No.	Mix	Lot	Welder	Date	1 Hr., Air Cool After Each Tempering Heat Treatment - °F			Hardness HRB
UD	170-B	8964	87	JHK	6/18	*1400	1400	-	97.3
UE	171-B	8965	88	JHK	6/18	*1400	1400	-	98.9
UF	172-B	8966	89	OSJ	6/18	*1400	1400	-	98.8
UG	173-B	8967	90	OSJ	6/18	*1400	1400	1450	96.8
UI	174-B	8969	92	JHK	6/20	*1450	-	-	25.4 HRC
UJ	175-B	8970	93	JHK	6/20	*1450	-	-	98.8
UK	176-B	8971	94	JFT	6/20	*1450	-	-	94.5
UL	177-B	8972	95	JFT	6/20	*1450	-	-	94.5
VL	178-B	8974	97	OSJ	6/28	1450	-	-	93.7
VM	179-B	8975	98	OSJ	6/28	1450	-	-	96.8
VN	180-B	8976	99	SAL	6/28	1450	-	-	98.8
VO	181-B	8977	100	SAL	6/28	1450	-	-	96.6
XW	182-B	8979	101	OSJ	8/15	*1450	-	-	95.0
XX	183-B	8980	102	JHK	8/15	*1450	-	-	95.5
XY	184-B	8981	103	JHK	8/15	*1450	-	-	94.9
XZ	185-B	8982	104	OSJ	8/15	*1450	-	-	92.9
YA	186-B	8983	105	OSJ	8/15	*1450	-	-	93.3
ZA	187-B	8963	85A	JHK	9/6	1450	1400	1400	97.9
ZB	188-B	8972	95A	JHK	9/6	1450	1400	1400	23.3 HRC
DH	189-B	8963	85A	JHK	11/3	1450	1400	-	99.8
DI	190-B	9002	95B	JHK	11/3	1450	1400	-	99.2
IM	191-B	9029	111	JFT	1/12/76	*1450			95.0
IN	192-B	9029	111	JHK	1/13	*1450			95.5
IO	193-B	9029	111	SAL	1/14	*1450			95.7
IP	194-B	9029	111	JHK	1/15	*1450			95.1
IQ	195-B	9029	111	OSJ	1/15	*1450			95.1
JH	196-B	9028	109	JHK	1/19	*1450			93.1
JI	197-B	9028	109	JFT	1/19	*1450			92.8
JJ	198-B	9028	109	SAL	1/20	*1450			93.1
JK	199-B	9028	109	OSJ	1/21	*1450			93.6
JL	200-B	9028	109	JFT	1/22	*1450			95.2
KN	201-B	9031	113	JHK	1/27	*1450			97.0
LG	202-B	9029	111	OSJ	2/4	*1450			96.5
LH	203-B	9029	111	SAL	2/5	*1450			95.7
LI	204-B	9029	111	JHK	2/9	*1450			97.0
LY	205-B	9031	113	JHK	2/9	*1450			98.0

*Plates cooled to room temperature before tempering.

TABLE II
SMAW TEST PLATE HEAT TREATMENTS

Code	Plate No.	Mix	Lot	Welder	Date	1 Hr., Air Cool After Each Tempering Heat Treatment - °F	Hardness HRB
PO	206-B	GTAW	R-4001	BRP	3/24	*1450	90.1
PR	207-B	GTAW	R-4001	BRP	3/24	*1450	91.2
TG	208-B	9042	115	JHK	4/12	*1450	97.5
TH	209-B	9028	109	JHK	4/13	*1450	93.1
TI	210-B	9028	109	JHK	4/13	*1450	93.1
TT	211-B	9029	111	JHK	4/14	*1450	95.7
TU	212-B	9029	111	JHK	4/14	*1450	96.1
TV	213-B	9028	109	JHK	4/14	*1450	95.0
TW	214-B	9029	111	JHK	4/14	*1450	96.7
VZ	215-B	9052	120	JHK	5/11	*1450	92.7
WA	216-B	9051	121	JHK	5/11	*1450	86.6
WO	217-B	9029	111	JHK	5/18	*1450	86.6
WP	218-B	9054	123	JHK	5/18	*1450	88.3
WR	219-B	9029	111	JFT	5/19	*1450	88.0
LN	220-B	9029	111-GTA Remelt	OSJ	11/2	*1450	97.0
LO	221-B	9029	111-GTA Remelt	OSJ	11/3	*1450	96.0
PO	222-B	9106	124	JHK	12/15	*1450	93.0
PP	223-B	9107	125	JHK	12/15	*1450	94.6
PR	224-B	9108	126	OSJ	1/3	*1450	96.1
PS	225-B	9109	127	SAL	1/3	*1450	90.6
RA	226-B	9108	126-GTA Remelt	OSJ	1/4	*1450	96.4

*Plates cooled to room temperature before tempering.

TABLE III
Shielded Metal Arc Undiluted Weld Pads

Chemical Analysis (Wt.%)

Lot No.	Cr-Eq.	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	Parts Added MM
1	13.10	.25	.006	.009	.71	.090	9.03	.03	.96	.09	.03	.011	.03	<.001	.004	.26	.53	<.001	.008	
2	8.84	.31	.008	.010	.87	.110	8.71	.84	1.44	.10	.04	.013	.03	<.001	.004	.07	.63	<.001	.007	
3	-	.08	.010	.008	1.18	.078	7.83	.11	.97	.04	.01	.009	.03	<.001	.005	.34	<.01	<.001	-	
4	-	.33	.008	.008	1.08	.094	8.51	.03	1.94	.22	.04	.012	.03	<.001	.004	.32	.70	<.001	-	
5	-	.32	.007	.011	.85	.088	9.35	.98	.05	.36	.05	.014	.03	<.001	<.001	.27	.25	<.001	-	
6	-	.43	.008	.009	.60	.090	9.36	.33	.49	.64	.05	.014	.03	<.001	.003	.18	.59	<.001	-	
7	9.78	.19	.010	.007	.95	.073	8.88	.49	.96	.07	.02	.010	.03	<.001	.003	.24	.01	<.001	.010	
8	9.81	.21	.007	.008	.92	.075	8.81	.99	1.49	.07	.03	.012	.03	<.001	.003	.23	.04	<.001	.012	
9	15.21	.18	.009	.011	.86	.075	8.70	.03	1.93	.07	.03	.011	.03	<.001	.001	.23	<.01	<.001	.011	
10	12.54	.20	.010	.008	.93	.11	8.98	.02	.97	.17	.04	.012	.03	<.001	.003	.32	.50	<.001	.010	.5
11	12.09	.25	.009	.008	.96	.12	9.25	.02	.94	.18	.06	.013	.03	<.001	.003	.30	.50	<.001	.019	1.0
12	12.81	.34	.008	.008	1.04	.11	9.32	.02	.95	.16	.06	.013	.03	<.001	.001	.30	.45	<.001	.017	1.5
13	13.48	.45	.008	.008	1.06	.11	9.23	.02	.94	.16	.06	.013	.03	<.001	<.001	.30	.51	<.001	.016	2.0
14	13.37	.34	.008	.007	.90	.11	9.37	.02	.96	.15	.05	.013	.03	<.001	<.001	.31	.48	<.001	.016	
15	13.40	.38	.009	.008	.93	.11	9.25	.01	.96	.16	.05	.013	.03	<.001	.005	.30	.47	<.001	.016	.5*
16	13.83	.50	.008	.008	.99	.12	9.34	.02	.97	.17	.05	.012	.03	<.001	<.001	.31	.46	<.001	.016	1.0*
17	14.93	.68	.009	.008	.97	.12	9.37	.02	.96	.19	.06	.013	.03	<.001	.002	.30	.48	<.001	.017	1.5*
18	15.83	.84	.009	.008	1.01	.12	9.25	.01	.94	.21	.07	.013	.03	<.001	.002	.31	.52	<.001	.020	2.0*
19	12.38	.23	.009	.007	.71	.11	8.87	.74	1.93	.06	.03	.013	.03	<.001	.002	.31	.01	<.001	.018	
20	12.22	.22	.009	.006	.77	.10	9.06	.01	.99	.09	.03	.013	.03	<.001	.003	.29	.50	<.001	.031	
21	12.31	.22	.007	.006	.82	.10	9.22	.01	.99	.09	.03	.010	.03	<.001	.003	.29	.56	<.001	.033	
22	10.59	.27	.010	.008	.55	.11	9.18	.41	.92	.08	.03	.012	.03	<.001	.001	.29	.60	<.001	.039	
26	8.93	.15	.009	.007	.73	.11	8.83	.10	.87	.09	.03	.012	.03	<.001	.004	.19	.40	<.001	.038	
27	7.99	.11	.009	.008	.75	.12	8.80	.10	.87	.08	.02	.012	.03	<.001	.005	.18	.41	<.001	.041	.5
30	7.68	.12	.010	.007	.46	.095	8.84	.53	1.01	.04	.03	.012	.03	<.001	.004	.18	<.01	<.001	.050	
31	7.08	.09	.010	.006	.46	.094	8.66	.51	.96	.04	.03	.012	.03	<.001	.005	.17	<.01	<.001	.052	.3
32	8.59	.24	.010	.008	.49	.11	8.90	1.12	1.46	.12	.04	.013	.03	<.001	.003	.27	<.01	<.001	.054	
33	10.51	.18	.009	.007	.80	.094	9.16	.10	.87	.10	.03	.011	.03	<.001	.004	.21	.43	<.001	.038	
34	13.79	.52	.009	.008	.57	.098	9.08	.39	.93	.15	.05	.012	.03	<.001	.007	.33	.53	<.001	.037	.5
35	10.12	.20	.009	.007	.80	.11	9.23	.10	.86	.11	.03	.012	.03	<.001	.004	.21	.43	<.001	.036	
36	8.98	.30	.009	.010	.95	.13	8.41	.39	1.40	.18	.04	.013	.03	<.001	.002	.04	.44	<.001	.015	
37	11.37	.27	.009	.009	.51	.086	8.85	1.13	1.62	.22	.02	.012	.03	<.001	.005	.32	<.01	<.001	.046	
38	10.39	.35	.009	.011	1.01	.15	9.14	.45	1.56	.25	.04	.013	.03	<.001	.003	.06	.55	<.001	.010	
39	10.90	.36	.010	.009	.50	.083	8.89	1.11	1.43	.17	.02	.013	.03	<.001	.004	.30	<.01	<.001	.047	

MM - Mischmetal (34% Rare Earth Metals)

*ReF_3 - Rare Earth Fluorides (84% Rare Earth Oxide - Re_2O_3)

TABLE III (cont.'d)

Shielded Metal Arc Undiluted Weld Pads

Lot No.	Cr-Eq.	Chemical Analysis (Wt. %) Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	Parts Added MM
44	11.11	.27	.011	.007	.48	.067	9.08	.50	1.05	.10	.02	.010	.03	<.001	.002	.25	<.01	<.001	.051	
46	10.87	.29	.010	.007	.46	.085	9.14	.34	1.06	.11	.02	.011	.03	<.001	<.001	.25	<.01	<.001	.067	
49	12.36	.47	.011	.009	.43	.079	9.09	.78	1.39	.06	<.01	.009	.03	.003	<.001	.28	.28	.001	.061	
50	12.08	.41	.011	.008	.47	.079	9.20	.78	1.41	.06	.01	.009	.03	.003	<.001	.28	.29	.001	.063	
51	9.85	.14	.011	.010	.50	.086	9.07	.82	1.46	.05	.02	.010	.04	.003	.008	.25	.32	.002	.062	
52	9.97	.16	.011	.011	.49	.089	9.11	.83	1.50	.05	.02	.010	.04	.003	.006	.25	.31	.002	.063	.5
54	7.62	.10	.011	.007	.33	.082	8.84	.86	.85	.04	.01	.012	.03	.001	.003	.19	<.01	.001	.008	
55	8.04	.12	.011	.007	.35	.080	8.91	.85	.86	.04	.01	.011	.03	.001	.002	.20	<.01	<.001	.008	.5
56	7.21	.07	.011	.007	.32	.086	8.93	.50	.85	.03	.01	.011	.03	.001	.001	.19	<.01	.002	.060	
57	7.43	.13	.011	.006	.33	.084	8.86	.51	.82	.03	.01	.010	.03	.001	.002	.20	<.01	.001	.062	.5
67	12.17	.49	.011	.010	.30	.080	9.39	.50	.85	.07	.01	.011	.03	.004	.002	.28	.29	.002	.056	
68	9.28	.33	.011	.013	.93	.16	9.10	.42	1.60	.09	.03	.014	.03	<.001	.003	.05	.50	<.001	.008	
86	7.61	.20	.010	.007	.35	.076	8.51	.47	.80	.03	<.01	.007	.03	.003	.001	.16	<.01	.003	.052	.3
91	11.69	.21	.011	.012	.55	.090	8.36	1.05	2.13	.06	.02	.013	.03	<.001		.27	<.01	.002	.032	
106	10.46	.21	.011	.009	.60	.054	8.31	.04	.97	.01	<.01	.012	.03	<.001		.16	.14	<.001	.047	
107	10.36	.19	.011	.009	.57	.059	8.37	.02	.96	.02	<.01	.012	.03	<.001		.16	.14	<.001	.048	
108	10.21	.19	.013	.012	.59	.056	8.35	.01	.93	.02	<.01	.012	.04	<.001		.16	.14	<.001	.052	
109	10.99	.20	.011	.010	.64	.060	9.06	.02	1.02	.01	<.01	.013	.04	<.001	.001	.16	.14	<.001	.052	
110	12.55	.23	.012	.013	.69	.069	9.92	.01	1.16	.03	<.01	.015	.04	<.001	.001	.20	.17	.001	.059	
111	11.08	.20	.011	.010	.64	.064	9.14	.02	1.03	.04	<.01	.013	.03	<.001	.001	.16	.13	.001	.053	
112	10.31	.17	.011	.012	.61	.061	8.88	.01	.97	.03	<.01	.011	.04	<.001	.001	.13	.13	<.001	.050	
114	11.15	.26	.007	.016	.57	.085	9.19	.05	1.02	.06	.01	.021	.05	<.001	.001	.19	.19	<.001	.054	
116	11.58	.17	.011	.010	.59	.031	8.65	.02	1.01	.03	<.01	.013	.04	<.001	<.001	.15	.14	<.001	.053	
117	10.23	.07	.011	.010	.63	.030	8.22	.02	1.01	.02	<.01	.013	.03	<.001	.001	.12	.12	<.001	.049	
118	11.76	.15	.011	.010	.70	.040	9.35	.02	1.06	.04	<.01	.012	.04	<.001	.002	.15	.15	<.001	.056	
119	11.02	.06	.010	.009	.67	.034	9.31	.02	1.02	.03	<.01	.012	.03	<.001	.001	.14	.15	<.001	.052	
122	11.76	.21	.011	.014	.49	.075	8.74	.02	1.01	.04	<.01	.014	.03	<.001	<.001	.17	.78	<.001	.047	

TABLE IV

Chemical Composition - Wt. %

Plate No.	Lot No.	Cr Eq	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	MM(1)
100-A	1	13.10	.25	.006	.009	.71	.090	9.03	.03	.96	.09	.03	.011	.03	<.001	.004	.26	.53	<.001	.008	
101-A	14	13.37	.34	.009	.007	.90	.11	9.37	.02	.96	.15	.05	.013	.03	<.001	.001	.31	.48	<.001	.016	
102-A	10	12.17	.22	.010	.008	.86	.122	9.09	<.01	.94	.13	.06	.013	.03	<.001	.003	.33	.56	<.001	.016	.5
103-A	11	13.20	.33	.009	.008	.94	.115	9.10	<.01	.95	.15	.05	.013	.03	<.001	.003	.34	.55	<.001	.016	1.0
104-A	15	13.70	.41	.009	.008	.92	.121	9.23	<.01	.93	.18	.06	.011	.03	<.001	.005	.35	.54	<.001	.016	.5*
105-A	19	12.83	.24	.010	.010	.68	.114	9.03	.72	1.89	.08	.03	.012	.03	<.001	.003	.33	.01	<.001	.015	
106-A	20	12.51	.23	.010	.009	.77	.106	9.06	<.01	.97	.12	.03	.012	.03	<.001	.002	.31	.62	<.001	.031	
107-A	21	12.12	.20	.010	.008	.80	.107	9.07	.01	.95	.12	.03	.012	.03	<.001	.005	.31	.57	<.001	.030	1.0
108-A	23	11.13	.24	.009	.008	.50	.099	8.92	.38	.94	.10	.03	.012	.03	.002	.004	.30	.51	<.001	.036	
109-A	24	10.82	.18	.009	.009	.51	.098	8.91	.39	.98	.09	.03	.013	.03	.002	.009	.30	.53	<.001	.038	.5
110-A	25	11.22	.23	.009	.009	.54	.10	9.09	.38	.97	.10	.03	.013	.03	.003	.006	.30	.54	<.001	.038	1.0
111-A	28	11.62	.32	.010	.010	.52	.11	9.09	.40	1.01	.12	.03	.014	.03	.003	.008	.31	.52	<.001	.039	.5*
112-A	29	12.51	.38	.009	.009	.54	.10	9.06	.39	1.01	.13	.03	.014	.03	.003	.007	.32	.53	<.001	.037	1.0*
113-A	31	7.28	.07	.011	.009	.46	.089	8.53	.49	.96	.04	.02	.011	.03	<.001	.004	.17	.05	<.001	.045	.3
114-A	31	6.95	.08	.011	.009	.44	.095	8.59	.51	.97	.04	.02	.011	.03	<.001	.004	.16	.03	<.001	.048	.3
115-A	23	11.74	.24	.010	.010	.50	.096	9.01	.39	.97	.09	.03	.012	.03	.002	.006	.31	.51	<.001	.035	
116-A	28	12.44	.34	.009	.010	.52	.10	9.11	.39	.97	.12	.03	.012	.03	.003	.007	.32	.49	<.001	.036	.5*
117-A	26	9.05	.10	.010	.010	.69	.10	8.83	.11	.88	.08	.02	.011	.03	<.001	.003	.17	.40	<.001	.037	
118-A	27	10.0	.18	.010	.010	.72	.098	8.81	.10	.87	.09	.02	.011	.03	<.001	.005	.20	.40	<.001	.034	.5
119-A	32	8.58	.20	.011	.011	.45	.10	8.86	1.14	1.47	.10	.03	.014	.03	<.001	.003	.26	.02	<.001	.051	
120-B	7	9.19	.17	.009	.008	.88	.080	9.25	.46	.88	.07	.02	.011	.03	<.001	.002	.20	<.01	<.001	.016	
121-B	8	9.47	.21	.010	.010	.88	.081	9.13	.87	1.31	.08	.02	.011	.04	<.001	.002	.21	<.01	<.001	.017	
123-B	39	10.55	.30	.011	.010	.47	.083	9.06	1.12	1.45	.14	.02	.013	.03	<.001	.004	.29	<.01	<.001	.047	
125-B	41	11.01	.28	.011	.010	.47	.088	9.38	.52	1.11	.12	.02	.012	.03	<.001	.004	.26	<.01	<.001	.052	
126-B	42	10.05	.26	.011	.010	.45	.097	9.27	.79	1.05	.10	.02	.012	.04	<.001	.005	.24	<.01	<.001	.011	
127-B	43	10.16	.33	.011	.011	.46	.088	9.33	1.06	1.37	.08	.02	.013	.04	<.001	.005	.27	<.01	<.001	.049	

(1) MM - Mischmetal (15% Cerium, 5% Neodymium, 7% Lanthanum, 1.5% Praseodymium, 6% other Rare Earth Metals, 16% Mn, 6% Ca, 5% Fe, 0.16% Carbon, Balance approx. 38% Si)

*REF_3 - Rare Earth Fluorides (84% Rare Earth Oxide - RE_2O_3)

TABLE IV (cont.'d)

Chemical Composition - Wt. %

Plate No.	Lot No.	Cr Eq	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	MM
128-B	45	9.64	.26	.013	.011	.46	.079	9.10	1.02	1.35	.07	.02	.012	.04	<.001	.004	.25	<.01	<.001	.049	.5
129-B	10	13.32	.29	.010	.011	.89	.121	9.10	.01	.92	.16	.04	.012	.04	<.001	.007	.35	.53	<.001	.011	
130-B	19	13.10	.27	.010	.012	.65	.117	8.65	.72	1.90	.10	.02	.011	.03	<.001	.006	.34	<.01	<.001	.011	
131-B	48	10.03	.31	.012	.010	.60	.10	8.69	.49	.89	.10	.02	.011	.03	<.001	.005	.28	.53	<.001	.049	
132-B	53	10.34	.36	.012	.012	.87	.14	9.53	.43	1.51	.11	.02	.011	.03	<.001	.004	.06	.48	<.001	.014	
133-B	51	9.50	.14	.012	.012	.47	.077	8.84	.82	1.42	.04	.01	.012	.04	.003	.002	.23	.28	<.001	.060	
134-B	52	9.42	.14	.012	.012	.48	.077	8.71	.81	1.41	.04	.01	.012	.04	.003	.002	.23	.29	<.001	.059	.5
135-B	53	10.09	.38	.011	.012	.90	.14	9.27	.42	1.49	.11	.02	.012	.03	<.001	.002	.05	.48	<.001	.011	
136-B	54	7.47	.09	.011	.009	.33	.083	8.88	.82	.81	.03	.01	.011	.04	.001	.002	.19	<.01	<.001	.009	
137-B	55	7.64	.10	.011	.009	.33	.082	8.85	.81	.81	.04	<.01	.010	.03	.001	.002	.20	<.01	<.001	.010	.5
138-B	56	7.62	.08	.011	.009	.33	.077	9.08	.50	.80	.03	.01	.011	.04	.001	.002	.19	<.01	<.001	.058	
139-B	57	7.77	.10	.011	.010	.34	.082	9.21	.50	.81	.03	.01	.011	.04	.001	.002	.20	<.01	<.001	.060	.5
140-B	58	7.53	.08	.011	.010	.26	.081	8.70	.48	.78	.03	.01	.011	.04	.001	.001	.18	.26	.002	.059	
141-B	59	8.44	.12	.011	.011	.28	.078	9.07	.50	.81	.03	.01	.012	.04	.001	.001	.20	.29	.002	.062	.5
142-B	60	10.15	.38	.012	.009	.70	.089	9.44	<.01	.88	.01	<.01	.011	.03	<.001	.001	.02	<.01	<.001	.012	
143-B	61	10.68	.39	.011	.011	.65	.074	9.43	.04	.88	.01	<.01	.010	.03	<.001	.001	.02	<.01	<.001	.014	
144-B	62	9.72	.26	.011	.013	.84	.11	9.23	.42	1.49	.07	.02	.012	.03	<.001	.003	.05	.47	.001	.034	
145-B	63	9.24	.24	.010	.014	.85	.11	8.97	.41	1.48	.07	.01	.012	.03	<.001	.003	.05	.49	<.001	.035	.5
146-B	64	10.24	.27	.010	.013	.85	.11	9.07	.42	1.52	.07	.02	.012	.03	<.001	.004	.15	.34	<.001	.047	
147-B	65	11.20	.28	.010	.013	.86	.11	9.32	.43	1.58	.08	.01	.013	.03	<.001	.002	.27	.23	<.001	.068	
148-B	66	11.04	.28	.010	.013	.85	.11	9.33	.69	1.56	.08	.02	.013	.03	<.001	.003	.38	<.01	<.001	.069	

TABLE IV (cont.'d)

Chemical Composition - Wt. %

Plate No.	Lot No.	Cr Eq	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	MM
149-B	43	10.32	.32	.012	.010	.44	.085	9.17	1.07	1.44	.08	.02	.012	.03	<.001	.002	.27	<.01	<.001	.049	
150-B	68	9.64	.31	.012	.012	.80	.13	9.26	.40	1.39	.08	.02	.011	.03	<.001	.001	.05	.47	<.001	.014	
151-B	69	13.39	.24	.012	.013	.63	.11	9.07	.71	1.89	.10	.02	.012	.03	<.001	<.001	.33	<.01	<.001	.014	
152-B	70	10.20	.33	.013	.012	.43	.084	9.27	1.01	1.38	.07	.01	.012	.03	<.001	<.001	.26	<.01	<.001	.051	
153-B	71	9.59	.25	.012	.013	.84	.11	9.16	.40	1.47	.07	.02	.012	.03	<.001	<.001	.05	.45	<.001	.034	.5
154-B	72	10.71	.29	.012	.013	.81	.11	9.39	.63	1.43	.08	.01	.012	.03	<.001	<.001	.35	<.01	<.001	.063	
155-B	73	9.13	.25	.012	.009	.32	.075	9.03	.78	.81	.04	<.01	.009	.03	.002	<.001	.20	<.01	.003	.010	
156-B	74	9.03	.27	.013	.010	.33	.076	8.95	.77	.80	.04	<.01	.009	.03	.003	<.001	.20	<.01	.003	.012	.5
157-B	75	8.74	.24	.013	.010	.31	.076	8.88	.48	.81	.04	<.01	.008	.03	.002	<.001	.20	<.01	.003	.055	
158-B	76	9.03	.25	.013	.010	.33	.071	8.96	.47	.80	.04	<.01	.009	.03	.002	<.001	.20	<.01	.002	.055	.5
159-B	77	9.57	.27	.013	.011	.33	.075	9.14	.47	.79	.04	<.01	.009	.03	.002	<.001	.20	.27	.003	.054	
160-B	78	9.80	.29	.012	.011	.34	.071	9.11	.47	.79	.04	<.01	.009	.03	.002	<.001	.20	.26	.003	.052	.5
161-B	79	13.13	.50	.012	.013	.46	.074	9.19	.76	1.41	.07	<.01	.010	.03	.003	<.001	.27	.29	.002	.054	
162-B	80	12.20	.41	.013	.014	.48	.076	9.08	.77	1.45	.06	.01	.011	.03	.003	<.001	.26	.29	.002	.056	
163-B	81	9.18	.30	.012	.009	.47	.098	8.57	.40	.93	.03	.03	.012	.03	<.001	<.001	.14	<.01	<.001	.012	
164-B	82	8.37	.28	.011	.009	.47	.075	8.48	.40	.95	.03	.03	.012	.03	<.001	<.001	.11	<.01	<.001	.054	
165-B	83-1	8.41	.20	.011	.009	.29	.064	9.06	.48	.80	.03	<.01	.008	.03	.002	<.001	.15	<.01	.002	.058	.3
166-B	83-2	8.53	.21	.011	.008	.31	.069	9.15	.47	.80	.03	<.01	.008	.03	.002	<.001	.16	<.01	.002	.056	.3
167-B	83-3	8.62	.25	.011	.010	.33	.067	9.06	.48	.78	.03	<.01	.009	.04	.003	<.001	.16	<.01	.002	.055	.3
168-B	84	10.08	.22	.011	.010	.31	.071	9.03	.03	.79	.03	<.01	.008	.03	.003	<.001	.16	<.01	.002	.057	.3
169-B	85	9.24	.45	.011	.010	.65	.080	8.81	.02	.89	.01	<.01	.008	.03	<.001	<.001	.02	<.01	<.001	.049	
170-B	87	11.51	.25	.012	.012	.32	.063	9.14	.49	1.30	.04	<.01	.010	.04	.003	<.001	.22	<.01	.004	.058	.5
171-B	88	10.87	.27	.012	.011	.35	.087	9.50	.50	1.27	.05	<.01	.010	.04	.003	<.001	.22	<.01	.004	.057	.5
172-B	90	12.28	.26	.012	.012	.31	.063	8.99	.50	1.54	.04	<.01	.009	.04	.003	<.001	.21	<.01	.004	.058	.5
173-B	90	11.52	.27	.012	.012	.32	.080	9.02	.50	1.50	.04	<.01	.010	.04	.003	<.001	.22	<.01	.003	.056	
176-B	94	9.56	.22	.013	.010	.63	.085	9.10	.03	.89	.01	<.01	.010	.03	<.001	.001	.17	<.01	<.001	.050	
177-B	95	9.88	.22	.014	.011	.63	.084	9.08	.03	.91	.01	<.01	.010	.03	<.001	.001	.17	<.17	<.001	.052	

TABLE IV (cont.'d)

Chemical Composition - Wt. %

Plate No.	Lot No.	Cr Eq	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2	MM
170-B	87	11.51	.25	.012	.012	.32	.063	9.14	.49	1.30	.04	<.01	.010	.04	.003	<.001	.22	<.01	.004	.058	.5
171-B	88	10.87	.27	.012	.011	.35	.087	9.50	.50	1.27	.05	<.01	.010	.04	.003	<.001	.22	<.01	.004	.057	.5
172-B	89	12.28	.26	.012	.012	.31	.063	8.99	.50	1.54	.04	<.01	.009	.04	.003	<.001	.21	<.01	.004	.058	.5
173-B	90	11.52	.27	.012	.012	.32	.080	9.02	.50	1.50	.04	<.01	.010	.04	.003	<.001	.22	<.01	.003	.056	
174-B	92	16.25	1.32	.011	.010	.57	.12	9.73	.41	.94	.07	.07	.012	.04	>.009	.008	.17	<.01	.005	.013	
175-B	93	16.03	1.26	.011	.010	.57	.076	9.62	.40	.94	.07	.07	.012	.04	>.009	.010	.13	<.01	.007	.051	
176-B	94	9.56	.22	.013	.010	.63	.085	9.10	.03	.89	.01	<.01	.010	.01	<.001	.001	.17	<.01	<.001	.050	
177-B	95	9.88	.22	.014	.011	.63	.084	9.08	.03	.91	.01	<.01	.010	.01	<.001	.001	.17	.17	<.001	.052	
178-B	97	7.98	.16	.013	.010	.57	.070	8.71	.03	.87	.02	<.01	.009	.03	<.001	.001	.02	<.01	<.001	.049	
179-B	98	9.19	.21	.013	.010	.59	.069	8.82	.04	.84	.02	.01	.010	.03	<.001	.001	.11	<.01	<.001	.050	
180-B	99	10.56	.36	.013	.011	.64	.074	9.02	.03	.88	.01	.01	.010	.03	.004	.001	.13	.16	.004	.051	
181-B	100	9.50	.22	.013	.011	.62	.082	8.92	.03	.88	.01	<.01	.009	.03	<.001	<.001	.14	.17	<.001	.050	.5
182-B	101	9.14	.38	.012	.009	.59	.070	8.37	.02	.87	.06	<.01	.011	.03	<.001	.003	.02	<.01	.001	.047	
183-B	102	9.84	.19	.013	.011	.60	.074	8.68	.02	.88	.04	<.01	.012	.03	<.001	.003	.16	.15	<.001	.047	
184-B	103	10.12	.23	.014	.012	.61	.072	8.73	.02	.89	.01	<.01	.012	.03	<.001	<.001	.17	.15	<.001	.048	
185-B	104	10.01	.18	.013	.012	.57	.067	8.48	.02	.88	.01	<.01	.012	.03	<.001	<.001	.15	.41	<.001	.048	
186-B	105	11.05	.19	.013	.012	.57	.071	8.52	.02	1.23	.01	<.01	.012	.03	<.001	.002	.15	.15	<.001	.045	
187-B	85A	9.26	.46	.009	.012	.88	.11	9.61	.02	.94	.01	.06	.015	.03	<.001	.006	.03	<.01	<.001	.050	
188-B	95A	10.51	.22	.010	.012	.85	.10	9.71	.02	.96	.01	.05	.015	.03	<.001	.006	.20	.17	<.001	.050	
189-B	85A	10.13	.55	.008	.011	.91	.11	9.95	.04	.95	.02	.07	.010	.04	<.001	.004	.03	<.01	<.001	.050	
190-B	95B	10.10	.19	.009	.010	.83	.10	9.57	.03	.99	.02	.05	.016	.04	<.001	.002	.19	.17	<.001	.053	
191-B	111	9.82	.23	.012	.011	.68	.070	9.08	.03	.99	.05	<.01	.013	.03	<.001	.002	.16	.14	<.001	.049	
192-B	111	9.99	.19	.012	.011	.65	.070	9.20	.03	1.00	.04	<.01	.013	.03	<.001	.001	.16	.14	<.001	.047	
193-B	111	11.02	.20	.011	.011	.66	.071	9.38	.03	1.03	.05	<.01	.014	.03	<.001	.001	.16	.13	<.001	.052	
194-B	111	10.88	.20	.011	.010	.67	.070	9.33	.03	1.01	.05	<.01	.014	.03	<.001	.001	.16	.13	<.001	.053	
195-B	111	10.86	.19	.011	.010	.65	.069	9.27	.03	1.00	.05	<.01	.014	.03	<.001	<.001	.16	.13	<.001	.051	
196-B	109	10.58	.20	.011	.011	.69	.073	9.27	.03	1.02	.01	<.01	.014	.04	<.001	<.001	.16	.13	<.001	.050	
197-B	109	10.64	.19	.011	.010	.66	.070	9.26	.03	1.00	.01	<.01	.014	.04	<.001	<.001	.16	.14	<.001	.049	
198-B	109	10.66	.20	.011	.012	.65	.068	9.14	.03	1.01	.01	<.01	.014	.03	<.001	<.001	.16	.14	<.001	.051	
199-B	109	10.54	.17	.011	.011	.65	.069	9.38	.03	1.00	.01	<.01	.013	.03	<.001	<.001	.15	.15	<.001	.052	
200-B	109	10.35	.17	.011	.010	.65	.069	9.21	.03	.99	.01	<.01	.012	.03	<.001	<.001	.15	.14	<.001	.051	

TABLE IV (cont.'d)

Chemical Composition - Wt. %

Plate No.	Lot No.	Cr Eq	Si	S	P	Mn	C	Cr	Ni	Mo	Cb	Ti	Co	Cu	B	Sol. Al	V	W	Zr	N_2 MM
201-B	113	10.30	.19	.012	.014	.61	.078	9.05	.02	.97	.04	<.01	.013	.04	<.001	<.001	.16	.15	<.001	.050
202-B	111	10.29	.20	.011	.011	.66	.077	9.09	.03	.98	.05	<.01	.012	.04	<.001	.002	.16	.13	<.001	.052
203-B	111	10.21	.18	.011	.010	.64	.077	9.17	.02	.97	.05	.01	.012	.03	<.001	.001	.15	.13	<.001	.054
204-B	111	10.24	.20	.011	.011	.65	.079	9.27	.03	.95	.05	.01	.012	.04	<.001	.004	.15	.12	<.001	.052
205-B	113	10.61	.23	.012	.013	.64	.079	9.03	.01	.94	.06	.01	.012	.03	<.001	.002	.17	.16	<.001	.051
206-B	GTAW	11.99	.02	.006	.013	.37	.034	9.22	.06	1.12	.04	<.01	.019	.04	<.001	.003	.14	.15	<.001	.047
207-B	GTAW	12.58	.05	.006	.014	.38	.030	9.20	.07	1.15	.05	<.01	.020	.05	<.001	.007	.14	.16	<.001	.043
208-B	115	11.22	.26	.008	.014	.57	.064	9.14	.05	1.02	.05	.01	.021	.05	<.001	.002	.14	.15	<.001	.053
209-B	109	10.65	.17	.011	.011	.64	.067	9.23	.03	1.01	.01	<.01	.014	.04	<.001	.002	.15	.14	<.001	.047
210-B	109	10.52	.17	.012	.010	.65	.070	9.25	.03	1.01	.01	<.01	.014	.04	<.001	.001	.15	.13	<.001	.047
211-B	111	11.09	.20	.011	.011	.67	.065	9.16	.03	1.04	.04	<.01	.015	.04	<.001	.001	.16	.12	<.001	.049
212-B	111	10.88	.18	.010	.010	.65	.066	9.22	.03	1.00	.04	<.01	.013	.04	<.001	.001	.16	.13	<.001	.049
213-B	109	10.93	.20	.011	.012	.67	.066	9.23	.03	1.02	.01	<.01	.015	.04	<.001	.001	.16	.14	<.001	.048
214-B	111	11.14	.20	.010	.010	.66	.066	9.20	.03	1.05	.04	<.01	.015	.04	<.001	.001	.16	.15	<.001	.050
215-B	120	12.12	.21	.010	.009	.68	.028	8.84	.02	.99	.04	<.01	.013	.03	<.001	<.001	.16	.15	<.001	.051
216-B	121	11.54	.11	.010	.008	.67	.026	8.80	.02	.99	.03	<.01	.012	.03	<.001	<.001	.15	.15	<.001	.047
217-B	111	11.09	.21	.011	.010	.67	.068	9.28	.03	1.01	.05	<.01	.014	.04	<.001	.001	.16	.14	<.001	.049
218-B	123	12.76	.22	.010	.013	.45	.069	9.21	.03	1.01	.05	<.01	.014	.03	<.001	.001	.17	.83	<.001	.048
219-B	111	11.0	.19	.011	.011	.64	.068	9.28	.04	1.02	.04	<.01	.014	.04	<.001	.001	.16	.15	<.001	.049
220-B	111	10.65	.18	.011	.007	.64	.077	9.22	.04	1.02	.04	<.01	.014	.04	<.001	<.001	.16	.14	<.001	.044
GTA Remelt																				
221-B	111	10.95	.16	.010	.006	.62	.068	9.40	.03	.99	.04	<.01	.013	.03	<.001	<.001	.15	.13	<.001	.044
GTA Remelt																				
222-B	124	11.04	.22	.010	.005	.70	.089	9.15	.03	.97	.05	.01	.015	.03	<.001	.003	.16	.12	<.001	.016
223-B	125	10.79	.22	.011	.005	.69	.083	9.19	.03	.97	.04	.01	.015	.03	<.001	.004	.16	.13	<.001	.033
224-B	126	11.15	.24	.010	.005	.71	.076	9.45	.03	1.00	.05	<.01	.015	.04	.0027	.001	.17	.14	<.001	.049
225-B	127	9.48	.01	.010	.008	.71	.055	8.97	.03	1.01	.02	<.01	.015	.03	<.001	.001	.11	.11	<.001	.044
226-B	126	11.76	.22	.010	.005	.70	.060	9.54	.04	1.00	.05	<.01	.015	.04	.0023	.001	.17	.13	<.001	.048
GTA Remelt																				

TABLE V

Delta Ferrite Determinations in 9 Cr SMA Weld Metal

Lot No.	Delta Ferrite Estimation By Chemical Analysis GE Cr Equivalent (1)	Delta Ferrite Present	Delta Ferrite % Estimation By Metallography
1	13.10	Yes	15 - 20
2	8.84	No	<1.0
7	9.78	No	<1.0
8	9.81	No	<1.0
9	15.21	Yes	25 - 30
10	12.54	Yes	10 - 15
11	12.09	Yes	25
12	12.81	Yes	25 - 30
13	13.48	Yes	20 - 25
14	13.37	Yes	20 - 25
15	13.40	Yes	20
16	13.83	Yes	25 - 30
17	14.93	Yes	20
18	15.83	Yes	25 - 30
19	12.38	Yes	1 - 5
20	12.22	Yes	15 - 20
21	12.31	Yes	15 - 20
22	10.59	Maybe	1 - 5
26	8.93	No	1 - 5
27	7.99	No	<1.0
30	7.68	No	<1.0
31	7.08	No	1 - 5
32	8.59	No	<1.0
33	10.51	Maybe	5-10
34	13.79	Yes	5-10
35	10.12	Maybe	1-5
36	8.98	No	1-5

(1) Cr Equivalent = %Cr + 6 X %Si + 4 X %Mo + 1.5 X %W + 11 X %V + 5 X %Cb + 8 X %Ti + 12 X % Al (Soluble) -40 X % C -2 X %Mn -4 X %Ni -2 X %Co -30 X %N_2 -%Cu

The Ti, Al, and Cu coefficients are from "Thielemann on Rupture Properties of Ferrous Alloys", ASTM Proceedings, Vol. 40, 1940.

TABLE VI

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
100-A	1	GV-WA	+80	9	10	.005
		WG	+100	15	20	.007
		WE	+130	33	35	.020
		WF	+150	30	35	.022
		WB	+180	56	80	.040
		WC	+212	60	85	.044
		WD	+280	89	95	.066
		WH	+320	92	99	.066
101-A	14	GW-WA	+80	7	10	.022
		WH	+130	22	35	.017
		WB	+180	26	40	.022
		WC	+240	40	60	.031
		WD	+300	42	60	.032
		WG	+350	64	95	.047
		WF	+400	77	100	.056
		WE	+500	72	100	.061
102-A	10	HR-WH	+60	8	0	.002
		WD	+100	12	10	.006
		WE	+140	17	20	.012
		WF	+160	26	30	.020
		WA	+180	52	50	.037
		WB	+212	79	60	.056
		WG	+260	84	95	.059
		WC	+300	93	99	.070
103-A	11	HS-WH	+60	8	5	.001
		WB	+150	17	5	.009
		WA	+212	25	20	.022
		WC	+250	32	30	.024
		WD	+300	50	60	.034
		WE	+350	88	100	.060
		WF	+400	86	100	.058

TABLE VI

Test Plate No.	Lot No.	Sample No	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
104-A	15	HT-WE	+80	9	5	.001
		WD	+140	19	30	.012
		WA	+180	30	40	.021
		WB	+212	34	50	.027
		WF	+250	43	55	.028
		WH	+265	65	80	.042
		WG	+280	78	95	.060
		WC	+300	67	95	.051
105-A	19	HU-WE	+40	13	15	.007
		WD	+80	19	35	.014
		WH	+120	28	50	.020
		WF	+140	41	60	.031
		WA	+180	57	70	.042
		WB	+212	61	80	.046
		WG	+260	75	99	.056
		WC	+300	81	100	.064
106-A	20	HV-WD	+80	8	10	.022
		WF	+140	16	30	.013
		WA	+180	38	40	.026
		WB	+212	47	50	.033
		WE	+240	48	75	.037
		WH	+260	68	85	.050
		WG	+280	74	95	.052
		WC	+300	85	99	.063
107-A	21	HW-WE	+40	8	10	.001
		WD	+100	14	30	.009
		WF	+140	26	40	.018
		WA	+180	32	50	.025
		WB	+212	65	80	.042
		WH	+240	77	90	.054
		WG	+260	89	99	.061
		WC	+300	93	100	.064

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
108-A	23	IC-WA	+100	6	0	.002
		WG	+160	10	0	.004
		WB	+212	23	25	.018
		WE	+240	33	35	.025
		WF	+270	51	60	.040
		WH	+285	59	80	.044
		WC	+300	78	90	.058
		WD	+350	83	100	.062
109-A	24	ID-WA	+100	6	0	.001
		WB	+212	20	20	.012
		WE	+240	41	40	.029
		WF	+270	67	90	.067
		WC	+300	72	99	.053
		WD	+350	71	100	.054
110-A	25	IE-WA	+100	3	0	.001
		WB	+212	15	20	.008
		WE	+240	28	30	.020
		WF	+270	47	50	.031
		WC	+300	58	70	.039
		WD	+350	70	100	.048
111-A	28	IP-WB	+150	9	0	.002
		WG	+180	19	5	.013
		WA	+212	27	20	.016
		WH	+230	21	10	.012
		WF	+250	72	80	.051
		WC	+300	68	80	.048
		WD	+350	83	100	.062
		WE	+400	87	100	.061
112-A	29	IR-WB	+150	6	0	.001
		WA	+212	10	5	.003
		WF	+250	27	20	.017
		WC	+300	53	70	.036
		WD	+350	54	90	.038
		WE	+400	77	100	.052

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
113-A	31	JI-WF	+100	18	0	.007
		WG	+140	29	30	.021
(Heavy Weave Beads)		WF	+160	40	60	.027
		WH	+180	59	80	.042
		WA	+212	62	90	.044
		WD	+250	69	95	.051
		WB	+300	74	100	.055
		WC	+350	75	100	.053
114-A	31	JJ-WF	+100	10	0	.004
		WE	+160	25	25	.017
		WG	+180	37	40	.029
		WA	+212	41	70	.032
		WD	+250	45	75	.038
		WH	+280	73	100	.056
		WB	+300	62	95	.045
		WC	+350	69	100	.052
115-A	23	JK-WF	+100	13	0	.004
		WE	+160	26	20	.018
		WG	+180	39	50	.029
		WA	+212	35	30	.023
		WH	+230	75	80	.051
		WD	+250	74	90	.055
		WB	+300	77	95	.057
		WC	+350	84	100	.062
116-A	28	JL-WF	+100	7	0	.001
		WE	+160	16	15	.008
		WG	+180	19	15	.012
		WA	+212	18	15	.011
		WH	+230	48	30	.030
		WD	+250	63	60	.042
		WB	+300	84	90	.054
		WC	+350	79	100	.051
117-A	26	JM-WF	+100	10	0	.002
		WD	+160	23	25	.016
		WG	+185	28	30	.021
		WA	+212	42	40	.030
		WB	+250	59	90	.042
		WC	+300	66	100	.050
		WE	+350	65	100	.054

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
118-A	27	JN-WF	+100	5	0	.001
		WD	+160	10	10	.003
		WG	+185	18	20	.008
		WA	+212	22	25	.011
		WB	+250	32	50	.026
		WC	+300	47	80	.036
		WE	+350	51	100	.038
119-A	32	JO-WF	+100	9	0	.003
		WD	+160	15	10	.006
		WG	+185	26	25	.013
		WA	+212	35	50	.017
		WB	+250	42	95	.028
		WC	+300	44	100	.029
		WF	+350	45	100	.033
120-B	7	JS-WC	+60	14	0	.002
		WB	+100	20	20	.010
		WG	+130	31	40	.024
		WD	+160	44	60	.027
		WH	+185	54	80	.040
		WA	+212	57	90	.039
		WE	+250	58	90	.040
		WF	+300	64	100	.050
121-B	8	JT-WC	+60	12	0	.004
		WB	+100	19	15	.009
		WG	+130	38	50	.030
		WD	+160	42	60	.029
		WH	+185	65	90	.043
		WA	+212	69	95	.048
		WE	+250	76	100	.056
		WF	+300	85	100	.058
123-B	39	KL-WH	+70	10	0	.004
		WG	+100	22	10	.012
		WF	+130	38	25	.026
		WD	+160	41	30	.028
		WC	+185	48	40	.034
		WA	+212	73	80	.049
		WB	+250	89	90	.058
		WE	+300	91	100	.060

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
124-B	41	KV-WH	+70	9	0	.007
		WG	+100	20	10	.010
		WF	+130	26	25	.019
		WC	+160	41	40	.034
		WE	+185	63	60	.046
		WA	+212	78	80	.059
		WB	+250	86	95	.065
		WD	+300	88	99	.066
125-B	42	KW-WH	+70	14	0	.012
		WG	+100	26	15	.020
		WF	+130	42	25	.033
		WC	+160	57	50	.042
		WE	+185	76	70	.059
		WA	+212	91	90	.066
		WB	+250	99	95	.069
		WD	+300	97	100	.072
127-B	43	KX-WH	+40	13	0	.007
		WG	+80	22	10	.018
		WF	+130	63	50	.046
		WC	+160	65	60	.048
		WE	+185	79	70	.056
		WA	+212	89	90	.060
		WB	+250	90	95	.063
		WD	+300	101	100	.076

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
128-B	45	LU-WE	+100	16	5	.017
		WF	+130	34	25	.028
		WD	+160	58	60	.046
		WG	+185	71	75	.058
		WH	+145	56	50	.044
		WB	+212	74	80	.060
		WA	+250	80	90	.062
		WC	+300	89	100	.068
129-B	10	LZ-WG	+70	10	0	.008
		WF	+110	18	10	.010
		WD	+160	32	30	.027
		WE	+185	49	40	.034
		WA	+212	70	60	.054
		WH	+225	87	95	.053
		WB	+250	74	80	.057
		WC	+300	101	100	.071
130-B	19	MA-WG	+70	20	5	.016
		WF	+110	24	15	.021
		WH	+135	68	50	.040
		WD	+160	47	40	.041
		WE	+185	82	70	.058
		WA	+212	90	80	.064
		WB	+250	99	100	.069
		WC	+300	104	100	.073
131-B	48	MB-WG	+70	10	0	.007
		WF	+110	28	15	.020
		WH	+135	52	40	.032
		WD	+160	30	25	.026
		WE	+185	70	60	.052
		WA	+212	73	70	.054
		WB	+250	94	100	.072
		WC	+300	96	100	.075
132-B	53	ML-WE	+100	21	5	.015
		WF	+130	44	30	.035
		WD	+160	50	35	.039
		WA	+212	66	80	.048
		WB	+250	80	95	.064
		WC	+300	82	99	.065

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
133-B	51	MS-WF	+70	22	5	.020
		WE	+100	31	20	.021
		WG	+130	36	20	.025
		WD	+160	59	60	.045
		WA	+212	57	80	.048
		WB	+250	65	85	.052
		WC	+300	78	100	.063
134-B	52	MT-WF	+70	18	5	.010
		WE	+100	19	10	.015
		WG	+130	33	30	.025
		WD	+160	58	70	.047
		WA	+212	71	85	.057
		WB	+250	65	95	.063
		WC	+300	86	99	.067
135-B	53	MU-WF	+70	16	5	.011
		WE	+100	29	15	.021
		WG	+130	63	50	.043
		WD	+160	80	80	.056
		WA	+212	92	95	.070
		WB	+250	98	100	.072
		WC	+300	104	100	.073
136-B	54	MV-WF	+70	16	5	.010
		WE	+100	17	5	.013
		WD	+160	30	30	.025
		WA	+212	40	60	.035
		WG	+230	43	50	.036
		WB	+250	65	95	.051
		WC	+300	69	100	.052
137-B	55	MW-WF	+70	12	0	.007
		WE	+100	16	10	.012
		WD	+160	32	30	.026
		WA	+212	34	60	.034
		WG	+230	51	70	.040
		WB	+250	57	90	.043
		WC	+300	66	100	.050

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
138-B	56	MX-WF	+70	9	0	.004
		WE	+100	18	10	.012
		WD	+160	38	40	.026
		WA	+212	46	70	.044
		WG	+230	52	70	.046
		WB	+250	65	80	.046
		WC	+300	72	99	.050
139-B	57	MY-WF	+70	7	0	.004
		WE	+100	13	5	.007
		WD	+160	29	25	.024
		WA	+212	36	70	.032
		WG	+230	41	70	.034
		WB	+250	60	85	.042
		WC	+300	65	90	.051
140-B	58	NR-WH	+60	13	0	.011
		WG	+100	24	20	.019
		WF	+140	35	30	.030
		WE	+180	56	70	.045
		WA	+212	52	60	.044
		WB	+250	68	80	.060
		WC	+300	59	70	.046
		WD	+350	85	100	.072
141-B	59	NS-WH	+60	14	0	.011
		WG	+100	18	15	.017
		WF	+140	37	30	.032
		WE	+180	50	40	.040
		WA	+212	57	70	.046
		WB	+250	69	80	.057
		WC	+300	71	90	.063
		WD	+350	83	100	.068
142-B	60	NU-WC	-40	6	0	.003
		WH	-15	12	0	.008
		WB	+10	72	35	.054
		WG	+30	88	60	.060
		WD	+60	94	70	.070
		WE	+100	109	85	.074
		WF	+140	112	100	.081
		WA	+212	124	100	.085

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
143-B	61	NV-WC	-40	16	0	.009
		WH	-15	31	15	.023
		WB	+10	62	30	.044
		WD	+60	30	20	.025
		WH	+80	96	60	.070
		WE	+100	108	70	.075
		WF	+140	113	80	.080
		WA	+212	104	100	.084
144-B	62	NX-WH	+70	30	15	.020
		WF	+100	19	10	.018
		WG	+130	49	30	.035
		WD	+160	62	50	.043
		WE	+185	68	80	.049
		WA	+212	83	90	.064
		WB	+250	86	99	.065
		WC	+300	85	99	.068
145-B	63	WY-WH	+70	51	25	.032
		WF	+100	39	20	.028
		WG	+130	60	50	.046
		WD	+160	40	30	.029
		WF	+185	69	70	.057
		WA	+212	77	80	.060
		WB	+250	88	95	.064
		WC	+300	89	100	.068
146-B	64	NZ-WG	+40	11	0	.004
		WA	+70	30	20	.020
		WE	+100	33	20	.021
		WH	+115	47	30	.029
		WF	+130	50	40	.032
		WB	+160	60	60	.045
		WC	+212	69	80	.052
		WD	+250	70	99	.055
147-B	65	OA-WG	+40	10	0	.004
		WA	+70	26	15	.017
		WE	+100	38	20	.026
		WH	+115	34	20	.020
		WF	+130	55	40	.035
		WB	+160	64	70	.046
		WC	+212	76	95	.061
		WD	+250	77	95	.058

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
148-B	66	OB-WG	+40	11	0	.003
		WA	+70	15	5	.009
		WE	+100	35	15	.024
		WH	+115	52	30	.034
		WF	+130	56	40	.038
		WB	+160	67	60	.045
		WC	+212	85	95	.063
		WD	+250	81	100	.062
149-B	43	PK-WE	+10	14	0	.006
		WC	+50	27	10	.018
		WA	+100	47	30	.032
		WH	+115	63	60	.043
		WG	+130	67	70	.046
		WF	+160	79	80	.054
		WB	+212	87	95	.066
		WD	+260	82	100	.065
150-B	68	PL-WE	+10	9	0	.003
		WC	+50	24	10	.015
		WA	+100	34	15	.023
		WG	+130	42	25	.029
		WH	+145	54	50	.037
		WF	+160	62	80	.042
		WB	+212	70	90	.054
		WD	+260	75	100	.058
151-B	69	PM-WE	+10	6	0	.001
		WC	+50	25	10	.016
		WA	+100	28	15	.018
		WF	+160	46	30	.033
		WG	+185	85	80	.060
		WB	+212	63	70	.048
		WD	+260	82	90	.056
		WH	+320	80	100	.059
152-B	70	PN-WC	+50	11	0	.006
		WA	+100	24	10	.016
		WF	+130	30	15	.021
		WG	+145	44	40	.033
		WE	+160	50	60	.040
		WB	+212	66	80	.051
		WD	+260	87	100	.065

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
153-B	71	PO-WC	+50	11	0	.005
		WH	+70	42	25	.031
		WA	+100	48	30	.034
		WG	+115	54	50	.039
		WF	+130	62	70	.047
		WE	+160	70	80	.051
		WB	+212	78	90	.055
		WD	+260	87	100	.059
154-B	72	PP-WC	+50	9	0	.004
		WA	+100	19	5	.011
		WF	+130	39	20	.026
		WG	+145	43	35	.032
		WE	+160	58	60	.041
		WB	+212	67	80	.050
		WD	+260	78	100	.063
155-B	73	RY-WG	+40	11	0	.009
		WF	+70	24	15	.021
		WA	+100	36	20	.031
		WH	+115	40	40	.034
		WE	+130	68	70	.054
		WB	+160	70	80	.058
		WC	+212	79	95	.065
		WD	+250	82	100	.073
156-B	74	RZ-WG	+40	11	0	.008
		WF	+70	33	20	.026
		WA	+100	40	25	.036
		WE	+130	52	50	.044
		WH	+145	61	70	.051
		WB	+160	69	80	.054
		WC	+212	79	95	.064
		WD	+250	80	100	.066
157-B	75	SA-WF	+40	12	5	.010
		WG	+55	26	20	.019
		WE	+70	38	40	.031
		WA	+100	44	80	.034
		WB	+160	50	90	.042
		WC	+212	61	95	.051
		WD	+250	60	100	.052

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
158-B	76	SB-WE	+40	15	5	.012
		WF	+55	31	30	.024
		WD	+70	41	60	.032
		WA	+100	52	90	.042
		WB	+160	54	90	.045
		WC	+212	60	100	.050
159-B	77	SC-WF	+40	11	0	.007
		WE	+70	15	20	.013
		WA	+100	36	40	.026
		WB	+160	44	70	.034
		WG	+185	56	80	.042
		WC	+212	57	95	.052
		WD	+250	59	100	.050
160-B	78	SD-WG	+40	13	0	.008
		WH	+55	17	10	.010
		WF	+70	32	30	.024
		WA	+100	37	60	.031
		WE	+130	41	60	.033
		WB	+160	49	80	.037
		WC	+212	54	95	.049
		WD	+250	60	100	.052
161-B	79	SE-WG	+70	9	0	.007
		WA	+100	11	5	.006
		WF	+130	23	15	.022
		WB	+160	40	20	.029
		WC	+212	47	60	.041
		WD	+250	63	90	.051
		WE	+300	70	100	.059
162-B	80	SF-WF	+70	13	5	.009
		WA	+100	16	10	.010
		WE	+130	37	25	.028
		WB	+160	41	30	.032
		WG	+185	58	60	.043
		WC	+212	66	80	.051
		WD	+250	68	100	.055

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
163-B	81	SG-WC	+40	10	0	.004
		WB	+70	42	20	.025
		WF	+100	44	40	.036
		WG	+130	80	60	.051
		WE	+160	88	70	.054
		WA	+212	100	95	.068
		WD	+250	106	100	.072
164-B	82	SH-WC	+40	8	0	.003
		WB	+70	14	5	.006
		WF	+100	21	10	.015
		WH	+130	68	50	.041
		WE	+160	48	40	.033
		WG	+185	90	80	.060
		WA	+212	94	90	.064
		WD	+250	101	100	.066
165-B	83-1	TJ-WD	-60	3	0	.001
		WC	-20	7	10	.004
		WE	0	11	25	.008
		WF	+20	12	30	.009
		WG	+30	24	45	.015
		WB	+40	44	75	.036
		WA	+100	54	99	.046
166-B	83-2	TK-WE	-20	4	<5	.002
		WF	+20	10	20	.007
		WG	+50	29	40	.021
		WD	+70	33	80	.028
		WH	+80	39	35	.021
		WA	+100	35	80	.031
		WB	+160	57	90	.044
		WC	+212	66	98	.057
167-B	83-3	TL-WC	+40	8	5	.002
		WE	+70	24	30	.018
		WA	+100	25	40	.019
		WF	+130	30	70	.025
		WB	+160	47	90	.038
		WD	+212	49	99	.043

TABLE VI (cont.'d)

9%Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft-Lbs	% Shear Fracture	Mil Lateral Expansion
168-B	84	TM-WD	-20	2	0	.001
		WC	+40	17	35	.012
		WF	+70	12	20	.007
		WA	+100	27	60	.022
		WB	+160	48	80	.042
		WE	+212	55	95	.048
169-B	85	TN-WD	-20	7	0	.001
		WC	+40	60	35	.040
		WE	+70	66	40	.049
		WG	+80	64	50	.053
		WF	+90	86	80	.059
		WA	+100	88	95	.060
		WB	+140	99	95	.073
170-B	87	UD-WA	+70	9	0	.005
		WB	+100	31	20	.024
		WD	+130	47	50	.034
		WC	+160	56	70	.041
		WE	+212	60	90	.048
		WF	+250	64	100	.053
171-B	88	UE-WD	+40	7	0	.003
		WA	+70	32	20	.023
		WB	+100	40	40	.029
		WE	+130	44	60	.032
		WC	+160	57	80	.045
		WF	+212	63	95	.049
		WG	+250	65	100	.055

TABLE VI (cont.'d)

9%Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft-Lbs	% Shear Fracture	Mil Lateral Expansion
172-B	89	UF-WA	+70	11	0	.007
		WB	+100	21	15	.015
		WD	+130	30	40	.026
		WC	+160	45	60	.034
		WE	+212	49	80	.039
		WF	+250	54	100	.048
173-B	90	UG-WF	+10	10	0	.006
		WD	+40	19	10	.013
		WA	+70	24	20	.018
		WB	+100	43	40	.030
		WE	+130	54	60	.042
		WC	+160	61	80	.048
		WG	+212	67	95	.058
		WH	+250	69	100	.060
176-B	94	UK-WF	+10	14	0	.008
		WD	+40	35	20	.024
		WA	+70	36	20	.028
		WB	+100	64	50	.047
		WE	+130	77	70	.060
		WC	+160	95	90	.076
		WG	+212	98	100	.079
		WH	+250	99	100	.081
177-B	95	UL-WD	+40	18	5	.010
		WH	+55	56	40	.042
		WA	+70	66	50	.046
		WB	+100	71	60	.052
		WE	+130	74	70	.061
		WC	+160	92	90	.068
		WF	+212	95	95	.070
		WG	+250	98	100	.071

TABLE VI (cont.'d)

9%Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft-Lbs	% Shear Fracture	Mil Lateral Expansion
178-B	95	VL-WB	+40	16	5	.011
		WG	+55	46	30	.034
		WA	+70	60	50	.051
		WC	+100	67	60	.053
		WH	+130	80	90	.065
		WD	+160	86	90	.068
		WE	+212	93	100	.071
		WF	+250	95	100	.072
179-B	98	VM-WB	+40	20	5	.015
		WG	+55	30	20	.021
		WA	+70	43	30	.030
		WC	+100	54	50	.041
		WH	+130	65	80	.055
		WD	+160	78	80	.059
		WE	+212	83	100	.069
		WF	+250	87	100	.072
180-B	99	VN-WA	+70	12	0	.007
		WB	+100	13	0	.009
		WH	+115	29	20	.023
		WF	+130	45	40	.038
		WC	+160	52	50	.040
		WG	+185	76	70	.055
		WD	+212	84	90	.062
		WE	+250	86	100	.066
181-B	100	VO-WB	+40	15	5	.009
		WG	+55	48	30	.033
		WA	+70	64	50	.050
		WC	+100	66	60	.052
		WH	+130	81	80	.063
		WD	+160	88	90	.066
		WE	+212	91	95	.068
		WF	+250	99	100	.076

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
182-B	101	XW-WF	0	10	0	.004
		WG	+25	50	25	.038
		WE	+50	51	25	.041
		WH	+75	70	40	.052
		WA	+100	60	30	.046
		WB	+160	91	70	.066
		WC	+212	97	90	.071
		WD	+300	115	100	.085
183-B	102	XX-WG	+25	8	0	.005
		XX-WE	+50	21	5	.014
		WF	+75	49	25	.040
		WA	+100	66	40	.049
		WH	+130	70	70	.061
		WB	+160	84	80	.062
		WC	+212	99	90	.074
		WD	+300	103	100	.079
184-B	103	XY-WE	+50	11	0	.008
		WF	+75	24	10	.018
		WA	+100	52	30	.042
		WG	+130	81	60	.056
		WB	+160	61	50	.049
		WH	+185	75	80	.055
		WC	+212	88	80	.066
		WD	+300	91	100	.069
185-B	104	XZ-WG	+25	36	20	.026
		WE	+50	20	10	.017
		WF	+75	69	70	.054
		WA	+100	62	70	.053
		WH	+130	90	90	.065
		WB	+160	81	90	.064
		WC	+212	89	95	.070
		WD	+300	94	100	.074
186-B	105	YA-WF	0	8	0	.004
		WG	+25	24	10	.018
		WE	+50	61	50	.046
		WH	+75	56	50	.045
		WA	+100	65	60	.051
		WB	+160	82	90	.064
		WC	+212	86	95	.065
		WD	+300	94	100	.070

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
187-B	85A	ZA-WB	+40	18	0	.007
		WA	+75	32	20	.020
		WF	+90	43	40	.031
		WC	+110	109	60	.065
		WD	+150	126	80	.069
		WE	+212	150	100	.083
189-B	85A	DH-WB	+40	20	5	.007
		WA	+75	35	20	.020
		WF	+90	76	50	.047
		WC	+110	68	40	.042
		WG	+130	122	90	.068
		WD	+150	109	90	.062
		WE	+212	120	100	.073
190-B	95B	DI- WA	+75	15	5	.004
		WB	+110	28	15	.016
		WE	+130	43	30	.028
		WC	+150	67	50	.043
		WG	+180	88	80	.057
		WD	+212	98	90	.064
		WF	+280	102	100	.068
191-B	111	IM- WG	+20	11	0	.006
		WE	+60	21	5	.016
		WF	+80	55	40	.040
		WA	+100	58	35	.042
		WH	+130	84	80	.057
		WB	+160	69	70	.054
		WC	+212	91	95	.072
		WD	+300	85	100	.069
192-B	111	IN- WF	+20	34	10	.023
		WE	+60	47	20	.032
		WG	+80	74	60	.054
		WA	+100	70	50	.052
		WH	+130	82	70	.058
		WB	+160	86	90	.063
		WC	+212	92	95	.067
		WD	+300	101	100	.077

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
193-B	111	IO- WF	+20	8	0	.003
		WE	+60	13	0	.006
		WG	+80	50	30	.034
		WA	+100	71	60	.053
		WH	+130	53	50	.041
		WB	+160	87	80	.063
		WC	+212	99	100	.078
		WD	+300	98	100	.076
194-B	111	IP - WF	+20	11	0	.005
		WE	+60	35	15	.024
		WG	+80	31	10	.019
		WA	+100	55	30	.041
		WH	+130	67	60	.044
		WB	+160	71	60	.055
		WC	+212	93	95	.074
		WD	+300	94	100	.077
195-B	111	IQ - WF	+20	17	0	.008
		WE	+60	44	20	.030
		WG	+80	66	50	.050
		WA	+100	64	40	.044
		WH	+130	92	80	.067
		WB	+160	91	80	.064
		WC	+212	106	90	.080
		WD	+300	106	100	.078
196-B	109	JH- WG	0	6	0	.002
		WH	+20	8	0	.004
		WF	+40	50	25	.034
		WE	+70	56	30	.041
		WA	+100	78	60	.056
		WD	+130	81	80	.061
		WB	+160	90	95	.074
		WC	+212	91	99	.072

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
197-B	109	JI-WG	+40	12	0	.009
		WH	+60	66	50	.053
		WE	+70	28	10	.020
		WF	+85	63	40	.050
		WA	+100	74	60	.055
		WD	+130	84	80	.062
		WB	+160	93	90	.069
		WC	+212	99	99	.075
198-B	109	JJ-WH	0	7	0	.002
		WG	+40	44	25	.029
		WE	+70	32	30	.025
		WF	+85	53	40	.042
		WA	+100	68	60	.050
		WD	+130	80	70	.063
		WB	+160	93	90	.066
		WC	+212	99	99	.078
199-B	109	JK-WG	0	19	0	.013
		WH	+20	40	25	.026
		WF	+40	50	30	.036
		WE	+70	66	50	.043
		WA	+100	75	70	.053
		WD	+130	85	90	.064
		WB	+160	86	95	.066
		WC	+212	97	99	.076
200-B	109	JL-WG	0	9	0	.004
		WF	+40	21	10	.019
		WE	+70	38	40	.033
		WA	+100	48	70	.043
		WD	+130	82	80	.040
		WB	+160	79	90	.060
		WC	+212	94	99	.075
201-B	113	KN-WG	+40	9	0	.002
		WF	+70	29	20	.021
		WA	+100	26	30	.019
		WH	+115	59	50	.044
		WE	+130	66	60	.051
		WB	+160	69	70	.057
		WC	+212	84	95	.062
		WD	+300	89	100	.069

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
202-B	111	LG-WC	+20	12	5	.006
		WF	+70	48	30	.034
		WA	+100	40	25	.026
		WE	+130	63	60	.046
		WB	+160	71	80	.050
		WG	+212	90	100	.066
		WD	+300	81	100	.062
203-B	111	LH-WG	+20	7	0	.006
		WF	+70	45	35	.033
		WA	+100	46	30	.033
		WE	+130	68	70	.045
		WB	+160	78	80	.051
		WC	+212	94	90	.069
		WD	+300	95	100	.068
204-B	111	LI-WF	+70	15	5	.010
		WA	+100	18	5	.010
		WE	+130	48	50	.035
		WB	+160	56	60	.038
		WC	+212	69	90	.055
		WD	+300	80	100	.065
205-B	113	LY-WG	+20	11	5	.005
		WF	+70	52	35	.033
		WA	+100	58	40	.036
		WE	+130	70	60	.049
		WB	+160	80	80	.055
		WC	+212	100	100	.076
		WD	+300	100	100	.072
206-B	GTAW	PO-WG	+40	23	5	.014
		WE	+60	>240	100	.073
		WA	+60	>240	100	.075
		WF	+70	79	30	.045
		WD	+80	98	60	.048
		WB	+100	105	50	.035
		WC	+160	>240	100	.079

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
207-B	GTAW	PR-WG	+40	15	0	.009
		WA	+60	22	5	.012
		WE	+60	34	10	.021
		WF	+70	>240	100	.072
		WD	+80	>240	100	.076
		WB	+100	>240	100	.074
		WC	+160	>240	100	.080
208-B	115	TG-WG	+40	17	5	.011
		WA	+60	21	0	.017
		WB	+100	34	30	.025
		WF	+130	97	70	.066
		WC	+160	94	70	.070
		WD	+212	103	90	.075
		WE	+250	114	100	.082
209-B	109	No impacts - to be used for creep samples.				
210-B	109	No impacts - to be used for creep samples.				
211-B	111	No impacts - to be used for creep samples.				
212-B	111	No impacts - to be used for creep samples.				
213-B	109	No impacts - to be used for .505 tensiles.				
214-B	111	No impacts - to be used for .505 tensiles.				
215-B	120	VZ-WA	0	3	0	.001
		WE	+60	11	0	.004
		WB	+100	25	10	.020
		WH	+130	34	25	.026
		WC	+160	95	80	.059
		WD	+212	92	90	.056
		WF	+350	100	100	.077
		WG	+500	108	100	.077
216-B	121	WA-WA	0	9	0	.004
		WE	+60	9	0	.004
		WB	+100	17	5	.010
		WC	+160	20	10	.015
		WD	+212	32	20	.029
		WG	+280	37	30	.033
		WF	+350	74	90	.059
		WH	+500	71	100	.067

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft.-Lbs.	% Shear Fracture	Mil Lateral Expansion
217-B	111	WO-WH	0	7	0	.001
		WF	+60	48	30	.031
		WA	+100	46	30	.035
		WG	+130	79	70	.057
		WB	+160	83	80	.054
		WD	+212	95	99	.067
		WC	+250	93	99	.067
		WE	+300	101	100	.070
218-B	123	WP-WF	+60	7	0	.002
		WA	+100	10	0	.004
		WG	+130	24	20	.013
		WB	+160	42	40	.032
		WD	+212	56	60	.041
		WC	+250	73	80	.052
		WE	+300	90	100	.068
		WH	+400	99	100	.065
219-B	111	WR-WF	+60	27	20	.015
		WA	+100	59	40	.040
		WG	+130	64	60	.046
		WB	+160	77	80	.058
		WD	+212	84	95	.060
		WC	+250	88	100	.066
		WE	+300	94	100	.071
		WH	+400	90	100	.069
220-B	111	LN-WE	0	14	5	.013
	GTA Remelt	WG	+30	38	20	.031
		WF	+40	27	20	.023
		WH	+50	79	70	.056
		WD	+60	77	60	.055
		WA	+100	88	70	.063
		WB	+160	96	95	.072
		WC	+212	104	100	.078
221-B	111	LO-WE	0	8	0	.008
	GTA Remelt	WD	+60	30	30	.028
		WH	+60	68	60	.052
		WG	+70	79	60	.060
		WF	+80	85	70	.064
		WA	+100	79	60	.059
		WB	+160	94	95	.072
		WC	+212	95	100	.074

TABLE VI (cont.'d)

9% Cr Shielded Metal Arc Weld Deposits

Test Plate No.	Lot No.	Sample No.	Test Temp. °F	Energy Absorption Ft-Lbs	% Shear Fracture	Mil Lateral Expansion
222-B	124	PO-WE	+50	11	0	.007
		WF	+75	36	20	.024
		WA	+100	48	50	.036
		WB	+160	53	60	.043
		WG	+175	88	80	.067
		WD	+190	90	90	.067
		WC	+212	94	90	.064
		WH	+250	90	95	.070
223-B	125	PP-WE	0	8	0	.002
		WH	+20	10	0	.003
		WG	+35	20	5	.016
		WD	+50	66	40	.044
		WF	+75	76	60	.053
		WA	+100	83	70	.066
		WB	+160	102	95	.071
		WC	+212	106	100	.076
224-B	126	PR-WD	+50	13	0	.007
		WG	+75	21	10	.017
		WA	+100	37	25	.027
		WE	+130	49	60	.034
		WB	+160	71	70	.055
		WH	+190	80	90	.059
		WC	+212	83	95	.068
		WF	+250	87	100	.070
225-B	127	PS-WD	+70	14	5	.012
		WA	+100	16	10	.013
		WE	+130	24	20	.018
		WB	+160	31	30	.025
		WH	+190	31	30	.032
		WC	+212	46	60	.036
		WF	+250	51	90	.045
		WG	+300	53	90	.049
226-B	126	RA-WD	+50	26	5	.018
	GTA Remelt	WH	+100	59	40	.040
		WF	+115	82	85	.058
		WE	+130	74	85	.055
		WB	+160	87	90	.063
		WC	+212	92	95	.066
		WG	+250	106	100	.078

TABLE VII

SUMMARY OF CHARPY V-NOTCH IMPACT RESULTS

Plate No.	Lot No.	Hardness HV50	Hardness HRC	Transition Temperature, °F: 50 Ft.-Lbs.	Transition Temperature, °F: 35 Mil Lateral Expansion	Transition Temperature, °F: 100% Shear FATT	Upper Energy Shelf (Ft.-Lbs.)
100-A	1	258	23.7	168	162	300	92
101-A	14	270	25.4	328	317	400	74
102-A	10	261	24.1	168	178	280	92
103-A	11	261	24.0	300	302	350	86
104-A	15	266	24.8	254	260	320	78
105-A	19	268	25.2	150	148	280	74
106-A	20	265	24.6	248	224	300	85
107-A	21	265	24.6	206	210	280	92
108-A	23	297	29.1	268	262	320	84
109-A	24	284	27.5	246	260	280	72
110-A	25	294	28.8	278	284	350	70
111-A	28	286	27.7	232	232	350	87
112-A	29	289	28.1	294	298	400	77
113-A	31	244	21.3	182	178	300	74
114-A	31	253	22.8	272	224	350	69
115-A	23	259	23.8	234	234	350	82
116-A	28	272	25.7	248	246	300	84
117-A	26	252	22.7	226	228	300	66
118-A	27	292	28.5	320	288	350	51
119-A	32	299	29.4	*	*	280	45
120-B	7	278	26.6	178	178	280	64
121-B	8	278	26.5	176	172	280	85
123-B	39	251	22.6	187	187	260	91
125-B	41	250	22.4	173	162	300	88
126-B	42	236	20.0	143	139	250	99
127-B	43	243	20.9	135	112	300	101

*Did not attain these impact conditions.

TABLE VII (cont.'d)
SUMMARY OF CHARPY V-NOTCH IMPACT RESULTS

Plate No.	Lot No.	Hardness HV50	Hardness HRB	Transition Temperature, °F 50 Ft.-Lbs.	Transition Temperature, °F 35 Mil Lateral Expansion	Transition Temperature, °F 100% Shear FATT	Upper Energy Shelf (Ft.-Lbs.)
128-B	45	234	97.2	140	135	300	89
129-B	10	245	98.8	186	186	280	101
130-B	19	236	97.6	145	150	250	104
131-B	48	243	98.5	150	148	250	96
132-B	53	262	24.1 HRC	160	132	260	82
133-B	51	218	94.7	174	150	300	78
134-B	52	216	94.3	144	146	280	86
135-B	53	242	98.3	122	120	240	104
136-B	54	225	95.8	240	212	280	69
137-B	55	229	96.5	228	218	300	66
138-B	56	223	95.4	240	188	300	72
139-B	57	221	95.1	258	255	350	65
140-B	58	219	94.9	171	155	350	85
141-B	59	234	97.2	180	150	350	83
142-B	60	199	91.3	6	0	140	124
143-B	61	203	92.1	2	0	212	113
144-B	62	244	98.4	132	130	250	86
145-B	63	240	98.0	111	110	270	89
146-B	64	254	23.0 HRC	130	133	250	70
147-B	65	244	98.6	122	130	220	77
148-B	66	248	99.2	110	118	230	85
149-B	43	248	99.3	104	110	230	87
150-B	68	239	98.0	142	142	260	75
151-B	69	238	97.8	170	166	280	82
152-B	70	244	98.6	160	148	260	87
153-B	71	237	97.6	90	106	260	87
154-B	72	254	23.0 HRC	156	150	260	78
155-B	73	217	94.5	122	115	220	80
156-B	74	218	94.6	130	96	220	80
157-B	75	233	96.9	160	122	210	61
158-B	76	239	97.8	92	78	165	60
159-B	77	250	99.5	178	166	220	59
160-B	78	246	98.9	164	148	250	60
161-B	79	256	23.2 HRC	194	190	280	70
162-B	80	244	98.6	180	170	250	68
163-B	81	241	98.2	116	110	230	106
164-B	82	239	97.9	144	126	250	101
165-B	83-1	231	96.8	56	40	100	54
166-B	83-2	220	95.1	123	110	210	66
167-B	83-3	228	96.3	*	152	216	49
168-B	84	217	94.5	168	138	228	55
169-B	85	228	96.3	38	26	120	99

*Did not attain 50 ft/lbs.

TABLE VII (cont.'d)

SUMMARY OF CHARPY V-NOTCH IMPACT RESULTS

Plate No.	Lot No.	Hardness HV50	Hardness HRB	Transition Temperature, °F 50 Ft.-Lbs.	35 Mil Lateral Expansion	100% Shear FATT	Upper Energy Shelf (Ft.-Lbs.)
170-B	87	235	97.1	140	134	250	64
171-B	88	245	98.8	148	140	250	65
172-B	89	242	98.4	220	168	250	54
173-B	90	232	96.8	116	110	250	69
176-B	94	217	94.5	85	84	180	99
177-B	95	217	94.5	60	60	200	98
178-B	97	212	93.7	58	56	200	95
179-B	98	231	96.8	86	80	190	87
180-B	99	245	98.8	140	126	250	86
181-B	100	230	96.6	58	58	250	99
182-B	101	220	95.0	48	20	300	115
183-B	102	223	95.5	77	72	300	103
184-B	103	220	94.9	120	92	300	91
185-B	104	208	92.9	72	60	250	94
186-B	105	210	93.3	64	50	250	94
187-B	85A	239	97.9	92	94	212	150
189-B	85A	245	98.8	87	95	190	125
190-B	95B	254	23.1 HRC	137	138	250	102
191-B	111	220	95.0	75	85	300	85
192-B	111	223	95.5	63	65	300	101
193-B	111	225	95.7	80	81	300	98
194-B	111	221	95.1	89	84	250	94
195-B	111	221	95.1	65	70	220	106
196-B	109	209	93.1	66	64	160	91
197-B	109	208	92.8	76	72	220	99
198-B	109	209	93.1	82	74	220	99
199-B	109	212	93.6	42	42	220	97
200-B	109	222	95.2	84	72	220	94
201-B	113	233	97.0	101	104	280	89
202-B	111	229	96.5	113	110	240	91
203-B	111	225	95.7	105	107	220	95
204-B	111	232	97.0	137	153	300	80
205-B	113	240	98.0	89	99	220	100
206-B	GTAW	195	90.1	55	59	140	>240
207-B	GTAW	200	91.2	65	68	70	>240
208-B	115	236	97.5	117	112	250	114
209-B	109	209	93.1	To be used for creep samples.			
210-B	109	209	93.1	To be used for creep samples.			
211-B	111	225	95.7	To be used for creep samples.			
212-B	111	227	96.1	To be used for creep samples.			
213-B	109	220	95.0	To be used for 505 Tensiles.			
214-B	111	231	96.7	To be used for 505 Tensiles.			

TABLE VII (cont.'d)

SUMMARY OF CHARPY V-NOTCH IMPACT RESULTS

Plate No.	Lot No.	Hardness HV50	Hardness HRB	Transition Temperature, °F: 50 Ft.-Lbs.	Transition Temperature, °F: 35 Mil Lateral Expansion	Transition Temperature, °F: 100% Shear FATT	Upper Energy Shelf (Ft.-Lbs.)
215-B	120	208	92.7	152	132	200	100
216-B	121	180	86.6	293	240	350	74
217-B	111	178	86.6	100	92	200	101
218-B	123	185	88.3	178	170	300	99
219-B	111	183	88.0	102	87	200	94
220-B	111 GTA Remelt	233	97.0	40	42	200	104
221-B	111 GTA Remelt	226	96.0	57	53	200	95
222-B	124	208	93.0	103	98	200	94
223-B	125	218	94.6	40	45	160	106
224-B	126	227	96.1	124	126	220	87
225-B	127	196	90.6	240	208	250	53
226-B	126 GTA Remelt	229	96.4	95	98	250	100

TABLE VIII

Weld Metal Composition Ranges

Plates 100-226	Content, wt %		Plates 100-226	Content, wt %	
Element	Min.	Max.	Element	Min.	Max.
C	0.026	0.14	Co	0.008	0.021
Cr	8.37	9.95	N_2	0.008	0.069
Mo	0.78	1.90	Sol Al	<0.001	0.010
W	<0.01	0.83	B	<0.001	0.009
V	0.02	0.38	Zr	<0.001	0.007
Nb	0.01	0.18	Mn	0.26	0.94
Ti	<0.01	0.07	Si	0.01	1.32
Ni	<0.01	1.14	P	0.005	0.014
Cu	0.01	0.05	S	0.006	0.014

120 plates tested in Charpy

TABLE IX

CVN RESULTS FOR LOT 111

Welding Conditions	Transition Temp. (° F) 50 ft-lbs	35 mils Lateral Expansion	100% Shear FATT	Upper Energy Shelf (ft-lbs)
Standard Weave	75	85	300	85
Stringer Bead	63	65	300	101
40 amps + 195 amps @ 5 kHz Background	80	81	300	98
40 amps + 195 amps @ 10 kHz Background	89	84	250	94
40 amps + 195 amps @ 15 kHz Background	65	70	220	106
40 amps + 195 amps @ 17 kHz Background	105	107	220	95
40 amps + 195 amps @ 20 kHz Background	137	153	300	80
115 amps+ 120 amps @ 10 kHz Background	100	92	200	101
100 amps + 135 amps @ 15 kHz Background	102	87	200	94
5/32" dia., Weave	101	104	280	89
5/32" dia., Stringer	89	99	220	100
Alloyed Core	117	112	250	114
GTA Remelt @ 61 KJ/in	40	42	200	104
GTA Remelt @ 40.5 KJ/in	57	53	200	95
Standard Weave with 0.33% N_2	40	45	160	106

Nominal Composition	C	Cr	Mo	V	W	Cb	N_2	HRB
	.075	9	1	.16	.14	.04	.05	.95

SECTION VI

CREEP AND STRESS RUPTURE TESTING

B. W. Roberts

LIST OF FIGURES

Figure No.		Page
1	Comparison of Air and Argon Tests on Heat ESR XA 3218 at a Stress of 28 ksi and Temperature of 1100° F	175
2	Comparison of Air and Argon Tests on Heat 91887 at a Stress of 28 ksi and Temperature of 1100° F	176
3	Comparison of Air and Argon Tests on Heat ESR XA 3218 at a Stress of 24 ksi and Temperature of 1100° F	177
4	Comparison of Air and Argon Tests on Heat 91887 at a Stress of 24 ksi and Temperature of 1100° F	178
5	Larson Miller Correlation of Timken Modified 9Cr-1Mo Steel Alloys	179
6	Larson Miller Correlation of Heat 91887	180
7	Larson Miller Correlation of Heat ESR XA 3218	181
8	Larson Miller Correlation of Heat ESR XA 3177 Tested in Air	182
9	Larson Miller Correlation of Weld SMA 109 Tested in Air	183
10	Larson Miller Correlation of Weld SMA 111 Tested in Air	184
11	Comparison of Five Heats of Modified 9Cr-1Mo Steel Tested in Air at a Stress of 28 ksi and Temperature of 1100° F to Rupture	185
12	Comparison of Five Heats of Modified 9Cr-1Mo Steel Tested in Air at a Stress of 28 ksi and Temperature of 1100° F during Initial 5 Percent Strain	186
13	Minimum Tensile and Yield Strength for the Class of Material	187
14	Larson Miller Correlation of Time-to-Rupture for Class of Material	188
15	Larson Miller Correlation of Time to 0.2 Percent Tertiary for Class of Material	189
16	Larson Miller Correlation of Secondary Creep Rate for Class of Material	190

LIST OF FIGURES (cont.'d)

Figure No.		Page
17	Larson Miller Correlation of Time to 0.1 Percent Total Strain for Class of Material	191
18	Larson Miller Correlation of Time-to-Rupture for Heat 91887	192
19	Larson Miller Correlation of Time to 0.2 Percent Tertiary for Heat 91887	193
20	Larson Miller Correlation of Secondary Creep Rate for Heat 91887	194
21	Larson Miller Correlation of Time to 1.0 Percent Total Strain for Heat 91887	195
22	Stress Intensity S_o as a Function of Temperature for Class of Material and Heat 91887	196
23	Stress Intensities S_m and S_t for Class of Material	197
24	Stress Intensities S_m and S_t for Heat 91887	198

LIST OF TABLES

Table No.		Page
1	Summary of Timken Data for Parameter Analysis	199
2	Creep and Stress Rupture Results for Heat 91887	201
3	Creep and Stress Rupture Results for Heat ESR XA 3218	202
4	Creep and Stress Rupture Results for Heat ESR XA 3177	203
5	Creep and Stress Rupture Results for Weld SMA 109	204
6	Creep and Stress Rupture Results for Weld SMA 111	205
7	Tensile and Yield Strength Summary for Class of Material	206

LIST OF TABLES (cont.'d)

Table No.		Page
8	Estimates of Minimum Tensile and Yield Strength Between 70 and 900° F (21 and 482° C)	207
9	Values of the Equation Constants in the Larson Miller Curve-Fits for Class of Material	208
10	Expected Values of Stress-to-Rupture for Class of Material from Larson Miller Analysis	209
11	Minimum Values of Stress-to-Rupture for Class of Material from Larson Miller Analysis	210
12	Expected Values of 0.2 Percent Tertiary for Class of Material from Larson Miller Analysis	211
13	Minimum Values of 0.2 Percent Tertiary for Class of Material from Larson Miller Analysis	212
14	Expected Values for Secondary Creep Rate for Class of Materials from Larson Miller Analysis	213
15	Minimum Values of Secondary Creep Rate for Class of Materials from Larson Miller Analysis	214
16	Expected Values of 1 Percent Total Strain for Class of Material from Larson Miller Analysis	215
17	Minimum Values of 1 Percent Total Strain for Class of Material from Larson Miller Analysis	216
18	Raw Data Used in Analysis of Rupture for Class of Material	217
19	Raw Data Used in Analysis of 0.2 Percent Tertiary for Class of Material	219
20	Raw Data Used in Analysis of Secondary Creep Rate for Class of Material	220
21	Raw Data Used in Analysis of One Percent Total Strain for Class of Material	221
22	Comparison of Minimum Tensile and Yield Strengths for Heat 91887 and Class of Material	222
23	Values of the Equation Constants in the Larson Miller Curve-Fits for Heat 91887	223

LIST OF TABLES (cont.'d)

Table No.		Page
24	Expected Values of Stress-to-Rupture for Heat 91887 from Larson Miller Analysis	224
25	Minimum Values of Stress-to-Rupture for Heat 91887 from Larson Miller Analysis	225
26	Expected Values of 0.2 Percent Tertiary for Heat 91887 from Larson Miller Analysis	226
27	Minimum Values of 0.2 Percent Tertiary for Heat 91887 from Larson Miller Analysis	227
28	Expected Values for Secondary Creep Rate for Heat 91887 from Larson Miller Analysis	228
29	Minimum Values for Secondary Creep Rate for Heat 91887 from Larson Miller Analysis	229
30	Expected Values of 1 Percent Total Strain for Heat 91887 from Larson Miller Analysis	230
31	Minimum Values of 1 Percent Total Strain for Heat 91887 from Larson Miller Analysis	231
32	Raw Data Used in Analysis of Rupture for Heat 91887	232
33	Raw Data Used in Analysis of 0.2 Percent Tertiary for Heat 91887	233
34	Raw Data Used in Analysis of Secondary Creep Data for Heat 91887	234
35	Raw Data Used in Analysis of One Percent Total Strain for Heat 91887	235
36	Stress Intensity S_o for Class of Material	236
37	Stress Intensity S_o for Heat 91887	237
38	Stress Intensity S_m for Class of Material and Heat 91887	238
39	Stress Intensity S_t for Class of Material and Heat 91887	239
40	Stress Intensity S_t for Class of Material and Heat 91887	240
41	Stress Intensity S_t for Class of Material and Heat 91887	241
42	Stress Intensity S_t for Class of Material and Heat 91887	242
43	Stress Intensity S_t for Class of Material and Heat 91887	243

LIST OF TABLES (cont.'d)

Table No.		Page
44	Stress Intensity S_t for Class of Material and Heat 91887	244
45	Stress Intensity S_t for Class of Material and Heat 91887	245
46	Stress Intensity S_{mt} for Class of Material	246
47	Stress Intensity S_{mt} for Heat 91887	247
48	Stress Intensity S_{mt} for Heat 91887 with Analysis Using Less Conservative Larson Miller Constant	248

VI. CREEP AND STRESS RUPTURE TESTING - B. W. Roberts

A. Introduction

Creep tests have been performed on three base metal and two weld metal heats. A total of 42 creep tests have been completed and 6 are presently in test. Four of the tests were run in argon to evaluate the effect of a non-oxidizing atmosphere.

Parametric analysis of a similar alloy developed by Timken provided a convenient basis for comparison with the C-E alloys. Stresses needed for ASME Code Case 1592 were developed for the "class of material" and for the most favorable C-E composition (Heat No. 91887). From these stresses and the appropriate design factors, values of So, Sm, Sy, St, and Smt were calculated for both the class and the most favorable alloy.

B. Experimental Procedure

Creep tests were performed on conventional lever-arm type constant-load creep rupture machines. Test specimens were 0.252 inch (6.40×10^{-3}m) in diameter, with a 2-inch (5.08×10^{-2}m) gage length. Cylindrical ridges were machined in the reduced section to establish the gage length and to enable attachment of an extensometer.

For the tests in argon, the argon supply system consisted of two bottles of high purity argon, which flowed through two stages of pressure reduction to produce a final supply pressure of 2 psig. Each bottle of argon was supplied with an analysis with a specified total impurities no greater than 20 ppm.

The typical gas analysis was a) nitrogen, 3-12 ppm); b) oxygen, 7-8 ppm; c) water, less than 1 ppm; and d) hydrocarbons, less than 1 ppm. The reduced pressure argon flowed through a Matheson Hydrox purifier, which was designed to reduce the combined oxygen plus water impurity to below 0.1 ppm, and into a manifold. Each creep machine chamber took its supply from the manifold and exhausted through a flow meter into the atmosphere. After an initial purge with a high flow rate, a flow rate of 1 cc/min was maintained during the test.

The sample dimensions were the same for the argon and air tests, except for the cylindrical ridges for extensometer attachment, which were larger for the argon tests. The test chamber consisted of very flexible bellows attached to upper and lower flanges, which were welded to the sample ridges. Metal V seals were provided between the bellows flange and the sample flange to provide high temperature sealing.

C. Results and Discussion

The initial emphasis in the creep and stress rupture testing was to make a comparison of behavior in air versus argon. The remainder of the program then shifted to the conventional air tests and to parametric analysis of the data.

Air versus Argon Comparison - Two tests each for Heat ESR XA 3218 and 91887 were run in argon. Counterpart tests were run in air to rupture except for the lowest stress test on Heat 91887, which is presently running. Figure 1 - 4 show the results for these tests. In all instances, the tests in air have lower creep rates and longer rupture times than the tests in argon. However, the significance of these results must be interpreted in view of the "normal scatter" in rupture results. On material from the same heat tested under the same conditions, it is not unusual to find a

scatter of $\pm$ 0.2 of a log cycle. In the ratio of maximum time to minimum time, this amounts to a factor of approximately 2.5. None of the test pairs which have run to failure have exceeded this ratio. However, it appears that the 25 ksi (165 MPa) test at 1100° F (593° C) will exceed the 2.5 ratio for rupture times. In spite of the possibility of explaining the results in terms of scatter, the systematic nature of the results strongly suggests that there is an environmental effect in which argon has a deleterious effect. It also appears that Heat 91887 is more affected than ESR XA 3218.

Timken Reference Material - At the initiation of creep testing, it was desirable to find a material which could be used as a basis for comparison. Timken did some exploratory work on the modified 9Cr-1Mo steels, as summarized in References 1 and 2. Two of the heats were tested over rather large time and temperature ranges and were chosen for a parametric analysis. Table 1 summarizes the stress rupture data used in the parametric analysis. Because of its simplicity and wide usage, the Larson Miller parameter was selected for the analysis. A computer program was written to optimize the Larson Miller constant, C, based on least squares methods. The two heats were combined for the analysis and first through third order curve-fits of the master curve were tried. The second order master curve was chosen as best for the intended application. The optimized constant was 35.3, which is much higher than the value of 20 usually used. The equation for the fit to the data is

$$P = (T + 460)\ (C + \log t_r) = a + b \log\sigma + d\ (\log\sigma)^2$$

where

P = Larson Miller parameter

T = temperature, ° F

C = Larson Miller constant = 35.3

t_r = rupture time, hours

a = constant = 70834.69

b = constant = 3772.931

d = constant = -8640.211

σ = stress, ksi

A plot of the Larson Miller correlation of the Timken data is shown in Figure 5.

Individual Heat Comparison to Timken Reference Material - Tables 2 - 6 show the tabular results for the creep tests for the three base metals (91887, ESR XA 3218, ESR XA 3177) and the two weld metals (SMA 109, SMA 111). The rupture time results are plotted on the basis of the Larson Miller parameter, using a constant of 35.3 in Figures 6 - 10, where the average line from the two Timken heats is provided as a basis for comparison. Results to date indicate that a) Heats ESR XA 3218, ESR XA 3177, and SMA 111 are reasonably close to the Timken line; b) Heat 91887 is significantly superior to the Timken line; and c) Heat SMA 109 is inferior to the Timken line. No additional testing is planned for Heat SMA 109 because of its poor creep resistance. In addition, the results show that material code "DP"* is stronger than material code "WC" for Heat 91887.

Figure 11 and 12 show the creep curves for all five heats at 28 ksi and 1100° F. The Timken correlation predicts rupture in 102 hours at this condition. Figure 11 covers the strain range to rupture while Figure 12 only covers the strain range to 5%, which is the maximum strain accumulation permitted by ASME Code Case 1592 for elevated temperature service. One of the main conclusions from Figures 11 and 12 is that both Heat 3177 and SMA 111 exhibit more primary creep than the other heats. Heat ESR XA 3177 has essentially the same rupture time as ESR XA 3218, but always attains a given strain much sooner due to the large primary creep contribution.

*"DP" and "WC" represent two different consolidation sequences.

Stresses Necessary for ASME Code Case 1592 - The short and long time properties must be considered in arriving at the allowable stresses for ASME Code Case 1592. In this section, the properties for the "class of material" as well as the properties for the most favorable heat from the standpoint of creep resistance (Heat 91887) will be estimated.

Class of Material - The tensile and yield strengths from 30 C-E heats of material were used to establish the short-term properties at 70, 900, 1000, and 1100° F (21, 482, 538, and 593° C). The basic data and the average and minimum values of tensile strength are tabulated in Table 7. The minimum is defined as 1.65 standard deviations below the average, where

$$\text{Standard Deviation} = \left[\frac{\sum_{i=1}^{n} (y_i - y_m^2)}{n-1}\right]^{1/2}$$

This definition would assure that 95% of the data lies above the minimum for an infinite population, having a normal distribution. While this is not a rigorous method for a finite population, it is adequate for present purposes. It is somewhat reassuring that none of the observed values fall below the calculated minimum. Between 70 and 900° F (21 and 482° C), no tensile data has been acquired by C-E. However, Table 1 shows results for one of the Timken heats. By forcing the ratio of 900° F to 70° F (482° C to 21° C) strengths to align for the Timken and class of material analysis, an estimate was made for this temperature range, as shown in Table 8. This is obviously not a well established region and more tensile tests should be run in this temperature range. Figure 13 shows a plot of the minimum yield and tensile strength as a function of temperature.

For the time dependent properties, ASME Code Case 1592 requires consideration of a) stress rupture; b) onset of tertiary creep; c) secondary (or minimum) creep rate; and d) one (1) percent total strain accumulation. In arriving at the rupture properties, data from the two Timken heats in Table 1 and all of the C-E heats in Tables 2 - 6, except SMA 109, was evaluated. The Larson Miller parameter method was chosen using a second order master curve. Rather than using a Larson Miller constant of 35.3, previously determined for the Timken data alone, a new optimized constant of 30.6 was determined for the broader data base.

In arriving at the values for onset of tertiary, secondary creep rate, and one (1) percent total strain, only the four C-E heats (SMA 109 excluded) were considered. It should be noted that the onset of tertiary creep was selected by the 0.2 percent offset definition since more reproducible results are obtained in this manner. The same Larson Miller constant of 30.6 was used except for secondary creep rate where an optimized value of 31.5 was used. A second order master curve was used in all cases.

The minimums were determined in a manner similar to that for tensile and yield strength. That is, a shift of 1.65 standard deviations from the average curve was used. Again, this is not statistically rigorous but is adequate for the present purpose. The definition of standard deviation for a second order curve-fit in which the parameter, P, is the dependent variable, is

$$\text{Standard Deviation} = \left[\frac{\sum_{i-1}^{n} (P_i - P_c)}{i - 3} \right]^{1/2}$$

In summary, the parametric curve-fits to the four-time dependent properties required by ASME Code Case 1592, are shown in Figures 14-17. The average, minimum, and maximum lines are shown. The equation defining the curve-fits is:

$$P = a + b\ (\log\sigma) + d\ (\log\sigma)2$$

where

$$P = (T + 460)\ (C + \log t)$$

for rupture, teriary and 1% strain and

$$P = (T + 460)\ (C - \log\dot{\varepsilon}_s)$$

for secondary creep rate.

Values of a, b, c, and d for average and minimum properties are tabulated in Table 9. Values of stresses for various times and temperatures based on Figures 14-17 and Table 9, are shown in Tables 10-17. Tabulations of the raw data used in the analysis of the time dependent data is shown in Tables 18-21.

Most Favorable Heat (91887) - The tensile and yield strengths of Heat 91887 are well above the minimum values determined for the class of material at all four test temperatures, as shown in Table 7. However, the strength of a heat with the same nominal composition as 91887, but with minimum room temperature properties, must be considered. While there is no exact method to establish this strength, it seems reasonable to use the "ratioing" method. Table 22 shows the results from this method of analysis. The basic conclusion is that a hypothetical Heat 91887 with minimum tensile and yield strength properties would be equal to or slightly better than the minimum properties established for the class of material. On that basis, the tensile and yield strength for code stress consideration for Heat 91887 will be assumed the same as the class of material previously established and summarized in Table 7 and Figure 13.

The time dependent properties for Heat 91887 were determined from Larson Miller parametric analyses, using Larson Miller constants previously determined for the class of material. These constants were selected because they were determined from a much larger data base. Experience has shown that the optimum Larson Miller constant is very sensitive to the data base, particularly when a small number of points are available. The parametric curve-fits to the four time dependent properties required by ASME Code Case 1592, are shown in Figures 18-21. The average, minimum, and maximum lines are shown. Second order master curves were used as for the class of material. Values of a, b, c, and d for average and minimum properties are tabulated in Table 23. Values of stresses for various times and temperatures based on Figures 12-21 and Table 23 are shown in Tables 24-31.

VI.A CODE CASE 1592 ALLOWABLE DESIGN STRESSES

A. Derivation

ASME Publication E00097, entitled "Criteria for Design of Elevated Temperature Class 1 Components in Section III, Division I, of the ASME Boiler and Pressure Vessel Code, details the procedures to establish the time dependent and time independent "stress intensities" or "allowable stresses", referred to symbolically as S_o, S_m, S_y, S_t, and S_{mt}. A brief definition of the stress intensities summary of the criteria employed and calculation of values for both the class of material and Heat 91887 follows.

B. Definitions and Discussion

S_o = The Maximum Allowable Value of General Primary - Membrane Stress Intensity for Design Conditions - This stress limit is controlled by the criteria in Section VIII, Division 1, of the Code. The time independent quantitites are tensile strength and yield strength. The time dependent quantities are rupture stress and minimum creep rate, based on 100,000 hours. Specifically, the following factors are used:

1. Tensile - 1/4 the "tensile strength at temperature", where the "tensile strength at temperature" is defined as the smaller of
   a. specified minimum tensile strength at room temperature; or
   b. a value 10% greater than the minimum tensile strength at temperature.

2. Yield - Ferritic - 5/8 minimum yield strength at temperature.

3. Rupture -
   a. 0.67 average rupture stress for 100,000 hours; or
   b. 0.8 minimum rupture stress of 100,000 hours.

It should be noted that many materials currently in the Code used a value of 0.60 on average 100,000 hour rupture stress rather than 0.67. Therefore, the S_o values developed in subsequent sections will use both values to enable direct comparison with materials using the more conservative criteria.

4. Secondary (or Minimum) Creep Rate - The average secondary creep rate for 0.01 percent creep per 1000 hours (equivalent to 1 percent per 100,000 hours).

Tables 36 and 37 show the calculations for S_o for the class of material and Heat 91887, respectively. Values are shown using both 0.67 and 0.60 times the 100,000 hour rupture strength. The final results are plotted in Figure 22.

For the class of material, the tensile strength controls to approximately 1010° F (543° C) and 975° F (524° C), using a factor of 0.67 and 0.060, respectively. Using the 0.67 factor, the average rupture strength controls to 1100° F (593° C) and then the minimum rupture strength controls to 1200° F (649° C). Using the 0.60 factor, the average rupture strength controls beyond 975° F (524° C).

For Heat 91887, the tensile strength controls to approximately 1040° F (560° C) and 1010° F (543° C), using a factor of 0.67 and 0.60, respectively. Using the 0.67 factor, the average rupture strength controls to 1150° F (621° C), and the minimum rupture strength controls at 1200° F (649° C). Using the 0.60 factor, the average rupture strength controls beyond 1010° F (543° C).

S_m = The Time Independent Design Stress Intensity - This stress limit is controlled by either tensile or yield strength. For ferritic steels, the following criteria are used:

1. Tensile - 1/3 the "tensile strength at temperature", where the "tensile strength at temperature" is defined as the smaller of:

   a. specified minimum tensile strength at room temperature; or
   b. a value 10% greater than the minimum tensile temperature.

2. Yield - 2/3 minimum yield strength at temperature.

Table 38 shows the calculation of S_m for both the class of material and Heat 91887. It can be seen that tensile strength controls over the entire temperature range from 70 - 1100° F (21 - 593° C).

S_y - The Yield Strength of a Material at a Given Temperature - This value is the minimum yield strength at temperature, which is tabulated in Tables 7 and 8, and plotted in Figure 13.

S_t = Time Dependent Design Stress Intensity - This stress limit is controlled by either rupture, onset of tertiary creep, or one percent total strain accumulation.

1. Rupture - 2/3 of the minimum stress to cause rupture in time t;
2. Tertiary - 80 percent of the minimum stress to cause the onset of tertiary creep in time t; and
3. Total Strain - the minimum stress to produce one percent total strain in time t.

Tables 39-45 show the calculation of S_t for both the class of material and Heat 91887, and the results are plotted in Figures 23 and 24, along with the S_m line. In all time and temperature ranges, the value of S_t is controlled by the minimum rupture strength for both the class of material and Heat 91887. It is also interesting to note that Heat 91887 is better than the class of material by a factor of approximately three on time at a given stress and temperature over the entire range of stress, temperature, and time.

S_{mt} = General Membrane Stress Intensity - The lower of either S_m (time independent) or S_t (time dependent) for a given time, $_t$. Tables 46 and 47 show tabulation of S_{mt} for the class of material and Heat 91887, respectively. In the stress region controlled by the time dependent stress intensity, S_t, the parametric analyses were based on a Larson Miller constant of 30.6. However, it appears that a higher value of the constant may be appropriate for Heat 91887. Table 48 shows the values of S_{mt} obtained when using a Larson Miller constant of 35.3. The predicted stress values are higher, particularly at the longer times. Obviously, more experimental data is required on a range of heats encompassing the composition and processing of a "preferred" alloy before an optimum analysis of the data can be performed.

REFERENCES

1. Timken Resume of High Temperature Investigations Conducted During 1963 - 1965.

2. Rupture Data on Timken Heat No. 18723 in letter from J. C. Donohue to C. T. Ward, dated March 12, 1976. Subsequently included in letter from C. T. Ward to S. D. Harkness, dated March 21, 1975.

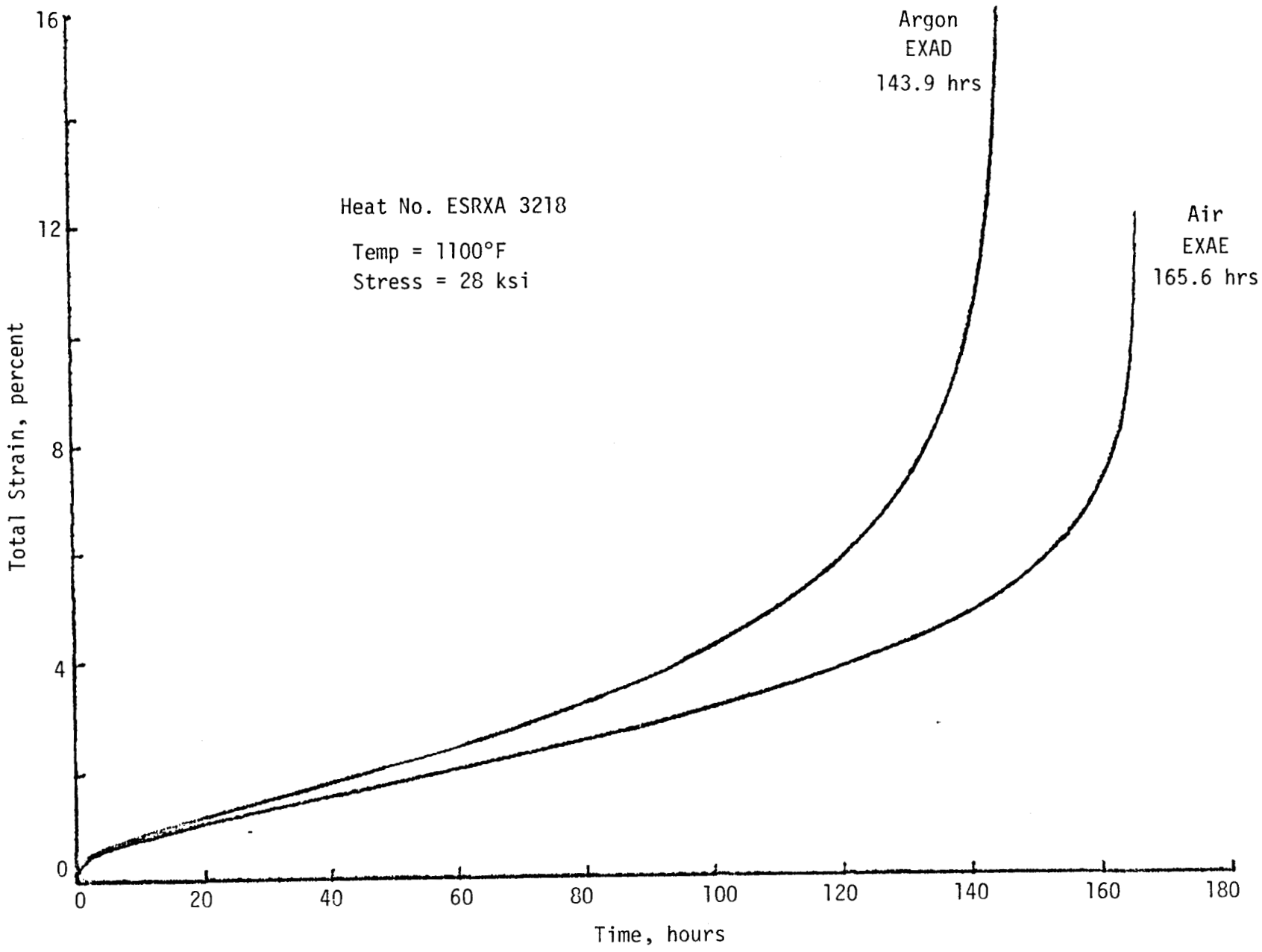


FIGURE 1. Comparison of Air and Argon Tests on Heat ESRXA 3218 at a Stress of 28 ksi and Temperature of 1100°F.

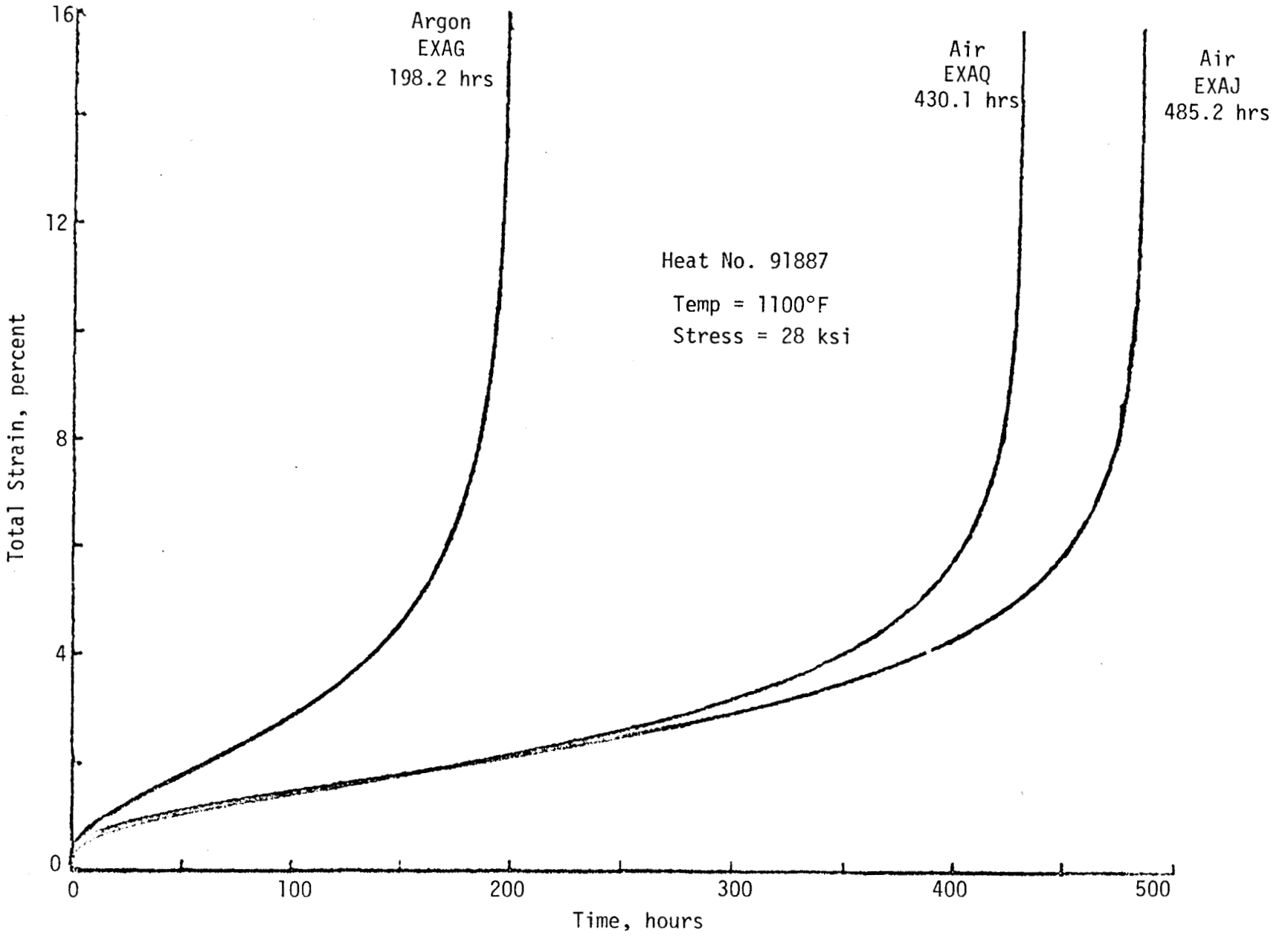


FIGURE 2 Comparison of Air and Argon Tests on Heat 91887 at a stress of 28 ksi and Temperature of 1100°F.

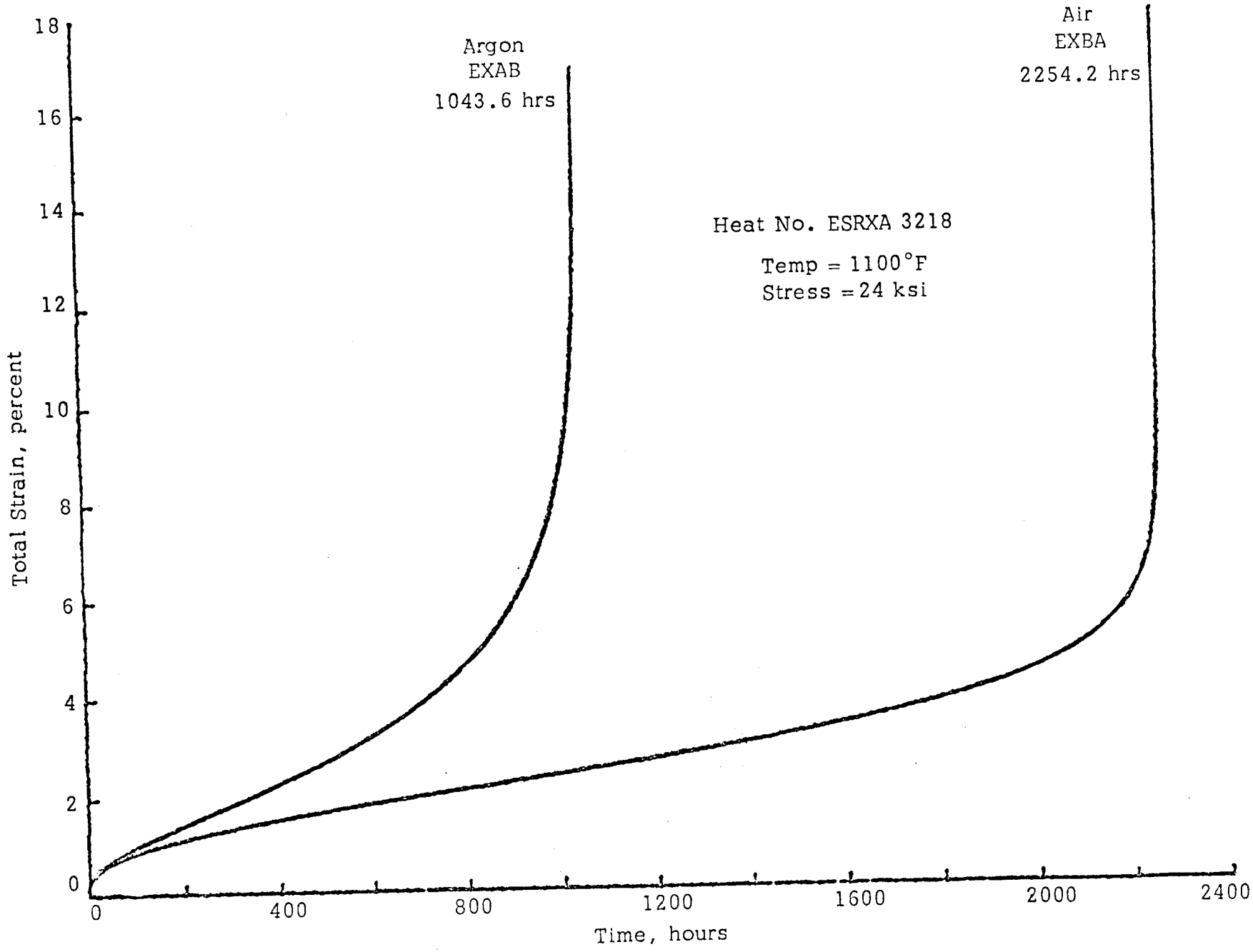


FIGURE 3. Comparison of Air and Argon Tests on Heat ESRXA 3218 at a Stress of 24 ksi and Temperature of 1100°F

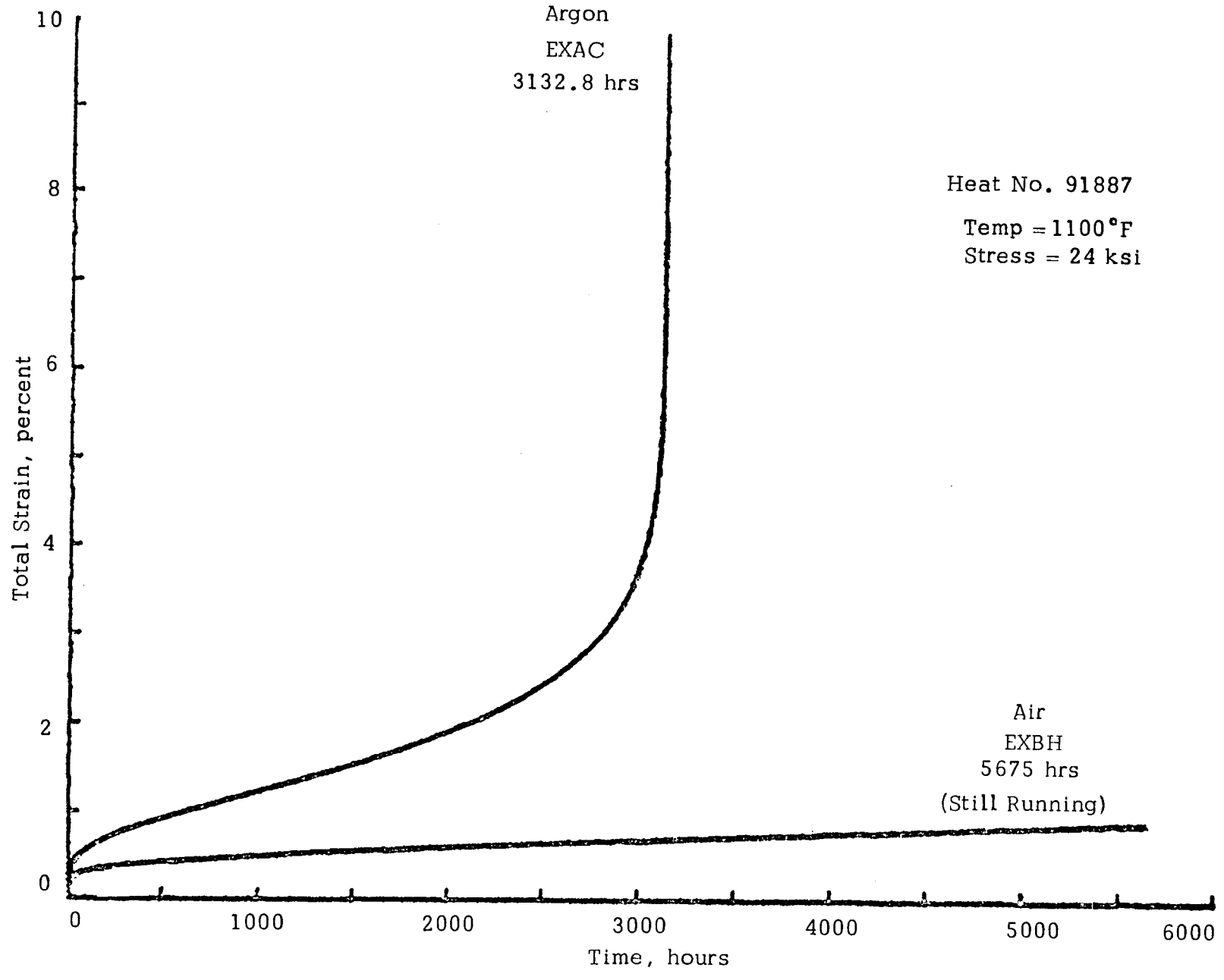
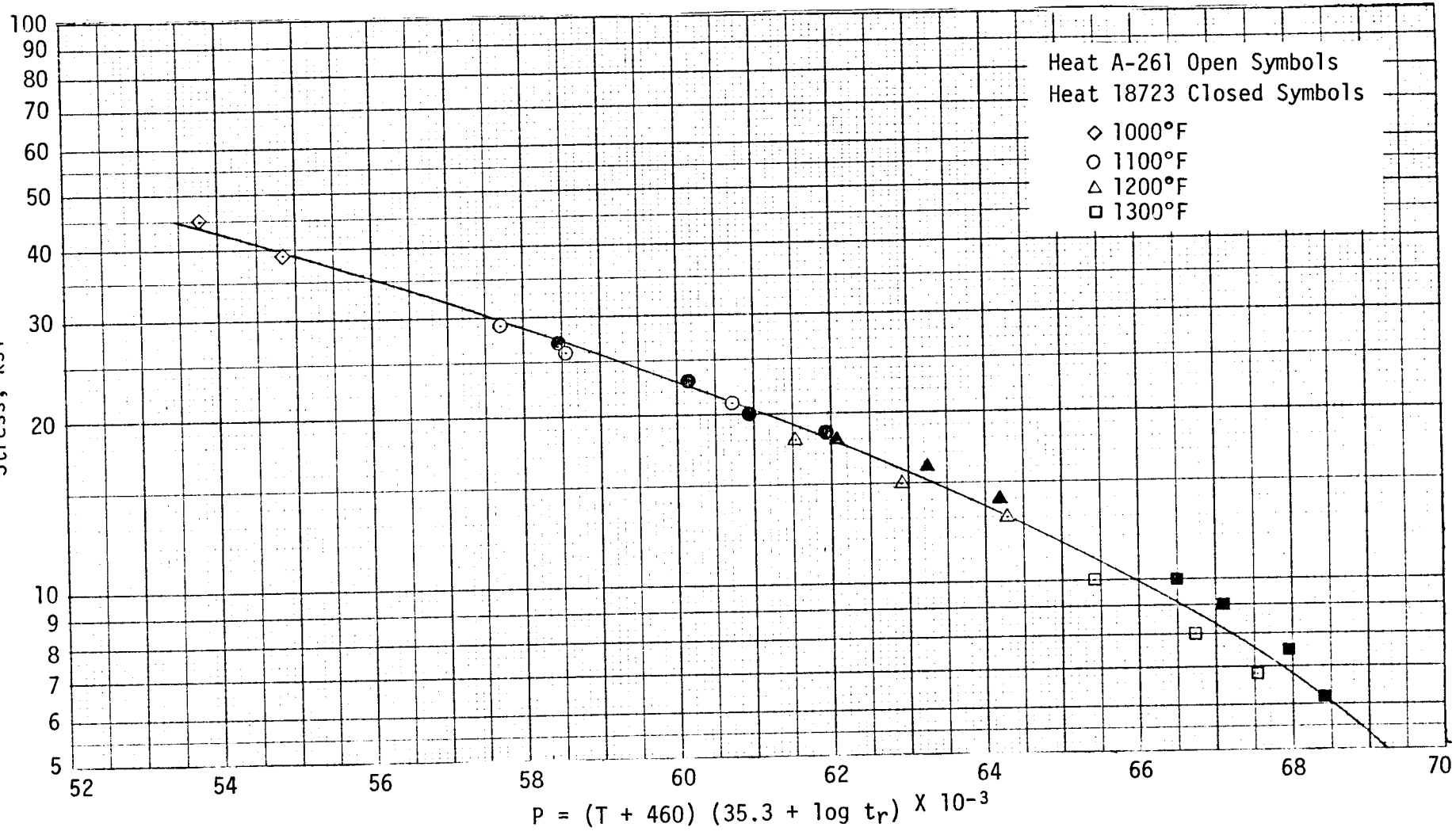


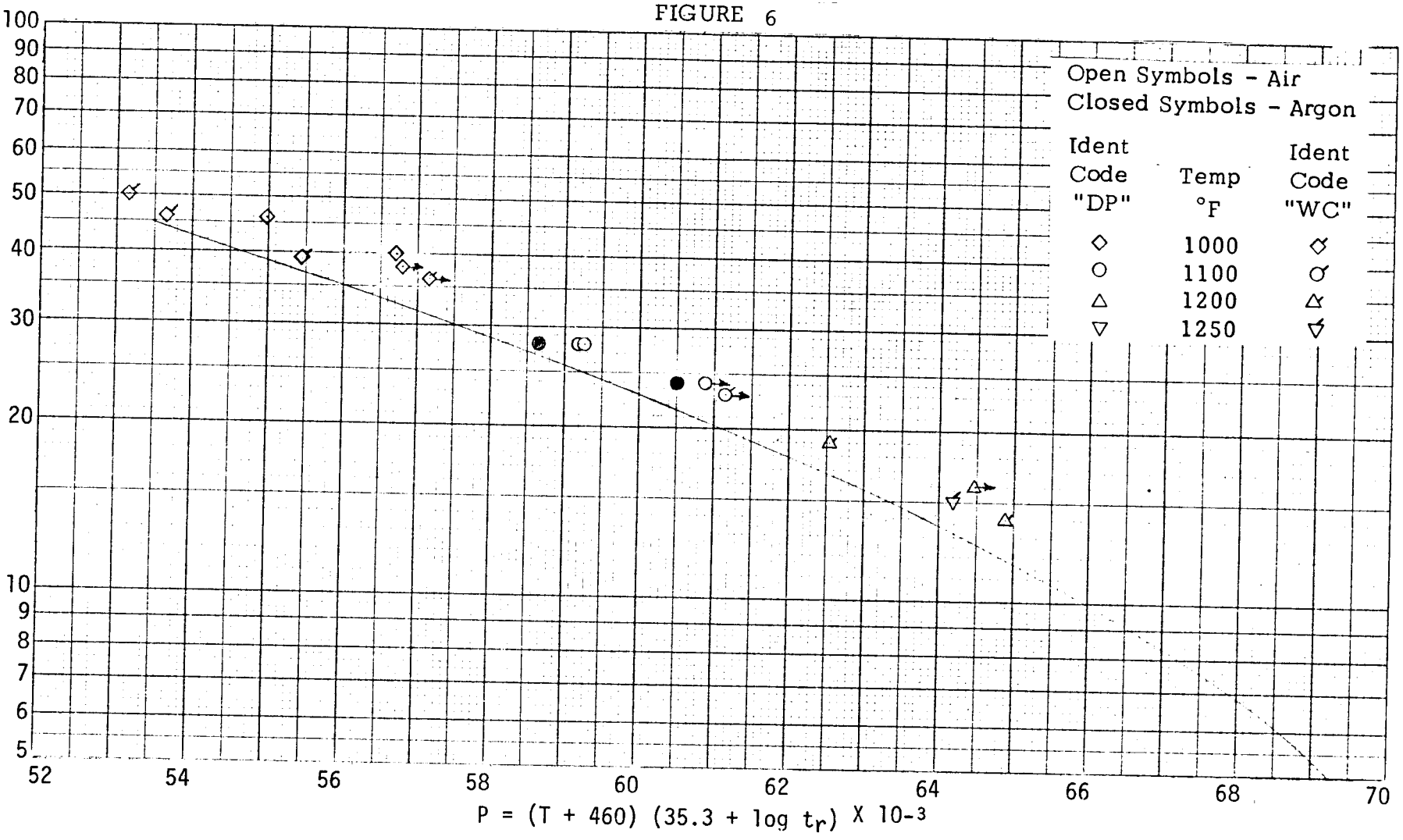
FIGURE 4 Comparison of Air and Argon Tests on Heat 91887 at a Stress of 24 ksi and Temperature of 1100°F

FIGURE 5



Larson-Miller Correlation of Timken Modified 9 Cr - 1 Mo Steel Alloys

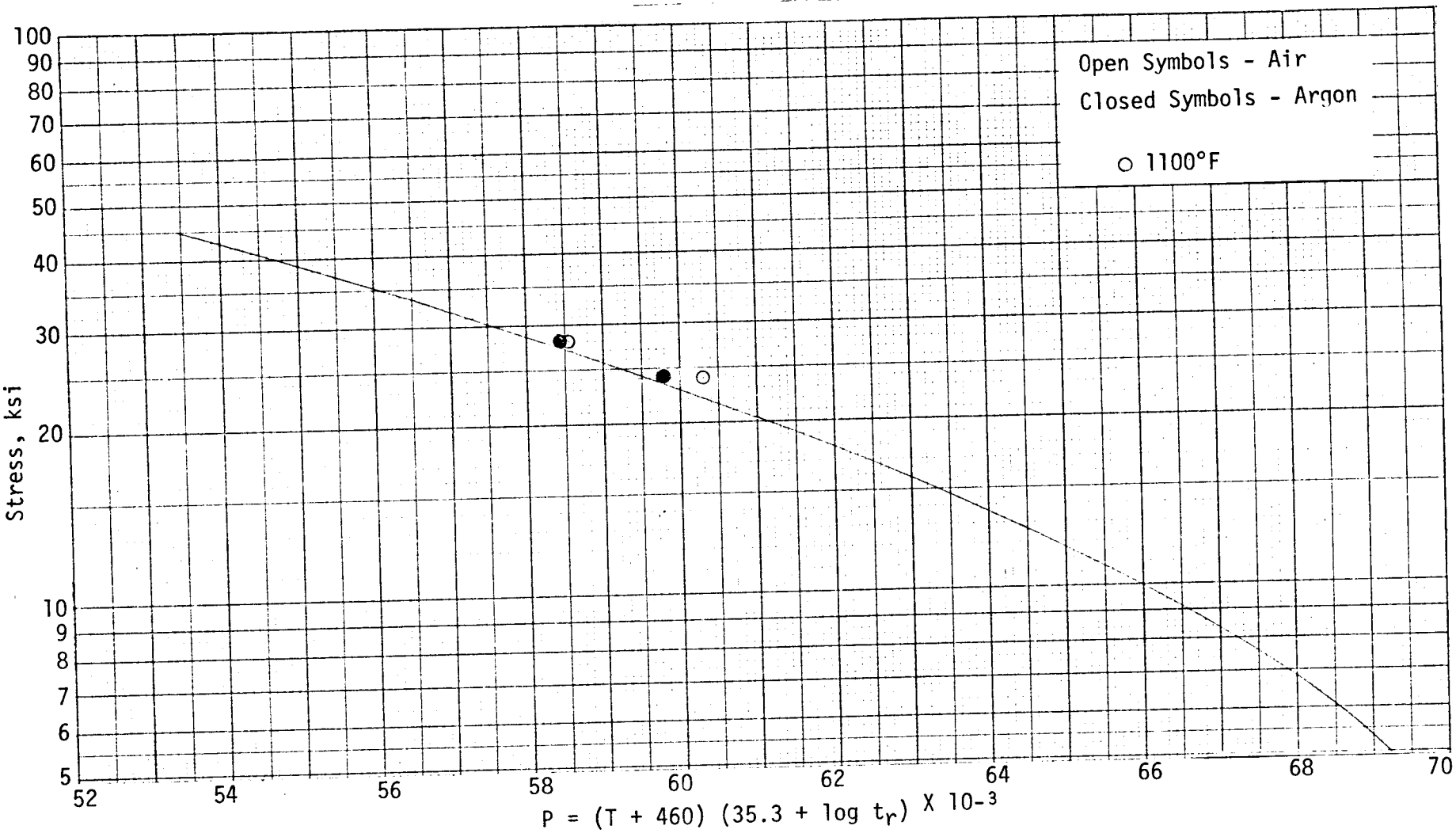
FIGURE 6



Larson-Miller Correlation of Heat 91887

Revised 6-28-77

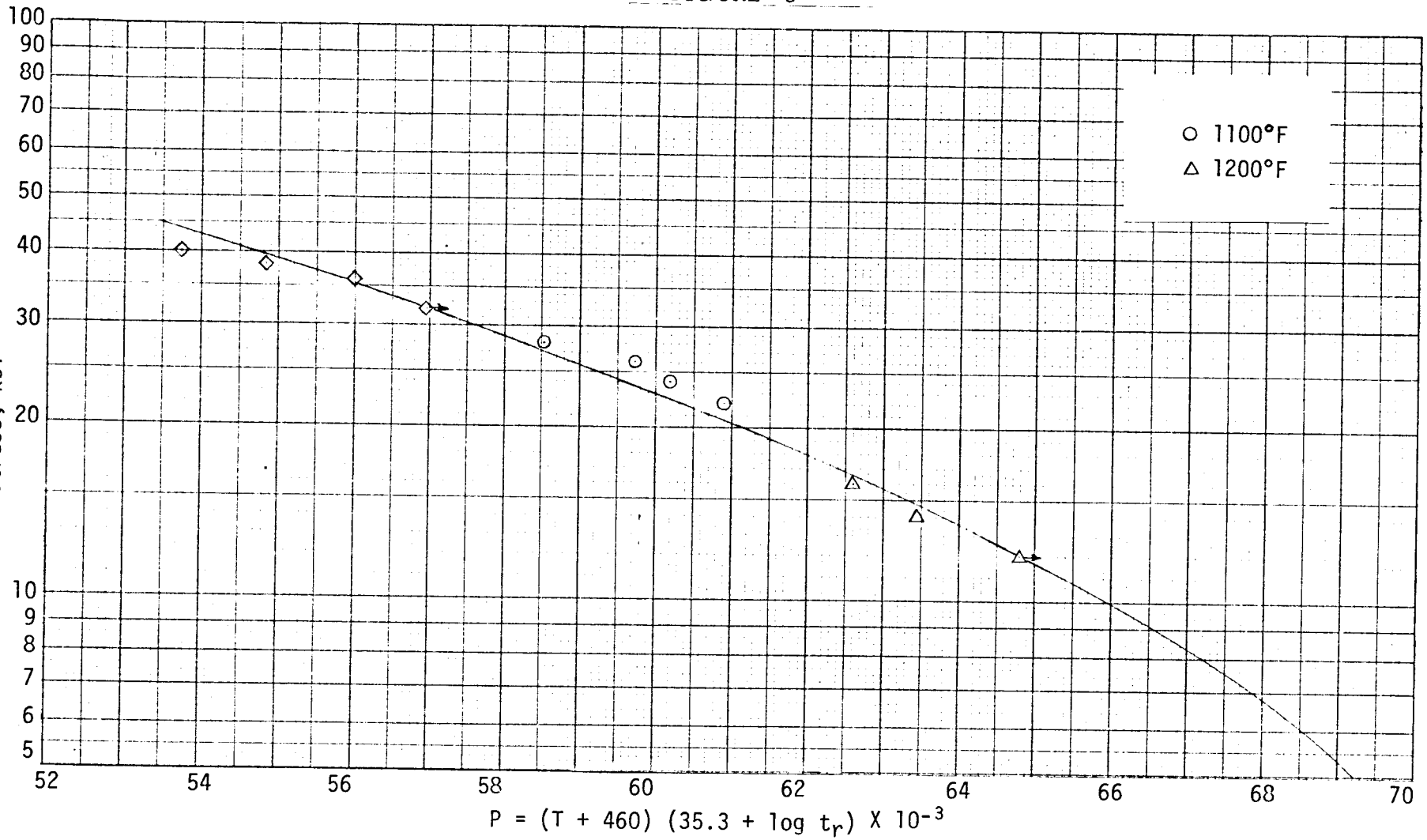
FIGURE 7



Larson-Miller Correlation of Heat ESRXA 3218

Revised 11-29-76

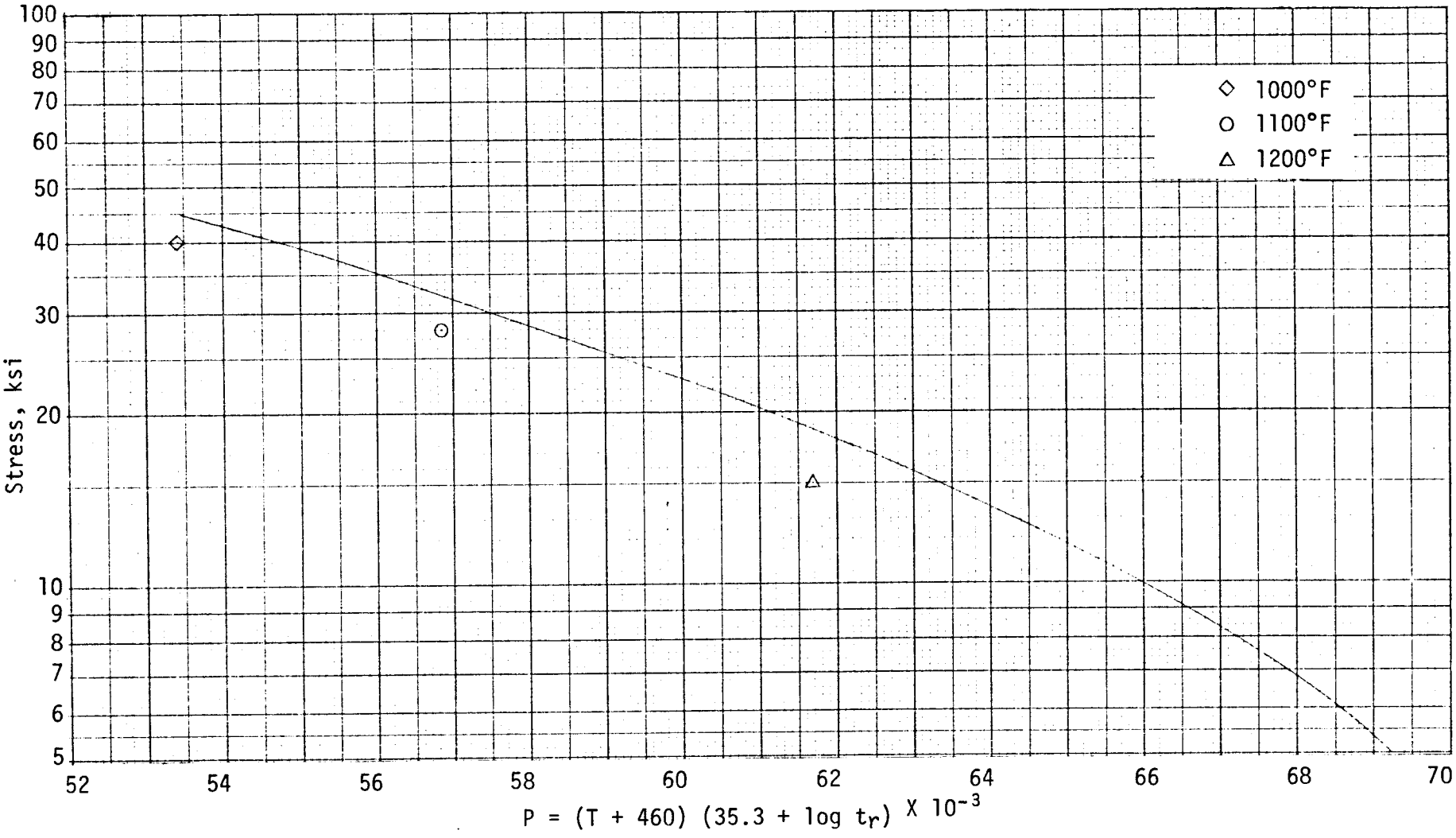
FIGURE 8



Larson-Miller Correlation of Heat ESRXA 3177 Tested in Air

Revised 6-28-77

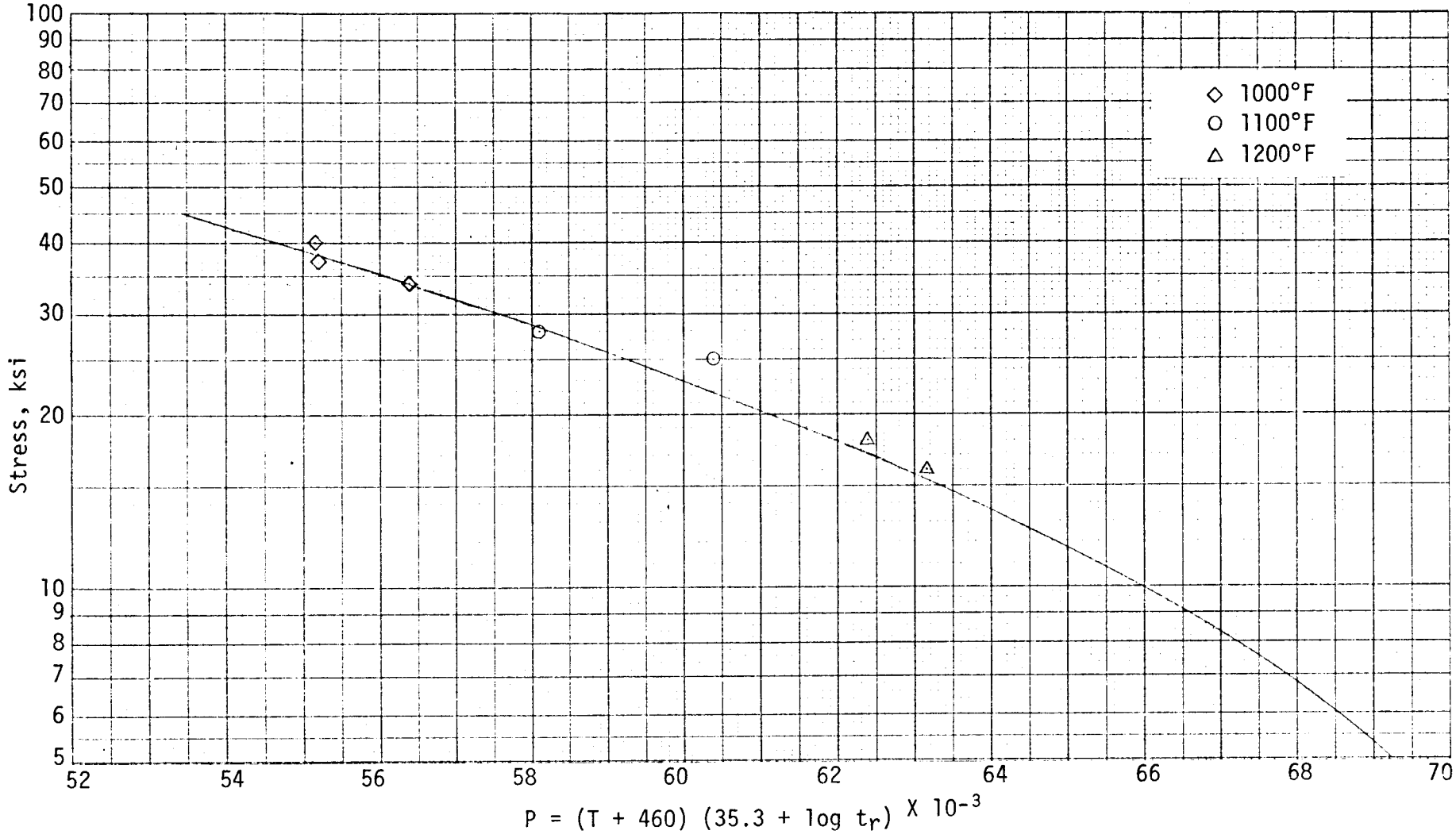
FIGURE 9



Larson-Miller Correlation of Weld SMA 109 Tested in Air

Revised 8-4-76

FIGURE 10



Larson-Miller Correlation of Weld SMA 111 Tested in Air

Revised 3-23-77

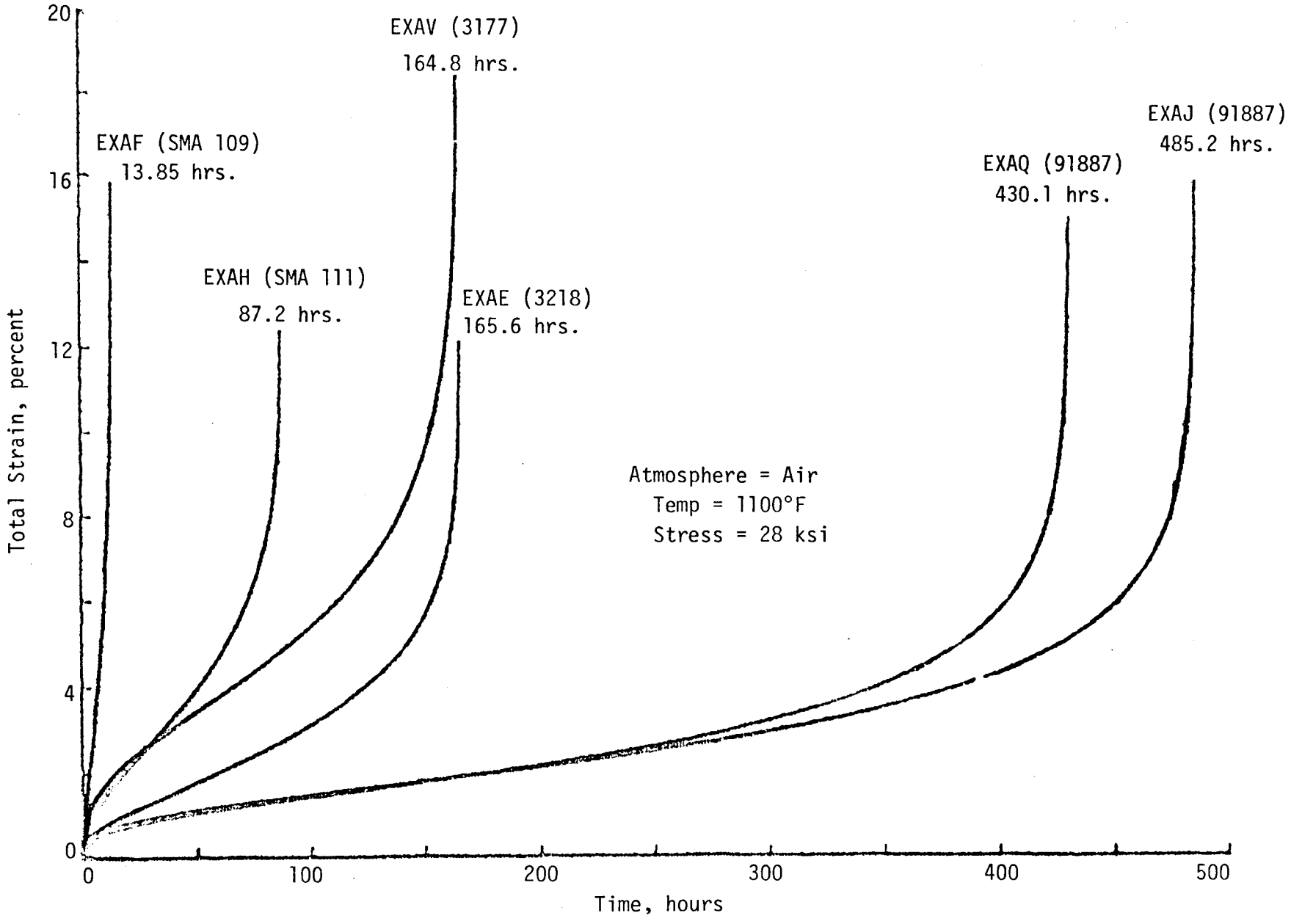


FIGURE 11. Comparison of Five Heats of Modified 9 Cr - 1 Mo Steel Tested in Air at a Stress of 28 ksi and Temperature of 1100°F to Rupture.

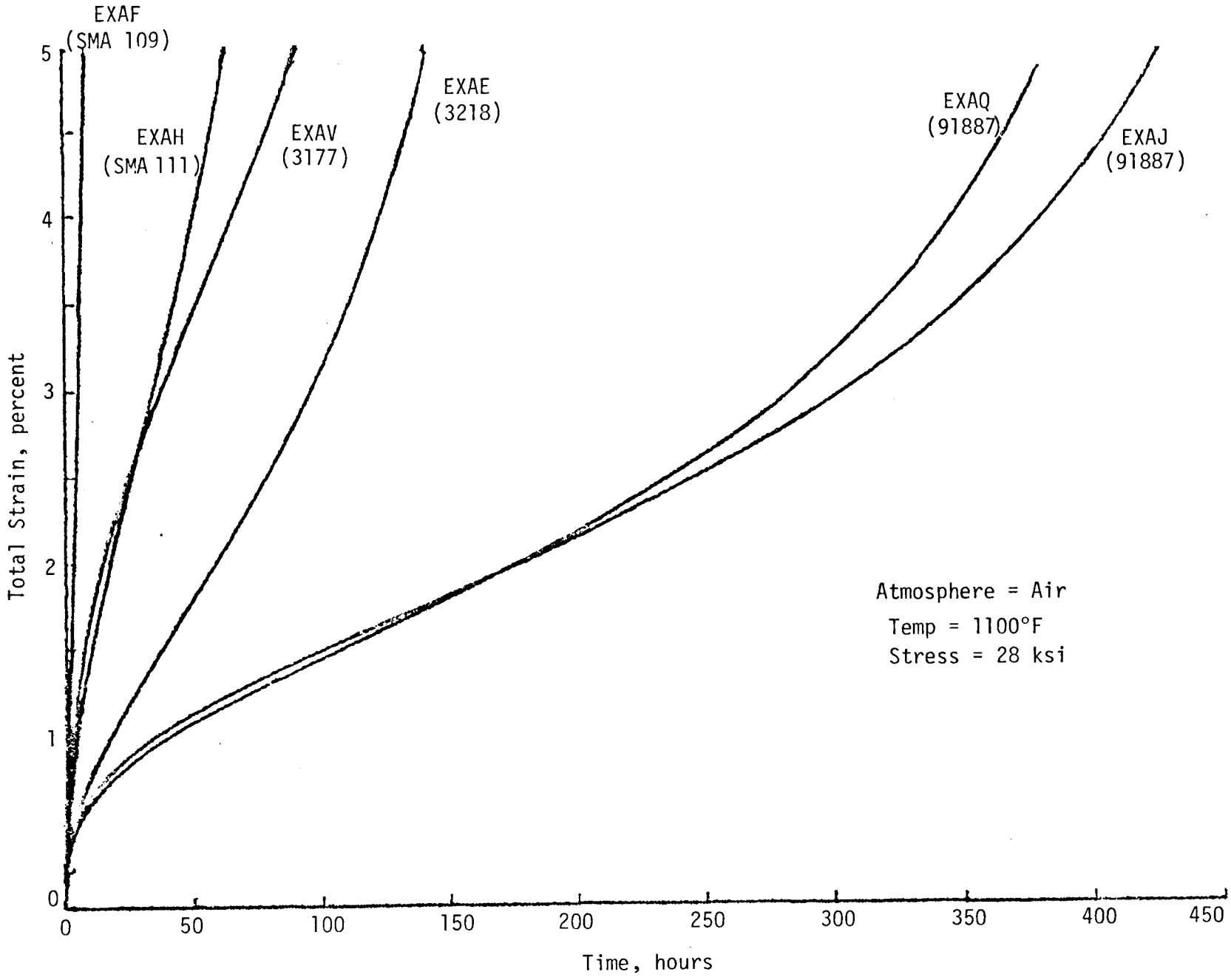


FIGURE 12. Comparison of Five Heats of Modified 9 Cr - 1 Mo Steel Tested in Air at a Stress of 28 ksi and Temperature of 1100°F During Initial 5 Percent Strain.

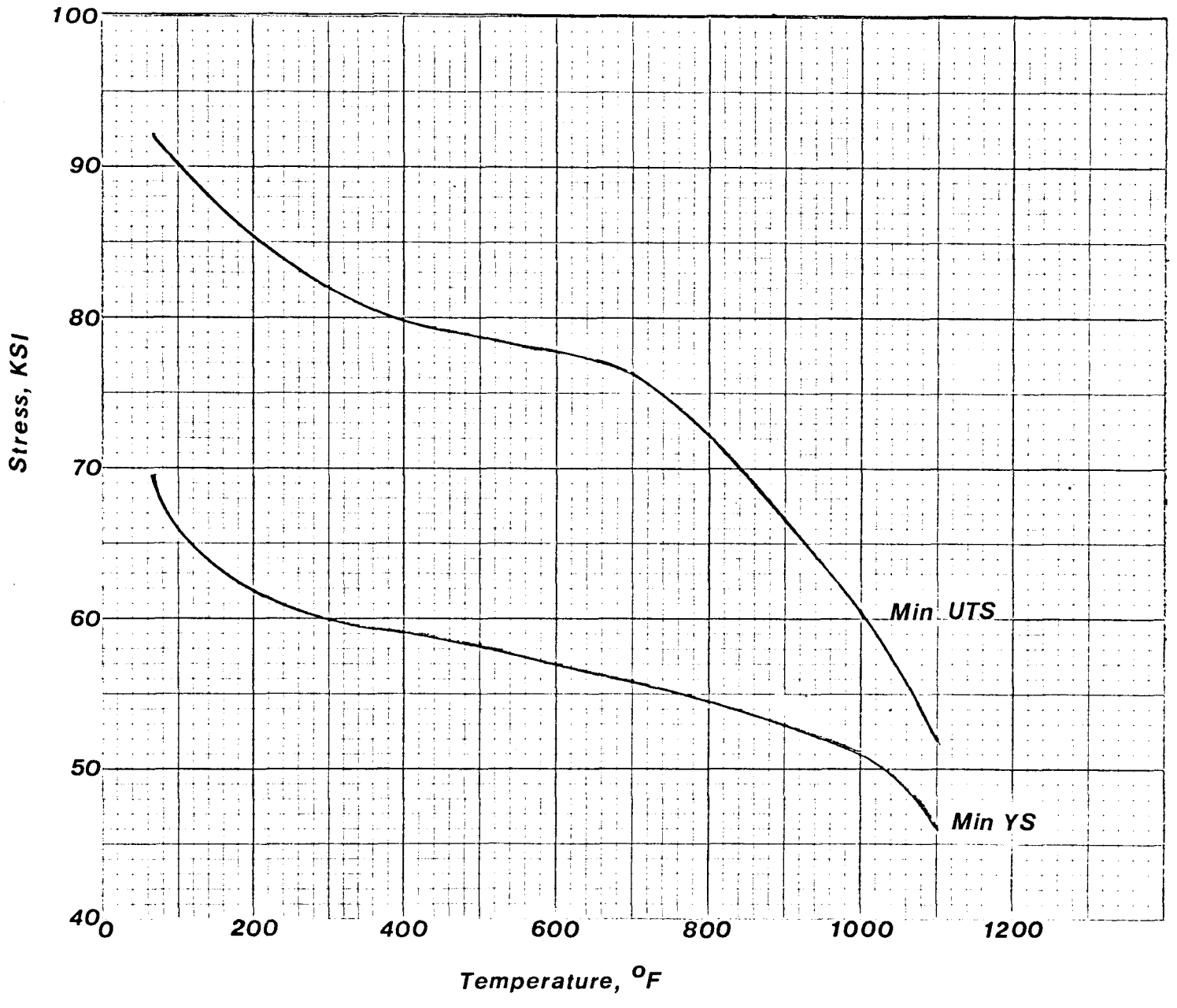


Figure 13. Minimum Tensile and Yield Strength for the Class of Material

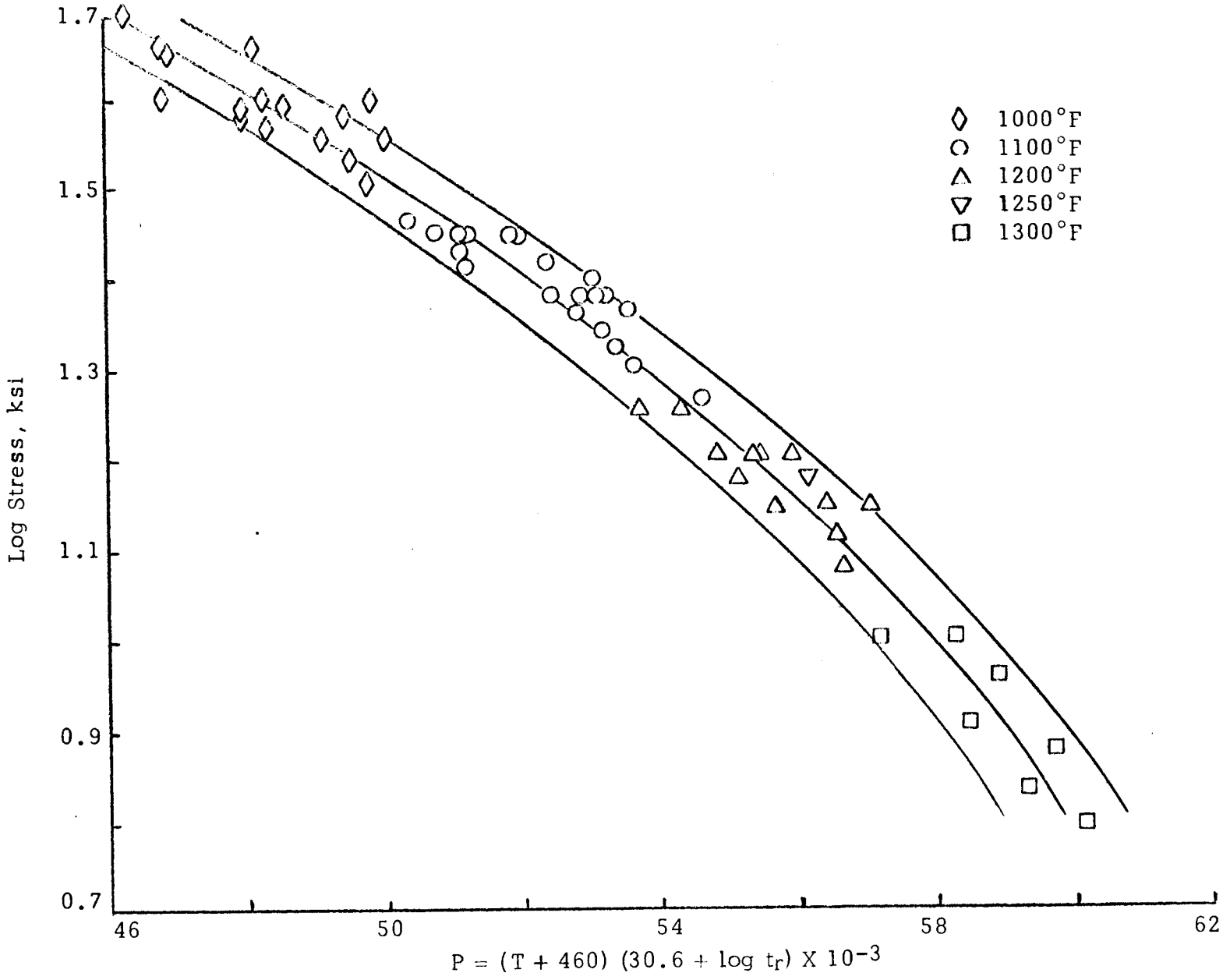


FIGURE 14 Larson-Miller Correlation of Time-to- Rupture for Class of Material

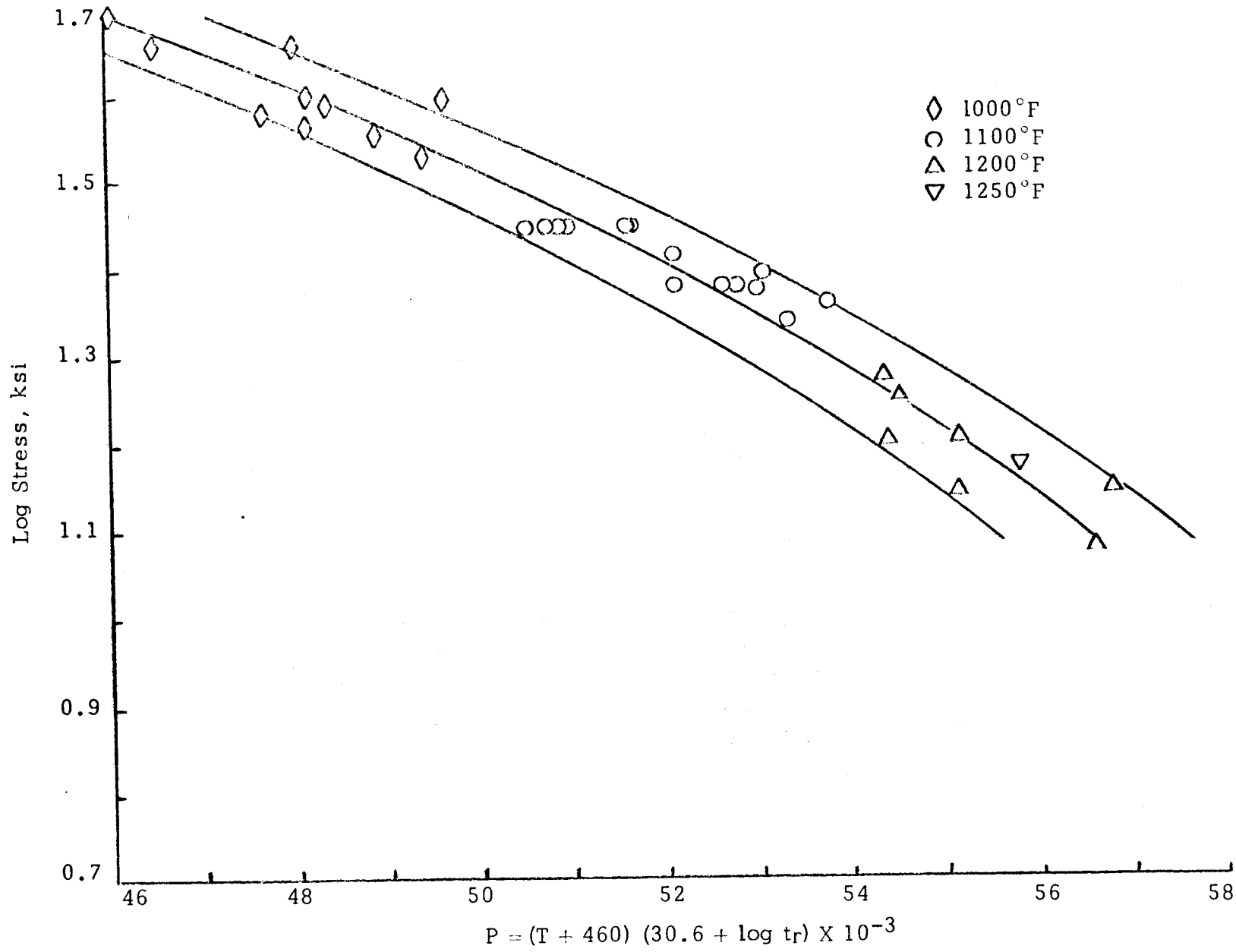


FIGURE 15 Larson-Miller Correlation of Time to 0.2 Percent Tertiary for Class of Material

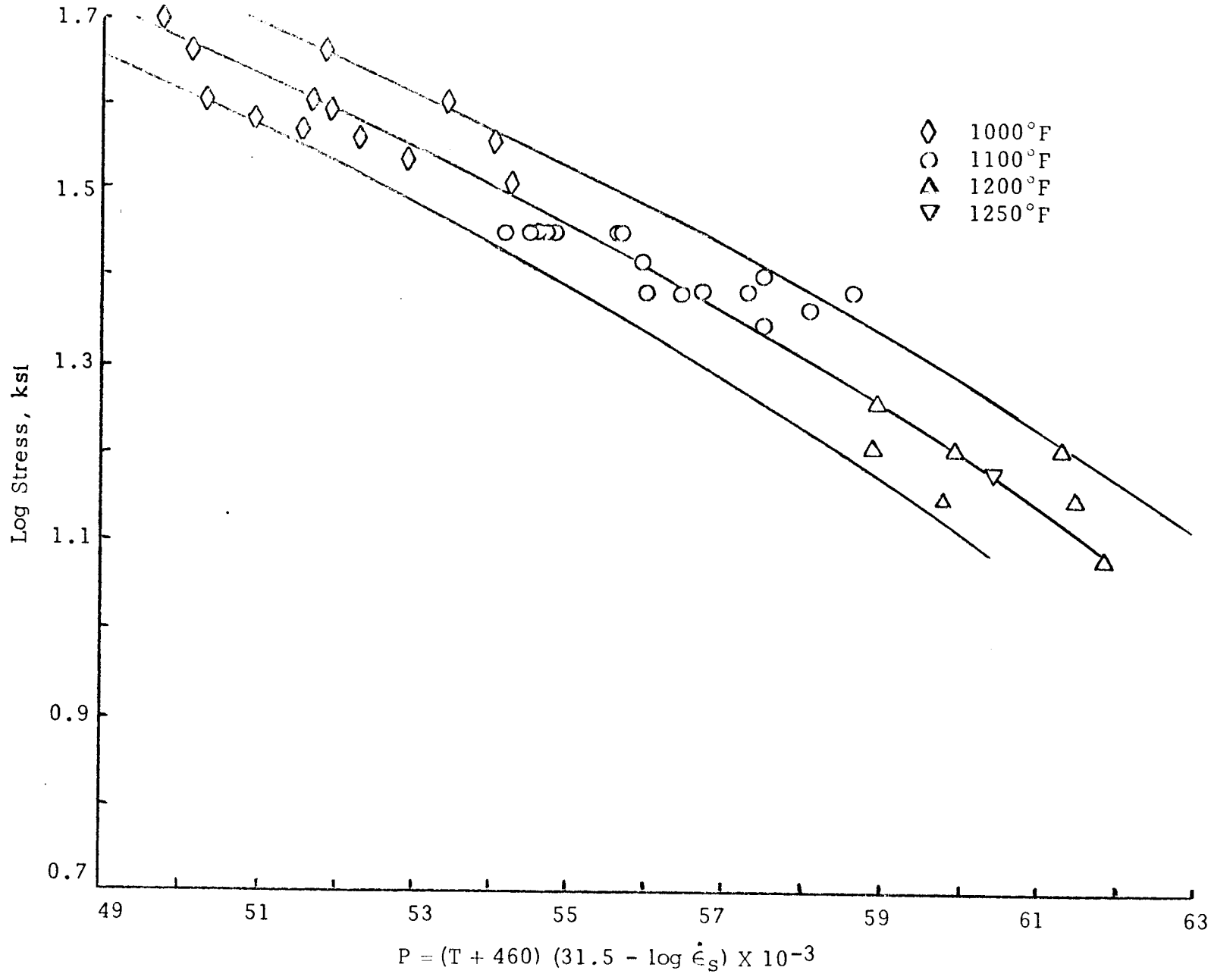


FIGURE 16 Larson-Miller Correlation of Secondary Creep Rate for Class of Material

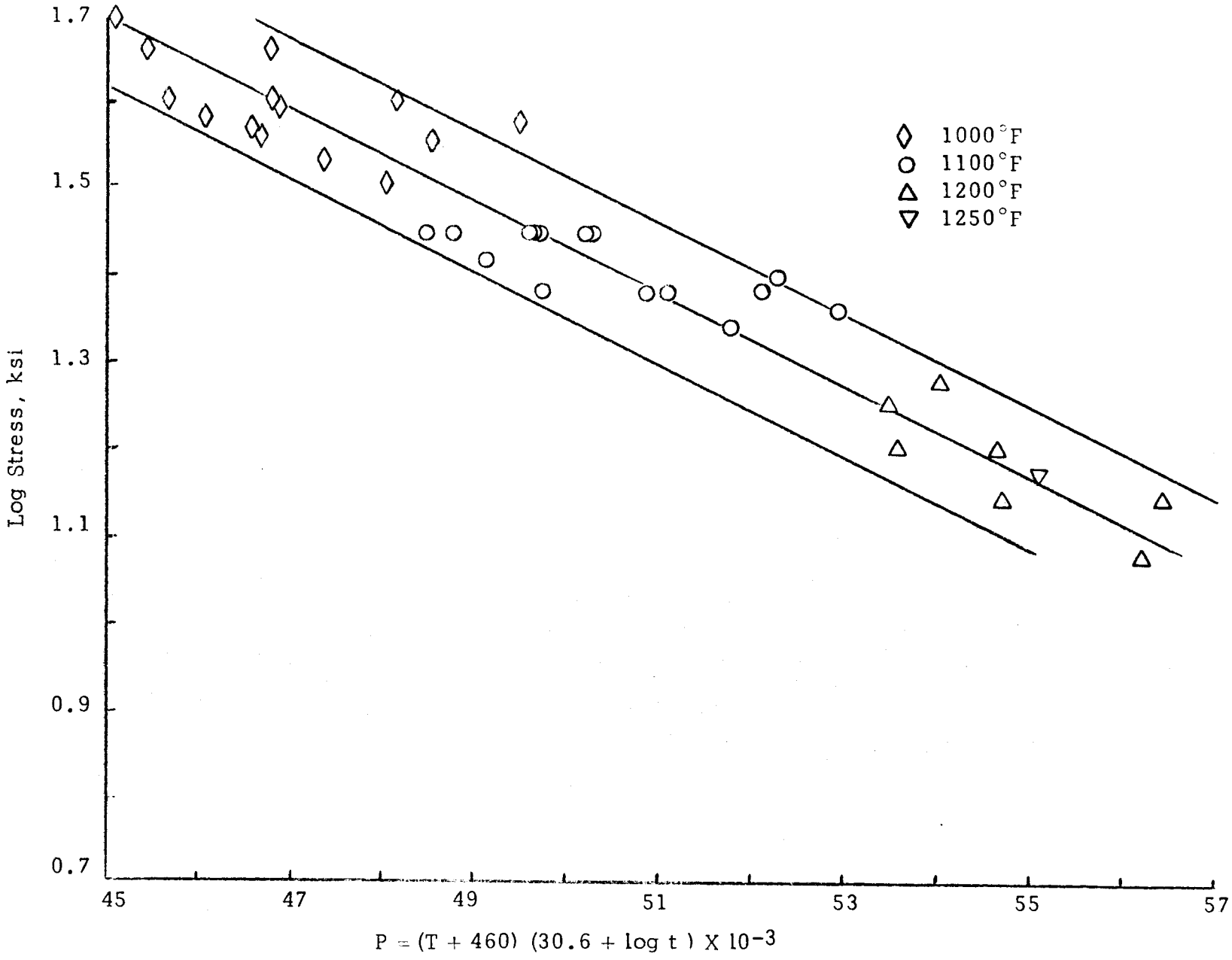


FIGURE 17 Larson-Miller Correlation of Time to 1.0 Percent Total Strain for Class of Material

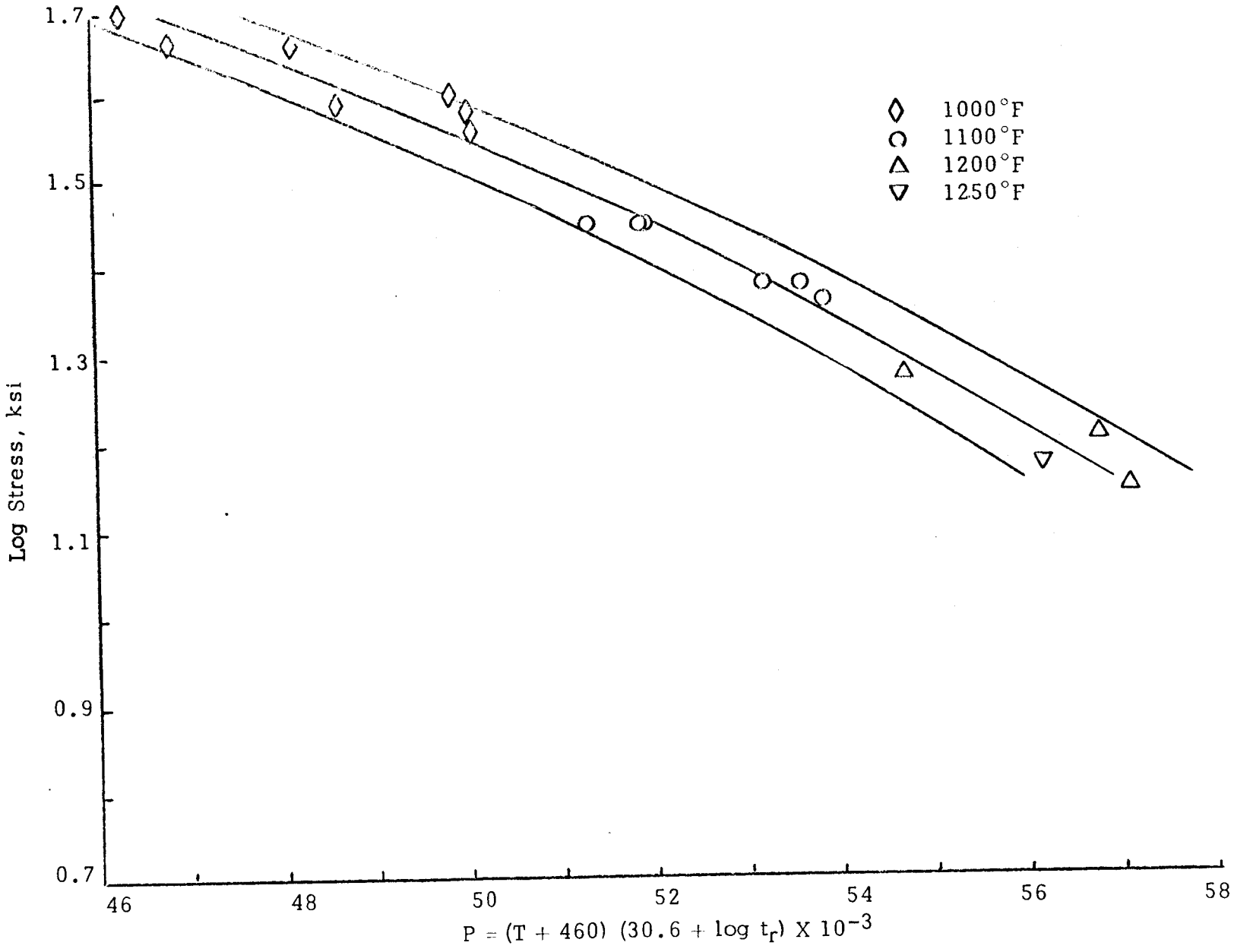


FIGURE 18 Larson-Miller Correlation of Time-to-Rupture for Heat 91887

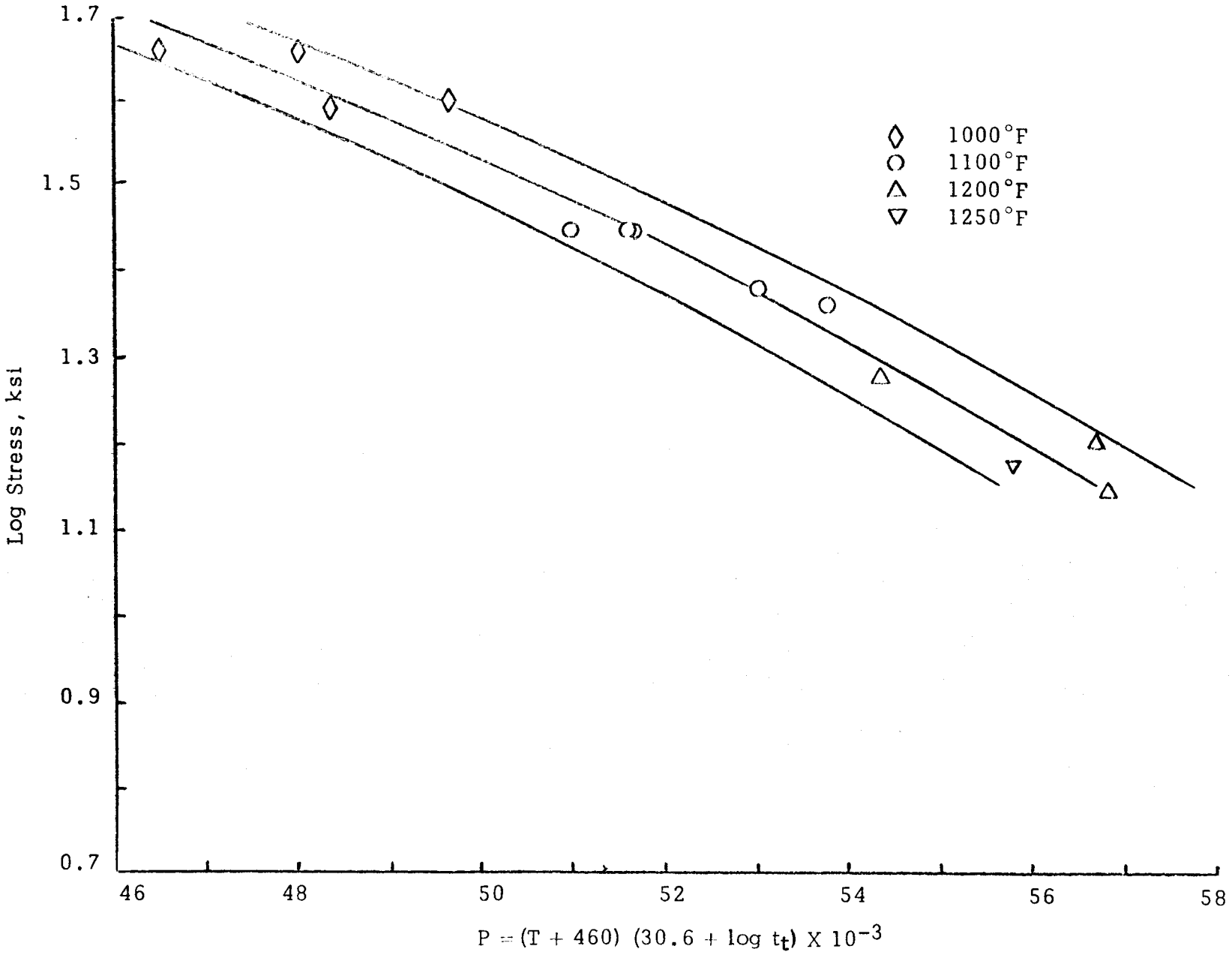


FIGURE 19 Larson-Miller Correlation of Time to 0.2 Percent Tertiary for Heat 91887

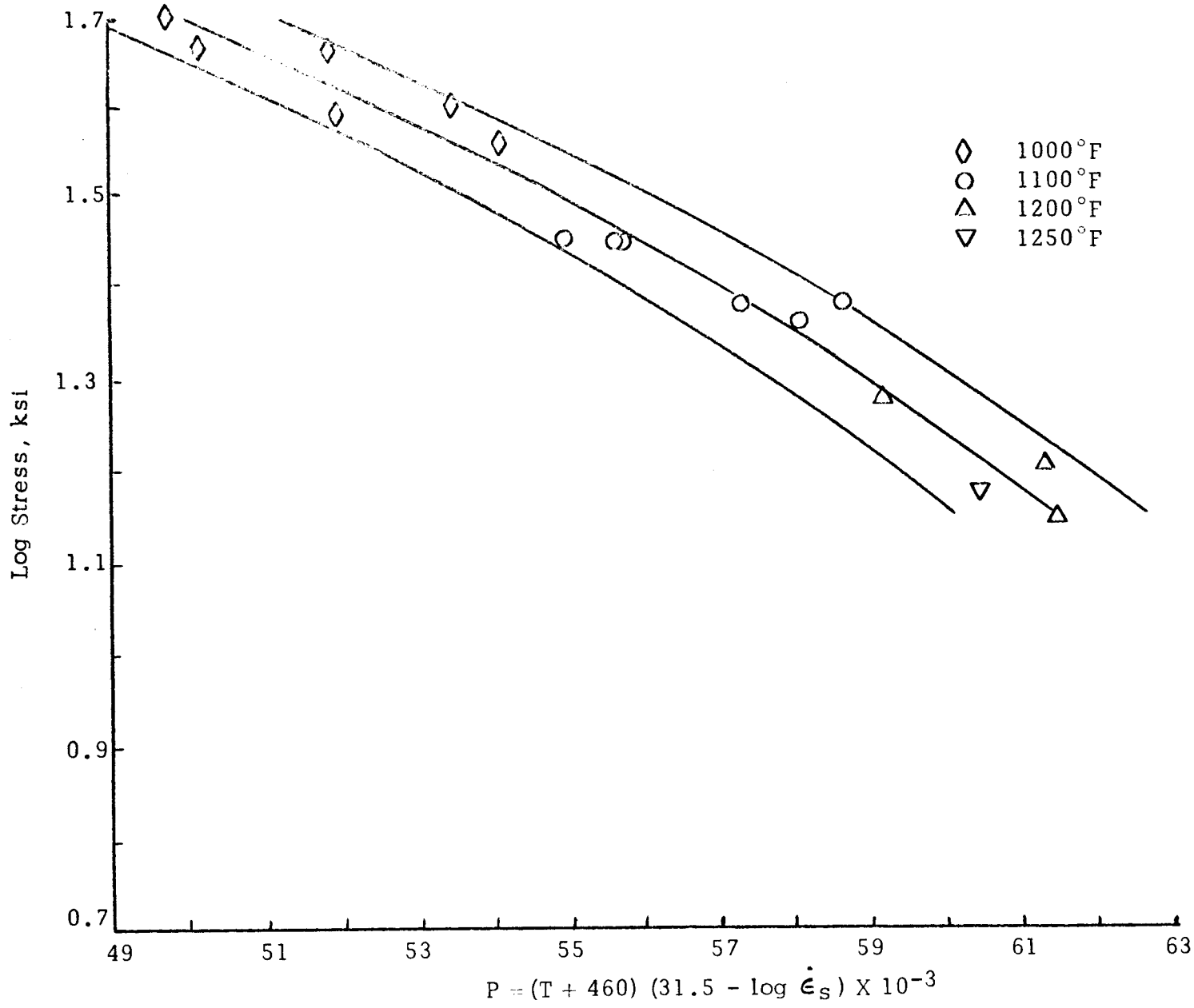


FIGURE 20 Larson-Miller Correlation of Secondary Creep Rate for Heat 91887

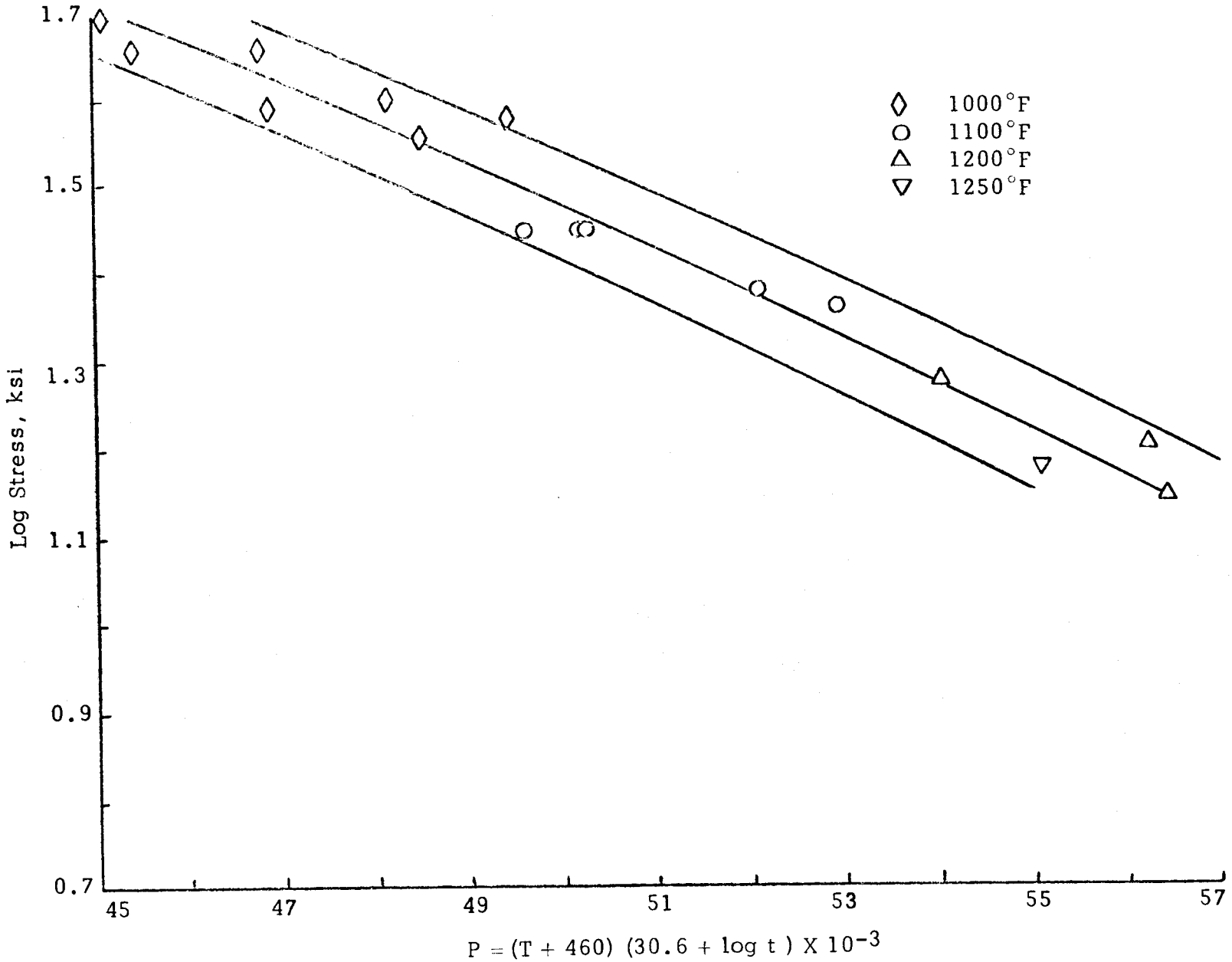


FIGURE 21 Larson-Miller Correlation of Time to 1.0 Percent Total Strain for Heat 91887.

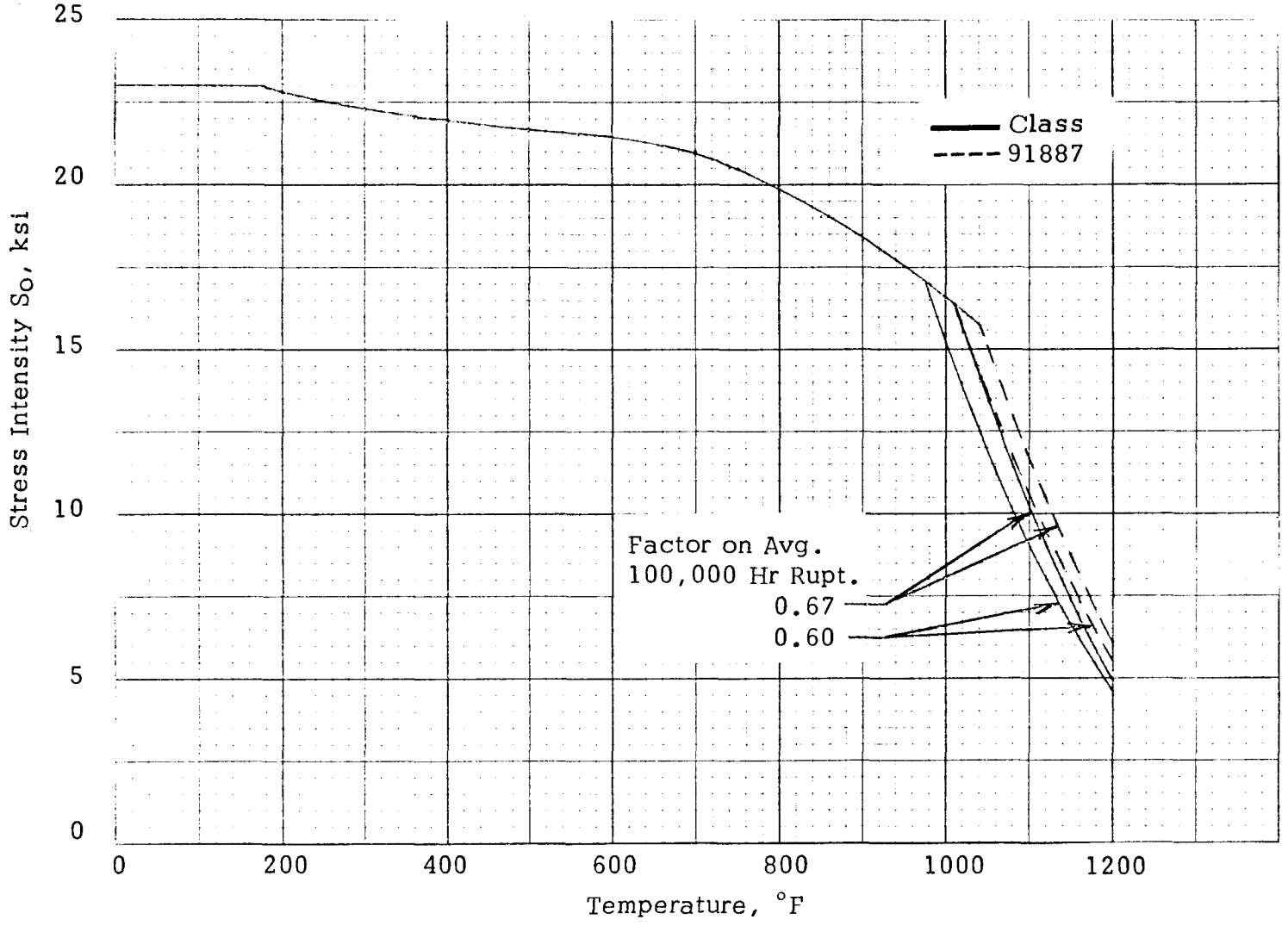


Figure 22. Stress Intensity S_o as a Function of Temperature for Class of Material and Heat 91887.

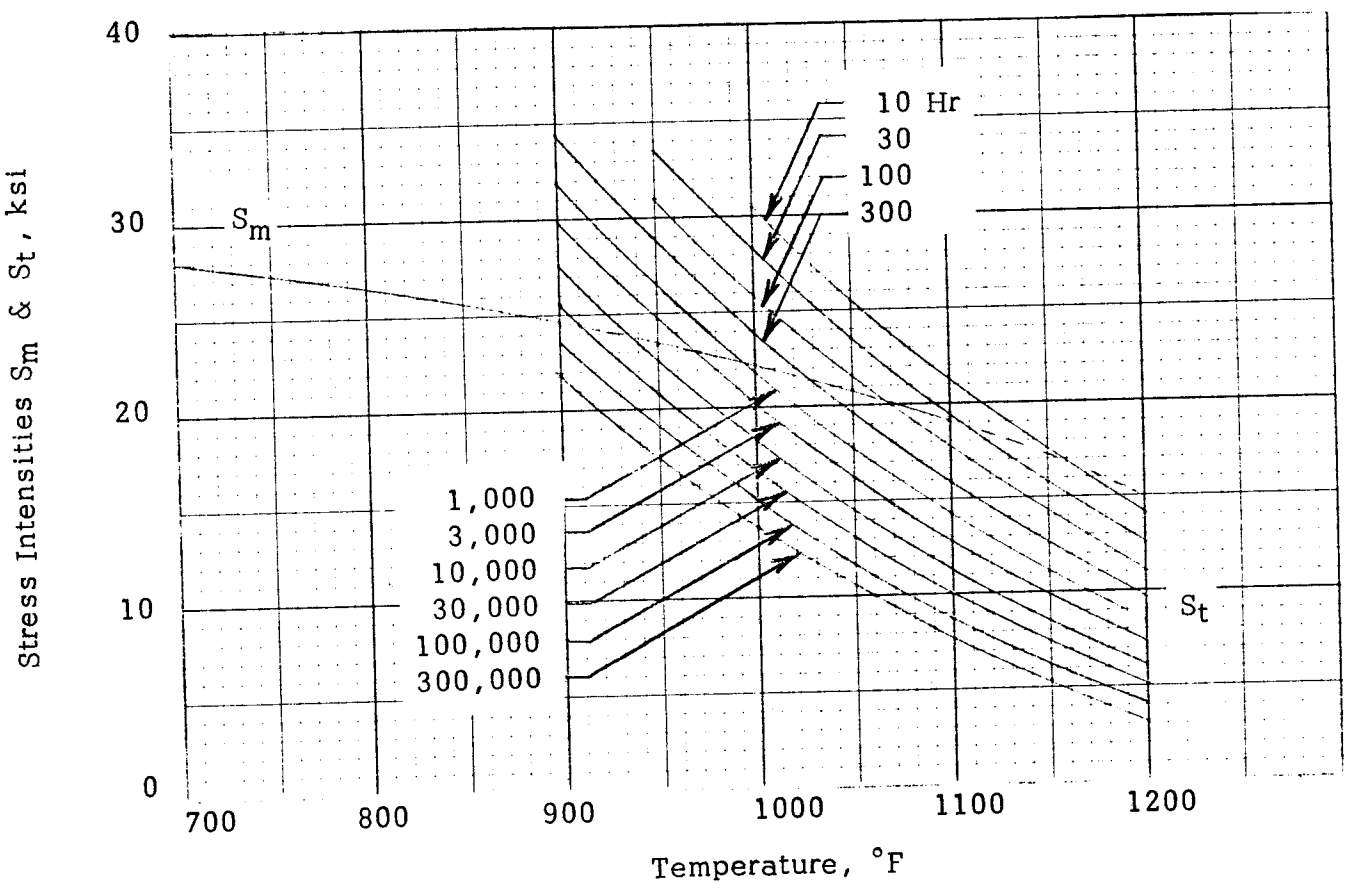


Figure 23. Stress Intensities S_m and S_t for Class of Material

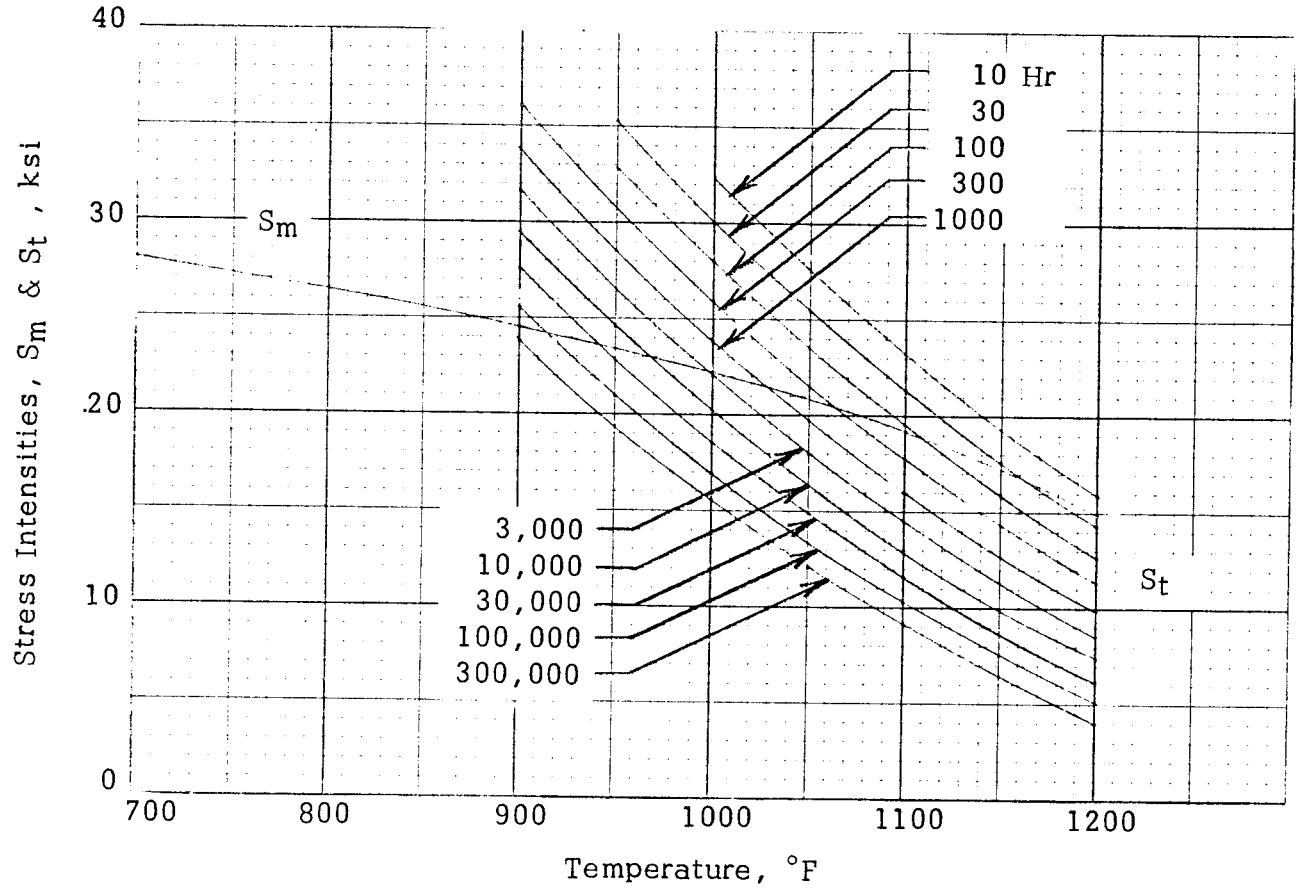


Figure 24. Stress Intensities S_m and S_t for Heat 91887

TABLE 1

SUMMARY OF TIMKEN DATA FOR PARAMETER ANALYSIS

Heat Number A261

Composition

C	Mn	Si	Cr	Ni	Mo	V	Cb	N_2	Al	Zr	B
0.105	0.45	0.65	9.33	0.20	1.06	0.31	0.120	0.047	0.027	0.007	0.011

Heat Treatment Normalize 1900°F, Temper 1350°F

Tensile Properties

Temp °F	Yield Strength, ksi	Tensile Strength, ksi	Percent Elongation	Percent Red. Area
Room	81.5	105.8	22	68.3
Room	85.5	108.2	23	67.7
300	71.5	95.8	22	71.3
500	69.2	92.2	22	65.5
700	66.0	89.7	20	61.4
900	62.4	78.5	24	74.0
1000	55.0	69.3	25	78.4
1100	48.2	55.7	32	85.5

Rupture Properties

Temp °F	Stress ksi	Rupture Time, hrs	Percent Elongation	Percent Red. Area
1000	45	34.2	31	79
1000	39	184.2	31	81
1100	29	49.1	30	81
1100	26	167.6	27	83
1100	21	4201.5	22	69
1200	18	58.5	30	84
1200	15	396.2	25	79
1200	13	2680.4	24	56
1300	10	74.8	34	83
1300	8	411.6	41	79
1300	6.8	1185.9	43	63

TABLE 1 (Cont,)

SUMMARY OF TIMKEN DATA FOR PARAMETER ANALYSIS

Heat Number 18723

Composition

C	Mn	Si	Cr	Ni	Mo	V	Cb	N_2	P	S
0.13	0.55	0.47	8.65	0.16	1.03	0.25	0.045	0.053	0.012	0.011

Heat Treatment Normalize 1900°F, Temper 1350°F

Rupture Properties

Temp °F	Stress ksi	Rupture Time, hrs	Percent Elongation	Percent Red. Area
1100	27	151.4	32.0	85.4
1100	23	1839.7	34.0	51.1
1100	20	5927.9	11.7	38.9
1100	18.5	25366.5	6.2	13.3
1200	18	127.6	37.5	84.7
1200	16	628.2	27.3	78.5
1200	14	2361.4	11.7	27.3
1300	10	305.4	28.9	65.4
1300	9	681.0	35.2	62.4
1300	7.5	2038.3	25.0	32.5
1300	6.2	3714.4	14.1	16.7

TABLE 2. CREEP AND STRESS RUPTURE RESULTS FOR HEAT 91887

Sample Ident.	Stress ksi	Temp °F	Atm.	Ld. Str. in/in	End Primary		Min Creep Rate, Hr^{-1}	Onset Tertiary		Rupture Time, Hrs	Rupture Elong, %	Red. in Area, %
					Str, in/in	Time, Hr		Str, in/in	Time, Hr			
EXAC	24	1100	Argon	0.00124	0.0100	610	5.99×10^{-6}	0.0148	1400	3132.8	15	85
EXAG	28	1100	Argon	0.00142	0.0154	38	2.01×10^{-4}	0.0219	70	198.2	27	89
EXAJ	28	1100	Air	0.00147	0.0144	93	6.32×10^{-5}	0.0199	180	485.2	16	85
EXAL	40	1000	Air	0.00153	0.0133	540	7.96×10^{-6}	0.0241	1840	3444.6	15	84
EXAQ	28	1100	Air	0.00133	0.0120	67	7.00×10^{-5}	0.0194	171	430.1	31	97
*EXAS	15	1250	Air	0.00151	0.0063	15	1.46×10^{-4}	0.0117	52	171.9	(B)	84
*EXAT	50	1000	Air	0.00244	0.0105	2.1	2.65×10^{-3}	0.0173	4.6	12.8	15	79
*EXAU	46	1000	Air	0.00236	0.0116	4.2	1.46×10^{-3}	0.0220	11.2	28.5	19	80
EXBG	46	1000	Air	0.00213	0.0122	45	1.02×10^{-4}	0.0213	131	228.9	15	83
EXBH	24	1100	Air	0.00117	0.0056	1500	8.32×10^{-7}			>5194 (A)		
EXBJ	16	1200	Air	0.00090	0.0037	300	3.85×10^{-6}			>3468 (A)		
* EXBK	19	1200	Air	0.00146	0.0048	20	7.41×10^{-5}	0.0091	75	230.4	(B)	81
*WC-A	14	1200	Air	0.0012	0.0043	500	2.99×10^{-6}	0.0100	2400	6073.4	29	78
*WC-B	23	1100	Air	0.0012	0.0078	1000	1.86×10^{-6}			>7700 (A)		
*WC-C	39	1000	Air	0.0023	0.0170	100	8.79×10^{-5}	0.0307	250	486.0	35	80
*WC-E	36	1000	Air	0.0014	0.0159	1500	3.00×10^{-6}			>7150 (A)		
DP-TC	38	1000	Air	0.00165						> 3950 (A)		

NOTE: (A) Test in progress.
(B) Broke outside gage length.
* Test material from internal identification code "WC". Other material from internal identification code "DP". Sample identification beginning EX tested at C-E and other identification tested at Materials Technology Corp.

Revised 6-28-77

TABLE 3 . CREEP AND STRESS RUPTURE RESULTS FOR HEAT ESR XA 3218

Sample Ident.	Stress ksi	Temp °F	Atm.	Ld. Str. in/in	End Primary		Min Creep Rate, Hr^{-1}	Onset Tertiary		Rupture Time, Hrs	Rupture Elong, %	Red. in Area, %
					Str, in/in	Time, Hr		Str, in/in	Time, Hr			
EXAB	24	1100	Argon	0.00128	0.0148	207	3.94×10^{-5}	0.0205	347	1043.6	17	79
EXAD	28	1100	Argon	0.00137	0.0108	17	3.09×10^{-4}	0.0228	55	143.9	25	85
EXAE	28	1100	Air	0.00134	0.0114	23	2.40×10^{-4}	0.0221	67	165.6	15	82
EXBA	24	1100	Air	0.00123	0.0178	550	1.40×10^{-5}	0.0270	1200	2254.2	15	70

NOTE: (A) Test in progress.

Revised 3-23-77

TABLE 4. CREEP AND STRESS RUPTURE RESULTS FOR HEAT ESR XA 3177

Sample Ident.	Stress ksi	Temp °F	Atm.	Ld. Str. in/in	End Primary		Min Creep Rate, Hr^{-1}	Onset Tertiary		Rupture Time, Hrs	Rupture Elong, %	Red. in Area, %
					Str, in/in	Time, Hr		Str, in/in	Time, Hr			
EXAV	28	1100	Air	0.00151	0.0283	33	3.59×10^{-4}	0.0427	73	164.8	24	87
EXAW	16	1200	Air	0.00142	0.0084	31	1.05×10^{-4}	0.0135	79	257.2	(B)	53
EXAX	24	1100	Air	0.00147	0.0212	284	2.05×10^{-5}	0.0370	1033	1920.9	19	77
EXAY	40	1000	Air	0.00206	0.0109	5.5	1.07×10^{-3}	0.0253	19.1	32.0	(B)	82
EXBC	14	1200	Air	0.00135	0.00469	47	3.09×10^{-5}	0.0107	235	840.6	14	49
EXBE	36	1000	Air	0.00152	0.0321	268	4.93×10^{-5}	0.0508	633	1123.7	21	83
EXBF	26	1100	Air	0.00149	0.0311	230	4.38×10^{-5}	0.0441	515	963	22	83
EXBI	38	1000	Air	0.00140	0.0181	23	4.15×10^{-4}	0.0493	95	179.1	25	77
WB-A	32	1000	Air	0.00145	0.0158	900	2.17×10^{-6}			>5152 (A)		
WB-B	22	1100	Air	0.0013	0.0110	550	4.33×10^{-6}	0.0261	3600	5385.1	25	58
WB-C	12	1200	Air	0.0017	0.0081	900	1.80×10^{-6}	0.0100	1800	5692.7	B	22

NOTE: (A) Test in progress.
(B) Broke outside gage length.

Sample identification beginning EX tested at C-E and other identification tested at Materials Technology Corp.

Revised 8-5-77

TABLE 5 . CREEP AND STRESS RUPTURE RESULTS FOR WELD SMA 109

Sample Ident.	Stress ksi	Temp °F	Atm.	Ld. Str. in/in	End Primary		Min Creep Rate, Hr^{-1}	Onset Tertiary		Rupture Time, Hrs	Rupture Elong, %	Red. in Area, %
					Str, in/in	Time, Hr		Str, in/in	Time, Hr			
EXAF	28	1100	Air	0.00124	0.0132	1.7	4.83×10^{-3}	0.0275	4.6	13.85	24	80
EXAM	40	1000	Air	0.00140	0.0079	2.3	2.07×10^{-3}	0.0150	5.7	19.45	(A)	73
EXAO	15	1200	Air	(B)	0.0140(B)	23 (B)	3.30×10^{-4}(B)	0.0190(B)	38	73.1	(A)	56

NOTE: (A) Broke outside gage length.
(B) Test problems prevented accurate determination.

Revised 8-4-76

TABLE 6 CREEP AND STRESS RUPTURE RESULTS FOR WELD SMA 111

Sample Ident.	Stress ksi	Temp °F	Atm.	Ld. Str. in/in	End Primary		Min Creep Rate, Hr^{-1}	Onset Tertiary		Rupture Time, Hrs	Rupture Elong, %	Red. in Area, %
					Str, in/in	Time, Hr		Str, in/in	Time, Hr			
EXAH	28	1100	Air	0.00130	0.0163	12	5.91×10^{-4}	0.0390	49	87.2	16	78
EXAI	18	1200	Air	0.00051	0.0094	35	9.66×10^{-5}	0.0192	131	192.2	(B)	34
EXAK	40	1000	Air	0.00115	0.0203	90	1.30×10^{-4}	0.0342	192	300.9	14	74
EXAP	25	1100	Air	0.00117	0.0088	560	4.50×10^{-6}	0.0158	2090	2551.9	5	36
EXAR	16	1200	Air	0.00053	0.0055	40	2.60×10^{-5}	0.0143	350	549.8	(B)	13
EXBB	37	1000	Air	0.00221	0.0161	48	1.61×10^{-4}	0.0381	183	323.8	18	75
EXBD	34	1000	Air	0.00110	0.0223	450	1.78×10^{-5}	0.0391	1380	2056.4	13	73

NOTE: (A) Test in progress.
(B) Broke outside gage length.

Revised 3-23-77

Table 7 . Tensile and Yield Strength Summary for Class of Material

Identification		Room Temp.		900°F		1000°F		1100°F	
Number	Processing History	UTS	Yield	UTS	Yield	UTS	Yield	UTS	Yield
3090	HP, HF, Hot Rolled to 1/2"	100.4	76.0	75.6	58.8	67.4	55.6	59.0	50.8
3154A	HP, HF, Cold Rolled to 1/2"	110.0	86.4	76.8	63.6	66.0	58.8	54.2	48.4
3154A	HF to 1/2"	113.2	87.6	87.6	68.4	73.4	63.6	58.3	54.0
3154B	HP, HF, Hot Rolled to 1/2"	115.2	93.6	85.6	73.2	74.4	64.8	61.7	53.4
3155	Hot Rolled to 1/2"	108.0	82.7	79.6	62.8	70.8	60.0	60.0	55.8
3156	HP, HF, Cold Rolled to 1/2"	117.8	90.0	86.3	68.4	74.6	63.0	62.6	56.4
3157	HP, HF, Cold Rolled to 1/2"	118.3	87.6	83.0	65.4	71.1	60.0	61.7	52.8
3159	Hot Forged to 1/2" (by Cartech)	116.7	94.8	87.8	80.4	77.4	68.0	70.3	62.4
3160	Hot Forged to 1/2" (by Cartech)	121.4	97.8	92.8	84.0	81.5	74.4	66.0	61.2
3161	Hot Forged to 1/2" (by Cartech)	114.0	96.0	80.3	70.8	72.0	64.8	63.0	60.0
3161	HF to 1" Hot Rolled to 1/2", MML	107.5	86.4	78.3	61.2	69.0	61.8	59.4	55.6
3162	Hot Forged to 1/2" (by Cartech)	106.0	90.0	76.3	64.8	69.8	63.6	59.2	55.8
3162	HF to 1" Hot Rolled to 1/2", MML	104.8	80.4	73.2	60.0	65.0	54.6	55.2	51.0
3163	Hot Forged to 1/2" (by Cartech)	110.6	91.2	81.7	70.8	73.0	66.1	61.6	56.4
3163	HF to 1" Hot Rolled to 1/2" MML	113.1	90.2	84.4	73.2	76.8	68.4	66.0	60.0
3175	Hot Rolled to 1/2" MML	117.6	104.0	87.4	80.4	78.6	73.2	66.4	64.8
3176	Hot Rolled to 1/2" MML	105.7	86.4	77.2	67.2	70.5	63.0	59.8	56.4
3177	Hot Rolled to 1/2" MML	120.2	101.6	87.3	78.4	76.2	70.8	62.2	58.8
3178	Hot Rolled to 1/2" MML	109.6	99.0	81.0	68.8	74.4	64.8	64.4	59.4
3179	Hot Rolled to 1/2" MML	100.6	79.8	71.0	62.0	66.0	57.6	56.6	52.8
3180	Hot Forged to 1/2" (by Cartech)	98.5	75.0	71.4	58.8	64.2	55.8	58.2	50.2
3181	Hot Rolled to 1/2" MML	102.8	80.8	73.6	61.2	66.0	59.4	53.6	49.2
3182	Hot Forged to 1/2" (by Cartech)	96.5	74.1	72.1	58.8	65.3	54.7	56.0	50.4
3183	Hot Forged to 1/2" (by Cartech)	96.7	74.2	72.4	58.8	64.6	53.4	55.8	48.6
3184	Hot Forged to 1/2" (by Cartech)	95.5	74.9	68.8	57.6	63.1	53.3	53.6	48.0
3185	Hot Forged to 1/2" (by Cartech)	95.9	72.4	72.2	53.9	63.8	52.7	54.2	48.0
3186	Hot Rolled to 1/2" MML	97.0	74.4	70.8	61.8	62.8	58.2	55.0	50.4
3187	Hot Rolled to 1/2" MML	94.9	73.7	70.4	57.6	63.7	54.9	56.8	49.2
3188	Hot Rolled to 1/2" MML	92.8	74.4	68.0	58.8	61.2	54.4	54.2	48.0
91887	Hot Rolled to 3/4" MML	97.7	79.9	70.6	63.6	64.9	58.8	56.2	53.0
	Average, KSI	106.6	85.2	78.1	65.8	69.6	61.1	59.4	54.0
	Average, MPa	735	587	538	454	480	421	410	372
	Minimum, KSI	92.1	69.7	66.6	53.0	60.5	51.1	52.1	46.1
	Minimum, MPa	635	481	459	365	417	352	359	318

Table 8 . Estimates of Minimum Tensile and Yield Strength between 70 and 900°F (21 and 482°C)

Quantity	Temperature				
	21°C 70°F	149°C 300°F	260°C 500°F	371°C 700°F	482°C 900°F
Min UTS, KSI Min UTS, MPa	92.1 635	82.1 566	78.8 543	76.3 526	66.6 459
Min YS, KSI Min YS, MPa	69.7 481	59.9 413	58.3 402	55.8 385	53.0 365

Table 9 Values of the Equation Constants in the Larson-Miller Curvefits for Class of Material

Quantity	Qty	a	b	C	d
Rupture	Avg Min	61636 60731	3902.49	30.6	-7647.79
0.2 Percent Tertiary	Avg Min	57471 56458	9828.51	30.6	-9745.11
Secondary Creep Rate	Avg Min	68293 66822	3269.55	31.5	-8467.61
1 Percent Strain	Avg Min	78586 77021	-20990.9	30.6	720.88

Table 10 Expected Values of Stress-to-Rupture for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A	A 52.6 (363)	49.2 (339)	45.6 (315)	42.5 (293)	39.3 (271)	36.5 (252)
950	510	A	A	A 51.2 (353)	47.7 (329)	44.1 (304)	41.0 (282)	37.7 (260)	34.9 (241)	32.0 (220)	29.4 (203)
1000	538	A 50.3 (347)	46.7 (322)	43.0 (297)	39.8 (275)	36.5 (252)	33.7 (232)	30.7 (212)	28.2 (194)	25.6 (176)	23.3 (161)
1050	566	42.5 (293)	39.2 (270)	35.8 (247)	32.9 (227)	29.9 (206)	27.3 (188)	24.7 (170)	22.4 (154)	20.0 (138)	18.0 (124)
1100	593	35.5 (245)	32.6 (225)	29.5 (203)	26.8 (185)	24.1 (166)	21.8 (150)	19.4 (134)	17.4 (120)	15.3 (105)	13.5 (93)
1150	621	29.4 (203)	26.7 (184)	23.9 (165)	21.5 (148)	19.1 (132)	17.1 (117)	14.9 (102)	13.0 (90)	11.2 (77)	9.6 (66)
1200	649	24.0 (165)	21.5 (148)	19.0 (131)	16.9 (116)	14.7 (101)	12.8 (88)	10.9 (75)	9.3 (64)	7.7 (53)	6.3 (43)

A - Above stress range of master curve (50 KSI).

Table 11 Minimum Values of Stress-to-Rupture for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A 51.6 (356)	47.9 (330)	44.7 (308)	41.4 (285)	38.4 (265)	35.4 (244)	32.8 (226)
950	510	A	A 50.3 (347)	46.5 (321)	43.3 (299)	39.9 (275)	37.0 (255)	33.9 (234)	31.3 (216)	28.6 (197)	26.2 (181)
1000	538	45.7 (315)	42.4 (292)	38.9 (268)	36.0 (248)	32.9 (227)	30.2 (208)	27.5 (189)	25.1 (173)	22.6 (156)	20.6 (142)
1050	566	38.4 (265)	35.4 (244)	32.2 (222)	29.5 (203)	26.7 (184)	24.3 (168)	21.8 (150)	19.7 (136)	17.5 (121)	15.7 (108)
1100	593	31.9 (220)	29.2 (201)	26.3 (181)	23.8 (164)	21.3 (147)	19.2 (132)	16.9 (117)	15.0 (104)	13.1 (90)	11.5 (79)
1150	621	26.2 (181)	23.7 (163)	21.1 (145)	18.9 (130)	16.6 (115)	14.7 (101)	12.7 (88)	11.1 (76)	9.3 (64)	7.9 (54)
1200	649	21.2 (146)	18.9 (130)	16.6 (114)	14.6 (101)	12.6 (87)	10.9 (75)	9.1 (63)	7.6 (53)	B 6.1 (42)	B 4.7 (33)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (6.2 KSI).

Table 12 Expected Values of 0.2 Percent Tertiary for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A	A 51.7 (357)	48.5 (334)	45.1 (311)	42.2 (291)	39.1 (270)	36.4 (251)
950	510	A	A	A 50.4 (347)	47.1 (325)	43.7 (301)	40.7 (280)	37.6 (259)	34.8 (240)	32.0 (220)	29.5 (203)
1000	538	49.5 (342)	46.2 (318)	42.7 (294)	39.6 (273)	36.4 (251)	33.7 (232)	30.8 (212)	28.3 (195)	25.6 (177)	23.4 (161)
1050	566	42.1 (291)	39.0 (269)	35.8 (247)	32.9 (227)	30.0 (207)	27.4 (189)	24.7 (171)	22.4 (155)	20.0 (138)	17.9 (124)
1100	593	35.5 (245)	32.6 (225)	29.5 (204)	26.9 (186)	24.2 (167)	21.8 (151)	19.4 (134)	17.2 (119)	15.0 (104)	13.1 (90)
1150	621	29.5 (203)	26.8 (185)	24.0 (165)	21.5 (149)	19.0 (131)	16.8 (116)	14.6 (101)	12.6 (87)	B 10.6 (73)	B 8.8 (60)
1200	649	24.0 (166)	21.6 (149)	19.0 (131)	16.7 (115)	14.4 (99)	12.4 (85)	B 10.3 (71)	B 8.4 (58)	B 6.3 (44)	B 3.8 (26)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 13 Minimum Values of 0.2 Percent Tertiary for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A 50.2 (346)	46.8 (322)	43.8 (302)	40.6 (280)	37.8 (261)	34.9 (241)	32.4 (223)
950	510	A 52.4 (361)	49.0 (338)	45.5 (314)	42.4 (203)	39.2 (270)	36.4 (251)	33.5 (231)	30.9 (213)	28.3 (195)	26.0 (179)
1000	538	44.7 (308)	41.6 (287)	38.3 (264)	35.4 (244)	32.4 (224)	29.9 (206)	27.2 (187)	24.8 (171)	22.4 (154)	20.2 (139)
1050	566	37.8 (260)	34.9 (240)	31.8 (219)	29.2 (201)	26.4 (182)	24.0 (166)	21.5 (148)	19.4 (133)	17.1 (118)	15.2 (104)
1100	593	31.5 (217)	28.8 (199)	26.0 (179)	23.6 (162)	21.0 (145)	18.8 (130)	16.5 (114)	14.5 (100)	12.4 (86)	B 10.6 (73)
1150	621	25.9 (179)	23.4 (161)	20.8 (143)	18.5 (128)	16.2 (112)	14.2 (98)	12.0 (83)	B 10.2 (70)	B 8.2 (56)	B 6.3 (44)
1200	649	20.9 (144)	18.6 (128)	16.1 (111)	14.0 (97)	B 11.8 (82)	B 9.9 (69)	B 7.9 (54)	B 5.9 (41)	B 4.3 (30)	

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 14 Expected Values for Secondary Creep Rate for Class of Materials from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10^{-3}	3×10^{-4}	10^{-4}	Rate, Hours^{-1} 3×10^{-5}	Rate, Hours^{-1} 10^{-5}	3×10^{-6}	10^{-6}	3×10^{-7}	10^{-7}	3×10^{-8}
900	482	A	A	A	A 51.9 (358)	49.0 (338)	45.9 (316)	43.2 (298)	40.3 (278)	37.9 (261)	35.3 (243)
950	510	A	A 50.1 (346)	47.1 (325)	44.0 (304)	41.3 (285)	38.5 (265)	36.0 (248)	33.4 (230)	31.2 (215)	28.8 (199)
1000	538	45.8 (316)	42.6 (294)	39.9 (275)	37.0 (255)	34.5 (238)	31.9 (220)	29.7 (205)	27.3 (188)	25.3 (174)	23.2 (160)
1050	566	38.9 (268)	36.0 (248)	33.4 (230)	30.8 (212)	28.5 (197)	26.2 (181)	24.1 (166)	22.0 (152)	20.2 (139)	18.3 (126)
1100	593	32.7 (226)	30.0 (207)	27.7 (191)	25.3 (175)	23.3 (161)	21.1 (146)	19.3 (133)	17.4 (120)	15.8 (109)	14.1 (97)
1150	621	27.2 (191)	24.8 (171)	22.7 (57)	20.5 (142)	18.7 (129)	16.8 (115)	15.1 (104)	13.4 (92)	12.0 (82)	B 10.5 (72)
1200	649	22.4 (154)	20.2 (139)	18.3 (126)	16.3 (113)	14.7 (101)	12.9 (89)	B 11.5 (79)	B 10.0 (69)	B 8.7 (60)	B 7.3 (51)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 15 Minimum Values of Secondary Creep Rate for Class of Materials from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10^{-3}	3×10^{-4}	10^{-4}	Rate, Hours^{-1} 3×10^{-5}	Rate, Hours^{-1} 10^{-5}	3×10^{-6}	10^{-6}	3×10^{-7}	10^{-7}	3×10^{-8}
900	482	A	A 51.4 (354)	48.5 (334)	45.4 (313)	42.7 (294)	39.9 (275)	37.5 (258)	34.9 (241)	32.7 (225)	30.3 (209)
950	510	46.9 (323)	43.8 (302)	41.1 (283)	38.2 (264)	35.8 (247)	33.2 (229)	31.0 (214)	28.6 (197)	26.6 (183)	24.5 (169)
1000	538	39.8 (275)	37.0 (255)	34.5 (238)	31.9 (220)	29.6 (204)	27.3 (188)	25.3 (174)	23.2 (160)	21.3 (147)	19.4 (134)
1050	566	33.6 (231)	30.9 (213)	28.7 (198)	26.3 (184)	24.2 (167)	22.1 (153)	20.3 (140)	18.4 (127)	16.8 (116)	15.1 (104)
1100	593	28.0 (193)	25.6 (176)	23.5 (62)	21.4 (147)	19.5 (135)	17.6 (121)	16.0 (110)	14.3 (98)	12.8 (88)	B 11.3 (78)
1150	621	23.1 (159)	20.9 (144)	19.0 (131)	17.1 (118)	15.4 (106)	13.7 (94)	12.2 (84)	B 10.7 (74)	B 9.4 (65)	B 8.1 (56)
1200	649	18.7 (129)	16.8 (115)	15.0 (104)	13.3 (92)	B 11.8 (81)	B 10.3 (71)	B 9.0 (62)	B 7.6 (53)	B 6.5 (45)	B 5.3 (36)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 16 Expected Values of 1 Percent Total Strain for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A		42.4 (292)	38.8 (268)	35.8 (247)	32.8 (226)	30.3 (209)
				54.3 (375)	50.1 (346)	45.9 (316)					
950	510	A	48.6 (335)	44.4 (306)	40.8 (282)	37.3 (257)	34.3 (237)	31.4 (216)	28.9 (199)	26.4 (182)	24.4 (168)
		52.9 (365)									
1000	538	43.5 (300)	39.9 (275)	36.3 (250)	33.3 (230)	30.4 (209)	27.9 (192)	25.4 (175)	23.4 (161)	21.3 (147)	19.6 (135)
1050	566	35.8 (247)	32.8 (226)	29.7 (205)	27.2 (188)	24.7 (171)	22.7 (156)	20.6 (142)	18.9 (130)	17.2 (119)	15.8 (109)
1100	593	29.5	26.9 (186)	24.4 (168)	22.3 (154)	20.2 (139)	18.5 (127)	16.7 (115)	15.3 (106)	13.9 (96)	12.7 (88)
1150	621	24.3 (203)	22.2 (153)	20.0 (138)	18.3 (126)	16.5 (114)	15.1 (104)	13.6 (94)	12.4 (86)	B 11.3 (78)	B 10.3 (71)
1200	649	20.1 (139)	18.3 (126)	16.5 (114)	15.0 (103)	13.5 (93)	12.3 (85)	B 11.1 (76)	B 10.1 (70)	B 9.1 (63)	B 8.3 (57)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 17 Minimum Values of 1 Percent Total Strain for Class of Material from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A 53.0 (365)	48.9 (337)	44.7 (308)	41.3 (285)	37.8 (261)	34.9 (241)	32.0 (221)	29.6 (204)	27.1 (187)	25.1 (173)
950	510	43.5 (300)	40.1 (276)	36.6 (252)	33.7 (232)	30.8 (212)	28.4 (196)	25.9 (179)	23.9 (165)	21.9 (151)	20.2 (139)
1000	538	35.8 (247)	32.9 (227)	30.0 (207)	27.5 (192)	25.1 (173)	23.1 (159)	21.0 (145)	19.3 (133)	17.6 (122)	16.2 (112)
1050	566	29.5 (204)	27.0 (187)	24.6 (169)	22.5 (155)	20.5 (141)	18.8 (129)	17.1 (118)	15.7 (108)	14.3 (98)	13.1 (90)
1100	593	24.4 (168)	22.3 (154)	20.2 (139)	18.4 (127)	16.7 (115)	15.3 (106)	13.9 (96)	12.7 (88)	B 11.5 (80)	B 10.6 (73)
1150	621	20.1 (139)	18.4 (127)	16.6 (114)	15.1 (104)	13.7 (94)	12.5 (86)	B 11.3 (78)	B 10.3 (71)	B 9.4 (65)	B 8.6 (59)
1200	649	16.6 (114)	15.2 (104)	13.7 (94)	12.4 (86)	B 11.2 (77)	B 10.2 (70)	B 9.2 (64)	B 8.4 (58)	B 7.6 (52)	B 6.9 (48)

A - Above stress range of master curve (50 KSI).
B - Below stress range of master curve (12 KSI).

Table 18 Raw Data Used in Analysis of Rupture for Class of Material

Temp, °F	Stress, ksi	Time, Hrs.	Description
1000	45.	34.2	A-261 TIMKEN RUPTURE
1000	39.	184.2	A-261 TIMKEN RUPTURE
1000	50.	12.8	EXAT 91887 RUPTURE
1000	46.	228.9	EXBG 91887 RUPTURE
1000	46.	28.5	EXAU 91887 RUPTURE
1000	40.	3444.6	EXAL 91887 RUPTURE
1000	39.	486.0	WC-C 91887 RUPTURE
1000	38.	1819.0	DP-TC 91887 STILL RUNNINGRUPTURE
1000	36.	4847.0	WC-E 91887 STILL RUNNINGRUPTURE
1000	40.	32.0	EXAY 3177 RUPTURE
1000	38.	179.1	EXBI 3177 RUPTURE
1000	36.	1123.7	EXBE 3177 RUPTURE
1000	32.	3138.0	WB-A 3177 STILL RUNNINGRUPTURE
1000	40.	300.90	EXAK SMA111 RUPTURE
1000	37.	323.80	EXBB SMA111 RUPTURE
1000	34.	2056.4	EXBD SMA111 RUPTURE
1100	29.	49.1	A-261 TIMKEN RUPTURE
1100	26.	167.6	A-261 TIMKEN RUPTURE
1100	21.	4201.5	A-261 TIMKEN RUPTURE
1100	27.	151.4	18723 TIMKEN RUPTURE
1100	23.	1839.7	18723 TIMKEN RUPTURE
1100	20.	5927.9	18723 TIMKEN RUPTURE
1100	18.5	25366.5	18723 TIMKEN RUPTURE
1100	28.	485.2	EXAJ 91887 RUPTURE
1100	28.	430.1	EXAQ 91887 RUPTURE
1100	28.	198.2	EXAG 91887 RUPTURE
1100	24.	3132.8	EXAC 91887 RUPTURE
1100	24.	2869.0	EXBH 91887 STILL RUNNING RUPTURE
1100	23.	5469.0	WC-B 91887 STILL RUNNING RUPTURE

Table 18 Raw Data Used in Analysis of Rupture for Class of Material (Cont.)

Temp, °F	Stress, ksi	Time, Hrs.	Description
1100	28.	164.8	EXAV 3177 RUPTURE
1100	26.	963.0	EXBF 3177 RUPTURE
1100	24.	1920.9	EXAX 3177 RUPTURE
1100	22.	3129.0	WB-B 3177 STILL RUNNINGRUPTURE
1100	28.	165.6	EXAE 3218 RUPTURE
1100	28.	143.9	EXAD 3218 RUPTURE
1100	24.	2254.2	EXBA 3218 RUPTURE
1100	24.	1043.6	EXAB 3218 RUPTURE
1100	28.	87.2	EXAH SMA111 RUPTURE
1100	25.	2551.9	EXAP SMA111 RUPTURE
1200	18.	58.5	A-261 TIMKEN RUPTURE
1200	15.	396.2	A-261 TIMKEN RUPTURE
1200	13.	2680.4	A-261 TIMKEN RUPTURE
1200	18.	127.6	18723 TIMKEN RUPTURE
1200	16.	628.2	18723 TIMKEN RUPTURE
1200	14.	2361.4	18723 TIMKEN RUPTURE
1200	16.	1142.0	EXBJ 91887 STILL RUNNING RUPTURE
1200	14.	5440.0	WC-A 91887 STILL RUNNING RUPTURE
1200	16.	257.20	EXAW 3177 RUPTURE
1200	14.	840.9	EXBC 3177 RUPTURE
1200	12.	3119.0	WB-C 3177 STILL RUNNINGRUPTURE
1200	18.	192.2	EXAI SMA111 RUPTURE
1200	16.	549.8	EXAR SMA111 RUPTURE
1250	15.	171.9	EXAS 91887 RUPTURE
1300	10.	74.8	A-261 TIMKEN RUPTURE
1300	8.	411.6	A-261 TIMKEN RUPTURE
1300	6.8	1185.9	A-261 TIMKEN RUPTURE
1300	10.	305.4	18723 TIMKEN RUPTURE
1300	9.	681.0	18723 TIMKEN RUPTURE
1300	7.5	2038.3	18723 TIMKEN RUPTURE
1300	6.2	3714.4	18723 TIMKEN RUPTURE

Table 19 Raw Data Used in Analysis of 0.2 Percent Tertiary for Class of Material

Temp, °F	Stress, ksi	Time, Hrs.	Description
1000	50.	8.13	EXAT 91887 .2 PCT TERTIARY
1000	46.	183.0	EXBG 91887 .2 PCT TERTIARY
1000	46.	17.2	EXAU 91887 .2 PCT TERTIARY
1000	40.	2527.0	EXAL 91887 .2 PCT TERTIARY
1000	39.	320.0	WC-C 91887 .2 PCT TERTIARY
1000	38.	109.0	EXBI 3177 .2 PCT TERTIARY
1000	36.	743.0	EXBE 3177 .2 PCT TERTIARY
1000	40.	234.7	EXAK SMA-111 .2 PCT TERTIARY
1000	37.	225.0	EXBB SMA-111 .2 PCT TERTIARY
1000	34.	1703.0	EXBD SMA-111 .2 PCT TERTIARY
1100	28.	304.0	EXAJ 91887 .2 PCT TERTIARY
1100	28.	282.0	EXAQ 91887 .2 PCT TERTIARY
1100	28.	117.0	EXAG 91887 .2 PCT TERTIARY
1100	24.	2320.0	EXAC 91887 .2 PCT TERTIARY
1100	23.	7030.0	WC-B 91887 .2 PCT TERTIARY
1100	28.	103.0	EXAV 3177 .2 PCT TERTIARY
1100	26.	620.0	EXBF 3177 .2 PCT TERTIARY
1100	24.	1290.0	EXAX 3177 .2 PCT TERTIARY
1100	22.	3670.0	WB-B 3177 .2 PCT TERTIARY
1100	28.	59.2	EXAH SMA-111 .2 PCT TERTIARY
1100	25.	2517.0	EXAP SMA-111 .2 PCT TERTIARY
1100	28.	80.3	EXAD 3218 .2 PCT TERTIARY
1100	28.	107.5	EXAE 3218 .2 PCT TERTIARY
1100	24.	613.0	EXAB 3218 .2 PCT TERTIARY
1100	24.	1691.0	EXBA 3218 .2 PCT TERTIARY
1200	19.	135.0	EXBK 91887 .2 PCT TERTIARY
1200	14.	4075.0	WC-A 91887 .2 PCT TERTIARY
1200	16.	146.0	EXAW 3177 .2 PCT TERTIARY
1200	14.	395.0	EXBC 3177 .2 PCT TERTIARY
1200	12.	3110.0	WB-C 3177 .2 PCT TERTIARY
1200	18.	167.7	EXAI SMA-111 .2 PCT TERTIARY
1200	16.	422.0	EXAR SMA-111 .2 PCT TERTIARY
1250	15.	103.0	EXAS 91887 .2 PCT TERTIARY

Table 20 Raw Data Used in Analysis of Secondary Creep Rate for Class of Material

Temp, °F	Stress, ksi	Time, Hrs.	Description		
1000	50.	2.65E-03	EXAT	91887	MCR
1000	46.	1.46E-03	EXAU	91887	MCR
1000	46.	1.02E-04	EXBG	91887	MCR
1000	40.	7.96E-06	EXAL	91887	MCR
1000	40.	1.07E-03	EXAY	3177	MCR
1000	40.	1.30E-04	EXAK	111	MCR
1000	39.	8.79E-05	WC-C	91887	MCR
1000	38.	4.15E-04	EXBI	3177	MCR
1000	37.	1.61E-04	EXBB	111	MCR
1000	36.	3.00E-06	WC-E	91887	MCR
1000	36.	4.93E-05	EXBE	3177	MCR
1000	34.	1.78E-05	EXBD	111	MCR
1000	32.	2.17E-06	WB-A	3177	MCR
1100	28.	2.01E-04	EXAG	91887	MCR
1100	28.	6.32E-05	EXAJ	91887	MCR
1100	28.	7.00E-05	EXAQ	91887	MCR
1100	28.	3.09E-04	EXAD	3218	MCR
1100	28.	2.40E-04	EXAE	3218	MCR
1100	28.	3.59E-04	EXAV	3177	MCR
1100	28.	5.91E-04	EXAH	111	MCR
1100	26.	4.38E-05	EXBF	3177	MCR
1100	25.	4.50E-06	EXAP	111	MCR
1100	24.	5.99E-06	EXAC	91887	MCR
1100	24.	8.32E-07	EXBH	91887	MCR
1100	24.	3.94E-05	EXAB	3218	MCR
1100	24.	1.40E-05	EXBA	3218	MCR
1100	24.	2.05E-05	EXAX	3177	MCR
1100	23.	1.86E-06	WC-B	91887	MCR
1100	22.	4.33E-06	WB-B	3177	MCR
1200	18.	9.66E-05	EXAI	111	MCR
1200	16.	3.85E-06	EXBJ	91887	MCR
1200	16.	1.05E-04	EXAW	3177	MCR
1200	16.	2.60E-05	EXAR	111	MCR
1200	14.	2.99E-06	WC-A	91887	MCR
1200	14.	3.09E-05	EXBC	3177	MCR
1200	12.	1.80E-06	WB-C	3177	MCR
1250	15.	1.46E-04	EXAS	91887	MCR

Table 21 Raw Data Used in Analysis of One Percent Total Strain for Class of Material

Temp. °F	Stress, ksi	Time, Hrs.	Description		
1000	50.	1.91	EXAT	91887	1 PCT
1000	46.	26.8	EXBG	91887	1 PCT
1000	46.	3.16	EXAU	91887	1 PCT
1000	40.	237.0	EXAL	91887	1 PCT
1000	40.	4.7	EXAY	3177	1 PCT
1000	40.	27.1	EXAK	111	1 PCT
1000	39.	31.0	WC-C	91887	1 PCT
1000	38.	1880.0	DP-TC	91887	1 PCT
1000	38.	8.5	EXBI	3177	1 PCT
1000	37.	19.0	EXBB	111	1 PCT
1000	36.	415.0	WC-E	91887	1 PCT
1000	36.	23.0	EXBE	3177	1 PCT
1000	34.	65.0	EXBD	111	1 PCT
1000	32.	195.0	WB-A	3177	1 PCT
1100	28.	41.7	EXAQ	91887	1 PCT
1100	28.	36.5	EXAJ	91887	1 PCT
1100	28.	15.6	EXAG	91887	1 PCT
1100	28.	17.8	EXAE	3218	1 PCT
1100	28.	14.6	EXAD	3218	1 PCT
1100	28.	2.86	EXAV	3177	1 PCT
1100	28.	4.47	EXAH	111	1 PCT
1100	26.	7.66	EXBF	3177	1 PCT
1100	25.	804.	EXAP	111	1 PCT
1100	24.	610.0	EXAC	91887	1 PCT
1100	24.	136.0	EXBA	3218	1 PCT
1100	24.	98.7	EXAB	3218	1 PCT
1100	24.	18.3	EXAX	3177	1 PCT
1100	23.	2100.	WC-B	91887	1 PCT
1100	22.	375.0	WB-B	3177	1 PCT
1200	19.	85.2	EXBK	91887	1 PCT
1200	18.	40.3	EXAI	111	1 PCT
1200	16.	46.0	EXAW	3177	1 PCT
1200	16.	202.	EXAR	111	1 PCT
1200	14.	2400.	WC-A	91887	1 PCT
1200	14.	213.0	EXBC	3177	1 PCT
1200	12.	1800.0	WB-C	3177	1 PCT
1250	15.	40.2	EXAS	91887	1 PCT

Table 22 Comparison of Minimum Tensile and Yield Strengths for Heat 91887 and Class of Material

Heat		RT	900°F	1000°F	1100°F
Ultimate Tensile Strength, KSI					
91887	Actual Ratio Min	97.7 1.000 92.1	70.6 0.723 66.6	64.9 0.664 61.2	56.2 0.575 53.0
Class	Min	92.1	66.6	60.5	52.1
Yield Strength, KSI					
91887	Actual Ratio Min	79.9 1.000 69.7	63.6 0.796 55.5	58.8 0.736 51.3	53.0 0.663 46.2
Class	Min	69.7	53.0	51.1	46.1

Table 23 Values of the Equation Constants in the Larson-Miller Curvefits for Heat 91887

Quantity	Qty	a	b	C	d
Rupture	Avg Min	60869 59982	6867.72	30.6	-8952.81
0.2 Percent Tertiary	Avg Min	63878 62828	2269.03	30.6	-7399.57
Secondary Creep Rate	Avg Min	64590 63352	9547.75	31.5	-10688.5
1 Percent Strain	Avg	73656 72383	-11793.1	30.6	-2845.50

Table 24 Expected Values of Stress-to-Rupture for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A	A	A				
							51.7 (356)	48.3 (333)	45.2 (312)	42.0 (290)	39.3 (271)
950	510	A	A	A	A						
				53.6 (370)	50.3 (347)	46.7 (322)	43.7 (301)	40.5 (279)	37.7 (260)	34.7 (239)	32.2 (222)
1000	538	A									
		52.8 (364)	49.3 (340)	45.7 (315)	42.6 (294)	39.3 (271)	36.5 (252)	33.5 (231)	30.9 (213)	28.3 (195)	26.0 (179)
1050	566	45.2 (312)	42.0 (290)	38.6 (266)	35.7 (246)	32.7 (225)	30.1 (208)	27.4 (189)	25.0 (172)	22.6 (156)	20.5 (141)
1100	593	38.3 (264)	35.3 (243)	32.2 (222)	29.6 (204)	26.8 (185)	24.4 (168)	21.9 (151)	19.8 (137)	17.6 (121)	15.7 (108)
1150	621	32.2 (222)	29.4 (203)	26.6 (183)	24.1 (166)	21.6 (149)	19.4 (134)	17.2 (119)	15.2 (105)	B 13.2 (91)	B 11.5 (79)
1200	649	26.7 (184)	24.1 (166)	21.5 (148)	19.3 (133)	17.0 (117)	15.0 (103)	B 12.9 (89)	B 11.2 (77)	B 9.4 (65)	B 7.8 (54)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 25 Minimum Values of Stress-to-Rupture for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A 54.1 (373)	A 50.5 (348)	47.4 (327)	44.1 (304)	41.3 (285)	38.3 (264)	35.7 (246)
950	510	A	A 52.9 (365)	49.2 (339)	46.1 (318)	42.7 (294)	39.8 (274)	36.8 (254)	34.2 (236)	31.4 (217)	29.0 (200)
1000	538	48.4 (334)	45.2 (312)	41.8 (288)	38.8 (268)	35.7 (246)	33.1 (228)	30.3 (209)	27.9 (192)	25.4 (175)	23.2 (160)
1050	566	41.2 (284)	38.2 (263)	35.1 (242)	32.3 (223)	29.5 (203)	27.0 (186)	24.5 (169)	22.3 (154)	20.0 (138)	18.1 (125)
1100	593	34.8 (240)	32.0 (221)	29.1 (201)	26.6 (183)	24.0 (165)	21.7 (150)	19.4 (134)	17.4 (120)	15.3 (105)	B 13.6 (94)
1150	621	29.0 (200)	26.4 (182)	23.8 (164)	21.5 (148)	19.1 (132)	17.0 (117)	14.9 (103)	B 13.1 (90)	B 11.2 (77)	B 9.6 (66)
1200	649	23.8 (164)	21.5 (148)	19.0 (131)	16.9 (117)	14.8 (102)	B 12.9 (89)	B 11.0 (76)	B 9.3 (64)	B 7.6 (52)	B 6.0 (41)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 26 Expected Values of 0.2 Percent Tertiary for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A	A	A				
						53.5 (369)	50.1 (345)	46.7 (322)	43.6 (301)	40.5 (279)	37.7 (260)
950	510	A	A	A							
				52.1 (359)	48.7 (336)	45.1 (311)	42.1 (290)	38.9 (268)	36.1 (249)	33.2 (229)	30.8 (212)
1000	538	A									
		51.2 (359)	47.7 (329)	44.1 (304)	41.0 (283)	37.8 (261)	35.0 (241)	32.1 (221)	29.6 (204)	27.0 (186)	24.7 (170)
1050	566	43.6 (301)	40.4 (279)	37.1 (256)	34.2 (236)	31.2 (215)	28.7 (198)	26.1 (180)	23.8 (164)	21.5 (148)	19.5 (134)
1100	593	36.8 (254)	33.8 (233)	30.8 (212)	28.2 (194)	25.5 (176)	23.3 (161)	20.9 (144)	18.9 (130)	16.8 (116)	15.1 (104)
1150	621	30.7 (212)	28.1 (194)	25.3 (174)	23.0 (159)	20.6 (142)	18.5 (128)	16.4 (113)	14.6 (101)	B 12.8 (88)	B 11.3 (78)
1200	649	25.4 (175)	23.0 (159)	20.5 (141)	18.4 (127)	16.3 (112)	14.4 (99)	B 12.6 (87)	B 11.0 (76)	B 9.4 (65)	B 8.0 (55)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 27 Minimum Values of 0.2 Percent Tertiary for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	Time, Hours 10	30	100	300	1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A 51.7 (356)	48.2 (332)	45.0 (310)	41.8 (288)	39.0 (269)	36.1 (249)	33.6 (232)
950	510	A 54.0 (372)	A 50.5 (348)	46.8 (322)	43.7 (301)	40.4 (279)	37.6 (259)	34.6 (239)	32.1 (221)	29.4 (203)	27.2 (188)
1000	538	46.0 (317)	42.8 (295)	39.5 (272)	36.6 (252)	33.6 (232)	31.0 (214)	28.3 (195)	26.0 (179)	23.7 (163)	21.6 (149)
1050	566	39.0 (269)	36.0 (248)	32.9 (227)	30.3 (209)	27.6 (190)	25.3 (174)	22.9 (158)	20.8 (143)	18.7 (129)	16.9 (117)
1100	593	32.7 (225)	30.0 (207)	27.2 (188)	24.8 (171)	22.4 (154)	20.3 (140)	18.1 (125)	16.3 (112)	14.4 (99)	B 12.8 (88)
1150	621	27.1 (187)	24.7 (170)	22.1 (152)	20.0 (138)	17.8 (123)	15.9 (110)	14.0 (97)	B 12.4 (85)	B 10.7 (74)	B 9.3 (64)
1200	649	22.2 (153)	20.0 (138)	17.7 (122)	15.8 (109)	B 13.9 (96)	B 12.2 (84)	B 10.5 (72)	B 9.0 (62)	B 7.6 (52)	B 6.3 (43)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 28 Expected Values for Secondary Creep Rate for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	Rate, Hours^{-1}: 10^{-3}	3×10^{-4}	10^{-4}	3×10^{-5}	10^{-5}	3×10^{-6}	10^{-6}	3×10^{-7}	10^{-7}	3×10^{-8}
900	482	A	A	A 57.6 (397)	A 54.3 (374)	A 51.4 (354)	48.3 (333)	45.6 (314)	42.8 (295)	40.4 (279)	37.7 (260)
950	510	A 55.9 (385)	A 52.5 (362)	49.6 (342)	46.5 (321)	43.8 (302)	40.9 (282)	38.4 (265)	35.8 (247)	33.5 (231)	31.1 (214)
1000	538	48.2 (332)	45.1 (311)	42.4 (292)	39.5 (272)	37.0 (255)	34.3 (236)	32.0 (221)	29.6 (204)	27.4 (189)	25.2 (174)
1050	566	41.4 (285)	38.4 (265)	35.9 (248)	33.2 (229)	30.8 (212)	28.4 (196)	26.2 (181)	24.0 (165)	22.0 (152)	20.0 (138)
1100	593	35.1 (242)	32.4 (223)	30.0 (207)	27.5 (190)	25.3 (174)	23.0 (159)	21.1 (145)	19.0 (131)	17.2 (119)	15.4 (106)
1150	621	29.5 (203)	26.9 (185)	24.7 (170)	22.4 (154)	20.4 (141)	18.3 (126)	16.5 (114)	14.6 (101)	B 13.0 (90)	B 11.2 (77)
1200	649	24.4 (168)	22.0 (152)	20.0 (138)	17.9 (123)	16.0 (110)	14.1 (97)	B 12.4 (85)	B 10.6 (73)	B 9.1 (63)	B 7.5 (52)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 29 Minimum Values for Secondary Creep Rate for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10^{-3}	3×10^{-4}	10^{-4}	Rate, Hours^{-1} 3×10^{-5}	Rate, Hours^{-1} 10^{-5}	3×10^{-6}	10^{-6}	3×10^{-7}	10^{-7}	3×10^{-8}
900	482	A	A 54.8 (378)	A 51.9 (358)	48.8 (336)	46.1 (318)	43.3 (299)	40.8 (281)	38.2 (263)	35.9 (248)	33.4 (230)
950	510	A 50.3 (347)	47.2 (325)	44.5 (307)	41.6 (287)	39.1 (270)	36.4 (251)	34.1 (235)	31.7 (219)	29.5 (203)	27.3 (188)
1000	538	43.2 (298)	40.3 (278)	37.7 (260)	35.1 (242)	32.7 (225)	30.3 (209)	28.1 (194)	25.9 (179)	23.9 (165)	21.8 (150)
1050	566	36.8 (254)	34.1 (235)	31.7 (219)	29.2 (201)	27.0 (186)	24.7 (170)	22.8 (157)	20.7 (143)	18.9 (130)	17.0 (117)
1100	593	31.0 (214)	28.4 (196)	26.2 (181)	23.9 (165)	21.9 (151)	19.8 (137)	18.0 (124)	16.1 (111)	14.4 (99)	B 12.7 (88)
1150	621	25.7 (177)	23.4 (161)	21.3 (147)	19.2 (132)	17.4 (120)	15.4 (106)	B 13.7 (94)	B 12.0 (83)	B 10.4 (72)	B 8.8 (61)
1200	649	21.1 (145)	18.9 (130)	17.0 (117)	15.0 (103)	B 13.3 (92)	B 11.5 (79)	B 9.9 (68)	B 8.3 (57)	B 6.8 (47)	B 5.1 (35)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 30 Expected Values of 1 Percent Total Strain for Heat No. 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A	A	A						
					52.3 (361)	48.5 (334)	45.2 (312)	41.8 (288)	38.9 (268)	36.0 (248)	33.5 (231)
950	510	A	A								
		54.8 (378)	51.0 (352)	47.1 (325)	43.8 (302)	40.4 (279)	37.5 (259)	34.5 (238)	32.0 (221)	29.4 (203)	27.2 (188)
1000	538	46.2 (319)	42.8 (295)	39.4 (272)	36.5 (252)	33.5 (231)	31.0 (214)	28.4 (196)	26.2 (181)	24.0 (165)	22.1 (152)
1050	566	38.9 (268)	35.9 (248)	32.9 (227)	30.3 (209)	27.7 (191)	25.4 (175)	23.2 (160)	21.3 (147)	19.4 (134)	17.8 (123)
1100	593	32.6 (225)	30.0 (207)	27.3 (188)	25.0 (172)	22.7 (157)	20.8 (143)	18.9 (130)	17.2 (119)	15.6 (108)	14.2 (98)
1150	621	27.2 (188)	24.9 (172)	22.6 (156)	20.6 (142)	18.6 (128)	16.9 (117)	15.3 (105)	B 13.9 (96)	B 12.5 (86)	B 11.3 (78)
1200	649	22.6 (156)	20.6 (142)	18.6 (128)	16.9 (117)	15.1 (104)	B 13.7 (94)	B 12.3 (85)	B 11.1 (77)	B 9.9 (68)	B 8.9 (61)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 31 Minimum Values of 1 Percent Total Strain for Heat 91887 from Larson-Miller Analysis

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	A	A 52.8 (364)	48.9 (337)	45.6 (314)	42.2 (291)	39.3 (271)	36.3 (250)	33.8 (233)	31.2 (215)	29.0 (200)
950	510	47.8 (330)	44.4 (306)	41.0 (283)	38.1 (263)	35.1 (242)	32.5 (224)	29.9 (206)	27.7 (191)	25.4 (175)	23.5 (162)
1000	538	40.2 (277)	37.2 (256)	34.2 (236)	31.6 (218)	29.0 (200)	26.8 (185)	24.5 (169)	22.6 (156)	20.6 (142)	18.9 (130)
1050	566	33.7 (232)	31.1 (214)	28.4 (196)	26.2 (181)	23.9 (165)	21.9 (151)	19.9 (137)	18.3 (126)	16.6 (114)	15.2 (105)
1100	593	28.2 (194)	25.9 (179)	23.5 (162)	21.5 (148)	19.5 (134)	17.9 (123)	16.2 (112)	14.7 (101)	B 13.3 (92)	B 12.1 (83)
1150	621	23.5 (162)	21.4 (148)	19.4 (134)	17.7 (122)	15.9 (110)	14.5 (100)	B 13.0 (90)	B 11.8 (81)	B 10.6 (73)	B 9.6 (66)
1200	649	19.4 (134)	17.7 (122)	15.9 (110)	14.4 (99)	B 12.9 (89)	B 11.7 (81)	B 10.4 (72)	B 9.4 (65)	B 8.4 (58)	B 7.5 (52)

A - Above stress range of master curve (50 KSI)

B - Below stress range of master curve (14 KSI)

Table 32 Raw Data Used in Analysis of Rupture for Heat 91887

Temp, °F	Stress, ksi	Time, Hrs.	Description
1000	50.	12.8	EXAT 91887 RUPTURE
1000	46.	228.9	EXBG 91887 RUPTURE
1000	46.	28.5	EXAU 91887 RUPTURE
1000	40.	3444.6	EXAL 91887 RUPTURE
1000	39.	486.0	WC-C 91887 RUPTURE
1000	38.	4580.0	DP-TC 91887 STILL RUNNINGRUPTURE
1000	36.	4847.0	WC-E 91887 STILL RUNNINGRUPTURE
1100	28.	485.2	EXAJ 91887 RUPTURE
1100	28.	430.1	EXAQ 91887 RUPTURE
1100	28.	198.2	EXAG 91887 RUPTURE
1100	24.	3132.8	EXAC 91887 RUPTURE
1100	24.	5560.0	EXBH 91887 STILL RUNNING RUPTURE
1100	23.	8321.0	WC-B 91887 STILL RUNNING RUPTURE
1200	19.	230.4	EXBK 91887 RUPTURE
1200	16.	3830.0	EXBJ 91887 STILL RUNNING RUPTURE
1200	14.	6073.4	WC-A 91887 RUPTURE
1250	15.	171.9	EXAS 91887 RUPTURE

Table 33 Raw Data Used in Analysis of 0.2 Percent Tertiary for Heat 91887

Temp, °F	Stress, ksi	Time, Hrs.	Description
1000	50.	8.13	EXAT 91887 .2 PCT TERTIARY
1000	46.	183.0	EXBG 91887 .2 PCT TERTIARY
1000	46.	17.2	EXAU 91887 .2 PCT TERTIARY
1000	40.	2527.0	EXAL 91887 .2 PCT TERTIARY
1000	39.	320.0	WC-C 91887 .2 PCT TERTIARY
1100	28.	304.0	EXAJ 91887 .2 PCT TERTIARY
1100	28.	282.0	EXAQ 91887 .2 PCT TERTIARY
1100	28.	117.0	EXAG 91887 .2 PCT TERTIARY
1100	24.	2320.0	EXAC 91887 .2 PCT TERTIARY
1100	23.	7030.0	WC-B 91887 .2 PCT TERTIARY
1200	19.	135.0	EXBK 91887 .2 PCT TERTIARY
1200	16.	3343.0	EXBJ 91887 .2 PCT TERTIARY
1200	14.	4075.0	WC-A 91887 .2 PCT TERTIARY
1250	15.	103.0	EXAS 91887 .2 PCT TERTIARY

Table 34 Raw Data Used in Analysis of Secondary Creep Data for Heat 91887

Temp, °F	Stress, ksi	Time, Hrs.	Description		
1000	50.	2.65E-03	EXAT	91887	MCR
1000	46.	1.02E-04	EXBG	91887	MCR
1000	46.	1.46E-03	EXAU	91887	MCR
1000	40.	7.96E-06	EXAL	91887	MCR
1000	39.	8.79E-05	WC-C	91887	MCR
1000	36.	3.00E-06	WC-E	91887	MCR
1100	28.	2.01E-04	EXAG	91887	MCR
1100	28.	6.32E-05	EXAJ	91887	MCR
1100	28.	7.00E-05	EXAQ	91887	MCR
1100	24.	5.99E-06	EXAC	91887	MCR
1100	24.	8.32E-07	EXBH	91887	MCR
1100	23.	1.86E-06	WC-B	91887	MCR
1200	19.	7.41E-05	EXBK	91887	MCR
1200	16.	3.85E-06	EXBJ	91887	MCR
1200	14.	2.99E-06	WC-A	91887	MCR
1250	15.	1.46E-04	EXAS	91887	MCR

Table 35 Raw Data Used in Analysis of One Percent Total Strain for Heat 91887

Temp, °F	Stress, ksi	Time, Hrs.	Description
1000	50.	1.91	EXAT 91887 1 PCT
1000	46.	26.8	EXBG 91887 1 PCT
1000	46.	3.16	EXAU 91887 1 PCT
1000	40.	237.0	EXAL 91887 1 PCT
1000	39.	31.0	WC-C 91887 1 PCT
1000	38.	1880.0	DP-TC 91887 1 PCT
1000	36.	415.0	WC-E 91887 1 PCT
1100	28.	41.7	EXAQ 91887 1 PCT
1100	28.	36.5	EXAJ 91887 1 PCT
1100	28.	15.6	EXAG 91887 1 PCT
1100	24.	610.0	EXAC 91887 1 PCT
1100	23.	2100.	WC-B 91887 1 PCT
1200	19.	85.2	EXBK 91887 1 PCT
1200	16.	1826.0	EXBJ 91887 1 PCT
1200	14.	2400.	WC-A 91887 1 PCT
1250	15.	40.2	EXAS 91887 1 PCT

Table 36 Stress Intensity S_o for Class of Material

Quantity	Stresses in ksi (MPa) for Temperatures in °F (°C)										
	70 (21)	300 (149)	500 (260)	700 (371)	900 (482)	950 (510)	1000 (538)	1050 (566)	1100 (593)	1150 (621)	1200 (649)
Min UTS	92.1	81.1	78.8	76.3	66.6	63.6	60.5	56.7	52.1		
RT Min UTS or 1.1 Min UTS	92.1	89.2	86.7	83.9	73.3	70.0	66.6	62.4	57.3		
Min YS	69.7	59.9	58.3	55.8	53.0		51.1		46.1		
Avg 100,000 Hr Rupture					39.3	32.0	25.6	20.0	15.3	11.2	7.7
Min 100,000 Hr Rupture					35.4	28.6	22.6	17.5	13.1	9.3	6.1
1/4 Min (or 1.1 Min) UTS	23.0	22.3	21.7	21.0	18.3	17.5	16.6	15.6	14.3		
5/8 Min YS	43.6	37.4	36.4	34.9	33.1		31.9		28.8		
0.67 Avg 100,000 Rupture					26.3	21.4	17.2	13.4	10.3	7.5	5.2
0.60 Avg 100,000 Rupture					23.6	19.2	15.4	12.0	9.2	6.7	4.6
0.80 Min 100,000 Rupture					28.3	22.9	18.1	14.0	10.5	7.4	4.9
Avg 1%/100,000 Hr MCR					37.9	31.2	25.3	20.2	15.8	12.0	8.7
S_o Using 0.67 Avg Rupture	23.0 (159)	22.3 (154)	21.7 (150)	21.0 (145)	18.3 (126)	17.5 (121)	16.6 (114)	13.4 (92)	10.3 (71)	7.4 (51)	4.9 (34)
S_o Using 0.60 Avg Rupture	23.0 (159)	22.3 (154)	21.7 (150)	21.0 (145)	18.3 (126)	17.5 (121)	15.4 (106)	12.0 (83)	9.2 (63)	6.7 (46)	4.6 (32)

Table 37 Stress Intensity S_o for Heat 91887

Quantity	Stresses in ksi (MPa) for Temperatures in °F (°C)										
	70 (21)	300 (149)	500 (260)	700 (371)	900 (482)	950 (510)	1000 (538)	1050 (566)	1100 (593)	1150 (621)	1200 (649)
Min UTS	92.1	81.1	78.8	76.3	66.6	63.6	60.5	56.7	52.1		
RT Min UTS or 1.1 Min UTS	92.1	89.2	86.7	83.9	73.3	70.0	66.6	62.4	57.3		
Min YS	69.7	59.9	58.3	55.8	53.0		51.1		46.1		
Avg 100,000 Hr Rupture					42.0	34.7	28.3	22.6	17.6	13.2	9.4
Min 100,000 Hr Rupture					38.3	31.4	25.4	20.0	15.3	11.2	7.6
1/4 Min (or 1.1 Min) UTS	23.0	22.3	21.7	21.0	18.3	17.5	16.6	15.6	14.3		
5/8 Min YS	43.6	37.4	36.4	34.9	33.1		31.9		28.8		
0.67 Avg 100,000 Rupture					28.1	23.2	19.0	15.1	11.8	8.8	6.3
0.60 Avg 100,000 Rupture					25.2	20.8	17.0	13.6	10.6	7.9	5.6
0.80 Min 100,000 Rupture					30.6	25.1	20.3	16.0	12.2	9.0	6.1
Avg 1%/100,000 Hr MCR					40.4	33.5	27.4	22.0	17.2	13.0	9.1
S_o Using 0.67 Avg Rupture	23.0 (159)	22.3 (154)	21.7 (150)	21.0 (145)	18.3 (126)	17.5 (121)	16.6 (114)	15.1 (104)	11.8 (81)	8.8 (61)	6.1 (42)
S_o Using 0.60 Avg Rupture	23.0 (159)	22.3 (154)	21.7 (150)	21.0 (145)	18.3 (126)	17.5 (121)	16.6 (114)	13.6 (94)	10.6 (73)	7.9 (54)	5.6 (39)

Table 38 Stress Intensity S_m for Class of Material and Heat 91887

Quantity	Stresses in ksi (MPa) for Temperatures in °F (°C)								
	70 (21)	300 (149)	500 (260)	700 (371)	900 (482)	950 (510)	1000 (538)	1050 (566)	1100 (593)
Min UTS	92.1	81.1	78.8	76.3	66.6	63.6	60.5	56.7	52.1
RT Min UTS or 1.1 Min UTS	92.1	89.2	86.7	83.9	73.3	70.0	66.6	62.4	57.3
Min YS	69.7	59.9	58.3	55.8	53.0		51.1		46.1
1/3 Min (or 1.1 Min) UTS	30.7	29.7	28.9	28.0	24.4	23.3	22.2	20.8	19.1
2/3 Min YS	46.5	39.9	38.9	37.2	35.3		34.1		30.7
S_m	30.7 (212)	29.7 (205)	28.9 (199)	28.0 (193)	24.4 (168)	23.3 (161)	22.2 (153)	20.8 (143)	19.1 (132)

Table 39 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 900°F (482°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary	53.0	48.9	44.7	41.3 34.4 40.2	37.8 31.9 37.4	34.9 29.8 35.0	32.0 27.6 32.5	29.6 25.6 30.2	27.1 23.6 27.9	25.1 21.9 25.9
S_t for Class				34.4 (237)	31.9 (220)	29.8 (205)	27.6 (190)	25.6 (177)	23.6 (163)	21.9 (151)
Heat 91887, Temperature = 900°F (482°C)										
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary		52.8	48.9	45.6 36.1 41.4	42.2 33.7 38.6	39.3 31.6 36.0	36.3 29.4 33.4	33.8 27.5 31.2	31.2 25.5 28.9	29.0 23.8 26.9
S_t for Heat 91887				36.1 (249)	33.7 (232)	31.6 (218)	29.4 (203)	27.5 (190)	25.5 (176)	23.8 (164)

Larson-Miller Constant = 30.6 in all analyses.

Table 40 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 950°F (510°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain	43.5	40.1	36.6	33.7	30.8	28.4	25.9	23.9	21.9	20.2
2/3 Min Rupture		33.5	31.0	28.9	26.6	24.7	22.6	20.9	19.1	17.5
0.8 Min Tertiary	41.9	39.2	36.4	33.9	31.4	29.1	26.8	24.7	22.6	20.8
S_t for Class		33.5 (231)	31.0 (214)	28.9 (199)	26.6 (183)	24.7 (170)	22.6 (156)	20.9 (144)	19.1 (132)	17.5 (121)
Heat 91887, Temperature = 950°F (510°C)										
Min 1% Total Strain	47.8	44.4	41.0	38.1	35.1	32.5	29.9	27.7	25.4	23.5
2/3 Min Rupture		35.3	32.8	30.7	28.5	26.5	24.5	22.8	20.9	19.3
0.8 Min Tertiary	43.2	40.4	37.4	35.0	32.3	30.1	27.7	25.7	23.5	21.8
S_t for Heat 91887		35.3 (243)	32.8 (226)	30.7 (212)	28.5 (197)	26.5 (183)	24.5 (169)	22.8 (157)	20.9 (144)	19.3 (133)

Larson-Miller Constant = 30.6 in all analyses.

Table 41 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 1000°F (538°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain	35.8	32.9	30.0	27.5	25.1	23.1	21.0	19.3	17.6	16.2
2/3 Min Rupture	30.5	28.3	25.9	24.0	21.9	20.1	18.3	16.7	15.1	13.7
0.8 Min Tertiary	35.8	33.3	30.6	28.2	25.9	23.9	21.8	19.8	17.9	16.2
S_t for Class	30.5 (210)	28.3 (195)	25.9 (179)	24.0 (165)	21.9 (151)	20.1 (139)	18.3 (126)	16.7 (115)	15.1 (104)	13.7 (94)
Heat 91887, Temperature = 1000°F (538°C)										
Min 1% Total Strain	40.2	37.2	34.2	31.8	29.0	36.8	24.5	22.6	20.6	18.9
2/3 Min Rupture	32.3	30.1	27.9	25.9	23.8	22.1	20.2	18.6	16.9	15.5
0.8 Min Tertiary	36.8	34.2	31.6	29.3	26.9	24.8	22.6	20.8	19.0	17.3
S_t for Heat 91887	32.3 (223)	30.1 (208)	27.9 (192)	25.9 (179)	23.8 (164)	22.1 (152)	20.2 (139)	18.6 (128)	16.9 (117)	15.5 (107)

Larson-Miller Constant = 30.6 in all analyses.

Table 42 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 1050°F (566°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary	29.5 25.6 30.2	27.0 23.6 27.9	24.6 21.5 25.4	22.5 19.7 23.4	20.5 17.8 21.1	18.8 16.2 19.2	17.1 14.5 17.2	15.7 13.1 15.5	14.3 11.7 13.7	13.1 10.5 12.2
S_t for Class	25.6 (177)	23.6 (163)	21.5 (148)	19.7 (136)	17.8 (123)	16.2 (112)	14.5 (100)	13.1 (90)	11.7 (81)	10.5 (72)
Heat 91887, Temperature = 1050°F (566°C)										
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary	33.7 27.5 31.2	31.1 25.5 28.8	28.4 23.4 26.3	26.2 21.5 24.2	23.9 19.7 22.1	21.9 18.0 20.2	19.9 16.3 18.3	18.3 14.9 16.6	16.6 13.3 15.0	15.2 12.1 13.5
S_t for Heat 91887	27.5 (190)	25.5 (176)	23.4 (161)	21.5 (148)	19.7 (136)	18.0 (124)	16.3 (112)	14.9 (103)	13.3 (92)	12.1 (83.4)

Larson-Miller Constant = 30.6 in all analyses.

Table 43 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 1100°F (593°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain	24.4	22.3	20.2	18.4	16.7	15.3	13.9	12.7	11.5	10.6
2/3 Min Rupture	21.3	19.5	17.5	15.9	14.2	12.8	11.3	10.0	8.7	7.7
0.8 Min Tertiary	25.2	23.0	20.8	18.9	16.8	15.0	13.2	11.6	9.9	8.5
S_t for Class	21.3 (147)	19.5 (134)	17.5 (121)	15.9 (110)	14.2 (98)	12.8 (88)	11.3 (78)	10.0 (69)	8.7 (60)	7.7 (53)
Heat 91887, Temperature = 1100°F (593°C)										
Min 1% Total Strain	28.2	25.9	23.5	21.5	19.5	17.9	16.2	14.7	13.3	12.1
2/3 Min Rupture	23.2	21.3	19.4	17.7	16.0	14.5	12.9	11.6	10.2	9.1
0.8 Min Tertiary	26.2	24.0	21.8	19.8	17.9	16.2	14.5	13.0	11.5	10.2
S_t for Heat 91887	23.2 (160)	21.3 (147)	19.4 (134)	17.7 (122)	16.0 (110)	14.5 (100)	12.9 (89)	11.6 (80)	10.2 (70)	9.1 (63)

Larson-Miller Constant = 30.6 in all analyses.

Table 44 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 1150°F (621°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary	20.1 17.5 20.7	18.4 15.8 18.7	16.6 14.1 16.6	15.1 12.6 14.8	13.7 11.1 13.0	12.5 9.8 11.4	11.3 8.5 9.6	10.3 7.4 8.2	9.4 6.2 6.6	8.6 5.3 5.0*
S_t for Class	17.5 (121)	15.8 (109)	14.1 (97)	12.6 (87)	11.1 (77)	9.8 (68)	8.5 (59)	7.4 (51)	6.2 (43)	5.3 (37)
Heat 91887, Temperature = 1150°F (621°C)										
Min 1% Total Strain 2/3 Min Rupture 0.8 Min Tertiary	23.5 19.3 21.7	21.4 17.6 19.8	19.4 15.9 17.7	17.7 14.3 16.0	15.9 12.7 14.2	14.5 11.3 12.7	13.0 9.9 11.2	11.8 8.7 9.9	10.6 7.5 8.6	9.6 6.4 7.4
S_t for Heat 91887	19.3 (133)	17.6 (121)	15.9 (110)	14.3 (99)	12.7 (88)	11.3 (78)	9.9 (68)	8.7** (60)	7.5** (52)	6.4** (44)

* Not considered because it is believed to be unrealistically low.

** Below the master parameter curve and not well founded experimentally.

Larson-Miller Constant = 30.6 in all analyses.

Table 45 Stress Intensity S_t for Class of Material and Heat 91887

Class of Material, Temperature = 1200°F (649°C)										
Stress in ksi (MPa) for Time in Hours										
	10	30	100	300	1000	3000	10,000	30,000	10^5	3×10^5
Min 1% Total Strain	16.6	15.2	13.7	12.4	11.2	10.2	9.2	8.4	7.6	6.9
2/3 Min Rupture	14.1	12.6	11.1	9.7	8.4	7.3	6.1	5.1	4.1	3.1
0.8 Min Tertiary	16.7	14.9	12.9	11.2	9.4	7.9	6.3	4.7*	3.4*	
S_t for Class	14.1 (97)	12.6 (87)	11.1 (77)	9.7 (67)	8.4 (58)	7.3 (50)	6.1 (42)	5.1 (35)	4.1** (28)	3.1** (21)
Heat 91887, Temperature = 1200°F (649°C)										
Min 1% Total Strain	19.4	17.7	15.9	14.4	12.9	11.7	10.4	9.4	8.4	7.5
2/3 Min Rupture	15.9	14.3	12.7	11.3	9.9	8.6	7.3	6.2	5.1	4.0
0.8 Min Tertiary	17.8	16.0	14.2	12.6	11.1	9.8	8.4	7.2	6.1	5.0
S_t for Heat 91887	15.9 (110)	14.3 (99)	12.7 (88)	11.3 (78)	9.9 (68)	8.6** (59)	7.3** (50)	6.2** (43)	5.1** (35)	4.0** (28)

* Not considered because it is believed to be unrealistically low.

** Below the master parameter curve and not well founded experimentally.

Larson-Miller Constant = 30.6 in all analyses.

Table 46 Stress Intensity S_{mt} for Class of Material

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	Time, Hours 10	30	100	300	1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	23.6 (163)	21.9 (151)
950	510	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	22.6 (156)	20.9 (144)	19.1 (132)	17.5 (121)
1000	538	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	21.9 (151)	20.1 (139)	18.3 (126)	16.7 (115)	15.1 (104)	13.7 (94)
1050	566	20.8 (143)	20.8 (143)	20.8 (143)	19.7 (136)	17.8 (123)	16.2 (112)	14.5 (100)	13.1 (90)	11.7 (81)	10.5 (72)
1100	593	19.1 (132)	19.1 (132)	17.5 (121)	15.9 (110)	14.2 (98)	12.8 (88)	11.3 (78)	10.0 (69)	8.7 (60)	7.7 (53)
1150	621	17.2** (119)	15.8** (109)	14.1 (97)	12.6 (87)	11.1 (77)	9.8 (68)	8.5 (59)	7.4 (51)	6.2 (43)	5.3 (37)
1200	649	14.1** (97)	12.6** (87)	11.1 (77)	9.7 (67)	8.4 (58)	7.3 (50)	6.1 (42)	5.1 (35)	4.1* (28)	3.1* (21)

* Below the master parameter curve and not well founded experimentally.

** Values beyond temperature where S_m well founded experimentally.

Larson-Miller Constant = 30.6 in all time-dependent analyses.

Table 47 Stress Intensity S_{mt} for Heat 91887

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	23.8 (164)
950	510	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	22.8 (157)	20.9 (144)	19.3 (133)
1000	538	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	22.1 (152)	20.2 (139)	18.6 (128)	16.9 (117)	15.5 (107)
1050	566	20.8 (143)	20.8 (143)	20.8 (143)	20.8 (143)	19.7 (136)	18.0 (124)	16.3 (112)	14.9 (103)	13.3 (92)	12.1 (83.4)
1100	593	19.1 (132)	19.1 (132)	19.1 (132)	17.7 (122)	16.0 (110)	14.5 (100)	12.9 (89)	11.6 (80)	10.2 (70)	9.1 (63)
1150	621	17.2** (119)	17.2** (119)	15.9** (110)	14.3 (99)	12.7 (88)	11.3 (78)	9.9 (68)	8.7* (60)	7.5* (52)	6.4* (44)
1200	649	14.9** (103)	14.3** (99)	12.7 (88)	11.3 (78)	9.9 (68)	8.6* (59)	7.3* (50)	6.2* (43)	5.1* (35)	4.0* (28)

* Below the master parameter curve and not well founded experimentally.

** Values beyond temperature range where S_m well founded experimentally.

Larson-Miller Constant = 30.6 in all time-dependent analyses.

Table 48 Stress Intensity S_{mt} for Heat 91887 with Analysis Using Less Conservative Larson-Miller Constant

STRESS VALUES-KSI (MPA)

Temperature (F)	Temperature (C)	10	30	100	Time, Hours 300	Time, Hours 1,000	3,000	10,000	30,000	10^5	3×10^5
900	482	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)	24.4 (168)
950	510	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	23.3 (161)	22.3 (154)	20.7 (143)
1000	538	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	22.2 (153)	21.0 (145)	19.5 (134)	17.9 (123)	16.6 (114)
1050	566	20.8 (143)	20.8 (143)	20.8 (143)	20.8 (143)	20.0 (138)	18.5 (128)	17.0 (117)	15.7 (108)	14.3 (99)	13.1 (90)
1100	593	19.1 (132)	19.1 (132)	19.1 (132)	17.8 (123)	16.2 (112)	14.9 (103)	13.5 (93)	12.3 (85)	11.1 (77)	10.1 (70)
1150	621	17.2** (119)	17.2** (119)	15.7** (108)	14.3 (99)	12.9 (89)	11.7 (81)	10.5 (72)	9.5 (66)	8.4* (58)	7.5* (52)
1200	649	14.9** (103)	13.9** (96)	12.5 (86)	11.3 (78)	10.1 (70)	9.1* (63)	8.0* (55)	7.1* (49)	6.1* (42)	5.3* (37)

* Below the master parameter curve and not well founded experimentally.

** Values beyond the temperature range where S_m well founded experimentally.

Larson-Miller Constant = 35.3 in all time-dependent analyses.

SECTION VII

SUMMARY

C. M. Owens

LIST OF FIGURES

Figure No.		Page
1	Charpy V-Notch Toughness Results for 9Cr-1Mo Plate Compared to PWR Vessel Steel SA 533-B	255
2	Comparison of Code Case 1592 S_{mt} Values at 1000° F for 316 SS, Grade 22 and C-E Developed 9Cr-1Mo	256
3	Comparison of Code Case 1592 S_{mt} Values at 1100° F for 316 SS, Grade 22 and C-E Developed 9Cr-1Mo	257
4	Creep Rupture Results for C-E Developed Base and Weld Metal Compared to Other Ferritic Candidate Alloys	258

LIST OF TABLES

Table No.		Page
1	Toughness and Stability of Various Ferritic Materials. Stability Measured After 2000 Hours at 950° F	259

VIII. SUMMARY - C. M. Owens

The inherent and potential advantages of the C-E developed 9Cr-1Mo alloys are numerous. Restated, the known advantages over Code qualified austenitics and Grade 22, are:

1. Improved resistance to caustic and chloride stress corrosion cracking;
2. Low thermal expansion;
3. High thermal conductivity and diffusivity;
4. Improved elevated temperature tensile strength
5. Excellent carbon stability;
6. Good steam side general corrosion resistance.

The potential advantages, which define the focus of this development effort, are improved toughness, weldability, and creep resistance. In addition to being improvements over Code approved materials, these benefits are particularly pertinent to comparison with other ferritics. Specifically, these improvements are:

1. Excellent and stable room temperature toughness;
2. Through hardening in thick sections;
3. Reasonable pre- and post-weld heat treatments;
4. Welded joints can be cooled to room temperature prior to stress relieving;
5. Stable microstructure provides for long-term improved creep strength and ductility.

On the more practical side, advantages include:

1. Structure is amenable to inservice ultrasonic inspection of welds;

2. Does not rust, easing field erection;

3. Core use is practical, eliminating troublesome dissimilar metal joints;

4. Hardware production (tubing) has been successfully demonstrated;

5. Can ease dependence on imported chromium and nickel.

Significant progress has been made by C-E in demonstrating improved toughness in the preferred base metal and weld metal compositions. Important comparisons are shown in Figure 1 and Table 1. The lack of stability exhibited by HT-9 in Table 1 is of particular import in view of the recent renewed interest in this material in this country. C-E has achieved stability in several compositions by controlling compositions and microstructures. A breakthrough with respect to weld metal toughness was described earlier in this paper, where "hammer stopper" values were achieved using the Gas Tungsten Arc process. In addition, because of the lower carbon content, all trial weldments were allowed to cool to room temperature prior to stress relieving. No cracking has been observed. This capability constitutes a very important practical advantage over available commercial ferritics viz HT-9. The prescribed welding procedure for HT-9 is a tortureous path involving very high temperature and the restriction that the weld must not be allowed to reach temperatures below 200° F before stress relieving. HT-9 is not very forgiving when welded and appears to be a risky venture for LMFBR application where high reliability is mandatory.

Improvements in creep resistance for the C-E developed alloy are dipicted in Figures 2, 3, and 4. Comparisons based on Code Case 1592 criteria are made to Code qualified materials and commercial ferritics.

Figures 2 and 3 demonstrate the 10^5 hours stability of the C-E alloy. Note particularly that at 1100° F, the S_{mt} stress for 316 SS falls below that of the 9Cr material. The improved performance of the 9Cr is predicted for longer time by comparing the slopes of the two curves at 10^5 hours.

Figure 4 shows the improved creep properties of the C-E composition over candidate ferritics. Again, the important consideration is the slope of the line generated for C-E base and weld metal results. HT-9 and EM-12 both show a significant decrease in creep strength with time which is indicative of microstructural instability.

The C-E development program has demonstrated improved toughness, weldability, and creep resistance for the 9Cr-1Mo alloy. Improvements realized constitute real benefits over all Code qualified materials and commercially available ferritic alloys. These improvements, coupled with the inherent advantages of the alloy class, will provide the design community with a substantially improved material for LMFBR structural application.

FIGURE 1: CHARPY V-NOTCH TOUGHNESS RESULTS FOR 9Cr-1Mo PLATE COMPARED TO PWR VESSEL STEEL SA 533-B

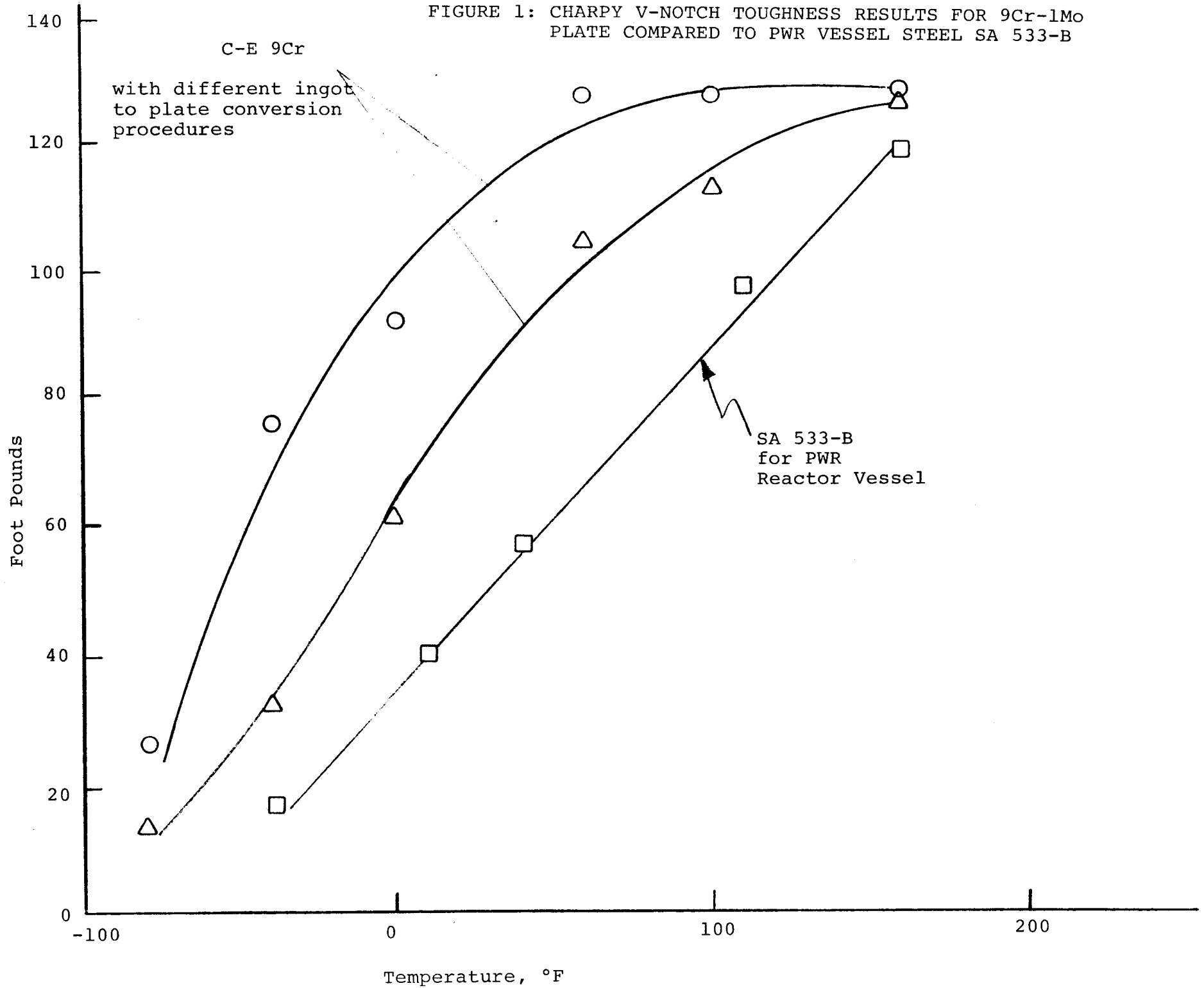
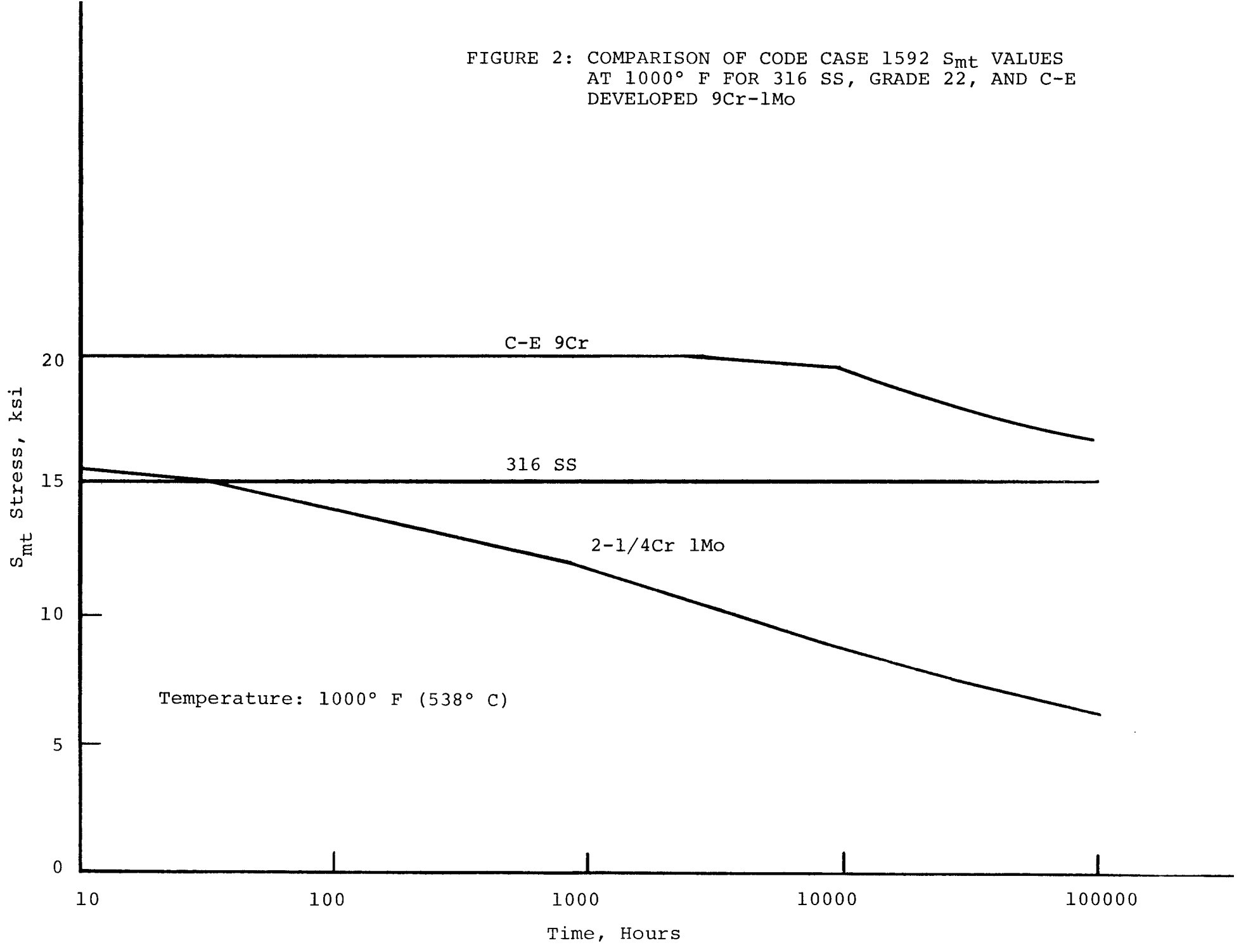


FIGURE 2: COMPARISON OF CODE CASE 1592 S_{mt} VALUES AT 1000° F FOR 316 SS, GRADE 22, AND C-E DEVELOPED 9Cr-1Mo



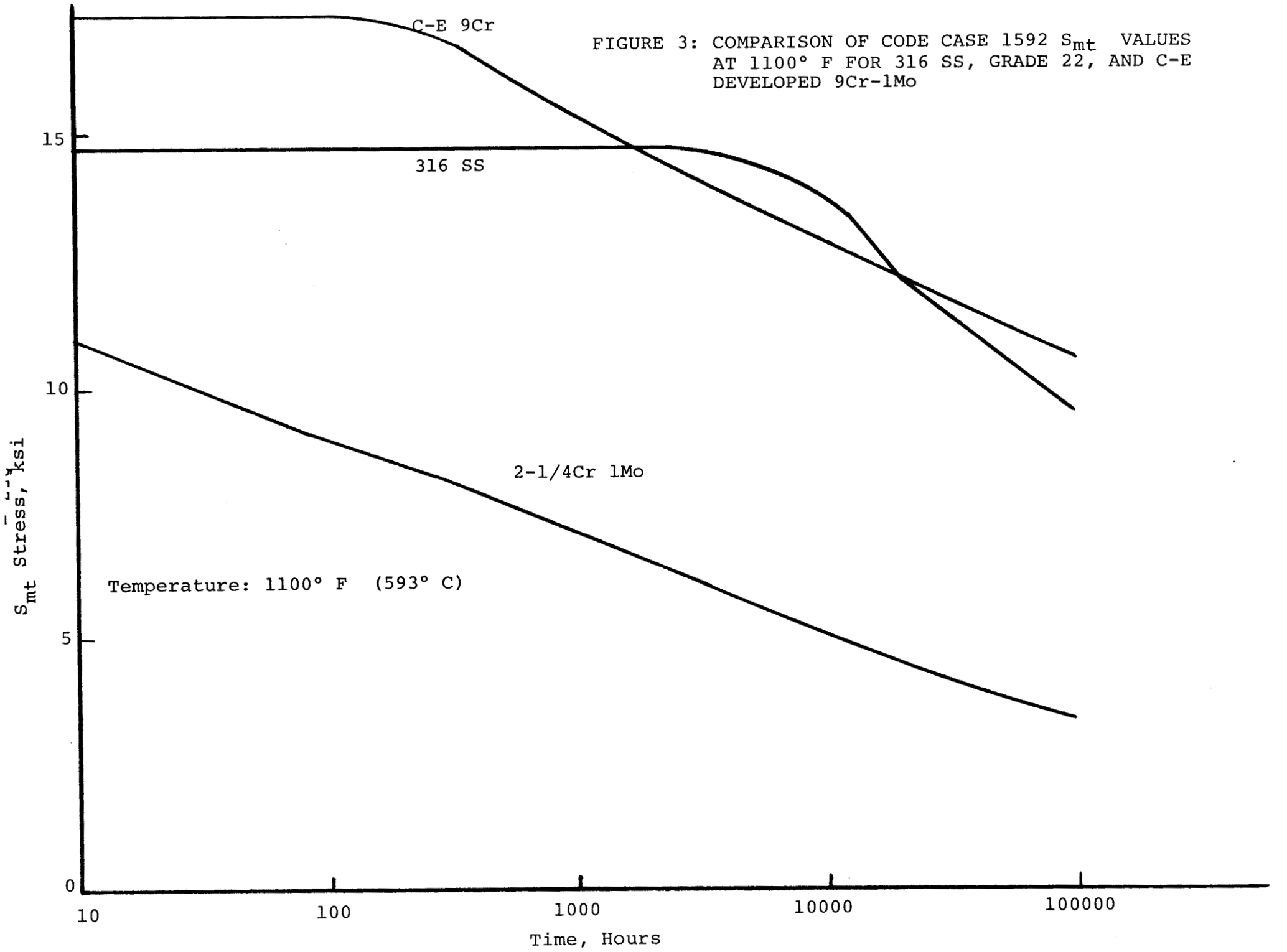
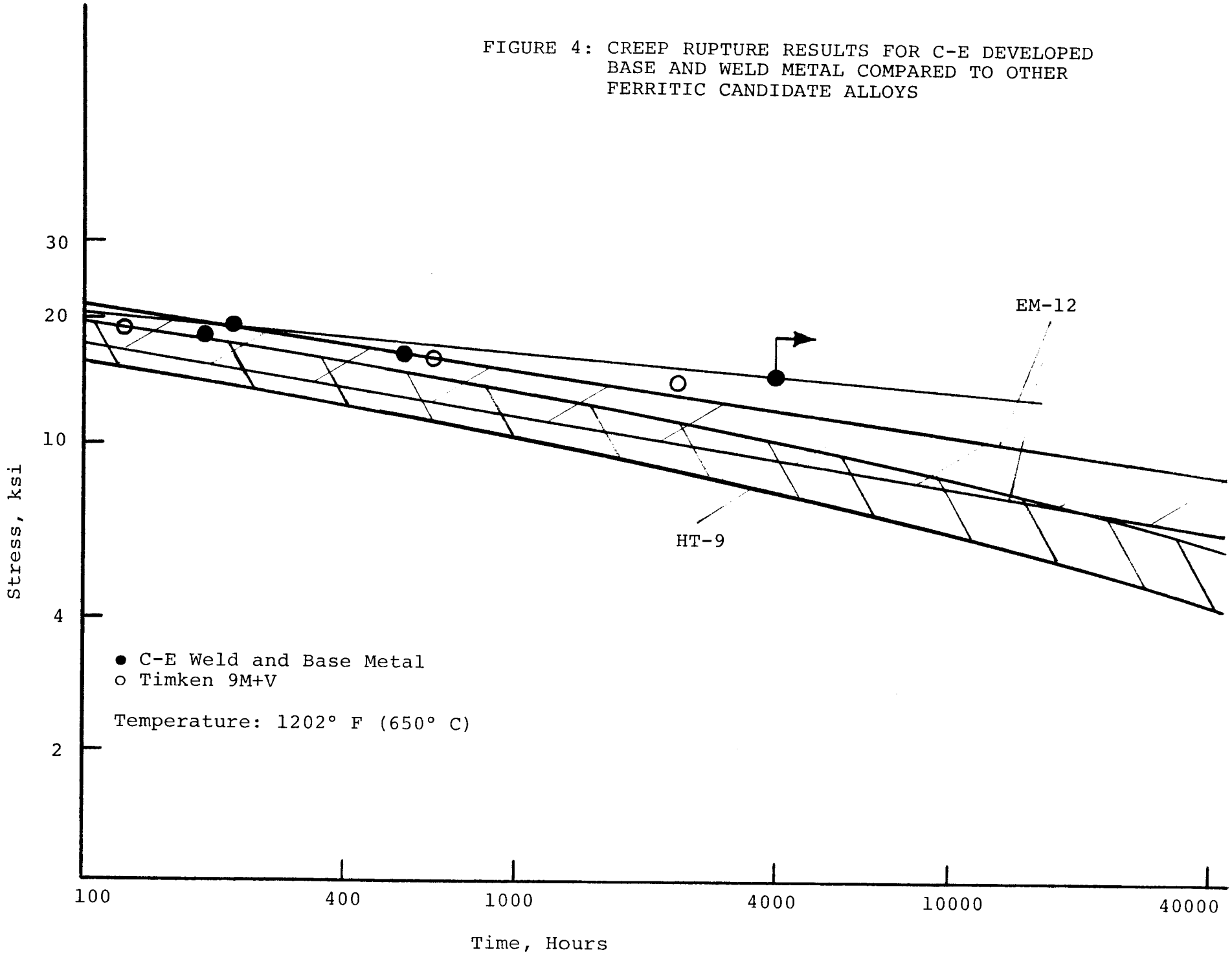


FIGURE 3: COMPARISON OF CODE CASE 1592 S_{mt} VALUES AT 1100° F FOR 316 SS, GRADE 22, AND C-E DEVELOPED 9Cr-1Mo

FIGURE 4: CREEP RUPTURE RESULTS FOR C-E DEVELOPED BASE AND WELD METAL COMPARED TO OTHER FERRITIC CANDIDATE ALLOYS

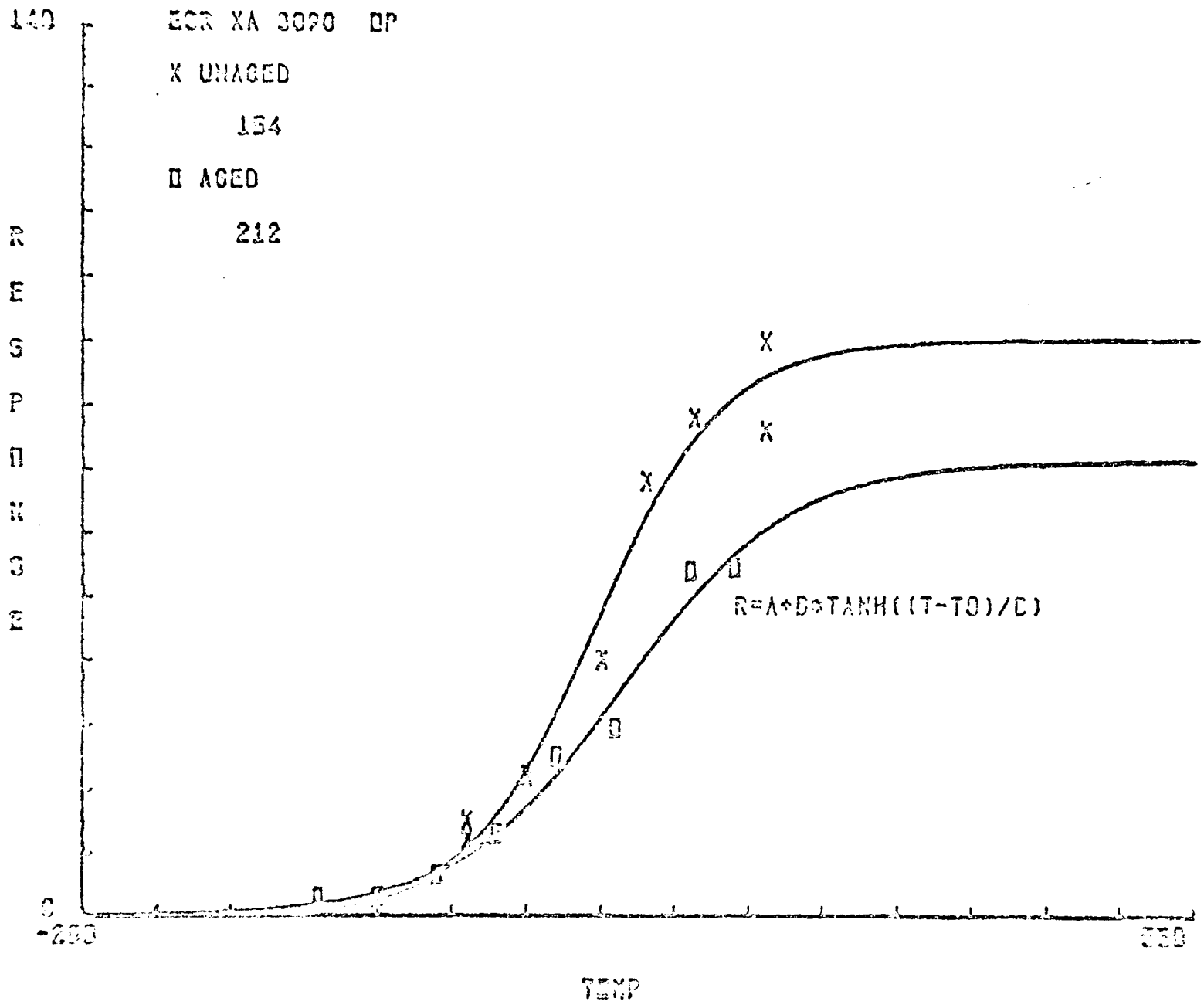


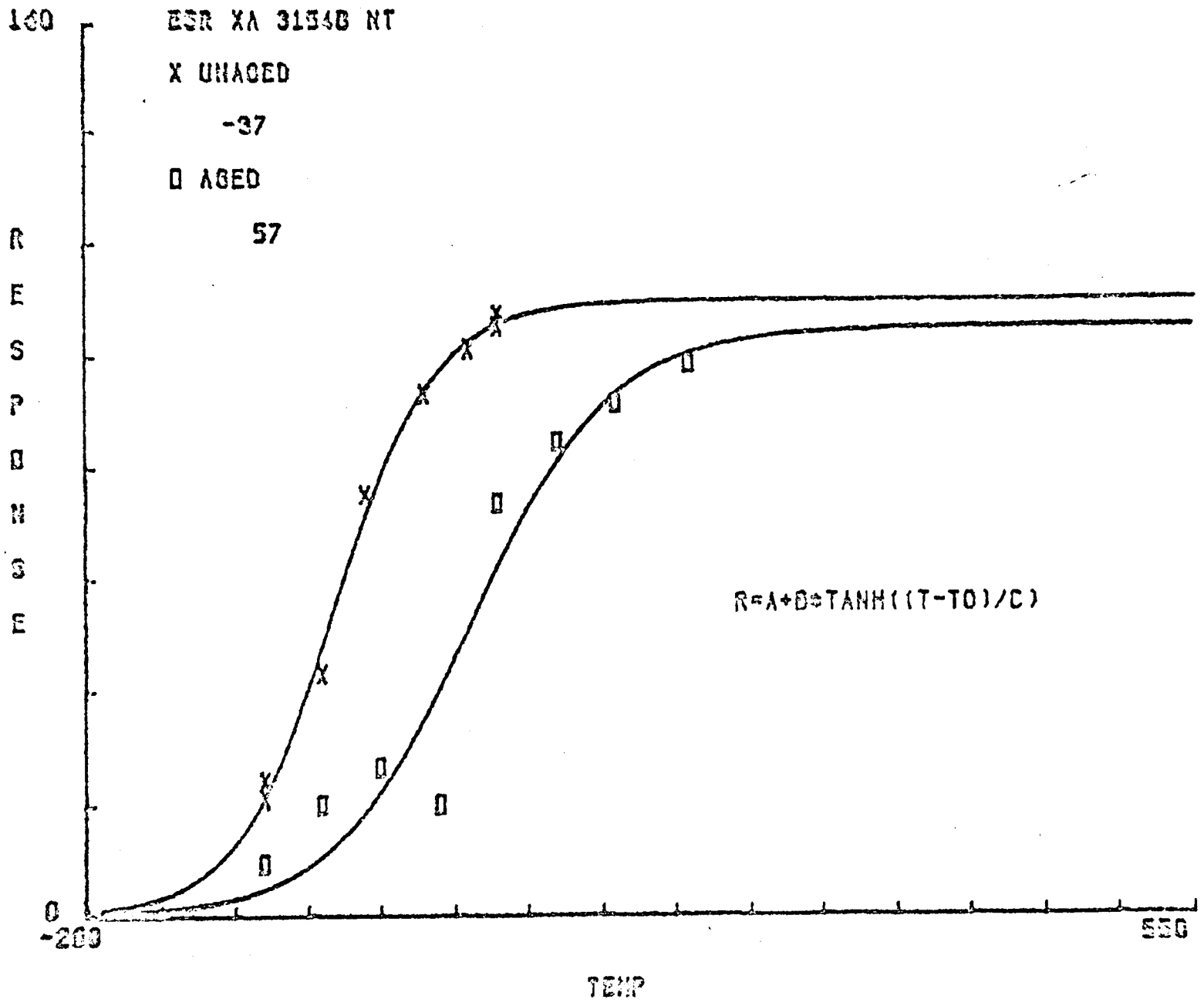
	50 Foot-Pound Transition Temp. °F		Upper Energy Shelf Foot Pounds	
	Before Aging	After Aging	Before Aging	After Aging
2-1/4Cr, 1Mo, N&T	0	118	93	83
2-1/4Cr, 1Mo, Q&T	- 67	74	86	80
HT-9	42	100	98	75
EM-12	154	212	76	70
C-E 9Cr	- 36	- 45	105	115
	- 36	- 41	123	130
	- 31	- 25	103	115

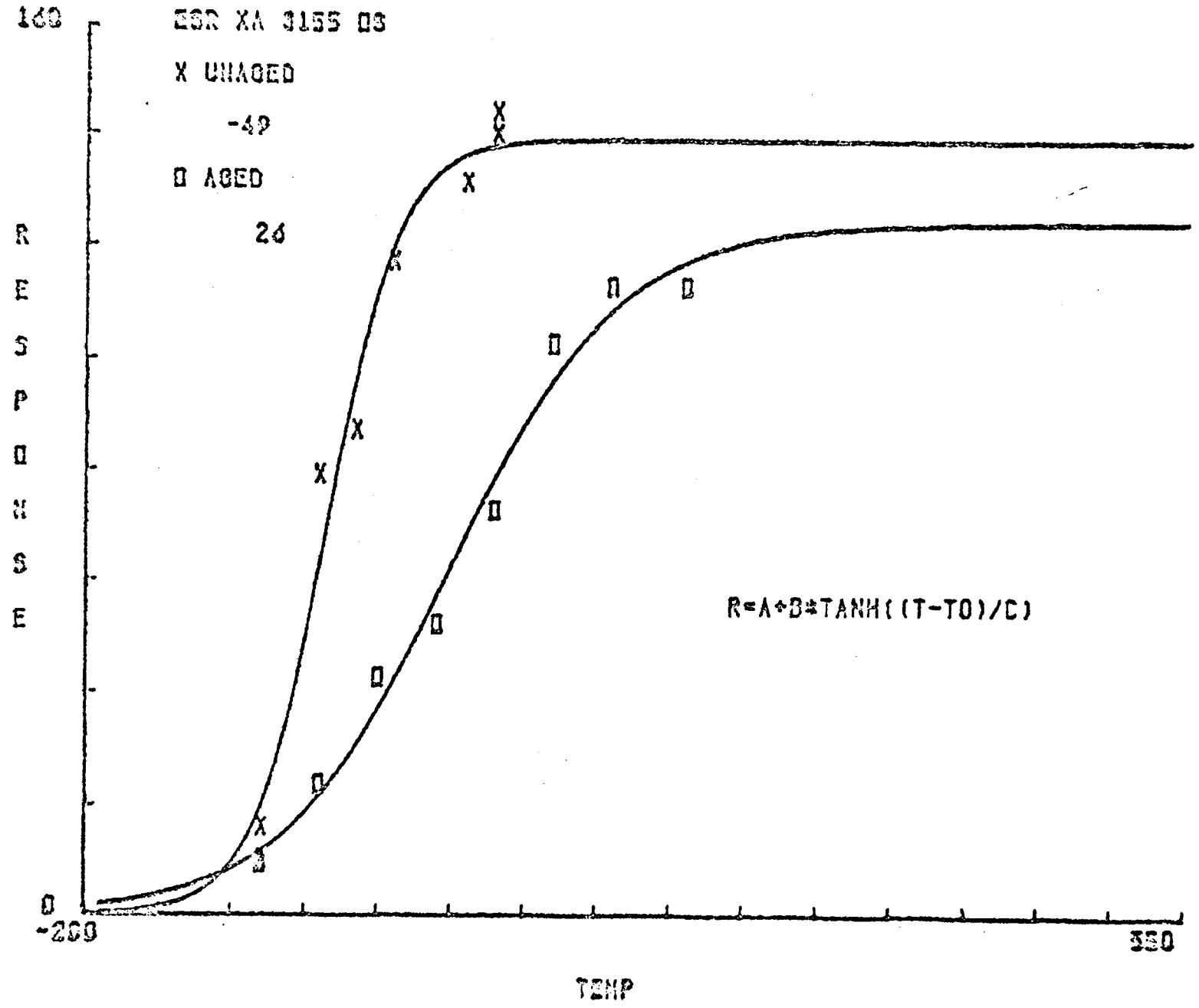
TABLE 1: TOUGHNESS AND STABILITY OF VARIOUS FERRITIC MATERIAL. AGING WAS FOR 2000 HOURS AT 950° F.

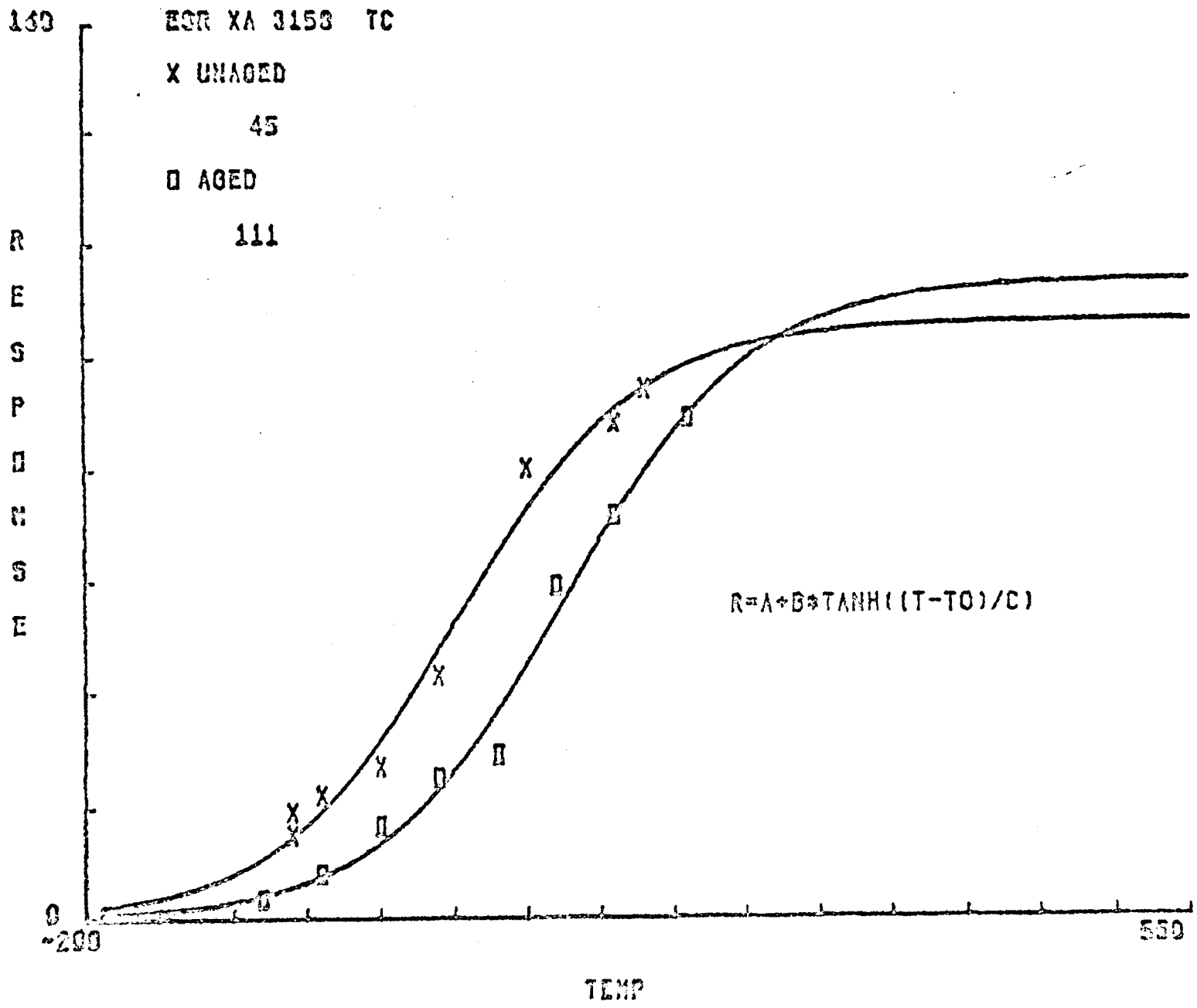
VIII - ACKNOWLEDGEMENT

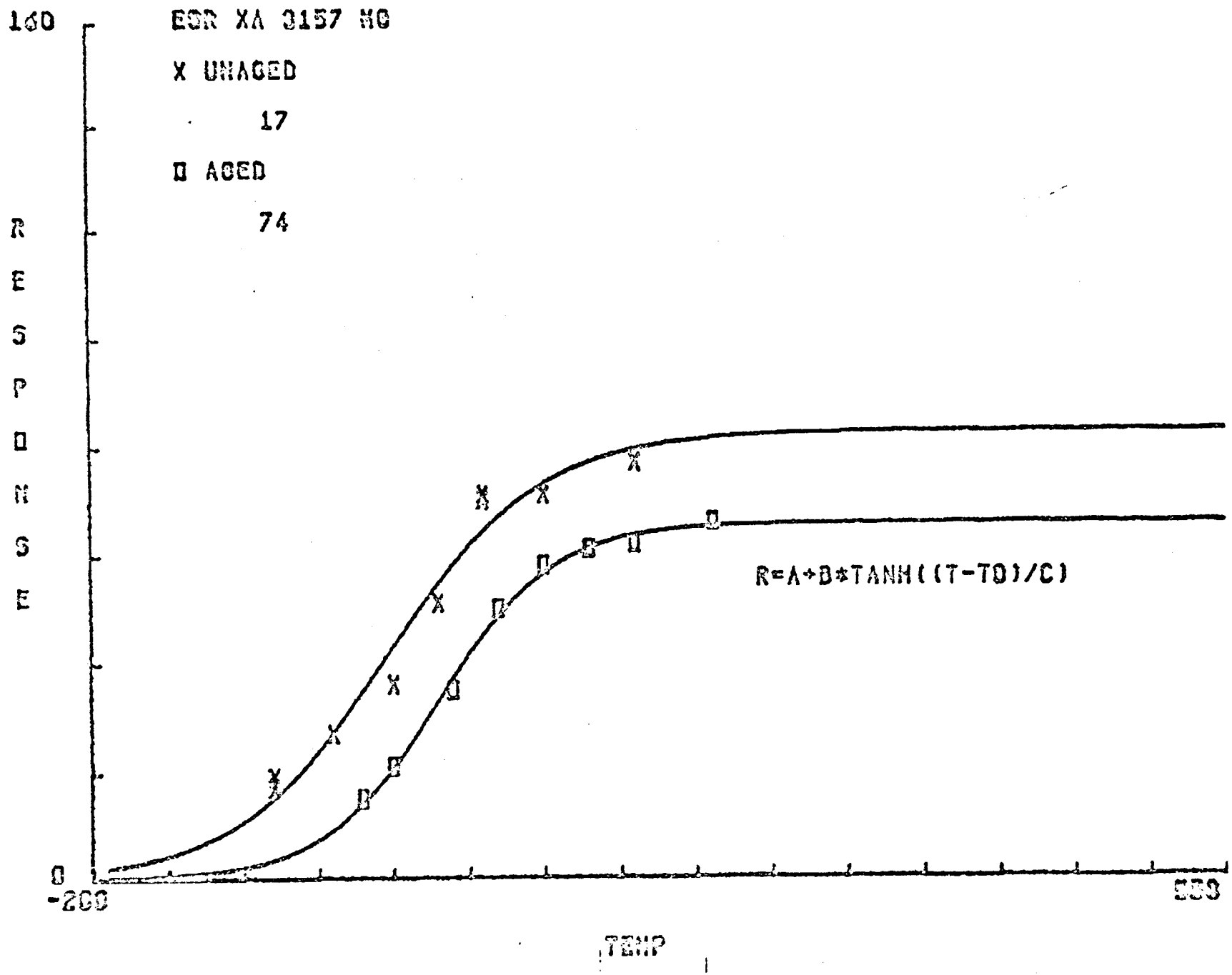
A number of people from the Chattanooga Metallurgical and Materials Laboratory as well as the Windsor Development Laboratory have provided invaluable assistance on this program. The authors wish to express their profound gratitude to these people for a job well done.

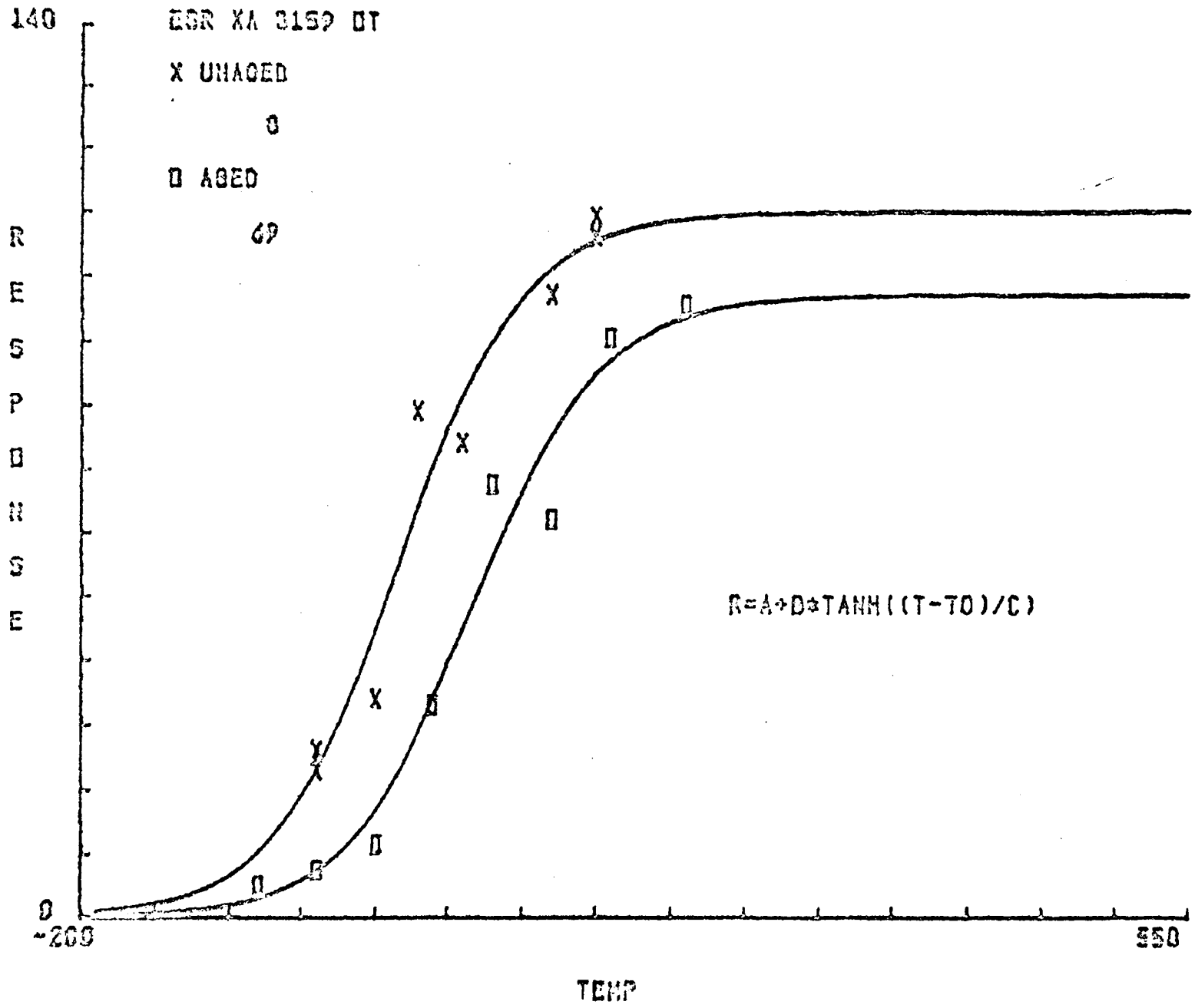

140
ECR XA 3090 DP
X UNAGED
134
D AGED
212
RESPONSE
R=A+D*TANH((T-TO)/C)
0
-200
350
TEMP

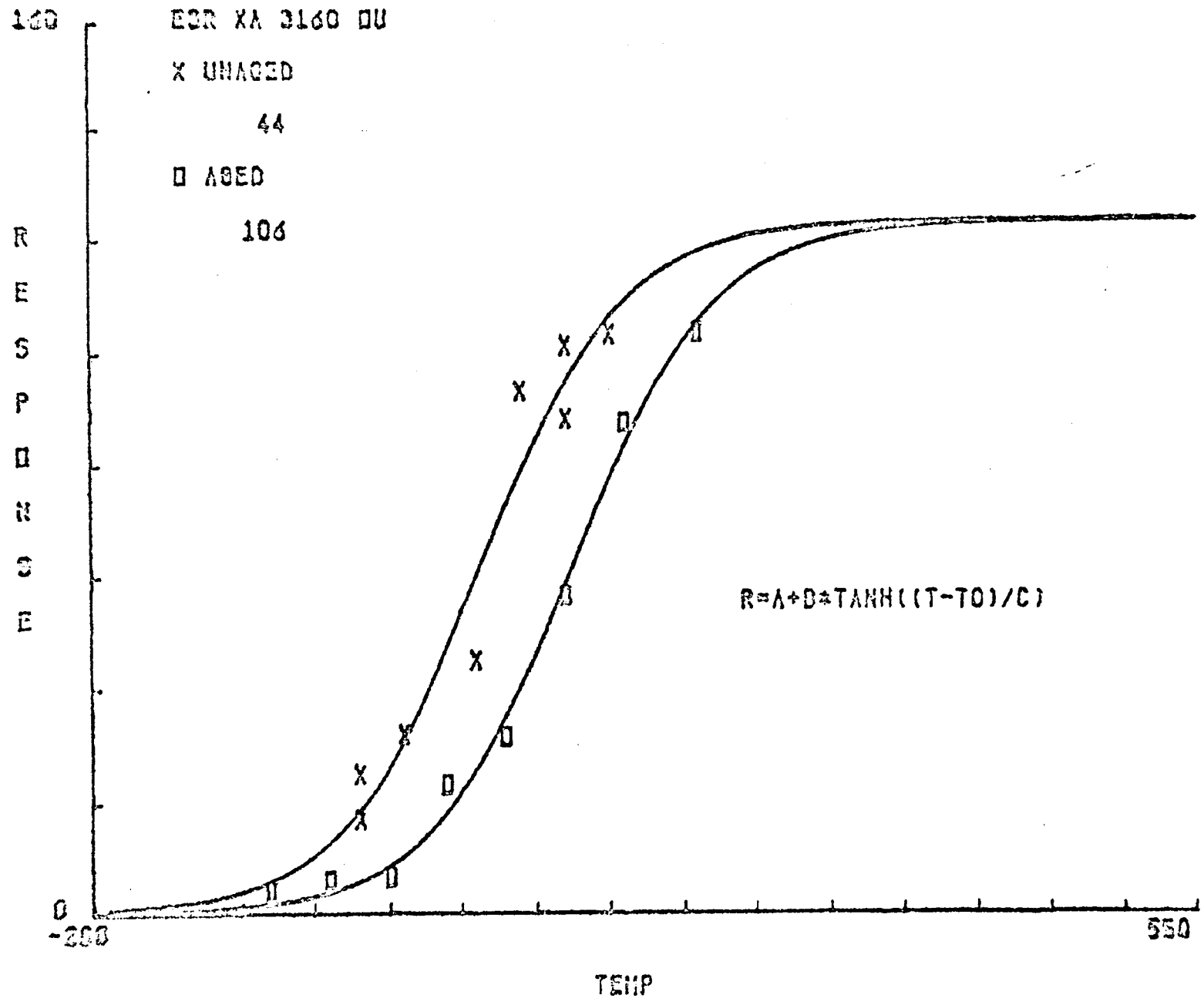

160
ESR XA 3154B NT
X UNAGED
-37
□ AGED
57
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

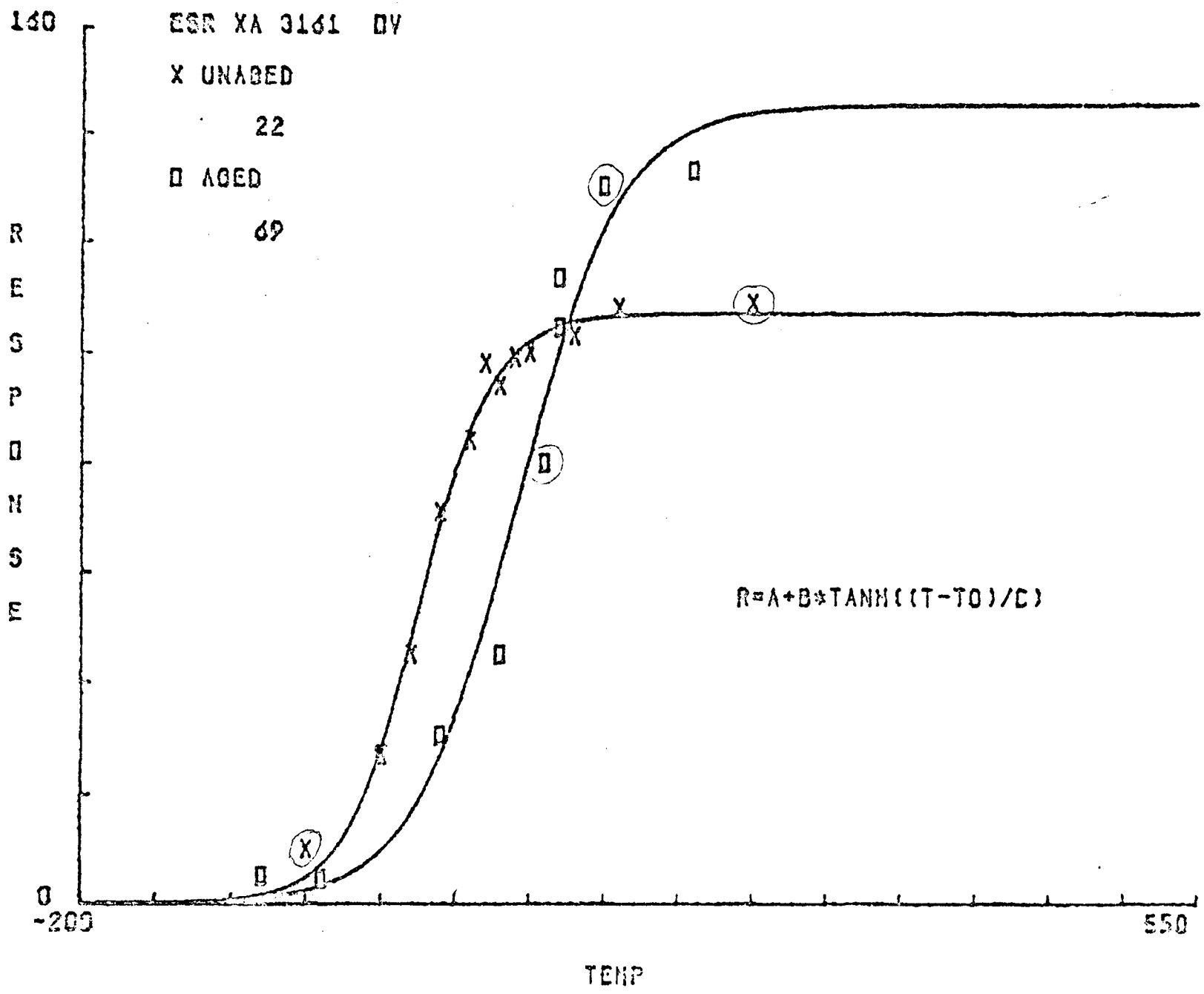

160
ESR XA 3155 03
X UNAGED
-49
□ AGED
26
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
350
TEMP

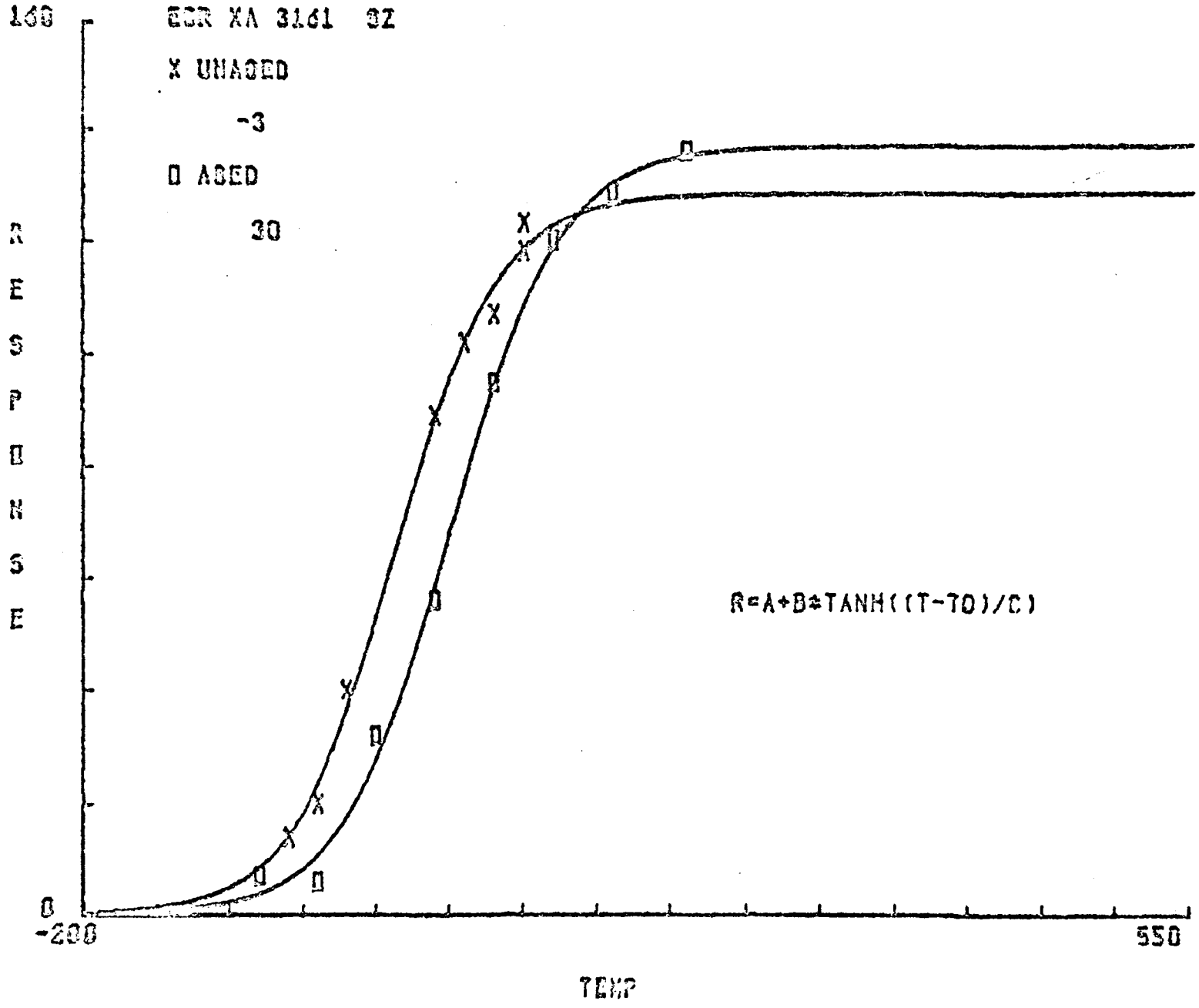

EGR XA 3153 TC
X UNAGED
45
O AGED
111
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
100
0
-200
550

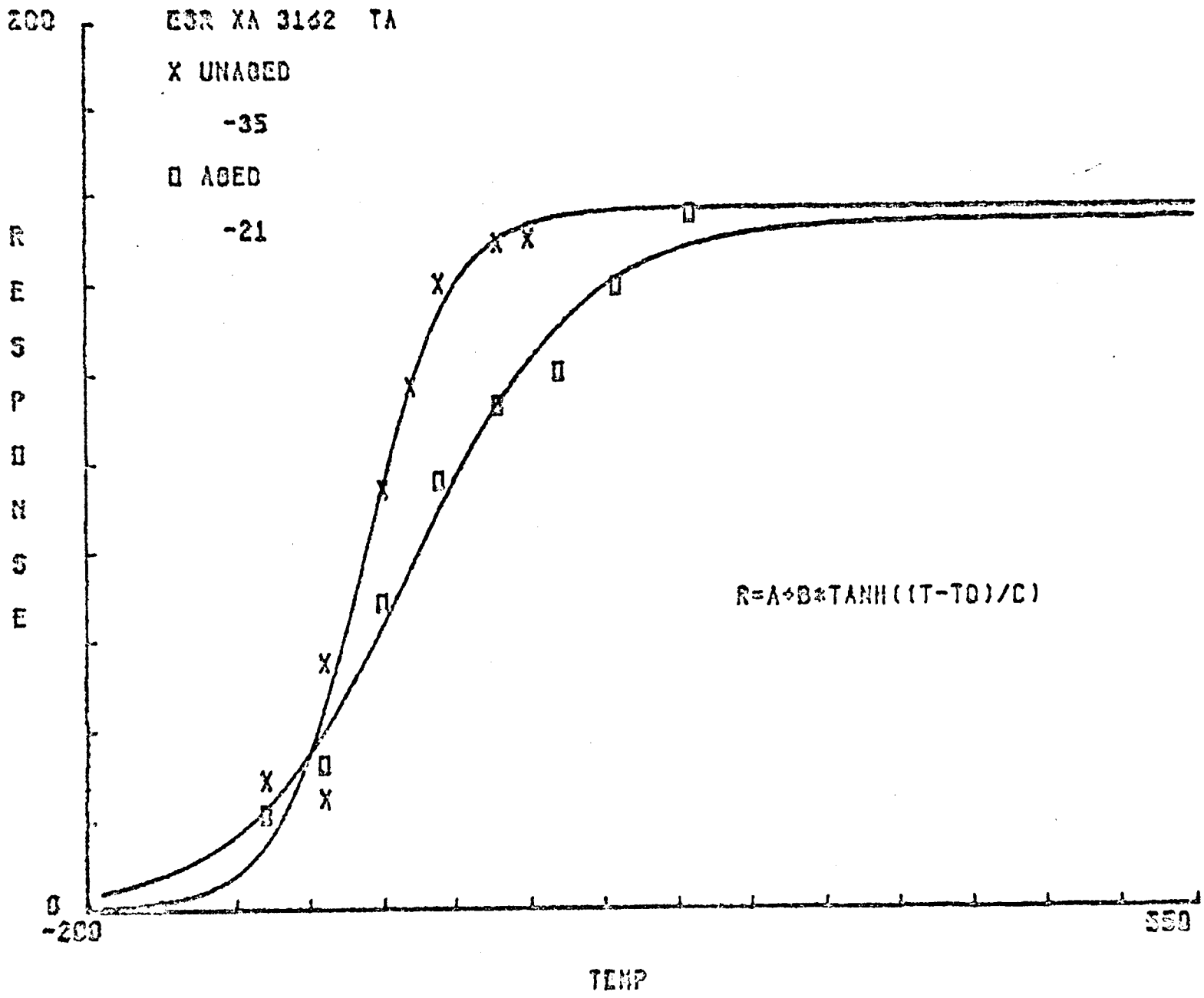

160
EOR XA 3157 HO
X UNAGED
17
□ AGED
74
RESPONSE
R=A+B*TANH((T-TO)/C)
0
-200
300
TEMP

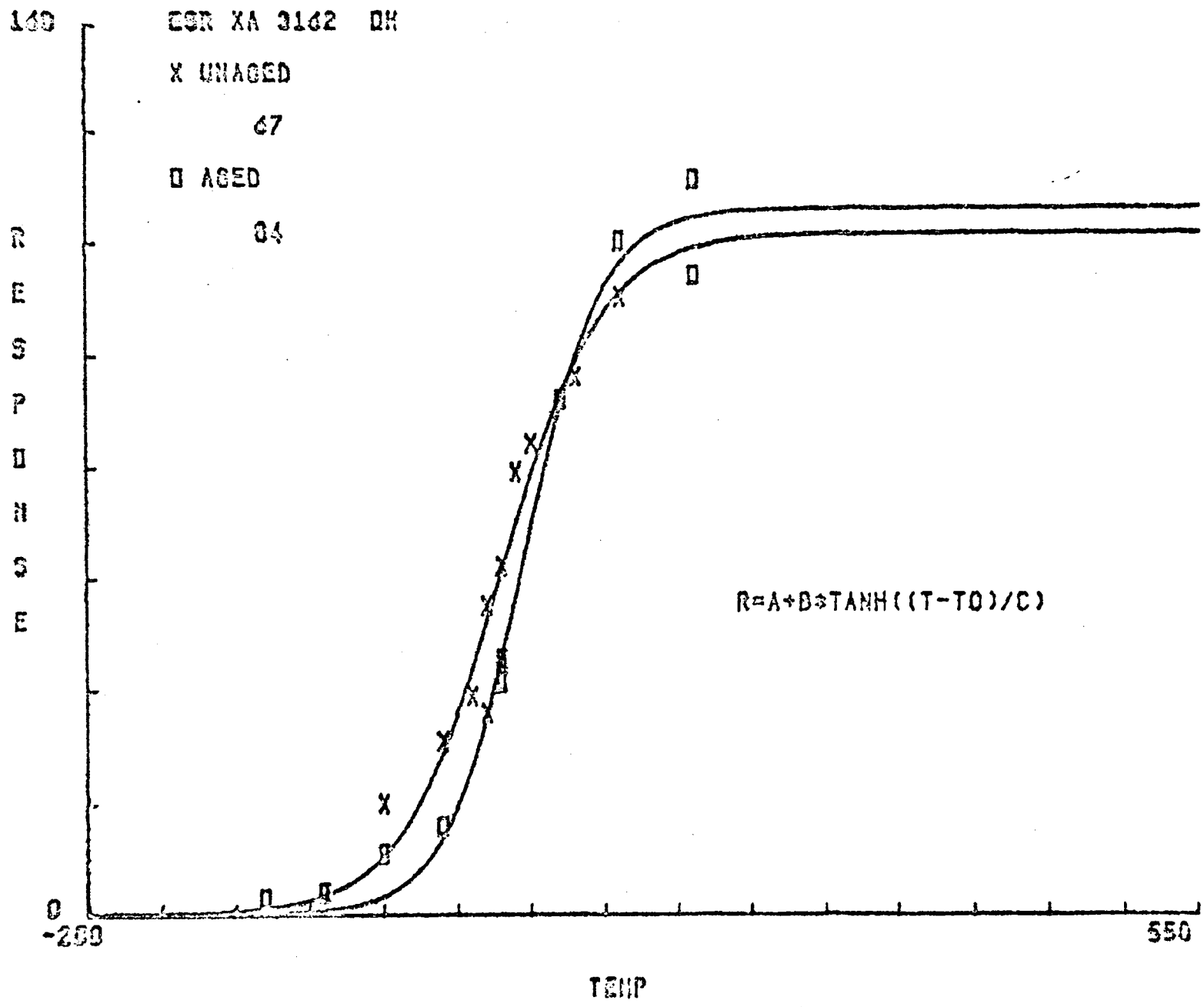

140
EGR XA 3159 DT
X UNAGED
0
□ AGED
69
R
E
S
P
O
N
S
E
R=A+D*TANH((T-TO)/C)
0
-200
550
TEMP

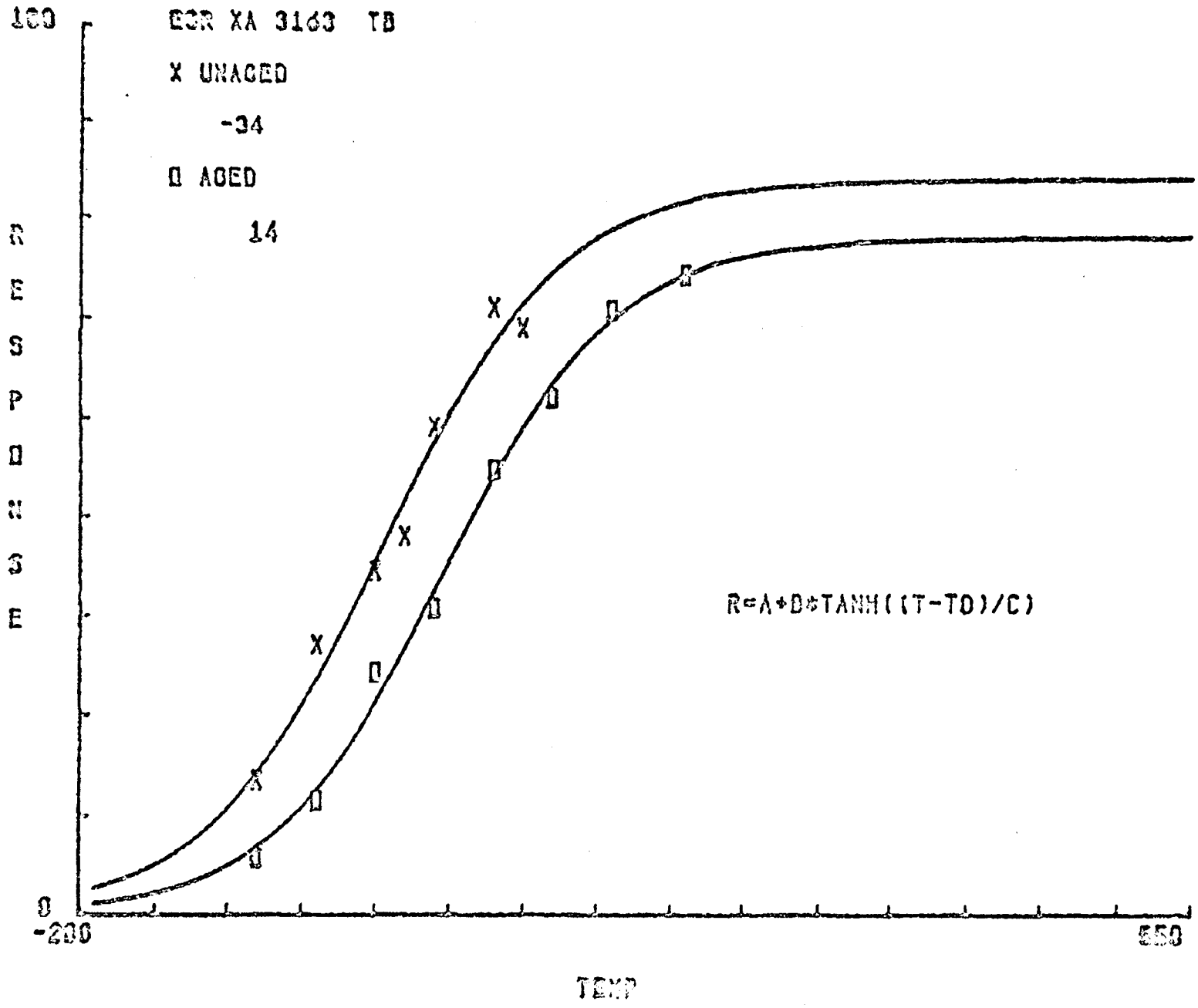

EOR XA 3160 DU
X UNAGED
44
D AGED
106
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
100
0
-200
550

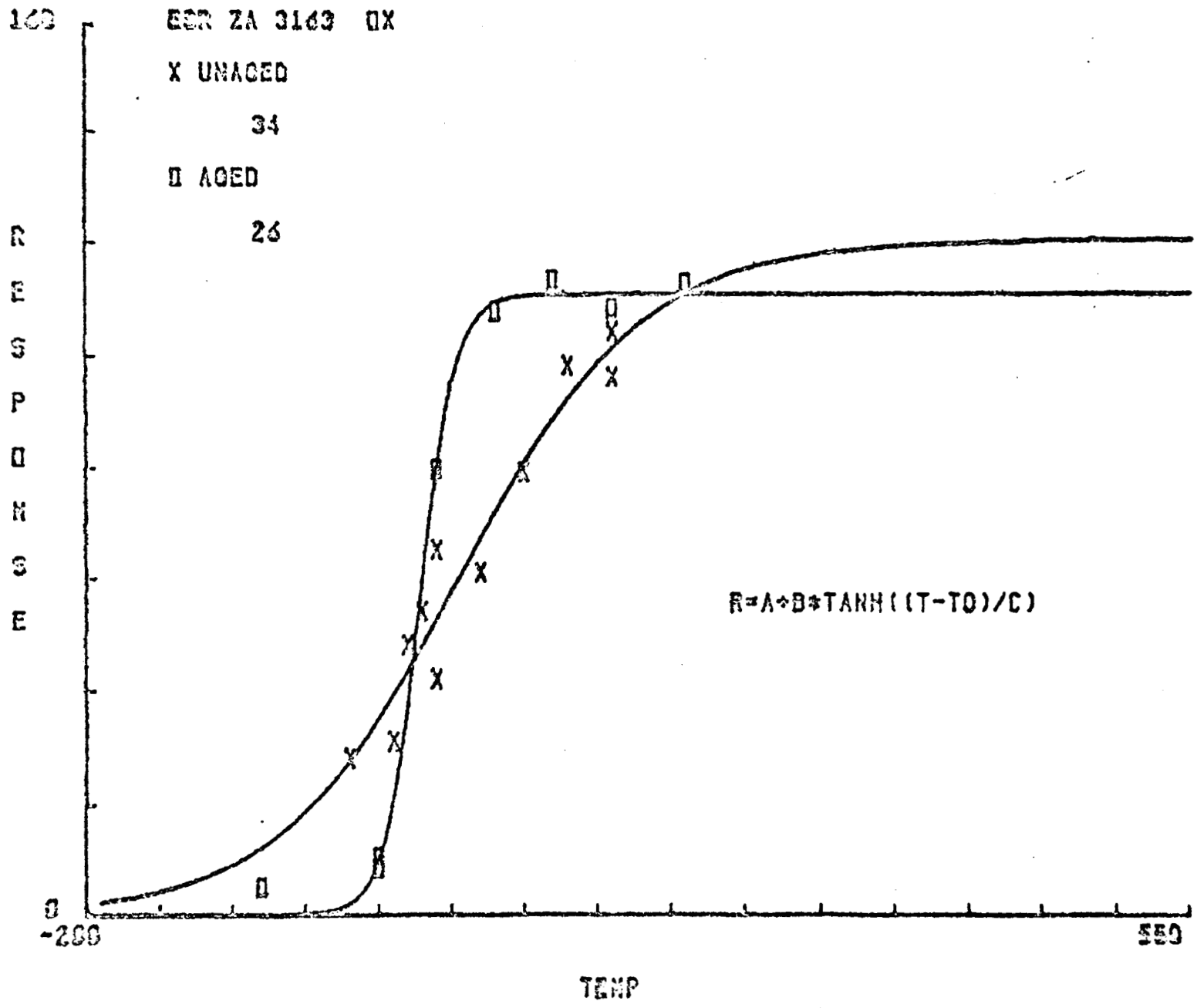

ESR XA 3161 DY
X UNAGED
22
□ AGED
69
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
160
0
-200
550

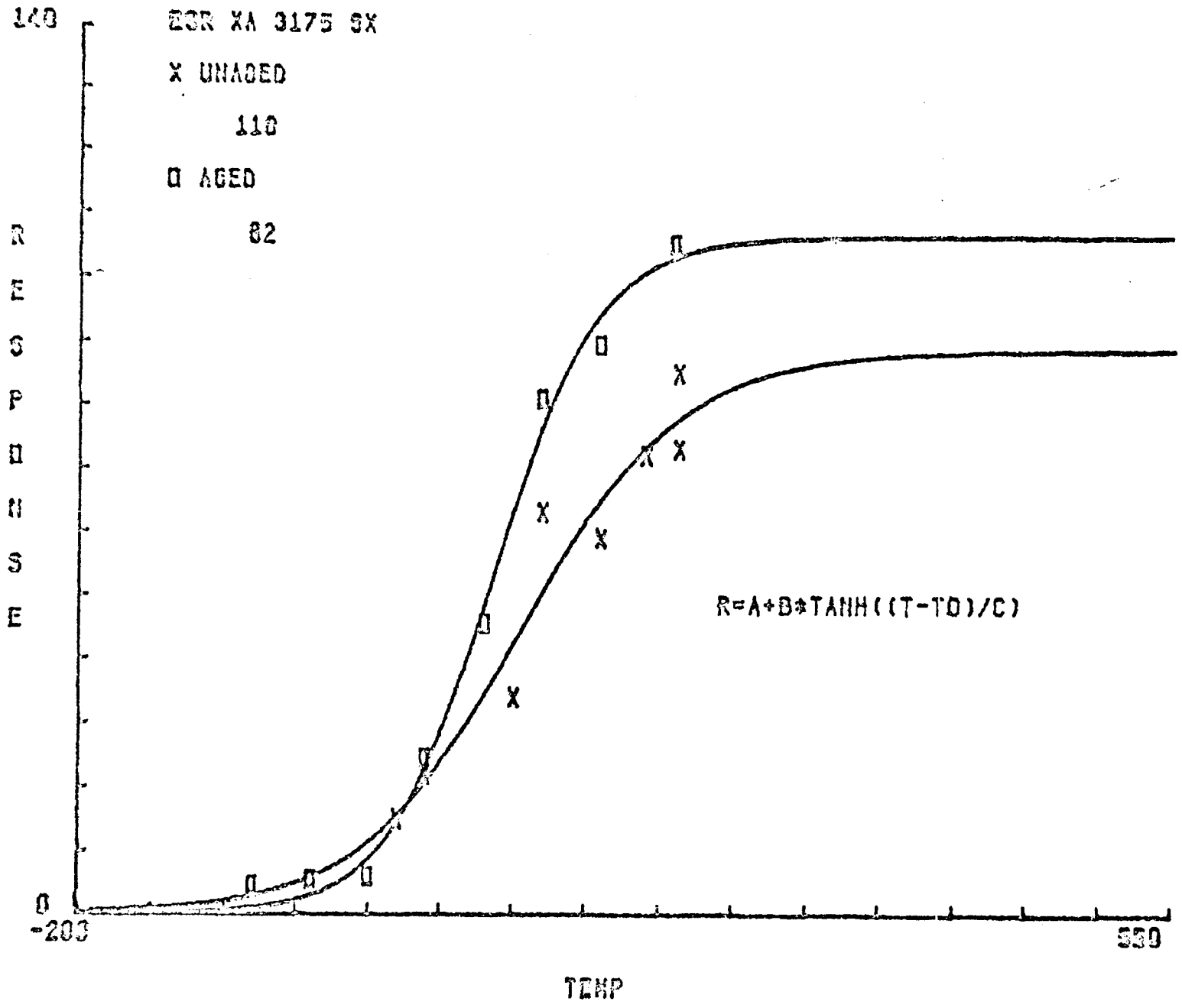

160
ECR XA 3161 8Z
X UNAGED
-3
O AGED
30
R E S P O N S E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

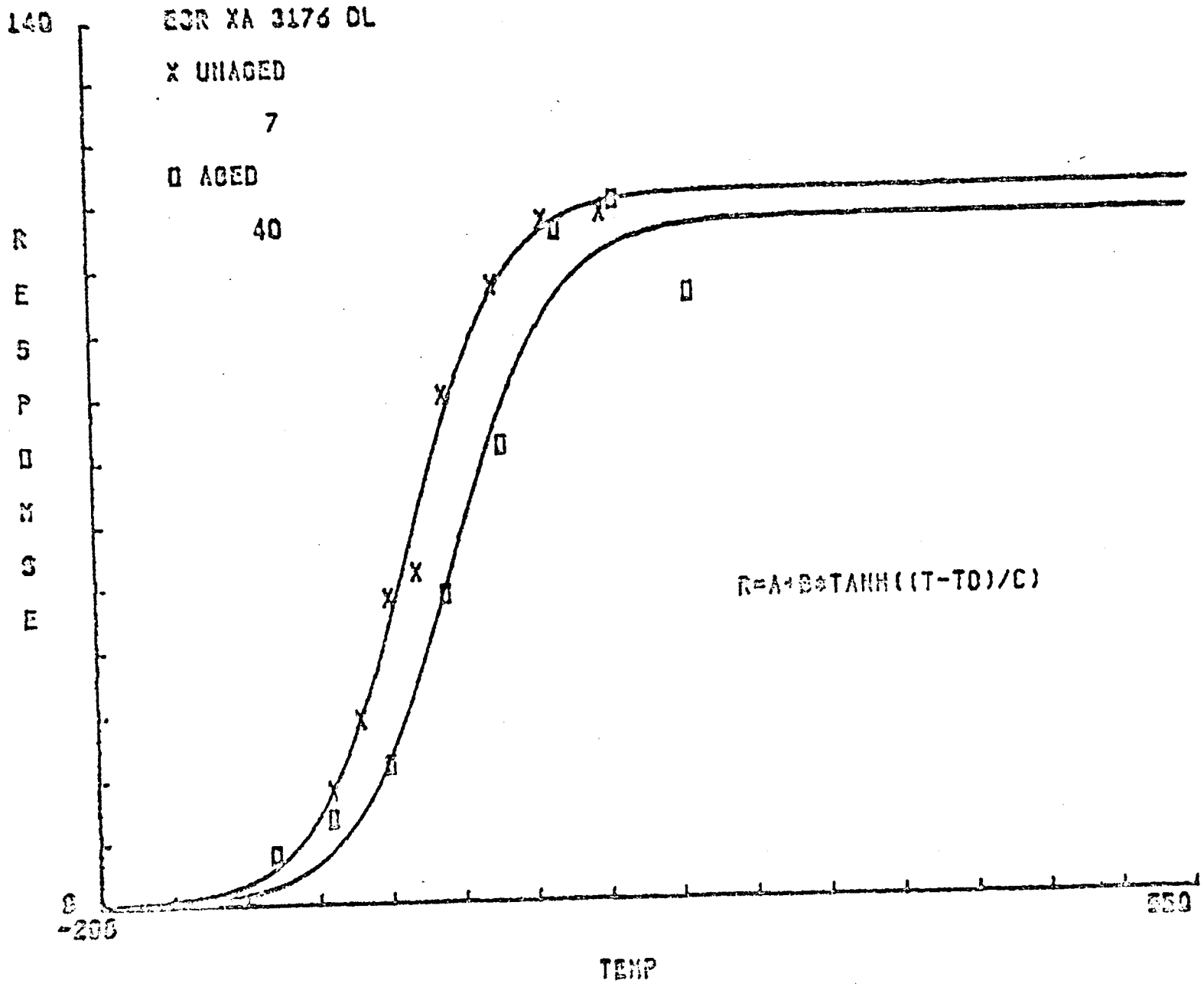

200
ESR XA 3162 TA
X UNAGED
-35
□ AGED
-21
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
350
TEMP

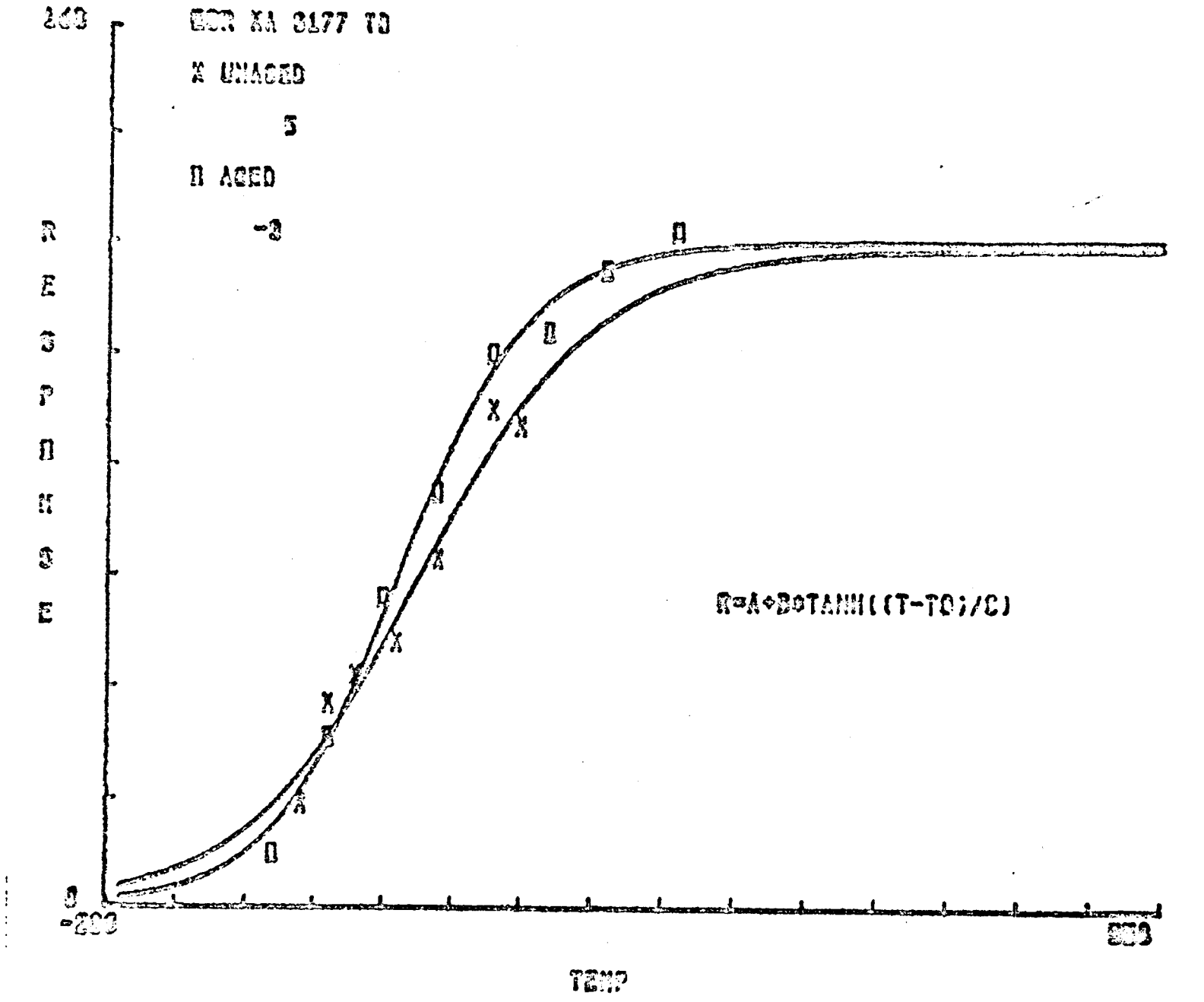

100
EOR XA 3162 DH
X UNAGED
67
D AGED
04
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

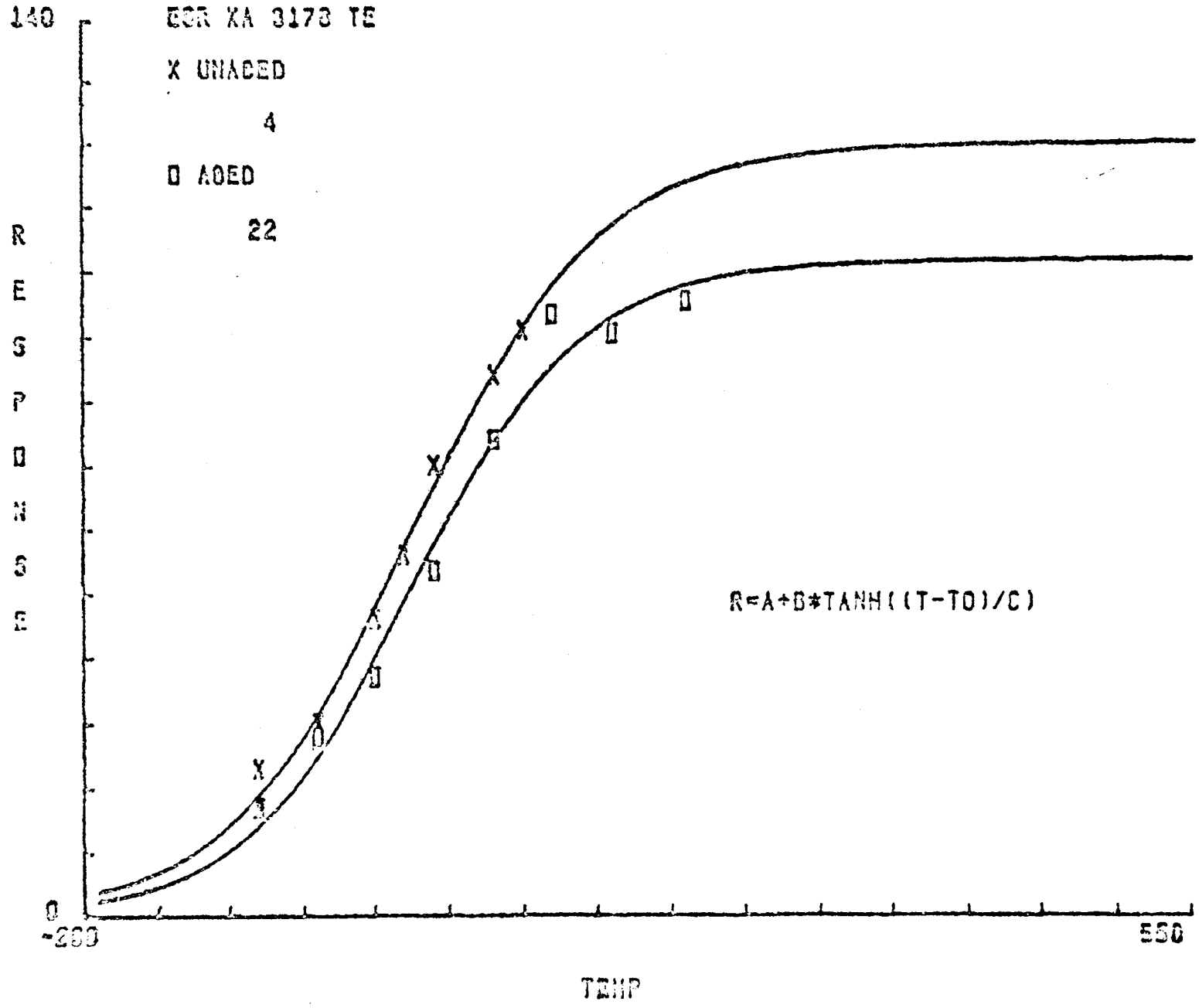

100
ECR XA 3163 TB
X UNAGED
-34
□ AGED
14
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

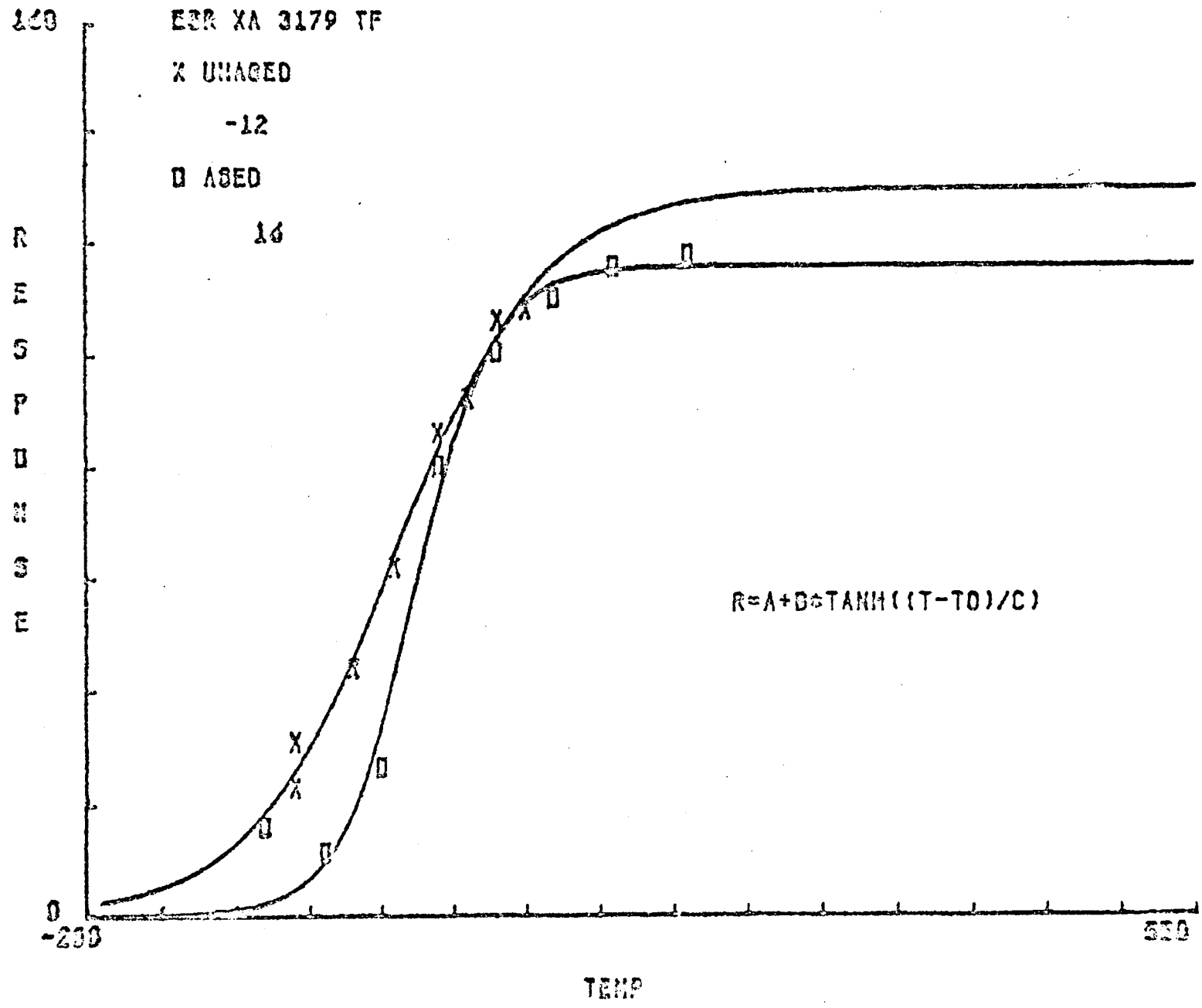

EBR ZA 3163 □X
X UNAGED
34
□ AGED
26
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
100
0
-200
550

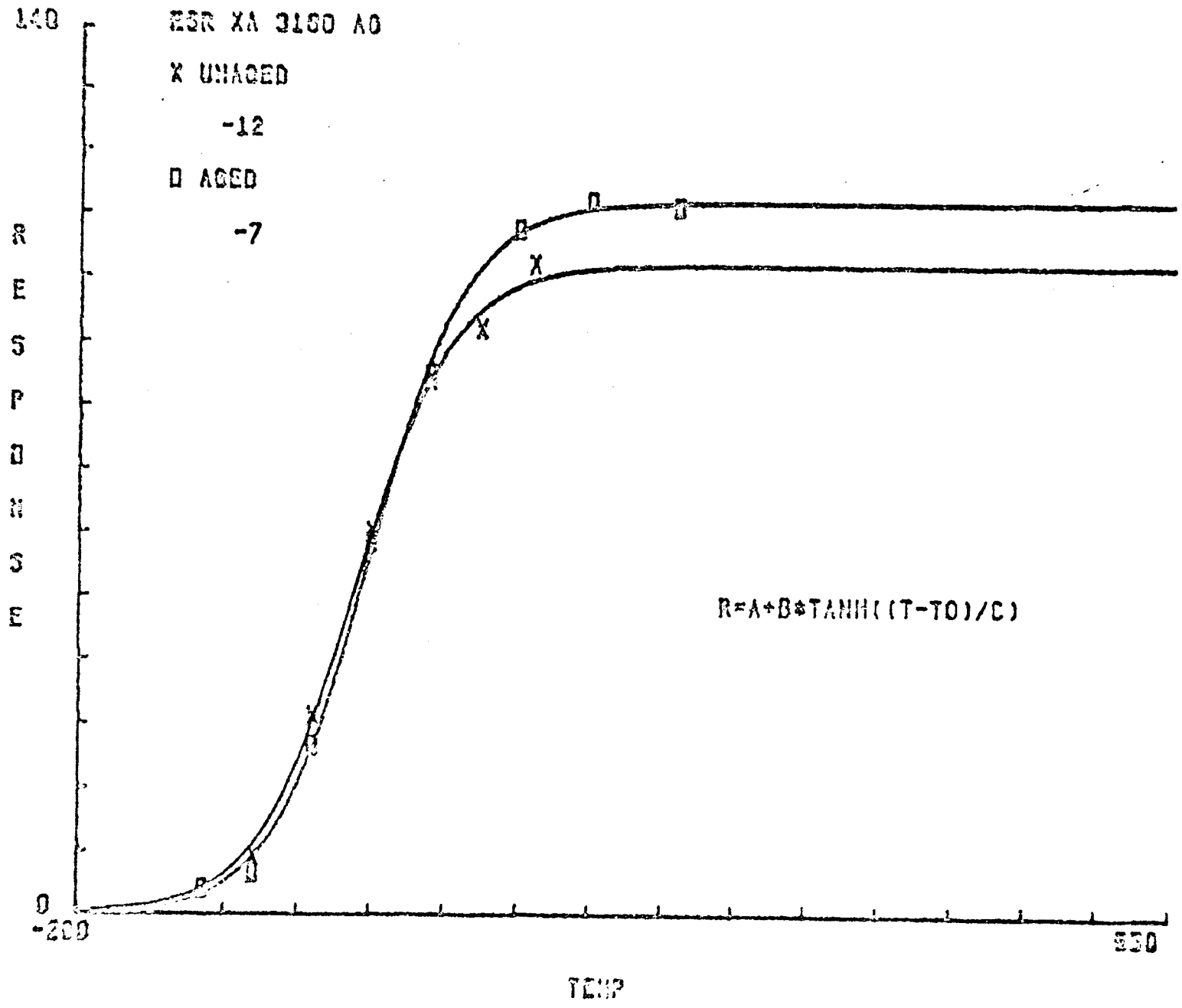

140
ECR XA 3175 SX
X UNAGED
110
O AGED
82
RESPONSE
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

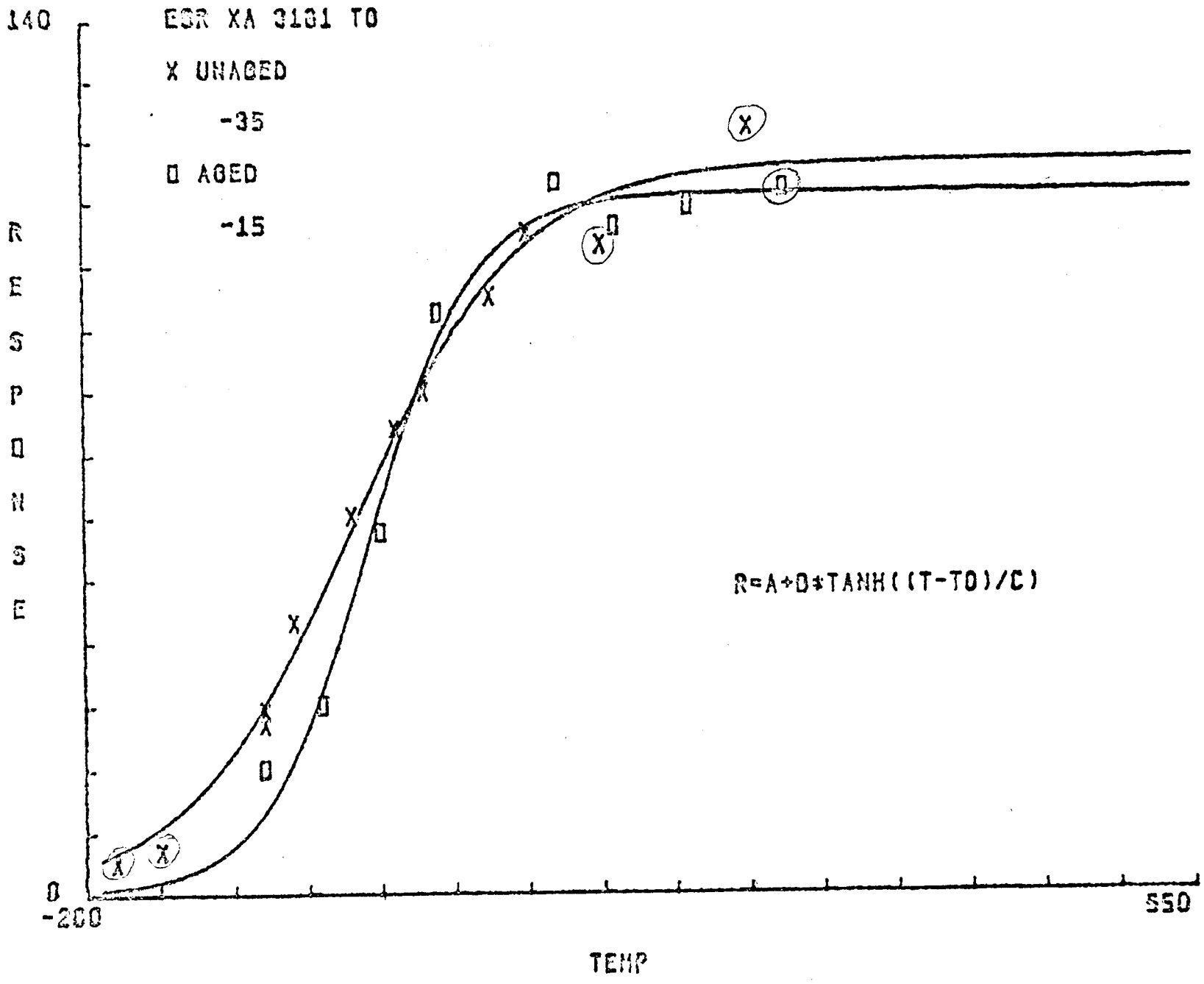

140
EOR XA 3176 DL
X UNAGED
7
O AGED
40
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
350
TEMP

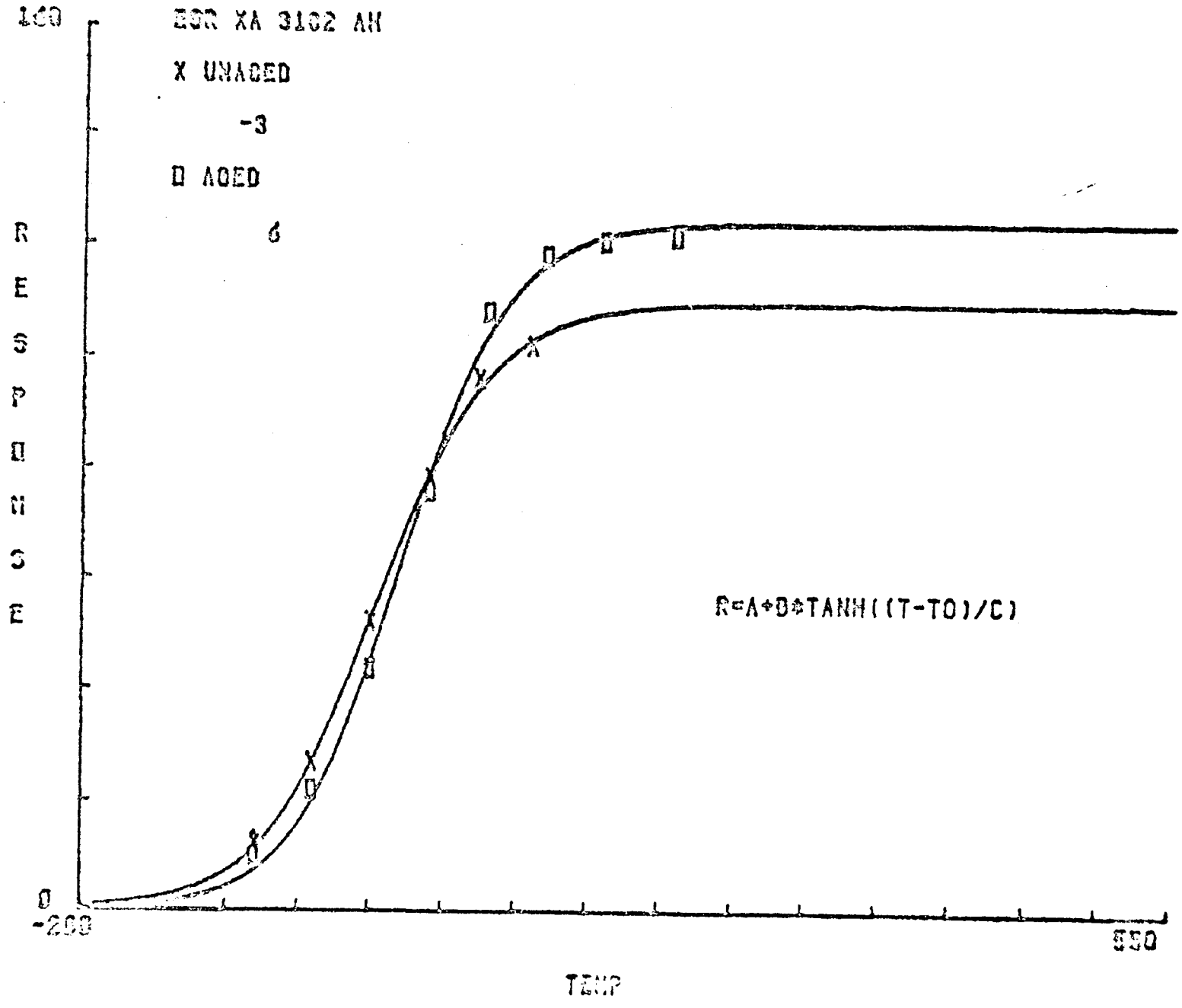

200
ECR XA 8177 TD
X UNAGED
5
D AGED
-3
R
E
S
P
O
N
S
E
0
-200
200
TEMP
R=A+BOTANH((T-TO)/C)

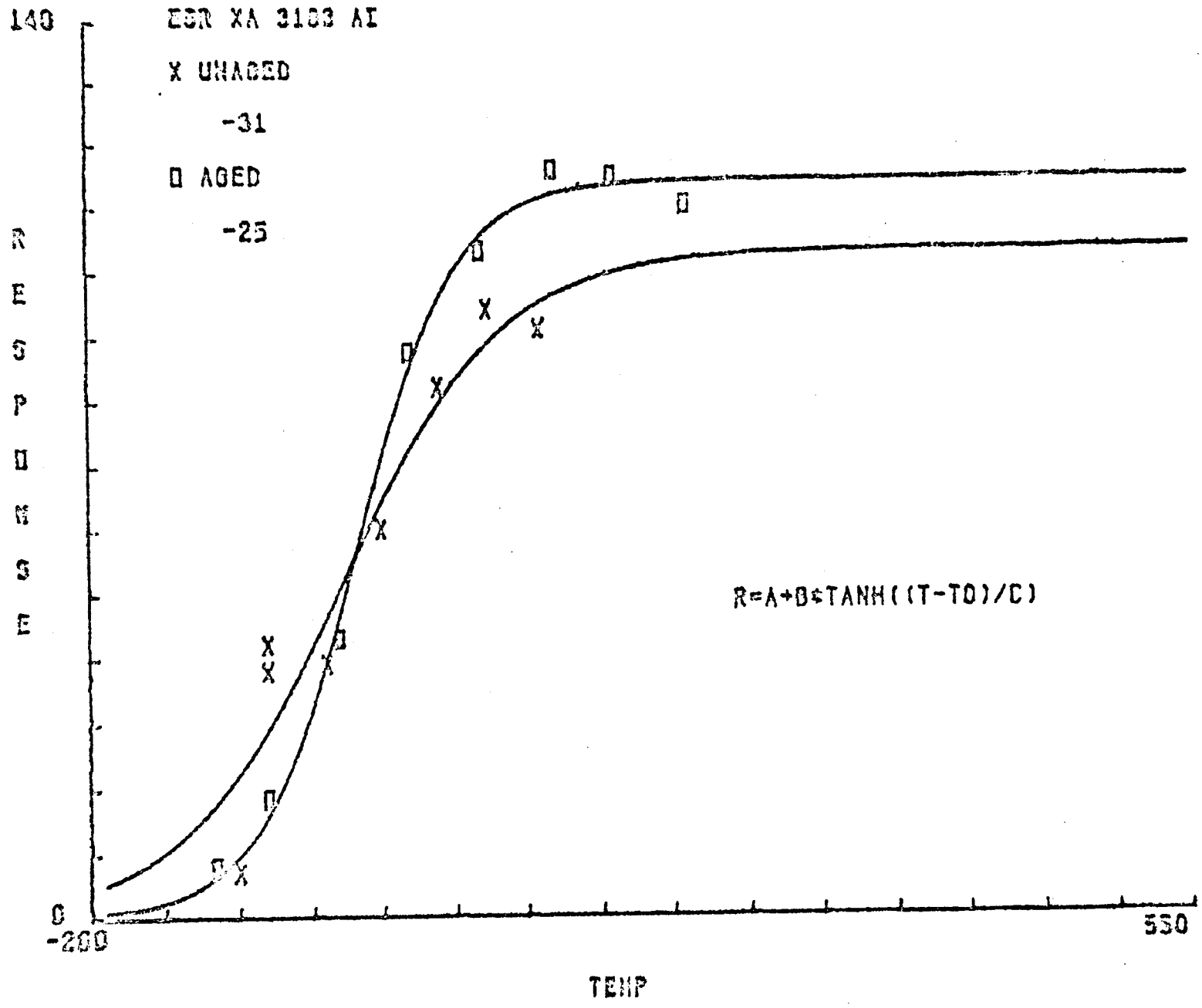

140
EGR XA 3173 TE
X UNAGED
4
O AGED
22
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

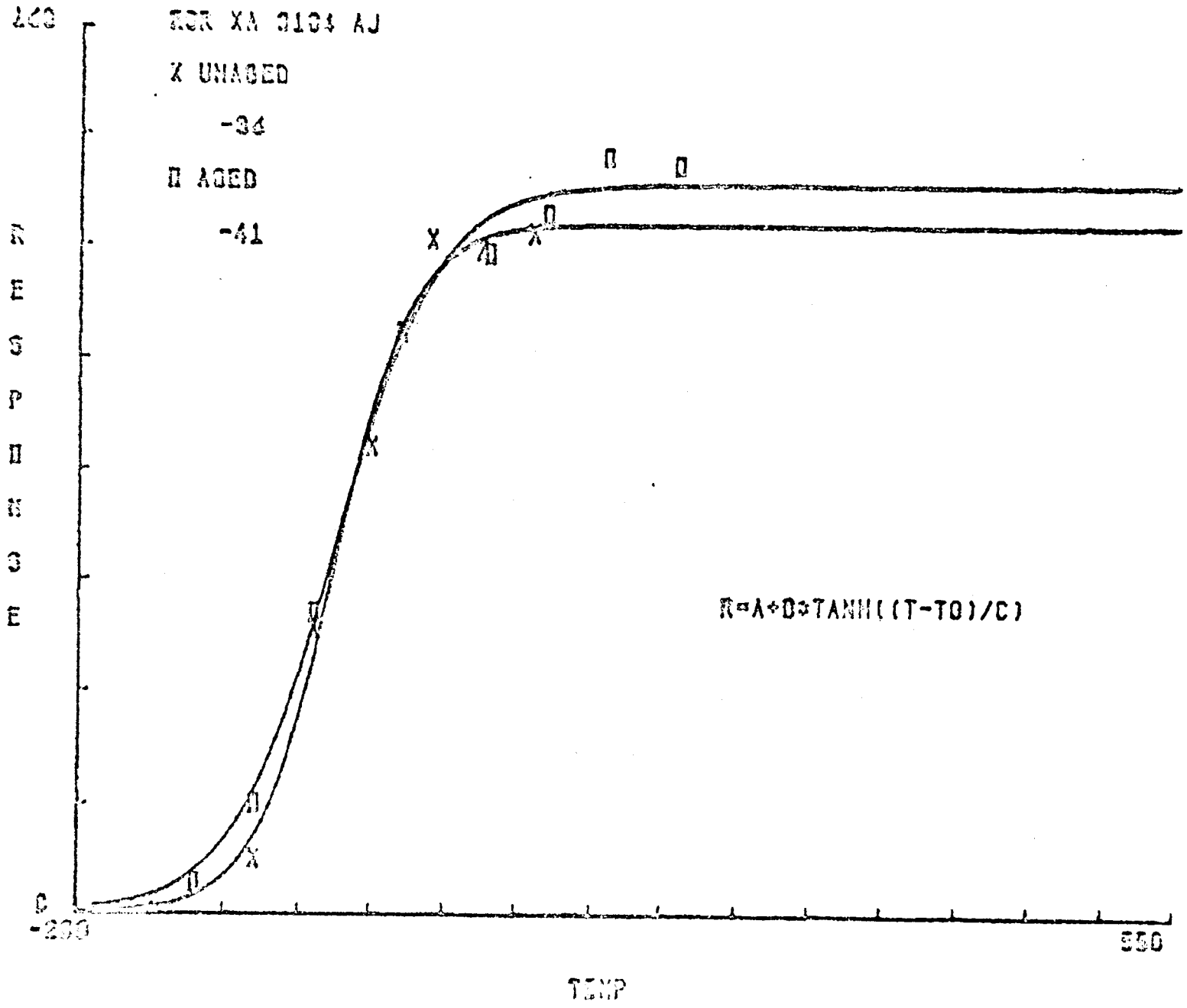

EBR XA 3179 TF
X UNAGED
-12
O AGED
16
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
0
-200
500

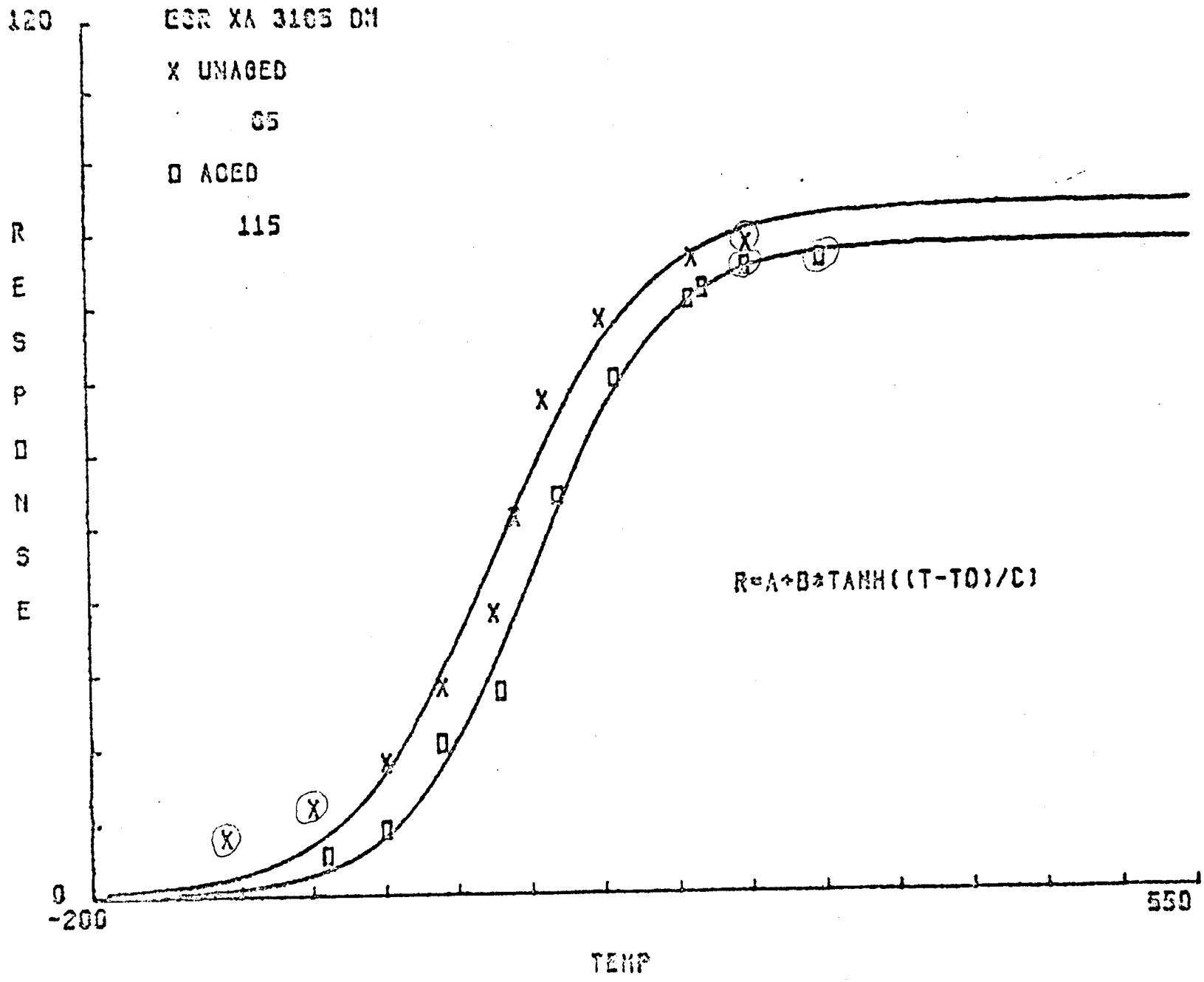

140
ESR XA 3160 A0
X UNAGED
-12
D AGED
-7
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

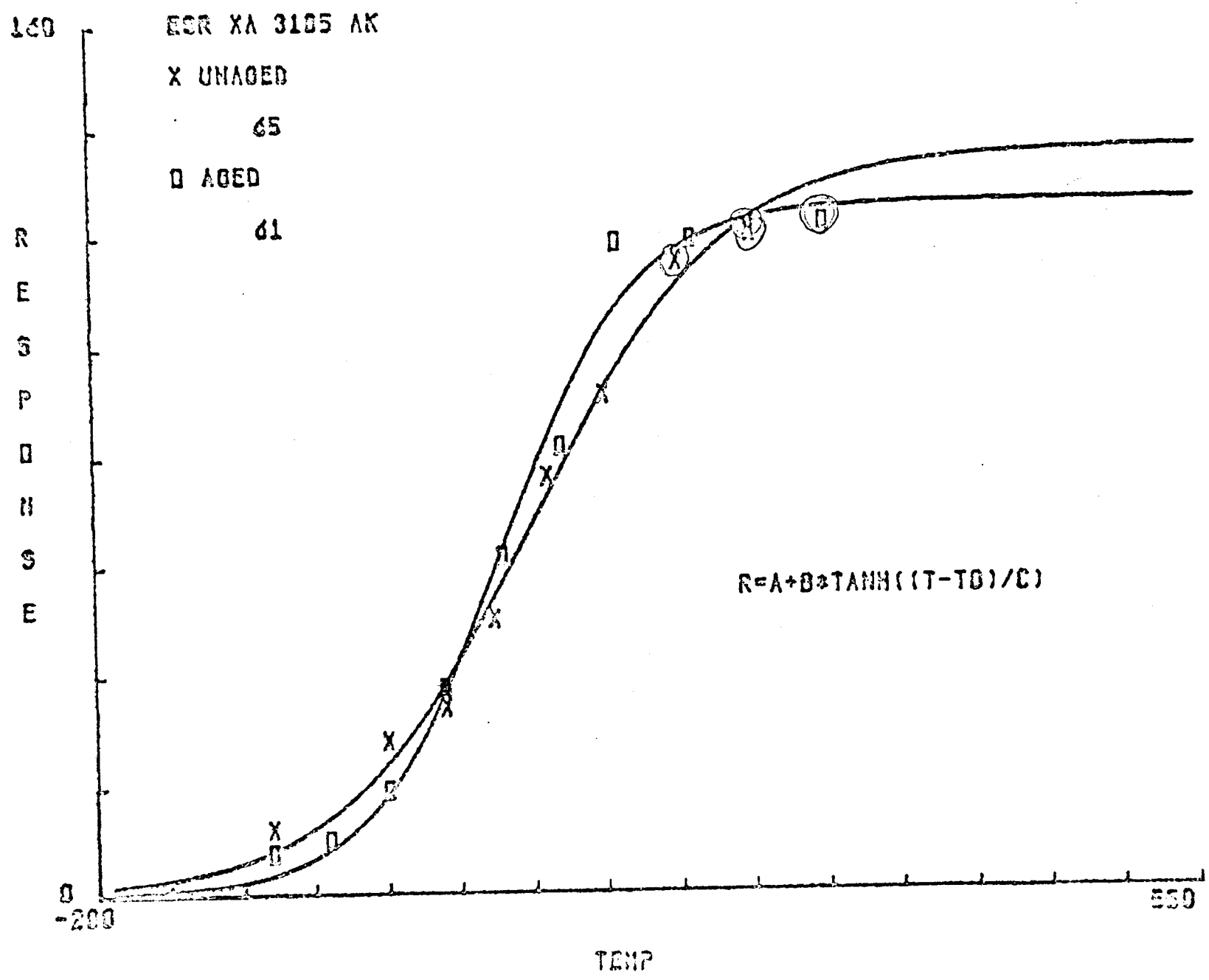

140
EGR XA 3131 TO
X UNAGED
-35
O AGED
-15
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

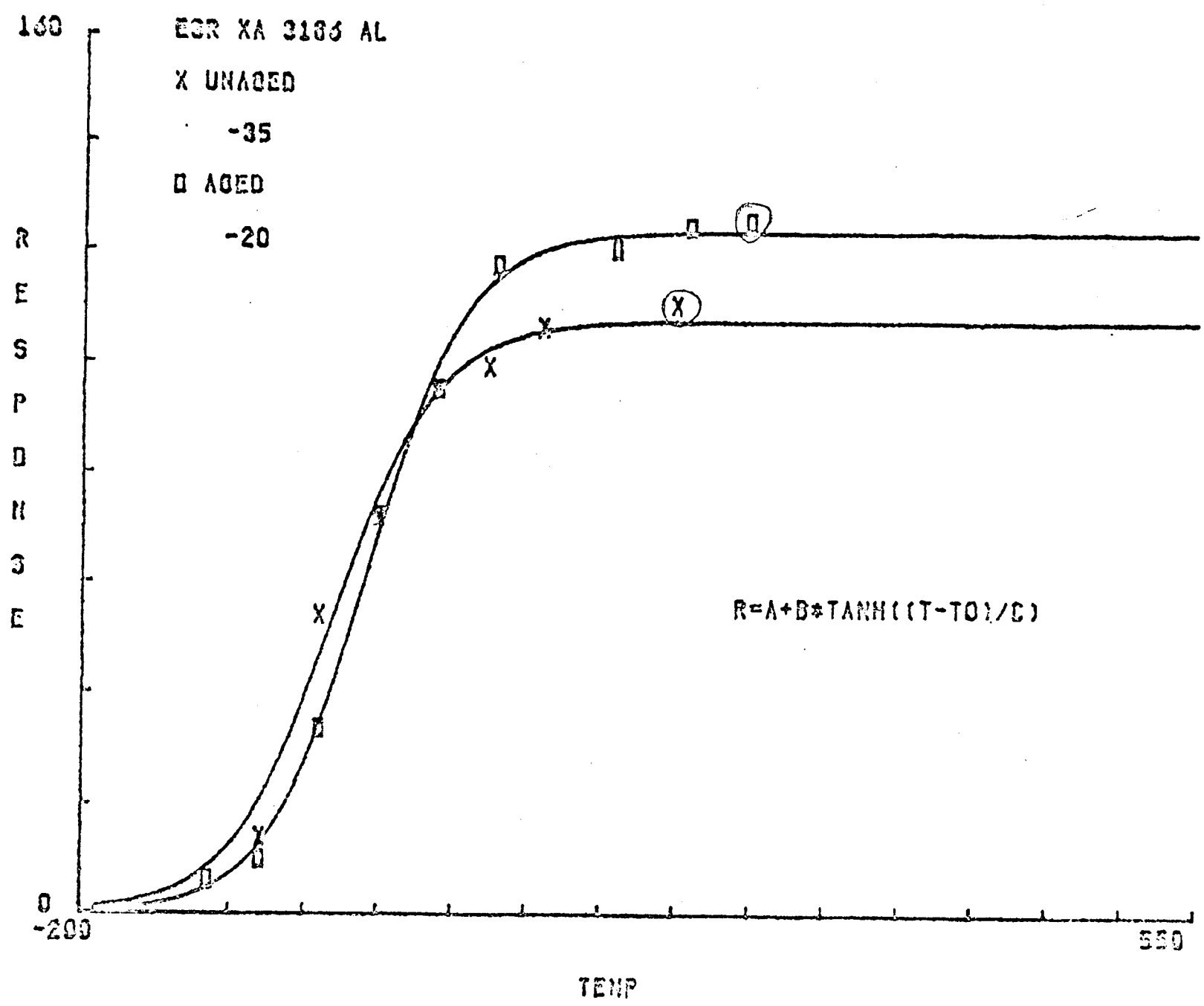

EGR XA 3102 AH
X UNAGED
-3
O AGED
6
R=A+B*TANH((T-TO)/C)
RESPONSE
100
0
-200
550
TEMP

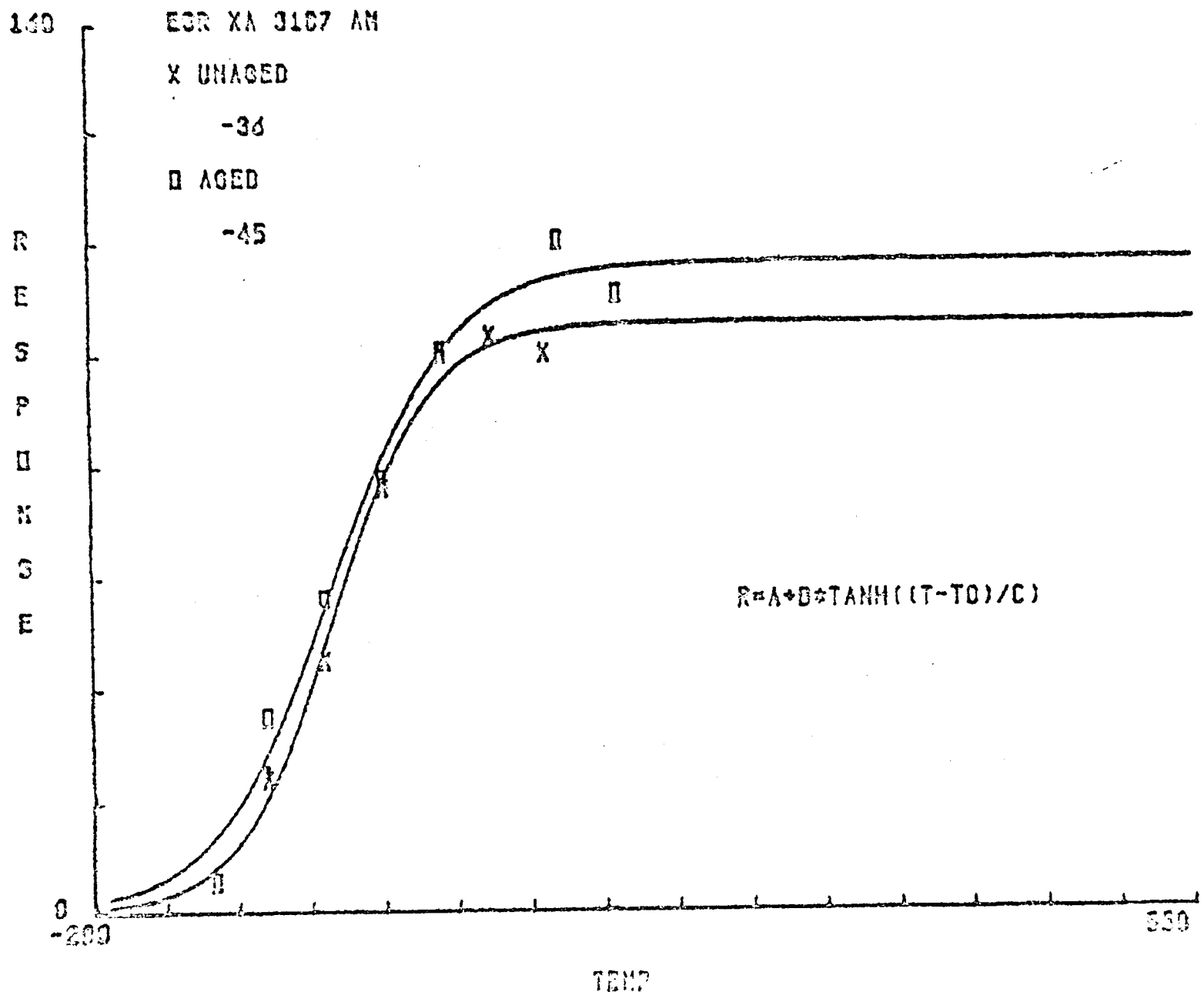

140
ESR XA 3103 AI
X UNAGED
-31
□ AGED
-25
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

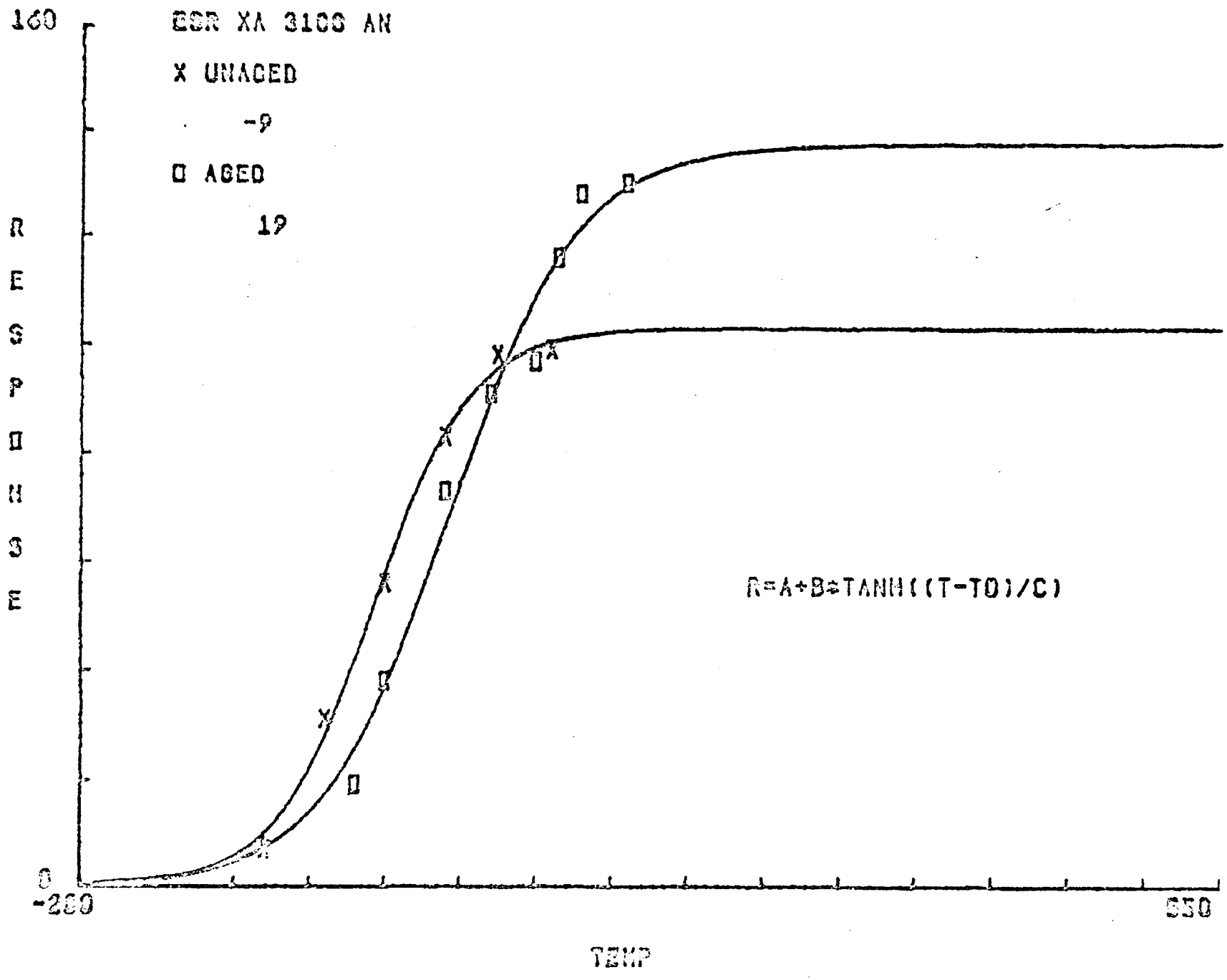

FOR XA 3103 AJ
X UNAGED
-34
O AGED
-41
R=A+B*TANH((T-TO)/C)
RESPONSE
TEMP
0
-200
550

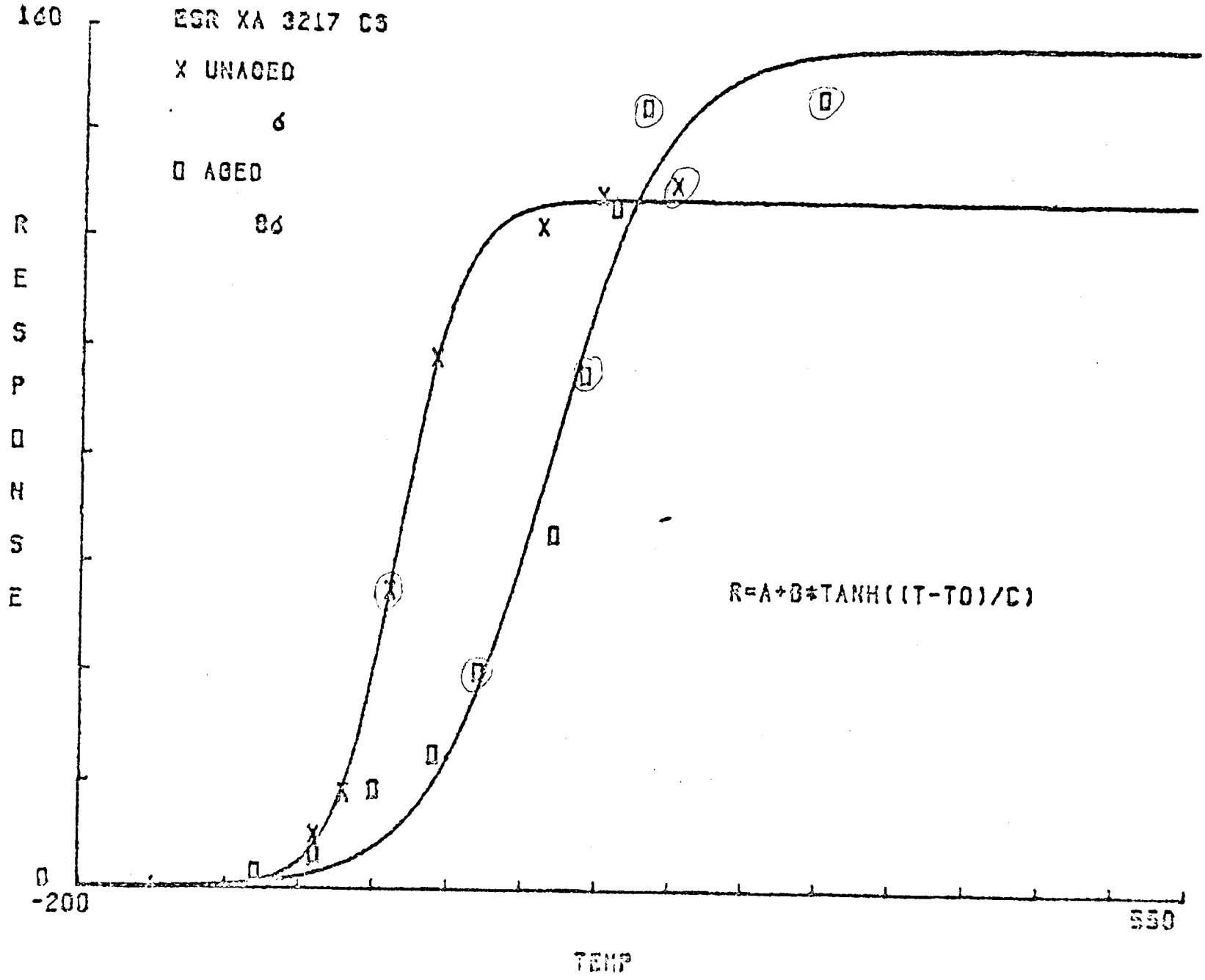

120
EOR XA 3105 DM
X UNAGED
65
O AGED
115
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

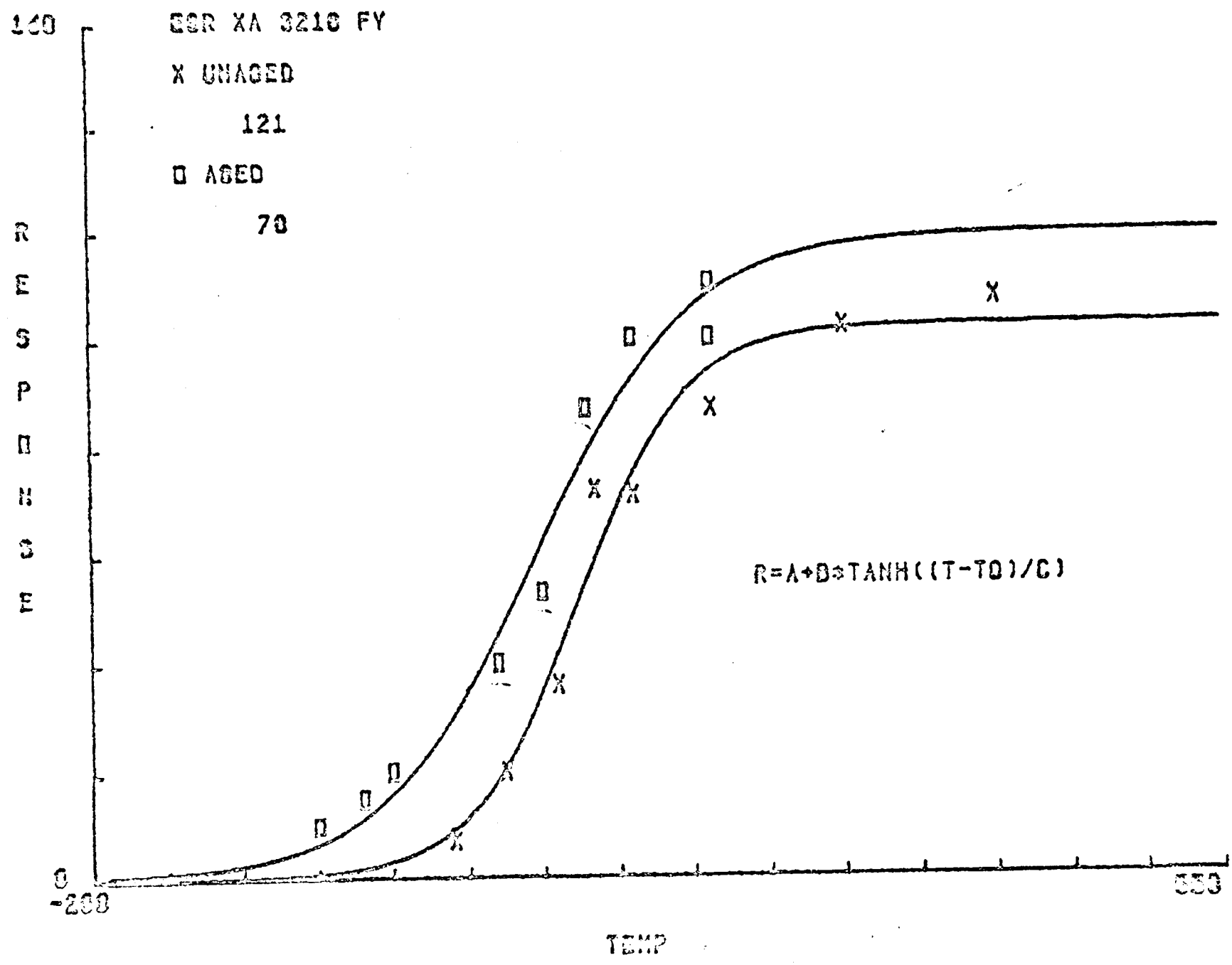

160
ESR XA 3105 AK
X UNAGED
65
O AGED
61
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
350
TEMP

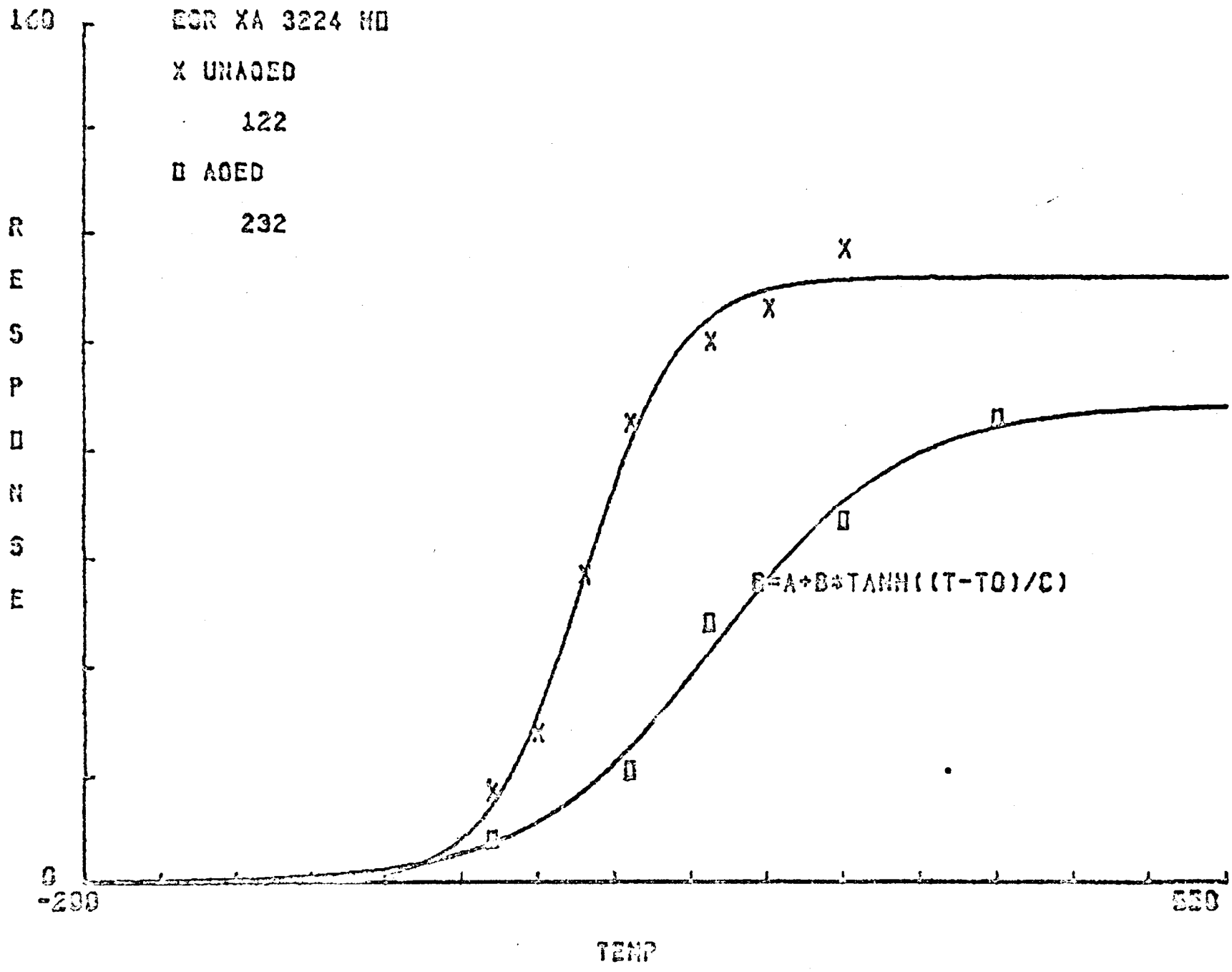

160
ECR XA 3103 AL
X UNAGED
-35
□ AGED
-20
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP

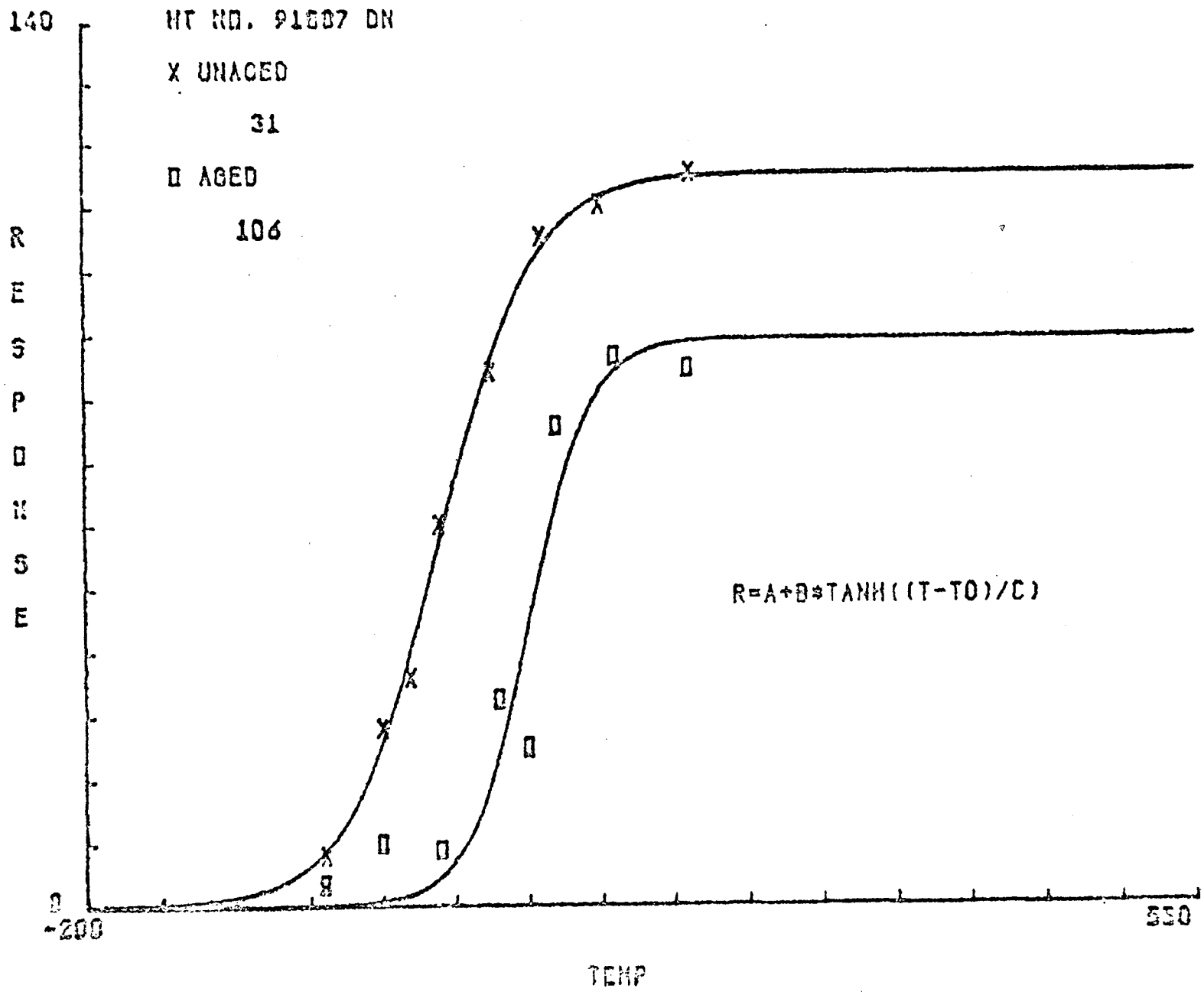

160
EOR XA 3107 AN
X UNAGED
-36
□ AGED
-45
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
350
TEMP


160
ESR XA 3100 AN
X UNAGED
-9
□ AGED
19
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
650
TEMP


160
ESR XA 3217 C3
X UNAGED
6
□ AGED
86
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP


100
0
-200
550
RESPONSE
TEMP
BSR XA 3210 FY
X UNAGED
121
□ AGED
70
R=A+B*TANH((T-TO)/C)


100
EOR XA 3224 HD
X UNAGED
122
□ AGED
232
R
E
S
P
O
N
S
E
0
-200
550
TEMP
B=A+B*TANH((T-TO)/C)


140
HT NO. 91807 DN
X UNAGED
31
□ AGED
106
R
E
S
P
O
N
S
E
R=A+B*TANH((T-TO)/C)
0
-200
550
TEMP