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THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE YIELD AND FRACTURE TOUGHNESS BEHAVIOR OF SELECTED STEELS FOR AN LMFBR SPENT FUEL SHIPPING CASK - A LITERATURE ASSESSMENT

MASTER

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THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE YIELD AND FRACTURE TOUGHNESS BEHAVIOR OF SELECTED STEELS FOR AN LMFBR SPENT FUEL SHIPPING CASK - A LITERATURE REVIEW

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February 1976

ABSTRACT

The available literature has been reviewed to determine the possible influences of strain rate and temperature on the yield and fracture toughness behavior of selected steels suggested for use in an LMFBR Spent Fuel Shipping Cask. Based on this information, recommendations have been made for further work which is intended to alleviate potential problems prior to their having a major impact on the shipping cask program.

1-2

TABLE OF CONTENTS

LIST OF FIGURES

THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE YIELD AND FRACTURE TOUGHNESS BEHAVIOR OF SELECTED STEELS FOR AN LMFBR SPENT FUEL SHIPPING CASK - A LITERATURE REVIEW

INTRODUCTION

The primary purpose of this survey was to assess the present state of knowledge as to the influence of strain rate and temperature on the flow and fracture characteristics of selected steels intended for use in the LMFBR spent fuel shipping cask. The strain rates and temperatures considered were chosen as those typical of cask applications, that is strain rates less than 10^{1}/sec and temperatures between -40° and 800° C.* Neutron irradiation effects were only considered insofar as they affect mechanical response; a more detailed discussion of their importance will be the subject of future work.

Finally, this literature survey is not intended to be a restatement of all available information, rather it is an evaluation of previous investigations and identifies those areas where, in the author's opinion, present knowledge requires further reinforcement

MATERIALS

Table I lists the chemical compositions of the principal structural materials being considered for the LMFBR shipping cask. These materials may be generally classified as austenitic, martensitic precipitation hardening stainless or ferritic steels. The alloys designated A516, A333, A334, and A350 are quite similar in composition and are supplied, depending upon section size, in either the normalized or quenched and tempered condition. The composition of A[illegible] suggests that it may be susceptible to temper embrittlement[1,2] if exposed for <u>long</u> times at temperatures between 350° - 550° C. Fortunately, the times involved are in excess of those for the LMFBR spent fuel shipping cask. Tables II through IV provide appropriate product form descriptions and specifications.

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*The latter temperature should be experienced only under a hypothetical fire associated accident, the normal operating temperature being 290° C.

TABLE 1

Chemical Composition of Candidate Materials for [illegible] Spent

Alloy Designation Austenite Steels	C (max)	Mn (max)	S (max)	Si (max)	Cr	Weight Ni	Pe P
304	0.08	2.0	0.03	1.0	18 - 20	8 - 12	0
304L	0.03	2.0	0.03	1.0	18 - 20	8 - 12	0.
321	0.08	2.0	0.03	1.0	18 - 20	11 - 15	0.
347	0.08	2.0	0.03	1.0	17 - 19	9 - 13	0.
316	0.08	2.0	0.03	1.0	16 - 18	10 - 14	0.
Ferritic							
A508 Cl 4, 4A	0.23	0.2 - 0.4	0.02	0.3	1.5 - 2	2.75 - 3.9	0.
Cl 5, 5A	0.23	0.2 - 0.4	0.02	0.3	1.5 - 2	2.75 - 3.9	0.
A533(a)							
Grade A	0.25	1.15 - 1.5	0.04	0.15 - 0.3		0.4 - 0.7	0.
B	0.25	1.15 - 1.5	0.04	0.15 - 0.3		0.7 - 1.0	0.
C	0.25	1.15 - 1.5	0.04	0.15 - 0.3		0.2 - 0.4	0.
D	0.25	1.15 - 1.5	0.04	0.1 - 0.3			0.
4140 (A320-L7)	0.38 - 0.48	0.75 - 1.0	0.04	0.2 - 0.35	0.8 - 1.1		0.
4340 (A320-L43)	0.38 - 0.43	0.6 - 0.85	0.04	0.2 - 0.35	0.7 - 0.9	1.65 - 2.0	0.
A516 Gr. 55	0.18 - .26	0.6 - 1.2	0.04	0.15 - 0.3			0.
60	0.21 - 0.27	0.6 - 1.2	0.04	0.15 - 0.3			0.
A333 Gr. 1	0.3	0.4 - 1.06	0.06				0.
A333 6	0.3	0.29 - 1.06	0.058	0.1 min.			0.
A350 Gr. LF1	0.3	1.06	0.05				0.
LF2	0.3	1.35	0.05	0.15 - 0.3			0.
Martensitic PH Stainless Steel							
17-4PH(b)	0.07	1.0	0.03	1.0	15.5 - 17.5	3.0 - 5.0	0.0

(a) Cu< 0.1, P < 0.01 wt. percent is recommended for maximum radiation stability.
(b) Cu - 3.0 - 5.0 weight percent.

ABLE I

erials for LMFBR Spent Fuel Shipment Cask

	Weight Ni	Percent P (max)	Ti (max)	Cb + Ta (max)	Mo	[illegible]e (min)	[illegible] (max)
20	8 - 1[illegible]	0.045				0.15	
20	8 - 10	0.045				0.15	
20	11 - 15	0.045	0.7				
19	9 - 13	0.045		1.1			
18	10 - 14	0.045			[illegible]		
2	2.75 - 3.9	0.02			0.4 - 0.6		0.03
2	2.75 - 3.9	0.02			0.4 - 0.6		[illegible]
	0.4 - 0.7	0.035			0.45 - 0.6		
	0.7 - 1.0	0.035			0.45 - 0.6		
	0.2 - 0.3	0.035			0.45 - 0.6		
		0.035			0.45 - 0.6		
1.0		0.04			0.15 - 0.[illegible]		
0.9	1.652.0	0.04			0.2 - 0.3		
		0.035					
		0.035					
		0.05					
		0.048					
		0.04					
		0.04					
17.5	3.0 - 5.0	0.04		0.15 - 0.45			

ility.

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TABLE II

Plate Materials

Material (Steels)	ASTM Specification and Grade
Austenitic	A240 Types 304, 304L, 321 and 347
Ferritic	A516 Grades 55 and 60 A588 Grade A, B, C

TABLE III

Forgings, Fittings and Bolting Materials

Material (Steels)	ASTM Specification and Grade
Forgings	
Ferritic	A508 Classes 4, 4A, 5 and 5A A350 Grades LF1 and LF2
Austenitic	A182 Types 304, 304L, 321 and 347 A473 Types 304, 304L, 321 and 347
Fittings	
Ferritic	A420 Grade WPL1
Austenitic	A403 Grades WP304, 304L, 321 and 347
Fittings	
Ferritic	A420 Grade WPL1
Austenitic	A403 Grades WP304, 304L, 321 and 347
Bolting	
Ferritic	A320 Grade L7, L43
Austenitic	A193 Types B8, B8C and B8T

TABLE IV

Pipe and Tube Materials

Materials (Steels)	ASTM Specifications and Grade
Pipe	
Ferritic	A333 Grades 1 and 6
Austenitic	A312 Types 304, 304L, 321 and 347
Tube	
Ferritic	A334 Grades 1 and 6
Austenitic	A213 Types 304, 304L, 321 and 347

The two additional materials presented in Table V are the ones currently being considered for LMFBR fuel cladding and primary shipping cask seals, although it should be recognized that both may be subject to change prior to completion of the cask program.

TABLE V

Miscellaneous

Material	Use
17-[illegible]	Primary Cask Seal
[illegible]	Fuel Rod Cladding

Nuclear reactor experience has shown that 304 stainless steel, if improperly processed, may be "sensitized".[illegible] Sensitization results in an increase in the environmental cracking susceptibility of this steel. This susceptibility may be decreased and/or eliminated by either re-solution treatment after fabrication or selecting a stabilized stainless steel, e.g., 347. Other methods of minimizing the problem of stress corrosion cracking include controlling the environment, i.e., eliminating Cl^- and [illegible], or maintaining the operative stress levels, including residual welding stresses, below the yield stress.

General corrosion resistance can be obtained by either fabricating the cask from a suitable austenitic stainless steel or by weld-overlay cladding the ferritic base metal. The latter appears to be the optimum approach since it takes advantage of both carbon steels and stainless steel in the cask design while maintaining a minimum cost. It should be noted, however, that weld cladding [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] low creep ductility.

Strain Rate/Temperature Yield Behavior

Extensive reviews of the strain rate [illegible] of ferrous alloys have been presented by [illegible], Kendall,[6] Dietche,[7] and [illegible], et al. In general, the influence of strain rate and temperature on the yield behavior of austenitic and ferritic steels are quite different.

Austenitic Steels

The yield [illegible] of [illegible] austenitic [illegible] [illegible] insensitive [illegible] strain rate [illegible] ferritic steels. Steichen[8-11] [illegible], while the room temperature yield strength of [illegible] increase by [illegible] per decade change in strain rate. [illegible] as well as [illegible] weld metal, is rather insensitive to strain rate [illegible] temperatures lie between [illegible] [illegible]. Increasing the test temperature [illegible] 600° C results in a significant increase in both the strength and tensile ductility with increasing strain rate. There does, however, appear to be some indication of a negative strain rate sensitivity in 304 stainless steel between [illegible] [illegible], the temperature range where serrated (jerky) flow is initially observed in austenitic stainless steels.[12-13] Furthermore, the results for [illegible] stainless steel weld metal are quite sensitive to specimen location, i.e., [illegible] ferrite level. This suggests that close control of weld practice is essential.

The effect of neutron irradiation on the tensile properties of austenitic stainless steel has been extensively investigated. [illegible] and [illegible] have recently shown that the low temperature [illegible] fast neutron (E > 1 MeV) radiation induced yield strength increases observed in types [illegible], [illegible], and [illegible] stainless steel

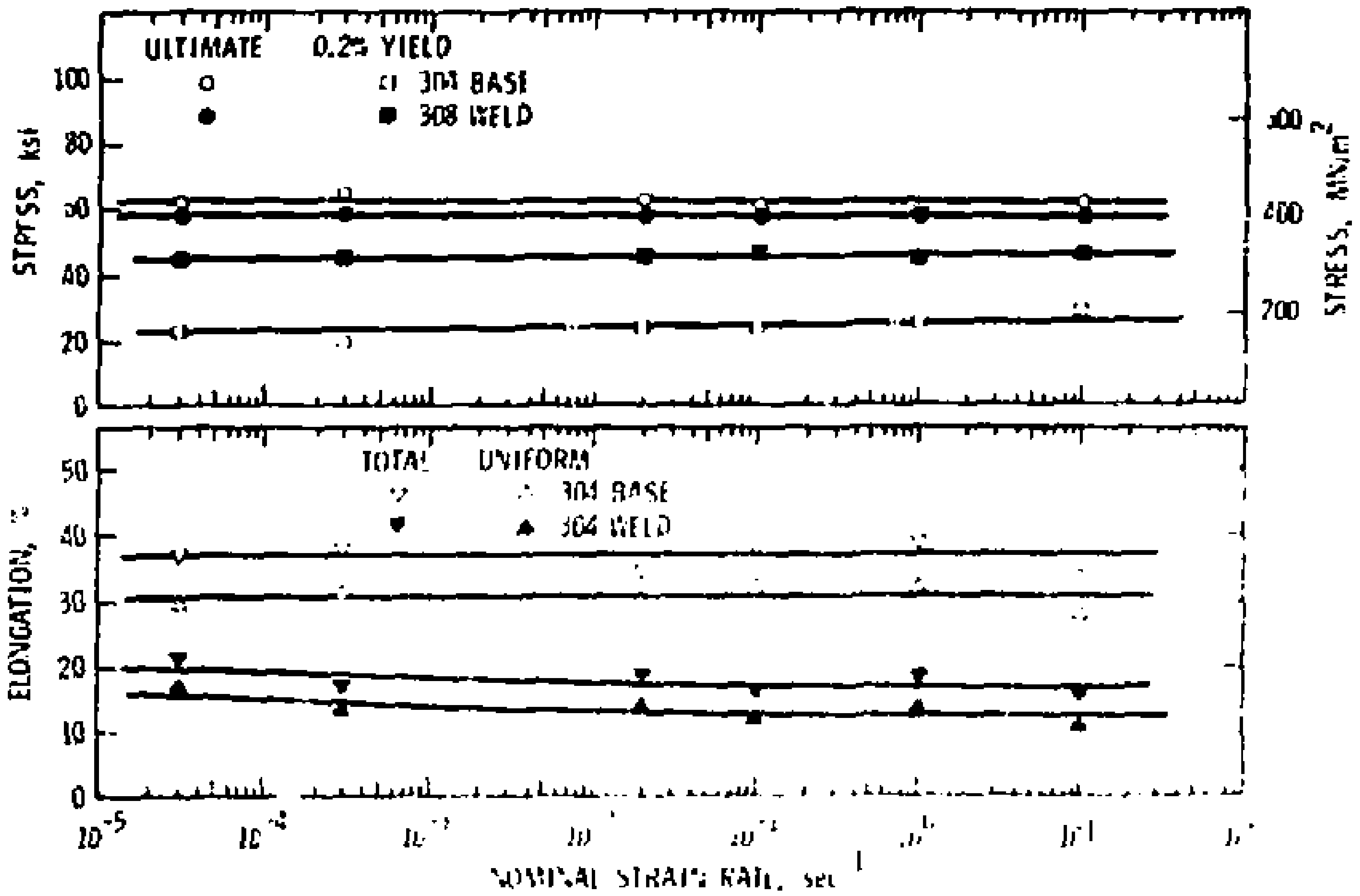

Figure 1. Effect [illegible]
type [illegible]

may be described prior to saturation by:

$$\Delta\sigma \sim C\left[\phi t/10^{17}\right]^{0.5} \qquad (1)$$

where $\Delta\sigma$ is the irradiation associated yield strength increase, ϕt the total fast neutron dose, and C is a function of the pre-irradiation metallurgical condition. Source analysis of a typical LMFBR shipping cask suggests that, over an anticipated ten-year lifetime, ϕt will be less than 10^{15} n/cm^2. If we assume that $C \sim 100 - 140$ MN/m^2,[19] then the expected radiation associated yield strength increase will be approximately 14 MN/m^2, i.e., less than 7 percent of the nominal room temperature yield strength of 304 stainless steel. These same authors note that the yield strength is the most sensitive indicator of low temperature radiation damage, the ultimate tensile strength and tensile ductility both exhibit lower percentage change at equivalent radiation levels. The above observations indicate that the neutron irradiation effects on the primary austenitic steels being considered for the LMFBR shipping cask should be minimal.

Ferritic Steels

As noted above, the strain rate sensitivity of bcc ferrous alloys is quite large when compared to fcc austenitic stainless steel. However, as the absolute yield strength, σ_y, increases, this rate and temperature sensitivity tends to decrease and, when a strength level of 130 ksi (896 MN/m^2) is reached, little sensitivity remains.[5] This suggests that the strain rate sensitivity of 4140, 4340, and 17-4PH should be minimal. Kendall[20,21] has shown that this assumption appears to be valid for 4140 and 4340 (Fig. 2). However, there is no information available on 17-4PH. Indeed, results on 18 Ni(300) Maraging steel, another precipitation hardening alloy system, indicate a 27.5 MN/m^2 per decade change in strain rate increase at room temperature and a similar decrease at 315° C.

Some years ago, Bennett and Sinclair[22] proposed that the low-temperature yield strength behavior of strain rate sensitive bcc metals might be described by a simple rate equation of the form

$$\sigma = RT \ln(A/\dot{\epsilon}) \qquad (2)$$

where σ is the flow stress corrected for loading mode variation, T the absolute temperature, $\dot{\epsilon}$ the strain rate, and A a frequency factor which is generally assigned

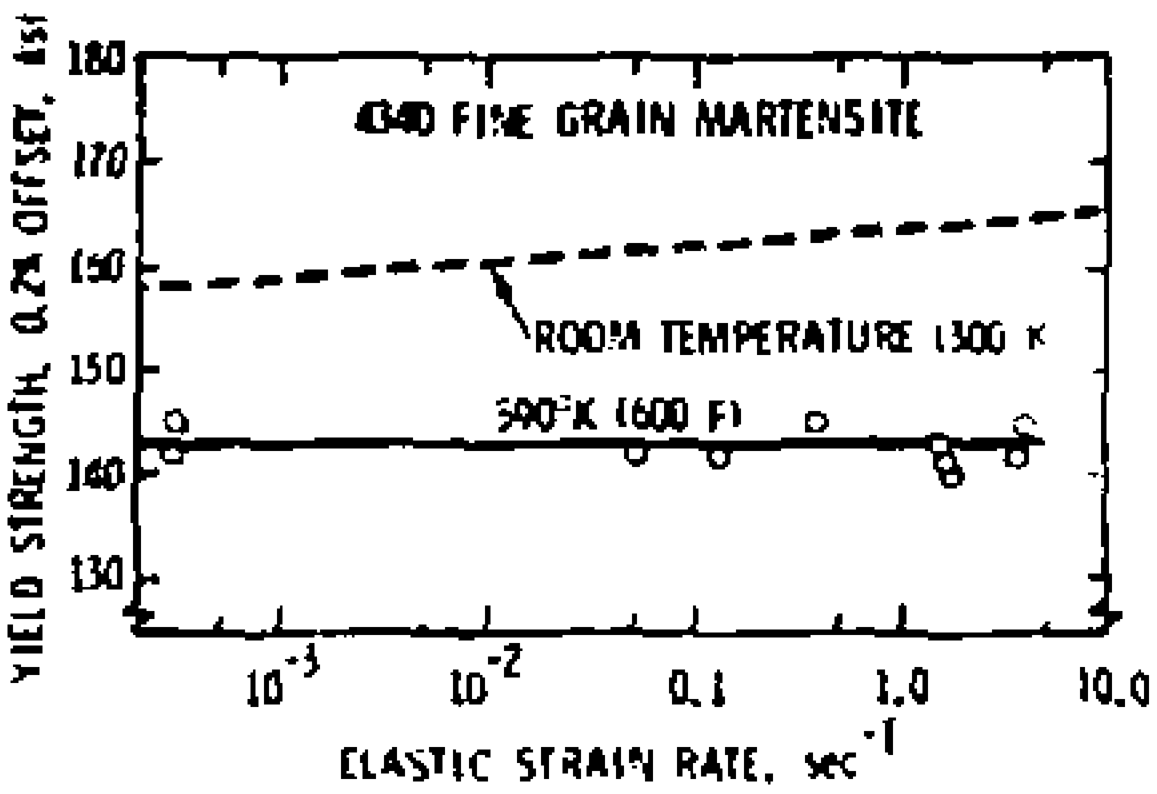

Figure 7. Yield stress versus elastic strain rate for 4340 fine grain martensite (21).

a value of 10^5/sec for iron. Steichen and Williams[23-26] have shown that this correlation gives a fairly accurate representation of the yield behavior of A533 B-1, A508, and A516 (Figs. 3-6). Data were not found for the other candidate materials [i.e., A350, A333(334)] which might indicate that their strain rate/temperature sensitivity could be described by Eq. (1). In addition, the influence of rate/temperature on the tensile ductility of the candidate materials is unclear; indeed, our operating conditions, in particular, temperatures, are such that dynamic strain aging and its accompanying decrease in tensile ductility are a strong possibility.[27]

Strain Rate/Temperature/Fracture Toughness

When the integrity of a structure depends upon the avoidance of catastrophic failure, two alternative design philosophies are available. One is based upon prevention of fracture initiation (i.e., the first extension of an existing flaw) and the other upon the prevention of total crack propagation through the structural members. In the present instance, the latter philosophy involves selecting materials and designs that arrest cracks prior to their penetrating the cask wall. For ferritic steels the toughness in the fully shear (ductile) mode is far greater than that in the cleavage (brittle) mode. Thus, to ensure maximum resistance to propagating cracks, steels should be selected that either do not exhibit a tough/brittle transition (i.e., stainless steel) or do show a fracture mode transition at temperatures well below the anticipated minimum operating temperature. However, it should be noted that under certain conditions, where the stored available energy of the structure is high, even the toughness associated with full shear fracture may not be sufficient to arrest propagating cracks.

Crack Initiation

Fracture toughness evaluation which considers initial crack extension is well established and is based upon linear-elastic and elastic-plastic fracture mechanics wherein crack initiation is described in terms of a critical stress intensity factor. Figs. 7 and 8 illustrate typical results for A533 B-1 and A508 steels; the plane strain fracture toughness, K_{IC}, increases with increasing temperature and decreasing strain rate. This sensitivity to strain rate and temperature again tends to decrease with increasing yield strength.[29,30] This suggests that the effects of strain rate and temperature on the fracture toughness of 4140, 4340, and 17-4PH may be minimal, at least at low temperatures. In addition, strain rate-temperature effects should also be low in austenitic steels, although this suggestion is rather difficult to assess since no fracture toughness data presently exist for these alloys.

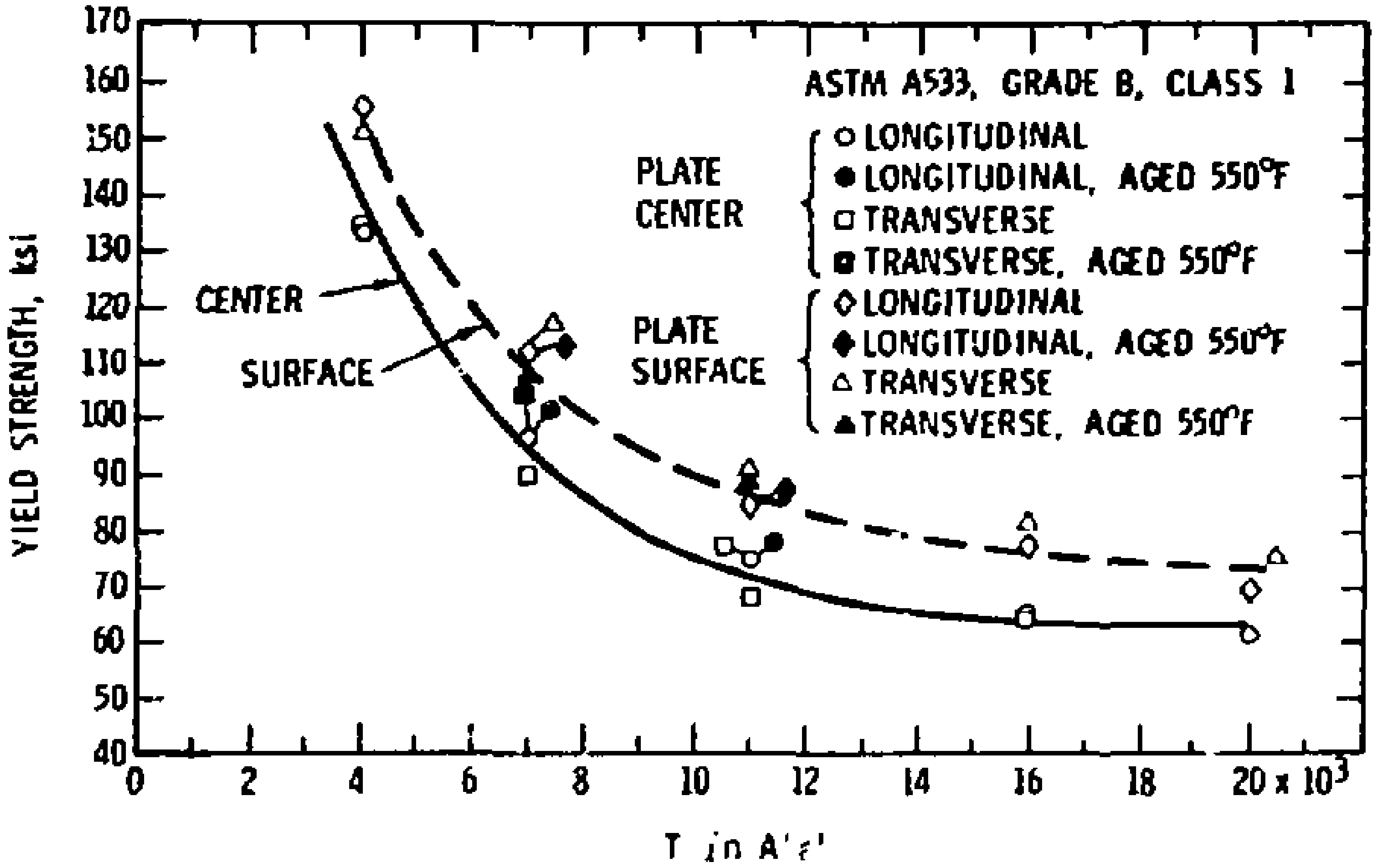

Figure 3. Rate-temperature correlation of [illegible] strength of ASTM A533, grade B, class 1 steel from [illegible] plate [illegible].

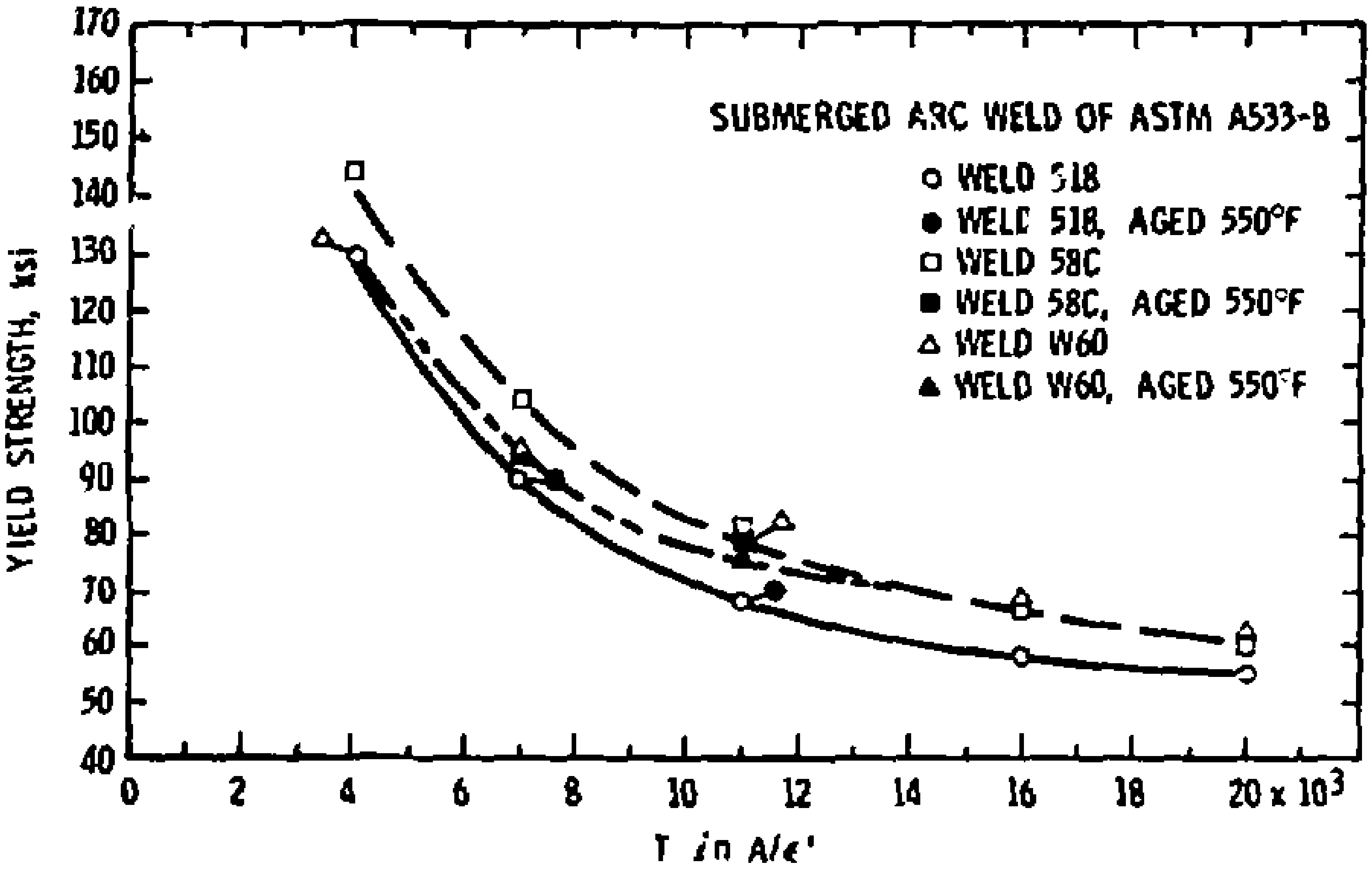

Figure 4. Rate-temperature correlation of the yield strength of three ASTM A533-B submerged-arc welds (26).

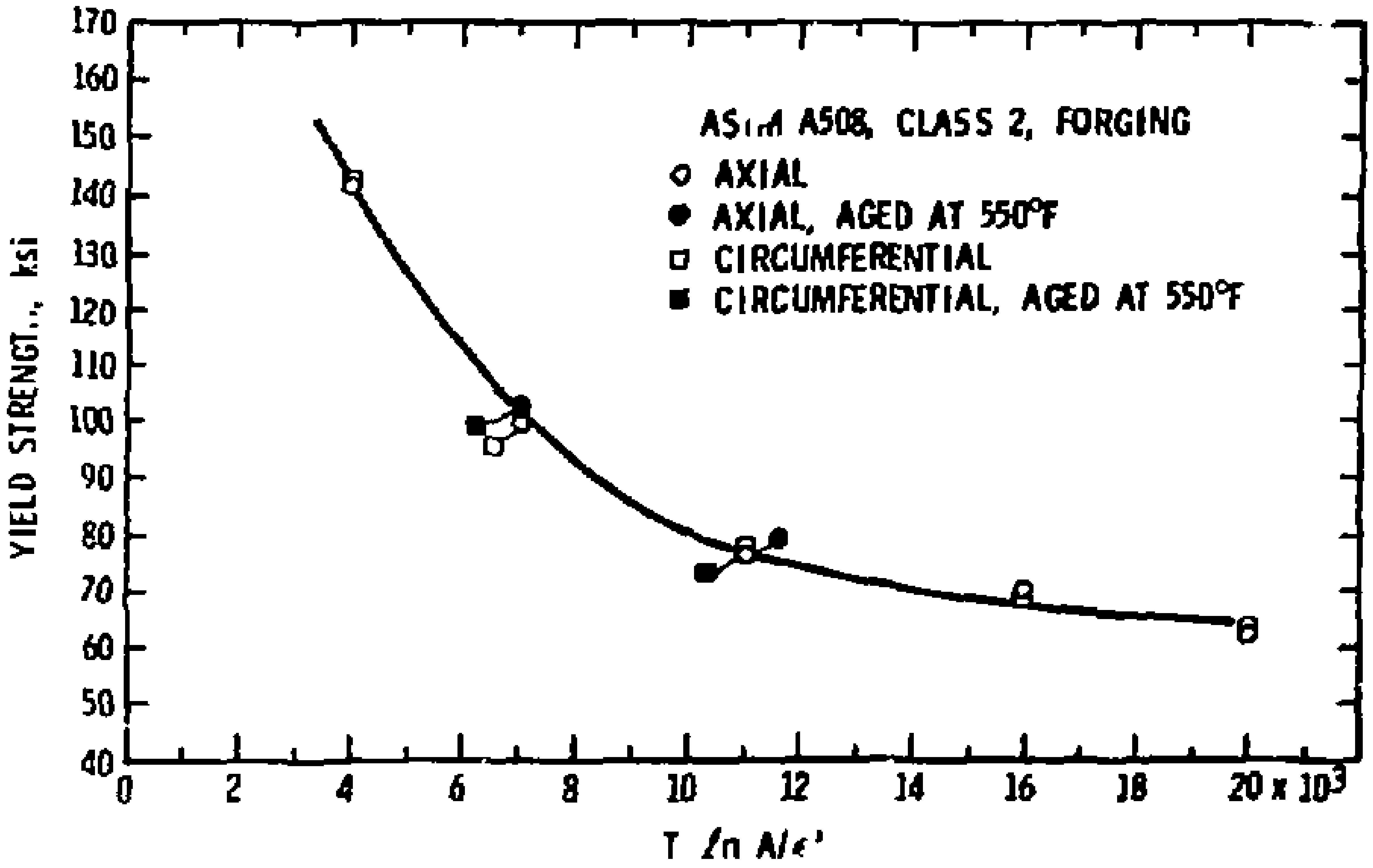

Figure [illegible]. Rate-temperature correlation of the yield strength of ASTM A508, class 2 forging ([illegible]).

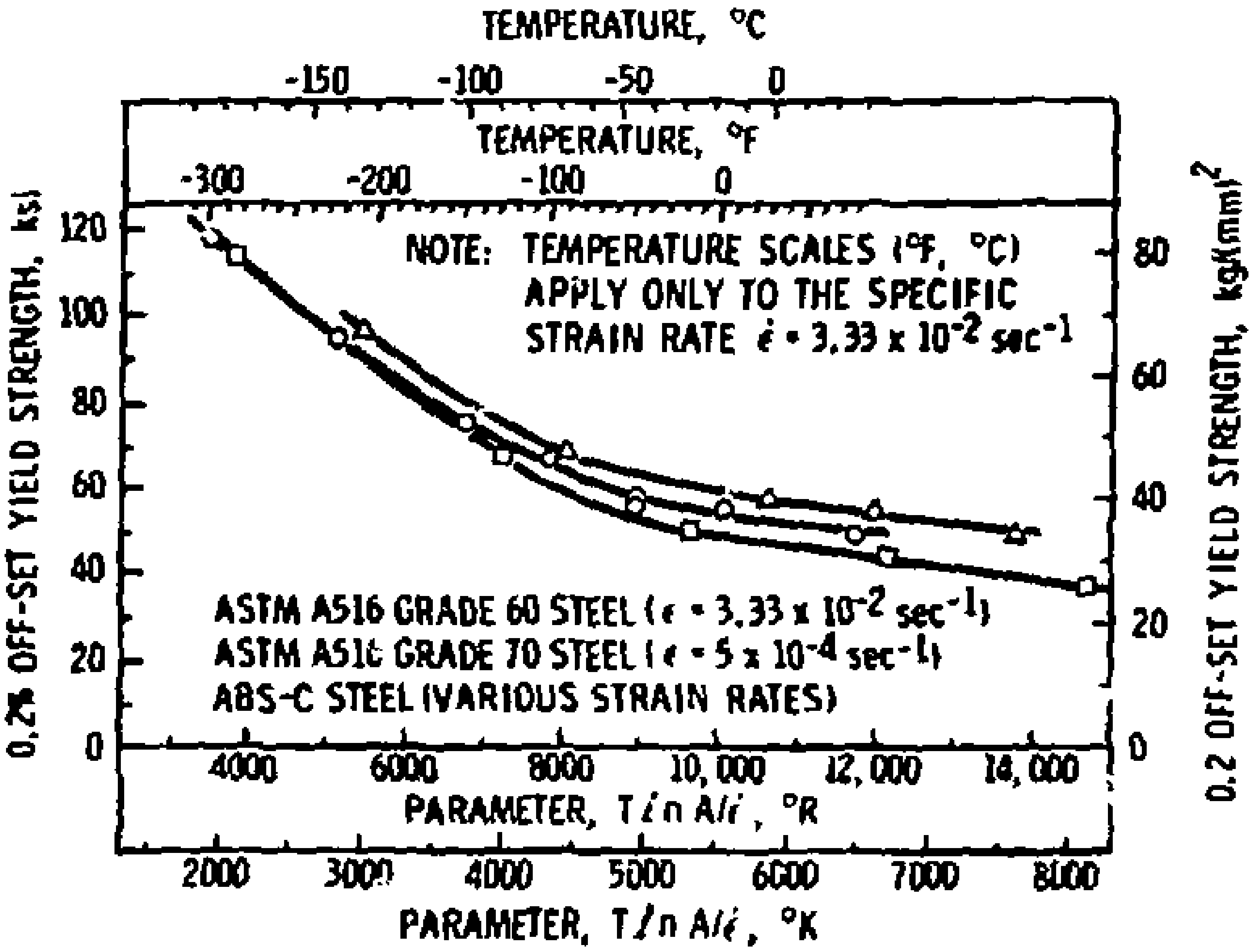

Figure 6. Rate-temperature correlation of the yield strength of ASTM A516 steel (29).

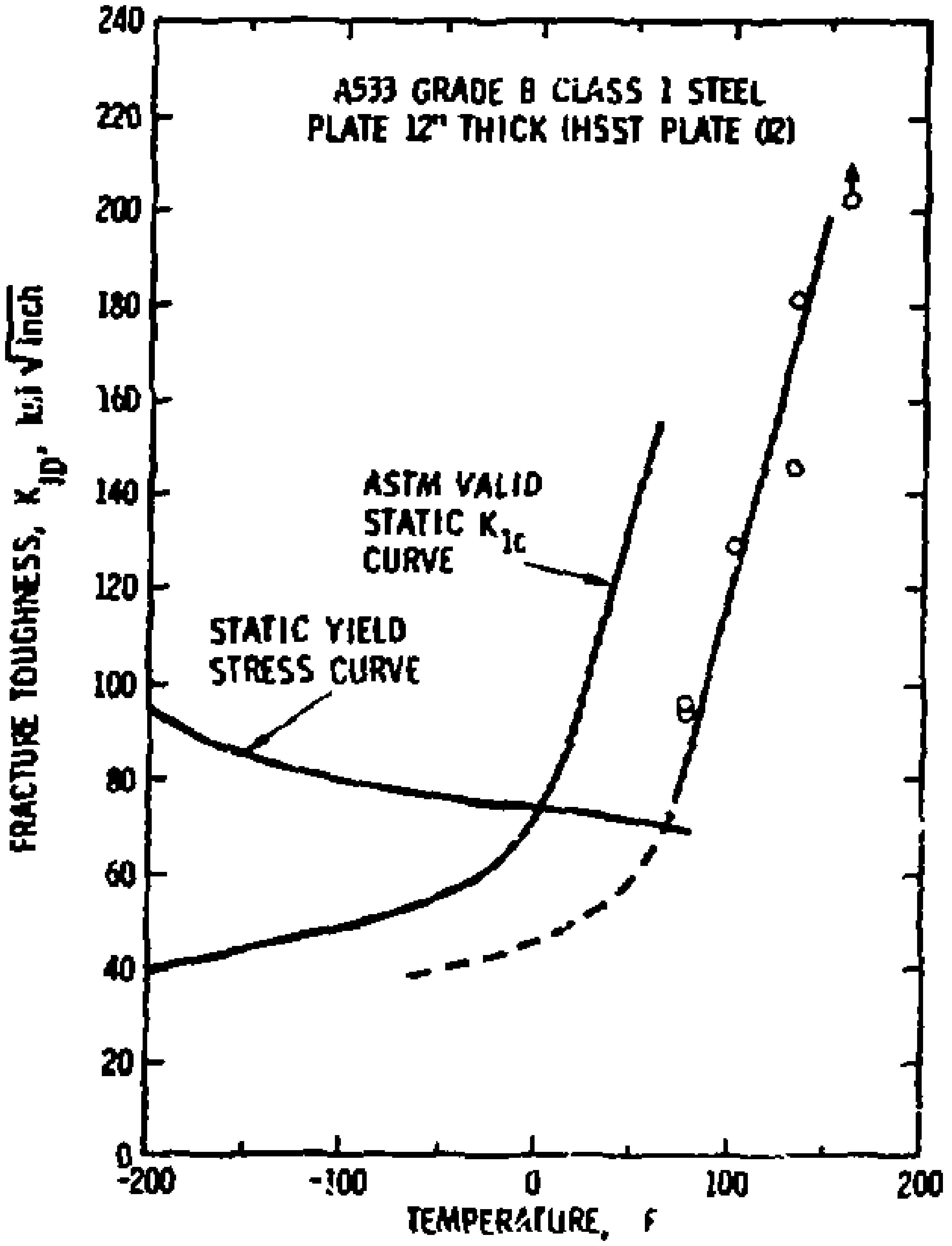

Figure 7. 8TCT dynamic toughness of ASTM A533 grade B, class 1 steel for rates between $K = 10^4$ and 10^5 $MNm^{-3/2}$/sec (28).

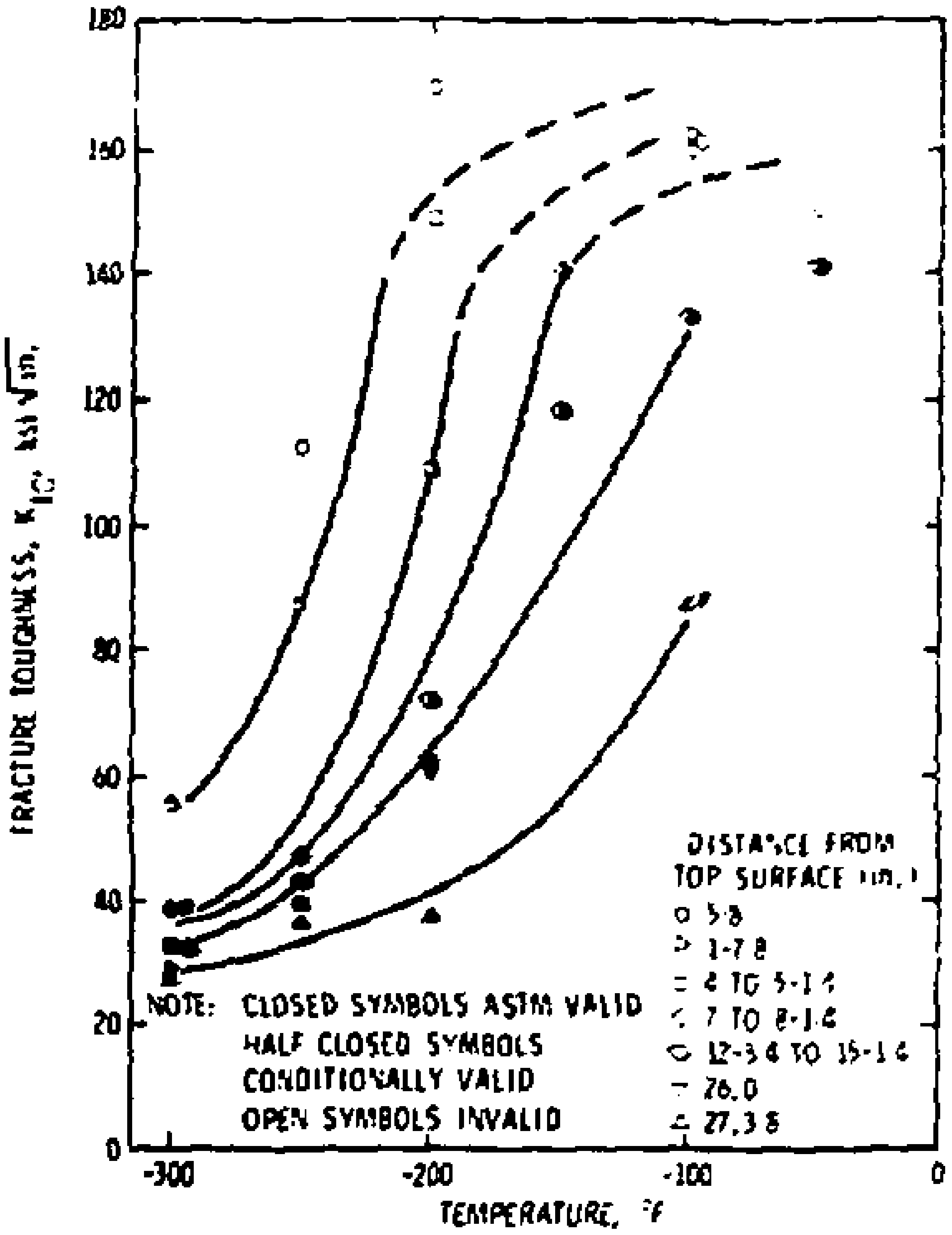

Figure 8. Fracture toughness of ASTM A508 class 4 forging [illegible].

It should be recognized that K_{IC} is not uniform through a heavy section, i.e., it decreases with increasing distance below the surface. The latter variation is accentuated when weldments are considered. Although the fracture toughness of A[illegible] weldments is generally higher than that of base metal, Fig. 9, there is a large amount of scatter between data taken from different weldments, Fig. 10. This is particularly true at low test temperature.

The fracture toughness of A533 may also be seriously degraded by irradiation Fig. 11. The extent of this damage depends upon both irradiation temperature and fluence, Fig. 1[illegible] and Table VI. Recent investigations[33,36,37] indicate that the radiation sensitivity of A533 B-1 can be virtually eliminated by controlling the residual, impurity content. Limiting Cu to less than 0.1 wt% and P to less than 0.01 wt% appears to be both feasible in production and has been found to minimize the radiation effects noted above. Interestingly, irradiation damage in A508 does not seem to be as severe as in A533 (compare Figs. 11 and 13).

Attempts to consider the strain rate and temperature sensitivity of K_{IC} in A333(334) and A350 were unsuccessful, no data base exists for these materials. Initial impressions were that these materials, which are essentially Fe-C-Mn alloys, will be quite similar to A51[illegible] and would therefore be more sensitive to strain rate and temperature changes than either A508 or A533.

Finally, [illegible]orton and [illegible]oemaker[38] have suggested that the previously proposed parametric representation of the flow characteristics of bcc metals can give an adequate description of the influence of temperature and strain rate of K_{IC}. James[39] has applied this technique to a rather limited temperature and strain rate regime in A51[illegible] Grade [illegible] and 7[illegible], Fig. 1[illegible], where the agreement appears quite good. Since the strain rate temperature conditions considered by James are far removed from those anticipated in the LMFBR spent fuel shipping cask, the general validity of this parametric representation for our present purposes cannot be assessed, although it does appear promising.

Crack Arrest

The consideration of alternative fracture toughness analysis, wherein the principal criteria involves crack propagation and arrest, is hampered by the absence of general mathematical formulations for running cracks which take into account the inertial and dynamic effects for various structural geometries.[40] However, some investigators[41-49] have suggested that a stress intensity factor does exist below

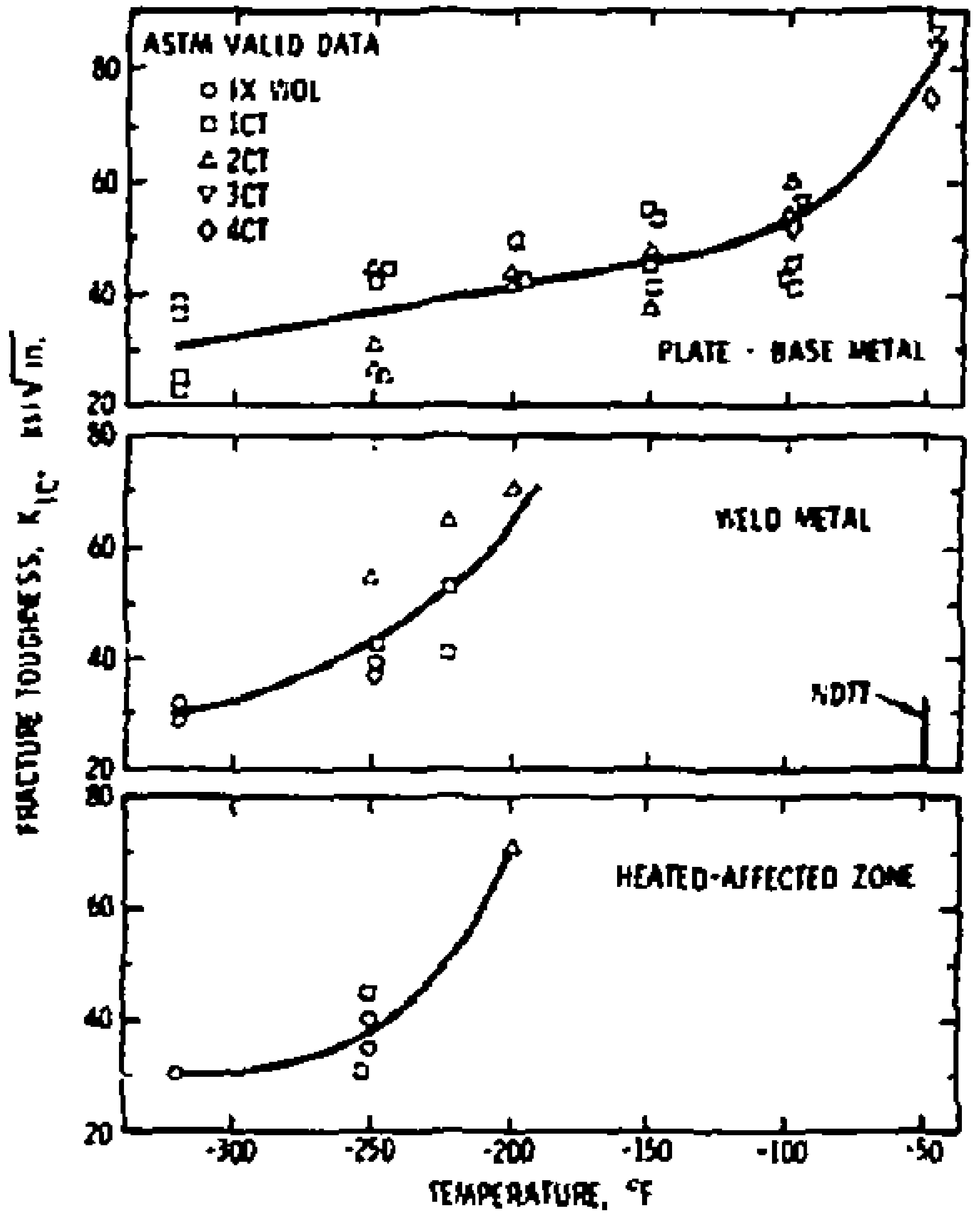

Figure 9. Results of fracture-toughness tests at center 20.3 cm of 29.85 cm thick weldment (Submerged Arc Process) of ASTM A533, grade B, class 1 steel plate 29.85 cm thick; static tests; nonirradiated (31).

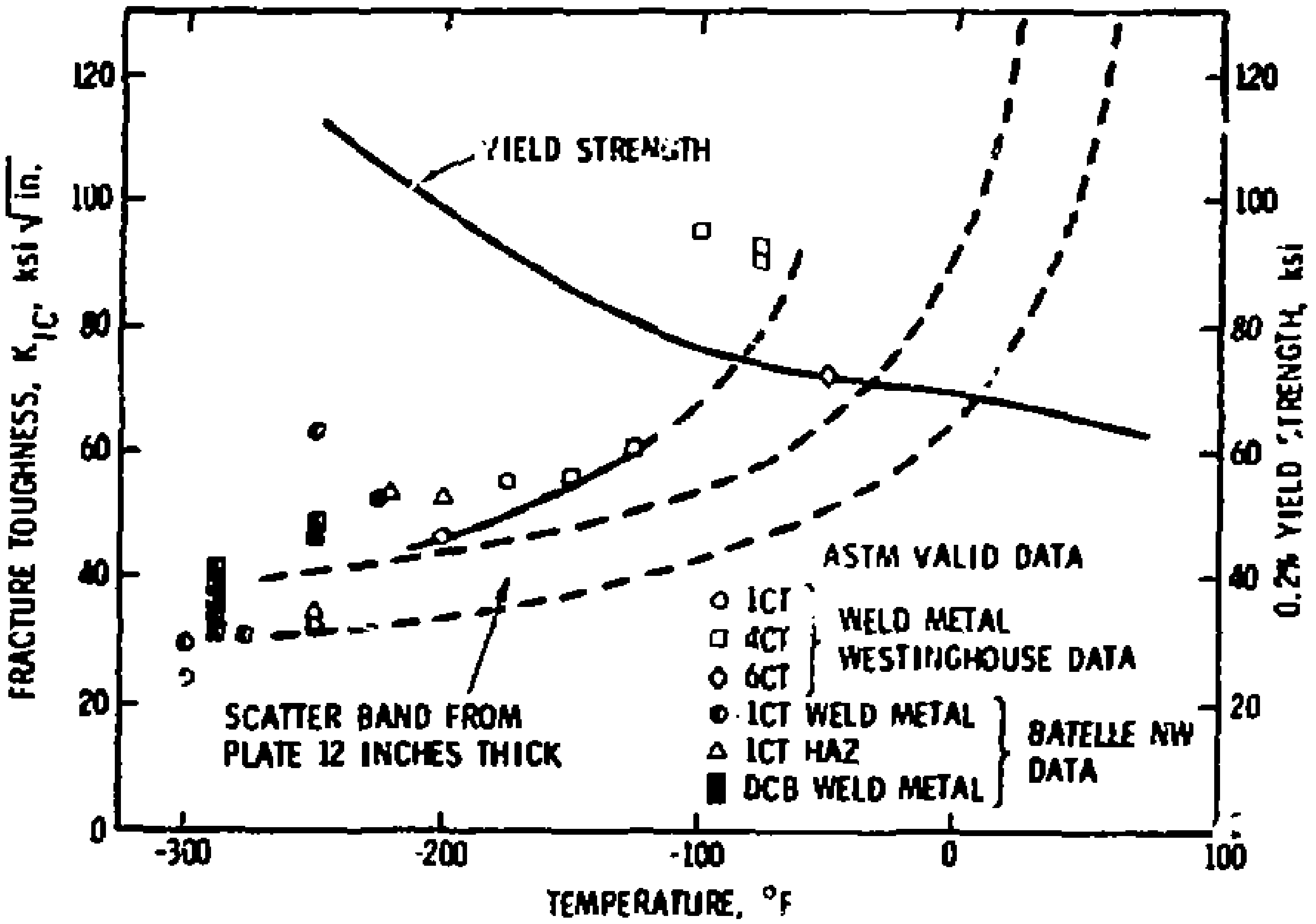

Figure 10. Temperature dependence of the weld and heat-affected zone fracture toughness of a 12 in (30.5 cm) thick weldment (Submerged Arc Process) of A533, grade B, class 1 steel plate 12 in (30.5 cm) thick; static tests - nonirradiated (31).

TABLE VI

Effect of Irradiation on Room-Temperature Tensile Properties of A302-B Steel(25)

Number of Specimens	Irradiation Temperature (°C)	Exposure 10^{19} n/cm^2 (> 1 MeV)	0.2% Yield Strength (MN/m^2)	Tensile Strength (MN/m^2)	Hardness Rockwell B	Elongation (%)	Reduction In Area (%)	True Strain at Load
10	-	0	49[illegible]	[illegible]	-	28.0	[illegible]	[illegible]
1	116	2.0	791	[illegible]	103	11.3	[illegible]	--
2	116	2.3	[illegible]	830	-	--	50.[illegible]	<0.02
2	1[illegible]	2.0	78[illegible]	79[illegible]	103	--	40.0	0.02
2	1[illegible]1	7.0	818	[illegible]18	102	3.0	--	<0.0[illegible]
2	[illegible]	9.0	[illegible]	[illegible]7	--	--	[illegible]	<0.02
2	[illegible]	[illegible] 5.7	[illegible]	[illegible]	103	--	47.0	0.12

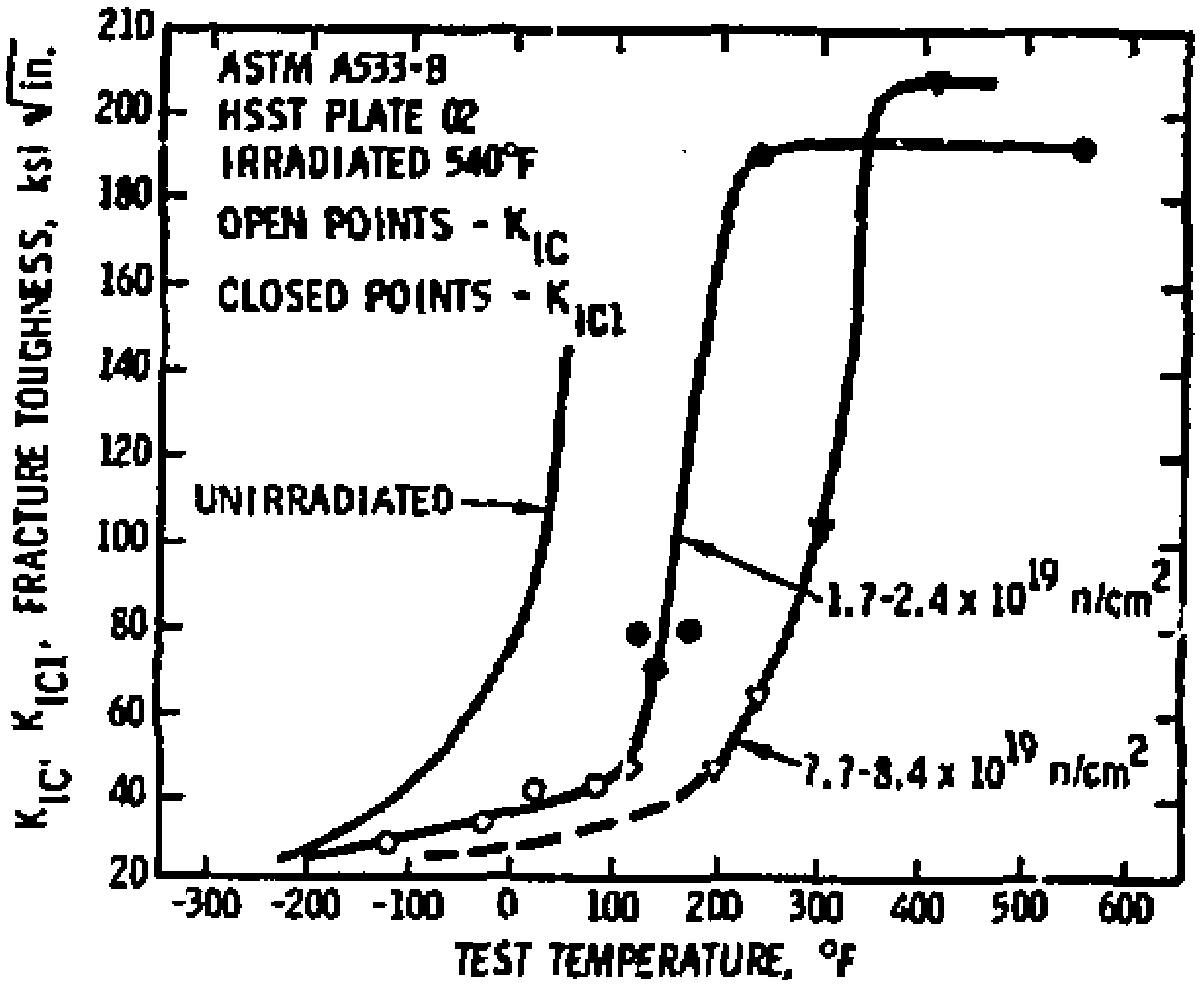

Figure 11. Irradiated and unirradiated fracture toughness as a function of temperature for ASTM A533, grade B, class 1 steel from HSST plate 02. Open data points are plane strain, K_{IC}, and closed are lower bound toughness, K_{ICl} (32).

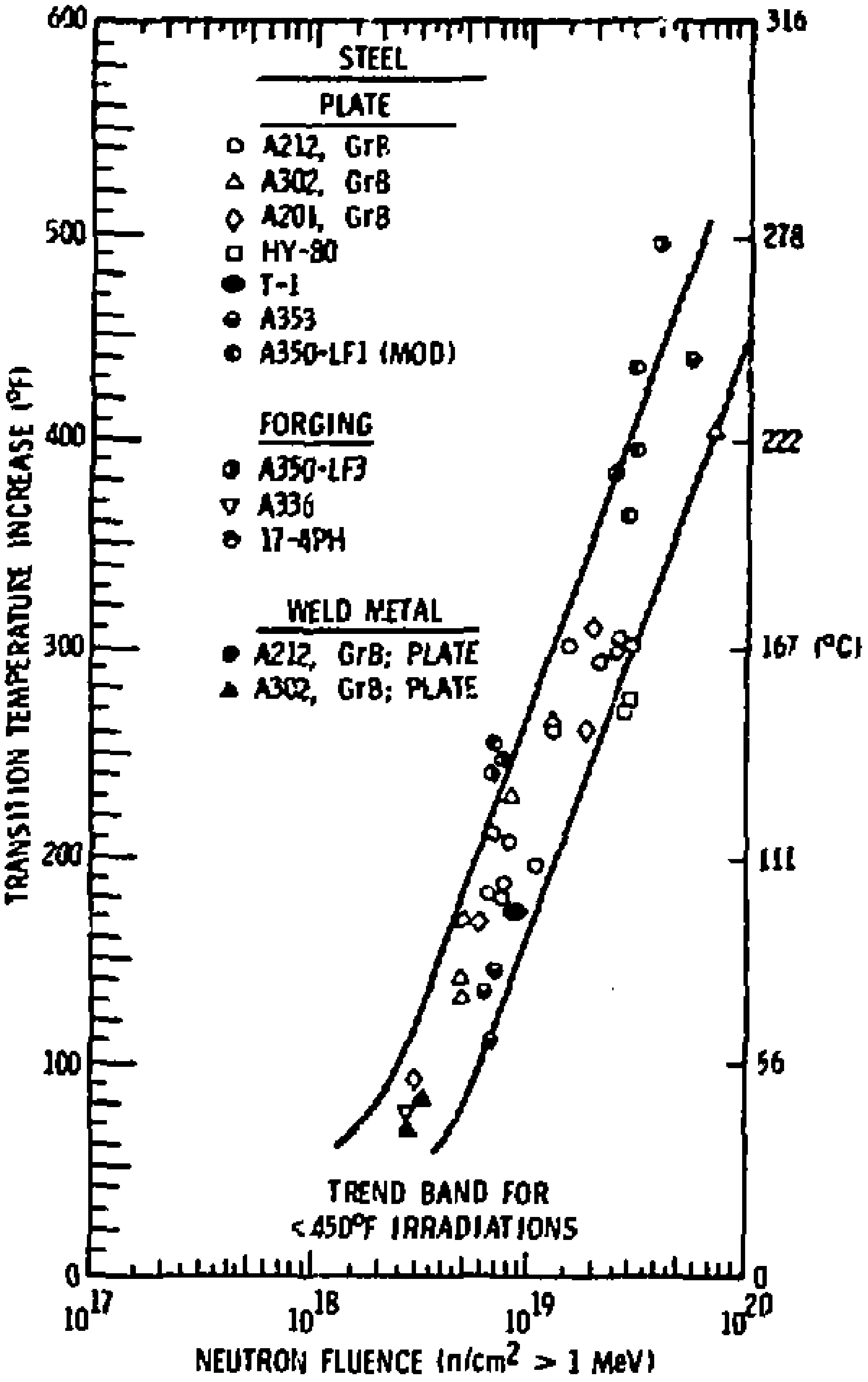

Figure 12. Increase in the transition temperature of steels resulting from irradiation at temperatures below 450° F (232° C) (33).

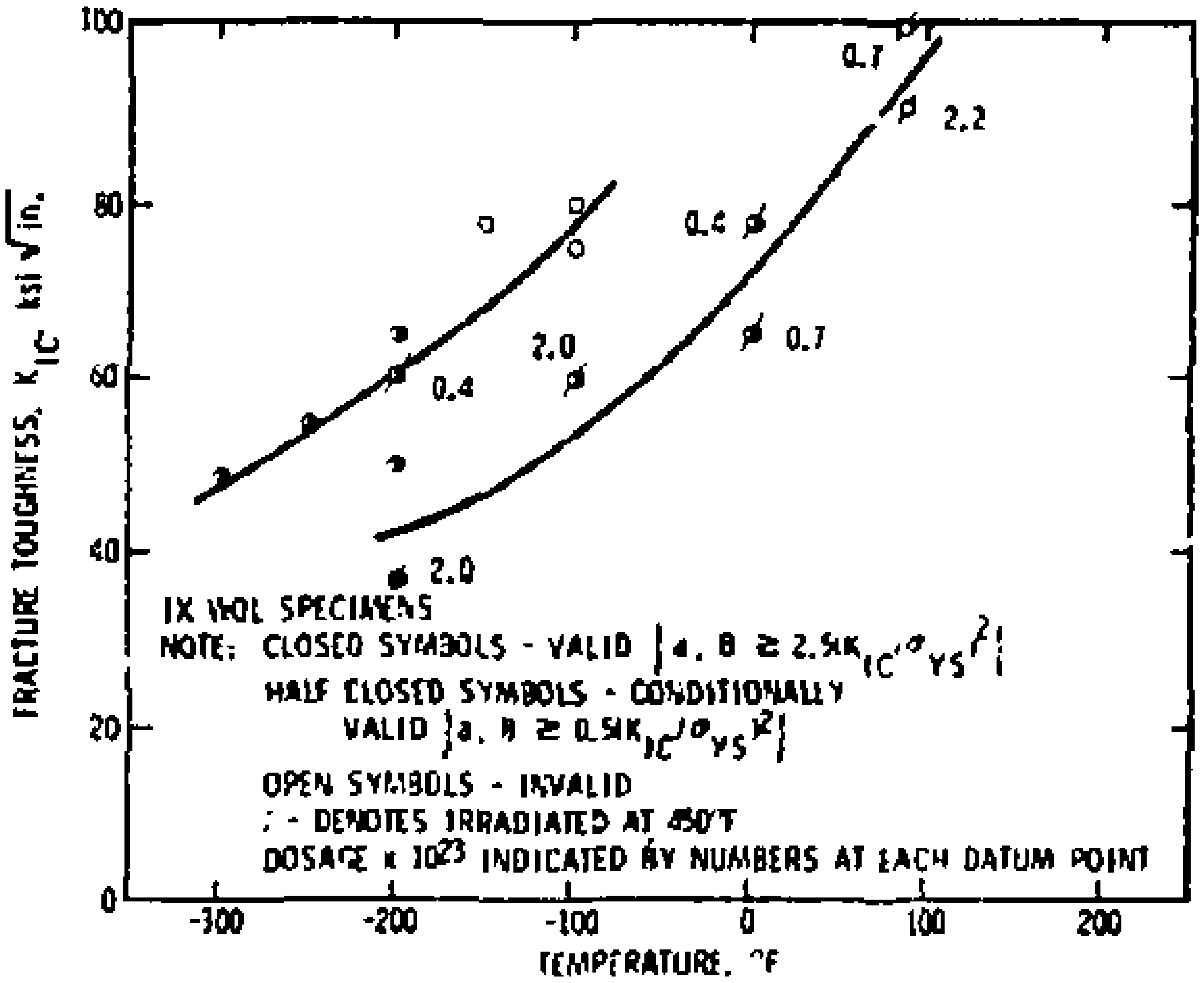

Figure 13. Fracture toughness versus temperature for relatively radiation insensitive ASTM A508, class 2 steel ring forging (31).

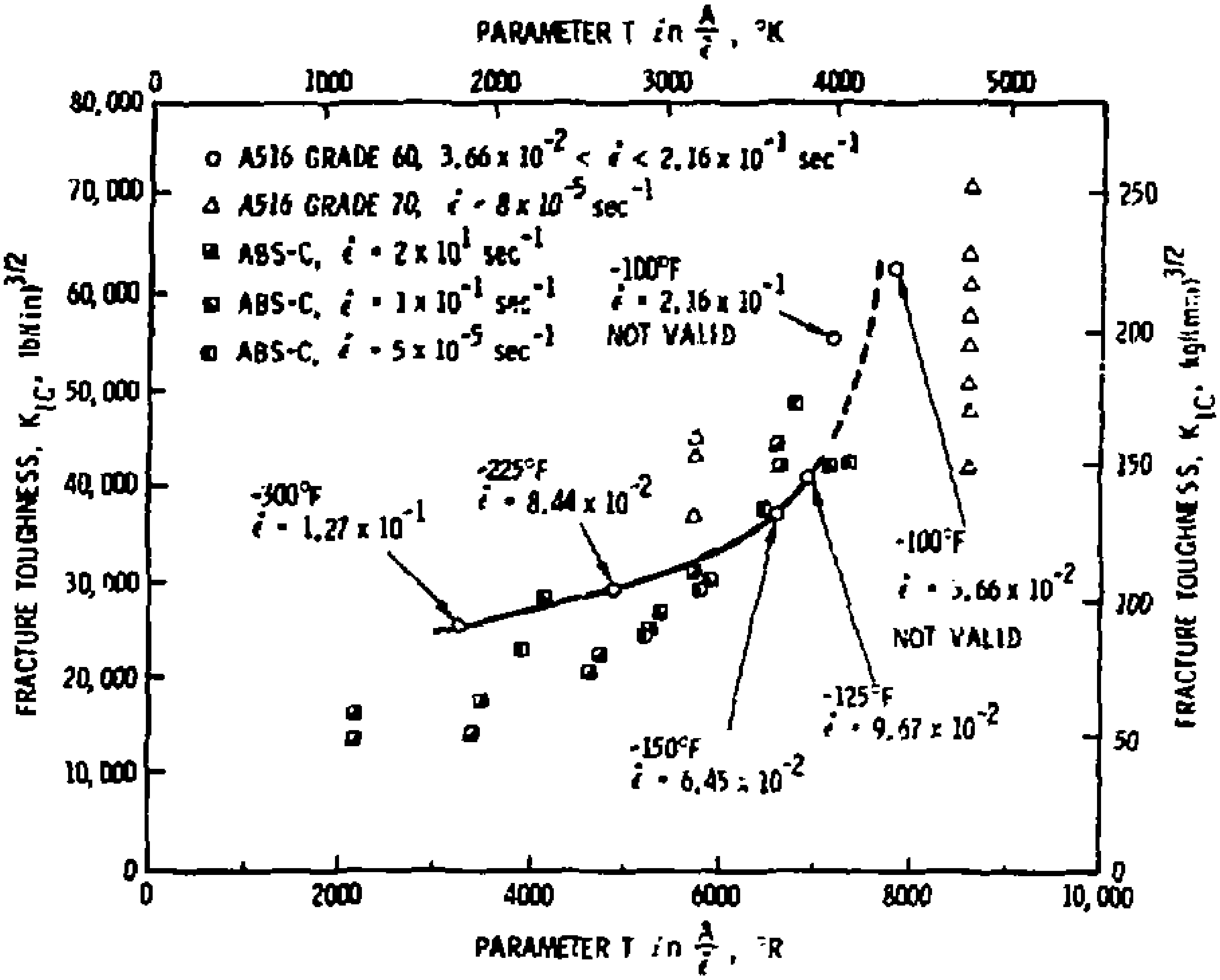

Figure 14. Parametric representation of fracture toughness of selected steels (39).

which a crack will not propagate (Hahn, et al.)[30,46-48] concluded that this arrest factor, K_a, is not a material property but depends upon the entire history of crack propagation. If true, the entire philosophy of using K_a as a design criteria is, in the reviewer's opinion, in doubt. Until this question is answered, particularly by a combined materials/stress analysis effort, the most logical approach to designing against catastrophic crack propagation, i.e., assuring that the crack will arrest prior to penetrating the cask wall, should rest upon Pellini's FAD procedures.[50-51]

RECOMMENDATIONS

Listed below are the reviewer's recommendations for cask baseline materials. In addition, those areas are presented which will require further evaluation and which may have an impact on cask safety and design.

Baseline Materials

Use	Baseline
Plate	A533 B1 Clad with 304L Cu < 0.1 wt. pct. P < 0.01 wt. pct.
Forging	A508 Class 4 Clad with 304L
Fittings	A403 Grade WP304
Bolting	A193 Type B8
Pipe	A312 Type 304L
Tube	A213 Type 304L

Process Parameters

1. Examine what influence variations in chemistry within allowable A533 and A508 specifications have on underclad cracking.
2. Examine the possible relationship between temper embrittlement and unclad cracking in A508.
3. Establish appropriate welding/fabrication practices for sub-scale and full-scale cask production.

Strain Rate/Temperature/Yield Behavior

1. Establish the strain rate sensitivity of candidate austenitic steels within temperature and irradiation conditions of interest to LMFBR fuel shipment cask.

2. Establish effect of varying δ ferrite content on strain rate and irradiation sensitivity of austenitic stainless steel weldments.
3. Establish influence of strain rate and temperature sensitivity on yield strength behavior of 17-4PH.
4. Confirm adequacy of Bennett-Sinclair relationship for describing the strain rate temperature sensitivity of low strength ferritic (bcc) steels.
5. Examine the extent of ductility loss as a function of strain rate and temperature in candidate casks ferritic steels, particular attention being paid to the temperature regime where dynamic strain aging is expected.

Strain Rate/Temperature/Fracture Toughness

1. Confirm the validity of the Corten-Shoemaker parametric representation for K_{IC} within the temperature range of interest.
2. Examine the influence of strain rate and temperature on the fracture toughness of 17-4PH and austenitic stainless steels.
3. Establish the underlying causes for the large scatter observed in heavy section weldments and develop methods for minimizing these effects.
4. Maintain an awareness of the present crack arrest programs, reviewing their impact upon the LMFBR spent fuel shipment cask at regular intervals.

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