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Structural Behavior of
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ABSTRACT

The fail safe performance of pressure retaining vessels involved in nuclear applications can depend greatly on the ability of various structural materials to sustain high stress/strain in the presence of flaws, particularly at elevated (upper shelf) operating temperatures. As a result, the static and dynamic fracture toughness of ASTM A508 Cl 2 (both American and Swedish grade material) and ASTM A533 Gr B Cl 1 (HSST 02 base plate) pressure vessel steels were developed between room temperature and 650°F (343°C). Dynamic fracture toughness of the Swedish grade A508 Cl 2 steel in the transition temperature range was also determined for direct comparison with the ASME specified minimum reference toughness K_{IR} curve. At upper shelf temperatures, dynamic fracture toughness of both the A508 Cl 2 and A533 Gr B Cl 1 steels proved superior to the static fracture toughness, which is a complete reversal of the fracture behavior commonly demonstrated in the transition temperature range, where the static fracture toughness typically proves superior. Furthermore, the static and dynamic fracture toughness of both materials decreased with increasing upper shelf temperatures.

INTRODUCTION

A considerable amount of effort has been expended in developing the dynamic fracture toughness properties of several materials in the transition temperature range.(1-6) In fact, pressure retaining materials for vessels utilized in nuclear applications must comply with minimum dynamic fracture toughness standards as set forth in Sections III and XI of the ASME Boiler and Pressure Vessel Code.(7) In brief, for a particular selected material, the dynamic fracture toughness (temperature corrected based on drop-weight nil-ductility transition (NDT) tests and Charpy impact tests)(7,8) must fall above an ASME specified minimum reference toughness K_{IR} curve. This K_{IR} concept is based on lower bound dynamic fracture toughness and crack arrest data generated on A508 Cl 2 and A533 Gr B Cl 1 pressure vessel steels.

On the other hand, comparatively little effort has been spent in developing the static and dynamic fracture toughness properties of pressure retaining materials at their elevated (upper shelf) operating temperatures. Indeed, until development of the multiple specimen J resistance curve test technique(9-11) and its adaptation to dynamic loading,(5,6) the evaluation and comparison of upper shelf static and dynamic fracture toughness properties of high toughness pressure vessel steels was not possible.

This paper describes an experimental effort designed to establish the upper shelf static and dynamic fracture toughness properties of materials similar to those utilized in formalizing the ASME specified minimum reference toughness K_{IR} curve. The upper shelf static and dynamic fracture toughness of both American and Swedish grade A508 Cl 2 steels was determined. Additionally, the static and dynamic fracture toughness properties of the A533 Gr B Cl 1 Heavy Section Steel Technology (HSST) 02 base plate originally developed by Shabbits were extended from room temperature to 650°F (343°C).[3]

The effect of three and nine point average measures of crack extension as well as the use of a tension loading correction factor in the calculation of J were also evaluated.

MATERIALS AND MECHANICAL PROPERTIES

ASTM A508 Cl 2 is a quenched and tempered vacuum treated carbon and alloy steel typically utilized in forgings for nuclear pressure vessel applications. Steels manufactured in America and Sweden which conform to the ASTM requirements for A508 Cl 2 steel were evaluated in this investigation. ASTM A533 Gr B Cl 1 is a manganese-molybdenum-nickel alloy plate steel utilized in the quenched and tempered condition for the construction of welded pressure vessels. Chemical compositions and heat treatments of the A508 Cl 2 and A533 Gr B Cl 1 steels are presented in Table 1. Both the American and Swedish grade A508 Cl 2 steels and the A533 Gr B Cl 1 steel conform to their respective chemical requirements as specified by ASTM. The Swedish A508 Cl 2 material exhibits both a significantly higher alloying content and lower trace element content than the American made steel.

The American grade A508 Cl 2 steel specimens were machined from a large nozzle cutout (overall dimensions unavailable) manufactured by Bethlehem Steel Corporation. The Swedish grade A508 Cl 2 steel was received as a 9.45 in. (24 cm) thick, 57.7 in. (146.5 cm) diameter nozzle cutout manufactured by Uddcomb of Sweden. The A533 Gr B Cl 1 specimens were removed from remnants of the Heavy Section Steel Technology (HSST) 02 base plate, which provided the material for Shabbits' original dynamic fracture toughness investigation.(3) Specimen orientations per ASTM E399 for the A508 Cl 2 and A533 Gr B Cl 1 steels were L-T and T-L, respectively.

Tensile properties of the American and Swedish grade A508 Cl 2 steels and the A533 Gr B Cl 1 steel are illustrated in Figures 1 through 3, respectively. The ASTM room temperature tensile requirements for A508 Cl 2 steel call for a minimum yield strength of 50 ksi (345 MPa), a range in ultimate strength of 80 to 105 ksi (550 to 725 MPa), a minimum elongation in 2 in. or 50 mm of 18 percent and a 38 percent minimum reduction in area. Both A508 Cl 2 steels easily conform to all the ASTM tensile requirements. Comparatively speaking, yield and ultimate strengths of the American grade A508 Cl 2 steel are superior to those of the Swedish grade steel while the American grade steel's ductility (reduction in area and elongation) is slightly lower (with exception of the three highest temperature reduction in area values).

The ASTM room temperature tensile requirements for A533 Gr B Cl 1 steel call for a minimum yield strength of 50 ksi (345 MPa), a range in ultimate strength of 80 to 100 ksi (550 to 690 MPa) and a minimum elongation in 2 in. or 50 mm of 18 percent. The A533 Gr B Cl 1 steel (HSST 02 base plate) complies with all the ASTM tensile requirements.

Charpy V-notch impact properties of the A508 Cl 2 steels are illustrated in Figures 4 and 5, respectively. Major impact properties of these materials are compared below. Although the 50 ft-lb energy and 35 mil lateral expansion temperatures are nearly identical, the impact properties of the Swedish grade A508 Cl 2 steel are superior to those of the American grade steel.

Material	50 ft-lb Energy Temp. °F	°C	35 mil Lateral Expansion Temp. °F	°C	FATT °F	°C	Upper Shelf Energy ft-lb	Level J
A508 Cl 2 (American Grade)	-16	-27	-10	-23	68	20	122	165
A508 Cl 2 (Swedish Grade)	-18	-28	-20	-29	38	3	141	191

Transition temperature dynamic fracture toughness data is typically plotted versus T-RT_{NDT} for comparison with the ASME specified minimum reference toughness K_{IR} curve, where RT_{NDT} is defined as a reference temperature. The method for establishing a reference temperature is outlined in detail in Section III, Division I and Subsection NB-2331 of the ASME Boiler and Pressure Vessel Code.[(7)] Drop weight NDT and reference temperatures for the Swedish grade A508 Cl 2 steel equal -10°F (-23°C). Dynamic transition temperature fracture toughness tests were conducted on the Swedish grade A508 Cl 2 steel only.

EXPERIMENTAL PROCEDURES

All static and dynamic fracture toughness tests were performed on 1.0 in. (2.5 cm) thick precracked compact-toughness (CT) specimens. These specimens were tested on a servo-hydraulic MTS machine with load frame and load cell capacities of 50 kips (22680 Kg) and 20 kips (9072 Kg), respectively. Dynamic capability was realized by employing a 90 gpm (341 liters/min) MTS teem valve (two stage with feedback). Load versus displacement traces were recorded for all tests. Load and displacement versus time traces were also recorded for each dynamic test. Typical load times for the dynamic transition temperature fracture toughness tests ranged from 1.1 to 5.2 milliseconds and corresponding $\dot{K}$ values averaged 4.0 x 10^4 ksi$\sqrt{\text{in.}}$/sec (4.4 x 10^4 MPa$\sqrt{\text{m}}$/sec). Load times for the upper shelf dynamic fracture toughness tests ranged from 7 to 26 milliseconds. Upper shelf temperature $\dot{K}$ values ranged from 0.85 to 3.8 ksi$\sqrt{\text{in.}}$/sec (0.94 to 4.21 MPa$\sqrt{\text{m}}$/sec).

Static Test Techniques

Static upper shelf fracture toughness values were obtained via the multiple specimen resistance curve test technique as set forth by Landes and Begley in Ref. 11. This technique is applicable to the ductile tearing upper shelf fracture regime where the onset of crack growth cannot be ascertained from the appearance of the load-deflection record. Compact toughness specimens were loaded to specific displacements, unloaded, heat tinted and broken open to reveal the amount of stable crack growth. Results of a test series were plotted as J versus stable crack extension (Δa). J was calculated from the load-displacement record and specimen dimensions using the approximation of Rice, et al.[12] corrected for the tension loading component as recommended by Landes, et al.[13]

$$J = \frac{1 + \alpha}{1 + \alpha^2} \frac{2A}{Bb}$$

where

$$\alpha = 2\sqrt{(a/b)^2 + (a/b) + 1/2} - 2(a/b + 1/2)$$

A is the area under the load-displacement record, B is the specimen thickness and b equals the specimen remaining ligament or

$$b = w - a$$

where w and "a" equal the specimen width and crack length, respectively. Both three and nine point average measures of stable crack extension were considered.

Dynamic Test Techniques

The dynamic test techniques employed in this investigation can be divided into two categories; 1) load-to-failure (Swedish grade A508 Cl 2 steel only) and 2) dynamic resistance curve. The interacting dynamic test parameters and characteristics are summarized in Table 2.

Load-to-Failure. All specimens tested at low and transition range temperatures were loaded dynamically to failure and sustained cleavage controlled fractures. The onset of crack extension was abrupt and unambiguous.

There was no stable growth. A sudden drop in the load deflection curve occurred at the fracture point. At low temperatures, the load versus displacement records were linear and the fracture toughness was calculated directly from the failure load as outlined in ASTM E399, although in some cases the specified size criterion was not met by the 1.0 in. (2.5 cm) thick CT specimens.

At transition temperatures, nonlinear load versus displacement records were observed although the specimen fractures were cleavage controlled. Fast fracture occurred at maximum load. For these tests J was calculated from the estimation method outlined by Rice, et al.[12] corrected for the tension loading component as recommended by Landes, et al.[13] The criterion for determining if a fracture was cleavage initiated consisted of evaluating the amount of stretching (blunting) experienced by the specimen as follows

$$\Delta\bar{a} \leq \frac{0.55\ J}{\sigma_Y}$$

where $\Delta\bar{a}$ is the average amount of stretching (blunting), J is calculated at the maximum load point and σ_Y is a flow stress midway between the material's yield and ultimate stresses. For ferritic steels, compliance with the above requirement indicates cleavage initiation; if $\Delta\bar{a}$ is larger, the mode of fracture initiation is fibrous.

At temperatures where upper shelf fracture toughness behavior was first observed, specimens loaded dynamically to failure experienced fractures which displayed a zone of ductile tearing followed by cleavage rupture. The point of fibrous crack initiation was not apparent from the load-displacement records, which ofttimes exhibited some load drop prior to fracture. Calculating a fracture toughness based on maximum load is clearly not related to the point of crack growth initiation. Crack growth may in fact occur prior to or after the maximum load. Therefore, it was not possible to obtain a dynamic fracture toughness value from a single specimen loaded-to-failure at upper shelf temperatures.

A schematic of this combined fracture behavior experienced by specimens loaded dynamically to failure at upper shelf temperatures is illustrated in Fig. 6. This schematic illustrates the interaction of the two basic fracture processes. The purpose of applying the previously stated requirement for cleavage initiation would guarantee that a particular dynamic fracture toughness test result occurred prior to the crosshatched zone of ductile tearing followed by cleavage rupture.

Although rather uncommon under static loading, two of four A533 Gr B Cl 1 steel specimens tested statically at 75°F (24°C) experienced this combined fracture behavior of stable ductile crack growth followed by cleavage rupture, the original intention being to load these specimens to a specific displacement per the resistance curve test technique. Unfortunately, because these specimens could not be heat tinted, it was difficult to accurately measure the degree of ductile tearing crack growth. This difficulty accounted for the need to estimate the static fracture toughness of A533 Gr B Cl 1 steel at 75°F (24°C).

Dynamic Resistance Curve. To obtain clearly defined dynamic fracture toughness values at upper shelf temperatures the resistance curve test technique developed by Landes and Begley and described earlier for static fracture toughness testing was employed. The only difference between dynamic and static multiple specimen resistance curve test procedures at upper shelf temperatures was the loading speed utilized. Compact toughness specimens were dynamically loaded to specific displacements (not to failure), unloaded, heat tinted and broken open to reveal the amount of stable crack growth.

RESULTS

Dynamic fracture toughness values generated on the Swedish grade A508 Cl 2 steel in the transition temperature range are plotted versus T-RT_{NDT} for comparison with the ASME specified minimum reference toughness K_{IR} curve in Fig. 7. The transition temperature dynamic fracture toughness of this Swedish grade A508 Cl 2 steel is superior to that demonstrated by a higher minimum yield strength (65 ksi, 450 MPa) American made A508 Cl 2a pressure vessel steel, although this Swedish grade A508 Cl 2 steel exhibited less conservatism relative to the ASME specified minimum reference toughness K_{IR} curve.[6] Furthermore, the dynamic fracture toughness of this Swedish grade A508 Cl 2 steel is also comparable with that reported by Van Der Sluys, et al. on a similar A508 Cl 2 steel at T-RT_{NDT} temperatures of -100 and 0°F (-73 and -18°C).[14]

Upper shelf static and dynamic fracture toughness values relative to the American and Swedish grade A508 Cl 2 pressure vessel steels are illustrated in Fig. 8. Fracture toughness values based on both three and nine point average measures of crack extension are included. As will be discussed later, the current multiple specimen J resistance curve test technique calls for a nine point average measure of crack extension. Fracture toughness values included in Fig. 8 which are based on a nine point average measure of crack extension therefore yield a reasonably true measure of the materials fracture toughness whereas those based on a three point average measure of crack extension must be considered minimum fracture toughness values.

The upper shelf dynamic fracture toughness of both A508 Cl 2 steels is superior to their static fracture toughness. In addition, both materials' static and dynamic fracture toughness decreases with increasing upper shelf temperatures. Similar behavior was previously reported relative to the upper shelf fracture toughness properties of several basic rotor steels.(15) Comparatively speaking, the Swedish grade A508 Cl 2 steel's static and dynamic fracture toughness values are superior to those of the American grade material. The Swedish grade A508 Cl 2 steel also displayed superior ductility and Charpy V-notch impact properties. The higher fracture toughness, ductility and impact properties demonstrated by the Swedish grade A508 Cl 2 steel are probably due to its superior chemistry as opposed to its lower strength level.

Server has reported static and dynamic fracture toughness values (197 and 228 ksi$\sqrt{in}$, 218 and 252 MPa$\sqrt{m}$) for a 71 ksi (488 MPa) yield strength A508 Cl 2 material at 350°F (177°C).(16) Server employed a nine point average measure of crack extension but did not include a tension loading correction component in his formula for calculating J. The majority of Server's tests were also conducted on 1.0 in. (2.5 cm) thick compact toughness specimens. Server's static and dynamic fracture toughness values agree quite closely with those generated on the American grade A508 Cl 2 steel.

The static and dynamic fracture toughness of the A533 Gr B Cl 1 HSST 02 base plate from -200 to 650°F (-129 to 343°C) is presented in Fig. 9. Also included in Fig. 9 are the transition temperature fracture toughness values previously reported by Shabbits.(3)

At upper shelf temperatures, the dynamic fracture toughness of A533 Gr B Cl 1 steel is superior to the static toughness. This is a complete reversal of the fracture behavior demonstrated in the transition temperature range, where the dynamic fracture toughness was inferior. As was the case for the A508 Cl 2 steels, the static and dynamic fracture toughness both decreased with increasing upper shelf temperatures.

Server reported static fracture toughness values on A533 Gr B Cl 1 HSST 02 base plate of 188 and 222 ksi$\sqrt{in.}$ (208 and 246 MPa$\sqrt{m}$) at 77 and 160 °F (25 and 71°C), respectively, and dynamic fracture toughness values at 160°F (71°C) of 194 and 233 ksi$\sqrt{in.}$ (215 and 258 MPa$\sqrt{m}$) depending on whether compact toughness or bend specimens were employed.(16) Typical load times for Server's dynamic compact toughness and bend specimens were 100 and 1 milliseconds, respectively. Load times for the compact toughness specimens tested in this investigation at upper shelf temperatures ranged between 7 and 26 milliseconds. It is not surprising therefore that Server's dynamic fracture toughness value generated at 160°F (71°C) with bend specimens checks quite closely with the dynamic fracture toughness value generated in this investigation at 150°F (66°C). On the other hand, his 160°F (71°C) dynamic fracture toughness value generated utilizing compact toughness specimens at the slower loading rate actually fell below his static fracture toughness value at this same temperature.

DISCUSSION

The static and dynamic J resistance curves for the American and Swedish grade A508 Cl 2 steels and the A533 Gr B Cl 1 steel are illustrated in Figs. 10 through 15, respectively. Madison and Irwin's equation for estimating dynamic yield strength as a function of temperature and test speed was utilized to calculate blunting lines relative to the dynamic resistance curves.[17,18]

At the time these fracture toughness tests were initially conducted, the multiple specimen J resistance curve test procedure called for a three point average measure of crack extension. Additionally, corrections for tension loading when utilizing compact toughness specimens[19] were not totally accepted and as such were not included. Prior to inclusion in this paper, all the raw J versus Δa data were re-evaluated based on a nine point average measure of crack extension and inclusion of the $(\frac{1 + \alpha}{1 + \alpha^2})$ tension loading correction factor in the formula for calculating J. Changing from a three to nine point average measure of crack extension shifts each J versus Δa data point closer to the blunting line and results in steeper sloping $(\frac{dJ}{da})$ resistance curves. Furthermore, inclusion of the tension loading correction factor increases each J value a minimum of ten percent. The combined influence of adapting both of these procedures to update vintage multiple specimen resistance curve data to current standards can produce surprising results, especially for very tough materials.

All of the data points which initially formed a proper J versus Δa resistance curve can now fall directly on the blunting line. This was the case for the Swedish grade A508 Cl 2 steel, both static and dynamic resistance curves at all test temperatures and for the American grade A508 Cl 2 steel dynamic resistance curves at 150 and 300°F (66 and 149°C). Resistance curves based on a nine point average measure of crack extension were still possible at each test temperature relative to the A533 Gr B Cl 1 steel. Any fracture toughness value which is based on a three point average measure of crack extension must therefore be considered as a minimum measure of a material's fracture toughness.

One of the major criticisms inherent in J testing is that it yields a very conservative measure of a material's fracture resistance, especially for tough materials similar to those investigated herein which are likely to experience considerable stable crack extension prior to fracture. Obviously, shifting from a three to nine point average measure of crack extension and employing a tension loading correction factor in the formula for calculating J eliminates part of this conservatism. Nevertheless, because J is based on crack initiation, elastic-plastic fracture toughness testing via J integral techniques will always yield a conservative measure of a material's fracture toughness, especially for high toughness materials at upper shelf temperatures.

CONCLUSIONS

1. The upper shelf dynamic fracture toughness of both the American and Swedish grade A508 Cl 2 steels as well as the A533 Gr B Cl 1 steel (HSST 02 base plate) proved superior to the upper shelf static fracture toughness. This is a complete reversal of the fracture behavior commonly demonstrated in the transition temperature range, where the static fracture toughness typically proves superior.
2. The upper shelf static and dynamic fracture toughness of both the American and Swedish grade A508 Cl 2 steels as well as the A533 Gr B Cl 1 steel decreases with increasing upper shelf temperatures.
3. The static and dynamic fracture toughness, ductility, and impact properties demonstrated by the Swedish grade A508 Cl 2 steel were superior to those of the American grade A508 Cl 2 steel.
4. All transition temperature dynamic fracture toughness values of the Swedish grade A508 Cl 2 pressure vessel steel fell above the ASME specified minimum K_{IR} curve.
5. Adapting a nine as opposed to three point average measure of crack extension shifts each J versus Δa data point closer to the blunting line and results in steeper sloping $(\frac{dJ}{da})$ resistance curves.
6. Inclusion of the tension loading correction factor in the formula for calculating J (applicable when utilizing compact toughness specimens) increases each J value a minimum of ten percent.

7. The combined influence of adapting both the above procedures to update vintage multiple specimen resistance curve data to current standards can cause many, if not all of the original J versus Δa data points, to fall on the blunting line, thus producing higher critical J_{Ic} or J_{Id} values and eliminating a small portion of the substantial conservatism inherent when utilizing elastic-plastic J integral test procedures to develop the fracture toughness of tough materials at upper shelf temperatures.

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TABLE 1

CHEMICAL COMPOSITIONS AND HEAT TREATMENTS OF A508 Cl 2 AND A533 Gr B Cl 1 PRESSURE VESSEL STEELS

Material		Chemical Composition, Wt. Percent												
		C	Mn	P	S	Si	Ni	Cr	Mo	V	Co	Cu	Al	Sn
A508 Cl 2 (American Grade)	Ladle	.20	.65	.009	.011	.24	.74	.35	.59	.01	.010			
	Check	.22	.70	.010	.011	.24	.74	.35	.60	.02	.010			
	Independent	.22	.65	.011	.019	.28	.69	.32	.58		.008	.071	.006	.007
A508 Cl 2 (Swedish Grade)	Independent	.22	.72	.003	.006	.17	.91	.43	.65	<.005	.020	.100		
A508 Cl 2	ASTM Requirements	.27 Max	.50-.90	.012* Max	.025 Max	.15-.35	.50-1.00	.25-.45	.55-.70	.05 Max		.100* Max		
A533 Gr B Cl 1 (HSST 02 Baseplate)	Ladle	.22	1.45	.011	.019	.22	.62		.53					
	Check	.22	1.48	.012	.018	.25	.68		.52					
A533 Gr B Cl 1	ASTM Requirements	.25 Max	1.15-1.50	.012* Max	.040 Max	.15-.30	.40-.70		.45-.60			.100* Max		

*Optional Supplementary Requirement

Material	Heat Treatment	
A508 Cl 2 (American Grade)	Austenitize	1550°F (843°C), hold 11 hrs., Water Quench
	Temper	1200°F (649°C), hold 22 hrs., Air Cool
A508 Cl 2 (Swedish Grade)	Austenitize	1652°F (900°C), hold 8.75 hrs., Water Quench
	Temper	1220-1229°F (660-665°C), hold 8 hrs., Air Cool
A533 Gr B Cl 1 (HSST 02 Baseplate)	Normalize	1650-1700°F (899-927°C), hold 4 hrs.
	Austenitize	1520-1620°F (827-882°C), hold 4 hrs., Water Quench
	Temper	1200-1245°F (649-674°C), hold 4 hrs., Air Cool
	Stress Relieve	1125-1175°F (607-635°C), hold 40 hrs., Furnace Cool to 600°F (316°C)

TABLE 2

DYNAMIC TEST PARAMETERS AND CHARACTERISTICS

Test Technique	← Load-to-Failure			→ Dynamic Resistance Curve (← - - - - - - - -)	← Curve →
Temperature	Low	Mid-Transition	Upper-Transition	Upper Shelf	
Fracture Behavior	Elastic	Elastic-Plastic	Elastic-Plastic	Ductile Tear Followed by Cleavage Rupture	Ductile Tear
Crack Initiation	Cleavage	Cleavage	Cleavage	Fibrous	Fibrous
Formula for Calculating K or J	$K_Q = \frac{P_Q}{BW^{1/2}} f(\frac{a}{W})$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$
Relationship Between K and J	$K = (\frac{EJ}{1-\nu^2})^{1/2}$	$K = (\frac{EJ}{1-\nu^2})^{1/2}$	$K = (EJ)^{1/2}$	$K = (EJ)^{1/2}$	$K = (EJ)^{1/2}$
Load-Displacement Record	Linear	Non-Linear	Non-Linear	Non-Linear	Non-Linear
Comments	Fracture Occurs at Maximum Load	Fracture Occurs at Maximum Load	Fracture Occurs at Maximum Load	Load-to-Failure Tests Invalid	Minimum Four Tests Required
$\frac{P_M}{P_Q}$	≤ 1.00	$1.00 < \frac{P_M}{P_Q} \leq 1.10$	> 1.10	> 1.10	> 1.10
Δa	$< \frac{0.55\ J}{\sigma_Y}$	$< \frac{0.55\ J}{\sigma_Y}$	$\leq \frac{0.55\ J}{\sigma_Y}$	$> \frac{0.55\ J}{\sigma_Y}$	$> \frac{0.55\ J}{\sigma_Y}$

$$\frac{P_M}{P_Q} = 1.00 \qquad \frac{P_M}{P_Q} = 1.10 \qquad \Delta a = \frac{0.55\ J}{\sigma_Y}$$

Curve 695096-B

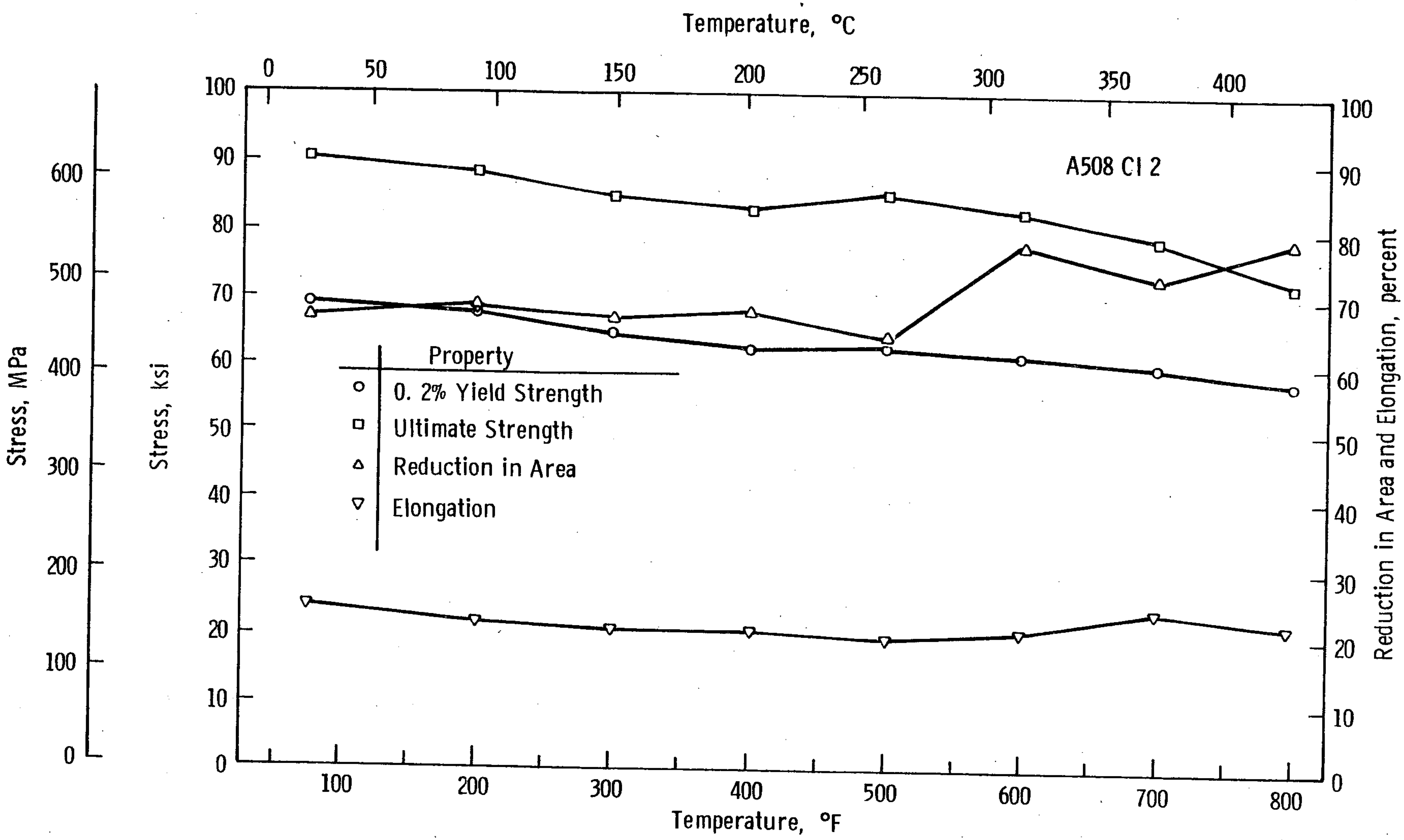


Fig. 1 —Tensile properties of A508 Cl 2 pressure vessel steel

Curve 695094-B

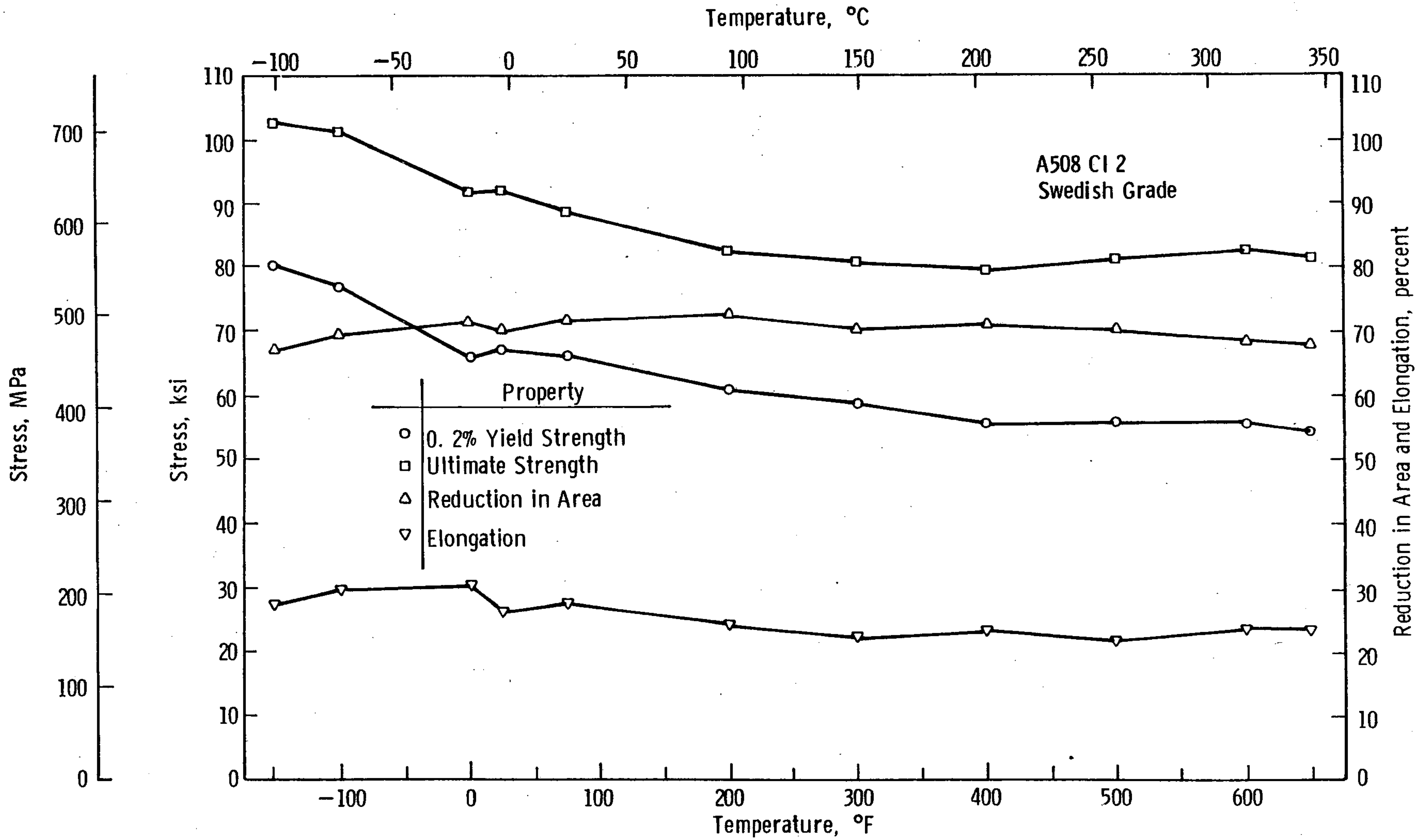


Fig. 2 —Tensile properties of A508 Cl 2 (Swedish Grade) pressure vessel steel

Curve 695095-B

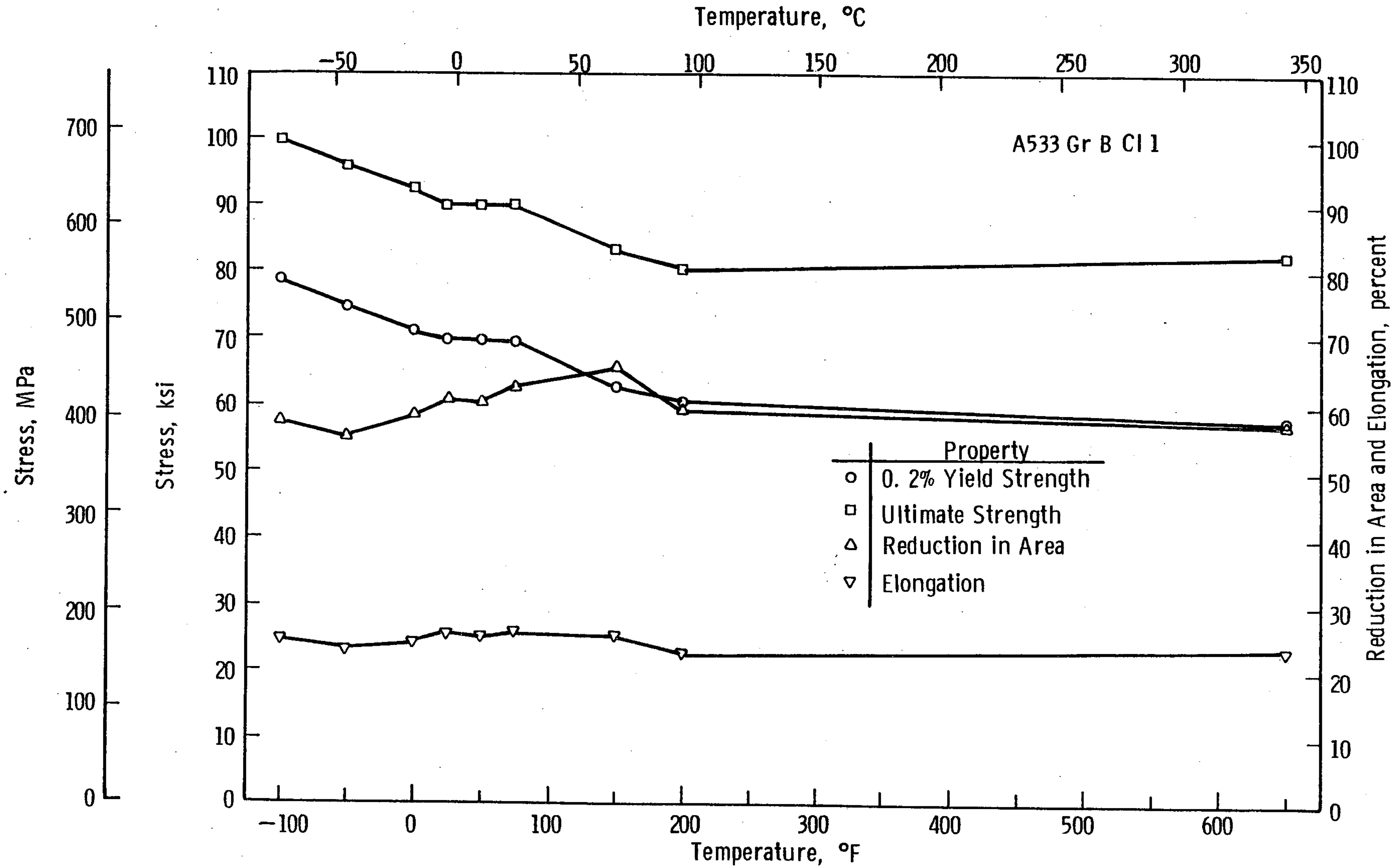


Fig. 3 —Tensile properties of A533 Gr B Cl 1 pressure vessel steel

Curve 695091-B

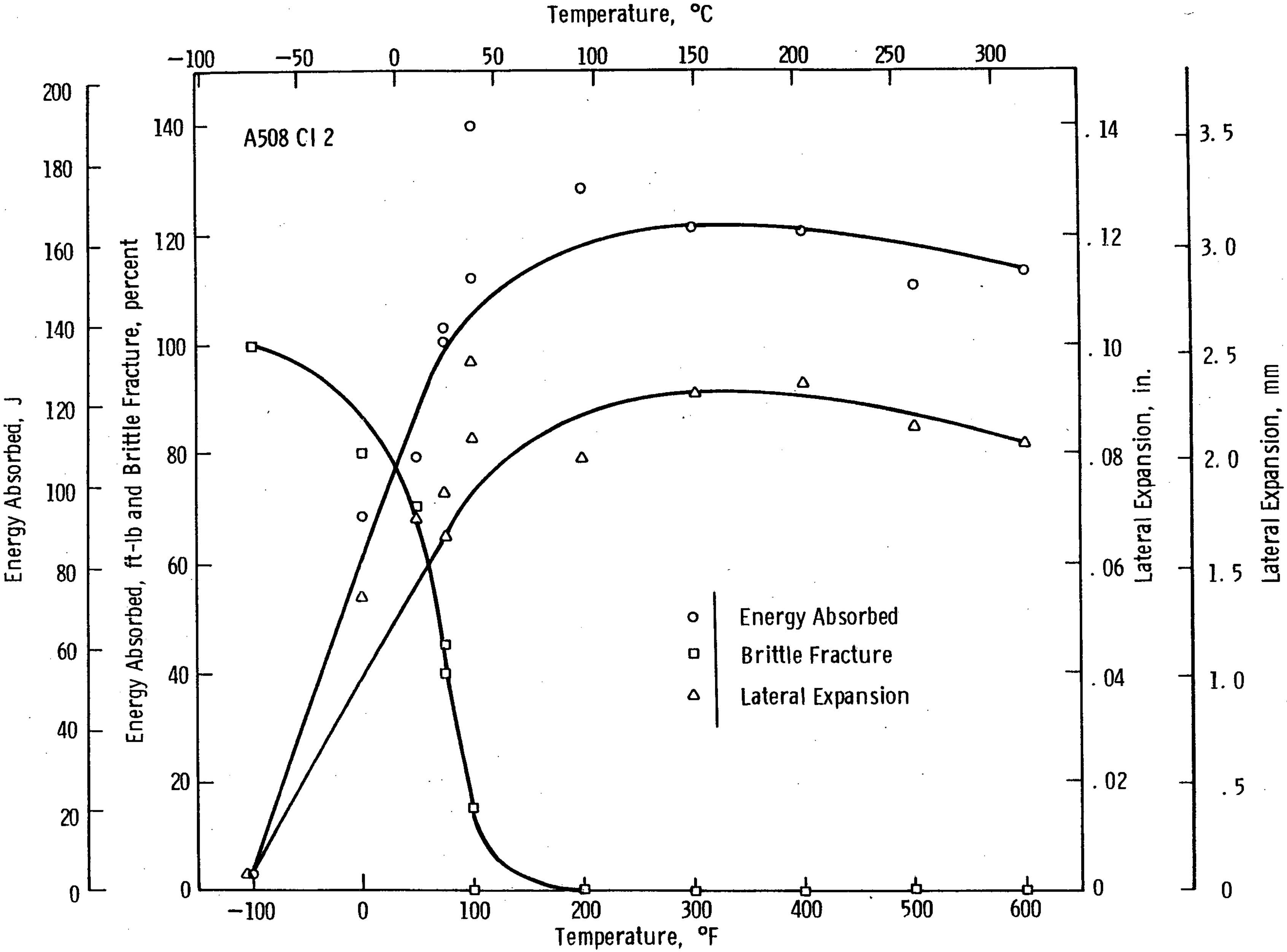


Fig. 4 —Charpy V-notch impact properties of A508 Cl 2 pressure vessel steel

Curve 695097-B

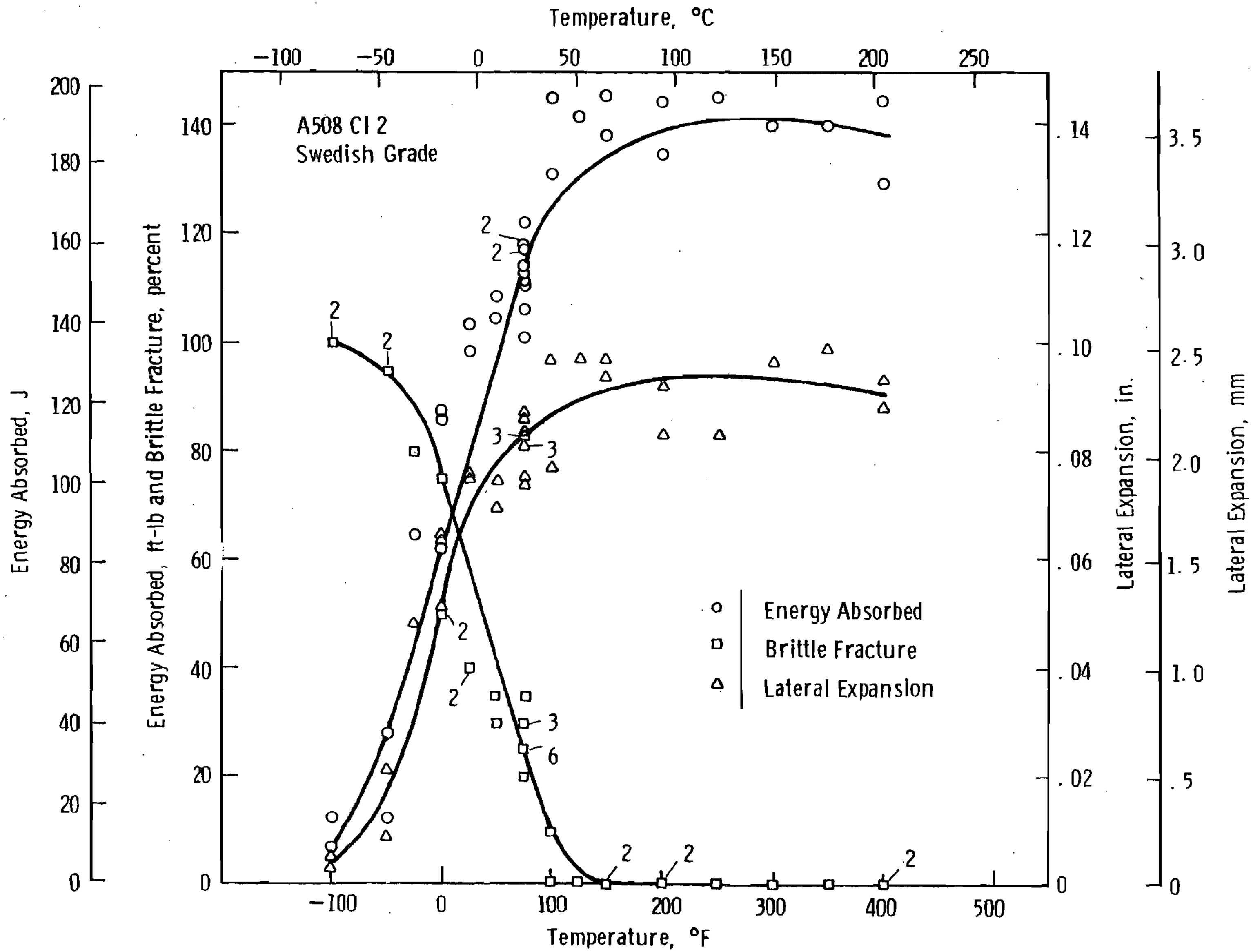


Fig. 5 —Charpy V-notch impact properties of A508 Cl 2(Swedish Grade) pressure vessel steel

Curve 695514-A

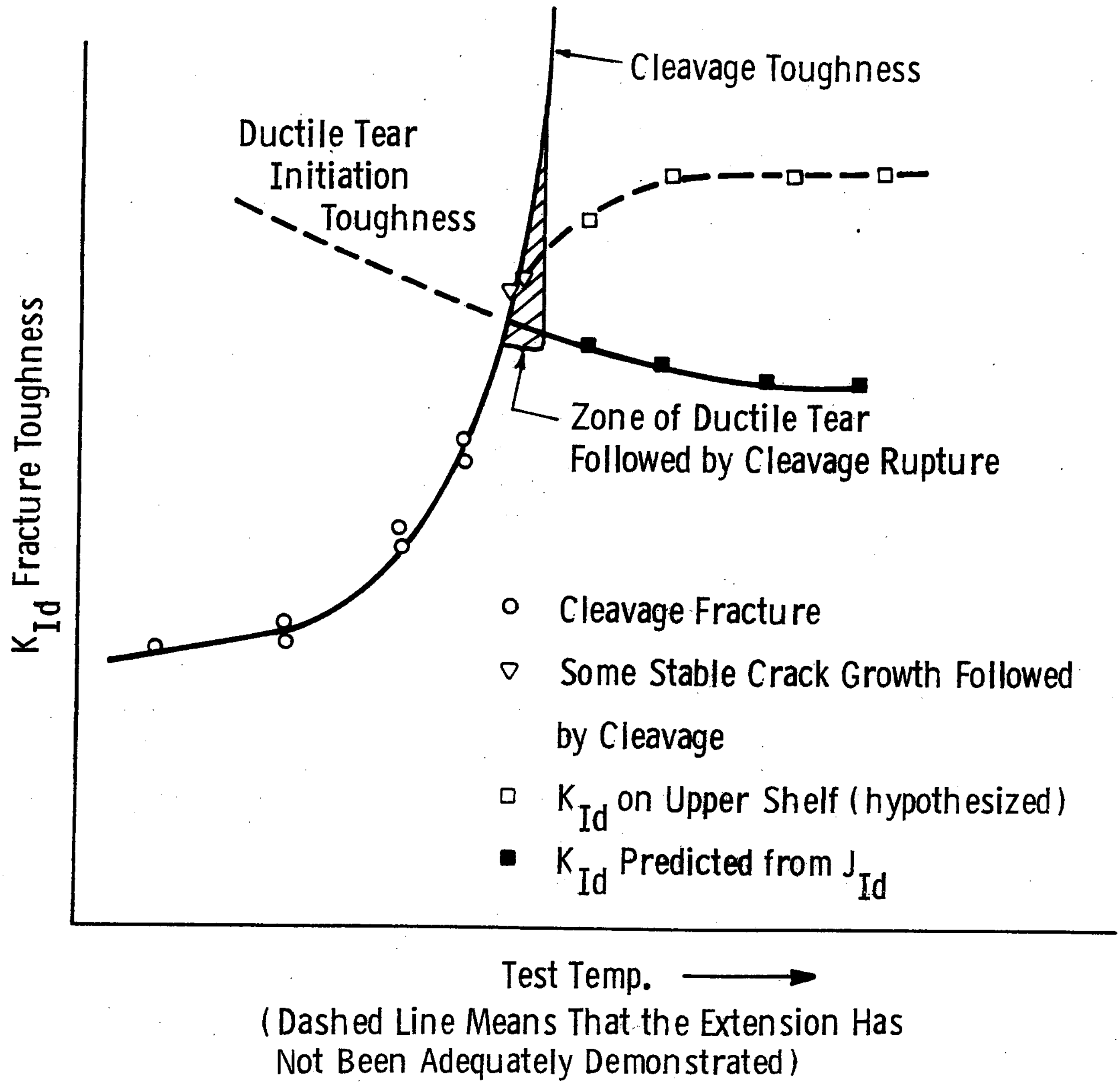


Fig. 6 — Schematic of K_{Id} transition temperature curve

Curve 695100-A

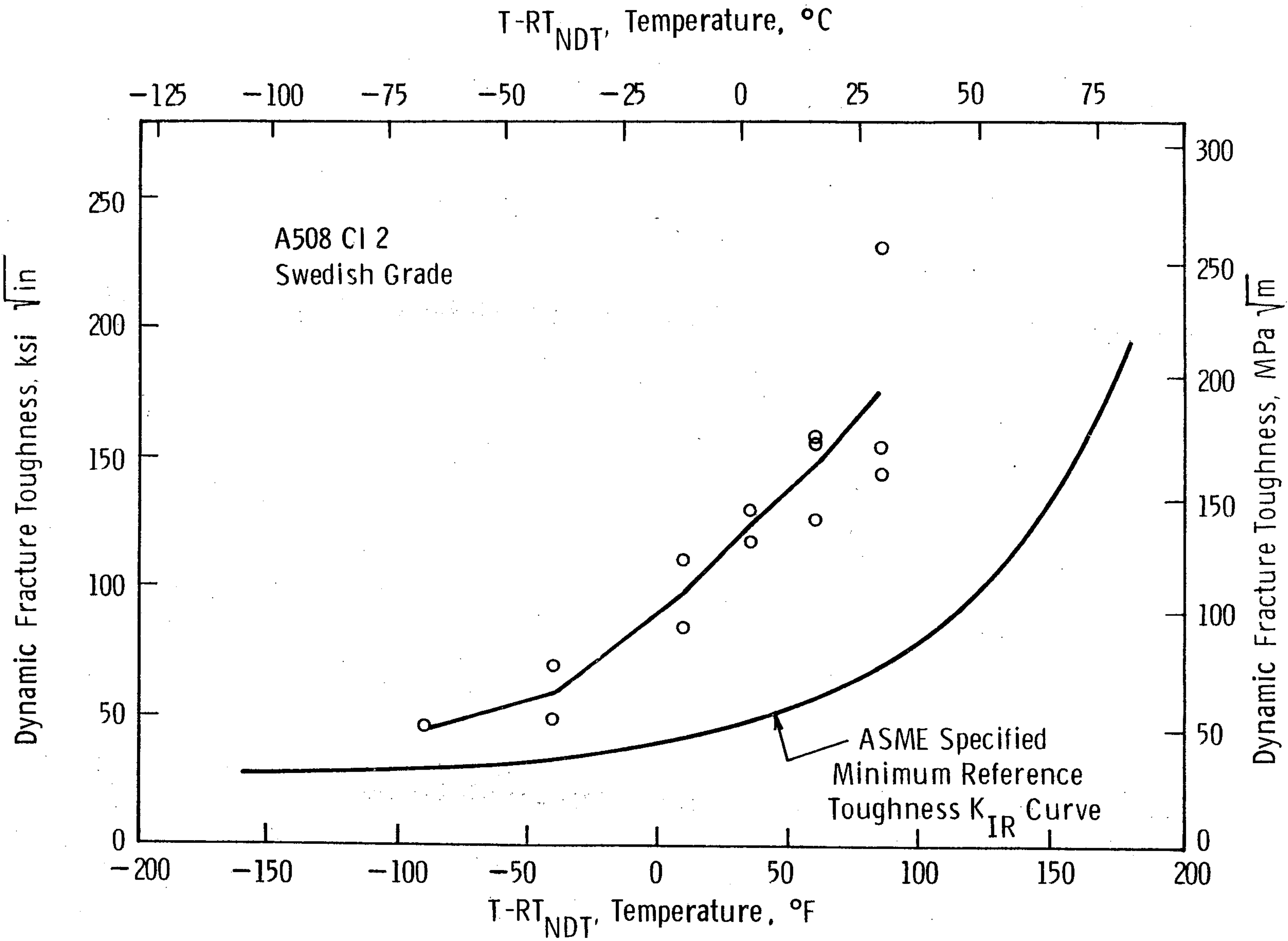


Fig. 7 — Dynamic fracture toughness versus T-RT$_{NDT}$ for A508 Cl 2 (Swedish Grade) pressure vessel steel

Curve 695194-B

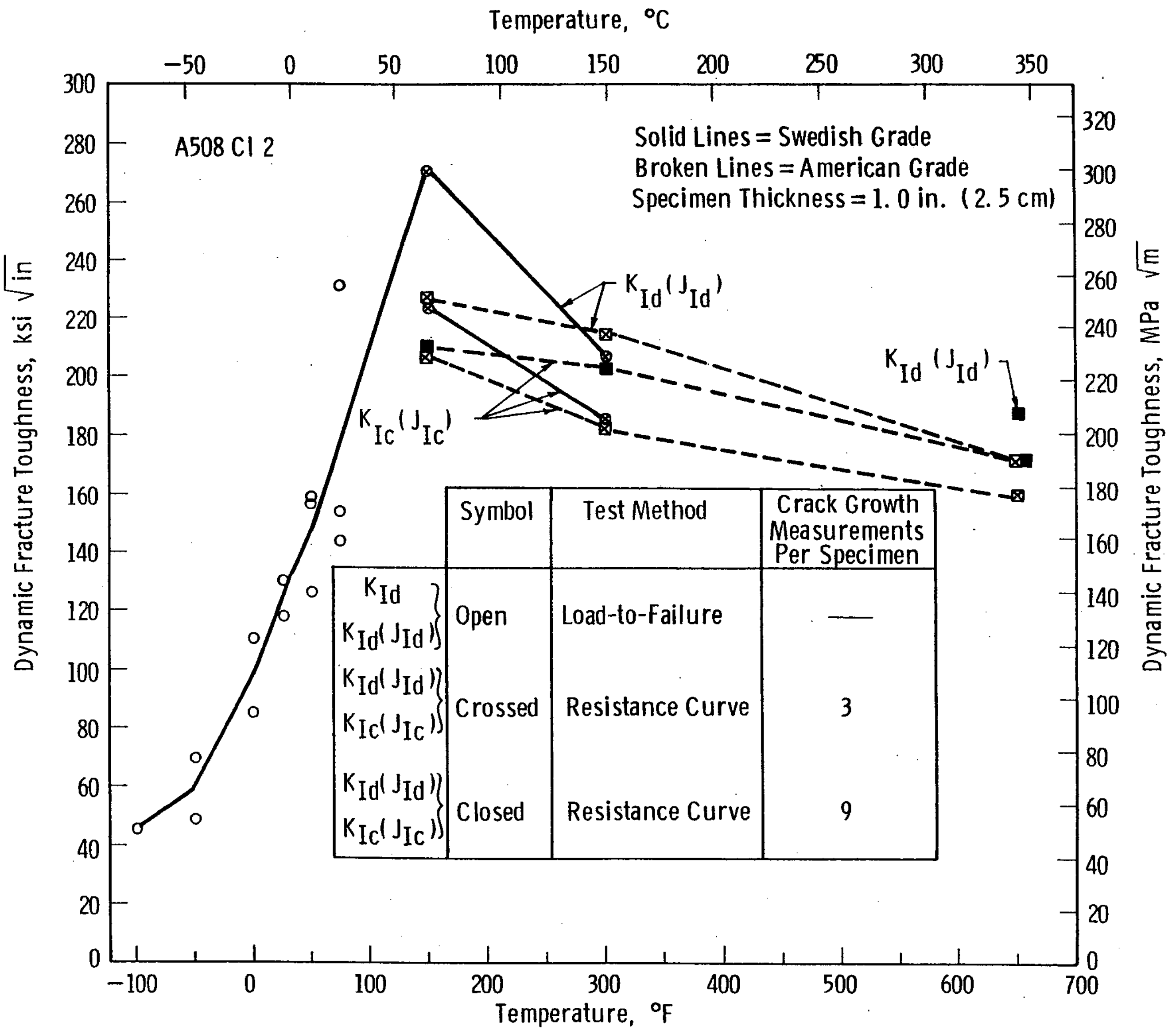
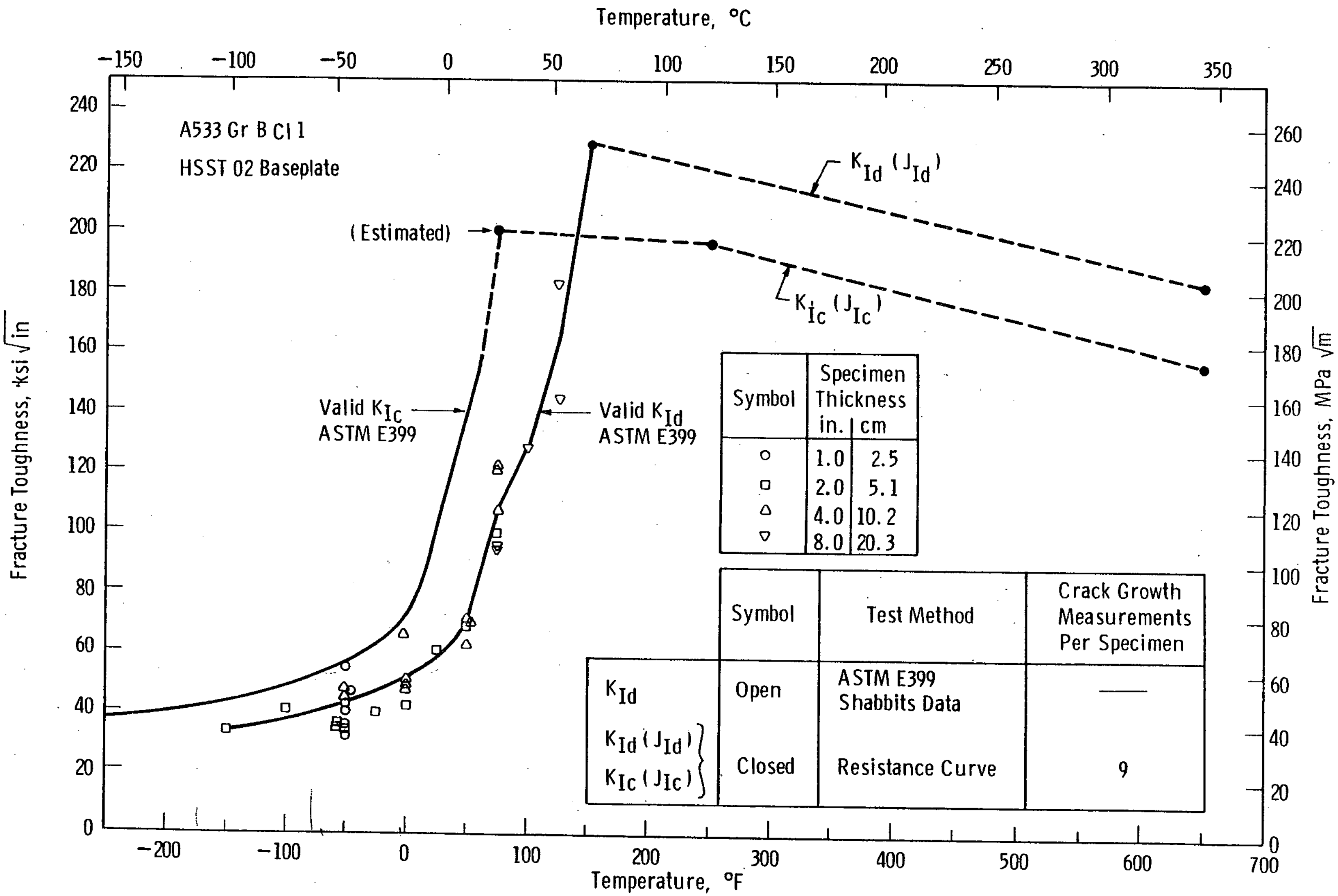


Fig. 8 —Dynamic fracture toughness of Swedish and American grades of A508 Cl 2 pressure vessel steel

Curve 695195-B



Symbol	Specimen Thickness in.	cm
○	1.0	2.5
□	2.0	5.1
△	4.0	10.2
▽	8.0	20.3

	Symbol	Test Method	Crack Growth Measurements Per Specimen
K_{Id}	Open	ASTM E399 Shabbits Data	——
K_{Id} (J_{Id}), K_{Ic} (J_{Ic})	Closed	Resistance Curve	9

Fig. 9 —Static and dynamic fracture toughness of A533 Gr B Cl 1 pressure vessel steel

Curve 695093-B

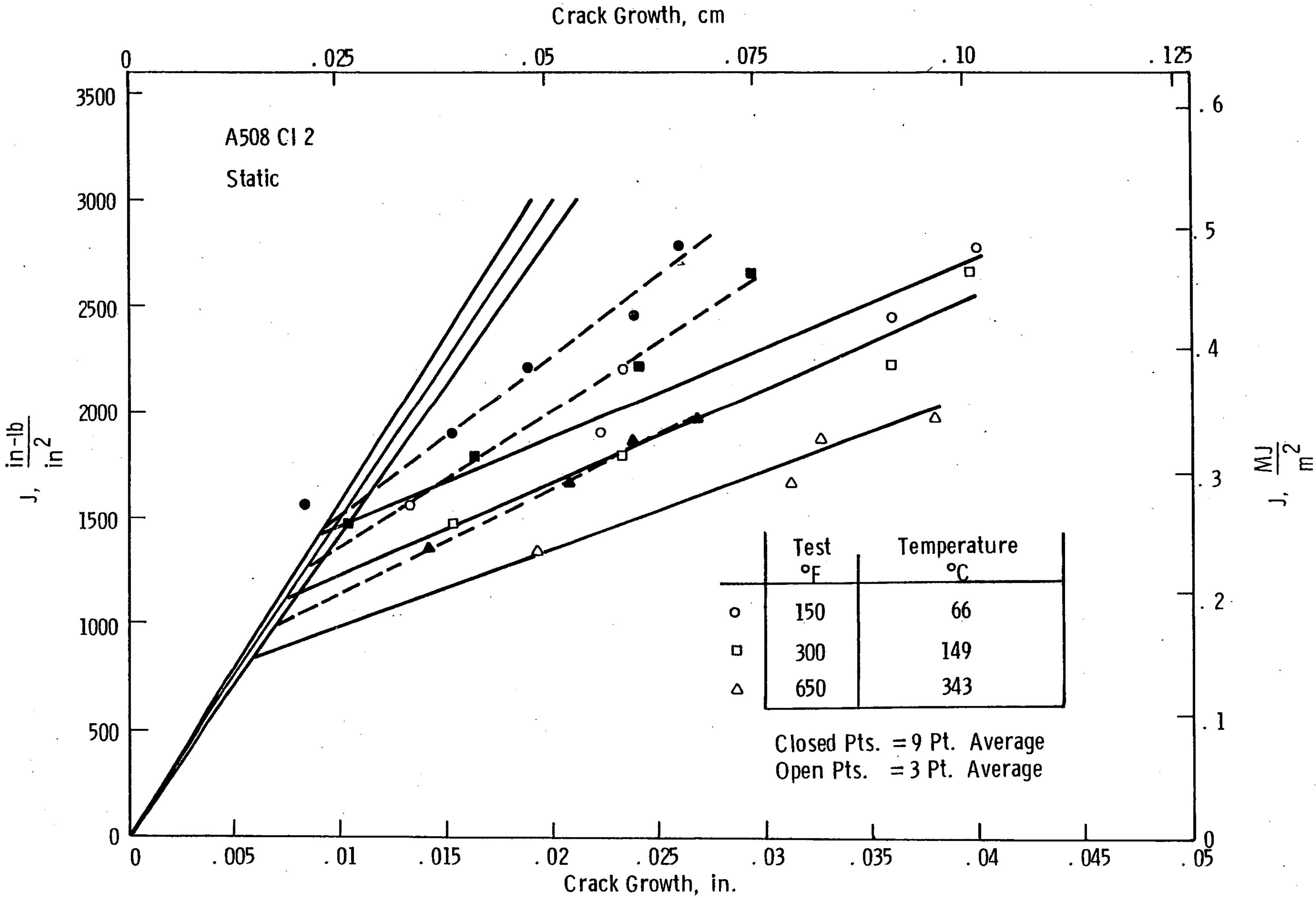


Fig.10—J resistance curves for A508 Cl 2 pressure vessel steel

Curve 695092-B

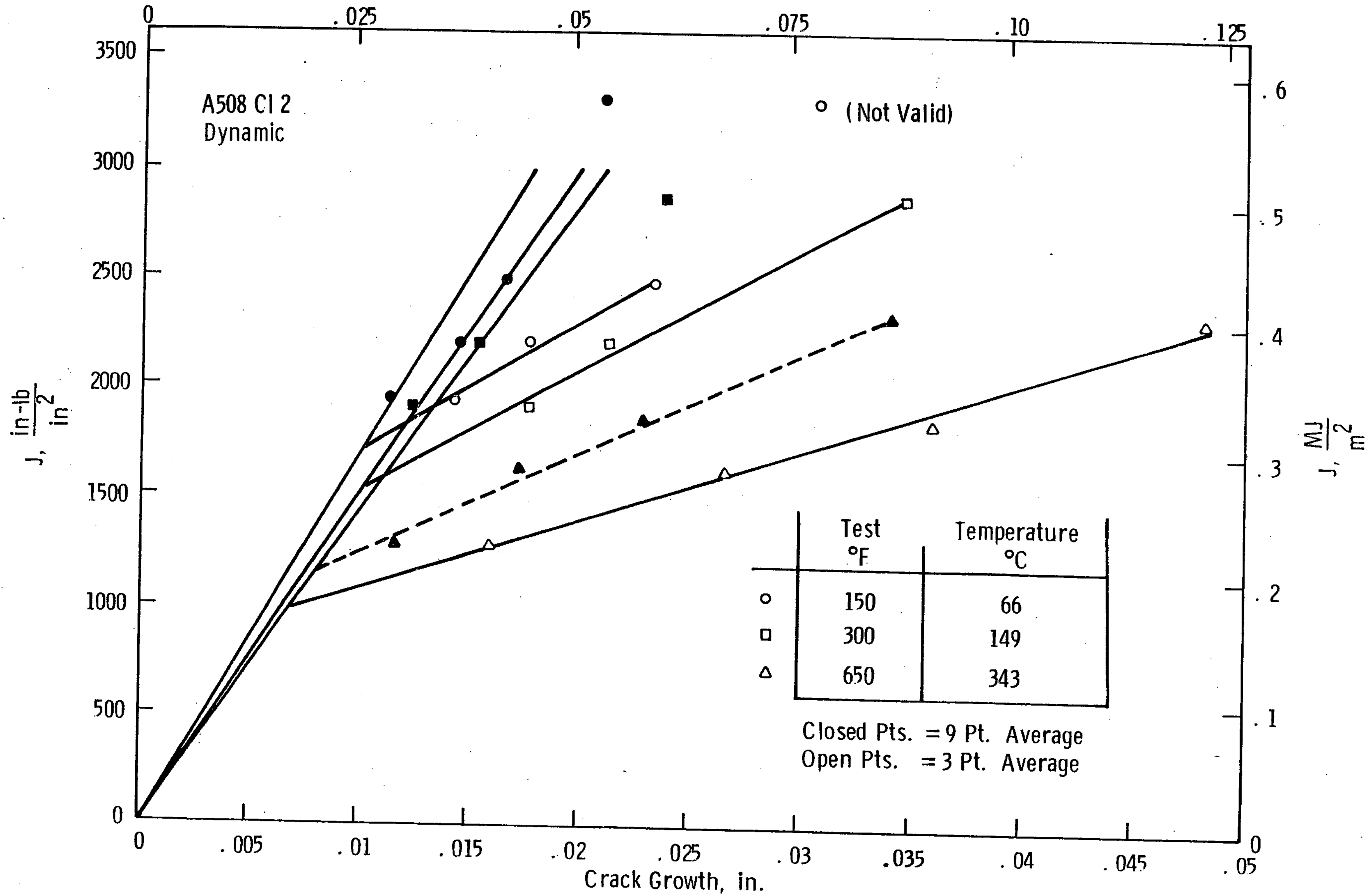


Fig.11—Dynamic J resistance curves for A508 Cl 2 pressure vessel steel

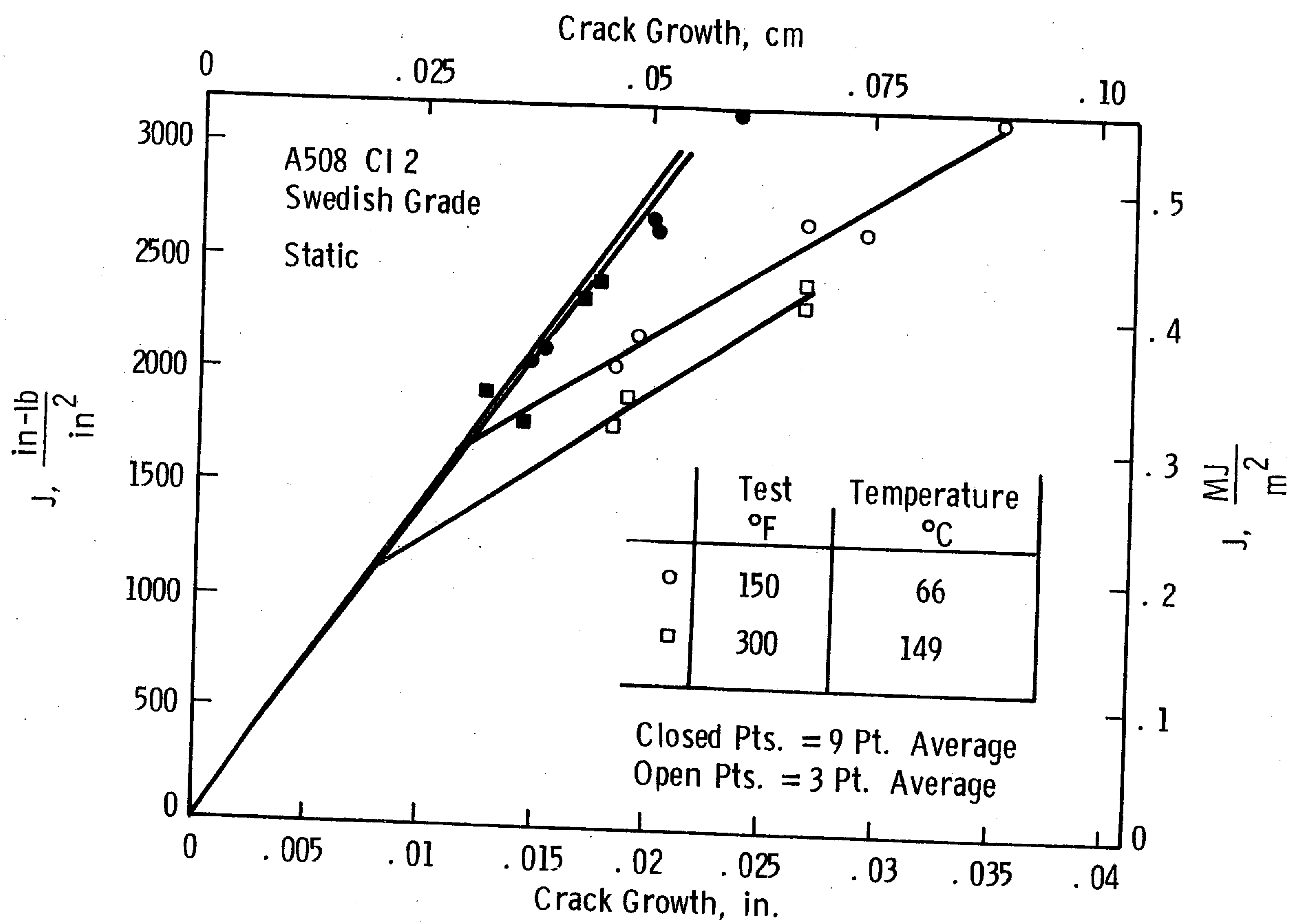


Fig. 12—J resistance curves for A508 Cl 2 (Swedish Grade) pressure vessel steel

Curve 695098-A

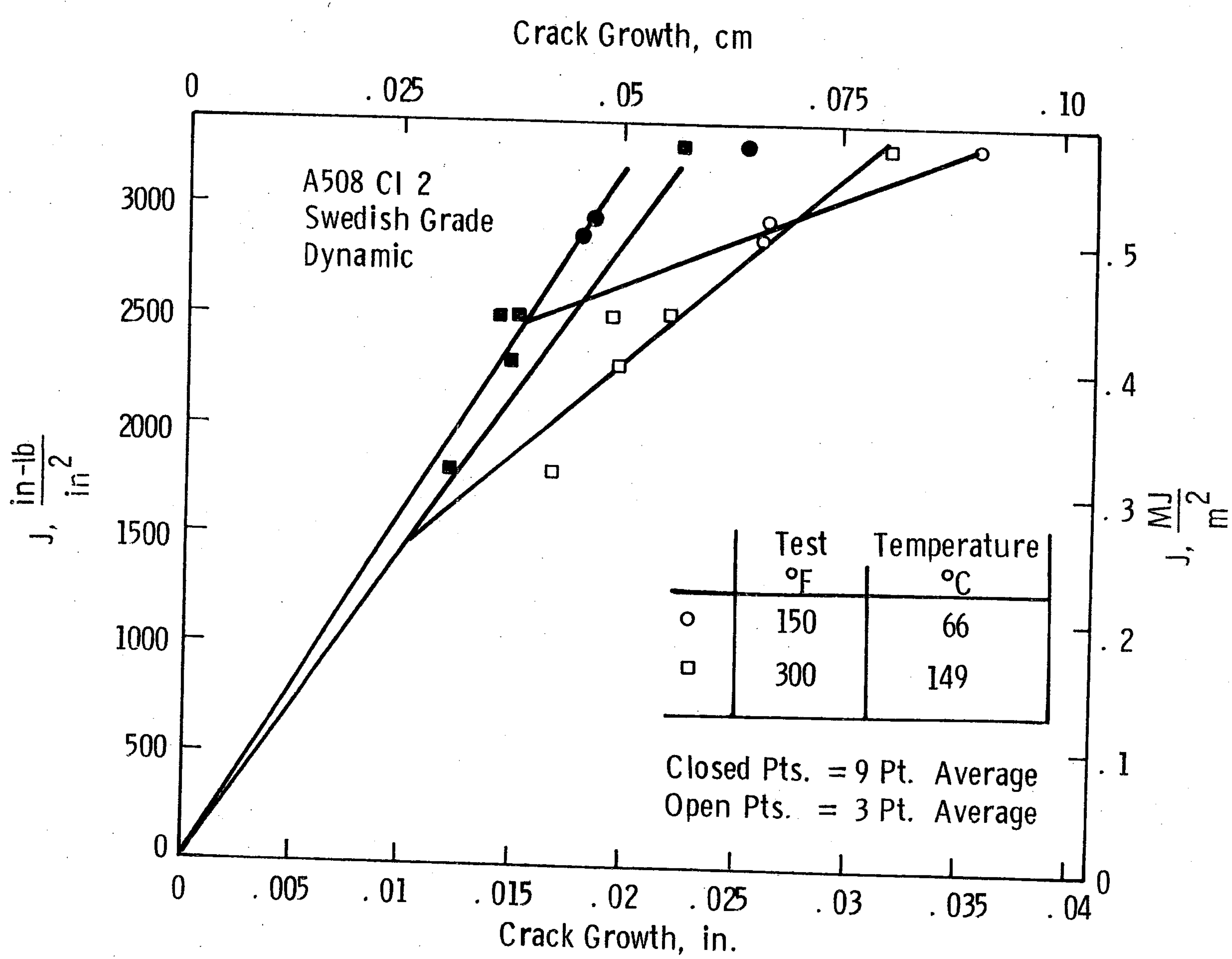


Fig.13—Dynamic J resistance curves for A508 Cl 2(Swedish Grade) pressure vessel steel

Curve 695197-A

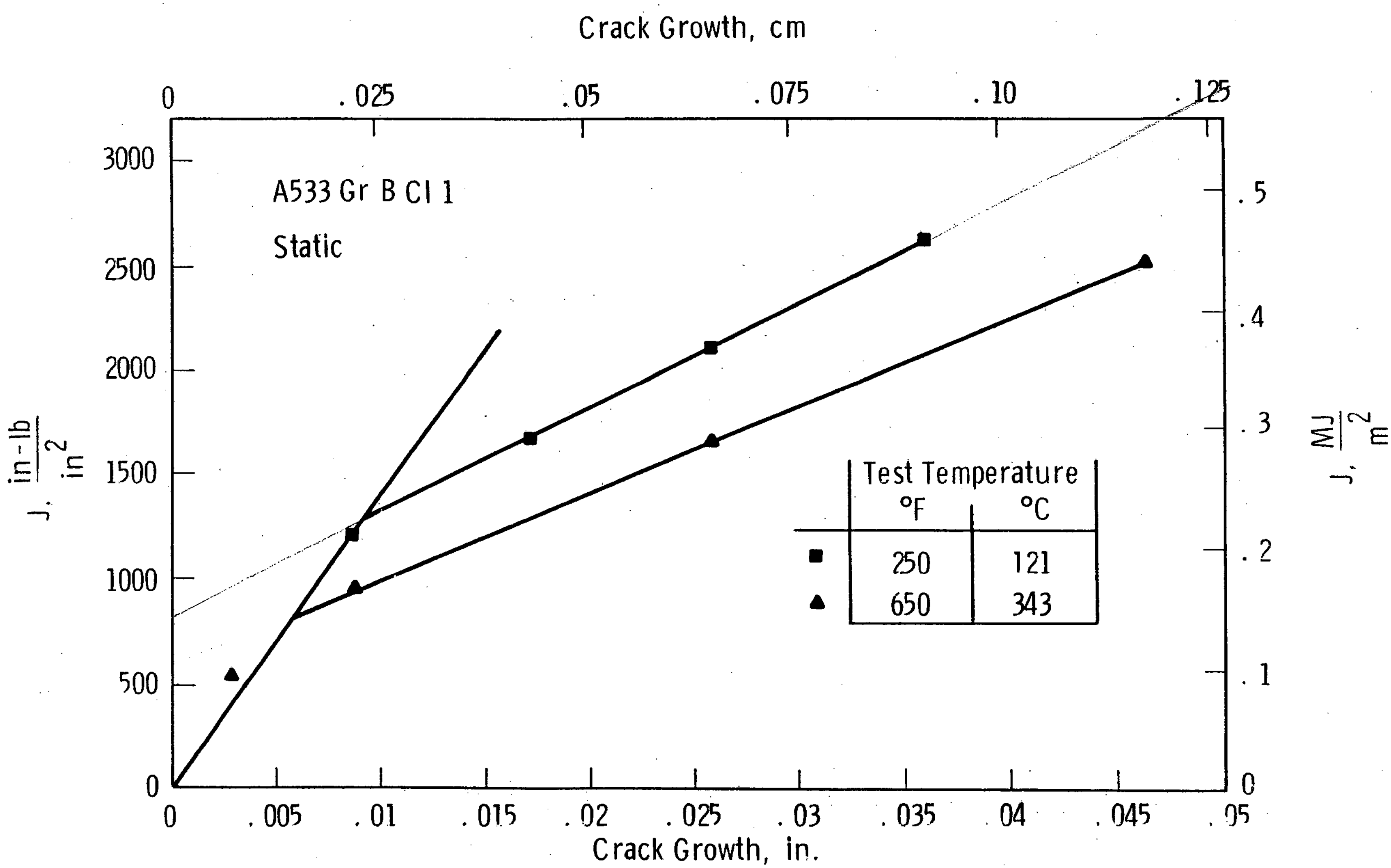


Fig. 14 — J resistance curves for A533 Gr B Cl 1 pressure vessel steel

Curve 695196-A

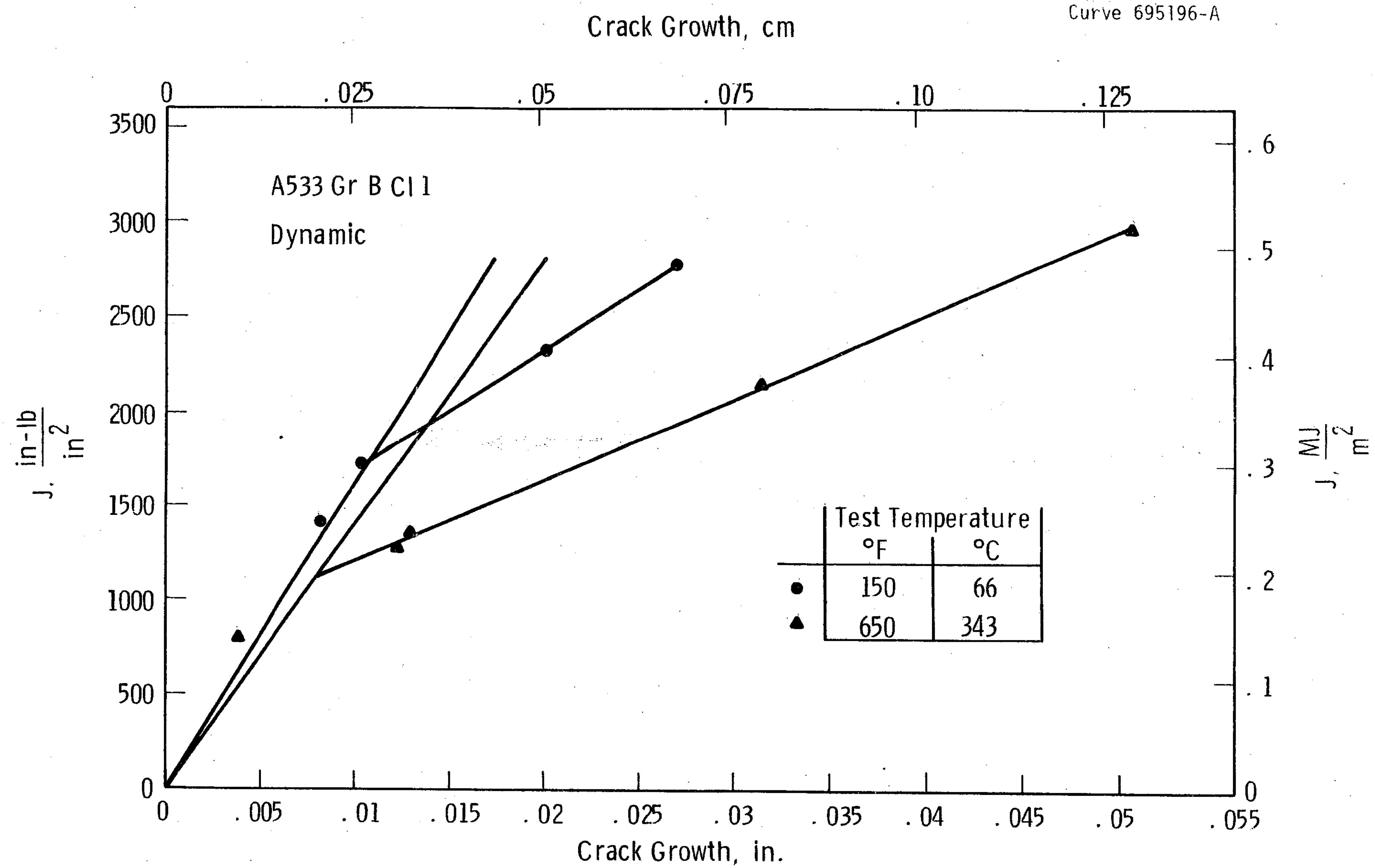


Fig. 15 —Dynamic J resistance curves for A533 Gr B Cl 1 pressure vessel steel