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THE INFLUENCE OF SECTION SIZE ON THE MECHANICAL PROPERTIES OF HEAT TREATED PRESSURE VESSEL STEELS

by

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

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INTRODUCTION

In 1954 the Pressure Vessel Research Committee of the American Welding Society revealed, through a literature survey,[1] a number of steels potentially useful for pressure vessel construction involving increased allowable design stresses. The conventional plain carbon structural steels were unable to fill this need except in heavy unwieldy section sizes. As design requirements became more stringent even the higher strength steels were unsatisfactory. In order to improve the properties of the high strength steels and minimize their section size, spray quenching was introduced. The advent of spray quenching resulted in the sponsorship by the PVRC of a number of research investigations. These programs revealed that spray quenching improved the properties of the steels and permitted their use in more reasonable section sizes.

An interest in the cooling rates that were being obtained at various positions across the thickness of the steel plates resulted from the commercial use of spray quenching. Numerous studies have been conducted, including those completed as a basis for the PVRC sponsored work at Lehigh University. All of these data were reported as the cooling rate (°F per second) at 1300°F. These data were in relatively poor agreement. For instance, there was a range of 10°F/second to 70°F/second reported for the midthickness cooling rate in a one inch section size.

The magnitude of these differences prompted the PVRC to sponsor a program at Lehigh University to determine the cooling rates that would be obtained through commercial spray quenching. This thesis reports the results of that program.

In addition to the cooling rate program, previously reported mechanical property data have been complemented by additional data and are herein reported as a function of section size rather than cooling rate. The results of the cooling rate studies have made this new presentation possible.

COOLING RATE STUDIES

Background

Prior to the initiation of the cooling rate studies, it was advisable to review the previously reported data in an effort to discover the causes of the discrepencies.

First, there appears to be a wide variation of the flow rate of the water spray. This point alone could be responsible for the differences reported. Secondly, the cooling rates were reported at 1300°F but no mention is made of the type of steel used. This too could be responsible for the wide gap in cooling rates. The temperature at which recalescence will begin is determined by the composition of the steel. A high alloy content will suppress recalescence. If the steel selected for a cooling rate study is of a high alloy grade then recalescence and its accompanying heat of transformation will not be reflected in the 1300°F cooling rate. Consequently the cooling rate reported for this material would be fast. Conversely, if the steel were a plain low carbon grade that underwent solid state transformation at or about 1300°F then the cooling rate based on the 1300°F criterion would be slow. This retardation of the cooling rate is attributed to the fact that the entire heat of transformation would be evolved over the temperature range of interest.

Equipment

A survey was conducted to establish the spray rates commercially employed for quenching plates. Correspondence with users of spray quenching apparatus suggested that 0.3 cubic inches of water per square inch of surface per plate side per second is a typical commercial rate. A spray quenching apparatus capable of delivering the desired quantity of water was designed. Figure I is a photograph of this apparatus showing the positions of the two commercial spray heads in relation to a one inch thick steel plate containing two thermocouples. Each spray head is constructed to deliver a uniform cone of water to each side of the plate. The heads are mounted in the sides of a container that measures 24 inches by 36 inches by 30 inches deep. A runoff pipe is located ten inches above the bottom of the container. Thus five cubic feet of water (equivalent to the volume of water obtained under commercial conditions in 60 seconds) is held in the container before runoff begins.

Experimental Procedure

The section thicknesses studied with this spray rig were 1/2 inch, 1 inch, 1-1/2 inches, 2 inches, 3 inches and 4-1/2 inches. The plate sizes were the same, 12 inches by 12 inches. The selection of this size plate conformed to a 5/2 x thickness requirement that assures the elimination of edge effects in the 4-1/2 inch plate. Cooling rates were measured at the midthickness and quarterthickness positions. Porcelain insulated chromel-alumel thermocouples were percussion welded to the plate at the bottom of six inch holes located six inches in from either side. The thermocouples were protected from the water by stainless steel tubes that extended above the top of the container (see Figure 1) when the plate was in the spraying position. These tubes eliminated the possibility of water entering the hole containing the thermocouple thereby causing erroneous cooling rates.

For each plate quenched, the time necessary to fill the five cubic foot volume below the runoff tube was noted. This permitted the calculation of the water flow rate. The average flow rate delivered by this rig was approximately 0.28 in^3/in^2/side/second.

The change in temperature with time resulting from spray quenching (and later air cooling) was determined in the following manner. The millivoltage output from the midthickness thermocouple was fed into a terminal box. Two leads were tapped from this terminal, one of which went to a Leeds and Northrup Speedomax recorder. This recorder was geared for two travel speeds, 1/2 inch per second and 1 inch per minute. The slower rate was used for air cooled plates. The second lead from the terminal was fed into the abscissa (pen) of a Mosely x-y Recordograph and provided the time axis. The ordinate of the Mosely recorder was used to record the millivoltage output from the quarter-thickness thermocouple.

An actual cooling rate determination was carried out in the following manner:

A 12" by 12" plate of the desired thickness had two 1/8 inch holes drilled in it to receive the 28 gauge chromel-alumel thermocouple. The holes were then counter-sunk and a male pipe fitting was welded in place.

The thermocouples, insulated with 1/8 inch alumina beads, were percussion welded to the base of these holes. A stainless steel tube containing a female fitting was placed over the thermocouple and the fittings were engaged. The prepared plates were placed in a 1650°F preheated furnace and were removed from the furnace after their temperature had equalized. The plates that were to be air cooled were wire brushed to remove any loose scale. (Those being spray quenched did not require this treatment because of the thermal shock of the water). When the temperature of the plate reached 1600°F the temperature controlling devices were activated. In the case of spray quenching the water and temperature devices were activated simultaneously.

Results

In order to avoid the previously mentioned recalescence the cooling rates for the various plate thicknesses were determined on the basis of a half-temperature criterion. The calculation of a cooling rate based on this criterion consists of dividing the half-temperature difference, in °F, by the time required to reach half-temperature. A sample calculation of a half-temperature cooling rate is given at the bottom of Table I. This wide temperature range, 770°F for spray quenching, includes nearly all of the metallurgical changes that will affect the cooling rate. A cooling rate based on the half-temperature criterion minimizes the effect of steel composition.

The experimental cooling rates obtained for the various section sizes are given in Table I. Each rate represents the results of at least two determinations. In addition to the determination of the cooling rate for spray quenching, a simultaneous study was conducted for air cooled plates. The results are plotted in Figure 2. This is a log-log plot of plate thickness (ordinate) versus cooling rate (abscissa). The mid-thickness and quarter-thickness cooling rates for the air-cooled specimens were essentially identical. Spray quenching resulted in a slight, but significant difference, between the mid-thickness and quarter-thickness locations.

Discussion of Results

The data given in Table I and plotted in Figure 2 were used as the basis for the derivation of mathematical equations that would permit the extrapolation of these cooling rates for section sizes beyond 4-1/2 inches. These equations are as follows:

For air-cooling; mid-thickness and quarter-thickness

$$\text{Log (C.R.)} = -.0696 - .813 \log t$$

For spray quenching

mid-thickness

$$\text{Log (C.R.)} = 1.202 - 1.007 \log t$$

quarter-thickness

$$\text{Log (C.R.)} = 1.285 - 1.018 \log t$$

where (C.R.) is cooling rate (°F/sec) and t is plate-thickness (in inches).

The actual calculations for the derivation of the equation for the air cooling are given in Appendix I. The derivations of the spray quenching equations were similar. The derivation of these equations permitted the extrapolation of the experimental data to 10 inch thick section sizes. As can be noted in Figure 2 the cooling rate in a 10 inch thick spray quenched plate is nearly identical to the cooling rate in a 1/2 inch thick air cooled plate. Assuming that microstructure is entirely dependent on the cooling rate, then the properties (microstructure) of a ten inch thick spray quenched plate would be nearly identical to those found in a 1/2 inch thick plate.

The deviation between the calculated cooling rates and the experimental cooling rates is about +14% maximum. This difference is within experimental error. The greatest source of error in the experimental data probably arose from the transfer of millivoltage reading from the Mosely x-y plot. The closest approximation that could be made was about ±.5 millivolts.

Other cooling rate data are available.[2] Some of these data are complete enough to permit a calculation of HTT cooling rates as well as the cooling rate at 1300°F. Pellini, of the Naval Research Laboratories, did some cooling rate studies during the last war. The results he obtained are given in Table II. Included in this Table are the results of this current study. The current values for 5 inches and above are extrapolations. Pellini's cooling rates are consistently lower than those reported in this study. This difference is attributed to his mode of quenching, dip quenching in circulating water versus the spray quench used in this study. One point, 7-3/8 inch thickness, was available from an industrial laboratory. This HTT cooling rate is even lower than Pellini's for the same thickness. No information is available concerning the spray rate used for the 7-3/8 inch plate. It is concievable that their rate was considerably below the current industrial level of 0.3 cubic inches of water per square inch of surface per side per second.

Cooling rate data were also available for air cooling. Table III contains these data. The values reported in this reference are considerably lower than these recorded in the current study. Moreover, the 1300°F cooling rate calculated from these data is lower than those reported by Stout.[3] Again, although the temperature-time data for this cooling study is complete, there is no indication of the lateral dimensions of the specimens used.

Mechanical Property Data

The satisfactory correlation of the cooling rate to plate thickness made possible a graphical presentation of the relationship between mechanical properties and section size for various pressure vessel steels. The relationship between mechanical properties and cooling rate was previously determined at Lehigh University. A brief review of this work is in order.

These earlier studies consisted of devising methods for producing in 1/2 inch thick steel plates thermal cycles representative of those found in spray quenched and normalized steels of heavier section sizes. In order to do this, cooling rates were measured, based on the 1300°F criterion, at various locations in 4 inch thick spray quenched and normalized steel plates. Based on these cooling rates, three techniques were developed that enabled the experimenters to obtain, in 1/2 inch thick steel plates, microstructures similar to those found at the various locations in the 4 inch thick plates.

Because of the availability of the original data collected at Lehigh University it was possible to convert the 1300°F cooling rates to HTT cooling rates. These changes were as follows:

Cooling Technique (1/2 inch thick plate)	Cooling Rate (1300°F) °F/Sec	Cooling Rate (HTT) °F/Sec
Cool in Foil Lined Box	0.25	0.5
Cool between Steel Plates	5.7	6.6
Oil Quench	36.	33.

The conversion of the 1300°F cooling rates to HTT cooling rates permitted the use of the equations developed earlier. Through these equations it was possible to relate section size to cooling rate and consequently to the mechanical properties that had been reported at these rates for the various steels.

There was a lack of information for HTT cooling rate versus mechanical property data in the range of 0.5 and 6.6°F/sec and 6.6 and 33°F/sec. Information for the lower range was obtained during the course of this investigation. A technique was developed that resulted in a HTT cooling rate of 2.8°F/sec. The technique consisted of cooling, from the appropriate austenitizing temperature, 2 inch by 18 inch by 1/2 inch thick steel plates in a blast of air. This blast, at a distance of 12 feet, was capable of delivering approximately 100 cubic feet of air per minute over the length of the plate.

Five steels were cooled from their respective austenitizing temperatures in this fashion. The steels and their compositions are given in Table IV. After heat treatment, the steels were subjected to mechanical tests similar to those run by Gross et al.[4]

The mechanical properties determined were yield strength, tensile strength, elongation, reduction in area, and transition temperature based on the 15 ft-lb, 15 mil and 50% fibrous fracture criteria.

Through the use of the equations developed during the cooling rate study each cooling rate was related to a position within a given plate thickness, i.e., mid-thickness or quarter thickness.

Results of Mechanical Properties Versus Plate Thickness

The mechanical properties of the five steels, A285, A212, A203, A302 and HY80, are given in terms of plate thickness in Tables V through IX respectively. These tables include the data gathered during the course of this investigation as well as those reported by Gross et al. Listed in each table are the as-cooled and as-cooled and stress relieved properties for each steel.

As can be noted in each of these Tables, a given mechanical property is reported for three different plate thicknesses. Actually a given cooling rate may be obtained at any one of a number of locations depending on the plate thickness. For example, the cooling rate at the center of a half inch spray quenched plate may be identical to the cooling rate at the surface of a much heavier section size. In addition, there is an overlap of cooling rates for spray quenching and air cooling.

An example of this can be seen in Figure 2. Approximately the same cooling rates were obtained at the mid-point of a 10 inch thick spray quenched plate and in a 1/2 inch thick air cooled plate.

In order to present these data in a more useful fashion Figures 3 through 6 were prepared. These Figures show the effect of section size on tensile strength, yield strength, 15 ft-lb Charpy V-notch transition temperature and 15 mil Charpy V-notch transition temperature respectively. Each of these Figures contain data for the as-cooled and as-cooled and stress relieved conditions.

Discussion of Figures

Both the A285 and A212 steels showed a loss in tensile and yield strength as plate thickness was increased. The effect of section size on the tensile properties of the as-cooled plates was greater than that encountered after stress relieving. The notch toughness of A285 was not affected appreciably, there being essentially no change with section size for the as-cooled condition, and only a slight increase in transition temperature being noted for the stress relieved condition.

The transition temperature of the A212 steel increased with thickness about 40°F for the section sizes shown. This difference in behavior between the A212 and A285 steels is probably due to the greater hardenability of the A212 steels. The chemistry of these two steels is essentially the same except for carbon content. The low carbon content of A285 detracts from this steel's hardenability, thereby causing it to be unresponsive to the cooling rates studied in this program. A212, because of its higher carbon content, is more hardenable. This higher hardenability is reflected in this steel's response to accelerated cooling. As the section size is increased (the cooling rate decreases) the microstructure of A212 becomes less refined, thereby causing a deterioration in its notch toughness.

The A203 steel in the as-cooled condition underwent a major loss in tensile strength, approximately 50,000 psi as the section size was increased. Accompanying this strength loss was an increase in notch toughness. This improvement in toughness was reflected in both the 15 mil and 15 ft-lb criteria. After stress relieving the strength was not appreciably affected by section size but there was a decrease in notch toughness.

The behavior of the A302 steel was similar to the A203.

The section size had no effect on the notch toughness of spray quenched HY80 steel up to a thickness of 3 inches. However, above 3 inches in thickness the notch toughness dropped off rapidly. This was true for both the as-cooled and as-cooled and stress relieved conditions. The tensile strength of the as-cooled HY80 decreased with section size. In the as-cooled and stress relieved condition this steel showed a slight increase in tensile strength with increased plate thickness. Due to the high alloy content of HY80 thin sections that have been spray quenched will transform almost completely to martensite. This martensite will be tempered during the subsequent stress relieving treatment. As section size is increased, the primary transformation product will be bainite and/or fine pearlite. These transformation products are not as affected by the stress relief treatment as is martensite.

SUMMARY

The results of the investigation reported can be summarized as follows:

1) A survey was made of commercial spray quenching. A spray rate of 0.3 cubic inches of water per square inch of surface per side per second was found to be a practicable value for production spray quenching.

2) For the above spray rate, cooling rates were measured at the mid-point and quarter-point of various section sizes from 1/2 inch to 4-1/2 inch thicknesses. From the observed cooling rates equations were derived to permit an approximation of the cooling rate, in °F per second, at the mid-thickness and quarter-thickness positions of plate thicknesses from 1/2 to 10 inches. These equations, based on the half-temperature cooling rate, are as follows:

For spray quenching

mid-thickness

$$\text{Log (C.R.)} = 1.202 - 1.007 \text{ log thickness}$$

quarter-thickness

$$\text{Log (C.R.)} = 1.285 - 1.018 \text{ thickness.}$$

In addition, an equation was derived for air cooling. Because of the similarity in cooling rates between the mid-thickness and quarter-thickness positions one equation suffices for both locations.

$$\text{Log (C.R.)} = -.0696 - .813 \text{ log thickness.}$$

3) A technique was devised for cooling 1/2 inch thick steel plate at a HTT rate of 2.8°F per second. Mechanical property data were obtained

for five steels cooled by this technique. This information was used to complement the data previously gathered for the same steels.

Through the use of the cooling rate equations discussed in 2 above these data were related to a section size. The relationship that was established permitted the presentation of mechanical properties as a function of section size. This presentation makes possible a rapid estimation of the mechanical properties one can anticipate for heat treated steel plates of various section sizes.

TABLE I

Experimental Cooling Rates for Normalized and Spray Quenched Plates of Various Thicknesses

Cooling Method	Plate Position	Cooling Rate in °F Per Second to Half-Temperature*					
		1/2 inch	1 inch	1-1/2 inch	2 inch	3 inch	4-1/2 inch
Spray Quenched	Quarter-Thickness	36	18	13	11	6.2	3.7
	Mid-Thickness	31	18	12	7	5.7	3.1
Normalized	Quarter-Thickness	1.5	0.84	0.64	0.54	0.32	0.26
	Mid-Thickness	1.5	0.84	0.60	0.48	0.32	0.26

*The cooling rate to half-temperature is determined by dividing the first half of the temperature change during cooling by the time required to produce the first half change.

Example: Quench from 1600°F with water at 60°F.

The half-temperature is $\frac{1600-60}{2} + 60 = 830$°F

If the time to cool from 1600°F to 830°F were 20 seconds, then the cooling rate to half-temperature would be $\frac{770°\text{F}}{20\text{ sec.}} = 38.5$°F/sec.

Table II - Comparison of Various Cooling Rate Studies - Water Quench

	Results of Various Cooling Rate Studies - HTT°F/sec		
Plate Thickness	Pellini(2) (Dip Quench)	Beth. Steel(2) (Spray Quench)	Author's Study (Spray Quench)
1	15.8		18
2	8.5		11
3	4.7		6.2
4	3.2		3.8
5	2.3		3.1
6	1.7		2.6
7	1.4	1.0*	2.2
8	1.1		1.8

* Plate Thickness - 7-3/8 inches.

Table III - Comparison of Various Cooling Rate Studies - Air Cooling

Results of Cooling Rate Studies - HTT°F/sec

Plate Thickness inches	Reference Study (2)	Author's Study
1	.78	.84
2	.38	.54
4	.19	.28
6	.10	.20

TABLE IV

CHEMICAL ANALYSES AND HEAT TREATING TEMPERATURES

Steel	Grade*	C	Mn	P	S	Si	Ni	Cr	Mo
ASTM A-285	C	0.20	0.53	0.020	0.016	-	-	-	
ASTM A-212	B	0.28	0.70	0.010	0.021	0.24	-	-	
ASTM A-203	D	0.15	0.64	0.010	0.026	0.22	3.64	-	
ASTM A-302	B	0.20	1.32	0.022	0.030	0.25	-	-	0.42
HY-80	High	0.15	0.28	0.016	0.015	0.19	2.86	1.72	0.50

Steel	Austenitizing Temperature °F	Stress-relieving or Tempering Temperature
A-285	1650	1150
A-212	1650	1150
A-203	1650	1150
A-302	1650	1150
HY-80	1650	1150

*All steels were firebox quality where applicable.

TABLE V

MECHANICAL PROPERTIES OF ASTM A-285 STEEL

Tensile Properties

Plate Thickness - Inches			Yield Strength 0.2% psi	Tensile Strength psi	Elongation, %	Reduction of Area %
	Spray Quench					
Air Cool	Mid Thick	Quarter Thick				
			As Cooled			
	.5	.6	55,600	82,800	28	72.0
	2.4	2.9	47,700	72,900	32	67.0
.25	5.5	6.5	40,900	70,400	34	66
1.9	~30	~30	42,400	67,000	33	65
			As Stress-Relieved, 1 Hr. 1150°F			
	.5	.6	51,600	74,100	30.5	71.5
	2.4	2.9	46,000	71,000	31	68.5
.25	5.5	6.5	39,400	68,300	34	67.5
1.9	~30	~30	42,000	66,200	31	67

TABLE V (Cont'd)

MECHANICAL PROPERTIES OF ASTM A-285 STEEL

Notch Toughness Properties

Plate Thickness - Inches Air Cool	Spray Quench Mid Thick	 Quarter Thick	15 ft-lb Transition Temperature, °F	15 mil Lateral Expansion Transition Temperature °F	50% Fibrous Fracture Transition Temperature °F
			As Cooled		
	.5	.6	+15	+ 5	+ 65
	2.4	2.9	+15	- 5	+ 65
.25	5.5	6.5	+35	+10	+105
1.9	∼30	∼30	+25	+10	+ 80
			As Stress-Relieved, 1 Hr., 1150°F		
	.5	.6	0	-15	+ 60
	2.4	2.9	+0	- 5	+ 65
.25	5.5	6.5	+40	+10	+100
1.9	∼30	∼30	+35	+15	+ 90

TABLE VI

MECHANICAL PROPERTIES OF ASTM A-212 STEEL

Tensile Properties

Plate Thickness - Inches			Yield Strength 0.2% psi	Tensile Strength psi	Elongation, %	Reduction of Area %
	Spray Quench					
Air Cool	Mid Thick	Quarter Thick				
			As Cooled			
	.5	.6	69,000	92,800	28.5	63.0
	2.4	2.9	59,200	85,600	29.5	62
.25	5.5	6.5	51,900	79,300	30.5	60.5
1.9	~30	~30	51,000	77,800	30.5	58
			As Stress Relieved, 1 Hr., 1150°F			
	.5	.6	60,700	87,800	28	67.0
	2.4	2.9	53,400	81,600	29.5	61.0
.25	5.5	6.5	50,900	76,600	30	61.0
1.9	~30	~30	48,700	77,200	29.5	57.5

TABLE VI (Cont'd)

MECHANICAL PROPERTIES OF
ASTM A-212 STEEL

Notch Toughness Properties

Plate Thickness - Inches			15 ft-lb Transition Temperature, °F	15 mil Lateral Expansion Transition Temperature °F	50% Fibrous Fracture Transition Temperature °F
	Spray Quench				
Air Cool	Mid Thick	Quarter Thick			
			As Cooled		
	.5	.6	-50	-45	-10
	2.4	2.9	-30	-35	+30
.25	5.5	6.5	-20	-30	+35
1.9	~30	~30	+10	0	+60
			As Stress Relieved, 1 Hr., 1150°F		
	.5	.6	-15	-20	+35
	2.4	2.9	- 5	-10	+25
.25	5.5	6.5	-10	-30	+50
1.9	~30	~30	+20	+10	+70

TABLE VII

MECHANICAL PROPERTIES OF ASTM A-203 STEEL

Tensile Properties

Plate Thickness - Inches			Yield Strength 0.2% psi	Tensile Strength psi	Elongation, %	Reduction of Area %
	Spray Quench					
Air Cool	Mid Thick	Quarter Thick				
			As Cooled			
	.5	.6	84,200	132,000	20	55
	2.4	2.9	63,900	103,000	27.5	67
.25	5.5	6.5	56,400	89,100	30	67
1.9	~30	~30	59,200	83,000	29	65
			As Stress Relieved, 1 Hr., 1150°F			
	.5	.6	74,600	90,900	27.5	75
	2.4	2.9	68,400	84,600	29.5	74
.25	5.5	6.5	65,400	81,100	30.5	72
1.9	~30	~30	62,400	78,500	32	70.5

TABLE VII (Cont'd)

MECHANICAL PROPERTIES OF
ASTM A-203 STEEL

Notch Toughness Properties

Plate Thickness - Inches			15 ft-lb Transition Temperature, °F	15 mil Lateral Expansion Transition Temperature °F	50% Fibrous Fracture Transition Temperature °F
	Spray Quench				
Air Cool	Mid Thick	Quarter Thick			
			As Cooled		
	.5	.6	-105	-65	-20
	2.4	2.9	-125	-115	-34
.25	5.5	6.5	-130	-150	-34
1.9	~30	~30	-130	-125	-48
			As Stress Relieved, 1 Hr., 1150°F		
	.5	.6	-205	-180	-95
	2.4	2.9	-170	-160	-70
.25	5.5	6.5	-180	-185	-65
1.9	~30	~30	-130	-130	-40

TABLE VIII

MECHANICAL PROPERTIES OF ASTM A-302 STEEL

Tensile Properties

Plate Thickness - Inches			Yield Strength 0.2% psi	Tensile Strength psi	Elongation, %	Reduction of Area %
	Spray Quench					
Air Cool	Mid Thick	Quarter Thick				
			As Cooled			
	.5	.6	100,000	149,000	13.5	49
	2.4	2.9	71,700	117,000	22.5	56.5
.25	5.5	6.5	74,400	110,900	19.5	56.5
1.9	~30	~30	54,800	94,200	24.0	56
			As Stress-Relieved, 1 Hr. 1150°F			
	.5	.6	87,600	106,000	21.0	63.5
	2.4	2.9	79,800	98,600	22.0	62.5
.25	5.5	6.5	83,700	100,300	20	53.5
1.9	~30	~30	66,400	85,700	27.0	63.0

TABLE VIII (Cont'd)

MECHANICAL PROPERTIES OF ASTM A-302 STEEL

Notch Toughness Properties

Plate Thickness - Inches			15 ft-lb Transition Temperature, °F	15 mil Lateral Expansion Transition Temperature °F	50% Fibrous Fracture Transition Temperature °F
	Spray Quench				
Air Cool	Mid Thick	Quarter Thick			
			As Cooled		
	.5	.6	+55	+110	+90
	2.4	2.9	+15	+ 25	+65
.25	5.5	6.5	0	0	+40
1.9	~30	~30	-10	- 15	+20
			As Stress-Relieved, 1 Hr. 1150°F		
	.5	.6	-85	- 80	-60
	2.4	2.9	-60	- 55	-35
.25	5.5	6.5	-65	- 65	-50
1.9	~30	~30	-60	- 60	-20

TABLE IX

MECHANICAL PROPERTIES OF HY 80 STEEL

Tensile Properties

Plate Thickness - Inches			Yield Strength 0.2% psi	Tensile Strength psi	Elongation, %	Reduction of Area %
	Spray Quench					
Air Cool	Mid Thick	Quarter Thick				
			As Cooled			
	.5	.6	134,000	189,000	16	61
	2.4	2.9	122,000	177,000	16	61
.25	5.5	6.5	111,700	167,200	17	59
1.9	30	30	96,000	154,000	18	55.5
			As Stress-Relieved, 1 Hr. 1150°F			
	.5	.6	107,000	120,000	23	73
	2.4	2.9	107,000	120,000	22	75
.25	5.5	6.5	110,000	132,000	20	67.5
1.9	30	30	100,000	128,000	21	65

TABLE IX (Cont'd)

MECHANICAL PROPERTIES OF HY 80 STEEL

Notch Toughness Properties

Plate Thickness - Inches			15 ft-lb Transition Temperature, °F	15 mil Lateral Expansion Transition Temperature °F	50% Fibrous Fracture Transition Temperature °F
	Spray Quench				
Air Cool	Mid Thick	Quarter Thick			
			As Cooled		
	.5	.6	-250	-70	- 60
	2.4	2.9	-250	-80	- 60
.25	5.5	6.5	-110	-40	+ 35
1.9	30	30	- 15	+30	+100
			As Stress-Relieved, 1 Hr. 1150°F		
	.5	.6	-270	-240	-175
	2.4	2.9	-275	-230	-165
.25	5.5	6.5	-230	-195	- 45
1.9	30	30	-140	- 75	+ 40

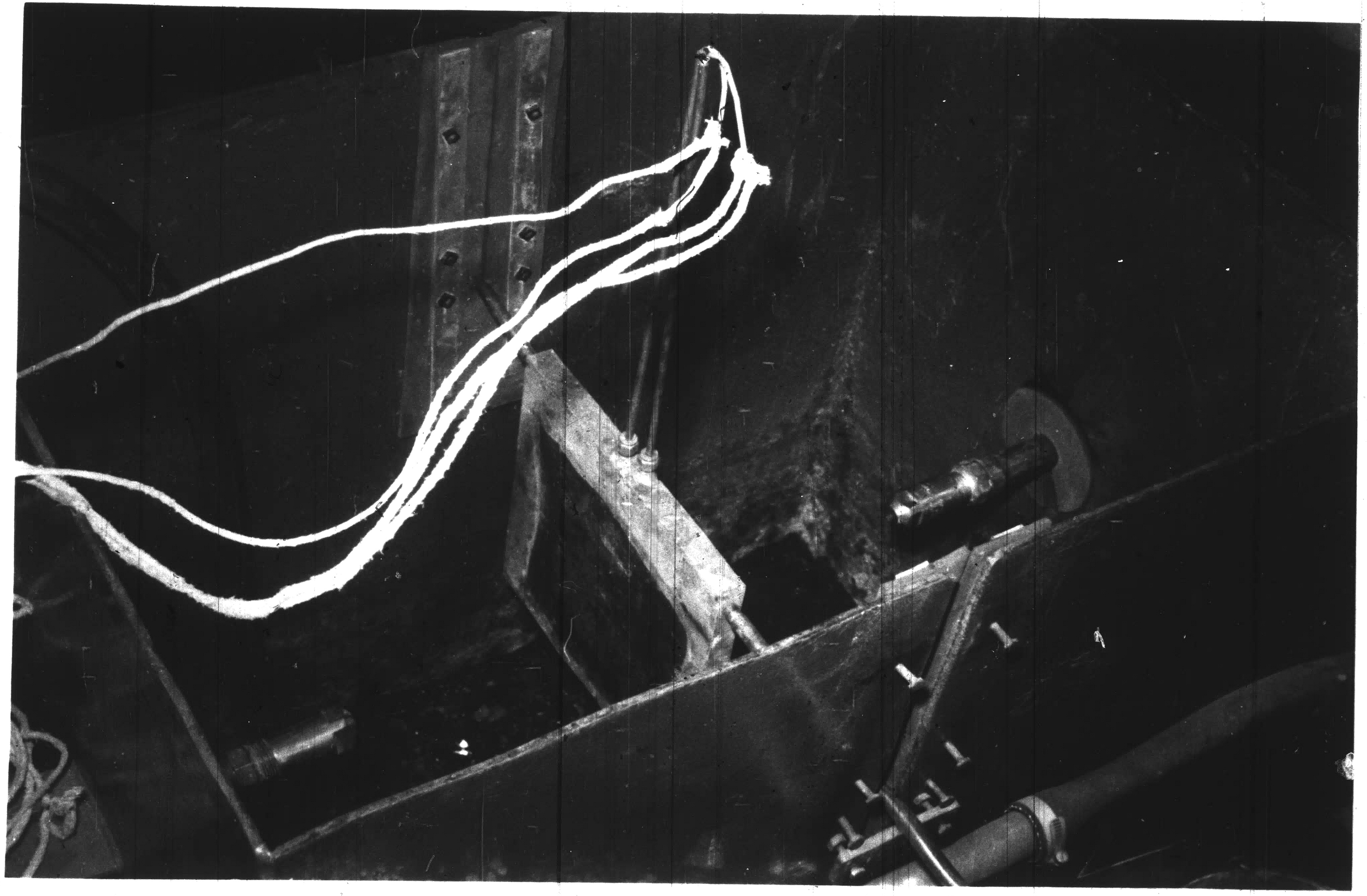
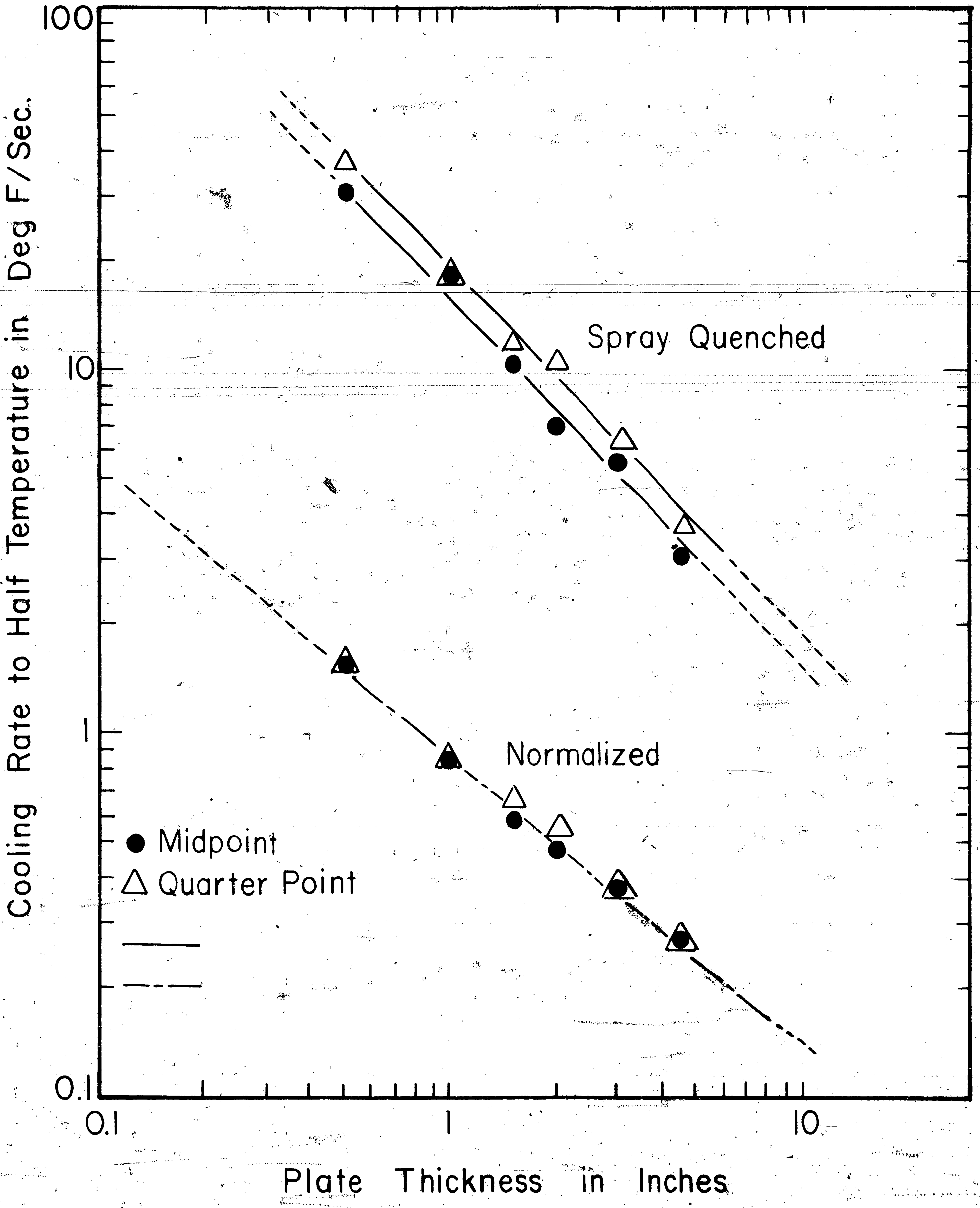


Figure 1 Apparatus for Spray-Quenching 12 inch by 12 inch Plates at Commercial Flow Rates.

Figure 2

Half-Temperature Cooling Rates in Spray-Quenched and Normalized Plates Up to 10 Inches Thick.



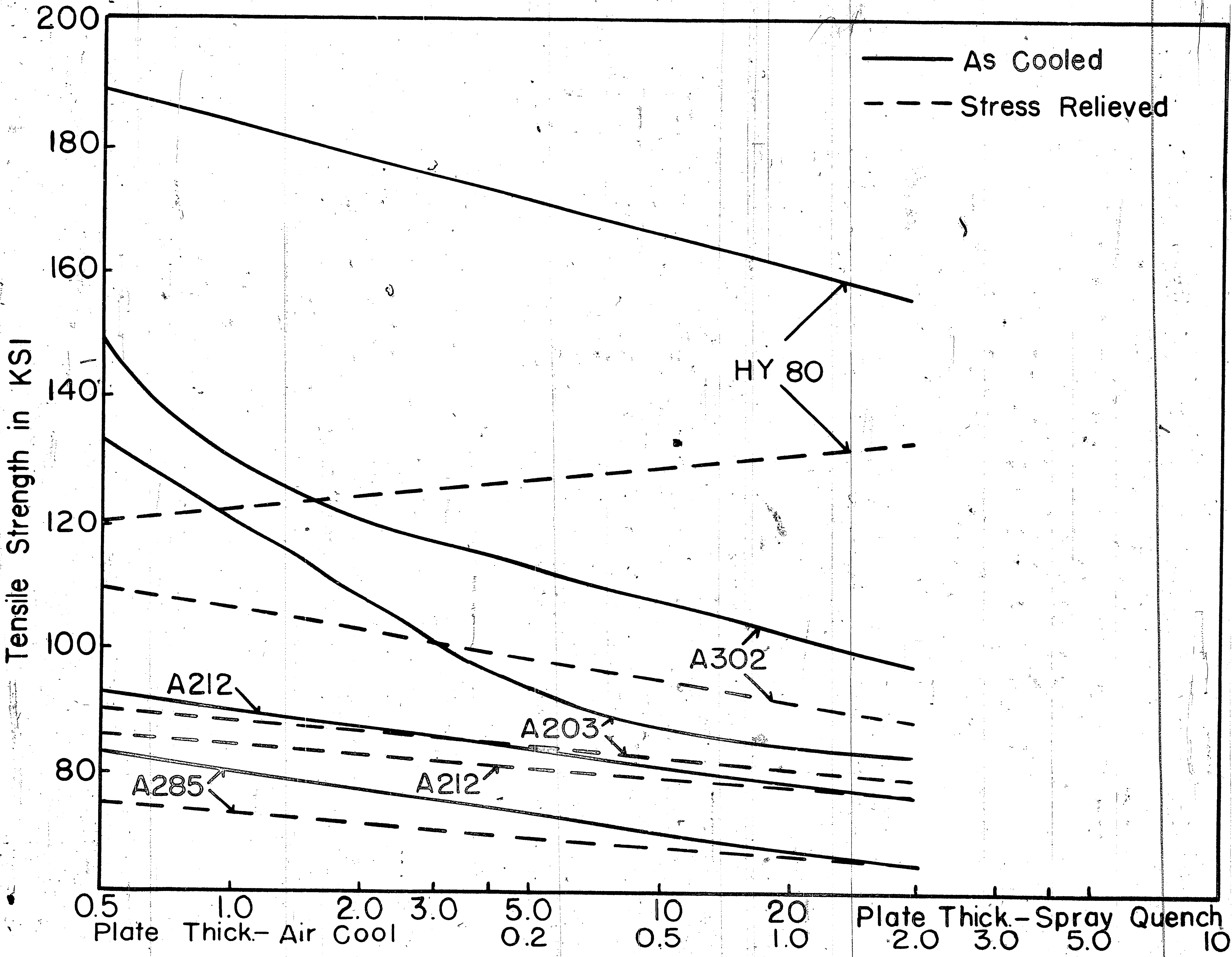


Figure 3 Effect of Plate Thickness on the Tensile Strength of Five Pressure Vessel Steels

Figure 4 Effect of Plate Thickness on the Yield Strength of Five Pressure Vessel Steels

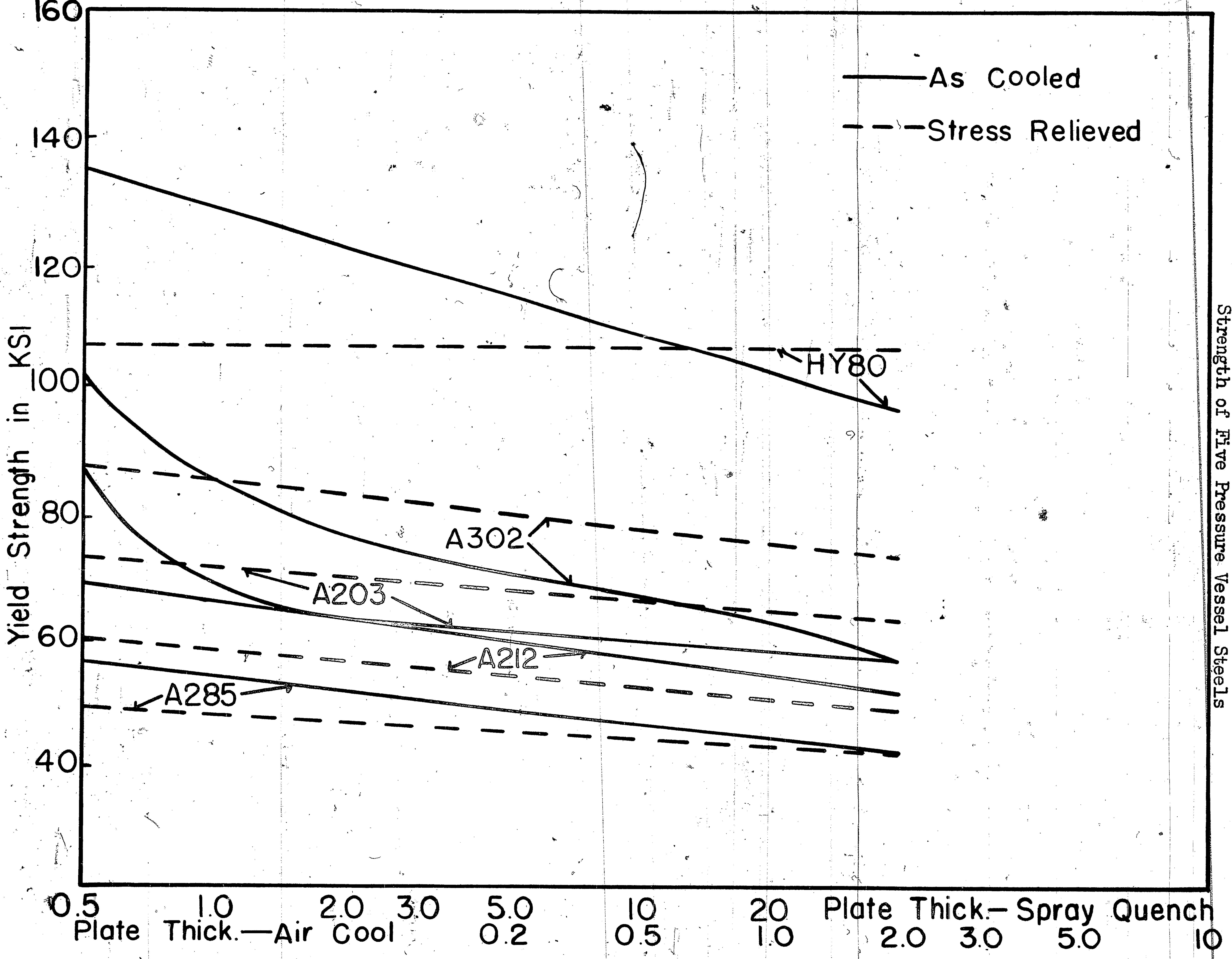
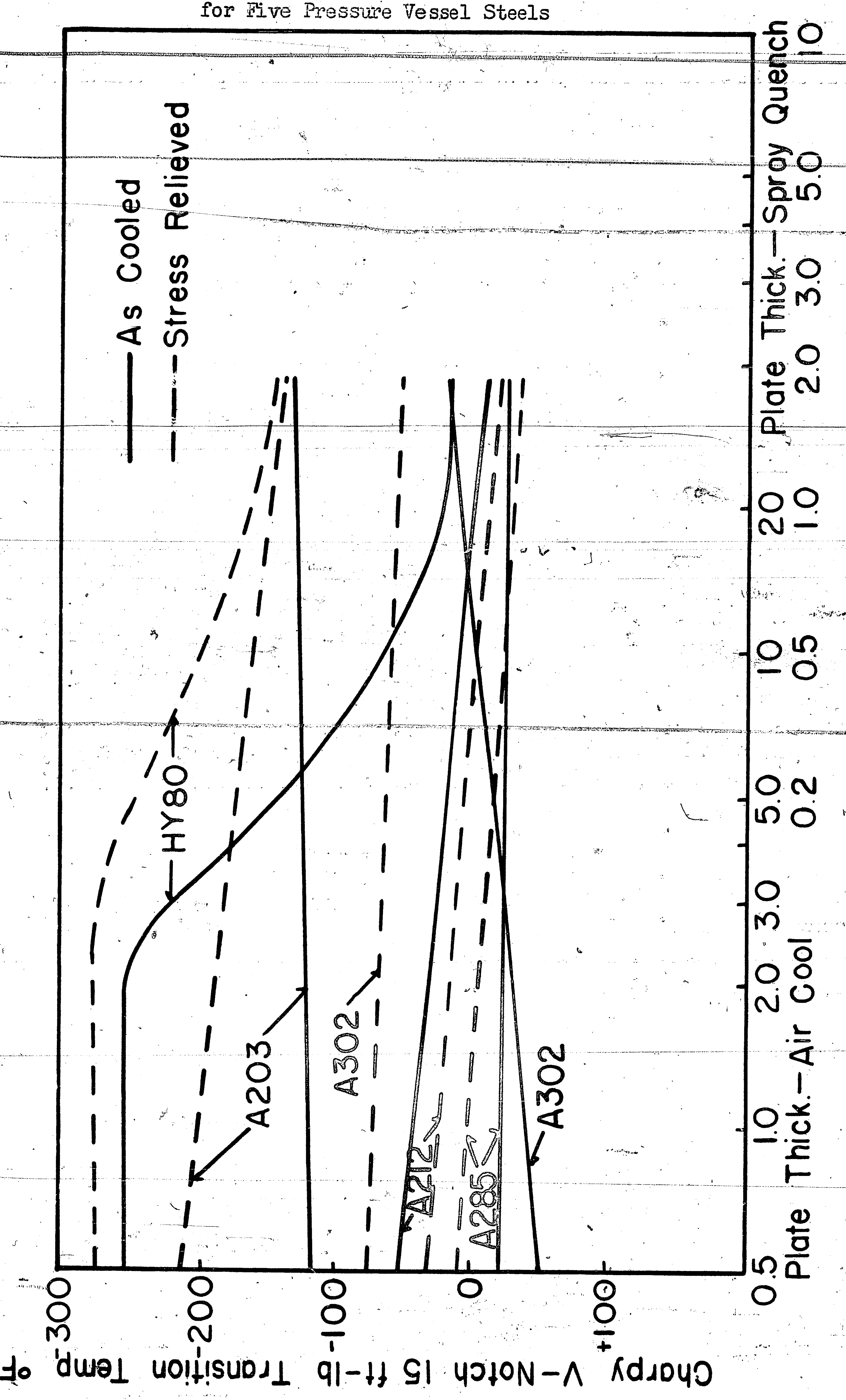


Figure 5 Effect of Plate Thickness on the 15 ft-lb Charpy V-Notch Transition Temperature for Five Pressure Vessel Steels



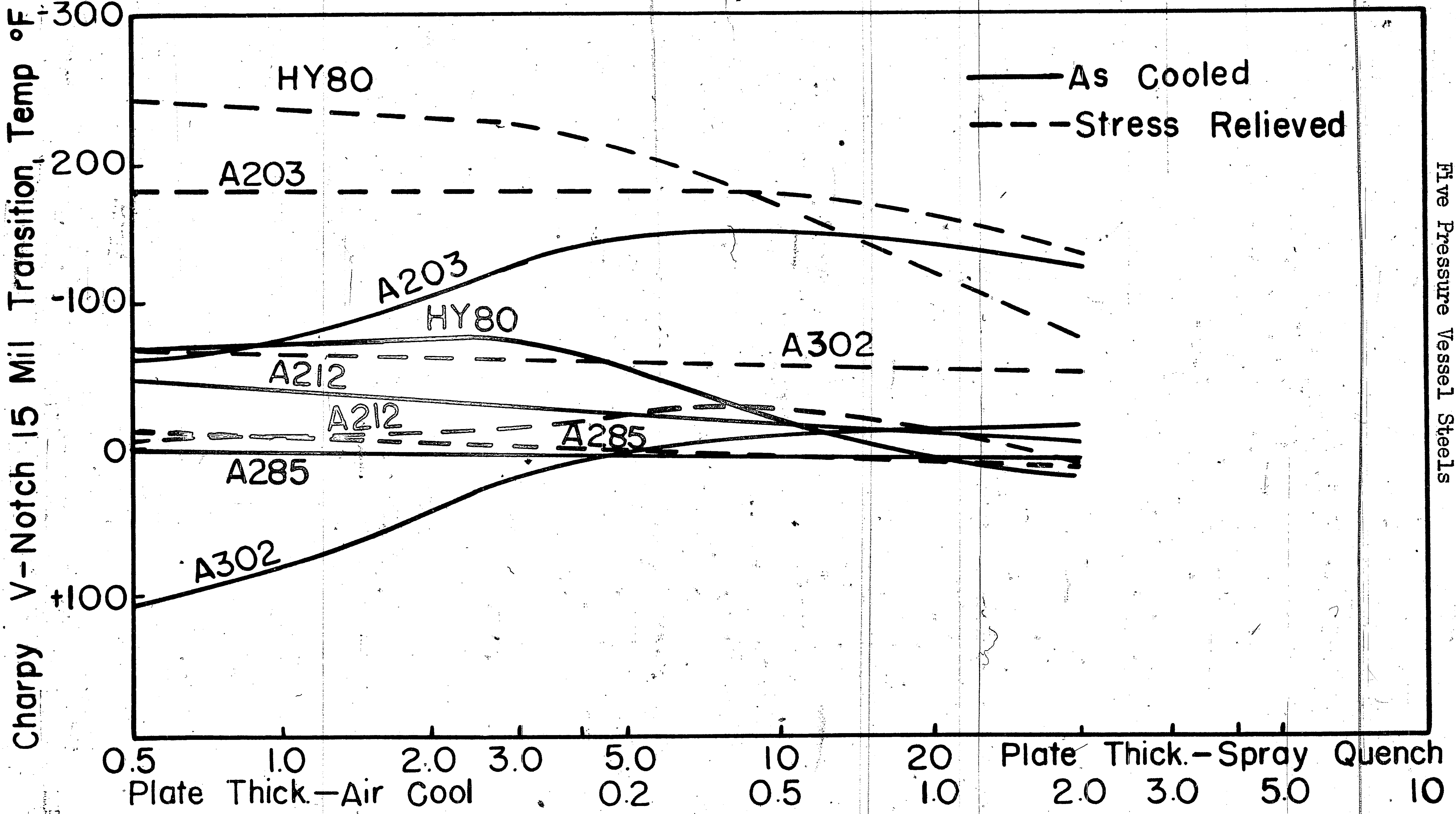


Figure 6 Effect of Plate Thickness on the 15 Mil Charpy V-Notch Transition Temperature for Five Pressure Vessel Steels

APPENDIX I

Derivation of a General Equation for Determining the Cooling Rate, in Air, For Various Plate Thicknesses.

Air Cool

x	y	log x	log y	y calc.	% dev.
.5	1.5	-.30103	.17609	1.496	.267
1.	.84	0	-.07572	.8519	1.42
1.5	.62	.17609	-.20761	.6127	1.18
2	.51	.30103	-.29243	.485	4.9
3	.32	.47712	-.49485	.3488	9.0
4.5	.65321	-.65321	-.58503	.2509	3.46

where x = plate thickness and y = cooling rate in °F/sec

$$y = ax^b$$

$$\log y = \log a + b \log x$$

$$.17609 = \log a + b\,(-.30103) \qquad -.29243 = \log a + b\,(.30103)$$

$$-.07572 = \log a + b\,(0) \qquad -.49485 = \log a + b\,(.47712)$$

$$-.02761 = \log a + b\,(.17609) \qquad -.58503 = \log a + b\,(.65321)$$

$$-.10724 = 3 \log a - .12494b \qquad -1.37231 = 3 \log a + 1.43136b$$

$$- .10724 = 3 \log a - .12494b$$

$$\underline{-1.37231 = 3 \log a + 1.43136b}$$

$$1.26507 = -1.55630b$$

$$b = -\frac{1.26507}{1.55630} = - .81287$$

$$-.10724 = 3 \log a - .12494\,(- .81287$$

$$-.10724 = 3 \log a + .10156$$

$$3 \log a = - .10156 - .10724$$

$$3 \log a = -.20880$$

$$\log a = -.06960 \qquad a = .8519$$

The observation equation becomes

$$y = .8519\, x^{-.81287}$$

$$\text{or } \log y = \log .8519 - .81287 \log x$$

$x = .5$

$$\log y = -.06960 - .81287\,(-.30103)$$

$$\log y = -.06960 + .24470$$

$$\log y = .17510$$

$$y = 1.496$$

$x = 1$

$$\log y = -.06960 - .81287\,(0)$$

$$\log y = -.06960$$

$$y = .8519$$

$x = 1.5$

$$\log y = -.06960 - .81287\,(.17609)$$

$$\log y = -.06960 - .14314$$

$$\log y = -.21274 \text{ or } 9.78726 - 10$$

$$y = .6127$$

$x = 2$

$$\log y = -.06960 - .81287\,(.30103)$$

$$\log y = .06960 - .24470$$

$$\log y = -.31430 \text{ or } 9.68570 - 10$$

$$y = .485$$

$x = 3$

$$\log y = -.06960 - .81287\,(.47712)$$

$$\log y = -.06960 - .38784$$

$$\log y = -.45744 \text{ or } 9.54256 - 10$$

$$y = .3488$$

$x = 4.5$ $\log y = -.06960 - .81287\ (.65321)$

$\log y = -.06960 - .53097$

$\log y = -.60057$ or $9.39943 - 10$

$y = .2509$

$x = 5$ $\log y = -.06960 - .81287\ (.69897)$

$\log y = -.06960 - .56871$

$\log y = -.63777$ or $9.36223 - 10$

$y = .2303$

$x = 6$ $\log y = -.06960 - .81287\ (.77815)$

$\log y = -.06960 - .63253$

$\log y = -.70213$ or $9.29787 - 10$

$y = .1985$

$x = 7$ $\log y = -.06960 - .81287\ (.84510)$

$\log y = -.06960 - .68697$

$\log y = -.75657$ or $9.24343 - 10$

$y = .1752$

$x = 8$ $\log y = -.06960 - .81287\ (.90309)$

$\log y = -.06960 - .73409$

$\log y = -.80369$ or $9.19631 - 10$

$y = .1571$

$x = 9$ $\log y = -.06960 - .81287\ (.95424)$

$\log y = -.06960 - .77567$

$\log y = -.84527$ or $9.15473 - 10$

$y = .1428$

x = 10 log y = -.06960 - .81287 (1)

log y = -.88247 or 9.11753 - 10

y = .1293

y	y calc.		% dev.
1.5	1.496	(1.5 - 1.496) = .004	-.267
.84	.8519	(.8519 - .84) = .0119	+1.42
.64	.6127	(.64 - .613) = .027	+4.22
.54	.485	(.54 - .485) = .055	+10.1
.32	.3488	(.32 - .349) = -.029	-9.06
.26	.2509	(.26 - .251) = .009	+3.46

BIBLIOGRAPHY

1. "Literature Survey of High Strength Steels," Subcommittee of Pressure Vessel Research Committee, The Welding Journal, May 1954, Vol. 33, P. 251s to 256s

2. Private Correspondence.

3. Stout, R.D., "Higher Strength Steels for Welded Structures," Welding Journal, July 1960, Vol. 39, P. 273s - 283s.

4. Gross, J. H., Kottcamp, E. H., Stout, R. D., "Effect of Heat Treatment on the Microstructure and Properties of Pressure Vessel Steels," Welding Journal, April 1958, Vol. 37, P. 160 s - 168s.

VITA

Domenic Andrew Canonico was born on January 18, 1930 in Chicago, Illinois. There he received his primary and secondary education, graduating from Crane Technical High School in June 1947. September of that year the author entered the Michigan College of Mining and Technology in Houghton, Michigan. In April of 1951, after satisfying the requirements for a Bachelor of Science degree in Metallurgical Engineering, he accepted a position in the magnesium foundry of the Aircraft Engine Division, Ford Motor Company in Chicago. On October 28, 1952 Domenic received a direct commission as a Second Lieutenant in the United States Air Force Reserve. He was ordered to active duty on January 1, 1953.

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