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Westinghouse Electric Corporation **Water Reactor Divisions**

Nuclear Technology Division

Box 355
Pittsburgh Pennsylvania 15230

September 18, 1980

NS-TMA-2312

Mr. James R. Miller, Chief
Special Projects Branch
Division of Project Management
U. S. Nuclear Regulatory Commission
Phillips Building
7920 Norfolk Avenue
Bethesda, Maryland 20014

Subject: Review of WCAP-9292

Dear Mr. Miller:

Enclosed are fifty (50) copies of responses to NRC questions on WCAP-9292 entitled "Dynamic Fracture Toughness of ASME SA 508 Class 2a and ASME SA 533 Grade A Class 2 Base and Heat Affected Zone Material and Applicable Weld Metals." The enclosed (non-proprietary) information is being provided in response to the Materials Engineering Branch request for additional information received via the July 25, 1979, letter from J. F. Stolz (NRC) to T. M. Anderson (Westinghouse).

Review of the enclosed documentation in the context of WCAP-9292 is requested. Furthermore, we request consideration of WCAP-9292 and this supplemental information in conjunction with specific safety analysis report references.

Very truly yours,

for T. M. Anderson, Manager
Nuclear Safety Department

CLG/TMA/jaw

Enclosure

cc: L. L. Kintner, 1L, 1A
R. M. Gamble, 1L, 1A

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120.0 MATERIALS ENGINEERING BRANCH

120.1 In the cover letter attached to Westinghouse Topical Report WCAP-9292 (letter C. Eicheldinger to J. F. Stolz, NS-CE-1730, dated March 17, 1978) it is stated that this report was submitted in support of nine licensing applications, as well as any future plants, using SA 508 Class 2a or SA 533 Grade A Class 2 steels in a pressure retaining component of the reactor coolant pressure boundary. Expand this list of plants to include (a) all operating plants, all plants currently under licensing review (CP or OL), and all standard NSSS designs (PDA or FDA), (b) the affected components, and (c) the specific location in the component (e.g., main coolant RV outlet nozzle, RV head flange, pressurizer manway) where the subject high strength steels have been, or will be, used.

Response: Table 120.1-1 identifies usages of SA 508 Class 2a and SA 533 Class 2 materials in primary pressure retaining applications by plant, component, and location in the component.

For future plants, including those referencing RESAR documents, SA 508 Class 2a and SA 533 Class 2 steels may be used in the following primary pressure retaining applications:

SA 508 Class 2a:	steam generator tubesheets steam generator support rings steam generator primary nozzles steam generator primary manways pressurizer nozzles pressurizer manways
SA 533 Class 2:	steam generator channel heads pressurizer heads pressurizer shells

TABLE 120.1-1

SA 508 Class 2a and SA 533 Class 2 Usages

STEAM GENERATOR

Plant (Docket Number)	SA 508 Class 2a				SA 533 Grade B Class 2
	Tubesheet	Primary Nozzle	Primary Manway	Support Ring	Channel Head (Dome)
Braidwood Unit 2 (50-457)	X				
Callaway Unit 2 (50-486)	X				
Catawba Unit 2 (50-414)	X				
Marble Hill Unit 2 (50-547)	X				
Millstone Unit 3 (50-423)	X				
Seabrook Unit 1 (50-443)	X				
Seabrook Unit 2 (50-444)	X				
South Texas Unit 1 (50-498)	X	X	X		X
South Texas Unit 2 (50-499)	X	X	X	X	X
Surry Unit 1 [Replacement] (50-280)	X				
Surry Unit 2 [Replacement] (50-281)	X				
Turkey Point Unit 1 [Replacement] (50-250)	X				
Turkey Point Unit 2 [Replacement] (50-251)	X				
Alvin W. Vogtle Unit 1 (50-424)	X				
Alvin W. Vogtle Unit 2 (50-425)	X				

TABLE 120.1-1

(Continued)

PRESSURIZER

Plant (Docket Number)	SA 508 Class 2a				SA 533 Grade A Class 2	
	Spray Nozzle	Surge Nozzle	Safety and Relief Nozzles	Manway	Shell	Heads
Beaver Valley Unit 2 (50-412)	X	X	X	X	X	X
Braidwood Unit 1 (50-456)	X	X	X	X	X	X
Braidwood Unit 2 (50-457)	X	X	X	X	X	X
Byron Unit 1 (50-454)	X	X	X	X	X	X
Byron Unit 2 (50-455)	X	X	X	X	X	X
Callaway Unit 1 (50-483)	X	X	X	X	X	X
Catawba Unit 1 (50-413)	X	X	X	X	X	X
Catawba Unit 2 (50-414)	X	X	X	X	X	X
Comanche Peak Unit 1 (50-445)	X	X	X	X	X	X
Comanche Peak Unit 2 (50-446)	X	X	X	X	X	X
Donald C. Cook Unit 2 (50-315)					X	X
Diablo Canyon Unit 2 (50-323)					X	X
Joseph M. Farley Unit 1 (50-348)					X	X
Joseph M. Farley Unit 2 (50-364)			X		X	X
Marble Hill Unit 1 (50-546)	X	X	X	X	X	X
Marble Hill Unit 2 (50-547)	X	X	X	X	X	X
William B. McGuire Unit 1 (50-369)					X	X
William B. McGuire Unit 2 (50-370)					X	X
Millstone Unit 3 (50-423)	X	X	X	X	X	X

TABLE 120.1-1

(Continued)

PRESSURIZER (CONTINUED)

Plant (Docket Number)	SA 508 Class 2a				SA 533 Grade A Class 2	
	Spray Nozzle	Surge Nozzle	Safety and Relief Nozzles	Manway	Shell	Heads
North Anna Unit 1 (50-338)					X	X
North Anna Unit 2 (50-339)					X	X
Seabrook Unit 1 (50-443)	X	X	X	X	X	X
Seabrook Unit 2 (50-444)	X	X	X	X	X	X
Sequoyah Unit 1 (50-327)					X	X
Sequoyah Unit 2 (50-328)					X	X
Shearon Harris Unit 1 (50-400)					X	X
Shearon Harris Unit 2 (50-401)	X	X	X	X	X	X
South Texas Unit 1 (50-498)	X	X	X	X	X	X
South Texas Unit 2 (50-499)	X	X	X	X	X	X
Virgil C. Summer (50-395)					X	X
Trojan (50-344)					X	X
Alvin W. Vogtle Unit 1 (50-424)	X	X	X	X	X	X
Alvin W. Vogtle Unit 2 (50-425)	X	X	X	X	X	X
Watts Bar Unit 1 (50-390)					X	X
Watts Bar Unit 2 (50-391)					X	X
Wolf Creek (50-482)	X	X	X	X	X	X
Zion Unit 2 (50-304)					X	X

120.2 (a) Present the details of typical material histories for the subject steels. The histories should include the as received metallurgical condition and all significant fabrication steps (e.g., type and degree of working, heat treatment time and temperature, welding process description, final product dimensions). Confirm that the steels will be used in the above stated conditions in all applications. If there are exceptions indicate what the exceptions are and what operating plants or plants under construction are affected.

(b) Present the details of the test specimen history for the subject steels. The history should include specimen origin (material, form, size and metallurgical condition), location and orientation of the specimens in the original product, degree of working, and heat treatment time and temperature.

Response: (a) SA 508 Class 2a forgings and SA 533 Class 2 plates are received in the quenched and tempered condition; these base materials have a specified minimum tempering temperature of 1175°F.

SA 508 Class 2a

Typical as received metallurgical conditions for SA 508 Class 2a forgings are presented below; this information has been extracted from actual material certifications for production materials and is considered to be representative.

Component Part	Heat Treatment
Steam Generator Tubesheet	Heated to 1590° ± 10°F, held 18 hr. and water quenched; tempered 1190° ± 10°F and held 18 hr.
Steam Generator Support Ring	Heated to 1575°F, held 16 hr. and water quenched; tempered 1180°F and held 20 hr.
	Heated to 1590° ± 10°F, held 8.5 hr. and water quenched; tempered 1250°F and held 13 hr.

Steam Generator Primary Nozzle	Heated to 1640°F, held 9 hr. and water quenched; tempered 1280°F and held 11 hr.
Steam Generator and Pressurizer Manways	Heated to 1560° ± 25°F, held 7.5 hr. and water quenched; tempered 1250° ± 25°F and held 7 hr.
	Heated to 1560° ± 15°F, held 12 hr. and water quenched; tempered $1180^{\circ}\,{}^{+15^{\circ}}_{-\ 5^{\circ}}$F and held 12 hr.
Pressurizer Nozzles	Heated to 1580° ± 10°F, held 2 hr. and water quenched; tempered 1240° ± 10°F and held 3 hr.

The production forgings (represented by WCAP-9292) encompass a complete range of thicknesses and degree of working [i.e., from tubesheets (approximately 24 inches) to small nozzles (weld end of approximately 1-1/2 inches)].

<u>SA 533 Grade A Class 2</u>

Typical as received metallurgical conditions for SA 533 Grade A Class 2 plates are presented in Table 3-2 of WCAP-9292. It should be noted that the SA 533 Grade A Class 2 test specimens were taken from actual production material; therefore, the as received conditions given in Table 3-2 of WCAP-9292 are considered to be representative.

During fabrication, SA 533 Grade A Class 2 plate material used for shells is shaped by cold forming to the shell curvature prior to welding.

SA 533 Grade B Class 2

A typical as received metallurgical condition for SA 533 Grade B Class 2 plates is presented below; this information has been extracted from actual material certifications for production materials and is considered to be representative.

Component Part	Heat Treatment
Steam Generator Channel Head	Heated to 1625°F/1675°F, held 1 hr. per inch thickness (minimum) and water quenched; tempered 1190°F and held 1 hr. per inch thickness (minimum).

All welding of these base materials is performed in accordance with ASME qualified procedures using:

- Submerged Arc Welding with ASME SFA 5.17 type EH-14 modified weld wire and Linde 0091 flux.
- Shielded Metal Arc Welding with ASME SFA 5.5 type E-9018-M electrodes.

The anticipated post-weld heat treatments (PWHT) for the primary pressure retaining weldments (of various thicknesses) range from 3 to 30 (accumulated) hours at 1125°F in accordance with the ASME Code requirements. The most typical PWHT is 10-15 hours at 1125°F or 15-18 hours at 1000°F.

Final dimensions are supplied to each customer via "as built drawings." Typical product dimensions of the steam generator tubesheet, support ring, primary nozzle, primary manway, channel head, and the pressurizer nozzles, manway, head, and shell are shown in Figures 120.2-1 through 120.2-10, respectively.

(b) The metallurgical conditions of the SA 508 Class 2a and SA 533 Grade A Class 2 test specimens are given in Tables 2-1 and 3-2 of WCAP-9292, respectively.

To represent the large range of thicknesses [noted in part (a)], SA 508 Class 2a test forgings were obtained from two of the vendors, which supply production forgings; the test forging thickness selected was 4 inches. The forged SA 508 Class 2a base plates measured 4x12x36 inches. The test specimen layouts for the SA 508 Class 2a base material and heat affected zone (HAZ) material are shown in Figures 120.2-11 and 120.2-12, respectively.

As stated in part (a), the SA 533 Grade A Class 2 test material was obtained from actual production material. The four SA 533 Grade A Class 2 base plates measured approximately 3.7x114x285 inches. The SA 533 Grade A Class specimens were oriented in the L-T orientation, as defined by ASTM E-399. The test specimen layouts for the SA 533 Grade A Class 2 base material and HAZ material/weld metal are shown in Figures 120.2-13 and 120.2-14, respectively.

As stated in WCAP-9292, the PWHT times on the weldments tested were 3/3.5 hours at 1125°F. Subsequent to submittal of WCAP-9292 to the NRC and in order to encompass the anticipated production PWHT ranges, Westinghouse has further investigated the effect of PWHT time and temperature on fracture toughness properties. Specifically, dynamic fracture toughness testing was performed on SA 508 Class 2a and SA 533 Grade B Class 2 steels, which have been subjected to one of the three following long time post-weld type stress relief heat treatments:

48 hours at 1000°F
24 hours at 1125°F
48 hours at 1125°F

The results of this testing are presented in Appendix A; all of the dynamic fracture toughness values exceed the ASME specified minimum reference toughness K_{IR} curve. The testing documented in WCAP-9292 and Appendix A considers (and exceeds) the PWHT ranges anticipated during production.

FIGURE 120.2-1

Steam Generator Tubesheet

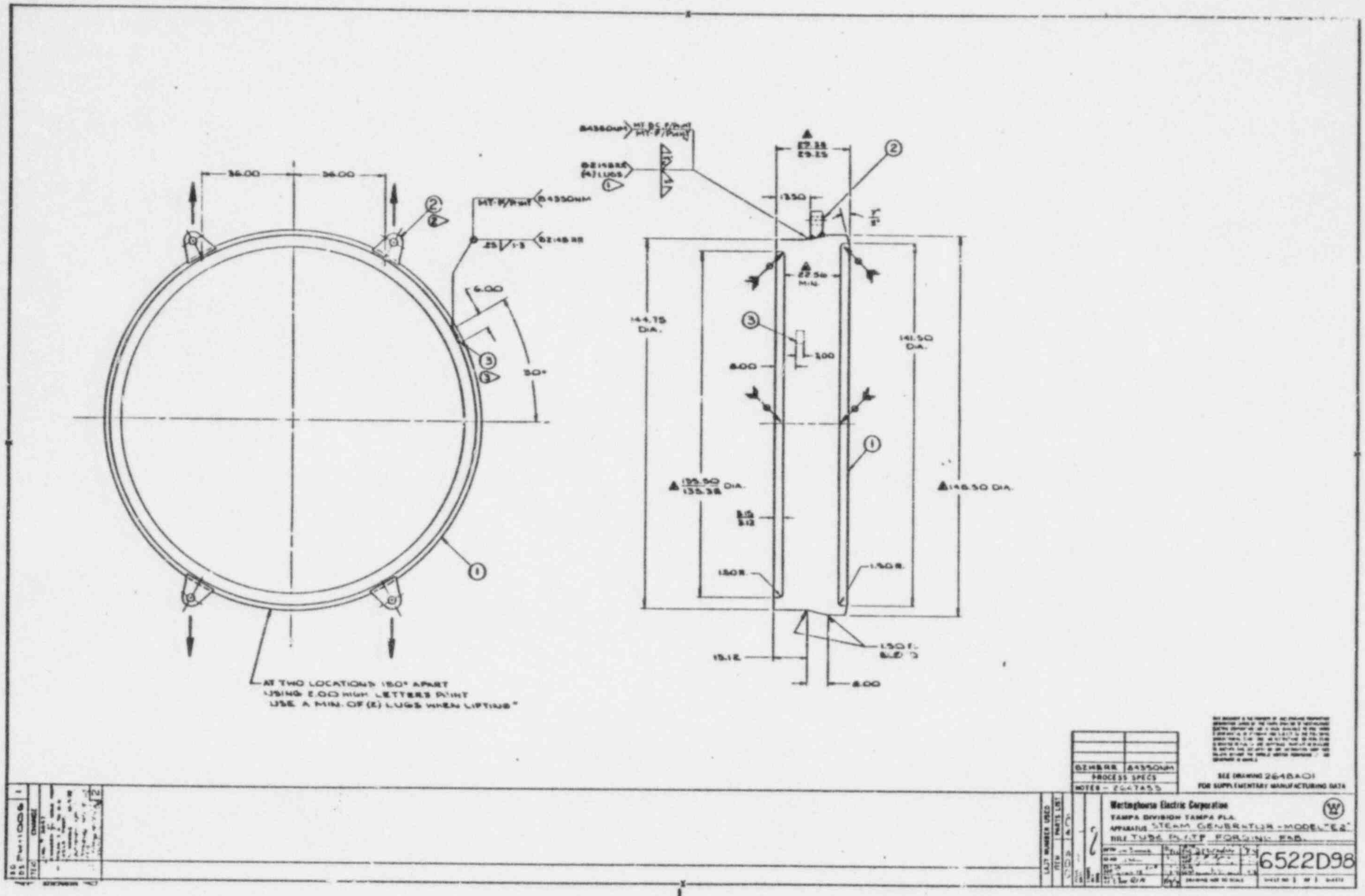


FIGURE 120.2-2

Steam Generator Support Ring

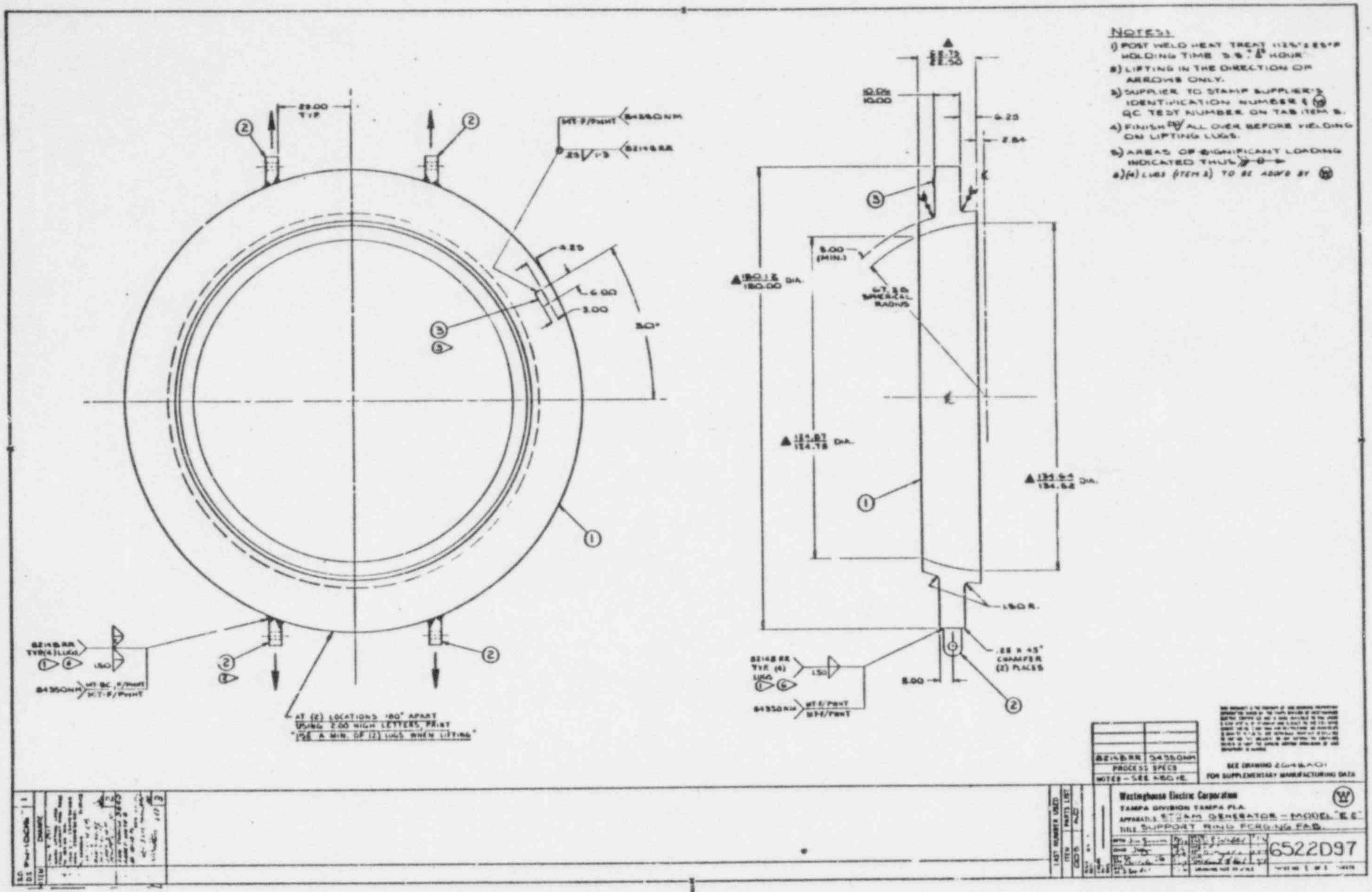


FIGURE 120.2-3

Steam Generator Primary Nozzle

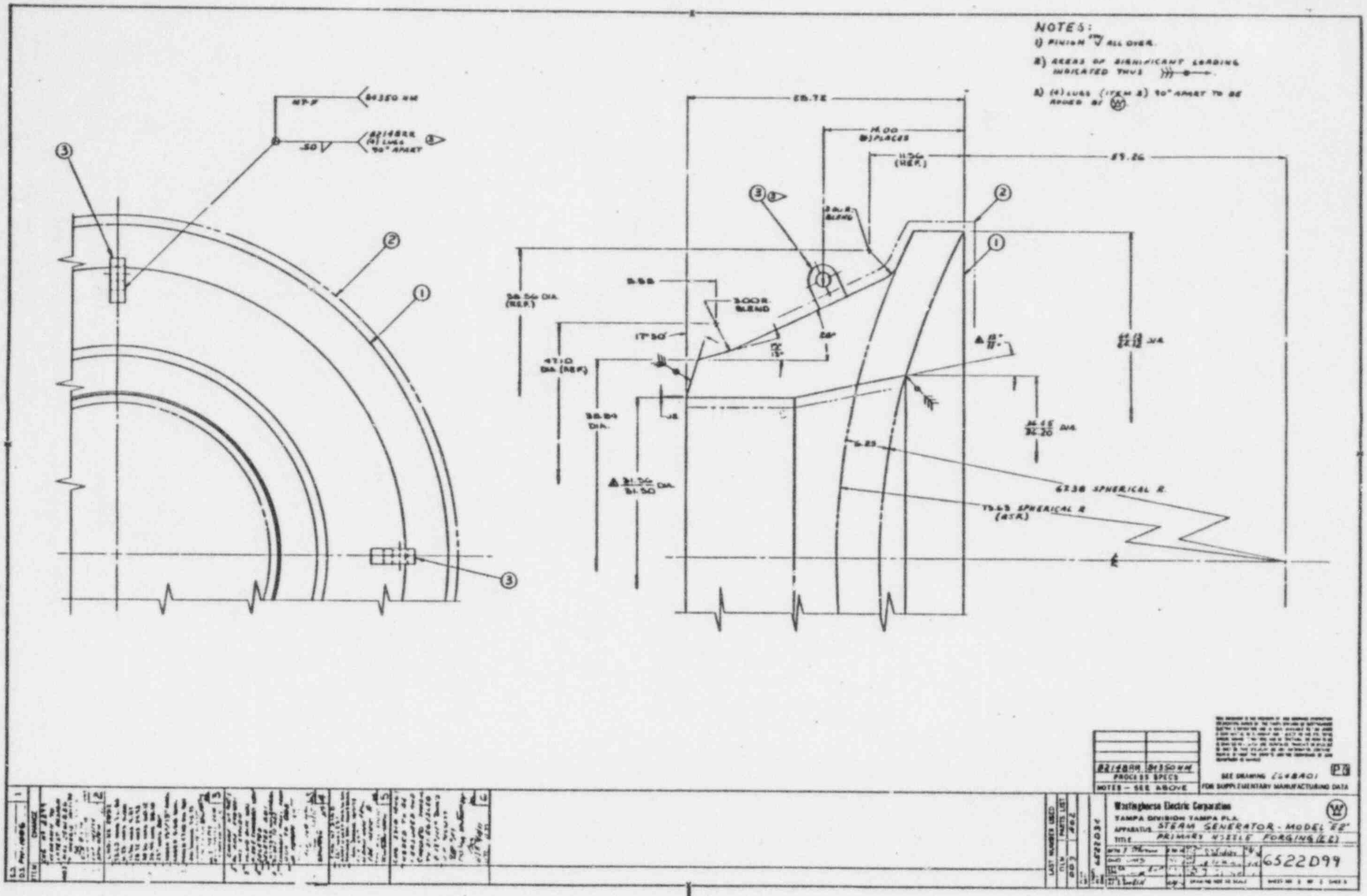


FIGURE 120.2-4

Steam Generator Primary Manway

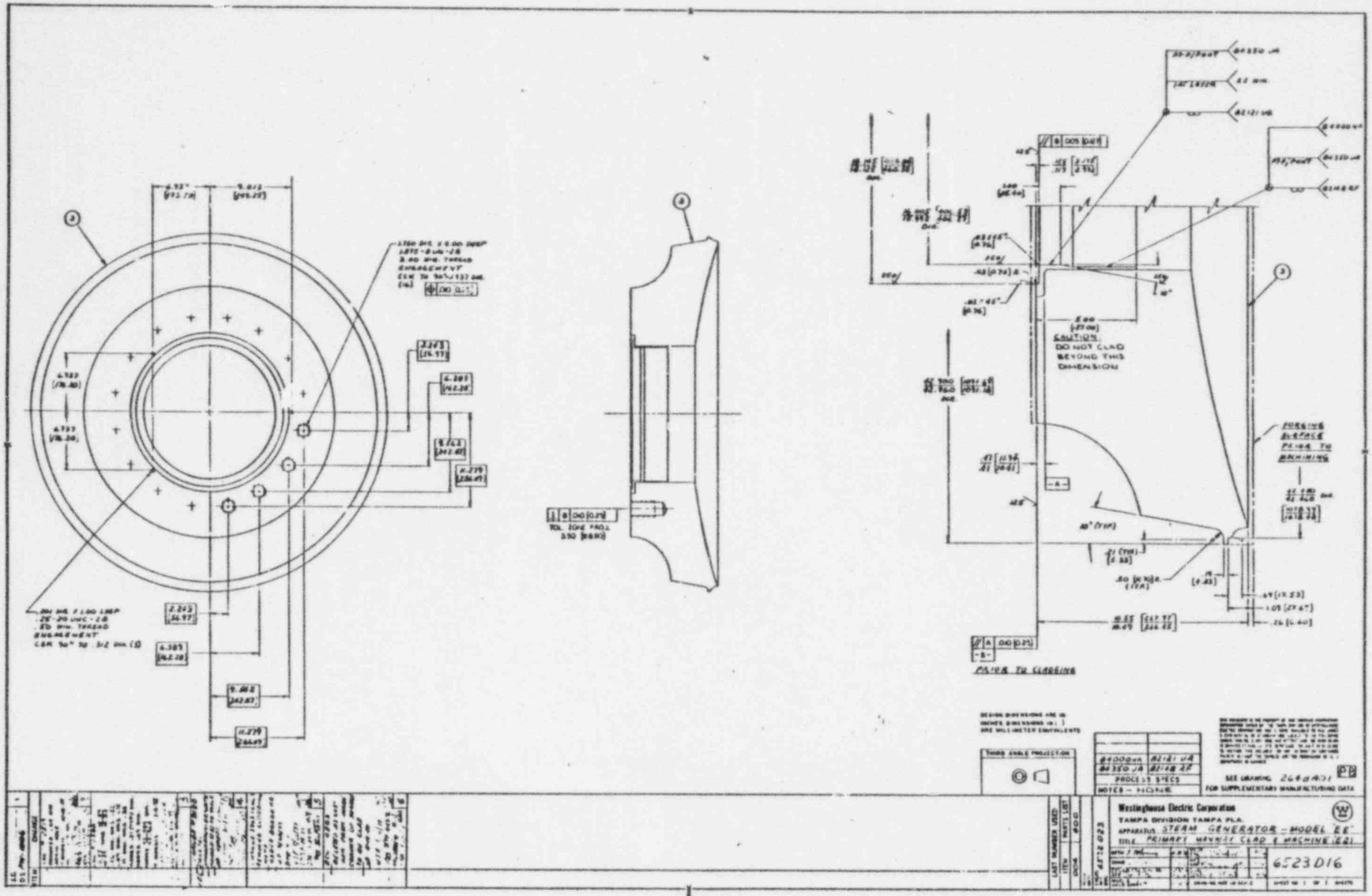


FIGURE 120.2-5

Steam Generator Channel Head

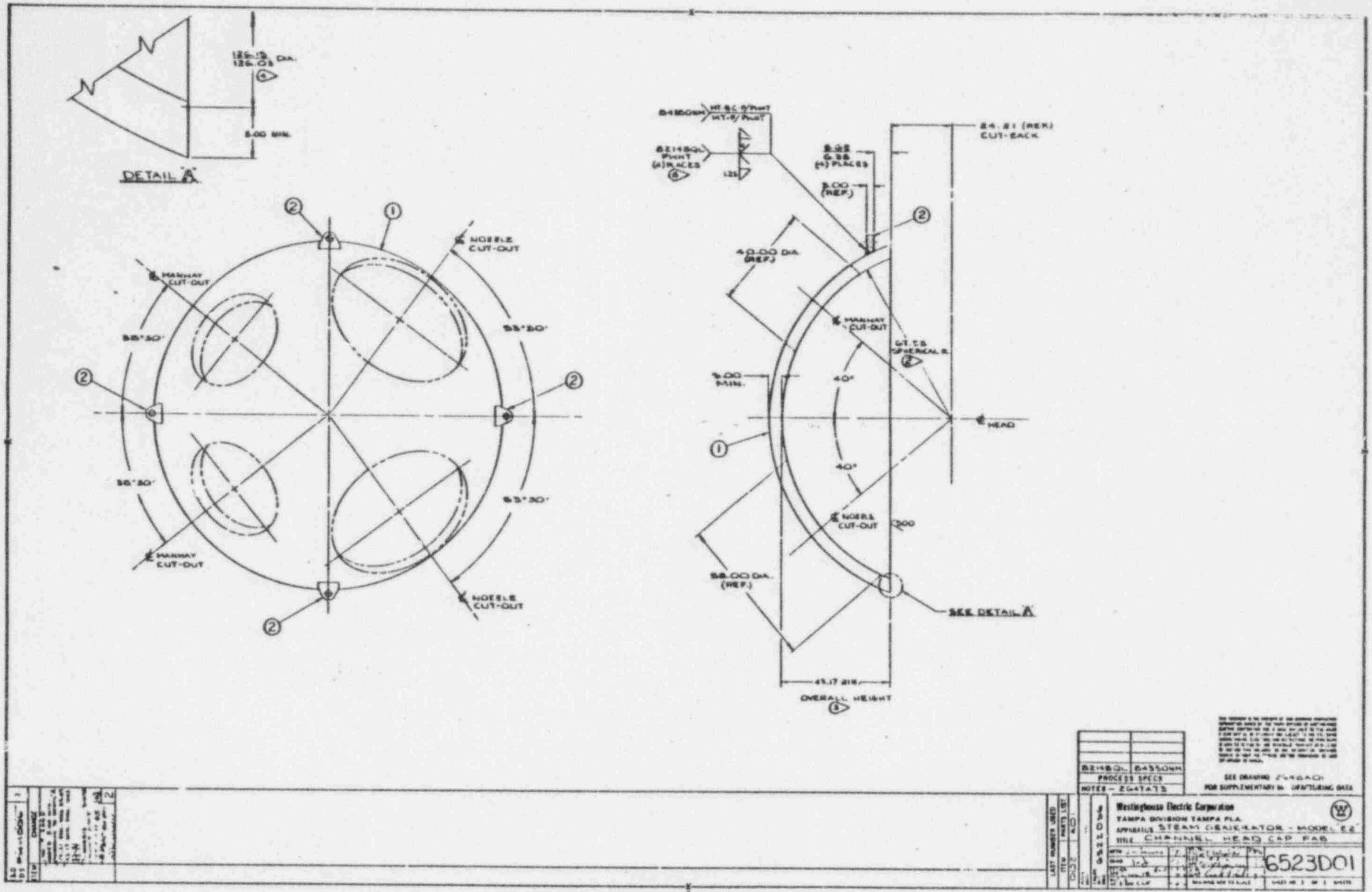
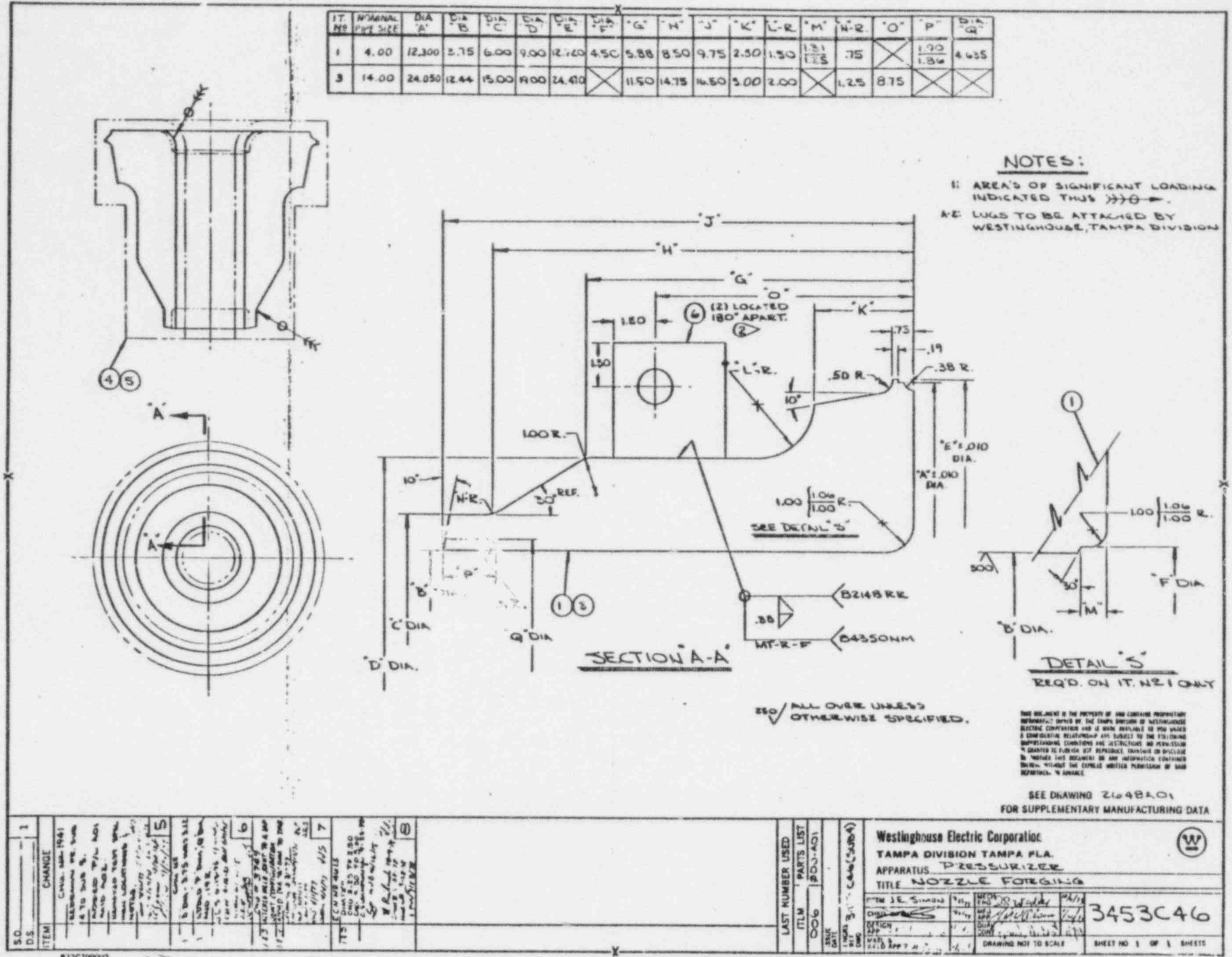


FIGURE 120.2-6

Pressurizer Nozzle



IT. NO	NOMINAL PIPE SIZE	DIA "A"	DIA "B"	DIA "C"	DIA "D"	DIA "E"	DIA "F"	"G"	"H"	"J"	"K"	"L"-R	"M"	"N"-R	"O"	"P"	DIA "Q"
1	4.00	12.300	3.75	6.00	9.00	12.720	4.50	5.88	8.50	9.75	2.50	1.50	1.31 1.25	.75	☒	1.90 1.86	4.635
3	14.00	24.050	12.44	15.00	19.00	24.410	☒	11.50	14.75	16.50	3.00	2.00	☒	1.25	8.75	☒	☒

NOTES:

1: AREA'S OF SIGNIFICANT LOADING INDICATED THUS

A-E: LUGS TO BE ATTACHED BY WESTINGHOUSE, TAMPA DIVISION

250 ALL OVER UNLESS OTHERWISE SPECIFIED.

SEE DRAWING 2648A01 FOR SUPPLEMENTARY MANUFACTURING DATA

FIGURE 120.2-7

Pressurizer Nozzle

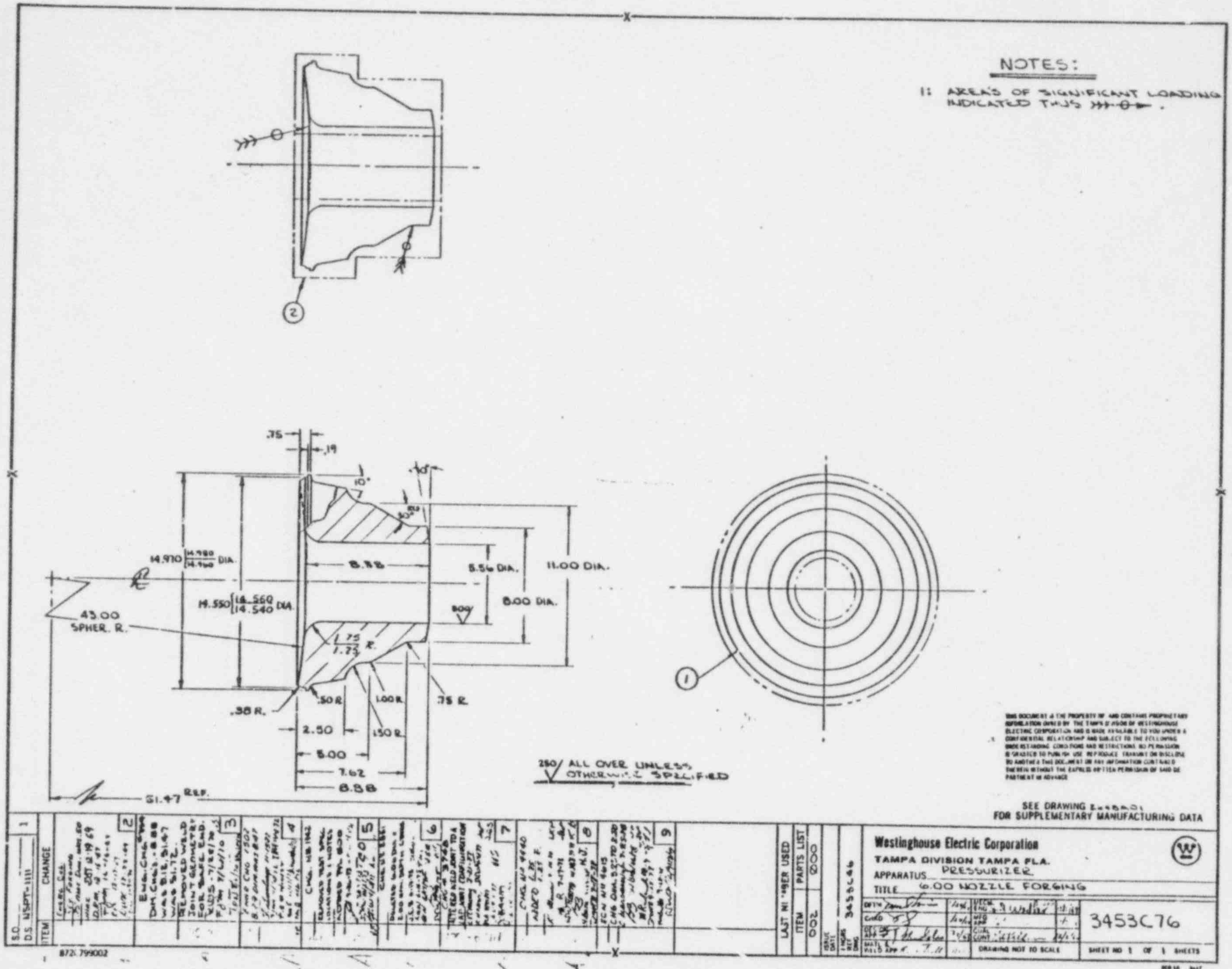


FIGURE 120.2-8

Pressurizer Manway

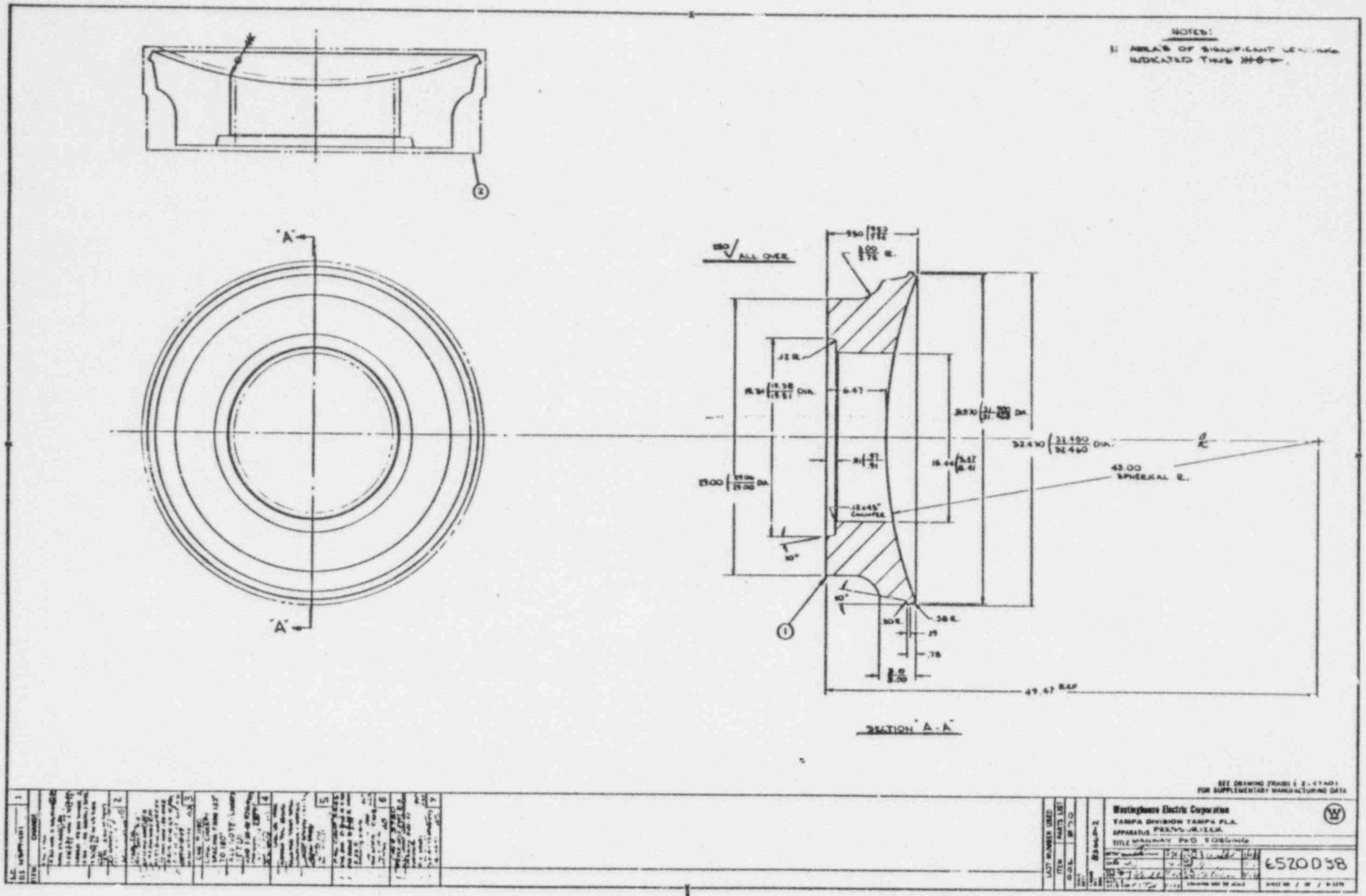
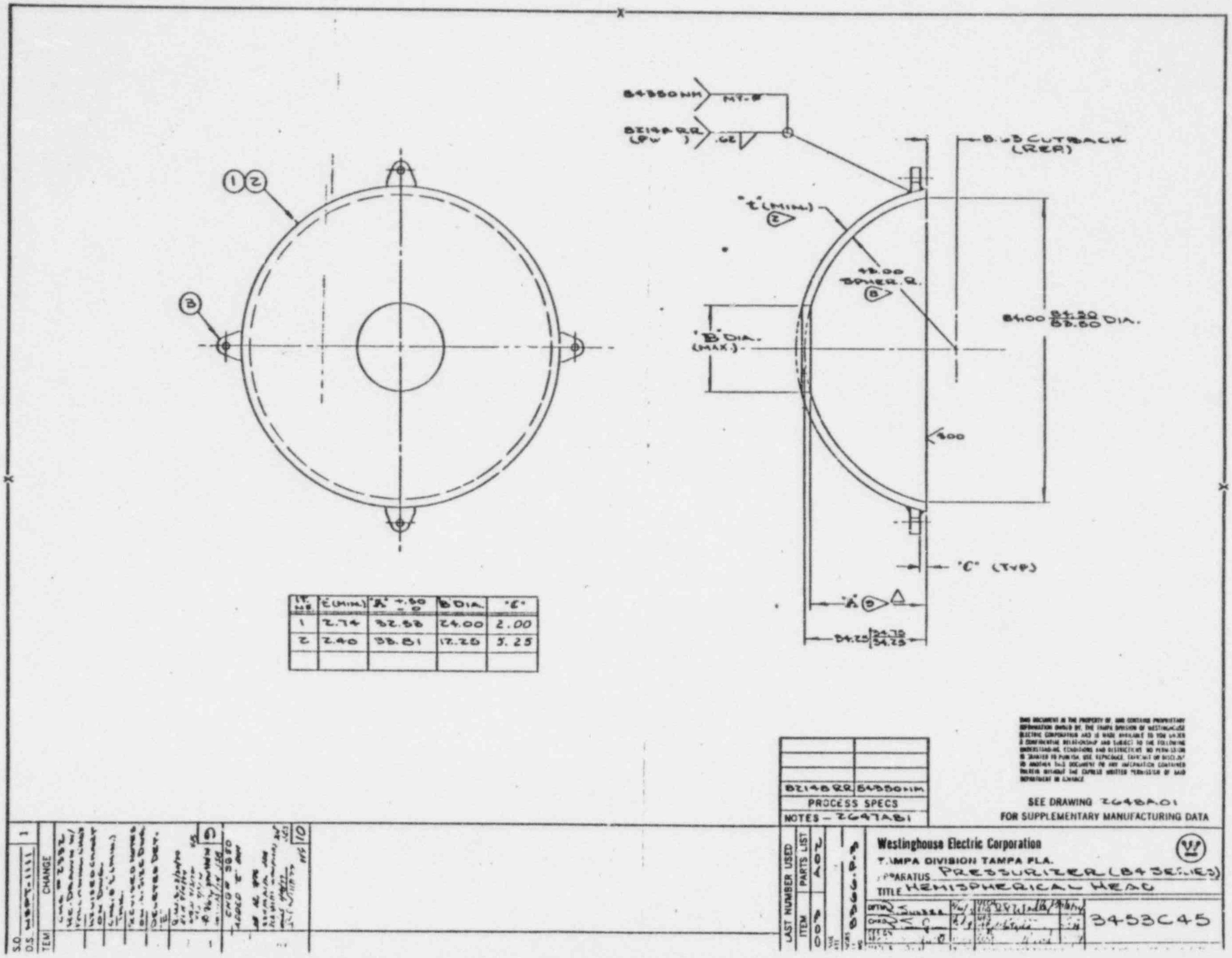


FIGURE 120.2-9

Pressurizer Head

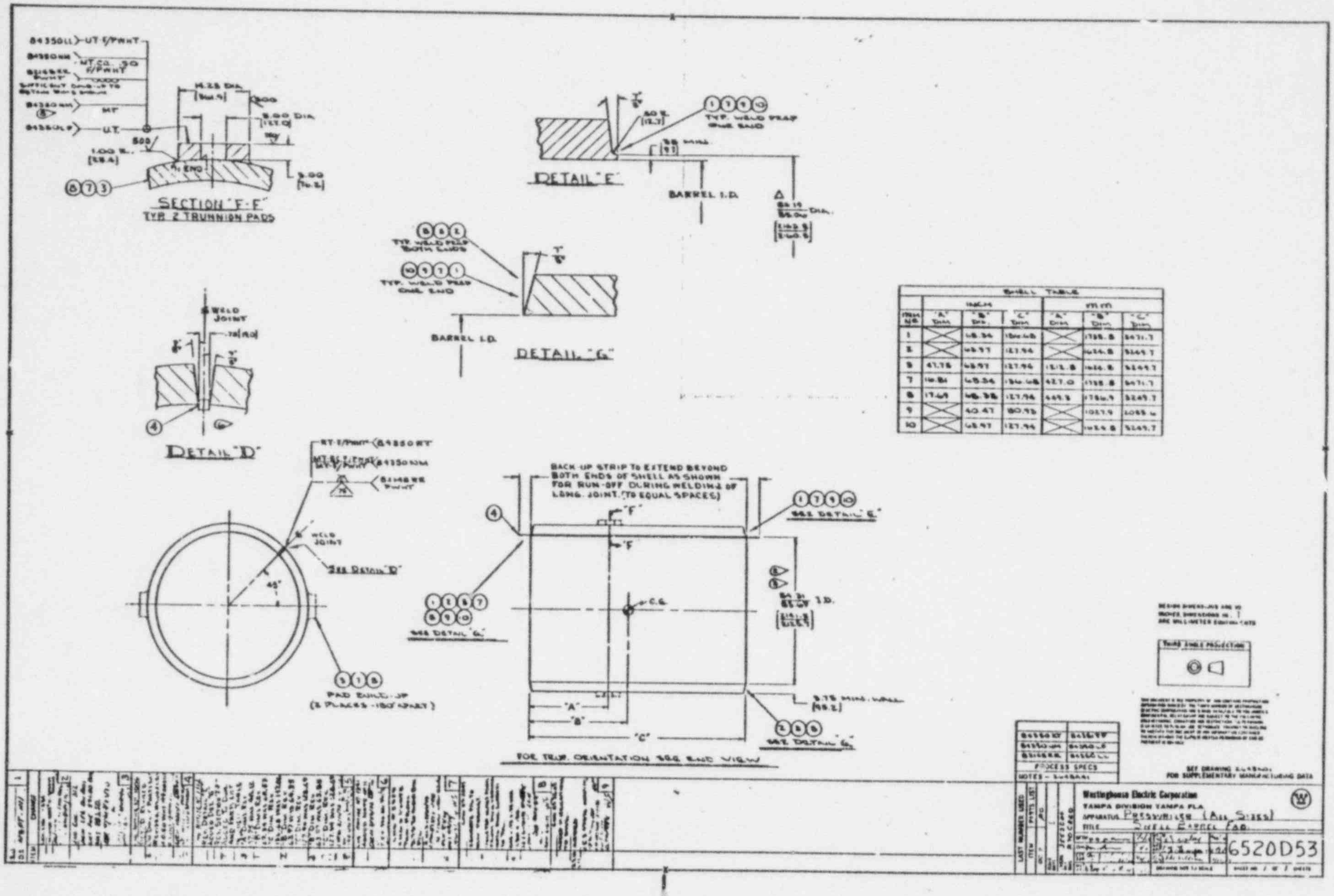


IT. NO.	t (MIN)	"A" +.50 −0	"B" DIA.	"C"
1	2.74	32.58	24.00	2.00
2	2.40	33.81	17.25	5.25

FIGURE 120.2-10

Pressurizer Shell

POOR ORIGINAL



SHELL TABLE						
	INCH			MM		
ITEM NO.	"A" DIM.	"B" DIM.	"C" DIM.	"A" DIM.	"B" DIM.	"C" DIM.
1	☒	68.34	186.48	☒	1735.8	5471.7
2	☒	63.97	127.94	☒	1624.8	3249.7
3	47.75	63.97	127.94	1212.8	1624.8	3249.7
7	16.81	68.34	186.48	427.0	1735.8	5471.7
8	17.69	69.38	127.94	449.3	1766.9	3249.7
9	☒	40.47	80.95	☒	1027.9	2055.6
10	☒	63.97	127.94	☒	1624.8	3249.7

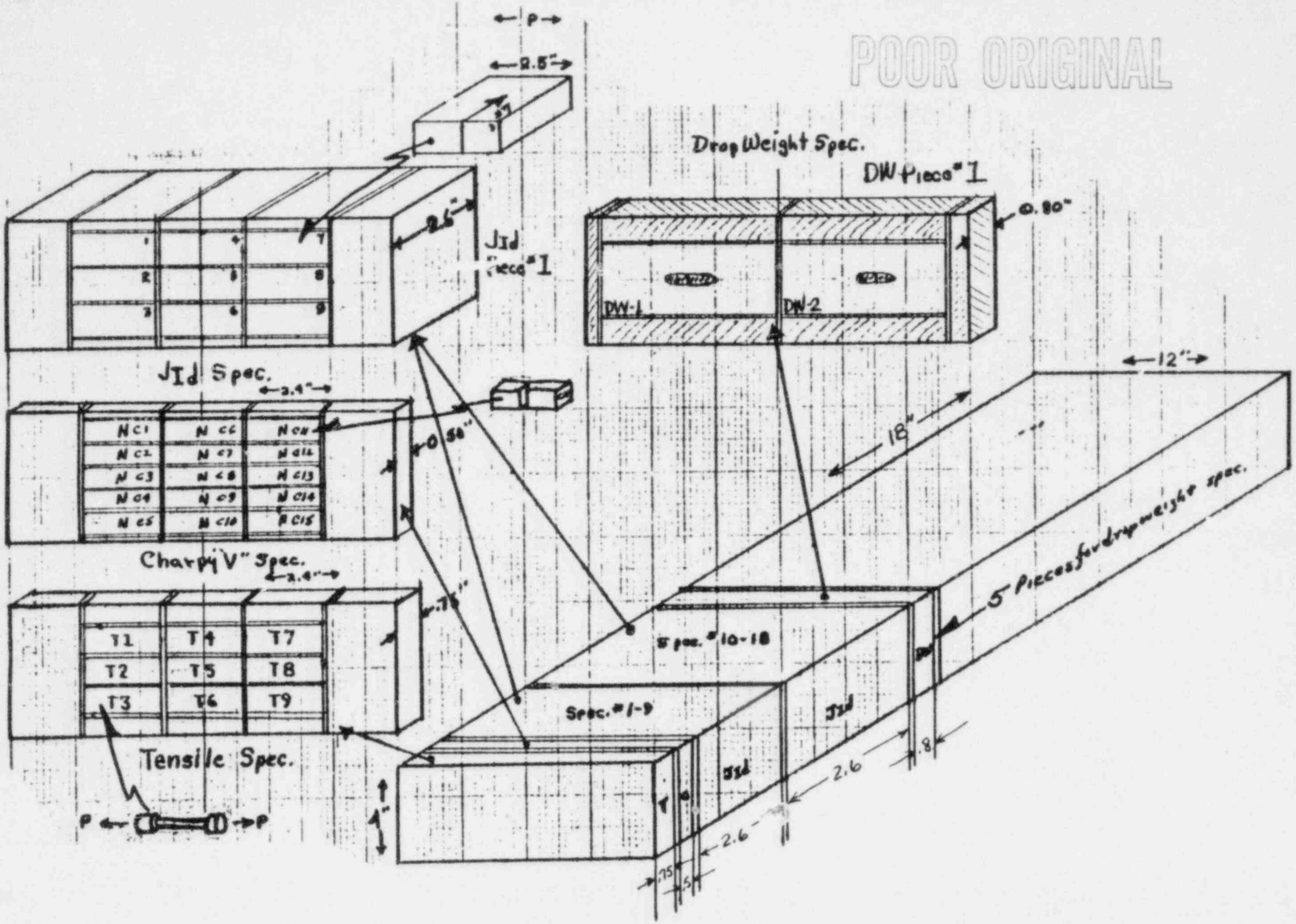


TABLE 120.2-11

SA 508 Class 2a Base Material Test Specimen Layout

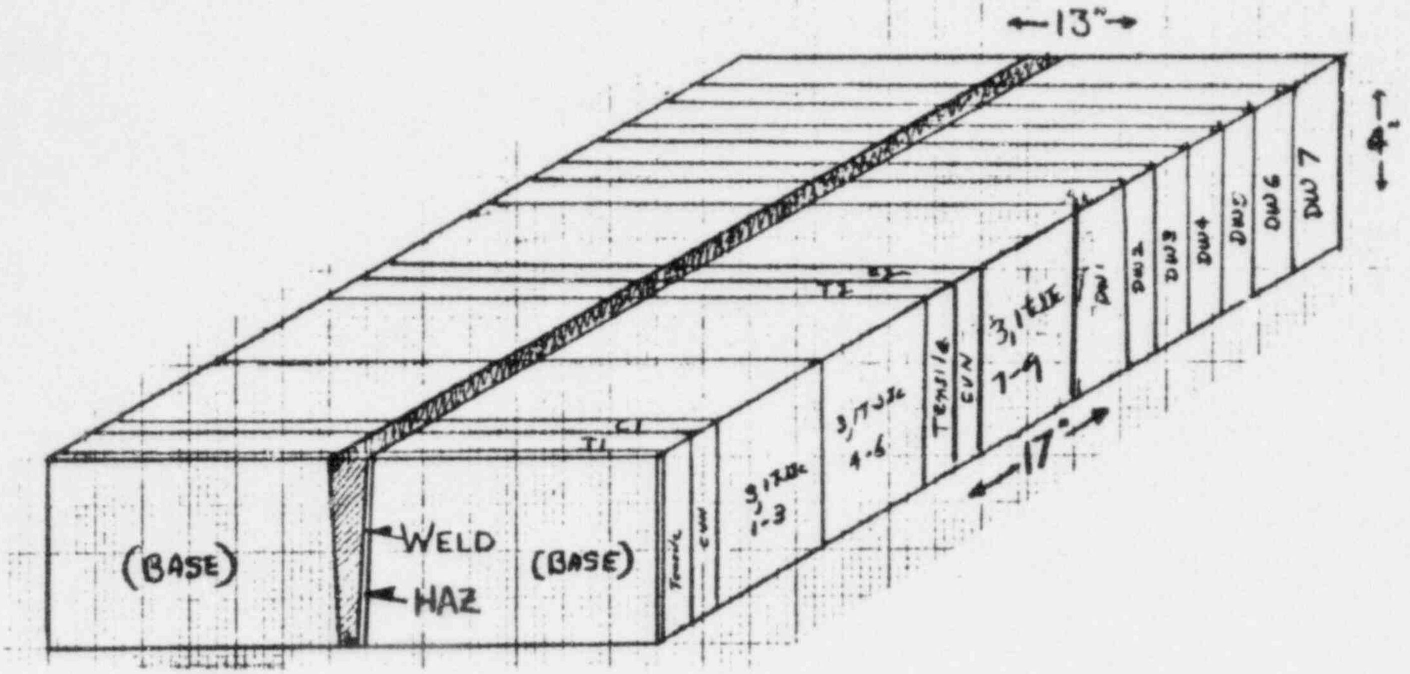


TABLE 120.2-12

SA 508 Class 2a HAZ Material Test Specimen Layout

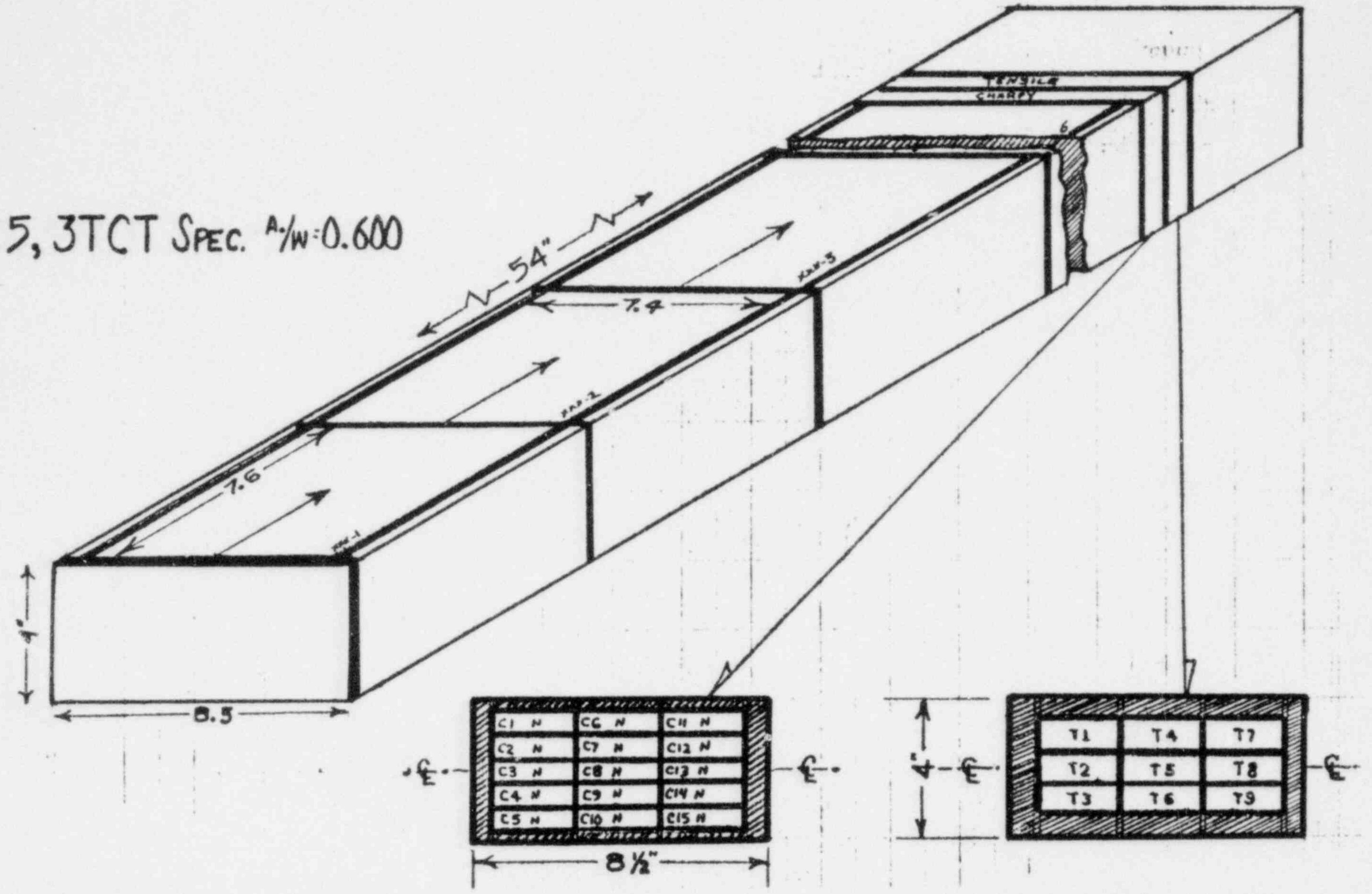


TABLE 120.2-13

SA 533 Grade A Class 2 Base Material Test Specimen Layout

Pieces 1^*, 2^+, 3^+, 4^*, 5^+, 6^*

$*$ - Weld Specimens

$+$ - HAZ Specimens

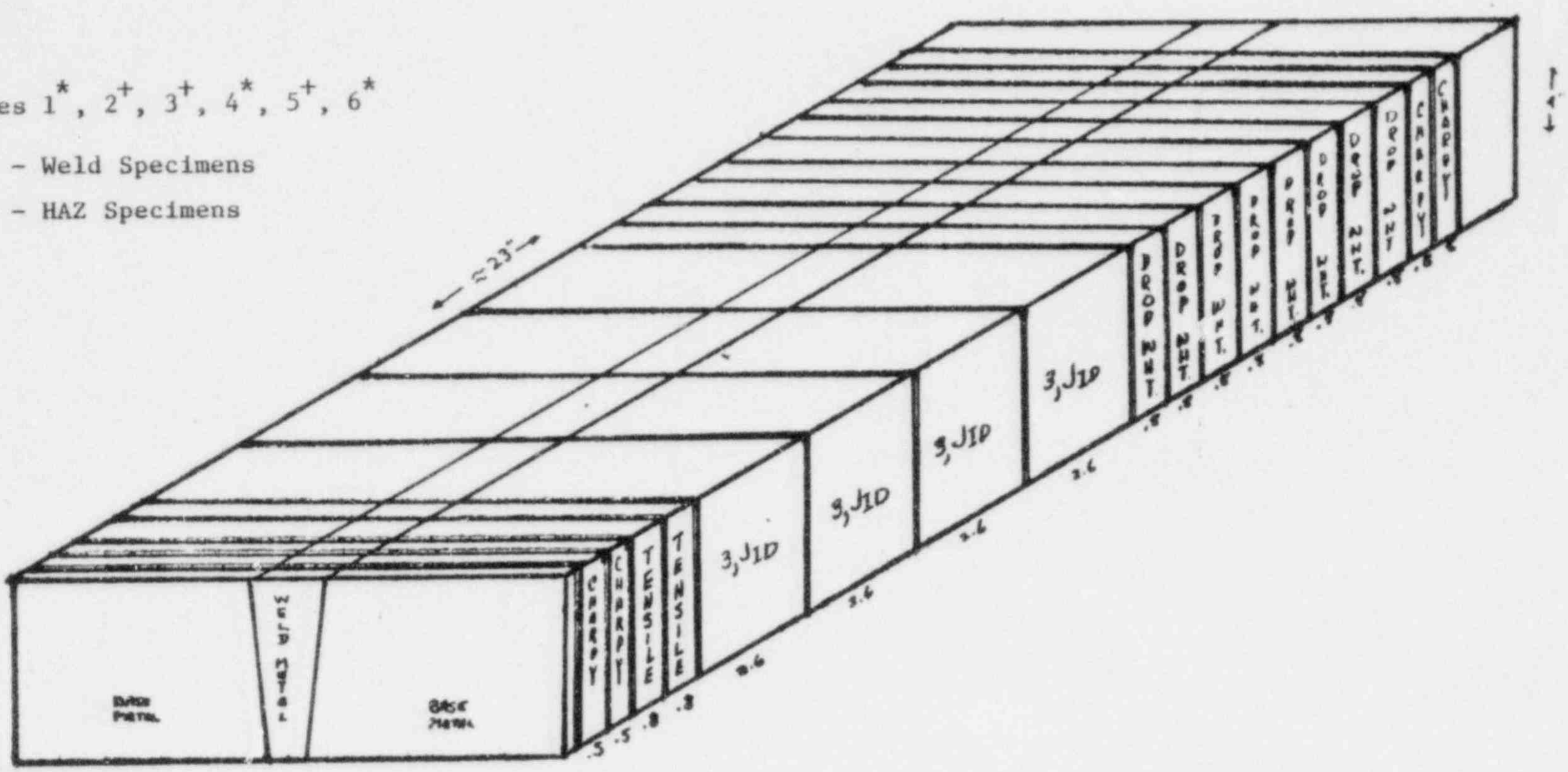


TABLE 120.2-14

SA 533 Grade A Class 2 HAZ Material/Weld Metal Test Specimen Layout

120.3 Paragraph G-2110(b), Appendix G of Section III of the ASME Code, states that if materials with a minimum specified yield strength greater than 50 KSI are to be used in conditions where radiation may affect the material properties, the effect of radiation on the K_{IR} curve shall be determined prior to the use of these materials in manufacture. The topical report presents no data on the effect of radiation on either SA 508 Class 2a or SA 533 Grade A Class 2 materials.

Paragraph IV.B of 10 CFR Part 50, Appendix G, requires that reactor vessel beltline materials have a minimum upper shelf energy, as determined from Charpy V-notch tests on unirradiated specimens, of 75 ft-lbs unless it can be demonstrated, by appropriate data and analyses, that lower values of upper shelf energy still provide adequate margin for deterioration from irradiation. From a review of the Charpy V-notch impact energy curves presented in the topical report for the subject steels, it has been determined that the initial upper shelf energy of SA 508 Class 2a material will be in the range of 60-65 ft-lbs. Also, no data or analyses were presented in the topical report to justify the use of this low upper shelf material in the reactor vessel beltline region.

It is our position that SA 508 Class 2a and SA 533 Grade A Class 2 materials not be used in the beltline region of any reactor vessel until sufficient data are provided for these materials to demonstrate (1) the effect of neutron irradiation on the material properties and (2) compliance with the minimum upper shelf requirements of Paragraph IV.B of 10 CFR Part 50, Appendix G.

Response: To date, SA 508 Class 2a and SA 533 Grade A Class 2 materials have not been used in any reactor vessel application, including the beltline region. Furthermore, SA 508 Class 2a and SA 533 Grade A Class 2 are not presently identified in the reactor vessel equipment specifications as materials for use in the reactor vessel beltline region. The information presented in WCAP-9292 does not qualify SA 508 Class 2a and SA 533 Grade A Class 2 materials for use in the beltline region of the reactor vessel.

120.4 (a) In Section 4-A of the report it is stated that at low temperatures (below the transition temperature) the material fracture toughness was calculated directly from the failure load, as outlined in ASTM E-399-74. However, it is also stated that in some cases the specified size criterion was not met by the one inch thick CT specimens. Identify all of the test results that did not meet the E-399-74 size criterion.

(b) For all other tests (those conducted above the transition temperature) identify the criterion that was used to determine the validity of the test and provide technical justification for using this criterion. Identify all of the test results that did not meet this criterion.

Provide technical justification for the inclusion of any results in this report that did not meet the test validity criteria.

Response: (a) The ASTM E-399 size criterion requires that the specimen crack length (a) and thickness (B) be greater than 2.5 times the conditional fracture toughness divided by the material's yield strength as shown below

$$a,\ B \geq 2.5\ (\frac{K_Q}{\sigma_{YS}})^2.$$

In Figures 120.4-1 through 120.4-4, the dynamic fracture toughness data points, which meet the ASTM E-399 size criterion, are circled. In determining which specimens meet this validity criterion, the specimen thickness was deemed the primary specimen dimension and the static yield strength was utilized in the calculations. Employing the static, rather than dynamic, yield strength is conservative and produces the minimum possible number of valid tests. As shown in Figures 120.4-1 through 120.4-4, six SA 508 Class 2a specimens and 12 SA 533 Grade A Class 2 specimens satisfied the ASTM E-399 size criterion; of the 12 SA 533 Grade A Class 2 specimens, only two were base metal tests. It should be noted that little advantage results from testing the substantially larger three inch thick compact tension specimens.

(b) Details of the dynamic test parameters and characteristics observed in analyzing all the SA 508 Class 2a and SA 533 Grade A Class 2 dynamic fracture toughness tests are summarized in Table 120.4-1. The primary test validity criterion employed in WCAP-9292 is the cleavage initiation criterion, which is included in Table 120.4-1 and discussed in the following paragraphs.

The behavior of each dynamic fracture toughness test specimen fell into one of five distinctly separate categories. These five categories are dependent in part on test temperature, observed specimen fracture behavior, and whether the load-to-failure or dynamic resistance curve test technique was utilized.

Of particular interest are the parameters which divide the various categories. These include: (a) the ratio of the maximum load experienced by the test specimen (P_M) to the five percent secant offset load (P_Q) and (b) the cleavage initiation criterion, defined by:

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

where Δa is the average amount of stretching (blunting) and σ_Y (effective yield strength) is a stress midway between the material's yield and ultimate stresses. The P_M/P_Q ratio governs which K versus J relationship is appropriate, while the cleavage initiation criterion determines whether the dynamic fracture toughness values obtained via a specimen loaded-to-failure at high transition range or upper shelf temperatures is valid. For ferritic steels, compliance with the cleavage initiation criterion indicates cleavage initiation; if Δa is larger, the mode of fracture initiation is fibrous.

Many of these dynamic test parameters and acceptance criteria were arrived at simultaneously by various investigators. For example, Davidson, in the preliminary draft of ASME E10.02 Task Group G "Supplemental Test Methods for Reactor Vessel Surveillance," recommended the identical elastic/elastic-plastic and cleavage/fibrous initiation criteria as those employed in WCAP-9292. In addition, Server et al., in "Experimental and Statistical Requirements for Developing a Well-Defined K_{IR} Curve" (EPRI NP-372) and Oldfield et al., in Appendix C of FCC77-1, "Analysis of Radiation Embrittlement Reference Toughness Curves" utilized the identical P_M/P_Q ratio to establish whether a dynamic fracture toughness test should be considered elastic or elastic-plastic. They also recommended cleavage and fibrous initiation criteria, defined below, which are similar to those utilized in WCAP-9292 except that they are related to the bulk specimen dimensions as opposed to the actual crack extension experienced by the specimen.

$$a, b, B \geq \frac{50 J_M}{\sigma_Y} \qquad \text{Cleavage Initiation}$$

$$a, b, B \geq \frac{25 J_M}{\sigma_Y} \qquad \text{Fibrous Initiation}$$

In the above expressions, a, b and B are the test specimen crack length, remaining ligament and thickness, respectively. Furthermore, the MPC/PVRC Working Group on Reference Toughness has employed the identical acceptance criteria in gathering over 300 heats of dynamic fracture toughness data, the purpose of which is to develop and recommend a new, statistically defined, reference toughness K_{IR} curve.

TABLE 120.4-1

DYNAMIC TEST PARAMETERS AND CHARACTERISTICS

Test Technique	← Load-to-Failure →			← – – – – – –	← Dynamic Resistance 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	$K_Q = \frac{P_Q}{BW^{½}} f(\frac{a}{W})$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$	$J = (\frac{1+\alpha}{1+\alpha^2}) \frac{2A}{Bb}$
Relationship Between K and J	$K = (\frac{EJ}{1-\nu^2})^{½}$	$K = (\frac{EJ}{1-\nu^2})^{½}$	$K = (EJ)^{½}$	$K = (EJ)^{½}$	$K = (EJ)^{½}$
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	$< \frac{0.55\ J}{\sigma_Y}$	$< \frac{0.55\ J}{\sigma_Y}$	$\leq \frac{0.55\ J}{\sigma_Y}$	$> \frac{0.55\ J}{\sigma_Y}$	$> \frac{0.55\ J}{\sigma_Y}$

$\frac{P_M}{P_Q} = 1.00$

$\frac{P_M}{P_Q} = 1.10$

$\Delta a = \frac{0.55\ J}{\sigma_Y}$

NOTES TO TABLE 120.4-1

A = area under load-load point displacement record in energy units

a = original crack size (includes machine notch plus fatigue precrack)

Δa = stable, ductile (fibrous) crack extension adjacent to specimen precrack

B = specimen thickness

b = initial uncracked ligament, $b = w-a$

E = Young's modulus

$f(\frac{a}{w})$ = function of $\frac{a}{w}$ per ASTM E-399

J = J - integral, elastic plastic fracture toughness

K = stress intensity factor, linear elastic fracture toughness

K_Q = conditional fracture toughness

P_M = maximum load

P_Q = five percent offset load as defined in ASTM E-399

W = specimen width (depth)

$(\frac{1+\alpha}{1+\alpha^2})$ = dimensionless coefficient value which corrects for the tensile strength

σ_{ut} = ultimate tensile strength

σ_Y = effective yield strength, $\sigma_Y = \frac{\sigma_{ys} + \sigma_{ut}}{2}$

σ_{ys} = 0.2% offset yield strength

ν = Poison's ratio

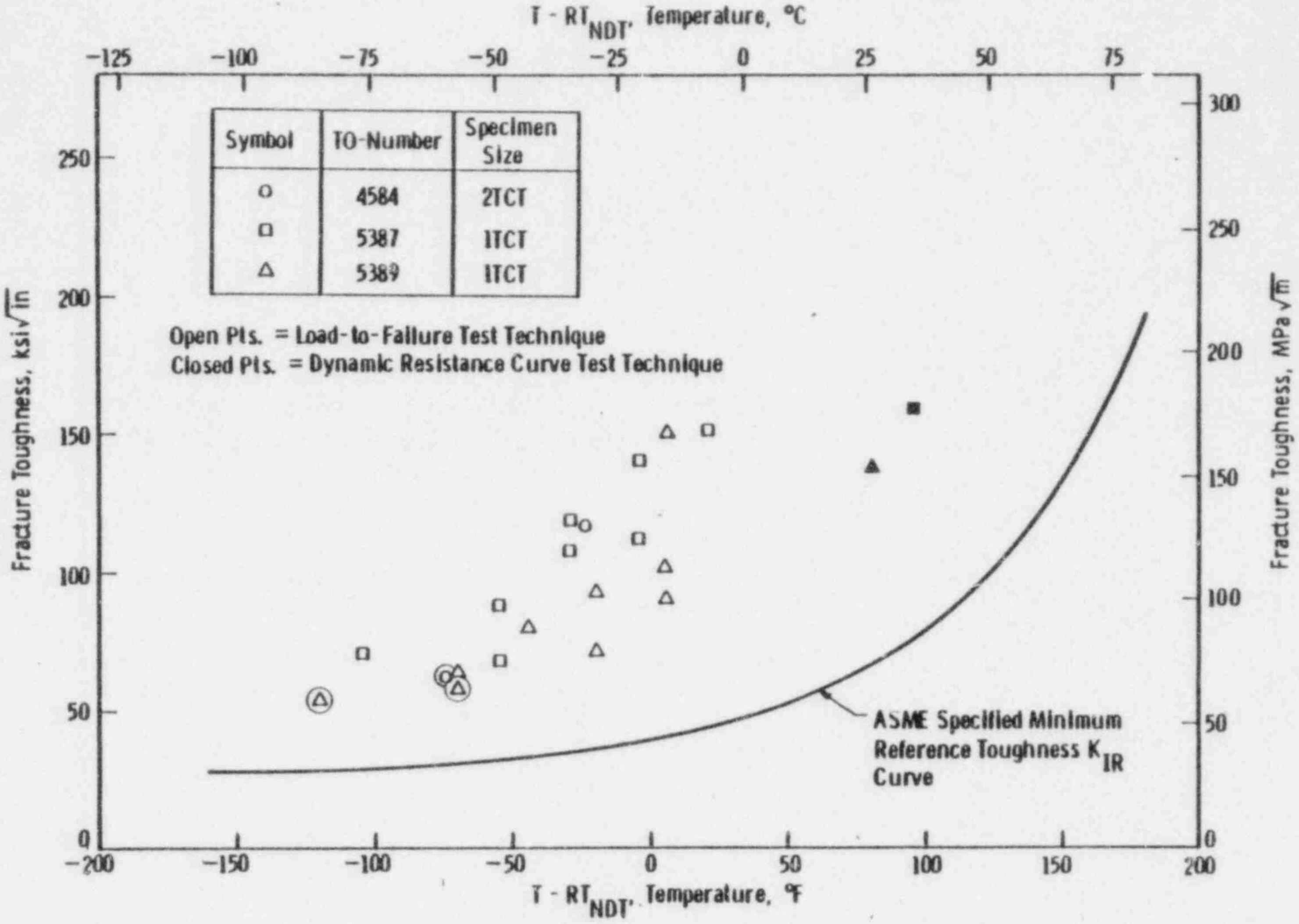


FIGURE 120.4-1 — Fracture toughness versus T-RT$_{NDT}$ for SA508 Cl 2a base material

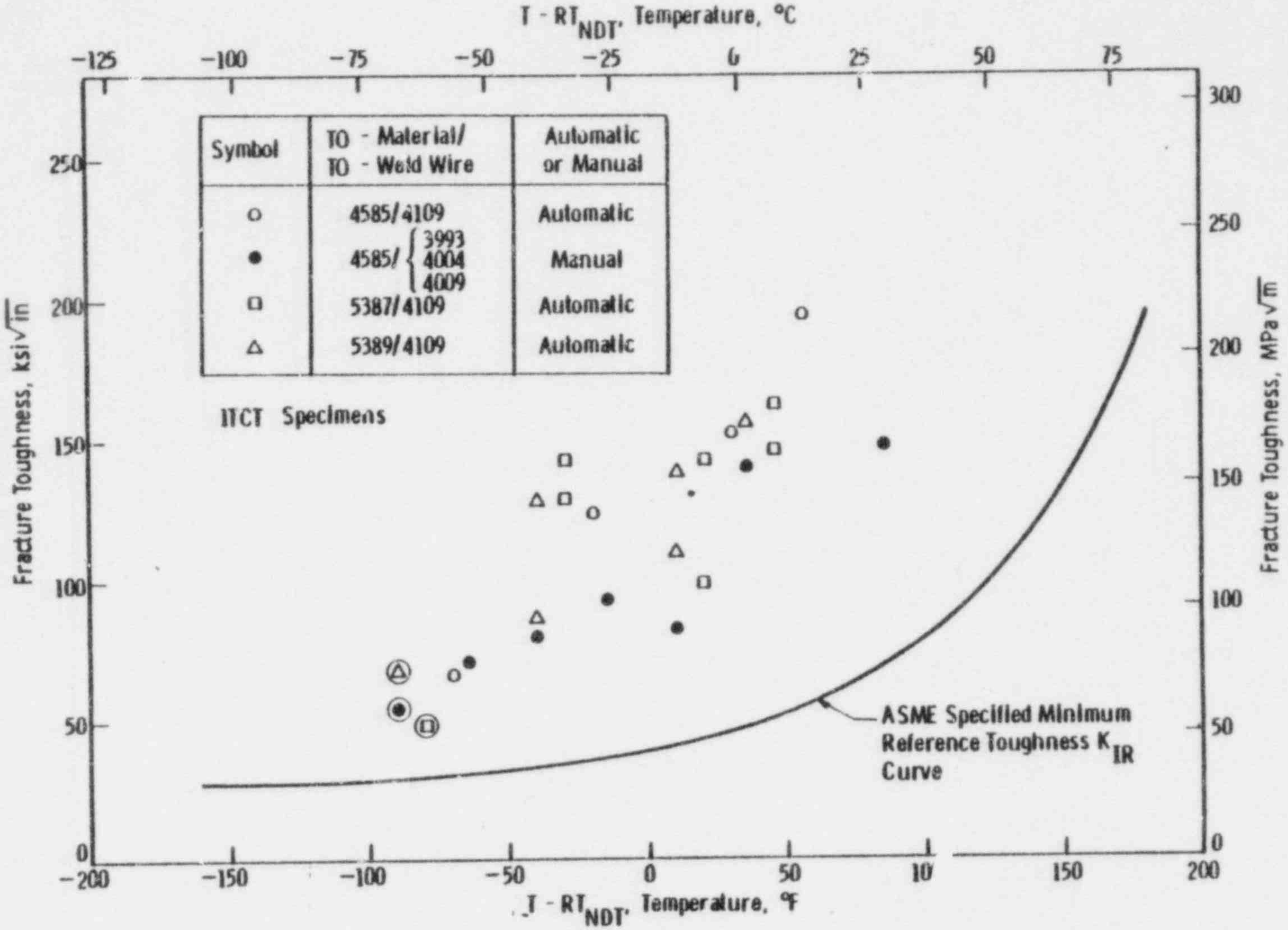
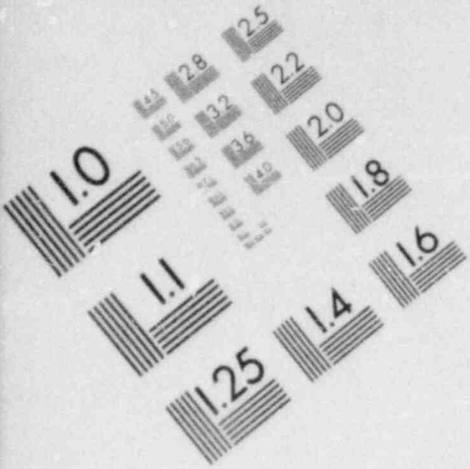


FIGURE 120.4-2– Fracture toughness versus T - RT_{NDT} for SA 508 Cl 2a heat affected zone material



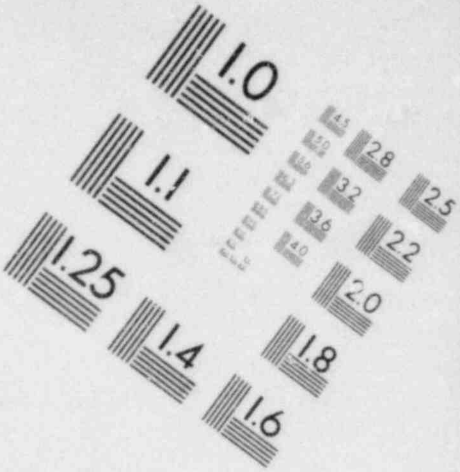
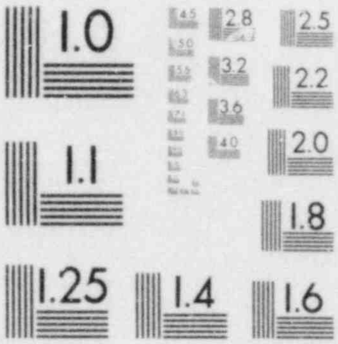
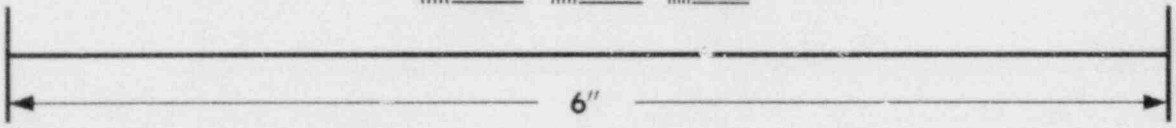
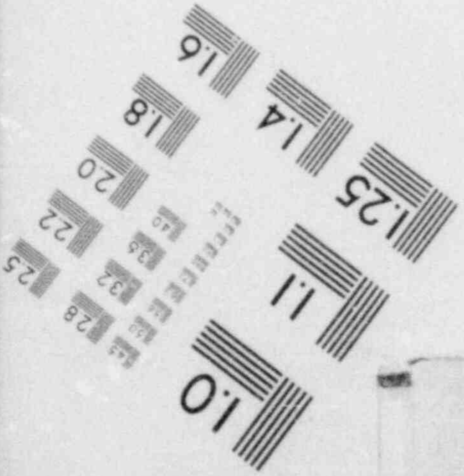


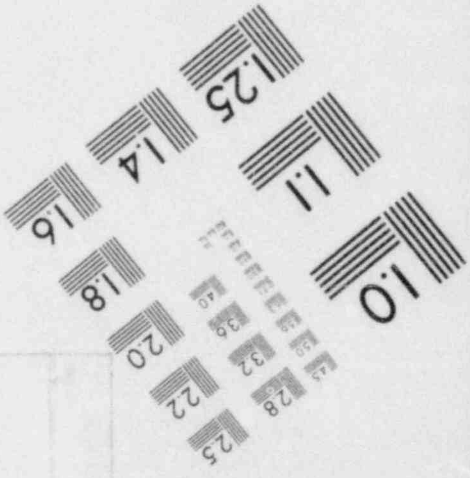
IMAGE EVALUATION
TEST TARGET (MT-3)

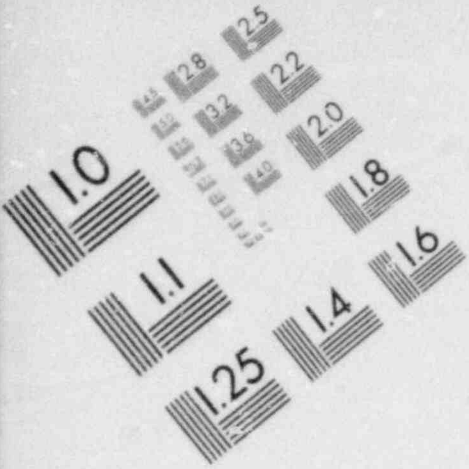




MICROCOPY RESOLUTION TEST CHART







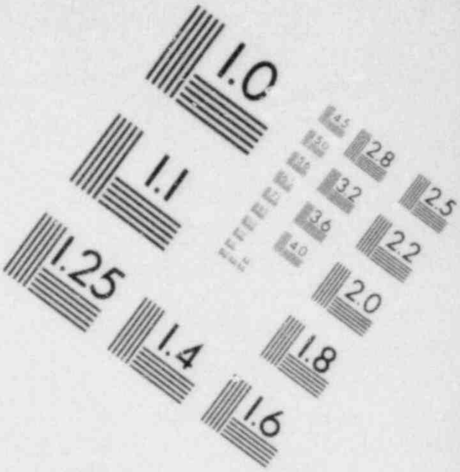
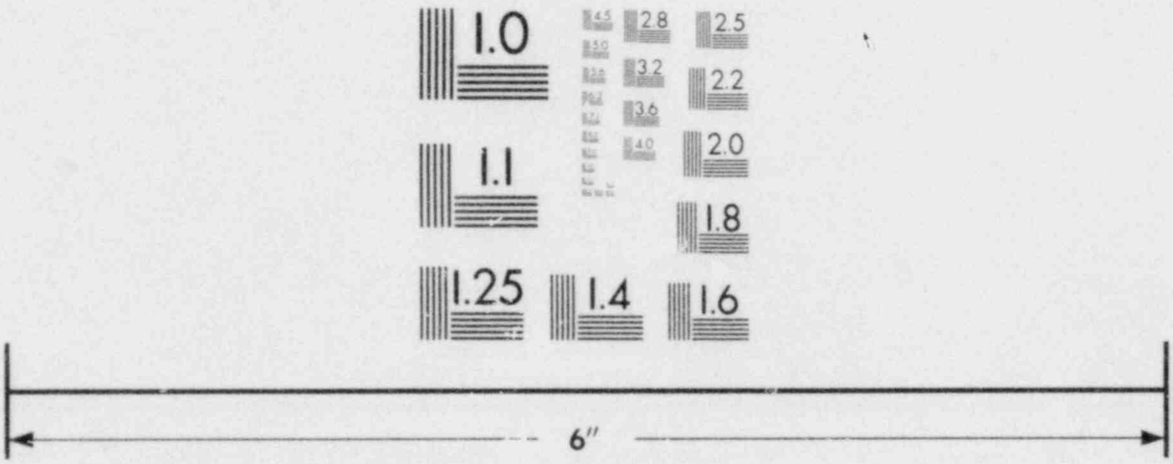


IMAGE EVALUATION
TEST TARGET (MT-3)

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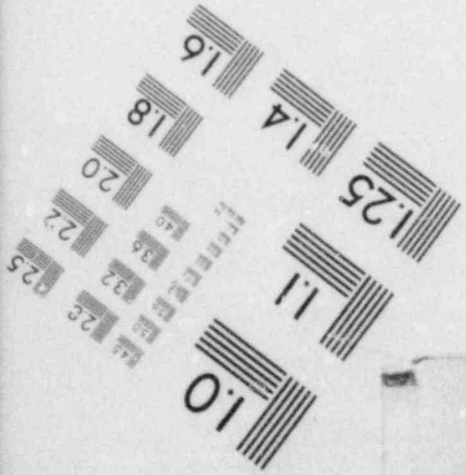
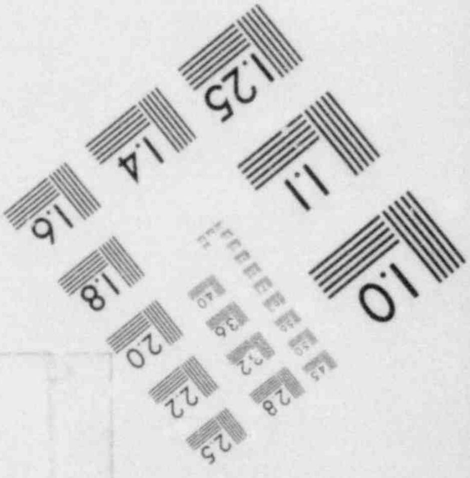




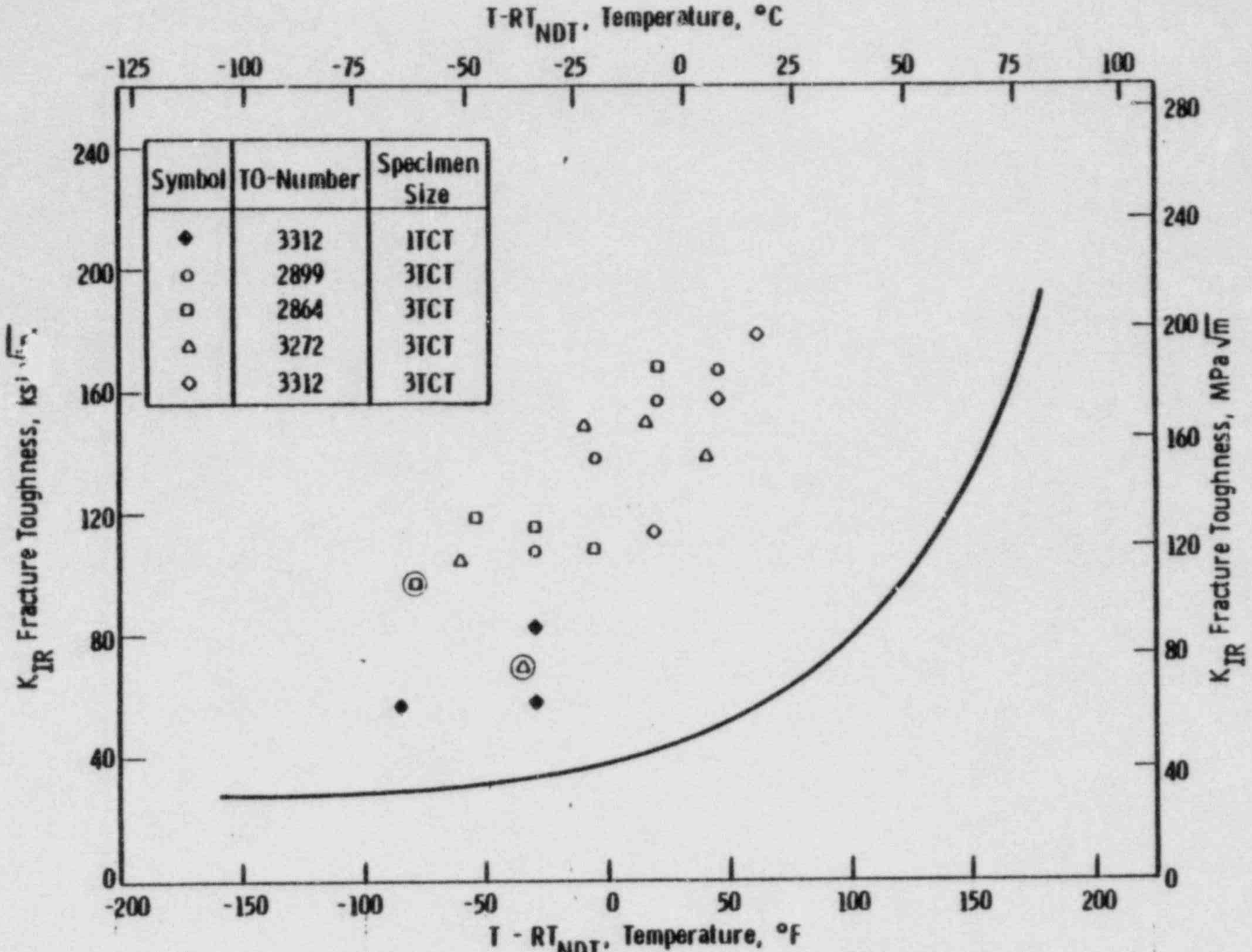


FIGURE 120.4-3 $-K_{IR}$ reference toughness curve for SA533 Gr A Cl 2 base material

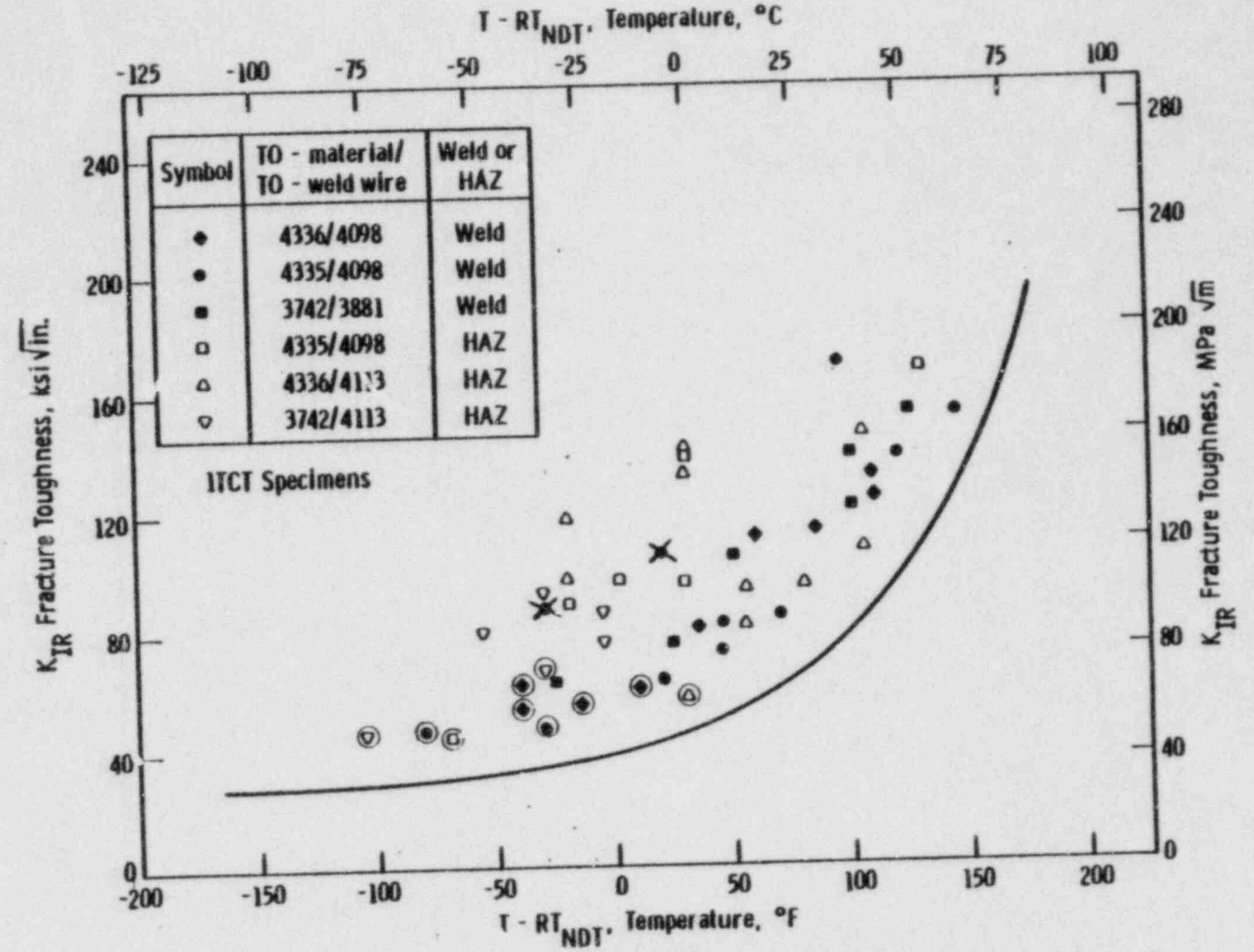


FIGURE 120.4-4 – K_{IR} reference toughness curve for SA533 Gr A Cl 2 weld and HAZ material

NOTE: The two data points marked with an X are in error and should be disregarded in this figure and in Figure 6-2 of WCAP-9292

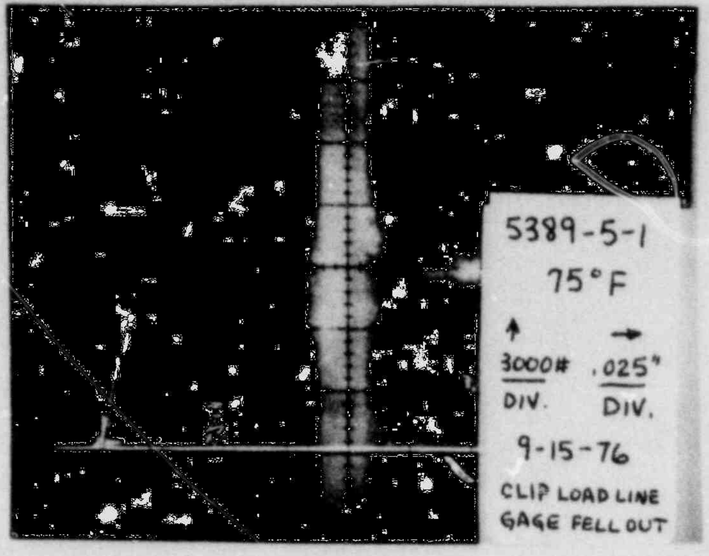
120.5 In order that we may verify the test results of this report, supply the load versus displacement curves for the following tests:

Reference Figure No.	Material	TO-Material/TO-Weld	Test Temperature
5-1	508-2a	5389	75°F
5-2	508-2a HAZ	5389/4109	25
6-1	533-2	2864	50
6-2	533-2 HAZ	4336/4113	25
6-2	533-2 Weld	4335/4098	125

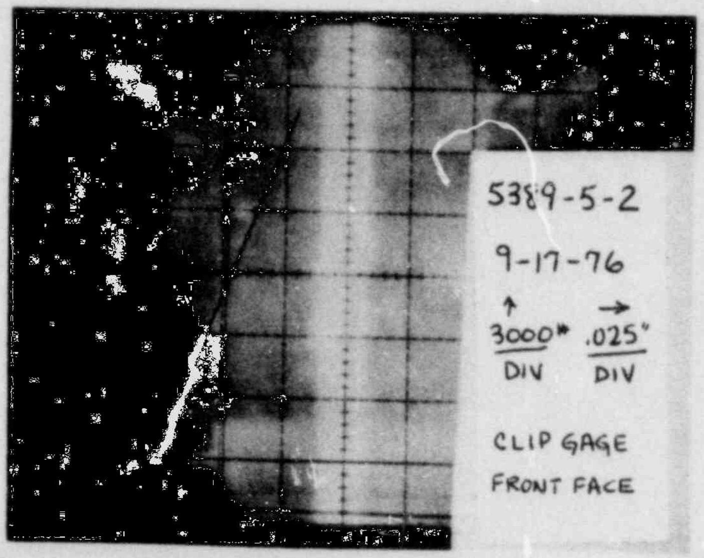
Also provide a sample calculation of the J and K values for one of these tests.

Response: Load-displacement records for the tests reflected in Figures 5-1, 5-2, and 6-2 of WCAP-9292 are given in Figure 120.5-1. Note that the load-displacement record corresponding to Figure 6-1 of WCAP-9292 is not available.

Table 120.4-1 (in the Response to Question 120.4) includes the formula for calculation of K or J values.



Load-displacement records
corresponding to
Figure 5-1 of WCAP-9292.



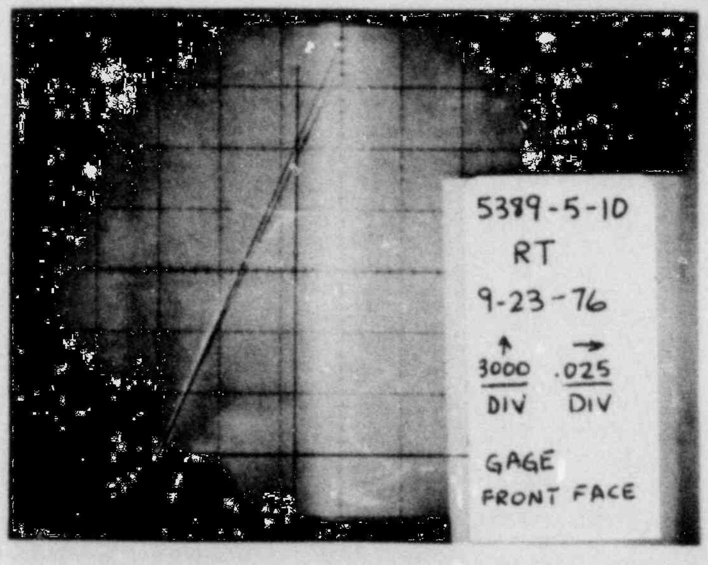
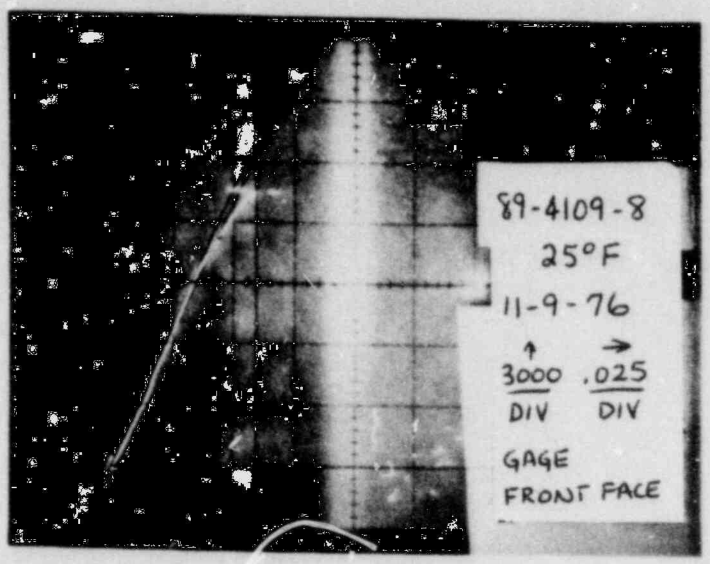
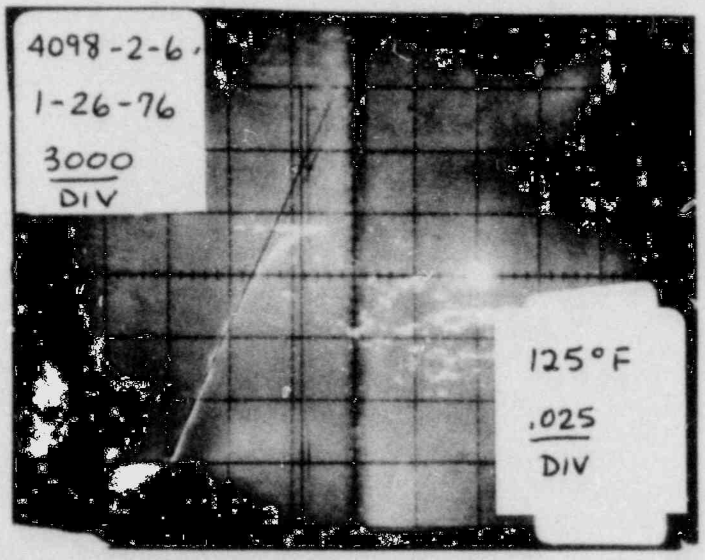


FIGURE 120.5-1

Load-Displacement Records

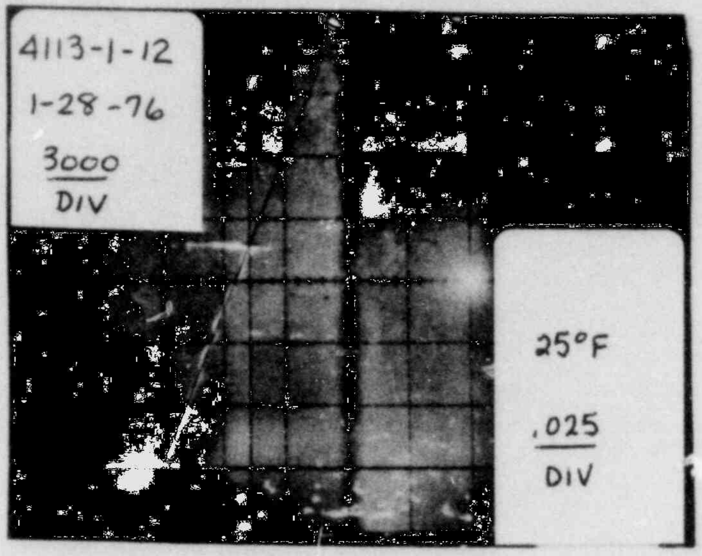


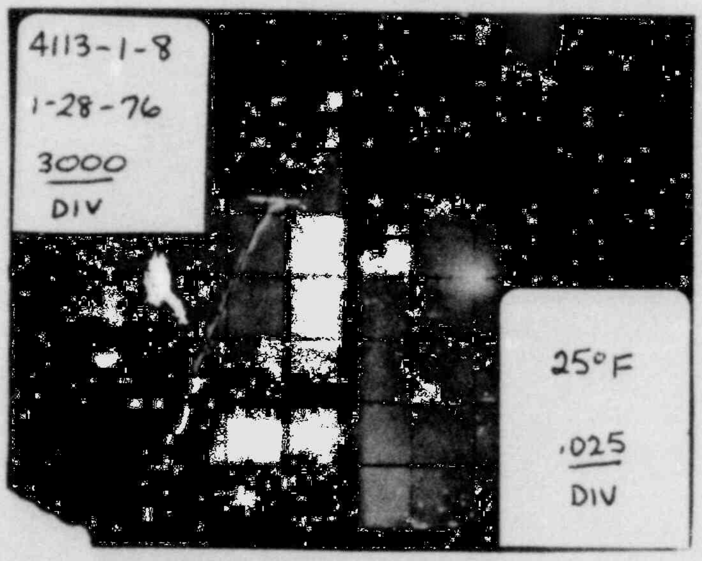
Load-displacement record corresponding to Figure 5-2 of WCAP-9292.



Load-displacement record corresponding to Figure 6-2 (Weld) of WCAP-9292.

FIGURE 120.5-1
(Continued)





Load-displacement records corresponding to Figure 6-2 (HAZ) of WCAP-9292.

FIGURE 120.5-1

(Continued)

120.6 Paragraph G-2110(b), Appendix G, Section III of the ASME Code states that the K_{IR} curve may be used for steels having a minimum specified yield strength greater than 50 ksi, but less than or equal to 90 ksi, if fracture mechanics data similar to the K_{ID} data of WRCB-175 are obtained for this material and if all of the data fall above the K_{IR} curve. This topical report utilizes linear elastic K_{ID} tests at low temperatures and J-integral R-curve tests at the upper transition region and upper shelf region temperatures to evaluate the dynamic fracture toughness of SA 533 Grade A Class 2 and SA 508 Class 2a steels and demonstrate compliance with the code requirement.

The results of the J-integral R-curve testing indicate that, in the upper transition and upper shelf temperature regions, SA 533 Grade A Class 2 steel has an adequate value of J_{ID} (and therefore, K_{ID}) and T (the tearing modulus). However, the same type tests conducted on SA 508 Class 2a steel were at temperatures relatively low in the transition region and consequently the data indicate that this material has comparatively low values of J_{ID} and T as compared to SA 533 Class 1 or 2 steels.

To demonstrate the adequacy of SA 508 Class 2a steel in the upper transition region and upper shelf region, the topical report should be modified to include either

(1) one or two additional J_{ID} test results (from actual testing or from the literature) at a test temperature of at least $T\text{-}RT_{NDT} = 150°F$; or

(2) an Appendix G type analysis that demonstrates the adequacy of the maximum experimental K_{ID} values obtained in this investigation for the material as used in actual components at normal full power operating conditions.

Response: Concern has been expressed due to the fact that the maximum transition temperature dynamic fracture toughness values (load-to-failure test technique) obtained on the SA 508 Class 2a base materials equaled approximately 150 ksi $\sqrt{in}$(166 MPa$\sqrt{m}$), compared with a maximum value of 200 ksi $\sqrt{in}$(221 MPa$\sqrt{m}$) for the ASME specified minimum reference toughness K_{IR} curve. In addition, upper shelf dynamic fracture toughness values (dynamic resistance curve test technique) also averaged approximately 150 ksi $\sqrt{in}$(166 MPa$\sqrt{m}$) (see Figure 5-1 of WCAP-9292).

The following paragraphs address these transition temperature and upper shelf dynamic fracture toughness values and demonstrate that effective dynamic fracture toughness values for SA 508 Class 2a steel (at transition range and upper shelf temperatures) are in excess of 200 ksi $\sqrt{in}$ (221 MPa $\sqrt{m}$). In particular, consideration is given to data which did not satisfy the cleavage initiation criterion, discussed in the response to Question 120.4 (that is, $\Delta a > \frac{0.55J}{\sigma_Y}$); however, this data indicates that stable crack extension can be sustained to effective dynamic fracture toughness values in excess of 200 ksi $\sqrt{in}$ (221 MPa $\sqrt{m}$).

Consider first the upper shelf dynamic fracture toughness values. Basically, these fracture toughness values were calculated utilizing J-integral techniques as opposed to linear elastic (K) techniques. The major difference between linear elastic (K) and elastic plastic (J) fracture toughness values is that the J values are based on crack initiation (zero crack extension due to actual material separation) whereas the K values are based on 2 percent effective crack growth (including the effect of plastic zone formation).

Logsdon has compared the upper shelf fracture toughness values developed via K and J test techniques for several materials.(1,2) Of particular interest are the results for an ASTM A471 NiCrMoV rotor steel (see Figure 120.6-1), where the upper shelf fracture toughness values were developed utilizing 8TCT specimens. In particular, at 250°F (121°C) fracture toughness based on crack initiation (J) equals approximately 150 ksi $\sqrt{in}$ (166 MPa$\sqrt{m}$) while the linear elastic fracture toughness values are slightly in excess of 200 ksi $\sqrt{in}$ (221 MPa$\sqrt{m}$). Seven inch thick specimens would be adequate to obtain valid ASTM E-399 fracture toughness values for this material at 250°F (121°C). The 250°F (121°C) resistance curve for this material (see Figure 120 6-2) extrapolated to 0.140 in. (0.36 cm) of crack extension (equivalent to 2 percent effective crack growth in a seven inch thick compact tension specimen) yields a J value of 1500 $\frac{\text{in-lb}}{\text{in}^2}$ (0.263 $\frac{\text{MJ}}{\text{m}^2}$). The corresponding equivalent fracture toughness value equals approximately 220 ksi $\sqrt{\text{in}}$ (224 MPa$\sqrt{\text{m}}$) and is plotted in Figure 120.6-1. This equivalent fracture toughness value exceeds the linear elastic fracture toughness values because a portion of the allowable effective crack growth in the linear elastic K_{IC} test is used up as platicity (crack blunting), the remainder going into actual crack extension.

If we estimate the dynamic yield strength of the SA 508 Class 2a steel to fall between 110 and 120 ksi (758 and 827 MPa) at 150°F (66°C), an eight inch thick specimen would be required to obtain valid dynamic fracture toughness values (per the ASTM E-399 size criterion) for this material. Dynamic fracture toughness values at the upper limits of the ASME specified minimum reference toughness K_{IR} curve were developed on eight inch thick compact tension specimens tested by Shabbits, and as such a maximum crack extension of 0.160 in. in these specimens was possible.$^{(3)}$ Standard resistance curves for the SA 508 Class 2a materials at 150°C (66°C) are included in Figure 5-4 of WCAP-9292. Stable crack growth has been demonstrated on both heats of SA 508 Class 2a material to approximately 0.040 in. (0.102 cm) of crack extension. Therefore, we can use the maximum J values observed for each heat of SA 508 Class 2a material since stable crack extension has been demonstrated to this point. These maximum J and corresponding K (J) values are presented in Table 120.6-1. Clearly, the SA 508 Class 2a steel can sustain stable crack extension to effective dynamic fracture toughness values in excess of 200 ksi $\sqrt{\text{in}}$ (221 MPa$\sqrt{\text{m}}$) at upper shelf temperatures.

The average tearing modulus for SA 508 Class 2a equals 66 (non-dimensional) (see Table 120.6-1). The higher the tearing modulus the greater the ability of a material to absorb energy upon additional crack extension. Materials which have a tearing modulus over 100 (high toughness stainless steels, etc.) typically demonstrate a high degree of stability against tearing mechanisms for all crack configurations. A tearing modulus below 10 virtually ensures tearing instability in some crack configurations as soon as J_{IC} and limit load are reached. Additionally, a typical rotor steel would have a tearing modulus near 30. Therefore, the SA 508 Class 2a steel demonstrates an average to above average ability to absorb energy upon additional crack extension.

Further evidence that SA 508 Class 2a has an effective dynamic fracture toughness in excess of 200 ksi $\sqrt{in}$ (221 MPa$\sqrt{m}$) can be noted by observing the modified resistance curves illustrated in Figure 5-5 of WCAP-9292. These modified resistance curves were obtained from specimens which were dynamically loaded directly to failure and where the degree of stable, ductile crack extension was fortunately marked by a change in fracture mode. Table 120.6-2 summarizes the various test parameters for each of the individual specimens which make up these modified resistance curves. Dynamic fracture toughness values obtained from these specimens were not included in Figure 5-1 of WCAP-9292 because they failed to meet the cleavage initiation criterion, defined by:

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

where Δa is the average amount of stretching (blunting) and σ_Y (effective yield strength) is a stress midway between the material's yield and ultimate stresses. For ferritic steels, compliance with the above requirement indicates cleavage initiation; if Δa is larger, the mode of fracture initiation is fibrous. Nevertheless, it is obvious that dynamic fracture toughness values as high as 264.2 ksi $\sqrt{in}$ (292.5 MPa$\sqrt{m}$) at corresponding crack extensions of 0.1267 in. (0.322 cm) have been observed.

Incidently, if Westinghouse would utilize the bulk specimen dimension cleavage/fibrous initiation criterion and concentrate on the specimen thickness (B) as the primary controlling dimension of interest, all the specimens which make up the modified resistance curves of Figure 5-5 of WCAP-9292 with the exception of those tested at 150°F (66°C) would meet the requirement for cleavage initiation. Those dynamic fracture toughness values which meet the bulk specimen dimension cleavage/fibrous initiation criterion are included in Figure 120.6-3.

In conclusion, effective dynamic fracture toughness values in excess of 200 ksi √in (221 MPa√m) have been demonstrated for SA 508 Class 2a steel at both transition range and upper shelf temperatures.

References

1. Logsdon, W. A., "Elastic Plastic (J_{IC}) Fracture Toughness Values: Their Experimental Determination and Comparison With Conventional Linear Elastic (K_{IC}) Fracture Toughness Values for Five Materials," Mechanics of Crack Growth, ASTM STP 590, American Society for Testing and Materials, 1976, page 43-60.

2. Logsdon, W. A. and Begley, J. A., "Upper Shelf Temperature Dependence of Fracture Toughness for Four Low to Intermediate Strength Ferritic Steels," Engineering Fracture Mechanics, Vol. 9, 1977, page 461-470.

3. Shabbits, W. O., "Dynamic Fracture Toughness Properties of Heavy Section A 533 Grade B Class 1 Steel Plate," HSSTP-TR-13, WCAP-7623, Westinghouse Electric Corporation, December 1970.

TABLE 120.6-1

Various Parameters from SA508 Class 2a Standard Resistance Curves at 150°F (66°C)

TO-Number	Crack Extension at Max. J		Maximum J		K(J) at Max. J		Slope $\frac{dJ}{da}$	Tearing Modulus T
	in	cm	$\frac{in-lb}{in^2}$	$\frac{MJ}{m^2}$	ksi√in	MPa√m	$\frac{lb}{in^2}$	
5387	.0348	.088	1308.2	.229	198.1	219.3	18637	69
5389	.0422	.107	1367.3	.239	202.5	224.2	19987	63

TABLE 120.6-2

Various Test Parameters for Each of the Individual Specimens Which Make up the SA508 Class 2a Modified Resistance Curves

Specimen Number	Temperature T		Temperature $T-RT_{NDT}$		Crack Extension		J		K(J)	
	°F	°C	°F	°C	in	cm	$\frac{in\text{-}lb}{in^2}$	$\frac{MJ}{m^2}$	ksi$\sqrt{in}$	MPa$\sqrt{m}$
5387-3-1	75	24	20	-7	.0317	.081	1201.1	.210	189.8	210.1
5387-3-5	100	38	45	7	.0146	.037	916.2	.160	165.8	183.5
5387-3-6	125	52	70	21	.0367	.093	1417.5	.248	206.2	228.3
5387-3-9	150	66	95	35	.0907	.230	2019.1	.354	246.1	272.4
5387-3-10	75	24	20	-7	.0160	.041	1074.7	.188	179.6	198.8
5389-5-5	100	38	30	-1	.0117	.030	831.9	.146	158.0	174.9
5389-5-6	125	52	55	13	.0417	.106	1191.7	.209	189.1	209.3
5389-5-9	150	66	80	27	.1267	.322	2326.9	.407	264.2	292.5

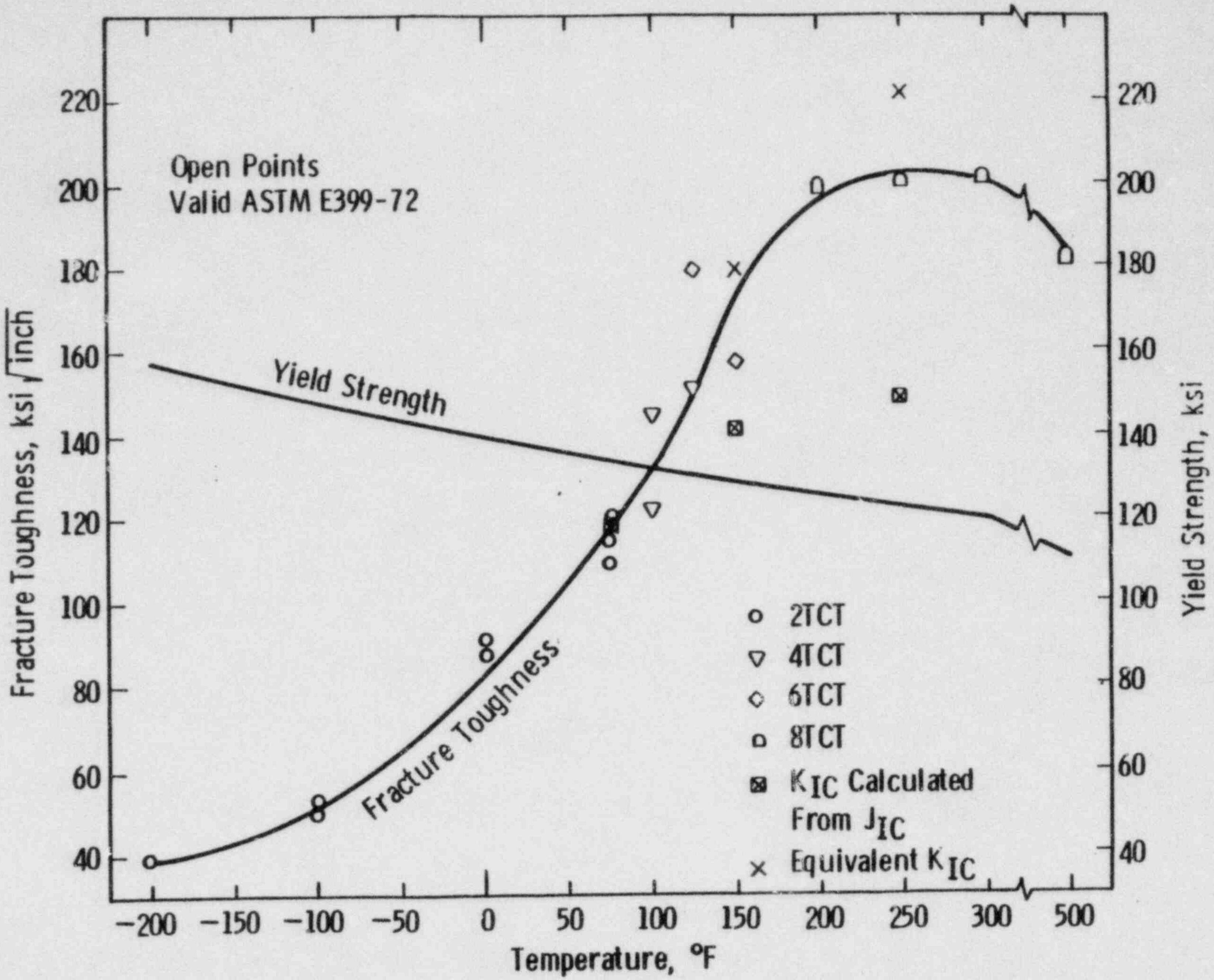


FIGURE 120.6-1 —Temperature dependence of yield strength and fracture toughness for an ASTM A471 Ni Cr Mo V rotor steel

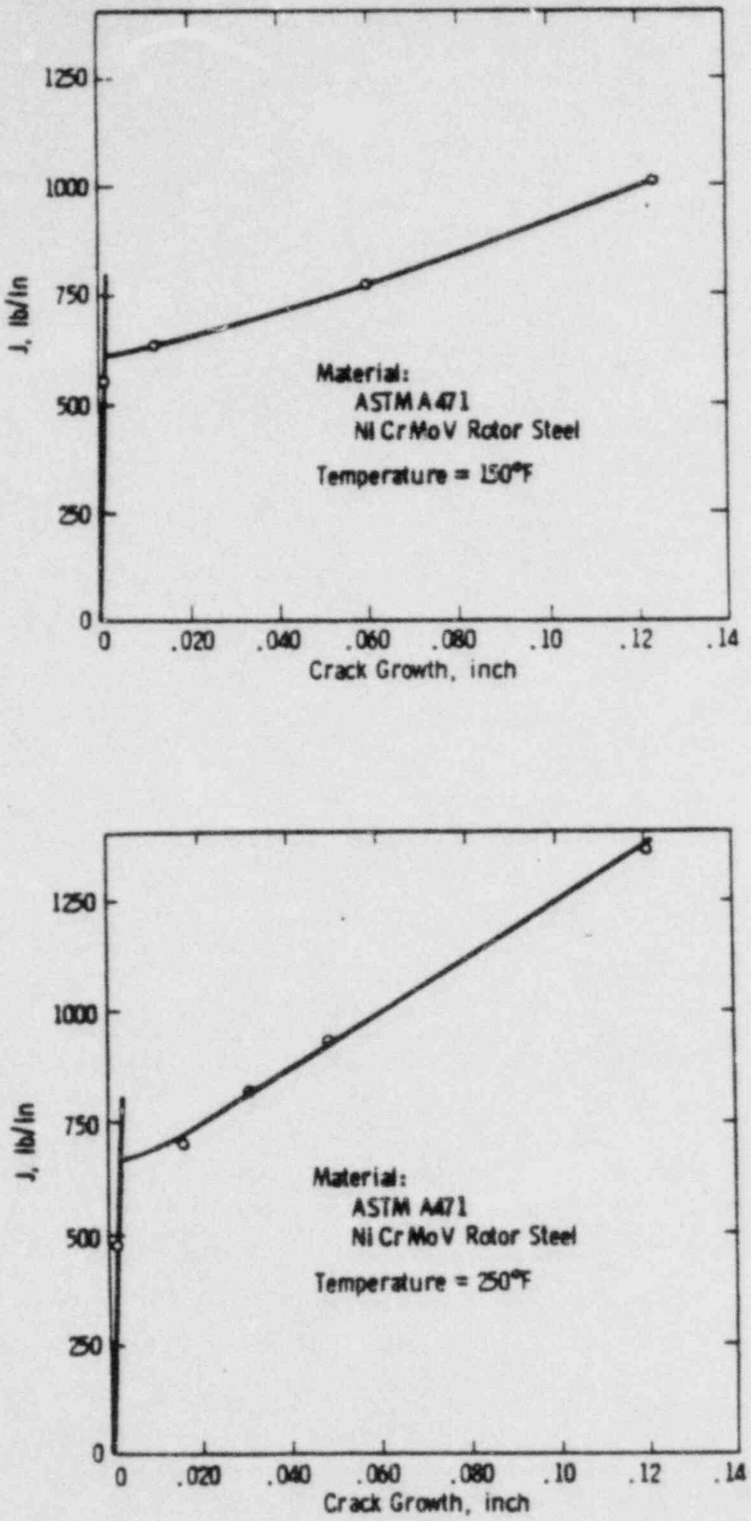


FIGURE 120.6-2 —J resistance curves for an ASTM A471 Ni Cr Mo V rotor steel at temperatures of 150°F and 250°F

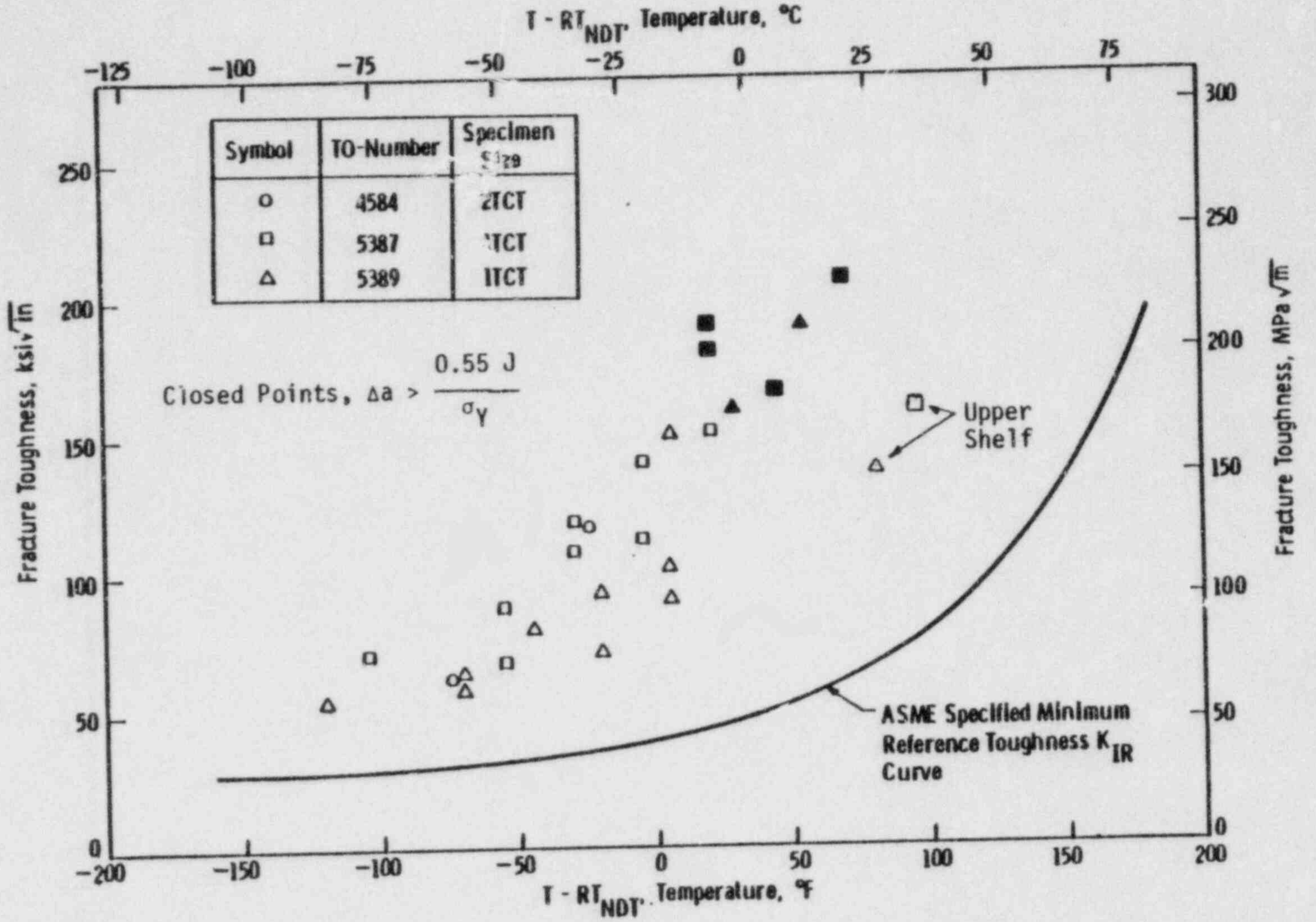


FIGURE 120.6-3 – **Fracture toughness versus T-RT_{NDT} for SA508 Cl 2a base material**

APPENDIX A

The Influence of Long Time Post-Weld Type Stress Relief Heat Treatments on the Dynamic Fracture Toughness of SA508 Class 2a and SA533 Grade B Class 2 Steels

INTRODUCTION

As stated in WCAP-9292, the PWHT times on the weldments tested were 3/3.5 hours at 1125°F. Subsequent to submittal of WCAP-9292 to the NRC and in order to encompass the anticipated production PWHT ranges, Westinghouse has further investigated the effect of PWHT time and temperature on fracture toughness properties. Specifically, dynamic fracture toughness testing was performed on SA 508 Class 2a and SA 533 Grade B Class 2 steels, which have been subjected to one of the three following long time post-weld type stress relief heat treatments:

48 hours at 1000°F
24 hours at 1125°F
48 hours at 1125°F

The results of this testing are presented herein; all of the dynamic fracture toughness values exceed the ASME specified minimum reference toughness K_{IR} curve.

RESULTS

Tensile

The influence of long time post-weld type stress relief heat treatments on the tensile properties of SA 508 Class 2a and SA 533 Grade B Class 2 pressure vessel steels, the chemical compositions and heat treatments of which are outlined in Table A-1, are illustrated in Figures A-1 and A-2, respectively. Each data point represents the average of two tensile tests. The ASTM room temperature tensile requirements for SA 508 Class 2a are a minimum yield strength of 65 ksi (450 MPa), a range in ultimate strength of 90 to 115 ksi (620 to 795 MPa), and minimum total elongation and area reductions of 16 and 35 percent, respectively. The minimum specified room temperature yield strength for SA 533 Grade B Class 2 steel equals 70 ksi (485 MPa), while all other tensile requirements are identical with those of the SA 508 Class 2a steel. Both steels easily conform to all ASTM tensile requirements irrespective of heat treatment (see Table A-2).

The yield and ultimate strengths of as received and stress relieved (48 hours at 1000°F, 538°C) SA 508 Class 2a steel were basically identical while the higher temperature (1125°F, 607°C) stress relief heat treatments resulted in an increase in both strength levels. It is difficult to observe a clear trend between heat treatment and strength relative to the SA 533 Grade B Class 2 steel. Interestingly, the 24 hours at 1125°F (670°C) stress relief produced the highest yield and ultimate strengths for both materials. The ductility (reduction in area and percent elongation) of both materials was essentially independent of stress relief heat treatment.

Charpy Impact

Charpy V-notch impact properties of the SA 508 Class 2a and SA 533 Grade B Class 2 steels are illustrated in Figures A-3 and A-4, respectively, and summarized along with the drop weight nil-ductility transition (NDT) temperatures and corresponding reference temperatures (RT_{NDT}) in Table A-3. 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. These reference temperatures are required so that the dynamic fracture toughness data can be plotted versus $T-RT_{NDT}$ for comparison with the ASME specified minimum reference toughness K_{IR} curve. Reference temperatures for the SA 508 Class 2a and SA 533 Grade B Class 2 steels were controlled by the 50 ft-lb energy absorption temperatures and drop weight NDT temperatures, respectively.

The higher temperature (1125°F, 607°C) stress relief heat treatments produced the highest: a) fracture appearance transition temperatures (FATT), b) 50 ft-lb energy absorption temperatures, c) 35 mil lateral expansion temperatures, d) drop weight NDT temperatures and e) corresponding reference temperatures relative to SA 508 Class 2a steel. Thus, the higher temperature stress relief heat treatments have a moderately detrimental influence on the Charpy impact and drop weight NDT properties of SA 508 Class 2a steel.

No obvious trend between the stress relief heat treatments and Charpy impact values is apparent relative to the SA 533 Grade B Class 2 steel, other than that the upper shelf energy absorption levels and lateral expansions behaved exactly opposite of those demonstrated by the SA 508 Class 2a steel. For the SA 533 Grade B Class 2 steel, the lowest temperature stress relief (1000°F, 538°C) produced the lowest level of upper shelf energy absorption and smallest lateral expansion. In addition, the various stress relief heat treatments had no influence on the drop weight NDT temperatures of SA 533 Grade B Class 2 steel and, since for this material the reference temperatures were controlled by the drop weight NDT temperatures, the reference temperatures were also unaffected by the stress relief heat treatments.

Dynamic Fracture Toughness

Dynamic fracture toughness properties were developed on two quenched and tempered pressure vessel steels (SA 508 Class 2a and SA 533 Grade B Class 2) which had been subjected to one of three long time post-weld type stress relief heat treatments:

48 hours at 1000°F (538°C)
24 hours at 1125°F (607°C)
48 hours at 1125°F (607°C)

Figure A-5 illustrates the dynamic fracture toughness properties of SA 508 Class 2a steel plotted versus absolute temperature. The closed points representing the upper shelf dynamic fracture toughness properties of SA 508 Class 2a were developed via the modified resistance curves of Figure A-6. Clearly, the SA 508 Class 2a steel stress relieved for 24 or 48 hours at 1125°F (607°C) demonstrates inferior dynamic fracture toughness compared with the as received or 1000°F (538°C) stress relieved material. This behavior is consistent with the Charpy impact and drop weight NDT properties developed on this material, where the highest temperature stress relief resulted in moderately inferior properties compared with the as received and 48 hours at 1000°F (538°C) properties. This same trend is observed when the data is plotted versus T-RT_{NDT} for comparison with the ASME specified minimum reference toughness K_{IR} curve (see Figure A-7). Although these long time post weld type stress relief heat treatments definitely degrade the dynamic fracture toughness of SA 508 Class 2a steel, the point that must be emphasized is that all the dynamic fracture toughness values easily exceeded the ASME specified minimum reference toughness K_{IR} curve.

Interestingly, the dynamic fracture toughness of SA 508 Class 2a steel was improved relative to the as received condition upon stress relieving for 48 hours at 1000°F (538°C). Further work to examine whether additional lower temperature post weld heat treatment temperatures (in particular 950°F, 510°C) can lend even greater improvements to this material's dynamic fracture toughness, while still maintaining adequate stress relief, is planned.

The dynamic fracture toughness of SA 533 Grade B Class 2 steel is plotted versus absolute temperature and versus T-RT_{NDT} in Figures A-8 and A-9, respectively. The lowest dynamic fracture toughness again results from the 48 hours at 1125°F (607°C) stress relief heat treatment. As was the case for the SA 508 Class 2a steel, however, all the dynamic fracture toughness values fall substantially above the ASME specified minimum reference toughness K_{IR} curve.

DISCUSSION

A comparison of the dynamic fracture toughness properties of three heats of SA 508 Class 2a base and HAZ material are plotted versus absolute temperature and versus T-RT_{NDT} in Figures A-10 and A-11, respectively. Note that of the three as-received base materials, TO-5388 has superior dynamic fracture toughness. The obvious question that results considers what if a particular heat of SA 508 Class 2a base material which demonstrates below average dynamic fracture toughness (for example TO-5389) were stress relieved for 48 hours at 1125°F (607°C), would its dynamic fracture toughness values fall above the ASME specified minimum reference toughness K_{IR} curve? If an identical degradation or shift in temperature at a particular dynamic fracture toughness level is assumed as that experienced by TO-5388 when stress relieved for 48 hours at 1125°F (607°C), the dynamic fracture toughness of TO-5389 would still fall comfortably above the ASME specified minimum reference toughness K_{IR} curve.

Clearly, the SA 508 Class 2a heat affected zone (HAZ) materials which were stress relieved for 3/3.5 hours at 1125°F (607°C) demonstrated superior dynamic fracture toughness compared with the corresponding base materials. As was the case for the SA 508 Class 2a base materials, subjecting the corresponding HAZ materials to post weld stress relief heat treatments approaching 48 hours will undoubtedly reduce their dynamic fracture toughness. Because of the superior, initial dynamic fracture toughness properties characteristics of these SA 508 Class 2a HAZ materials (already stress relieved for 3/3.5 hours at 1125°F, 607°C), this anticipated degradation in dynamic fracture toughness which accompanies long time post-weld stress relief heat treatments should not result in dynamic fracture toughness values for these HAZ materials which fall below or, for that matter, even approach the ASME specified minimum reference toughness K_{IR} curve.

Typical, actual post-weld stress relief heat treatments on the primary pressure retaining weldments in recently fabricated components were in the range of 10 to 15 hours at 1125°F (607°C) or 15 to 18 hours at 1000°F (538°C). Depending on weldment thickness, the anticipated post weld stress relief heat treatment times can range from 3 to 30 hours at 1125°F (607°C) per the ASME code requirements. Therefore, the dynamic fracture toughness properties of any SA 508 Class 2a or SA 533 Grade B Class 2 pressure vessel which was subjected to the most severe currently employed stress relief heat treatment should easily exceed the ASME specified minimum reference toughness K_{IR} curve.

TABLE A-1 - Chemical Compositions and Heat Treatments of SA508 Cl 2a and SA533 Gr B Cl 2 Pressure Vessel Steels

			Chemical Compositions, Wt. Percent										
Material	Identification		C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Al
SA508 Cl 2a	TO-5387	Ladle	.20	.75	.008	.010	.28	.75	.38	.61	.012	--	--
		Check	.23	.66	.010	.022	.26	.85	.35	.59	<.03	--	--
	TO-5388	Ladle	.21	.63	.006	.012	.25	.73	.34	.62	.03	--	--
		Check	.19	.77	.010	.009	.28	.83	.39	.60	<.03	--	--
	TO-5389	Ladle	.22	.70	.008	.006	.28	.78	.36	.65	.035	--	--
		Check	.22	.66	.011	.007	.28	.82	.35	.60	<.03	--	--
		ASTM Requirements	.27 Max	.50-1.00	.012* Max	.025 Max	.15-.40	.50-1.00	.25-.45	.55-.70	.05 Max	.10* Max	--
SA533 Gr B Cl 2	A4943-3	Ladle	.20	1.38	.013	.005	.25	.65	.18	.57	--	.19	.043
		ASTM Requirements	.25 Max	1.15-1.50	.012* Max	.015* Max	.15-.40	.40-.70	--	.45-.60	.05* Max	.10* Max	--

*Optional Restrictive Chemistry

Material		Heat Treatment
SA508 Cl 2a	Austenitize	1580°F (860°C), hold 4 hrs , Water Quench
	Temper	1230°F (666°C), hold 6 hrs , Furnace Cool
SA533 Gr B Cl 2	Austenitize	1650°F (899°C), hold 4 hrs , Water Quench
	Temper	1260°F (682°C), hold 4 hrs , Furnace Cool

TABLE A-2 - Room Temperature Tensile Properties of SA508 Cl 2a and SA533 Gr B Cl 2 Pressure Vessel Steels

Material	Heat Treatment	Yield Strength		Ultimate Strength		Reduction in Area	Elongation
		ksi	MPa	ksi	MPa	%	%
SA508 Cl 2a	As Received	79.0	545	97.5	672	59.4	22.1
	48 hrs at 1000°F	80.0	552	99.0	683	58.8	23.2
	24 hrs at 1125°F	87.3	602	103.9	716	57.6	19.7
	48 hrs at 1125°F	83.3	574	100.3	692	59.6	20.8
SA533 Gr B Cl 2	48 hrs at 1000°F	78.7	543	99.0	683	72.6	26.0
	24 hrs at 1125°F	82.0	565	100.7	694	71.2	23.3
	48 hrs at 1125°F	76.3	526	95.5	658	72.2	24.9

TABLE A-3 - Charpy Impact and Drop Weight Properties of SA508 Cl 2a and SA533 Gr B Cl 2 Pressure Vessel Steels

Material	Heat Treatment	FATT		50 ft-lb Energy Temp.		35 mil Lateral Exp. Temp.		NDT Temperature		RT_{NDT}	
		°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
SA508 Cl 2a	As Received	40	4	65	18	35	2	-10	-23	5	-15
	48 hrs at 1000°F	35	2	80	27	20	- 7	-10	-23	20	- 7
	24 hrs at 1125°F	95	35	125	52	55	13	40	4	65	18
	48 hrs at 1125°F	75	24	90	32	60	16	0	-18	30	- 1
SA533 Gr B Cl 2	48 hrs at 1000°F	40	4	25	- 4	15	- 9	-30	-34	-30	-34
	24 hrs at 1125°F	25	- 4	5	-15	-10	-23	-30	-34	-30	-34
	48 hrs at 1125°F	35	2	-10	-23	-40	-40	-30	-34	-30	-34

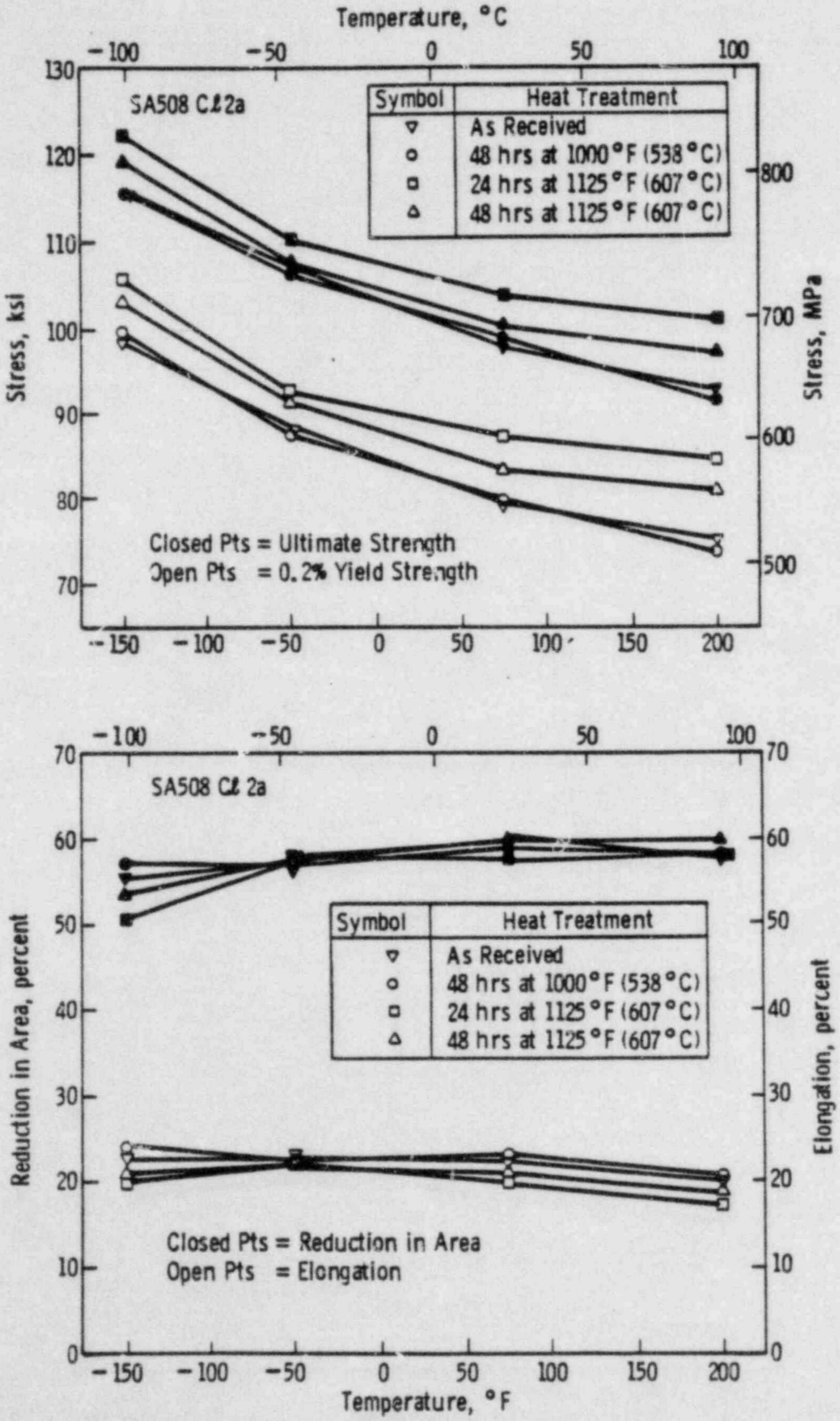


FIGURE A-1 —The influence of long-time post weld type heat treatments on the tensile properties of SA508 Cℓ2a pressure vessel steel

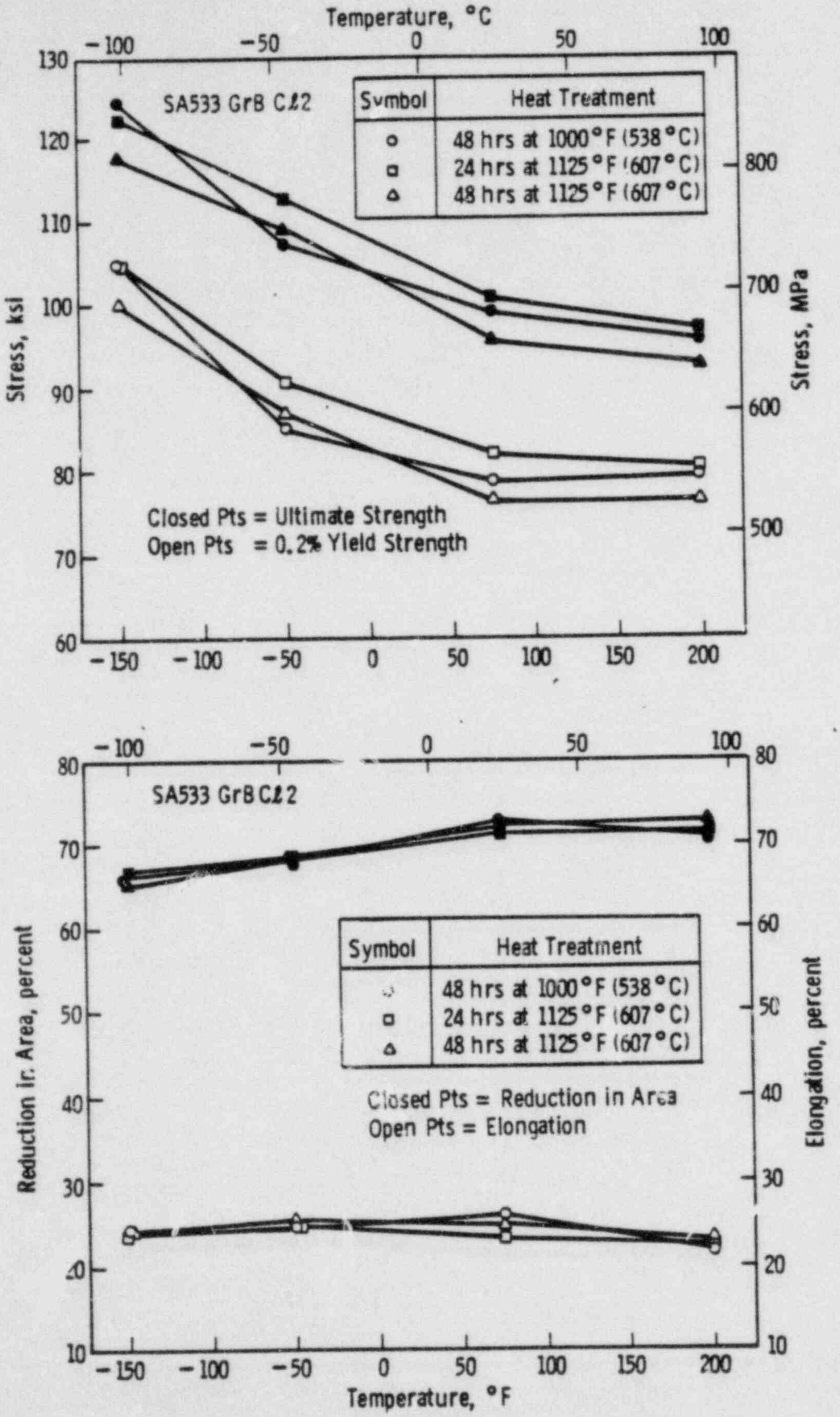


FIGURE —The influence of long-time post weld type heat treatments on the tensile properties of SA533 GrB Cℓ2 pressure vessel steel

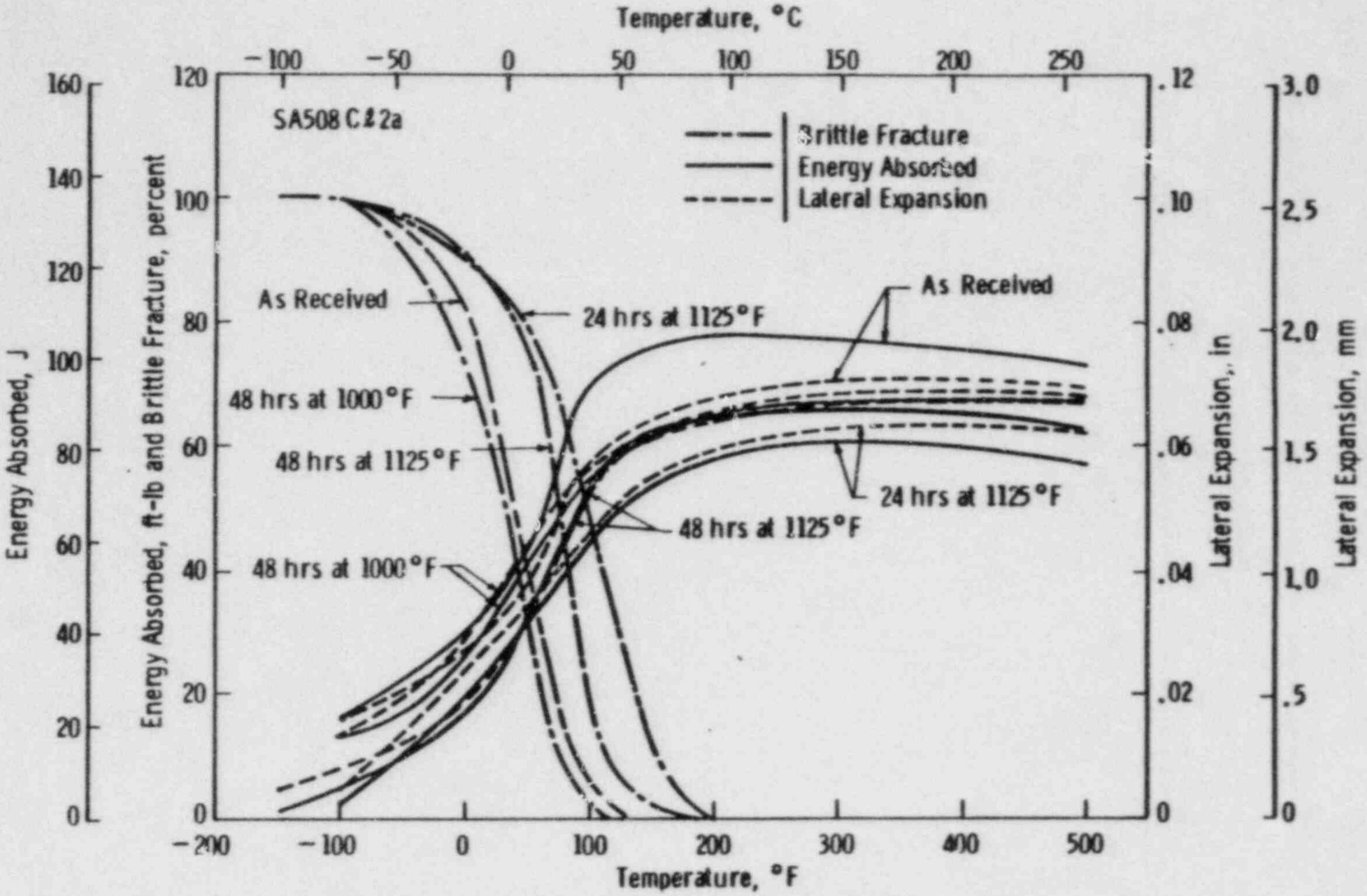


FIGURE A-3 — The influence of long-time post weld type heat treatments on the Charpy impact properties of SA508 Cℓ 2a pressure vessel steel

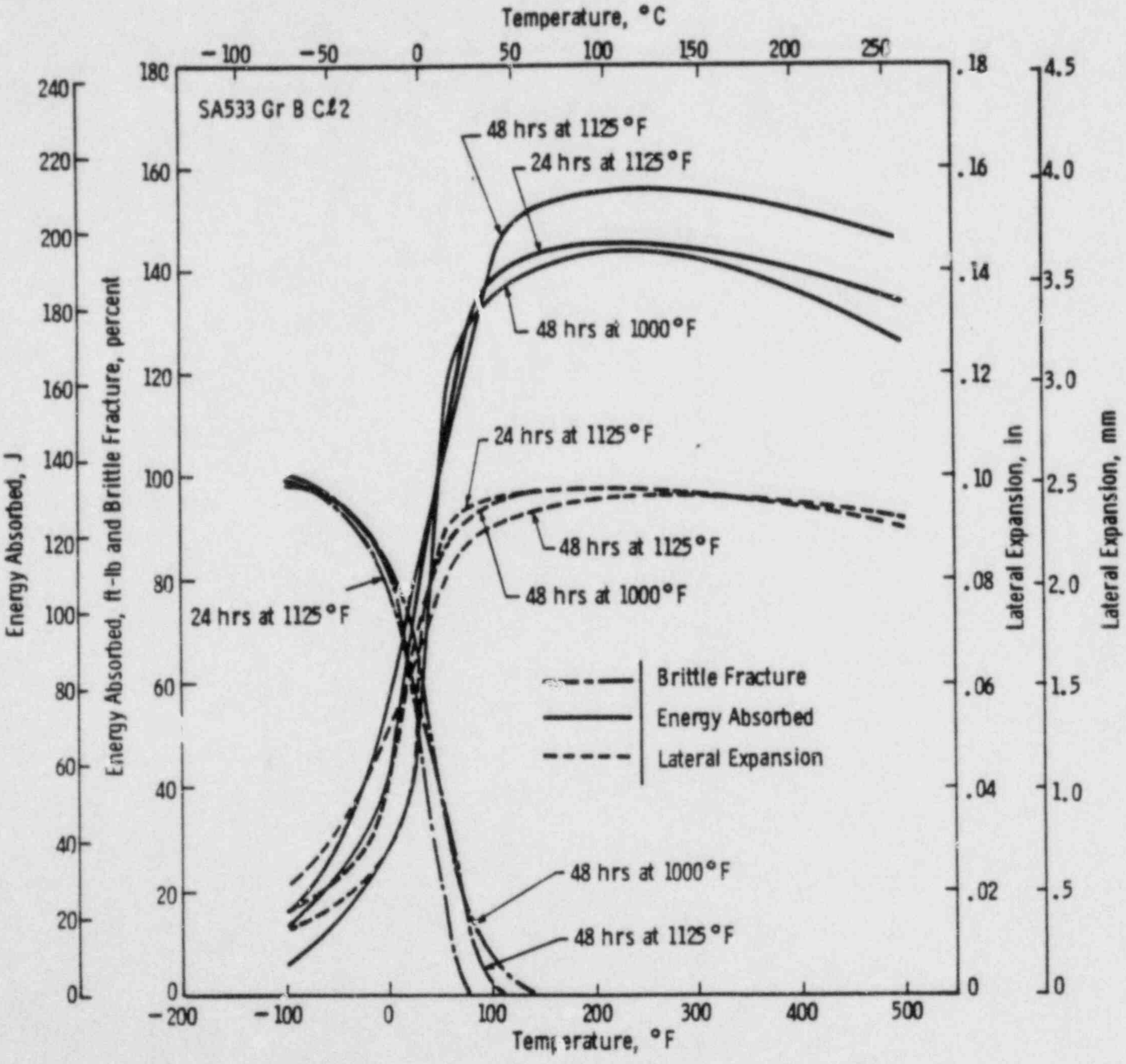


FIGURE A-4 —The influence of long-time post weld type heat treatments on the Charpy impact properties of SA533 GrB Cℓ2 pressure vessel steel

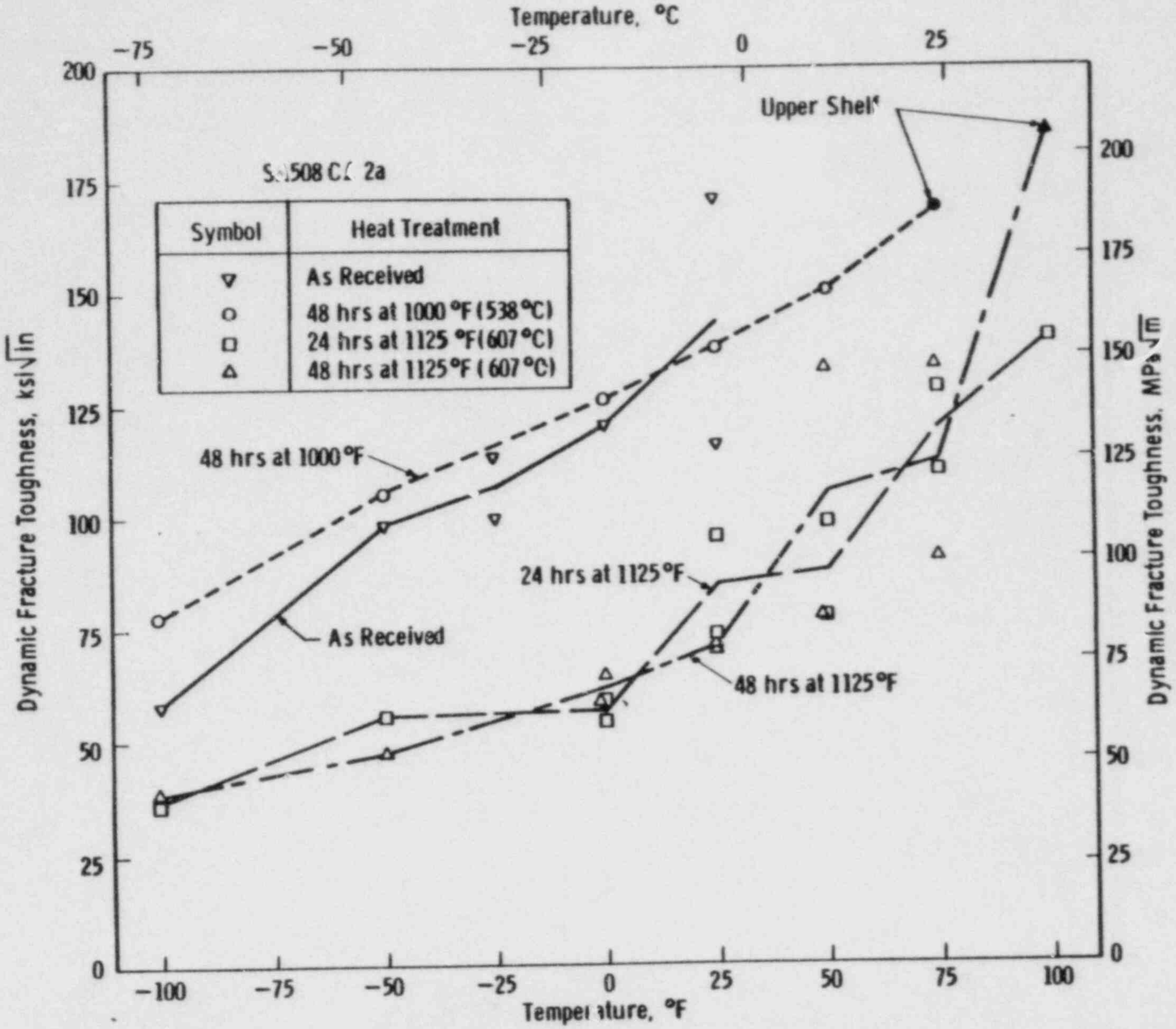


FIGURE A-5 —The influence of long-time, post weld type heat treatments on the dynamic fracture toughness of SA508 Cℓ 2a pressure vessel steel

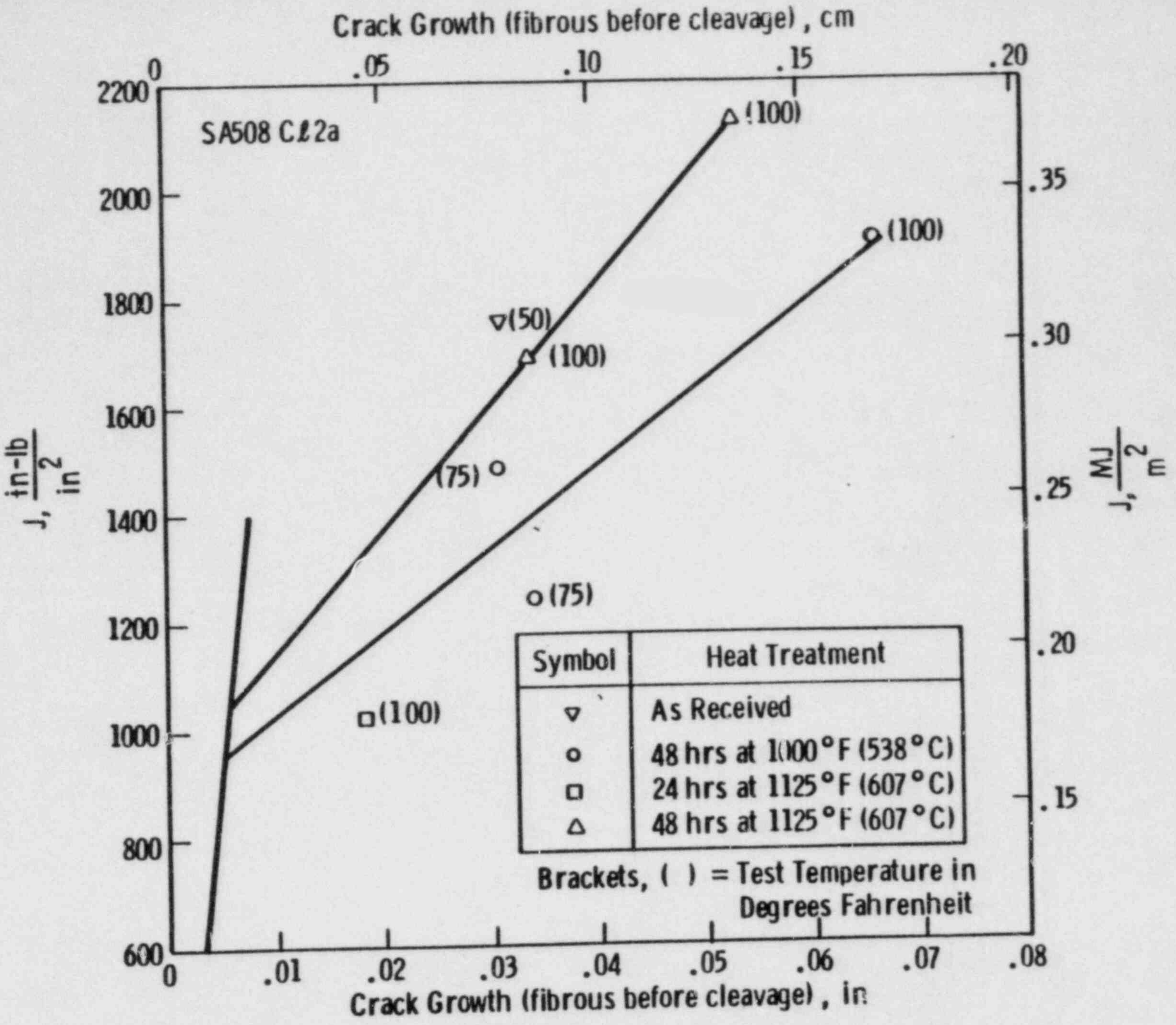


FIGURE A-6 —Modified J resistance curves for SA508 Cℓ 2a pressure vessel steel

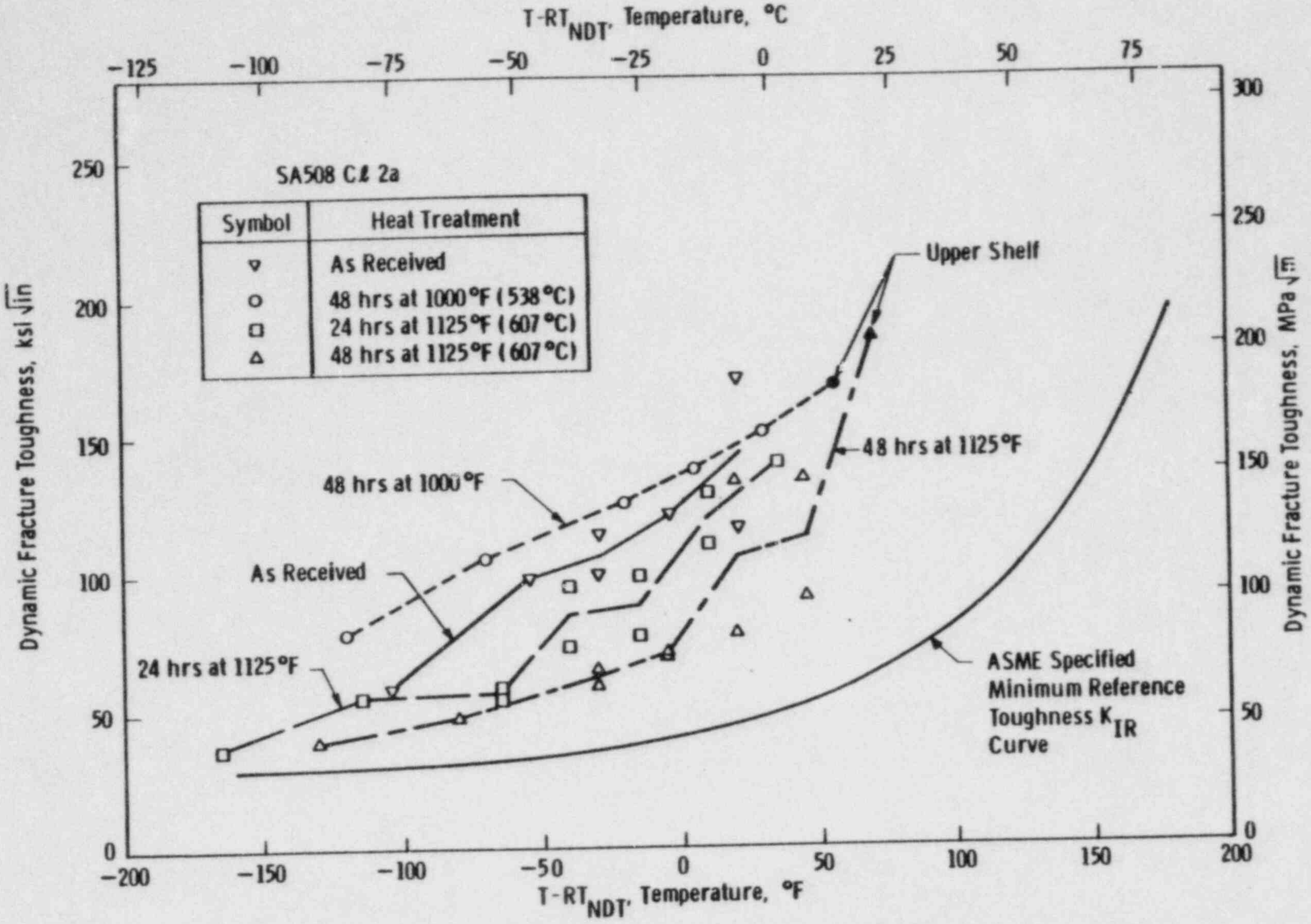


FIGURE A-7 —Fracture toughness versus T-RT_{NDT} for SA508 Cℓ 2a pressure vessel steel

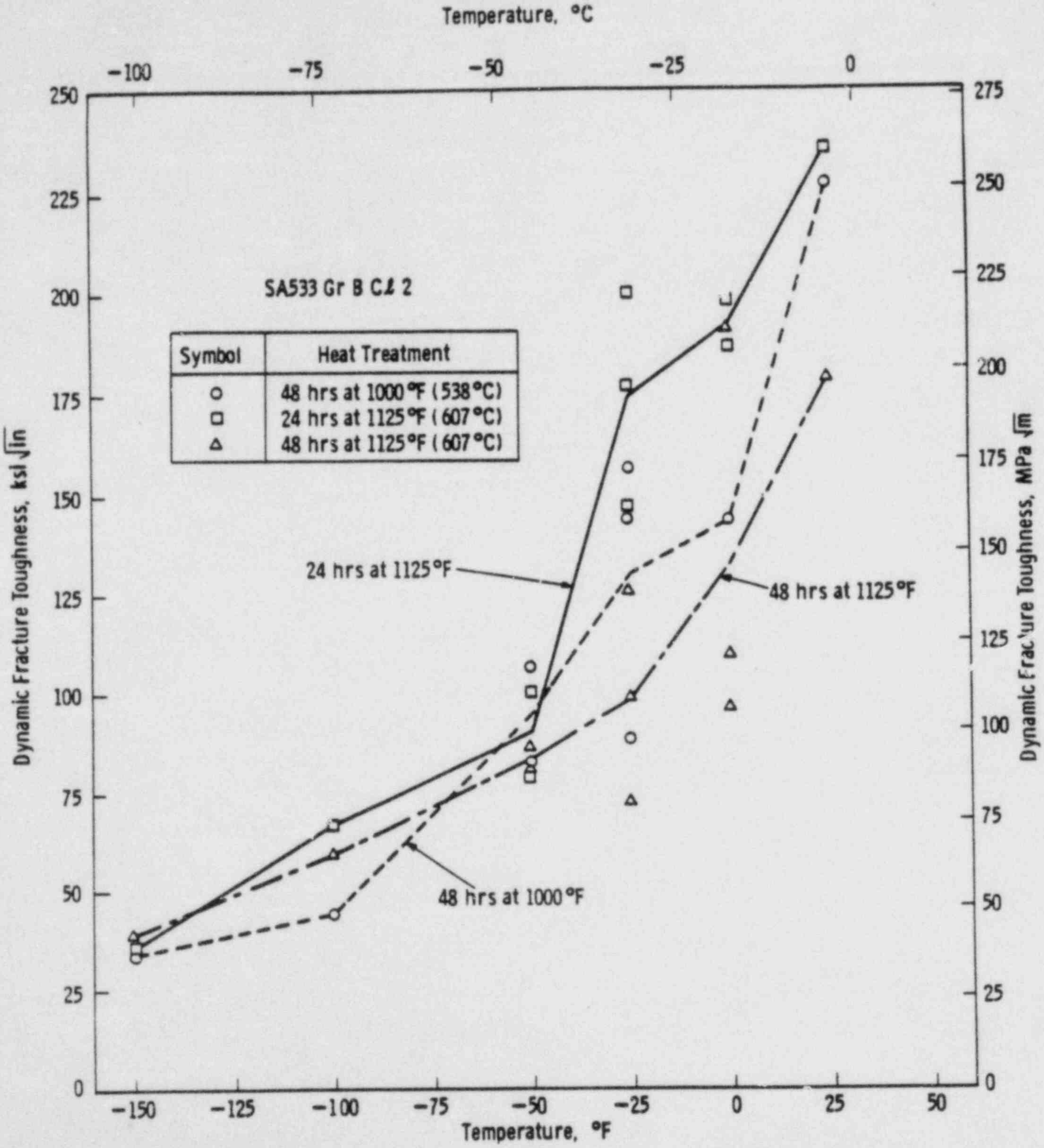


FIGURE A-8 —The influence of long-time post weld type heat treatments on the dynamic fracture toughness of SA533 Gr B Cℓ 2 pressure vessel steel

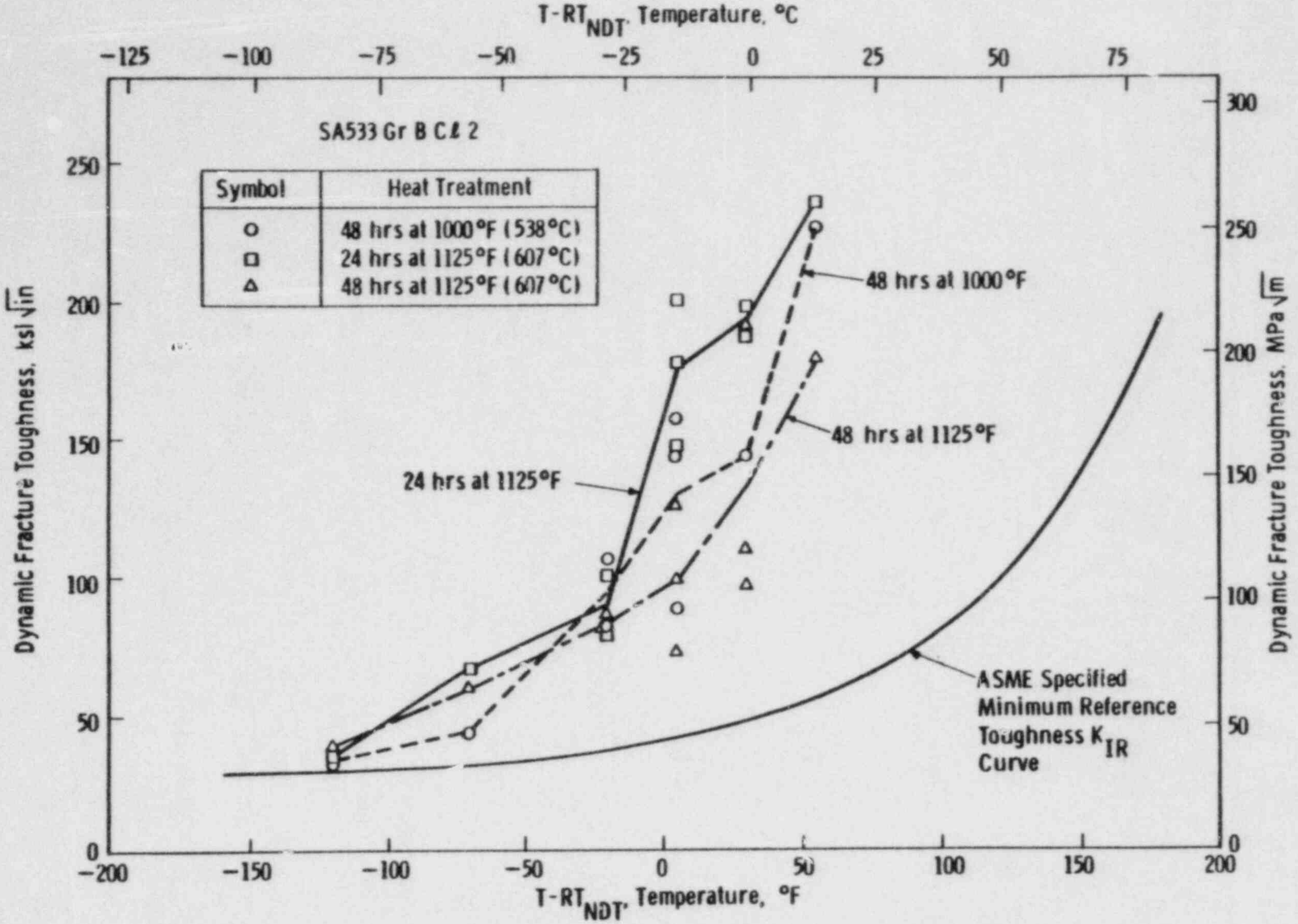


FIGURE A-9 —Fracture toughness versus T-RT_{NDT} for SA533 Gr B Cℓ 2 pressure vessel steel

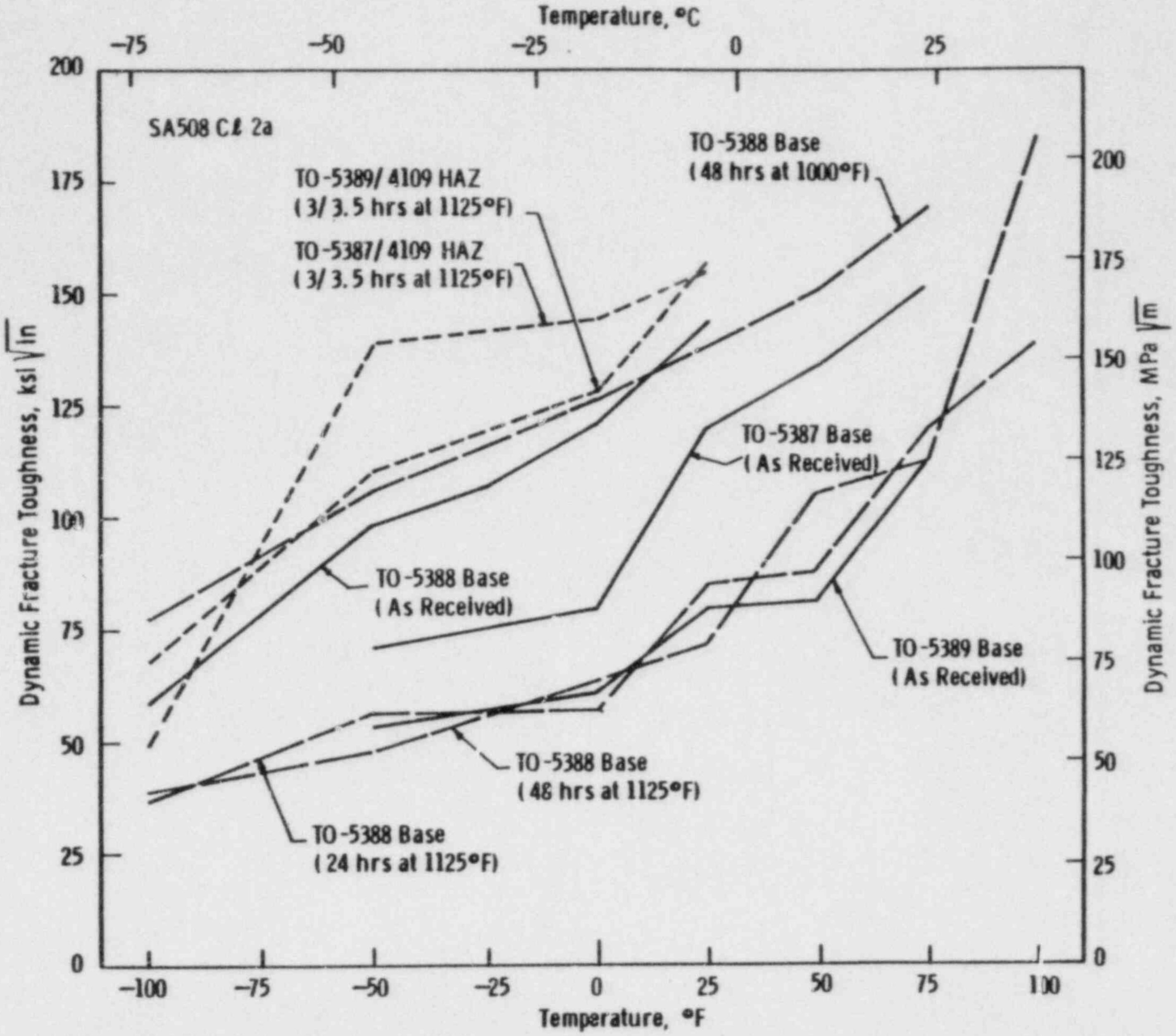


FIGURE A-10 — Comparison of the dynamic fracture toughness of several heats of SA508 Cℓ 2a base and HAZ material

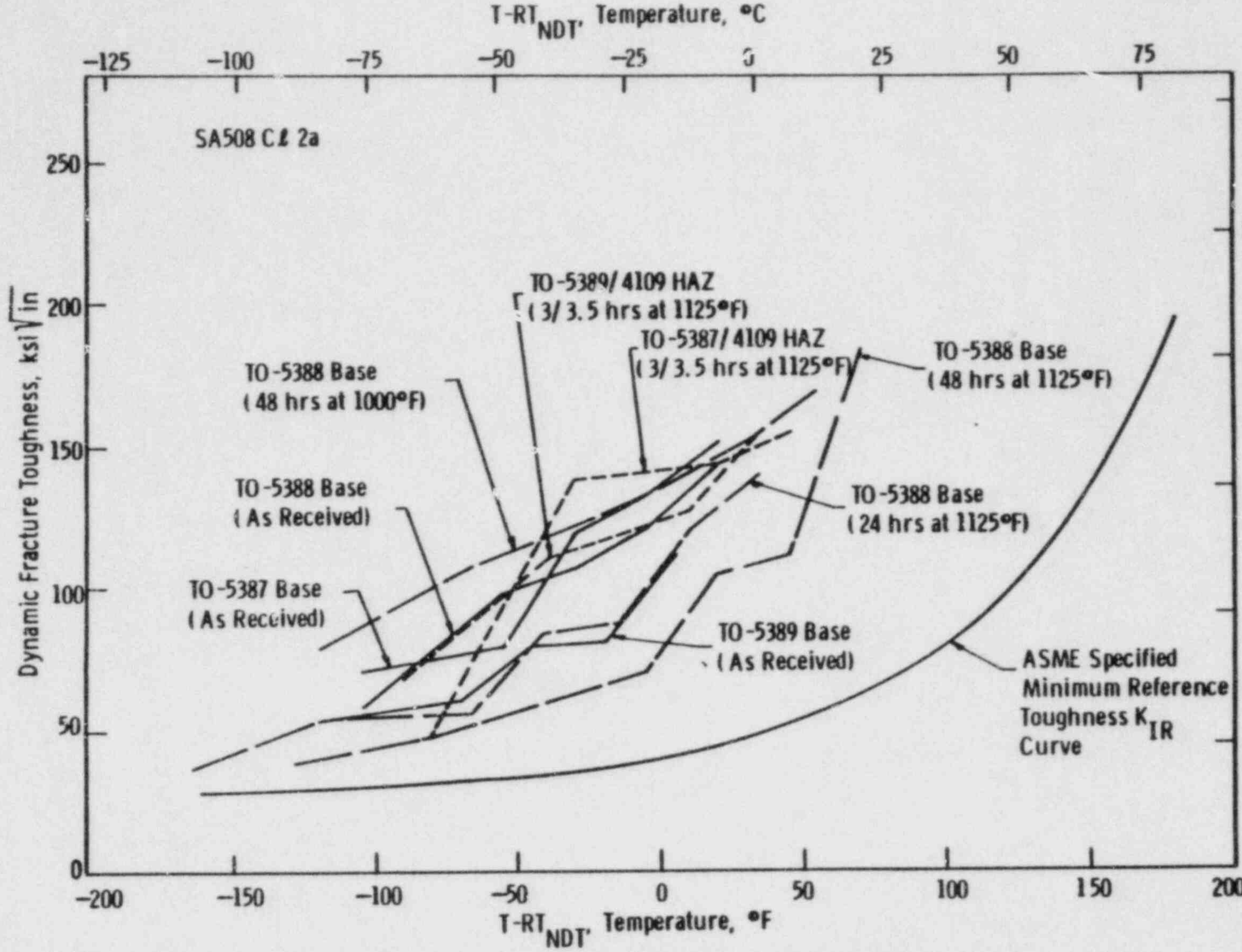


FIGURE A-11 — Fracture toughness versus T-RT$_{NDT}$ for several heats of SA508 Cℓ 2a base and HAZ material