CONF-801281--1

COMPARISON BETWEEN INSTRUMENTED PRECRACKED CHARPY AND COMPACT SPECIMEN TESTS OF CARBON STEELS*

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DE82 006811

Abstract

The General Atomic Company High Temperature Gas-Cooled Reactor (HTGR) is housed within a prestressed concrete reactor vessel (PCRV). Various carbon steel structural members serve as closures at penetrations in the vessel. A program of testing and evaluation is underway to determine the need for reference fracture toughness (K_{IR}) and indexing procedures for these materials as described in Appendix G to Section III, ASME Code for light water reactor steels. The materials of interest are carbon steel forgings (SA508, Class 1) and plates (SA537, Classes 1 and 2) as well as weldments of these steels. The fracture toughness behavior is characterized with instrumented precracked Charpy V-notch specimens (PCVN)—slow-bend and dynamic—and compact specimens (10-mm and 25-mm thicknesses) using both linear elastic (ASTM E399) and elastic-plastic (equivalent Energy and J-Integral) analytical procedures. For the dynamic PCVN tests, force-time traces are analyzed according to the procedures of the Pressure Vessel Research Council (PVRC)/Metal Properties Council (MPC).

Testing and analytical procedures are discussed and PCVN results are compared to those obtained with compact specimens. All fracture toughness data are compared to the existing K_{IR} curve from the ASME Code. Results obtained to date indicate the fracture toughness transition region from slow-bend PCVN specimens occurs at somewhat lower temperatures than that for the 10-mm-thick compact specimens, while the upper shelf region for the PCVN is lower than that for the 10-mm compact specimen. The dynamic PCVN results show a substantial shift in the transition region to higher temperatures and upper shelf values of fracture toughness similar to those for the 25.4-mm compact specimens.

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*Research sponsored by the Gas-Cooled Reactor Division, Office of Advance Nuclear Systems and Projects, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

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1. INTRODUCTION

The High Temperature Gas-Cooled Reactor (HTGR) designed by General Atomic Company (GA) is housed within a prestressed concrete reactor vessel (PCRV) such as shown in Figure 1. The primary function of the steel liner is to act as a leak-tight barrier to the helium coolant not to serve as a primary structural member. There are thick-section plates and forgings, however, which serve as closures at various penetrations in the vessel. These closures are structural in nature and, as such, are required by Section III, Division 2 of the ASME Boiler and Pressure Vessel Code to meet the toughness requirements of Section III, Division.[1] Guidelines for reference fracture toughness, K_{IR}, are provided in Appendix G (Protection Against Nonductile Failure)[2] of Division 1. These guidelines are presented in the form of a K_{IR} curve which requires indexing procedures using Charpy V-notch (Cv) impact and drop-weight Nil-Ductility Temperature (NDT) tests.

The guidelines were developed with low alloy steels used in the fabrication of light water reactor pressure vessels, whereas the structural steels in the PCRV are primarily carbon steels. A program of fracture toughness testing and analysis is being performed with the PCRV steels to determine the applicability of the Appendix G guidelines or whether a separate K_{IR} curve and/or indexing procedure must be developed for PCRV pressure boundary steels.

The fracture toughness behavior is characterized with instrumented precracked Charpy specimens (PCVN) (slow-bend and dynamic) and compact specimens (CS) (10-mm and 25.4-mm thicknesses) using both linear elastic (K_{IC}) and elastic-plastic analytical procedures (Equivalent Energy and J-Integral). The instrumented slow-bend and dynamic PCVN tests were chosen to investigate the plausibility of using small specimens to characterize the fracture toughness when larger specimens are impractical, as in heat-affected zones of weldments or when material availability is limited. For a specific material or class of materials, a correlation of small specimens to large specimens because of dimensional constraints, small specimens (such as PCVN) have less measure capacity, regarding fracture toughness, than do large specimens (such as 25.4 mm CS). For a specific material or class of materials, a correlation between small and large specimen fracture toughness would be helpful for characterizing toughness behavior as well as for the situations mentioned above. This is especially important in the transition region so that toughness degradation studies (e.g., radiation effects) can be confidently predicted.

2. EXPERIMENTAL PROCEDURES

2.1 Specimen Removal

All specimens reported here were oriented transverse to the major working direction with the notch (for Charpy and compact specimens) oriented perpendicular to the surface. Specimens were taken at a depth of at least one-quarter of the thickness from a rolled surface.

2.2 Nil-Ductility Temperature Tests

The drop-weight NDT was determined in accordance with the procedures of ASTM Standard E208.[3] The P-3 specimen was used for all tests and the Reference Temperature NDT (RT_{NDT}) was determined as required in paragraph NB-2330 of Reference 2. That is, if the material exhibits at least 50 ft-lbs energy absorption and 0.035 in. lateral expansion (68 joules and 0.889 mm) in a Cv test at a temperature 60°F (33°C) higher than the NDT, then the RT_{NDT} is equal to the NDT. If the Cv requirements are not met, tests are conducted at increasing temperature increments [normally 10°F (5.5°C)] until they are satisfied. The RT_{NDT} is then determined by subtracting 60°F (33°C) from the test temperature at which the Cv requirements are met.

2.3 Charpy V-Notch Impact Testing

Except for temperature conditioning, Charpy V-notch impact tests were conducted in accordance with the requirements of ASTM Procedure E-23.[4] A Dynatup instrumented tup and associated electronics were used to obtain force-time records of the test on a high speed Nicolet digital oscilloscope. All force-time traces were stored on magnetic tape cartridges through a

Hewlett-Packard 9825B computer and used to assist in fracture analyses when necessary. The testing system is shown in Figure 2 which details the instrumented tup and the automated specimen transfer device. The transfer device includes a temperature control chamber where specimens were heated by electrical resistance or cooled with nitrogen gas.

2.4 Precracked Charpy Slow-Bend Tests

Charpy V-notch specimens were precracked in a Physmet fatigue machine at room temperature to a crack length-to-specimen width ratio (a/W) of about 0.5. Fracture toughness tests were conducted in a Physmet slow-bend machine with temperature control by immersion in heated oil or cooled isopentane (cooled by dry ice or liquid nitrogen). Specimen loading was monitored by a load cell and displacement was measured with LVDTs mounted on the loading frame. An autographic record of load vs displacement was obtained and used in subsequent analyses.

2.5 Precracked Charpy Dynamic Tests

Charpy V-notch specimens were precracked as described in Section 2.4 and fracture toughness tests were conducted in the impact system described in Section 2.3. The input energy used was generally 136 joules (100 ft-lbs) and below (corresponding to impact velocity of 3.35 m/sec and slower) depending on the predicted energy absorption by the specimen. The impact velocity was minimized toreduce the effects of inertial loading.[5,6] Force-time traces were obtained and stored for analysis as described in Section 2.3.

2.6 Compact Specimen Tests

Compact specimens of 10-mm and 25.4-mm thicknesses were fatigue precracked at room temperature with an MTS servohydraulic machine in accordance with ASTM procedure E399[7] to an a/W of about 0.5. Fracture toughness tests were conducted in the same machine with temperature control by heated air or cooled nitrogen gas. A load cell and clip gage used to monitor load and displacement nitrogen gas. A load cell and clip gage used to monitor load and displacement provided an autographic record for analysis. For the 25.4-mm specimen, the clip gage was mounted on machined knife edges located along the loading line while knife edges were mounted on the front face of the 10-mm specimen.

2.7 Analytical Procedures

All precracked specimens were analyzed for elastic-plastic fracture toughness using both the Equivalent Energy[8] and J-Integral[9] procedures. The procedures of ASTM E399 were used to analyze for linear elastic behavior. For compact specimens, the Merkle-Corten analysis was applied to correct for the tensile component during loading.[10] Testing and analysis of the dynamic ~~PCCV~~ PCVN specimen generally followed the PVRC/MPC recommendations outlined in Reference 11. It should be noted that the analytical procedures utilized the assumption that the onset of crack extension occurs at maximum load. For purposes of this report, the onset of crack extension is defined as the onset of in-plane crack extension whereby the crack is extended in a direction parallel to the notch/fatigue crack. It is well known that variations in specimen size, geometry, and material can result in the onset of crack extension prior to maximum load. These observations provide a strong motivation for the current development of elastic-plastic fracture toughness procedures based on the resistance curve concept.

To determine the validity of using the maximum load point as the onset of crack extension, both slow-bend PCVN and 10-mm compact specimens were tested in resistance curve fashion at room temperature by loading each individual specimen to a predetermined displacement, unloading, heat-tinting and fracturing in liquid nitrogen.[12] The Equivalent Energy parameter, K_{Icd}, and the J-Integral parameter, J, were plotted vs the crack extension measured on the fracture surface. On a plot of J vs Δa (crack extension), the J values for the PCVN and the 10 mm compact specimen do not deviate from the blunting line until maximum load has been attained. For the 25.4-mm compact specimen, a computerized unloading compliance[13] procedure was employed and the observations were similar to those for the smaller specimens. It is concluded, then, that the use of maximum load as the measuring point for onset of crack extension is reasonable for these materials. For the slow-bend (3-pt bend) PCVN tests, displacement was measured between the loading tups and specimen supports. This mechod introduces extraneous displacements due to factors such as specimen indentation by the tup and supports as well as elastic displacements of the test fixtures. Since specimen load point displacement is required for proper analysis, the load-displacement record must be corrected for those extraneous displacements (referred to as machine errors). Two methods were used to determine the machine erross: (1) a compliance based correction similar to that described by Server[14] for compact specimen testing, and (2) the method discussed by ____[15] in which an unnotched specimen is loaded to measure the extraneous displacements. Both methods provided similar corrections and resulted in close agreement of the Equivalent Energy and J-Integral parameters for all tests.

3. MATERIAL DESCRIPTION

The base materials studied are shown in Table 1. All four materials are within the general classification of carbon steels with grain sizes ranging from ASTM 6 to 8. The drop-weight NDT and room temperature tensile properties are given in Table 2. It is interesting to note that the SA508, Class 1 forging, although much thicker than the plate steels, has the lowest NDT. Detailed results of characterization testing (metallography, hardness, chemical analyses, tensile, Charpy impact, and drop-weight NDT) are reported in ORNL/TM-7480.[16]

4. RESULTS

4.1 Charpy-Impact Results

The results of Cv impact tests are summarized in Figure 3. All materials showed high toughnesses. The two quenched and tempered steels exhibited lower transition temperatures and higher upper shelf energies than the two air-cooled steels. Figure 4 shows the C_V toughness vs temperature normalized to the RT_{NDT} for the four PCRV steels and SA533, Grade B, Class 1 (HSST Plate 02).[17] Except for plate P1, the PCRV steels exhibit superior Cv toughness behavior. It is interesting to note the differences among the steels when their absorbed energy values are compared at the NDT; three of the PCRV steels exhibit over twice the absorbed energy of the SA533 steel. Although not shown on the figure, all steels except plate P1 exhibit significant increases in absorbed energy at temperatures above the onset of upper shelf behavior (onset of upper shelf determined as described in References 16 and 18).

4.2 Slow-Bend Precracked Charpy Results

Results of slow-bend PCCV testing are shown in Figure 5. The fracture toughness of all four steels reached upper shelf levels at -50°C or lower, indicating fully ductile behavior at the NDT (see Section 3). As was seen with the Cv impact results, the quenched and tempered steels, F1 and P4, exhibited superior slow-bend PCCV toughness compared with the air-cooled steels.

4.3 Dynamic PCVN Results

Figure 6 shows the results of fracture toughness vs temperature for the PCVN impact tests. It can be seen by comparing Fig. 5 and 6 that the toughness behavior has "shifted" to higher temperatures. The transition regions experienced shifts of about 75 K as a consequence of the increased strain rates. The curves also indicate sharper transition behavior from low to high energy values than the slow-bend results. Additionally, it is apparent that calculated upper shelf toughness values are about 50% higher than those for the slow-bend tests. Of particular interest is the observation that the dynamic toughness values at the NDT for each steel are at the lower portions of the curves where brittle fracture dominates. As with the other test results discussed, the quenched and tempered steels exhibited superior toughness compared to the air-cooled steels.

4.4 Comparison of PCCV and Compact Specimen Results

Figures 7 through 10 provide comparisons of results obtained with slow-bend and dynamic PCVN specimens to those obtained with 10-mm and 25.4-mm CS for each of the PCRV steels. The K_{IR} curve from Appendix G, adjusted according to the RT_{NDT} of the particular material, is included on each figure. A consistent observation for all four steels is that the transition regions, of the slow-bend PCVN specimens appear to occur at lower temperatures than those of the 10-mm CS (designated CVCS to identify it as a Charpy thickness compact specimen). If a fracture toughness of 150 MPA $\sqrt{m}$ is selected as the transition point (arbitrarily selected near the central portion of the curve) the curves exhibit upward temperature shifts of 15–20 K to higher temperatures. The slow bend PCVN upper shelf fracture toughnesses, however, are about the same as are those of the corresponding CVCS. The 25.4-mm CS (designated 1TCS to identify it as a one-inch-thick compact specimen) fracture toughness behavior in the transition region is very similar to that of the CVCS. The upper shelf levels of the 1TCS curves are approximately 30% higher than those of the CVCS and simply reflect the lower measuring capacity of the smaller specimen.

Regarding the dynamic ~~PCCV~~ PCVN curves, the previously noted shift of the transition regions to higher temperatures is evident in Fig/ 7–10 for all four materials. In almost every case, the dynamic curve is steeper than the other curves which indicates, of course, a more rapid transition from brittle to ductile behavior with increasing temperature for the dynamic tests compared to the static tests (all static tests were conducted at the standard slow loading rate as defined in ASTM E399). An additional effect of the higher strain rate was to increase the calculated upper shelf toughness levels. The dynamic ~~PCCV~~ PCVN upper shelf toughnesses ranged from about 15 to 35% greater than those of the static CVCS and PCVN. Interestingly, the upper shelf toughnesses for the dynamic PCVN were within 10% of those for the static ITCS. Relative to the K_{IR} curve, the dynamic PCVN results are more conservative than those of the static ~~PCCV~~ PCVN and CS tests in that the dynamic curves are closer to the K_{IR} curve.

5. DISCUSSION

Notched impact tests with Cv and drop-weight NDT specimens has demonstrated that there is not a consistent correlation between absorbed energy at the NDT (or RT_{NDT}) for carbon steels as is sometimes observed for LWR pressure vessel steels. Correlations between drop-weight NDT and the various fracture toughness results in this study can be made only on a qualitative basis. For example, the RT_{NDT} occurs at or higher than the onset of slow-bend PCCV upper shelf and at or below the onset of dynamic ~~PCCV~~ PCVN lower shelf for all four materials. The use of the RT_{NDT} as a reference point for fracture toughness has received much attention in the literature for its use as an index with a variety of steels much broader than those represented by the LWR pressure vessel steels for which it was developed.

The shift of fracture toughness behavior to higher temperatures exhibited by the dynamic PCCV tests is an expected result from testing at much higher strain rates. Those tests provide a more conservative representation of fracture toughness than do any of the static tests. What is not known, however, is how well they may represent the toughness results given by larger high strain rate compact specimen tests. In this program, for example, dynamic tests with 25.4-mm and larger compact specimens are planned to verify the dynamic ~~PCCV~~ PCVN results and to more realistically represent the conditions under which the existing K_{IR} curve was constructed.

Although it is gratifying to observe the close agreement between the CVCS and 1TCS in the transition range, the disparity in that region between the slow-bend PCCV PCVN and CVCS is disconcerting. Although the two specimens are equal in thickness, the remaining ligament, for equal a/w, of the CVCS is twice that of the PCVN specimen. It is not clear that the ligament size should cause the observed differences in the transition region. Further testing and investigations are being performed to resolve the observations.

Regarding the similarity in upper shelf fracture toughness values of the dynamic PCVN and 1TCS, the results may be fortuitous. However, since measuring capacity is related to plastic zone size, it is not necessarily surprising to observe higher toughness values on the upper shelf due to the increased yield strength of the material under dynamic loading conditions. Whether this agreement is applicable to a broader range of materials is yet to be determined.

With regard to the K_{IR} curve shown in the figures, dynamic and crack arrest fracture toughness tests (with specimens larger than the PCVN) were used in the construction of the curve.[19] The data presented in the figures show that the static fracture toughness curves (at a toughness value of 150 MPa $\sqrt{m}$) occur at temperatures over 100°C lower than the K_{IR} curve. Thus, the need for dynamic tests is supported by the results shown.

In analyzing the full usefulness of the PCVN specimen, other types of analyses (e.g., energy per area) can be utilized. The program underway to characterize the steels used in the PCRV will, in fact, examine a broad range of analyses and correlations in that regard. The results presented here represent the initial efforts to examine the significance of the instrumented PCVN test relative to generally accepted fracture toughness concepts. Based on those results, the following observations and conclusions can be summarized:

1. There is no consistent correlation of Charpy impact energy at the NDT for these steels;
2. The dynamic PCVN ~~PCCV~~ test shifts the fracture toughness transition about 75 K higher than that for the static tests;
3. The dynamic PCVN tests exhibit increased upper shelf fracture toughnesses up to 30% higher than those for the slow-bend PCVN;
4. The NDT (equal to RT_{NDT}) occurs at the lower portion of the dynamic PCVN curve where brittle fracture dominates;
5. The transition regions of the slow-bend PCVN curves occur at temperatures 15–20 K lower than those of the Charpy thickness compact specimens for reasons unknown at this time;
6. The upper shelf toughnesses of the dynamic PCVN specimens are in agreement with those of the 25.4-mm compact specimens; and
7. The instrumented PCVN test is useful for providing more conservative fracture toughness behavior but its quantitative applicability has yet to be determined.

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Table 1. Description of Materials

Material Identification	Specification	Producer	Heat No.	Thickness mm (in.)	Heat Treatment[a]	Form
F1	SA508, Class 1 Case 1332-6	Japan Steel Works	49C510-1-1-3	140 (5 1/2)	WQ + T + SPWHT	Ring Forging
P1	SA537, Class 1	Armco Steel	47239	89 (3 1/2)	N + SPWHT	Plate, Formed to 3.95% Strain
P2	SA537, Class 1 Case 1557-1	Lukens Steel	RO 273	51 (2)	N + SPWHT	Plate, Formed to 1.95% Strain
P4	SA537, Class 2 Case 1557-1	Lukens Steel	RO 907	64 (2 1/2)	WQ + T + SPWHT	Plate, Formed to 1.56% Strain

[a] WQ - Water Quenched
T - Tempered
N - Normalized
SPWHT - Simulated Post Weld Heat Treatment

Table 2. NDT and Tensile Properties

Material Code	Specification	Drop-Weight NDT	Yield Strength[a] MPa (Ksi)	Ultimate Strength MPa (Ksi)	Total Elongation[b] (%)
F1	SA508 Class 1 Case 1332-1	-67°C (-70°F)	342 (49.5)	499 (72.3)	40.0
P1	SA537 Class 1	-40°C (-40°F)	353 (51.3)	551 (79.9)	32.2
P2	SA537 Class 1 Case 1557-1	-46°C (-50°F)	378 (54.9)	554 (80.4)	33.5
P4	SA537 Class 2 Case 1557-1	-51°C (-60°F)	404 (58.6)	571 (82.9)	31.6

[a] Lower yield strength values are reported and correspond to the 0.2% offset yield strength.

[b] The test specimens have an L/D ratio of 7. Elongation results have been corrected for an L/D ratio of 4.

Y-161602

LINER STEELS SERVE AS STRUCTURAL MEMBERS AT PENETRATIONS

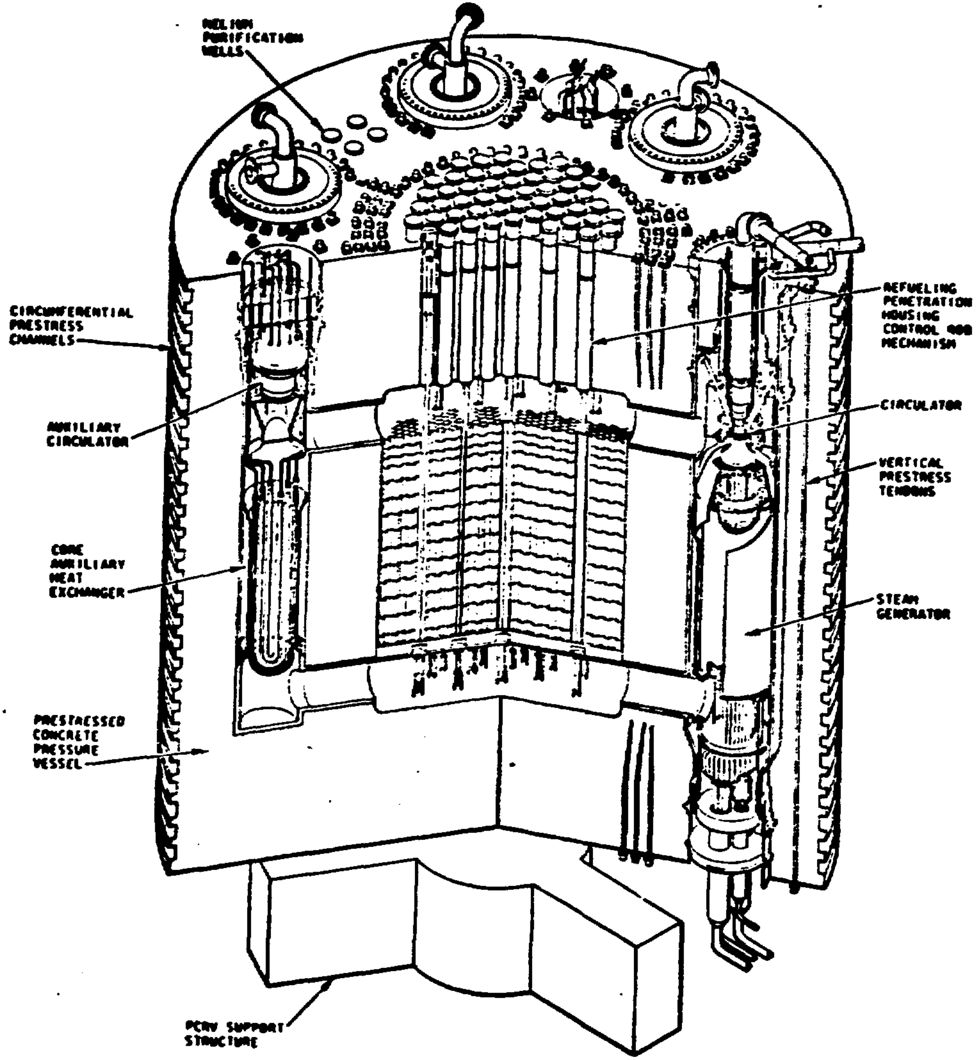
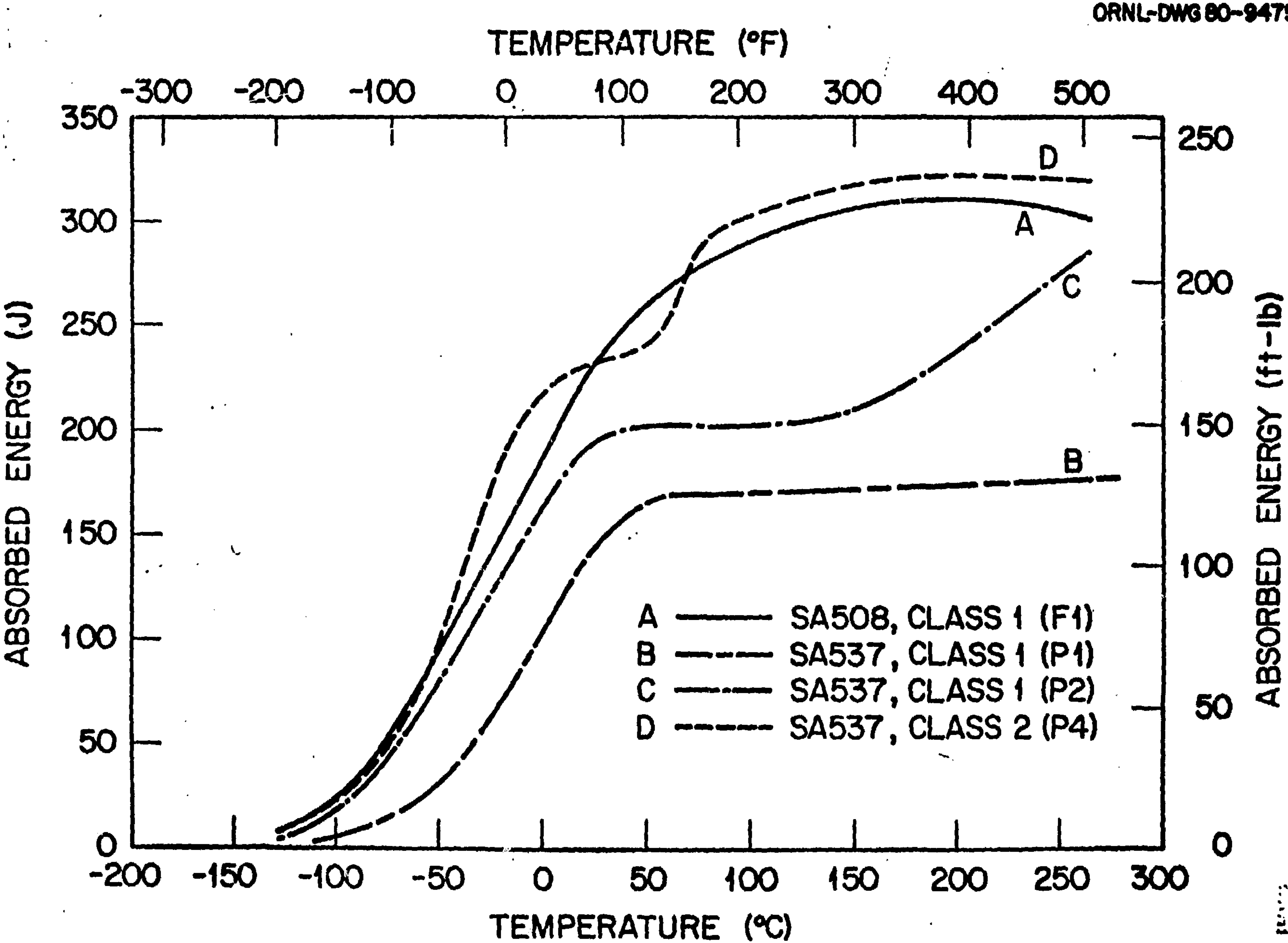


Figure 1

Y-170033


ORNL-DWG 80-9475
TEMPERATURE (°F)
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-200
-100
0
100
200
300
400
500
ABSORBED ENERGY (J)
350
300
250
200
150
100
50
0
ABSORBED ENERGY (ft-lb)
250
200
150
100
50
0
D
A
C
B
A SA508, CLASS 1 (F1)
B SA537, CLASS 1 (P1)
C SA537, CLASS 1 (P2)
D SA537, CLASS 2 (P4)
-200
-150
-100
-50
0
50
100
150
200
250
300
TEMPERATURE (°C)

Figure 3

ORNL-DWG 80-1182

CHARPY IMPACT TOUGHNESS OF PCRV LINER STEELS IS EQUAL TO OR SUPERIOR TO A LWR STEEL USED TO DEVELOP K_{IR} CURVE

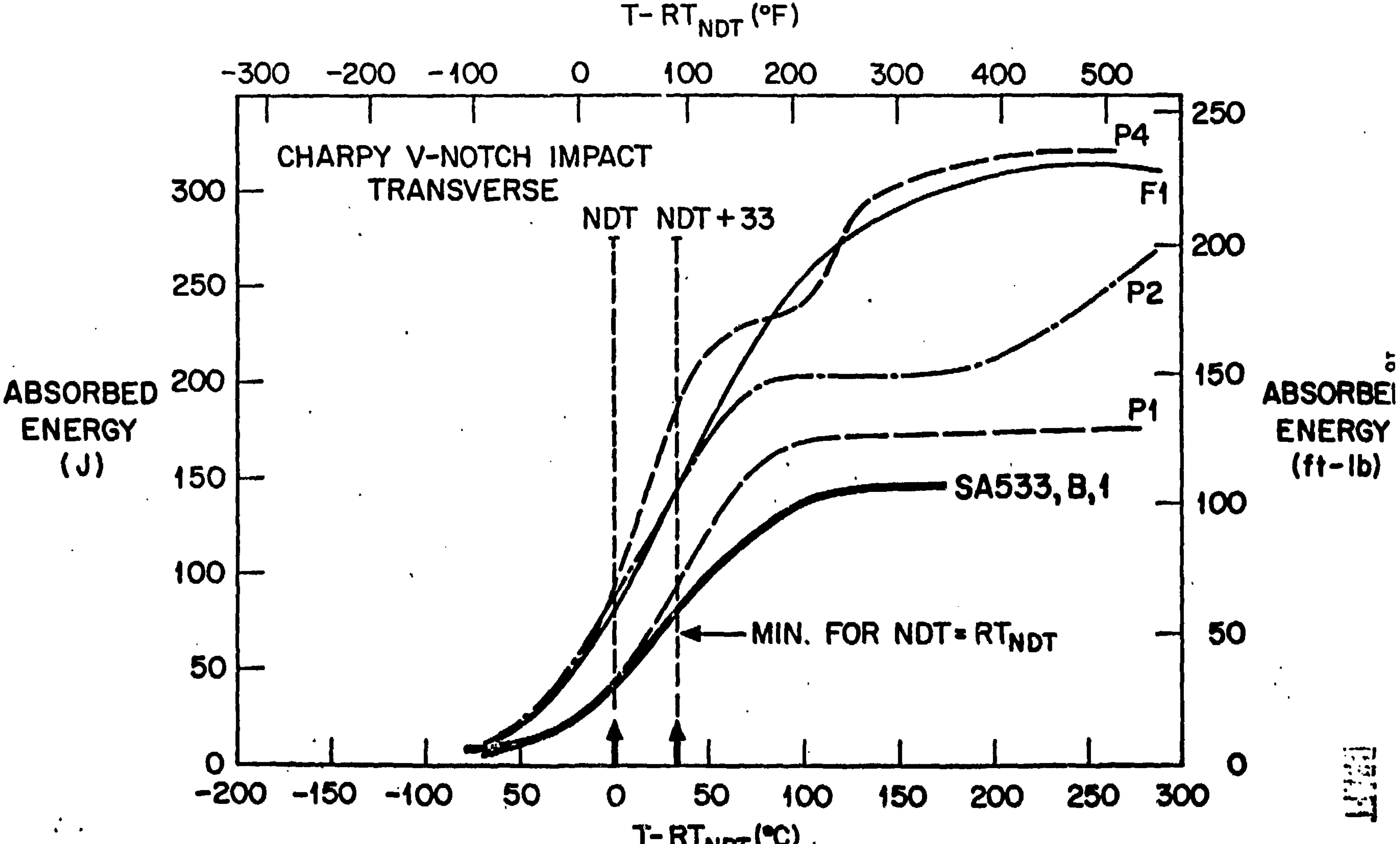

Figure 4