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USE OF INSTRUMENTED CHARPY TESTS TO DETERMINE ONSET OF UPPER-SHELF ENERGY

D. A. Canonico, W. J. Stelzman, R. G. Berggren, and R. K. Nanstad

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ABSTRACT

The definition of the Charpy V-notch (C_v) upper-shelf energy is an elusive target. Most researchers define the upper shelf as that temperature range in which the surface of the C_v specimen exhibits an appearance indicative of a 100% ductile fracture. The determination of the percent ductile fracture in a tested C_v specimen depends upon interpretation and can vary from individual to individual. We have sought to avoid the need for interpretation and have elected to base the selection of the C_v upper-shelf energy on the results from an instrumented impact test. The instrumented impact test provides a permanent record of the load-deflection history of a C_v specimen during the testing sequence. In the transition temperature regime (where the mode of failure changes from brittle at low temperatures to ductile at high temperatures) a precipitous drop in the load trace occurs. The amount of the drop decreases at higher temperatures until it is zero. The zero-drop-in-load temperature is identical to the onset of the C_v upper shelf. This relationship between the drop in load and energy in an instrumented impact test provides incontestable assurance that the C_v upper shelf has been obtained. This relationship between drop in load and temperature permits a prediction of the onset of the upper-shelf temperature with as few as two instrumented impact tests.

We have also shown that the nil-ductility temperature (NDT) (determined by the drop-weight test) is related to the C_v upper shelf. For the SA-508 Class 2 and SA-533 Grade B Class 1 steels employed in the fabrication of pressure vessels for light-water reactors C_v testing at NDT + 180°F (100°C) will provide upper-shelf energy values.

INTRODUCTION

Two steels are currently being employed in the fabrication of the pressure vessels for nuclear reactors — the SA-533 Grade B Class 1 and SA-508 Class 2 steels. Table 1 contains the chemical analysis and minimum mechanical property requirements for these steels. These pressure-vessel steels are embrittled as a consequence of an exposure to irradiation. The degree of embrittlement depends on the residual elements, specifically copper and phosphorus, which are usually found in commercial heats of these steels. This embrittlement is reflected by a change in the

Table 1. Material Specifications[a] for Pressure Vessel Steels

Material Identification	[illegible]	Mn	P	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SA-533 Grade B Class 1	0.25	1.15 1.50	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]		
SA-508 Class 2	0.27	0.50 0.90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2 1/4 Cr-1 Mo (ASTM A 387-67 Grade 22)	0.15	0.30 0.60	0.035	0.035	0.50		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
A 212-Grade B (ASTM A 212-61T)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	

[a] SA identification from [illegible]

[b] Single number indicates maximum [illegible]

toughness and strength properties. Surveillance programs employed in the nuclear industry are designed to predict the property changes that occur in the steels employed in the fabrication of a nuclear pressure vessel, and these changes are considered in the operation of an energy system.

United States Governmental regulations[1,2] dictate the minimum toughness requirements for these steels when they are initially put into service and during their serviceable lifetime. The Federal Register[1] describes the minimum allowable Charpy V-notch (C_v) upper-shelf energy of the steels employed in the fabrication of pressure vessels for nuclear applications. The Rules and Regulations state "the Charpy V-notch upper-shelf energy requirements for beltline region materials was set at 75 ft-lb for all cases without distinction as to the predicted amount of irradiation damage." These references suggest a standard definition of "upper-shelf" energy; however, such an explicit definition does not exist. In the absence of a standard definition, the Nuclear Regulatory Commission (NRC) has defined[2] the upper shelf ". . .as the average energy value for all specimens whose test temperature is above the upper end of the transition temperature region. Normally, at least three specimens should be included; more specimens should be included when the shelf level appears to be marginal." Assurance that the tests have indeed been conducted in the upper shelf is not guaranteed by this test procedure. The determination of the upper end of the transition temperature is not always self-evident. The upper-shelf behavior of various grades of steel is not consistent. The energy may increase, decrease, or remain constant. An example of each mode of

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[1] *Fed. Regist.*, 38(136): 19013 (July 17, 1973), Washington, D.C.

[2] U.S. Nuclear Regulatory Commission, *Regulatory Guide 1.99, Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials,* Tentative.

behavior is shown[3] in Fig. 1. The Charpy V-notch (C_v) data presented in Fig. 1 are from the same steel plate (plate 01) taken from three locations (1/8, 1/4, and 1/2 thickness) and two specimen orientations (RW and WR).[4] This plate satisfies the Code requirements for SA-533 Grade B Class 1 steel.

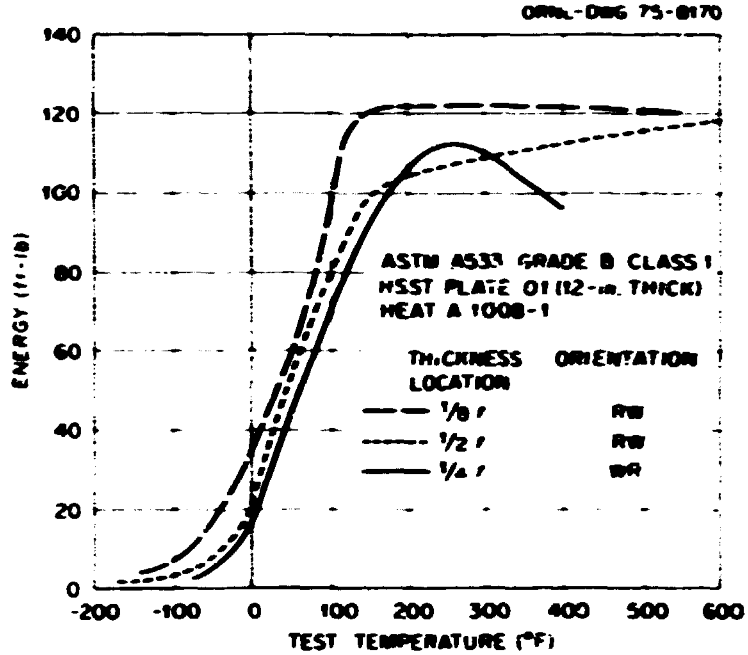

Fig. 1. Variation of Charpy V-Notch Upper-Shelf Energy in the Same Plate of SA-533 Grade B Class 1 Steel.

The requirement[1] is that the upper-shelf C_v energy of the steel used in the beltline region of a nuclear pressure vessel be at least 75 ft-lb (102 J). To determine how a reputable organization assures itself that it is indeed reporting C_v upper-shelf energy values, we interviewed three experimenters who are representative of the leading experts in this area of mechanical property testing. We specifically asked them to describe their method for assuring themselves that they are indeed reporting upper-shelf energy data. Each had a somewhat different methodology in

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[3] In Fig. 1 and subsequent figures English units are used. To convert to SI: Multiply energy values in foot-pounds by 1.3558 to get joules; multiply loads in pounds force by 4.4482 to get newtons; subtract 32 from Fahrenheit temperatures, then multiply by 5/9 to get Celsius degrees.

[4] The first letter describes the axis of the specimen. The second letter describes the fracture path. R is rolling direction; W is transverse to the rolling direction.

his testing program, but all depended on fracture appearance as their criterion. Their requirements are that the fracture surfaces of the C_v specimens exhibit an appearance indicative of nearly 100% shear fracture. A brief description of the method described by each experimenter interviewed is provided in the Appendix. The use of fracture appearance as a criterion depends on individual interpretation of the fracture surface. The probability for differences of opinion in the interpretation of the surface is great.

In view of the possible variations in C_v upper-shelf behavior shown in Fig. 1, (i.e., increasing energy with increase in temperature, decreasing energy with increase in temperature) and the human uncertainty involved in the interpretation of a fracture surface, the authors have determined an improved method for describing the C_v upper-shelf energy value of the steels employed in the fabrication of the nuclear pressure vessels used for Light Water Reactors (LWR). NRC is desirous of a standard method for assessing the effect of irradiation on the fracture toughness of the LWR pressure vessels. Its interest lies in the development of a definition of the C_v upper shelf based on a reproducible test procedure that is acceptable to the industrial community. It recognizes that the number of irradiated specimens is often limited, and a precise and repeatable method is desired for describing the C_v upper shelf. The authors feel that the method described in this report may satisfy the NRC needs.

REVIEW OF ARCHIVE TEST DATA

To avoid vagueness or misinterpretation in the selection of an upper-shelf energy value, we sought a definition based on a specific criterion that could be readily obtained in a conventional toughness test. Toward that end we reviewed the C_v data that have been obtained in the Heavy Section Steel Technology Program (HSST) test series and other Energy Research and Development Administration (ERDA) programs. The C_v tests were run on an instrumented Baldwin impact tester, Model SI1C. The tester shown in Fig. 2 automatically cools (or heats) the C_v specimen and moves it into position for testing. The striker that contacts the specimen is instrumented with strain gages, and a load-time curve can be obtained for each test. This capability was (and is) utilized during C_v testing. The ability to generate a load-time curve for the C_v test provides a permanent record of a test series. Hence, in addition to the absorbed energy (read from the machine dial), lateral expansion (a post-test measurement), and fracture appearance (estimated percent ductile fracture), a permanent record (Polaroid camera print or $x - y$ plot) of the load-time curve is obtained for each test.

We have reviewed the load-time curves for the state-of-the-art nuclear pressure vessel steels, as well as other plain carbon (ASTM A 212 Grade B) and low-alloy (2 1/4 Cr-1 Mo) steels. The chemical compositions of these latter two steels are given in Table 1. In reviewing the load-time records for these steels we found that in all the tests unstable crack extension — that is, pop-in — occurs in the transition temperature regime. This crack extension is reflected as a drop in load in the load-time curves and is an easily determined quantity. The drop-in-load value (ΔP) decreases

Fig. 2. Instrumented Impact Tester. Center photograph shows the entire system: impact tester, temperature-measuring equipment, electronic equipment for measuring and recording load and deflection. Upper right photograph is close-up view of strain-gaged tup. Lower left corner is view of automated Charpy specimen cooling (and heating) and loading apparatus.

with increasing temperature in the transition range, approaching zero at the temperature of the onset of upper shelf in a C_v test. This material behavior in a typical C_v test is illustrated in Fig. 3. It contains the results of a C_v test on the impact tester shown in Fig. 2. The Polaroid prints are representative of the data obtained when a C_v test series is conducted on an instrumented impact tester. The definition of the drop in load, ΔP, is provided in Fig. 3(b). A plain carbon steel, ASTM A 212 Grade B, has been used to demonstrate the variation in the load-time curves as a function of temperature. The drop in load, ΔP, in the P vs t curve can be easily observed in (c) through (g) in Fig. 3. The ΔP values vary from a maximum value of 3550 lb (15.6 kN) at 0°F (−18°C) to 800 lb (3.6 kN) at 80°F (27°C). At 100°F (38°C) the ΔP is zero. The temperature at which ΔP equals zero corresponds with the onset of the upper-shelf energy in a C_v test. This correlation is clearly seen in the graph in the center of Fig. 3.

A review of the archive C_v data available for SA-508 Class 2 and SA-533 Grade B Class 1 steels investigated in the HSST Program provided similar correlations between ΔP and the onset of the upper shelf. The curves presented in Fig. 4 are representative of the correlations between ΔP and C_v energy noted in this review. The results for the ASTM A 212 Grade B steel illustrated in Fig. 3 are also included. Both the SA-533 and -508 steels exhibit a decrease in the drop in load (pop-in) in the transition regime as a consequence of a temperature increase. The temperature at which ΔP becomes zero in both steels corresponds to the onset of upper shelf.

As a further check of the validity of this observation, we reviewed the load-time curves obtained from tests of irradiated nuclear pressure vessel steels and unirradiated low-carbon 2 1/4 Cr-1 Mo steel. The C_v curves and pop-in loads for a low-carbon 2 1/4 Cr-1 Mo steel are shown in Fig. 5. This steel had C_v energy values in excess of 240 ft-lb (330 J) at −50°F (−46°C) (the C_v specimen stopped the pendulum), and 8 ft-lb (11 J) at −75°F (−59°C). The corresponding ΔP values are zero and 3100 lb (13.8 kN). Again, the temperature at which ΔP becomes zero corresponds with the onset of the upper shelf. This heat of steel would not be used in the construction of a nuclear pressure vessel, but it does serve as an example of the applicability of the drop-in-load criterion for describing the onset of upper-shelf energy.

Figure 6 contains the results of tests conducted to determine the effect of irradiation on the C_v properties of pressure vessel steels. The irradiated materials provide results similar to those observed for the unirradiated steels; the temperature at which the drop in load becomes zero corresponds with the onset of the upper shelf. The temperature at which the onset of upper shelf occurs in the unirradiated condition is influenced by the anisotropy of the steel. It is evident in Fig. 6 that the WR orientation achieves upper shelf at a temperature approximately 40°F (22°C) lower than does the RW orientation. There is, however, a difference of about 30 ft-lb (40 J) between the two shelf values, the RW having the higher energy. The onset of upper shelf after irradiation is not influenced by the original plate anisotropy. The use of the drop-in-load correlation for defining the onset of upper shelf is particularly attractive when irradiated specimens are tested. The use of the ΔP criterion will minimize the number of specimens required to assure that upper-shelf energy values have been obtained.

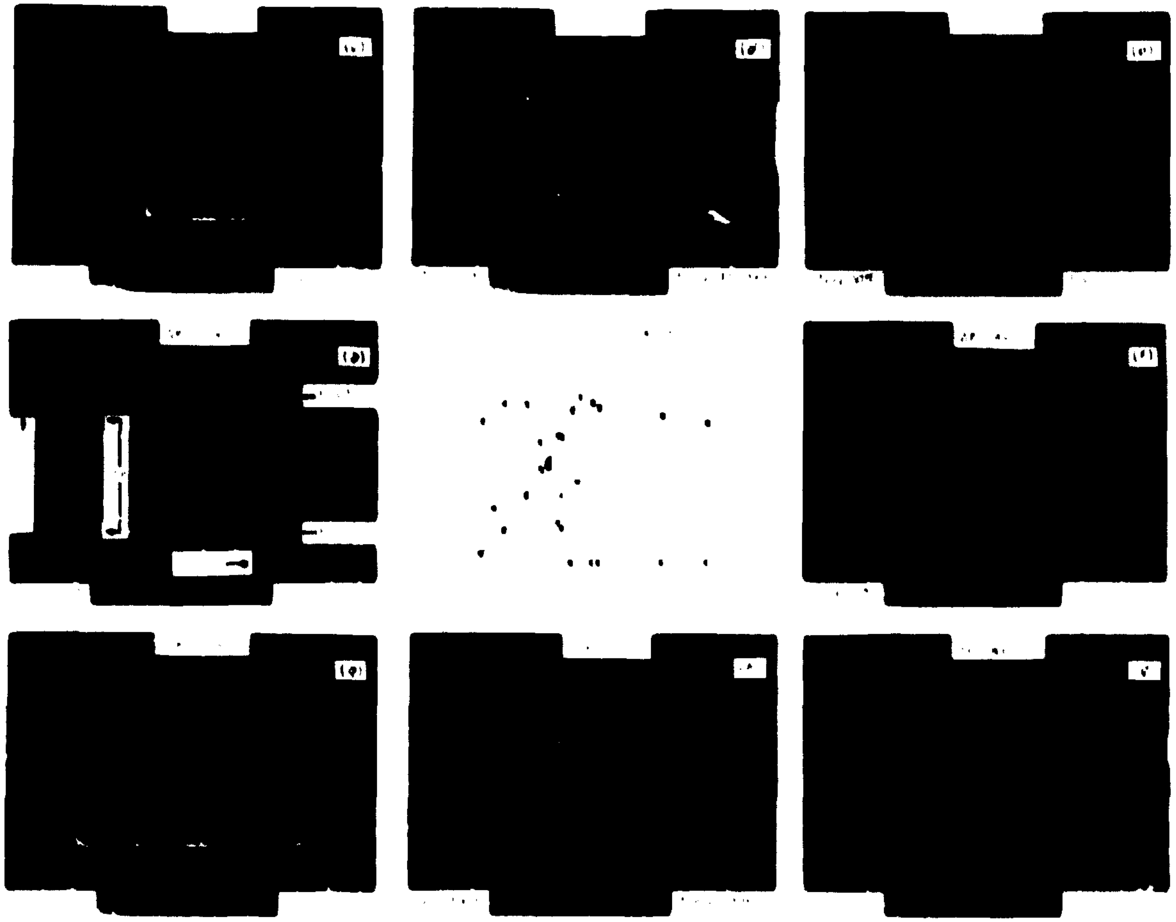

Fig. 3. Comparison of Instrumented Charpy "Pop-In" Load Drop with Charpy-V Impact Energy for ASTM A 212 Grade B Steel.

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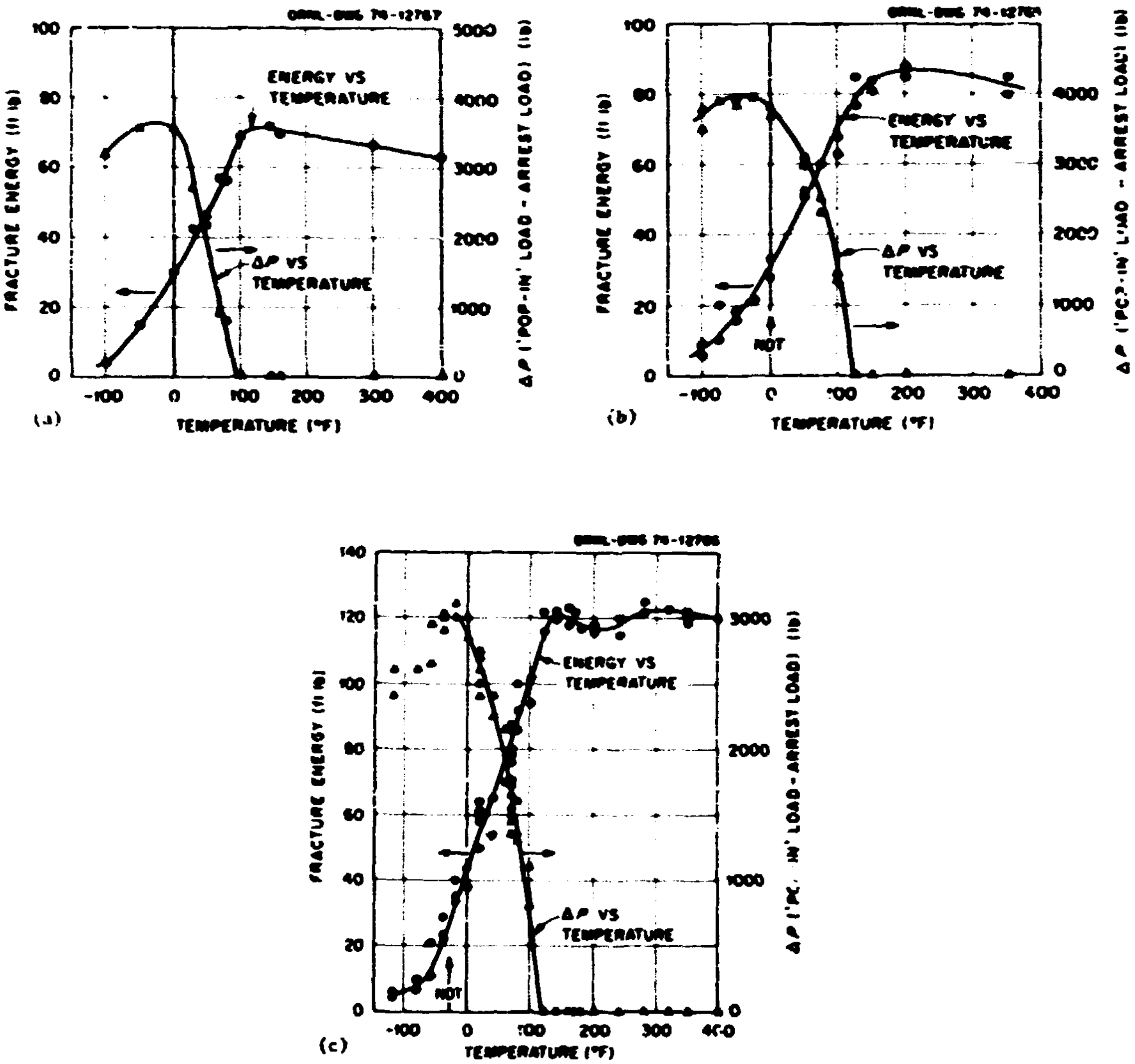
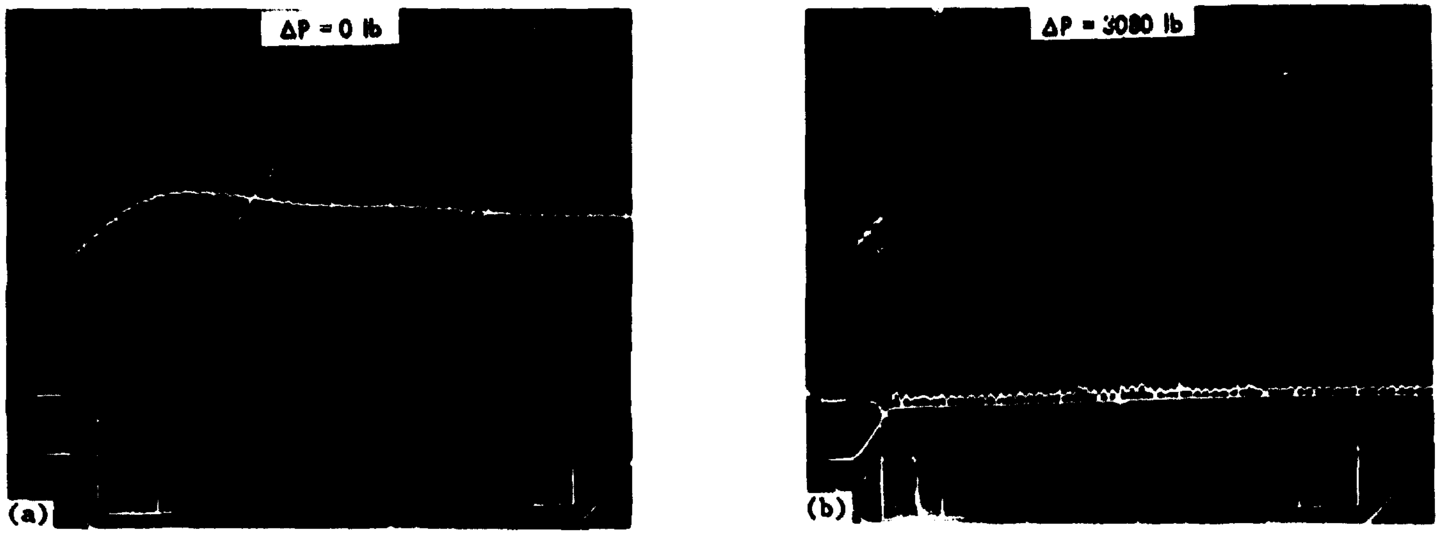


Fig. 4. Comparison of Instrumented Charpy "Pop-In" Load Drop with Charpy-V Impact Energy for Various Steels. (a) ASTM A 212 Grade B. (b) SA-508 Class 2. (c) SA-533 Grade B Class 1.



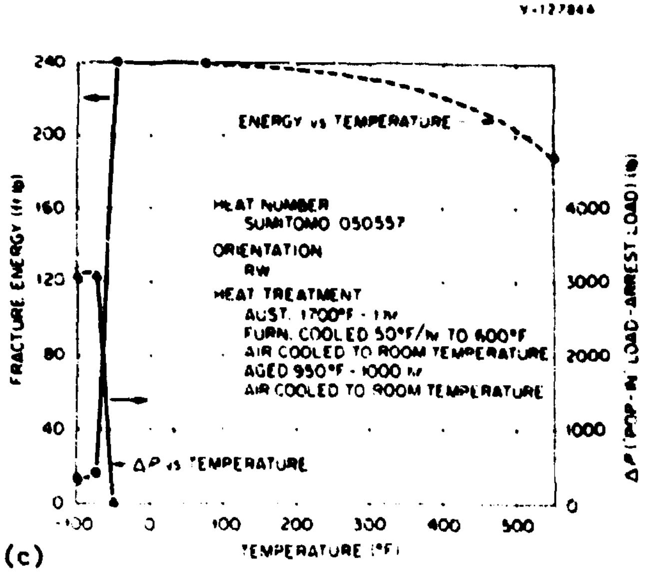


Fig. 5. Comparison of Load Drop with Charpy-V Impact Energy in Instrumented Tests of ASTM A 387 Grade D (2 1/4 Cr-1 Mo with 0.026% C). (a) Test at −50°F (−46°C), showing load drop ΔP = 0 and energy 240 ft-lb (330 J). (b) Test at −75°F (−59°C), showing load drop ΔP = 3080 lb (13.70 kN) and energy 16 ft-lb (21 J). (c) Fracture energy and load drop as functions of temperature.

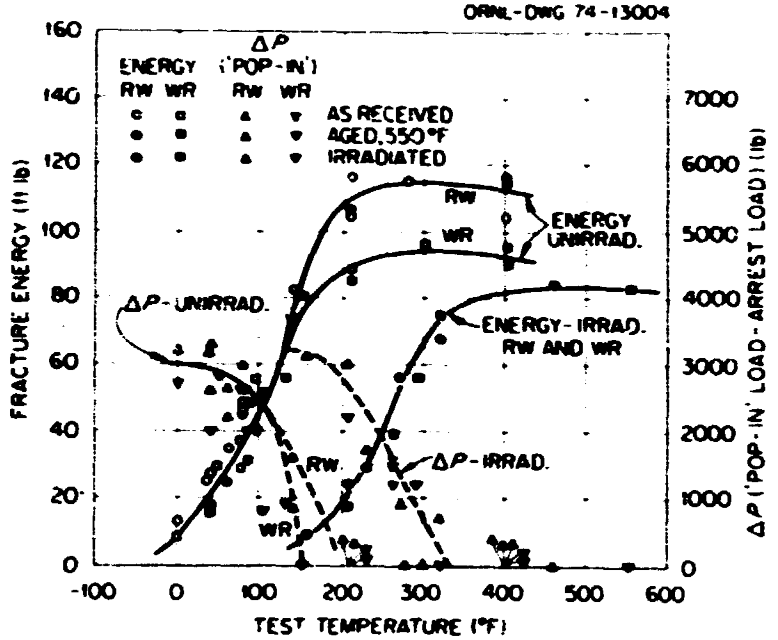


Fig. 6. "Pop-In" Load Drop and Charpy-V Impact Energy of SA-533 Grade B Class 1 Steel Quarter-Thickness Material, Unirradiated and Irradiated ($\approx 2 \times 10^{19}$ n/cm^2, > 1 MeV).

The drop-in-load correlation provides an unambiguous criterion for defining the onset of C_v upper-shelf energy. Such a criterion can be used by any organization with an instrumented impact tester that has the capability of obtaining a load-time (or load-deflection) curve for individual tests. Ideally, the instrumented test system is equipped to obtain a permanent copy of the load-time curve, and this information can become part of the record on the individual nuclear plant.

Figure 7 compares fracture appearance, drop in load, and onset of the upper-shelf energy for the SA-533 and SA-508 specimens used in the preparation of Fig. 5. The 100% fibrous fracture appearance and the zero value for drop in load occur at the same temperature. Hence, the upper-shelf energy values reported to date do indeed correlate with the data that would have been obtained using the drop-in-load criterion. The advantages of the zero-drop-in-load criterion, however, are: (1) the ability to quite precisely predict the zero-ΔP temperature when drop-in-load behavior is observed in a C_v test, (2) the availability of an electronically generated permanent copy that can be included in the record of a reactor plant, and (3) the avoidance of human interpretation of a fracture surface and the resulting possibility of differences of opinion.

In the absence of an instrumented impact tester we would recommend a correlation of the C_v testing procedures with the nil-ductility temperature (NDT). Rather than depend on fracture appearance, we would prefer to relate the testing program of the unirradiated material to the NDT, a material property determination that is required for all steels employed in the fabrication of a nuclear pressure vessel. A relationship between NDT and

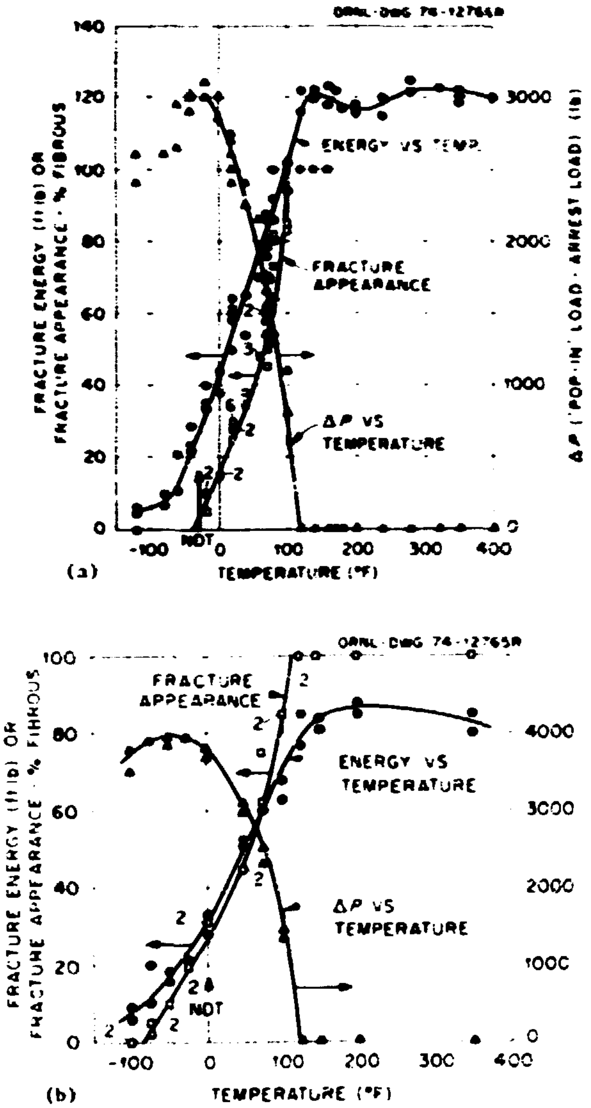


Fig. 7. Comparison of "Pop-In" Load Drop with Charpy-V Impact Energy for the Low-Alloy High-Strength Steels Employed in the Fabrication of the Pressure Vessels for Light-Water Reactors. The nil-ductility temperature was determined in accordance with ASTM E 208. (a) SA-533 Grade B Class 1. (b) SA-508 Class 2.

upper-shelf energy appears to exist for the low-alloy high-strength steels employed in the fabrication of nuclear pressure vessels. The NDT was determined by the drop-weight test for the SA-533 Grade B Class 1 and SA-508 Class 2 steels whose C_v toughness properties are presented in Fig. 7. The NDT for these two steels are −25 and 0°F (−32 and −18°C). At NDT + 125°F (69°C) and NDT + 150°F (83°C), the C_v values reflect upper-shelf toughness for the SA-533 Grade B Class 1 and SA-508 Class 2 steels respectively. Specifically, to obtain upper shelf C_v values for SA-533

Grade B Class 1 and SA-508 Class 2, testing should be conducted at NDT + 180°F (100°C). This increase above NDT, which is probably 20 to 60°F (11–33°C) above the temperature at which $\Delta P = 0$, will provide an assurance that C_v testing is being conducted on the upper shelf, and will vary from steel grade to steel grade. For example, the onset of upper shelf for the low-carbon 2 1/4 Cr-1 Mo steel shown in Fig. 5 is about 25°F (14°C) above the NDT. Hence, while we recommend NDT + 180°F (100°C) for the SA-508 Class 2 and SA-533 Grade B Class 1 steels, we do not consider the 180°F temperature add-on as being a universal constant for all steels.

In view of the behavioral pattern shown in Fig. 1 it may be prudent to determine the energy values at temperatures above the onset of upper shelf. When that information is needed we propose that the testing procedure be correlated with the operating temperature and/or NDT. For unirradiated steels we recommend that tests be conducted at NDT + 300°F (167°C), at NDT + 425°F (236°C), and at the operating temperature of the pressure vessel. These energy data, which are obtained in addition to the energy at the onset of the C_v upper shelf, will define the entire upper-shelf energy spectrum.

CONCLUSIONS

Criteria for determining the onset of the C_v upper-shelf energy have been suggested. These criteria can be applied as follows:

1. In an instrumented C_v test, the drop in load (in the load-time curves for the various tests) decreases with increasing temperature and is zero at the onset of the C_v upper-shelf energy. This observation permits the determination of the onset of the upper shelf with a minimal number of test specimens. Linear extrapolation of the ΔP values from tests conducted in the transition temperature regime to zero will provide the temperature at which onset of the upper shelf is achieved.

2. In the event that an instrumented impact tester is not available, an estimate of the temperature of the onset of the upper shelf can be based on the drop-weight NDT. For SA-508 Class 2 and SA-533 Grade B Class 1 steels, we recommend that tests be conducted at NDT + 180°F (100°C).

3. If the energy value is needed at a specific temperature in the upper-shelf range, then specimens must be tested at the temperature of interest.

4. To determine the variability of the upper-shelf energy for the current nuclear pressure vessel steels, we suggest that tests be conducted at

   (a) NDT + 180°F (100°C) (or at the temperature at which $\Delta P = 0$)
   (b) NDT + 300°F (167°C)
   (c) NDT + 425°F (236°C)
   (d) Operating Temperature

This procedure will also provide a basis for assessing the influence of irradiation on the upper-shelf energy values.

5. The application of the drop-in-load (ΔP) criterion to determine the onset of C_v upper shelf is particularly useful when irradiated surveillance specimens are tested. Usually, the number of specimens is

limited and the definition of the upper-shelf temperature range with a minimal number of specimens is necessary. The extrapolation of the ΔP values to zero guides the selection of the test temperatures.

ACKNOWLEDGMENTS

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APPENDIX

The following are summaries of the discussions between the identified ORNL personnel and the named researcher from the organization cited. The question posed to the individual named was "How does your organization assure itself that it has determined the upper-shelf energy value in a Charpy V-notch test?"

1. J. R. Hawthorne, Naval Research Laboratory
   (Discussion with R. G. Berggren, ORNL, May 5, 1975)

   During Charpy V-notch testing NRL investigators attempt to first find the temperature corresponding to the onset of 100% fibrous fracture as assessed by a fracture appearance criterion. They then test at 100 to 150°F (56–83°C) above the 100% fibrous fracture temperature. If sufficient specimens are available they also test specimens at 550°F (288°C). The individual experimental data points are reported and a visual best fit curve is drawn through the points. When the NRL investigators are tabulating the "upper-shelf" energy they report the energy value and temperature at which they obtain 100% fibrous fracture, the energy at 100 to 150°F above the 100% fibrous temperature, and the energy at 550°F. They also indicate whether the energy curve is rising (increase in absorbed energy with an increase in test temperature) or falling (decrease in absorbed energy with increase in test temperature) or constant with rising temperature.

2. T. U. Marston, Combustion Engineering Company
   (Discussion with R. G. Berggren, ORNL, July 21, 1975)

   Combustion Engineering Company, on current contracts involving core plate materials, prepares 24 specimens each in the transverse and longitudinal orientations. All tests are conducted in triplicate, and transversely oriented specimens are tested first. Testing sequence is as follows:

   1. Test at 100°F (38°C) (triplicate specimens). This is to check on 50 ft-lb (68 J), 0.035 in. (0.89 mm) lateral expansion requirements.
   2. Test at 160°F (71°C). If a minimum of 100% shear failure and 75 ft-lb (102 J) energy is obtained on all three specimens the investigators stop upper-shelf testing and report minimum value. If any specimen does not meet the 100% shear, 75 ft-lb requirement they proceed to:
   3. Test at 212°F (100°C). Requirement is 100% shear and 75 ft-lb energy. If the requirement is not met, the plate is rejected. (It may be re-heat-treated and retested.) They have found that they gain nothing by going above 212°F.
   4. They then proceed with tests at −40°F (−40°C) and tests to determine RT-NDT.
   5. When they have determined RT-NDT (transverse) they fill out the transition curve with any remaining specimens and determine the curve for longitudinal orientation material, keyed to the RT-NDT.

On present contracts they work from minimum specimen results.

3. H. Palme, Babcok and Wilcox Company
(Discussion with D. A. Canonico, ORNL, April 29, 1975)

Babcock and Wilcox Company prepares 30 Charpy V-notch specimens in addition to those required to determine RT-NDT. The inspectors prepare 15 each for the RW and WR orientations.[1] After the RT-NDT has been determined they test the 15 Charpy V-notch specimens in groups of three. Their goal is to test two sets (of three each) at a temperature at which they obtain 95% or more fibrous fracture. Usually the two test temperatures are 100°F (56°C) apart. They average the Charpy V-notch energies that are obtained at each temperature, and the upper-shelf energy is defined as the higher of the two averages. If the average of either set is below 75 ft-lb (102 J) they test another set of three at a higher temperature [at least 50°F (28°C) higher]. The Charpy V-notch upper-shelf energy is the higher average of the two sets over 75 ft-lb. If they do not obtain 75 ft-lb that heat of steel is not acceptable for the core region.

The specimens that remain after the toughness requirements are satisfied are used to obtain Charpy V-notch data at other temperatures.

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[1] The first letter describes the major specimen axis; the second letter describes the fracture propagation direction. (R signifies major rolling direction, W signifies transverse to the major rolling direction.)