Wide-Plate Crack-Arrest Tests Utilizing Prototypical and Degraded (Simulated) Pressure Vessel Steels

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ABSTRACT

Sixteen wide-plate crack-arrest tests have been completed, ten utilizing specimens fabricated from A533B class 1 material and six fabricated from a low-upper-shelf base material. Each test utilized a single-edge notched specimen that was subjected to a linear thermal gradient along the plane of crack propagation. Test results exhibit an increase in crack-arrest toughness (K_{Ia}) with temperature, with the rate of increase becoming greater as the temperature increases. When the wide-plate test results are compared with other large-specimen results, the data show a consistent trend in which the K_{Ia} data extend above the limit provided in ASME Section XI.

PROGRAM OBJECTIVE AND GOALS

The primary objective of the wide-plate crack-arrest studies is to generate data and associated analysis methods for understanding the crack-arrest behavior of prototypical reactor pressure vessel (RPV) steels at temperatures near and above the onset of the Charpy upper-shelf region. Program goals include: (1) extending the existing K_{Ia} databases to values above those associated with the upper limit in the *American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME B&PVC)*; (2) clearly establishing that crack arrest occurs prior to fracture-mode conversion; and (3) validating the predictability of crack arrest, stable tearing, and/or unstable tearing sequences for RPV materials.

MATERIAL PROPERTIES

WP-1 Test Series (A533B Material)

The initial series of wide-plate crack-arrest specimens is taken from the central portion of a 18.73-cm-thick plate of A533 grade B class 1 steel that is in a quenched and tempered condition. Properties of the plate include Young's modulus (E) = 206.9 GPa, Poisson's ratio (ν) = 0.3, coefficient of thermal expansion (α) = $11 \times 10^{-6}/°C$, and density (ρ) = 7850 kg/m^3. The ultimate

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strength of the material, for use in tensile instability calculations, is based on the average stress in the remaining ligament (σ_u) equal to 550 MPa. For tearing instability calculations, the material tearing resistance is represented as a power-law J-resistance curve

$$J_R = c(\Delta a)^m \tag{1}$$

where c = 0.3539, m = 0.4708, and the units J_R and Δa are MJ/m^2 and mm, respectively. Temperature-dependent fracture-toughness relations for initiation and arrest, based on small-specimen data, are given by

$$K_{Ic} = 51.28 + 51.90e^{0.036(T - RT_{NDT})} \tag{2}$$

$$K_{Ia} = 49.96 + 16.88e^{0.029(T - RT_{NDT})} \tag{3}$$

with units for K and T being MPa·$\sqrt{m}$ and °C, respectively. Drop-weight and Charpy V-notch test data indicate that RT_{NDT} = -23°C, and Charpy upper-shelf energy (USE) is 160 J with its onset occurring at 55°C.

WP-CE Test Series (A533B Material)

The WP-CE specimens were made from a second heat of A 533 grade B class 1 material that was provided by Combustion Engineering (CE), Inc. The material was characterized by CE (Ayres, 1987). Pertinent material properties include: nil-ductility transition temperature from -34 to -23°C, Charpy USE of 180 to 203 J, and minimum temperature for fully ductile behavior occurring at 43 to 49°C. Temperature-dependent fracture toughness relations are given in Eqs. (2) and (3) with the RT_{NDT} changed to that of the CE material.

WP-2 Test Series (Low-Upper-Shelf Material)

The WP-2 series of wide-plate crack-arrest specimens is taken from a 15.88-cm thick plate of 2 1/4 Cr-1 Mo steel supplied by Babcock and Wilcox after being heat treated in an effort to obtain a Charpy USE of 68 joules (50 ft-lb), or less. The drop-weight nil-ductility temperature for the material is 60°C, and the Charpy USE is 60-65 J with its onset occurring at ~150°C. The ultimate strength of the material used in tensile instability calculations is 500 MPa. For tearing instability conditions, the values of c and m in Eq. (1) are 0.1114 and 0.3832, respectively. Temperature-dependent fracture-toughness relations for initiation and arrest, which have been used for planning the WP-2 series tests are given by:

$$K_{Ic} = 39.53 + 93.47e^{0.036(T - DW_{NDT})} \tag{4}$$

$$K_{Ia} = 22.31 + 62.69e^{0.0177(T - DW_{NDT})} \tag{5}$$

with units of K and T being MPa·$\sqrt{m}$ and °C, respectively.

SPECIMEN PREPARATION, INSTRUMENTATION AND TESTING PROCEDURE

The 1 × 1 × 0.1 m, or 1 × 1 × 0.15 m, specimens were machined and precracked by ORNL. The precracking was done by hydrogen charging an electron-beam (EB) weld located at the base of a premachined notch in the plate. The initial total crack length, notch depth plus EB weld, for each specimen was nominally 0.2 m (a/W ~ 0.2). Each face of a specimen was grooved to a depth equal to 12.5% of the plate thickness. Starting with the third specimen in test series WP-1 (WP-1.3), the crack front of each specimen, with the exception of specimens WP-2.3 and WP-2.6, was machined into a truncated chevron configuration to reduce the tensile load required to achieve crack initiation. Upon completion of the machining operations, each specimen was shipped to NIST where it was welded to pull plates nominally having the same cross-section geometry as the specimen to produce the test article shown schematically in Fig. 1.

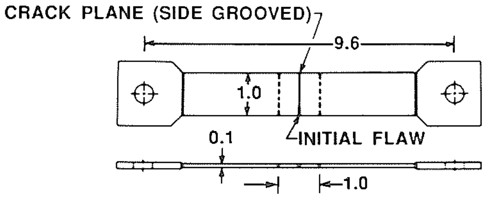

Fig. 1. Schematic of HSST wide-plate crack-arrest specimen.

To obtain pertinent data during a test, each wide-plate specimen was instrumented with three primary types of devices: (1) thermocouples, (2) strain gages, and (3) crack-opening-displacement gages. Up to 40 thermocouples were positioned on each specimen with the 20 thermocouples adjacent to the crack plane displayed graphically in real time to indicate the relationship between actual and desired thermal gradient across the specimen width. Strain gages were used to provide dynamic strain-field measurements for determination of crack velocity and assessing boundary conditions. Two capacitance-based crack-opening-displacement gages were mounted on the plate front and back faces at a/W ≈ 0.15. Also, an acoustic emission transducer was located on the lower pull tab of each specimen.

After instrumenting, the specimen was placed into the 27-MN capacity tensile testing machine and electric-resistance strip heaters attached to the back edge of the plate. A cooling chamber, into which liquid nitrogen (LN_2) was pumped and sprayed directly onto the specimen, was affixed at the notched edge of the plate. The back and front faces of the specimen were then insulated. A temperature gradient was imposed across the plate by spraying LN_2 onto the notched edge while heating the other edge. Liquid nitrogen flow and power to the heaters were adjusted to obtain the desired thermal gradient. Generally, the mid-plate (a/W = 0.5) temperature was selected to correspond to that of the onset of Charpy USE for the material tested, and the crack-tip temperature was varied to provide the desired initiation load. Upon obtaining the desired temperature gradient, tensile load was applied to the specimen at a rate which varied from 11 to 312 kN/s, depending on the test, until fracture occurred. Figure 2 presents a wide-plate crack-arrest specimen under test.

TEST SUMMARY

Tables 1 and 2 present a summary of the conditions for the A533B and low-upper-shelf materials, respectively. A detailed description of each of these tests is provided elsewhere (Naus et al., 1988; Naus et al., 1989; deWit and Fields, 1988). Fracture surfaces are presented in Fig. 3 for specimens WP-1.7 and WP-1.8, Fig. 4 for specimens WP-CE-1 and WP-CE-2, and Fig. 5 for specimens WP-2.1 through WP-2.6. Fracture surfaces for specimens WP-1.1 through WP-1.6 were presented in a previous SMiRT paper (Pugh et al., 1987). Fractographic examinations of the fracture surfaces confirm that the crack propagations occurred

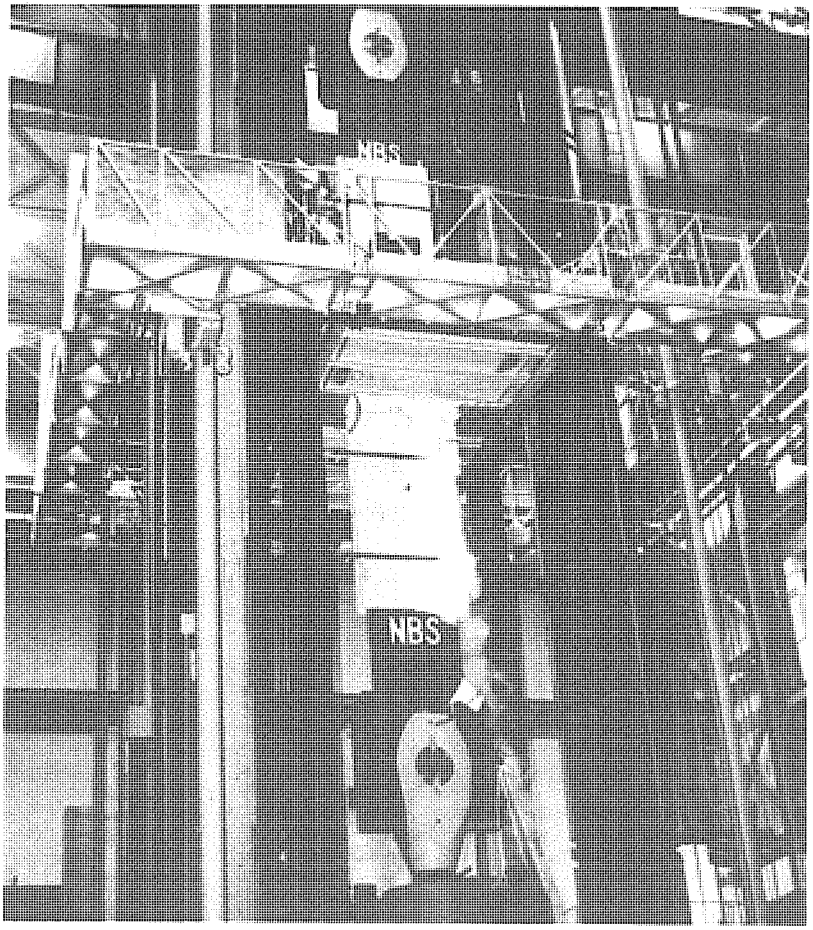

Fig. 2. Wide-plate crack-arrest specimen under test.

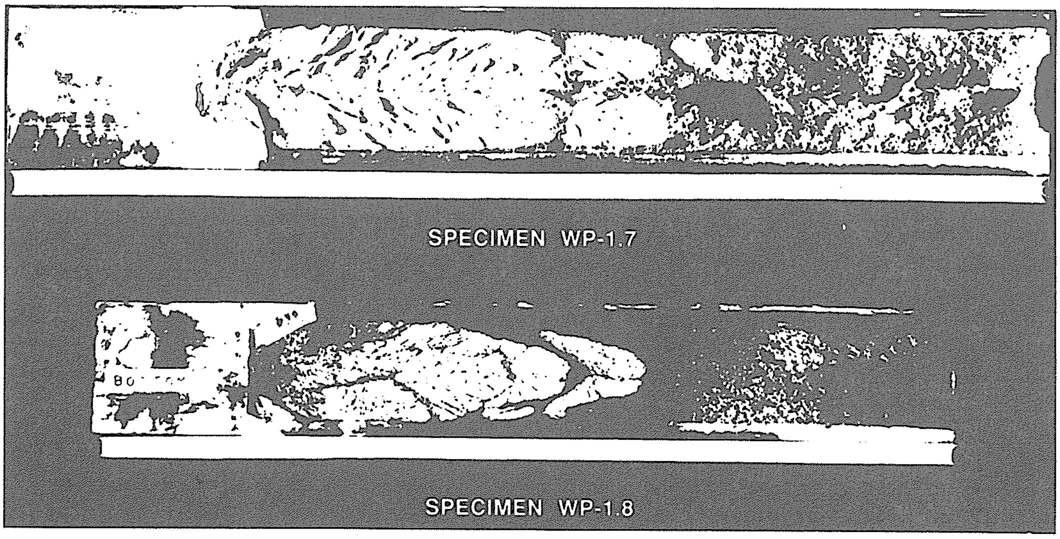

Fig. 3. Fracture surfaces of specimens WP-1.7 and WP-1.8.

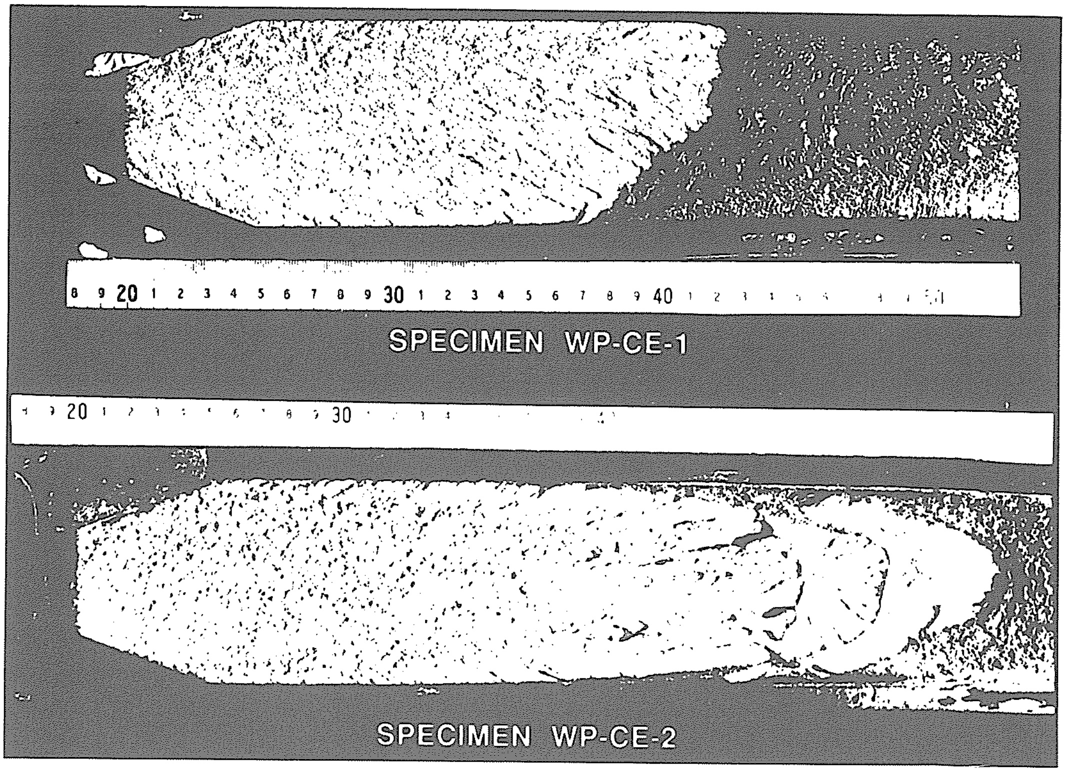

Fig. 4. Fracture surfaces of specimens WP-CE-1 and WP-CE-2.

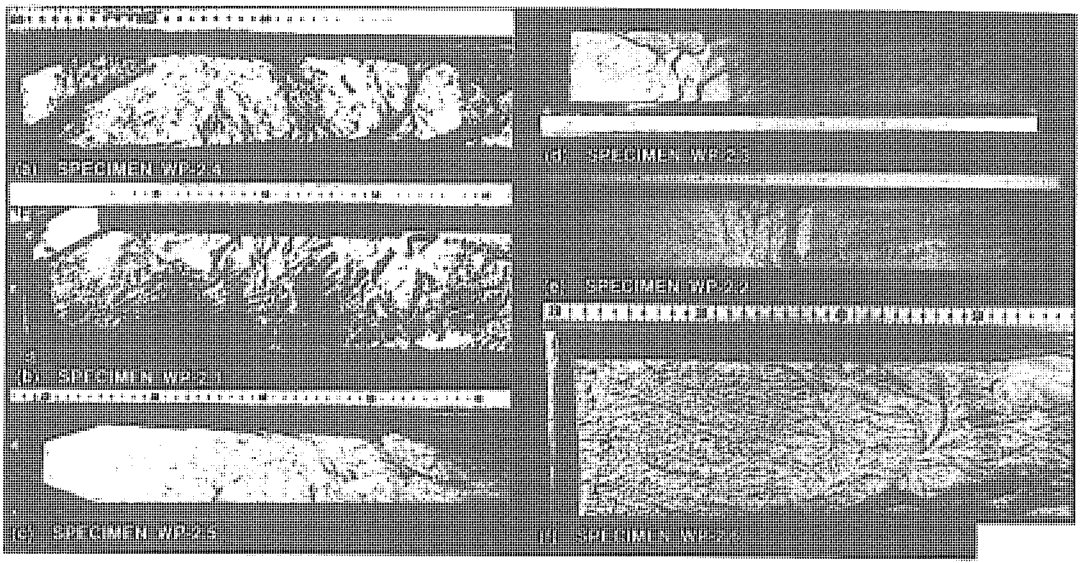

Fig. 5. Fracture surfaces of specimens WP-2.1 through WP-2.6.

TABLE 1

SUMMARY OF HSST WIDE-PLATE CRACK-ARREST TEST CONDITIONS AND RESULTS
FOR A533 GRADE B CLASS 1 STEEL: WP-1 AND WP-CE SERIES

Test No.	Crack location (cm)	Crack temperature (°C)	Initiation load (MN)	Arrest location (cm)	Arrest temperature (°C)	Arrest $T - RT_{NDT}$ (°C)	Crack-arrest toughness[e] $(MPa \cdot \sqrt{m})$
WP-1.1[a]	20	-60	20.1	50.2	51	74	NA
WP-1.2A	20	-33	18.9	55.5	62	85	424
WP-1.2B	55.5	62	18.9	64.5	92	115	685
WP-1.3	20[b]	-51	11.25	48.5	54	77	235
WP-1.4A	20.7[b,c]	-63	7.95	44.1	29	52	NA
WP-1.4B	44.1	29	9.72	52.7	60	83	387
WP-1.5A	20[b]	-30	11.03	52.1	56	79	231
WP-1.5B	52.1	56	11.03	58.0	72	95	509
WP-1.6A	20[b]	-19	14.50	49.3	54	77	275
WP-1.6B	49.3	54	14.50	59.3	80	103	397
WP-1.7A	20.2[b]	-24	26.2	52.8	61	84	319
WP-1.7B	52.8	61	26.2	63.5	88	111	555
WP-1.8A	19.8[b]	-47	26.5	44.9	40	63	345
WP-1.8B	44.9	40	26.5	50.4	55	78	484
WP-1.8C	50.4	55	26.5	59.4	79	102	563
WP-CE-1	20.0[b]	-34	10.14	42.0	36	70	170
WP-CE-2A[d]	20.1[b]	-40	14.60	46.6	42	76	218
WP-CE-2B	46.6	42	14.60	50.4	53	88	354
WP-CE-2C	50.4	51	14.60	52.5	60	95	576

[a] Specimen was warm prestressed by loading to 10 MN at 70°C. Specimen was also preloaded to 19 MN.

[b] Crack front cut to truncated chevron configuration.

[c] Pillow jack utilized to apply pressure load to specimen's machined notch.

[d] Specimen was warm prestressed to 14 MN at 25°C.

[e] Dynamic finite element analyses (fixed load, generation mode). K_{Ia} values are presently being reassessed to incorporate tunneling effects. Values should therefore not be considered as final.

by a predominantly cleavage mode with arrest events not preceded by conversion to ductile tearing (Naus et al., 1987).

POSTTEST ANALYSES AND COMPARISON OF DATA WITH OTHER LARGE-SCALE TEST RESULTS

Posttest Analyses

Posttest analyses were conducted for each test to investigate the interaction of parameters (plate geometry, material properties, temperature profile and mechanical loading) that affect the crack run-arrest events. Three-dimensional, static, finite-element (FE) analyses were performed to determine the stress-intensity factor at the time of crack initiation using the ORMGEN/ORVIRT (Bass and Bryson, 1982; Bass and Bryson, 1983) fracture-analysis

TABLE 2

SUMMARY OF HSST WIDE-PLATE CRACK-ARREST TEST CONDITIONS AND RESULTS FOR SPECIALLY HEAT TREATED 2 1/4 Cr-1 Mo STEEL: WP-2 SERIES

Test No.	Crack location (cm)	Crack temperature (°C)	Initiation load (MN)	Arrest location (cm)	Arrest temperature (°C)	Arrest T - DW_{NDT} (°C)	Crack-arrest toughness[e] (MPa·√m)
WP-2.4A[a]	20.3	45	7.52	25.1	61	1	–
WP-2.4B	25.1[b]	61	8.85	33.8	86	26	137
WP-2.4C	33.8	86	8.85	39.7	102	42	188
WP-2.4D	39.7	102	8.85	41.3	107	47	281
WP-2.4E	41.3	107	8.85	46.2	121	61	249
WP-2.4F	46.2	121	8.85	48.4	127	67	307
WP-2.4G	48.4	127	8.85	51.5	137	77	381
WP-2.4H	51.5	137	8.85	55.5	149	89	397
WP-2.1A[a]	19.9	55	11.90	27.5	80	20	106
WP-2.1B	27.5	80	11.90	33.5	96	36	153
WP-2.1D	33.5	96	11.90	37.0	105	45	158
WP-2.1E	37.0	105	11.90	40.0	112	52	170
WP-2.1F	40.0	112	11.90	45.0	125	65	201
WP-2.1H	45.0	125	11.90	49.0	135	75	293
WP-2.1I	49.0	135	11.90	52.7	145	85	371
WP-2.1J	52.7	145	11.90	55.5	152	92	406
WP-2.5A[a]	19.9	66	7.53	27.2	86	26	–
WP-2.5B	27.2[b]	86	8.90	35.0	104	44	171
WP-2.5C	35.0	104	8.90	43.5	124	64	190
WP-2.5D	43.5	124	8.90	47.8	135	75	268
WP-2.5E	47.8	135	8.90	51.6	144	84	306
WP-2.5F	51.6	144	8.90	56.0	154	94	366
WP-2.3A	20.0	66	15.3	34.0	97	37	144
WP-2.3B	34.0	97	15.3	37.5	106	46	232
WP-2.3D	37.5	106	15.3	39.7	111	51	255
WP-2.3F	39.7	111	15.3	45.7	126	66	258
WP-2.2A[a,c]	21.1	58	17.0	43.5	120	60	201
WP-2.2B	43.5	120	17.0	46.5	129	69	259
WP-2.2C	46.5	129	17.0	47.8	133	73	281
WP-2.2D	47.8	133	17.0	49.9	139	79	299
WP-2.2E	49.9	139	17.0	51.0	142	82	380
WP-2.2F	51.0	142	17.0	53.8	150	90	364
WP-2.2G	53.8	150	17.0	58.2	162	102	446
WP-2.6A[d]	22.4	65	19.3	35.7	104	44	204
WP-2.6B	35.7	104	19.3	39.7	115	55	259
WP-2.6C	39.7	115	19.3	41.0	119	59	286
WP-2.6D	41.0	119	19.3	43.0	125	65	350
WP-2.6F	43.0	125	19.3	46.0	133	73	328
WP-2.6G	46.0	133	19.3	48.0	139	79	411
WP-2.6H	48.0	139	19.3	54.0	156	96	413

[a] Crack front cut to truncated chevron configuration.

[b] After pop-in event.

[c] Specimen was warm prestressed by loading to 16 MN at 124°C.

[d] Specimen was warm prestressed by loading to 15.6 MN at 110°C.

[e] Dynamic finite element analyses (fixed load, generation mode). K_{Ia} values are presently being reassessed to incorporate tunneling effects. Values should therefore not be considered as final.

system in conjunction with the ADINA (Bathe, 1984) FE code. Quasistatic analyses utilized the WPSTAT code (Bass et al., 1985) to evaluate the static stress-intensity factors as a function of crack length and temperature differential across the plate. Elastodynamic analyses were carried out using the ADINA/VPF (Bass and Keeney-Walker, 1986) dynamic crack analysis code.

Tables 1 and 2 present crack-arrest toughness values (K_{Ia}) for the A533B and low-upper-shelf materials, respectively, which were computed by dynamic analyses. The generation-mode (fixed-load point) dynamic analysis K_{Ia} results from the wide-plate tests, presented in Fig. 6, extend consistently above the limit provided in Sect. XI of the *ASME Code* and exhibit a significant increase in toughness with temperature. This increase in K_{Ia} with temperature occurs at an accelerating rate suggesting that a temperature limit exists at or below which a cleavage crack propagation will arrest, no matter how high the applied driving force. (It should be noted, however, that the K_{Ia} results in Fig. 6 are presently being reassessed to incorporate the influence of tunneling. This may result in a slight revision to the values presented in Tables 1 and 2 and Fig. 6.)

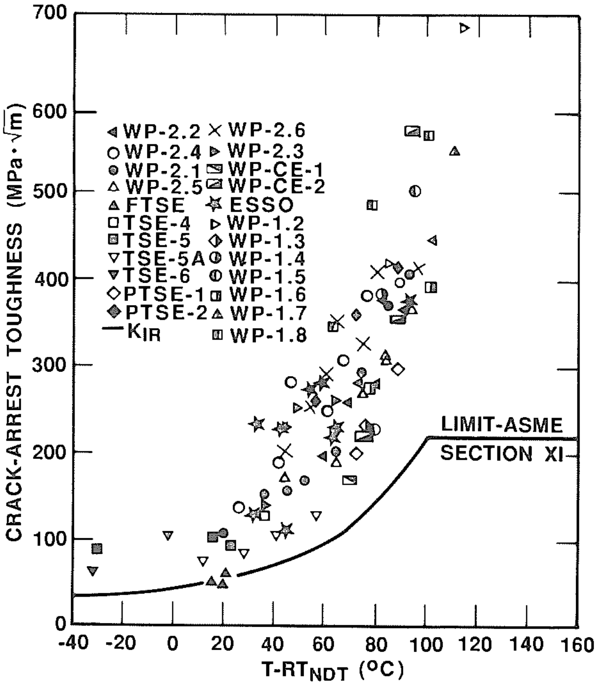

Fig. 6. A comparison of large specimen test results with fixed-load, generation-mode dynamic analysis crack-arrest toughness results for HSST wide-plate tests. Note that HSST wide-plate test results have not been adjusted to account for tunneling effects.

Comparison of Data with Other Large-Scale Test Results

The trend for K_{Ia} values to extend consistently above the limit provided in ASME Sect. XI is further substantiated in Fig. 6, which also presents data from several large-scale tests;i.e., French and ORNL thermal-shock experiments, ORNL pressurized-thermal-shock experiments, and Japanese ESSO tests (Naus et al., 1989).

CONCLUSIONS

The Heavy-Section Steel Technology (HSST) Program at ORNL has an integrated effort under way to extend the range of applicability of current state-of-the-art crack-arrest practices and to develop alternatives where improvements are needed. A consistent trend is formed when the crack-arrest data now available from the three types of HSST large-specimen tests are combined on a plot of K_{Ia} vs $T - RT_{NDT}$. Collectively, these data, along with other large-specimen test results, show that arrest can and does occur at temperatures up to and above that which corresponds to the onset of Charpy upper-shelf behavior, and the measured K_{Ia} values extend above the limit included in Sect. XI of the *ASME Code*. Further, the data suggest the existence of a limiting temperature above which a cleavage crack cannot propagate. In summary, the data being obtained under the HSST wide-plate crack-arrest program support: (1) the use of fracture-mechanics concepts to analyze cleavage run-arrest events, (2) the treatment of cleavage- and ductile-fracture modes as separate events, and (3) the fact that cleavage arrest can occur at toughness levels well above the ASME limit.

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