CONF-8810155--4

DE89 002192

HSST WIDE-PLATE TEST RESULTS AND ANALYSIS

D. J. Naus, B. R. Bass and J. Keeney-Walker
Oak Ridge National Laboratory (ORNL)
Oak Ridge, Tennessee 37831

and

R. J. Fields, R. deWit and S. R. Low III
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland 20899

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HSST WIDE-PLATE TEST RESULTS AND ANALYSIS*

D. J. Naus, B. R. Bass and J. Keeney-Walker
Oak Ridge National Laboratory (ORNL)
Oak Ridge, Tennessee 37831

and

R. J. Fields, R. deWit and S. R. Low III
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland 20899

ABSTRACT

Fifteen wide-plate crack-arrest tests have been completed to date, ten utilizing specimens fabricated from A533B class 1 material (WP-1 and WP-CE series), and five fabricated from a low upper-shelf base material (WP-2 series). 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 with temperature, with the rate of increase becoming greater as the temperature increases. When the wide-plate test results are combined with other large-specimen results the data show a consistent trend in which the K_{Ia} data extends above the limit provided in ASME Section XI.

1. INTRODUCTION

Current light-water reactor (LWR) pressure-vessel safety assessment methods are based in large measure on Sects. III and XI of the *American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (B&PVC)*. In pressurized-thermal-shock (PTS) scenarios, flaws on the inner surface of a reactor pressure vessel (RPV) have the greatest propensity to propagate because they are in the region of highest thermal stress, lowest temperature, and greatest irradiation damage. If such a flaw begins to propagate radially through the vessel wall, it will extend into a region of higher fracture toughness due to the higher temperatures and less irradiation damage. Although the thermal stresses may decrease with propagation depth, the stress-intensity factor caused by the elevated-pressure loading will be increasing.

The fracture toughness correlations contained in the *ASME B&PVC* embody the position that one cannot assume a crack-arrest toughness value (K_{Ia}) above $220 \text{ MPa}\cdot\sqrt{\text{m}}$ for LWR pressure-vessel steels. The imposition of this limit is

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 1886-8011-9B with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, inc.

based in part on the fact that no K_{Ia} data existed at or above this level and because Charpy tests showed that impact energy levels exhibit an upper-shelf behavior. Therefore, the nature of crack-arrest behavior and K_{Ia} extrapolations to temperatures higher than that at which this limit occurred could not be presumed.

The ASME limit does not impose difficulties in making assessments for LWR pressure vessels undergoing thermal shock transients with low accompanying pressure levels. However, PTS scenarios could lead to conditions where the driving force on a propagating crack increases to levels well in excess of the current ASME limit. Thus, safety assessment methods for this type of condition would require an understanding of the following points.

1. If the driving force on a crack exceeds $220 \text{ MPa}\cdot\sqrt{\text{m}}$ by a significant margin, can the material exhibit crack-arrest behavior?
2. If the materials do exhibit high K_{Ia} values with increasing temperature, what is the relationship between K_{Ia} and temperature? That is, does a temperature limit exist above which cleavage crack propagation cannot continue regardless of how high the driving force?
3. If crack arrest does occur at high temperatures where the material behavior is typically dominated by ductile behavior, then what interactions exist between the various fracture modes, including arrest, stable crack growth, unstable crack growth, and tensile instability?

2. 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 RPV steels at temperatures near and above the onset of the Charpy upper-shelf region. Program goals include (1) extending the existing K_{Ia} data bases to values above those associated with the upper limit in the 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 ductile materials. The wide-plate tests and analyses provide bases for obtaining and interpreting dynamic-fracture data (with relatively long crack runs) and bases for validation of viscoplastic fracture models and analysis methods.

3. MATERIAL PROPERTIES

3.1 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) = $11 \times 10^{-6}/^{\circ}\text{C}$, and density (ρ) = 7850 kg/m³. The

temperature-dependent yield stress for the material is given by

$$\sigma_y = 374.87 + 59.89e^{-0.00793T} \quad (1)$$

where σ_y and T have units in megapascals and degrees Celcius, respectively. The ultimate 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, which represents the lowest value determined for the temperature range of interest. For tearing instability calculations, the material tearing resistance is assumed to be given in the form of a power-law J-resistance curve

$$J_R = c(\Delta a)^m \quad (2)$$

where $c = 0.3539$, $m = 0.4708$, and the units of J_R and Δa are MJ/m² and mm, respectively. Temperature-dependent fracture-toughness relations for initiation and arrest, based on small-specimen data, are given by

$$K_{Ic} = 51.28 + 51.90e^{0.036(T - RT_{NDT})} \quad (3)$$

$$K_{Ia} = 49.96 + 16.88e^{0.029(T - RT_{NDT})} \quad (4)$$

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

Analytical studies have used a dynamic fracture toughness relation in the following form:

$$K_{ID} = K_{Ia} + A(T) \dot{a}^2, \quad (5)$$

where K_{Ia} is given by Eq. (4) and

$$A(T) = [329.7 + 16.25 (T - RT_{NDT})] \times 10^{-6}, \quad (6)$$

or

$$A(T) = [121.71 + 1.296 (T - RT_{NDT})] \times 10^{-6}, \quad (7)$$

if $(T - RT_{NDT})$ is greater or less than -13.9°C , respectively. Units for K_{ID} , A , $\dot{a}$, and T are megapascals times root meters, megapascals times square seconds times meters to the $-3/2$, meters per second, and degrees Celcius, respectively. The form of the K_{ID} expression in Eq. (5) and relations for

A(T) [Eqs. (6) and (7)] are derived from Ref. [1] by estimating that $RT_{NDT} = -6.1^\circ\text{C}$ for the material used in that study.

3.2 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 to ORNL by Combustion Engineering (CE), Inc. The material was characterized by CE, and the detailed results are presented in Ref. [2]. Pertinent material properties include:

1. an ultimate tensile strength ranging from ≈ 580 MPa at room temperature to ≈ 560 MPa at 66°C to ≈ 520 MPa at 120°C ,
2. a nil-ductility transition temperature from ≈ -34 to $\approx -23^\circ\text{C}$,
3. a Charpy upper-shelf energy of ≈ 180 to ≈ 203 J, and
4. the minimum temperature for fully ductile behavior occurring at ≈ 43 to $\approx 49^\circ\text{C}$.

Temperature-dependent fracture-toughness relations for the WP-CE material used for pretest planning were the same as Eqs. (3) and (4) with the RT_{NDT} changed to the appropriate value for the WP-CE material.

3.3 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. The material was supplied by Babcock and Wilcox after being heat treated in an effort to obtain a Charpy upper-shelf energy of 68 joules (50 ft-lb), or less.

Based on a limited number of tests, the tentative drop-weight nil-ductility temperature for the material is $\approx 60^\circ\text{C}$, and the Charpy upper-shelf energy is about 60 J with its onset occurring at about 150°C . The ultimate strength of the material, for use in tensile instability calculations, is based on the average stress in the remaining ligament (σ_u) equal to 500 MPa. For tearing instability conditions, the values of c and m in Eq. (2) are 0.1114 and 0.3832, respectively. Tentative temperature-dependent fracture-toughness relations for initiation and arrest, which have been used for planning the WP-2 series tests are given by:

$$K_{Ic} = 39.53 + 93.47e^{0.036(T - DW_{NDT})} \quad (8)$$

$$K_{Ia} = 22.31 + 62.69e^{0.0177(T - DW_{NDT})} \quad (9)$$

with units of K and T being $\text{MPa}\cdot\sqrt{\text{m}}$ and $^\circ\text{C}$, respectively, and the material $DW_{NDT} = 60^\circ\text{C}$. The dynamic fracture toughness relation is presented in Eq. (5) with 60°C used as the material RT_{NDT} .

4. SPECIMEN PREPARATION, INSTRUMENTATION AND TESTING PROCEDURE

4.1 Specimen Preparation

The $1 \times 1 \times 0.1$ m, or $1 \times 1 \times 0.15$ m, specimens such as shown in Fig. 1, 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 total crack length, notch depth plus EB weld, for each specimen was nominally 0.2 m ($a/W \sim 0.2$) and the flaw was oriented perpendicular to the rolling direction. Each side of a specimen was side 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 specimen WP-2.3, 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. A specimen pin-to-pin length of approximately 9.6 m was selected to minimize stress wave effects. Tables 1, 2 and 3 present dimensions for each of the specimens in the WP-1, WP-CE and WP-2 test series, respectively, which have been tested to date.

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

TABLE 1
WP-1 SERIES TEST SPECIMEN DIMENSIONS

Dimension	Symbol	Dimension (mm)							
		Specimen designation							
		WP-1.1	WP-1.2	WP-1.3	WP-1.4	WP-1.5	WP-1.6	WP-1.7	WP-1.8
Initial crack length	a_o	196.9	199	197	207.5	200	200	202	198
Thickness	B	101	101.8	99.5	99.6	101.7	101.8	152.4	152.4
Notched thickness	B_N	76.3	77.5	75.4	76.9	76.4	75.5	114.3	115.1
Chevron thickness (thickness at a_o)	B_C	NA ^a	NA ^a	47.5	33.8	41.2	40.0	61.0	56.2
Width	W	997	998	1000	1000	1000	1000	1000	1000

^aNot applicable.

TABLE 2
WP-CE SERIES TEST SPECIMEN DIMENSIONS

	Symbol	Dimension (mm)	
		Specimen designation	
		WP-CE-1	WP-CE-2
Initial crack length	a_o	200	201
Thickness	B	101.7	101.8
Notch thickness	B_N	76.3	76.2
Chevron thickness (thickness at a_o)	B_C	40.0	40.4
Width	W	1000	999.5

TABLE 3
WP-2 SERIES TEST SPECIMEN DIMENSIONS

Dimension	Symbol	Dimension (mm)				
		Specimen designation				
		WP-2.4	WP-2.1	WP-2.5	WP-2.3	WP-2.2
Initial crack length	a_o	203	202.6	199	200	213
Thickness	B	101.7	152.3	101.6	152.4	152.4
Notch thickness	B_N	76.3	113.9	76.2	113.8	113.8
Chevron thickness (thickness at a_o)	B_C	40.5	61.5	40.7	<i>b</i>	71.9
Width	W	1000	1000	999	1000	1000
Pop-in crack length	a_o'	251	NA ^a	264	NA ^a	NA ^a
Chevron thickness (thickness at a_o')	B_C'	75.5	NA ^a	NA ^a	<i>b</i>	<i>b</i>

^aNot applicable because either a pop-in did not occur (WP-2.1, WP-2.2 and WP-2.3) or the crack length after pop-in (a_o') was past the region of the plate where the crack front had been chevroned (WP-2.5).

^bSpecimen non-chevroned.

4.2 Instrumentation

Up to 40 thermocouples were positioned on each specimen as shown in Fig. 2. During the heating-cooling processes, the 20 thermocouples adjacent to the crack plane were displayed graphically in real time to indicate the relationship between the actual and desired thermal gradient across the specimen width. The 20 additional thermocouples indicated the temperature distribution at other positions on the specimen and pull plates and were used primarily for post-test analyses.

Although the number of strain gages has varied from test to test, up to a total of 25 gages have been utilized to provide dynamic strain-field measurements for determination of crack velocity and assessing boundary conditions. Strain gage locations utilized for tests WP-1.7 and WP-CE-1 are shown in Fig. 3. The crack-line gages (numbers 1 through 20 in Fig. 3) were two-element, 90° stacked, 350-ohm Karma alloy (nickel-chromium alloy) gages on a polyimide backing. Near and far field gages were either uniaxial or three-element 350-ohm constantan alloy gages. The strain gage signals were recorded either by a transient digital oscilloscope or a combination of oscilloscopes and a multichannel, wide band, frequency modulated, magnetic tape recorder. Operations of the oscilloscopes and recorder during a test were controlled by the microcomputer-based system shown schematically in Fig. 4.

Additional instrumentation that have been used in selected tests include: (1) capacitance-based crack-opening-displacement gages mounted on the front and back plate faces at an a/W that varied from 0.120 to 0.175, (2) an acoustic emission transducer located on the specimen lower pull tab, (3) a displacement gage mounted on the specimen centerline approximately 3.5 m below the crack plane, and (4) accelerometers mounted on the specimen centerline approximately 3.5 m below and 3.5 m above the crack plane. More detailed information on the instrumentation systems can be obtained from Ref. [3].

4.3 Heating-Cooling-Insulation Systems

After being instrumented, the specimen was placed into the NIST testing machine and individual electric-resistance strip heaters attached to the back edge of the plate. The primary heating zone was formed by two pairs of heaters attached to the specimen edge above and below the fracture plane. The second heating zone, consisting of two areas on either side of the first zone, was heated by two outward pairs of heaters. Temperature levels in the two zones were independently controlled to better achieve and maintain a linear thermal gradient.

The cold edge of the specimen (notch) was cooled by spraying liquid nitrogen (LN_2) directly onto the specimen surface using a copper-tube manifold system. The specimen cooling level could be controlled by manually setting a hand valve and with an on/off temperature controller interfaced with a thermocouple at the cold edge of the specimen.

Fig. 2. Thermocouple locations for a typical HSST wide-plate crack-arrest specimen.

$x = 97.5$ FOR WP-1.7 $x = 65$ FOR WP-CE-1

ALL DIMENSIONS IN MILLIMETERS

Fig. 3. Strain gage locations for a typical HSST wide-plate crack-arrest specimen.

Fig. 4. Schematic of HSST wide-plate crack-arrest data acquisition system.

Two types of thermal insulation were used to insulate the hot and cold edges of the specimen. On the hot edge of the plate mineral wool bats were positioned on the specimen face at the vertical center line and extended beyond the heated edge and the strip heaters. The cold side of the plate was insulated with styrofoam sheets which butt up against the mineral wool at the specimen center and extend beyond the cooled edge.

4.4 Testing Procedure

After completion of specimen insulation, all instrumentation was attached to the data acquisition system and a checkout conducted to demonstrate operability. A temperature gradient was imposed across the plate by LN_2 cooling of the notched edge while heating the other edge. Liquid nitrogen flow and power to the heaters were continuously 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 upper-shelf energy for the material being tested and the crack-tip temperature was varied to provide the desired initiation load. Final calibration of the strain gages, COD gages and the load cell were completed just prior to initiation of specimen loading. Tensile load was then applied (Fig. 5) to the specimen at a rate of 11 to 312 kN/s until fracture occurred. Four exceptions to this procedure occurred during the fifteen tests conducted to date. Specimens WP-1.1, WP-CE-2 and WP-2.2 were initially warm prestressed to guard against initiation at a low load, and specimen WP-1.4 utilized a pillow jack device to initiate crack propagation at a prescribed tensile load.

5. TEST SUMMARY

5.1 WP-1 Test Series

Table 4 presents a summary of conditions for each test in the WP-1 test series. The fracture surfaces for specimens WP-1.1 through WP-1.6 are presented in Fig. 6, and Fig. 7 presents the fracture surfaces for specimens WP-1.7 and WP-1.8. Since a description of tests WP-1.1 through WP-1.7 has been presented in a previous paper [4], it will not be repeated. Only a summary of test WP-1.8 will be provided.

Test WP-1.8 was the seventh test in the WP-1 series and the second which utilized a 152-mm-thick specimen. After obtaining a satisfactory thermal gradient, the specimen was loaded at an average rate of 20 kN/s until 24.5 MN was reached. Since a crack run-arrest event did not occur, the specimen was rapidly unloaded in an effort to sharpen the crack tip prior to application of a second load cycle. Two changes were then made in the testing procedure prior to application of a second load cycle: the crack tip temperature was lowered about 11°C to -47°C , and the specimen loading rate was increased to 312 kN/s. At a load of 26.5 MN, the crack run-arrest events initiated and lasted ~ 34 ms (cleavage crack propagation plus ductile tearing). Examination of the fracture surface and strain gage records indicated that three cleavage crack run-arrest events had occurred.

Fig. 5. Wide-plate crack-arrest specimen under test.

Fig. 6. Fracture surfaces of specimens WP-1.1 through WP-1.6.

Fig. 7. Fracture surfaces of 152-mm-thick specimens WP-1.7 and WP-1.8.

TABLE 4

SUMMARY OF HSST WIDE-PLATE CRACK-ARREST TEST CONDITIONS
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)
WP-1.1 ^a	20	-60	20.1	50.2	51	74
WP-1.2A	20	-33	18.9	55.5	62	85
WP-1.2B	55.5	62	18.9	64.5	92	115
WP-1.3	20 ^b	-51	11.25	48.5	54	77
WP-1.4A	20.7 ^{b,c}	-63	7.95	44.1	29	52
WP-1.4B	44.1	29	9.72	52.7	60	83
WP-1.5A	20 ^b	-30	11.03	52.1	56	79
WP-1.5B	52.1	56	11.03	58.0	72	95
WP-1.6A	20 ^d	-19	14.50	49.3	54	77
WP-1.6B	49.3	54	14.50	59.3	80	103
WP-1.7A	20.2 ^b	-24	26.2	52.8	61	84
WP-1.7B	52.8	61	26.2	63.5	88	111
WP-1.8A	19.8 ^b	-47	26.5	44.9	40	63
WP-1.8B	44.9	40	26.5	50.4	55	78
WP-1.8C	50.4	55	26.5	59.4	79	102
WP-CE-1	20.0 ^b	-34	10.14	42.0	36	70
WP-CE-2A ^d	20.0 ^b	-40	14.60	46.6	42	76
WP-CE-2B	46.6	42	14.60	50.4	53	88
WP-CE-2C	50.4	51	14.60	52.5	60	95

^aSpecimen was warm prestressed by loading to 10 MN at 70°C. Specimen was also preloaded to 19 MN.

^bCrack front cut to truncated chevron configuration.

^cPillow jack utilized to apply pressure load to specimen's machined notch.

^dSpecimen was warm prestressed to 14 MN at 25°C.

5.2 WP-CE Test Series

Table 4 presents a summary of the conditions for the two tests in the WP-CE test series. The fracture surfaces for the two specimens comprising this test series are presented in Fig. 8.

Test WP-CE-1 was the first wide-plate crack-arrest test which used the A 533 grade B class 1 material provided by Combustion Engineering, Inc. After

Fig. 8. Fracture surfaces of specimens WP-CE-1 and WP-CE-2.

obtaining a satisfactory thermal gradient, the specimen was loaded at an average rate of 24 kN/s. At a load of 10.14 MN, cleavage crack propagation initiated with a stable arrest occurring at $a/w = 0.37$ on the plate front face and at $a/w = 0.42$ on the plate back face. After holding the load constant for 150 s, loading was reinitiated at 24 kN/s. At a load of 15.26 MN, fibrous crack propagation began and was followed by a rapid drop in load to about 4.4 MN. After maintaining the load at this value for about 30 s, loading was reinitiated at 24 kN/s until at a load of 6.34 MN, complete separation of the plate occurred.

Prior to testing, specimen WP-CE-2 was warm prestressed at room temperature ($\sim 25^\circ\text{C}$) by loading it to 14 MN, holding the load for 5 minutes, and slowly reducing the load to 5 MN. While maintaining the load at 5 MN, the temperature gradient was developed. Having established a satisfactory thermal gradient, the specimen was loaded at a rate of 9.6 kN/s. At a load of 14.6 MN, the crack run-arrest events initiated. Examination of the fracture surface and strain gage records indicated that three cleavage crack run-arrest events occurred.

5.3 WP-2 Test Series

Table 5 presents a summary of the conditions for the tests in the WP-2 series that have been conducted to date. The fracture surfaces for the five specimens that have been tested are presented in Fig. 9. Since a description of tests WP-2.4, WP-2.1, WP-2.5 and WP-2.3 have been presented in a previous paper [4,5], it will not be repeated. Only a summary of test WP-2.2 will be provided.

Prior to testing, specimen WP-2.2 was warm prestressed at 120°C by loading it to 16 MN, holding the load for 5 minutes, and slowly reducing the load to 3 MN. While maintaining the load at 3 MN, the temperature gradient was developed. The specimen was loaded at a rate of 16.2 kN/s. At a load of 17 MN, the crack run-arrest events initiated. Examination of the fracture surface and strain gage records indicated that six to seven cleavage crack run-arrest events occurred.

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

6.1 Posttest Analyses

Posttest analyses were conducted for each wide-plate crack-arrest 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 (3-D), static, finite-element analyses were performed to determine the stress-intensity factor at the time of crack initiation using the ORMGEN/ORVIRT [6,7] fracture analysis system in conjunction with the ADINA-84 [8] finite-element code. Quasistatic analyses utilized the ORNL computer code WPSTAT [9] to evaluate the static stress-intensity factors as a function of crack length and temperature differential across the plate. WPSTAT also categorizes arrested crack lengths in terms of three types of

TABLE 5

SUMMARY OF HSST WIDE-PLATE CRACK-ARREST TEST CONDITIONS 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 - RT _{NDT} (°C)
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
WP-2.4C	33.8	86	8.85	39.7	102	42
WP-2.4D	39.7	102	8.85	41.3	107	47
WP-2.4E	41.3	107	8.85	46.2	121	61
WP-2.4F	46.2	121	8.85	48.4	127	67
WP-2.4G	48.4	127	8.85	51.5	137	77
WP-2.4H	51.5	137	8.85	55.5	149	89
WP-2.1A ^a	19.9	55	11.90	27.5	80	20
WP-2.1B	27.5	80	11.90	33.5	96	36
WP-2.1D	33.5	96	11.90	37.0	105	45
WP-2.1E	37.0	105	11.90	40.0	112	52
WP-2.1F	40.0	112	11.90	45.0	125	65
WP-2.1H	45.0	125	11.90	49.0	135	75
WP-2.1I	49.0	135	11.90	52.7	145	85
WP-2.1J	52.7	145	11.90	55.5	152	92
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
WP-2.5C	35.0	104	8.90	43.5	124	64
WP-2.5D	43.5	124	8.90	47.8	135	75
WP-2.5E	47.8	135	8.90	51.6	144	84
WP-2.5F	51.6	144	8.90	56.0	154	94
WP-2.3A	20.0	66	15.3	34.0	97	37
WP-2.3B	34.0	97	15.3	37.5	106	46
WP-2.3D	37.5	106	15.3	39.7	111	51
WP-2.3F	39.7	111	15.3	45.7	126	66
WP-2.2A ^a	21.1	58	17.0	43.5	120	60
WP-2.2B	43.5	120	17.0	46.5	129	69
WP-2.2C	46.5	129	17.0	47.8	133	73
WP-2.2D	47.8	133	17.0	49.9	139	79
WP-2.2E	49.9	139	17.0	51.0	142	82
WP-2.2F	51.0	142	17.0	53.8	150	90
WP-2.2G	53.8	150	17.0	58.2	162	102

^aCrack front cut to chevron configuration.^bAfter pop-in.

Fig. 9. Fracture surfaces of specimens WP-2.4, -2.1, -2.5, -2.3 and -2.2.

instability limits; i.e., reinitiation, tearing instability and tensile instability. Elastodynamic analyses are carried out using the ADINA/VPF [8] dynamic crack analysis code. The code is capable of performing both application-mode (crack tip is propagated incrementally when K_I , the dynamically computed stress-intensity factor, equals the specified dynamic fracture toughness value, K_{ID}) and generation-mode (crack tip is propagated incrementally according to a prescribed crack position vs time relationship with the values of fracture toughness determined from the dynamically computed K_I) analyses. For both modes of analysis, the dynamic stress-intensity factor is determined in each time step from the dynamic J-integral containing the appropriate inertial and thermal terms.

Tables 6 and 7 summarize crack-arrest toughness values for the WP-1, WP-CE and WP-2 series, which were computed by both static and dynamic analyses as well as those determined using handbook techniques [11,12]. The dynamic generation-mode (fixed-load) crack-arrest toughness results, presented in Fig. 10, extend consistently above the limit provided in ASME Sect. XI and exhibit a significant increase in toughness with temperature ($T - RT_{NDT}$). This increase in arrest toughness 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.

Fig. 10. Generation-mode (fixed load) crack-arrest toughness data versus temperature ($T - RT_{NDT}$) for HSST wide-plate tests.

6.2 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. 11, which presents data from several large-scale tests [13-24] plus the wide-plate test results.

TABLE 6

SUMMARY OF CRACK-ARREST TOUGHNESS VALUES
FOR A533 GRADE B CLASS 1 STEEL: WP-1 AND WP-CE SERIES

Test No.	Crack-arrest toughness values (MPa·√m)			
	Tada static SEN formulas		Fedderson alternate secant formula ^c	Dynamic FE ^d Generation mode
	Displ. control ^a	Load control ^b		
WP-1.1	391	813	340	NA
WP-1.2A	384	942	349	424
WP-1.2B	416	1489	419	685
WP-1.3	215	424	185	235
WP-1.4A	145	248	120	NA
WP-1.4B	331	433	170	387
WP-1.5A	217	472	191	231
WP-1.5B	229	616	213	509
WP-1.6A	279	565	242	275
WP-1.6B	306	881	290	397
WP-1.7A	351	793	311	319
WP-1.7B	385	1312	381	555
WP-1.8A	325	576	273	345
WP-1.8B	344	723	301	484
WP-1.8C	374	1083	356	563
WP-CE-1	180	293	148	170
WP-CE-2A	274	509	232	218
WP-CE-2B	285	597	249	354
WP-CE-2C	291	653	258	576

^a From Ref. [11] (pp. 2.10-2.11) while assuming
a = a_f and no further bending occurs due to propagation
of the crack.

^b From Ref. [11] (pp. 2.10-2.11) while assuming a = a_f
and full bending according to SEN formula when the final
crack depth is used.

^c $K_I = \sigma \left\{ \pi a \sec\left(\frac{\pi a}{2w}\right) \right\}^{1/2}$ with σ = far-field tensile
stress, a = a_f = final crack length, and w = full plate
width (Ref. [12]).

^d Dynamic finite element analyses (fixed load) using
ORNL program ADINA/VPF (Ref. [10]).

TABLE 7
SUMMARY OF CRACK-ARREST TOUGHNESS VALUES
FOR THE WP-2 TEST SERIES

Test No.	Crack-arrest toughness values (MPa-√m)			
	Tada static SEN formulas		Fedderson alternate secant formula ^c	Dynamic FED ^d
	Displ. control ^a	Load control ^b		
WP-2.4A	104	113	79	---
WP-2.4B	155	186	111	137
WP-2.4C	168	234	124	188
WP-2.4D	171	249	128	281
WP-2.4E	181	303	140	249
WP-2.4F	185	332	145	307
WP-2.4G	191	378	153	381
WP-2.4H	198	451	165	397

WP-2.1A	114	132	88	106
WP-2.1B	126	166	100	153
WP-2.1D	133	190	106	158
WP-2.1E	138	213	112	170
WP-2.1F	146	260	123	201
WP-2.1H	153	306	132	293
WP-2.1I	158	359	141	371
WP-2.1J	163	406	149	406

WP-2.5A	108	123	83	---
WP-2.5B	165	196	114	171
WP-2.5C	184	273	134	190
WP-2.5D	193	326	144	268
WP-2.5E	200	382	155	306
WP-2.5F	209	464	167	366

WP-2.3A	164	217	129	144
WP-2.3B	172	249	138	232
WP-2.3D	177	271	144	255
WP-2.3F	190	344	160	258

WP-2.2A	210	350	171	201
WP-2.2B	217	395	180	259
WP-2.2C	220	416	185	281
WP-2.2D	225	454	192	299
WP-2.2E	227	476	195	380
WP-2.2F	233	538	206	364
WP-2.2G	242	656	223	446

^aFrom Ref. [11] (pp. 2.10-2.11) while assuming $a = a_f$ and no further bending occurs due to propagation of the crack.

^bFrom Ref. [11] (pp. 2.10-2.11) while assuming $a = a_f$ and full bending according to SEN formula when the final crack depth is used.

$K_{I1} = \sigma \left\{ w a \sec\left(\frac{\pi a}{2w}\right) \right\}^{1/2}$ with σ = far-field tensile stress, $a = a_f$ = final crack length, and w = full plate width (Ref. [12]).

^dDynamic finite element analyses (fixed load) using ORNL program ADINA/VPF (Ref. [10]).

Fig. 11. High temperature crack-arrest toughness data versus temperature ($T - RT_{NDT}$) for wide-plate and other large specimen tests.

7. CONCLUSIONS

In conclusion, the HSST program has an integrated effort underway to extend the range of applicability of current state-of-the-art crack-arrest practices and to develop alternatives where improvements are needed. Fractographic examinations confirm that the crack propagation in the wide-plate tests occurred by a predominately cleavage mode and that the arrest events were not preceded by conversion to ductile tearing. Arrest may be followed by stable or unstable ductile crack growth, but these modes of fracture may be analyzed independent of the cleavage run-arrest events. A consistent trend is formed when the crack-arrest data from the three types of HSST large-specimen tests are combined on a plot of K_{Ia} vs $T - RT_{NDT}$ with other large-specimen data. Collectively these data 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 Section XI of the ASME code. Further, the data suggest the existence of a limiting temperature above which a cleavage crack cannot propagate no matter how high the applied driving force. 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.

REFERENCES

1. M. F. Kanninen et al., *Preliminary Analysis of Japanese Wide-Plate Dynamic Crack Propagation Arrest Experiments*, Subcontract report from Battelle Columbus Laboratories to Oak Ridge National Laboratory, December 1983.
2. D. J. Ayres et al., *Appendix G, Material Characterization in Tests and Analyses of Crack Arrest in Reactor Vessel Materials*, EPRI NP-5121-SP, prepared by Combustion Engineering, Inc., Windsor, Conn., for Electric Power Research Institute, Palo Alto, Calif., April 1987.
3. G. A. Danko et al., *Wide-Plate Crack-Arrest Tests: Instrumentation for Dynamic Strain Measurements*, NBSIR 85-3289, National Bureau of Standards, Gaithersburg, Maryland, December 1985.
4. D. J. Naus et al., "Summary of HSST Wide-Plate Crack Arrest Tests and Analyses," *Proc. of the U.S. Nuclear Regulatory Commission Fifteenth Water Reactor Safety Information Meeting held at National Bureau of Standards, Gaithersburg, Maryland*, NUREG/CP-0091, pp. 17-40, February 1988.
5. C. E. Pugh and D. J. Naus, "Integration of Wide-Plate Crack-Arrest Test Results," *Proc. of U.S. Nuclear Regulatory Commission Fourteenth Water Reactor Safety Information Meeting held at National Bureau of Standards, Gaithersburg, Maryland*, NUREG/CP-0082, pp. 195-225, February 1987.
6. B. R. Bass and J. W. Bryson, *Applications of Energy Release Rate Technique to Part-Through Cracks in Plates and Cylinders, Volume 1, ORMGEN-3D: A Finite Element Mesh Generator for 3-Dimensional Crack Geometries*, NUREG/CR-2997, Vol. 1 (ORNL/TM-8527/V1), Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., December 1982.
7. B. R. Bass and J. W. Bryson, *Applications of Energy Release Rate Technique to Part-Through Cracks in Plates and Cylinders, Volume 2, ORVIRT: A Finite Element Program for Energy Release Rate Calculations for 2-D and 3-D Crack Models*, NUREG/CR-2997, Vol. 2 (ORNL/TM-8527/V2), Union Carbide Corp., Nuclear Div., Oak Ridge Natl. Lab., February 1983.
8. K. J. Bathe, *ADINA - A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analyses*, Report A-1, Massachusetts Institute of Technology, Cambridge, Mass., 1984.
9. B. R. Bass, C. E. Pugh, and H. K. Stamm, "Dynamic Analyses of a Crack Run-Arrest Experiment in a Nonisothermal Plate," *Pressure Vessel Components Design and Analysis*, ASME Publication PVP, 98-2, 175-84, 1985.
10. B. R. Bass and J. Keeney-Walker, "Computer Program Development for Dynamic Fracture Analysis," pp. 5-12 in *Heavy-Section Steel Technology Program Semiann. Prog. Rep. April-September 1985*, NUREG/CR-4219, Vol. 2 (ORNL/TM-9593/V2), Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., January 1986.

11. R. Tada, P. C. Paris, and G. R. Irwin, *The Stress Analysis of Cracks Handbook*, Del Research Corp., Hellertown, Pa., 1973.
12. C. F. Feddersen, *Current Status of Plain Strain Crack Toughness Testing of High-Strength Metallic Materials*, Crack Arrest Methodology and Applications, ASTM STP-410, American Society for Testing and Materials, Philadelphia, Pa., 1967.
13. R. D. Cheverton et al., *Pressure Vessel Fracture Studies Pertaining to the PWR Thermal-Shock Issue: Experiments TSE-5, TSE-5A, and TSE-6*, NUREG/CR-4249 (ORNL-6163), Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., June 1985.
14. R. D. Cheverton et al., *Pressure Vessel Fracture Studies Pertaining to the PWR Thermal-Shock Issue: Experiment TSE-7*, NUREG/CR-4304 (ORNL-6177), Martin Marietta Energy System, Inc., Oak Ridge Natl. Lab., August 1985.
15. R. H. Bryan et al., *Pressurized-Thermal-Shock Test of 6-in.-Thick Pressure Vessels. PTSE-1: Investigation of Warm Prestressing and Upper-Shelf Arrest*, NUREG/CR-4106 (ORNL-6135), Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., April 1985.
16. R. H. Bryan et al., *Pressurized-Thermal-Shock Test of 6-in.-Thick Pressure Vessels. PTSE-2: Investigation of Low Tearing Resistance and Warm Prestressing*, NUREG/CR-4888 (ORNL-6377), Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., December 1987.
17. Japan Welding Council, *Structural Integrity of Very Thick Steel Plate for Nuclear Reactor Pressure Vessels*, JWES-AE-7806, 1977 (in Japanese).
18. T. Kanazawa, S. Machida, and T. Teramoto, "Preliminary Approaches to Experimental and Numerical Study of Fast Crack Propagation and Crack Arrest," pp. 39-58 in *Fast Fracture and Crack Arrest*, ASTM STP 627, American Society for Testing and Materials, Philadelphia, Pa., 1977.
19. N. Ohashi et al., "Fracture Toughness of Heavy Section LWR Pressure Vessel Steel Plate Produced by Basic Oxygen Furnace and Ladle Refining Process," *Proceedings of the Fourth International Conference on Pressure Vessel Technology*, Vol. 1, pp. 391-96, I. Mech. E., 1980.
20. T. Kanazawa et al., "Study on Fast Fracture and Crack Arrest," *Experimental Mechanics* 21(2), 77-88 (February 1981).
21. S. Machida, Y. Kawaguchi, and M. Tsukamoto, "An Evaluation of the Crack Arrestability of 9% Ni Steel Plate to an Extremely Long Brittle Crack," *Journal of the Society of Naval Architect of Japan* 150, 511-17 (1981), translation ORNL-tr-5052.

22. T. Kanazawa, S. Machida, and H. Yajima, "Recent Studies on Brittle Crack Propagation and Arrest in Japan," pp. 81-100 in *Fracture Mechanics Technology Applied to Material and Structure Design*, G. C. Sih, N. E. Ryan, and K. Jones (eds.), Martinus Nijhoff, The Hague, 1983.
23. Y. Nakano, "Stress Intensity Factor During Brittle Crack Propagation and Arrest in ESO Specimens," *18th National Symposium on X-Ray Study on Deformation and Fracture Solids*, The Soc. of Materials Science, Japan, July 13-14, 1981.
24. A. Pellissier-Tanon, P. Sollogoub, and B. Houssin, "Crack Initiation and Arrest in an SA 508 Class-3 Cylinder Under Liquid Nitrogen Thermal-Shock," Paper G/F 1/8, *Transactions of the 7th International Conference on Structural Mechanics in Reactor Technology*, Vol. G/H, pp. 137-42 (August 1983).