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Progress Report
June-December 1979

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Battelle Columbus Laboratories

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FOREWORD

This project is part of a larger, coordinated effort to establish a rational crack-arrest methodology for nuclear pressure vessels. Research is being performed at Battelle's Columbus Laboratories, the University of Maryland, and the Materials Research Laboratory, with the support of the U. S. Nuclear Regulatory Commission, and the Institut für Festkörpermechanik, Freiburg, Germany, with the support of the Electric Power Research Institute. The program is implementing recommendations of a PVRC/MPC Working Group on crack arrest and includes work on dynamic fracture-mechanics analysis, measurements of crack arrest in a variety of systems using common experimental materials, and photoelastic studies of fast fracture and arrest. The efforts of the four participating institutions are integrated and complementary, and they are being coordinated by the respective project managers: M. Vagins (NRC) and T. U. Marston (EPRI).

ABSTRACT

Analyses of two kinds of crack-arrest experiments have been carried out. The first case was a dynamic finite-difference analysis of tests on a photoelastic material carried out at the University of Maryland. Theory and experiments were shown to be in excellent agreement. The second case was a thermal-shock experiment (TSE-5) carried out by Oak Ridge National Laboratory. Agreement between theory and experiment was not as good here, possibly because the available data base was less detailed and because only an approximate dynamic analysis was carried out.

SUMMARY

The objective of this program is to develop a crack-arrest methodology for reactor-pressure-vessel steels and weldments. This report describes progress during the second half of CY 79, which was devoted to analysis of the standard test specimen, to expansion of the crack-arrest data base, and to support for the analysis of thermal-shock research at ORNL.

Crack-Arrest Test Procedures

Analytical

The BCL elastodynamic finite-difference code was applied to the analysis of run-arrest events in a photoelastic material. The capability of the code to describe the experimental results obtained by the University of Maryland was excellent, particularly when the measured velocity-dependent fracture toughness was used as an input. The dynamic analysis also was shown to have much superior predictive capability than does the static analysis.

Experimental

Characterization of the Cooperative Test Program steel (Heat CTP) was completed with K_{IC} measurements. At 23 C, upper-shelf stable-crack-growth behavior was observed, whereas unstable cleavage occurred at 0 C. Calculations also suggest that about half of the reported scatter in the K_{ID} data reflects a systematic relation between K_{ID} and velocity.

HSST Support Activities

Experimental

Crack-initiation toughness and crack-arrest toughness were measured for the steel used in ORNL thermal-shock Experiment TSE-5. With the

exception of the initiation of the last of the three jumps in the vessel, the toughness data generated using compact specimens were consistent with those deduced from the Oak Ridge experiment. Predictions of the jump lengths in the thermally shocked vessel were based on the toughness data obtained in this program, and they also were found to be good.

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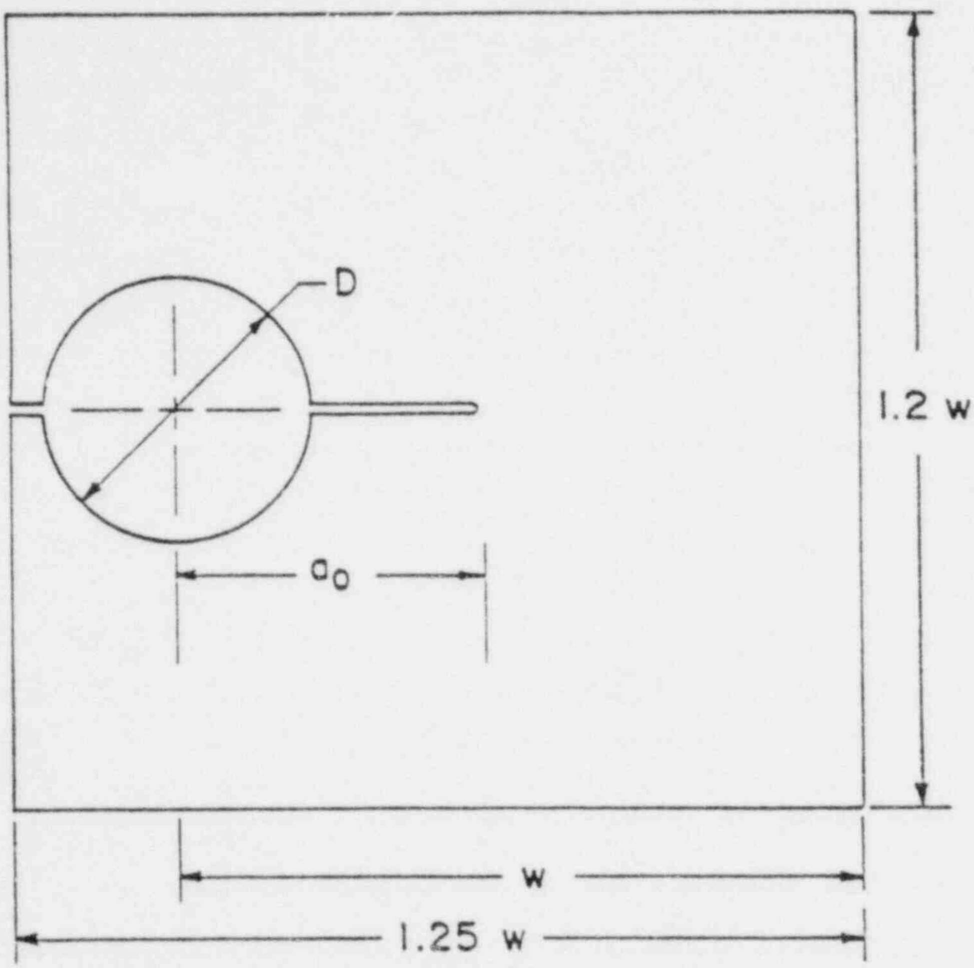
1. CRACK-ARREST TEST PROCEDURES

1.1. Comparison of Dynamic-Crack-Propagation/Arrest Computations With Experimental and Analysis Results Obtained by the University of Maryland

Computations of crack growth in Homolite 100 modified compact tension specimens (Figure 1-1) were performed using BCL's two-dimensional elastodynamic finite difference code, TWOD2. These computations were based on University of Maryland tests P-9, P-7, and P-10. Of most importance, more precise values of the load pin displacement were entered into the computations. Values of the static and dynamic elastic moduli (3964 MPa and 4861 MPa, respectively), and the $K_{ID} = K_{ID}$ ($\dot{a}$) relation were provided by Prof. Fourney (Figure 1-2). The static modulus, E_s, was used everywhere except in the relation between the fracture energy, R, and K_{ID} where the dynamic modulus, E_D, was used. In the University of Maryland analysis the moduli were used in the same manner. Comparisons of the BCL predicted results with the University of Maryland predicted and measured results for the three tests are shown in Figures 1-3 (a-c) and Tables 1-1 and 1-2.

In all cases both computer codes overpredicted the experimentally observed total crack jumps. The University of Maryland predictions were 10 to 19 percent higher while the BCL code predicted 28 and 15 percent longer crack jumps than experimentally observed in Tests P-9 and P-7, respectively. For Specimen P-10, the BCL computation predicted that the crack would not arrest within the specimen.

Because both the BCL and University of Maryland codes are based on linear elasticity, an overprediction of the experimentally observed crack jumps is not surprising. Kalthoff, et al (1977-78) found that the behavior of Homolite 100 is strongly viscoelastic. Consequently, due to the lack of incorporated viscoelastic effects, the dynamic effects in Homolite 100 would be over estimated and, in turn, the crack extension would also be overestimated.



w = 203.2 mm (8.0 inches)
D = 76.2 mm (3.0 inches)
a_0 = 88.9 mm (3.5 inches)

FIGURE 1-1. GEOMETRY AND DIMENSIONS OF THE STANDARD 12.7-mm-THICK MODIFIED COMPACT TENSION SPECIMEN USED FOR THE UNIVERSITY OF MARYLAND CRACK-PROPAGATION AND ARREST STUDIES ON HOMALITE

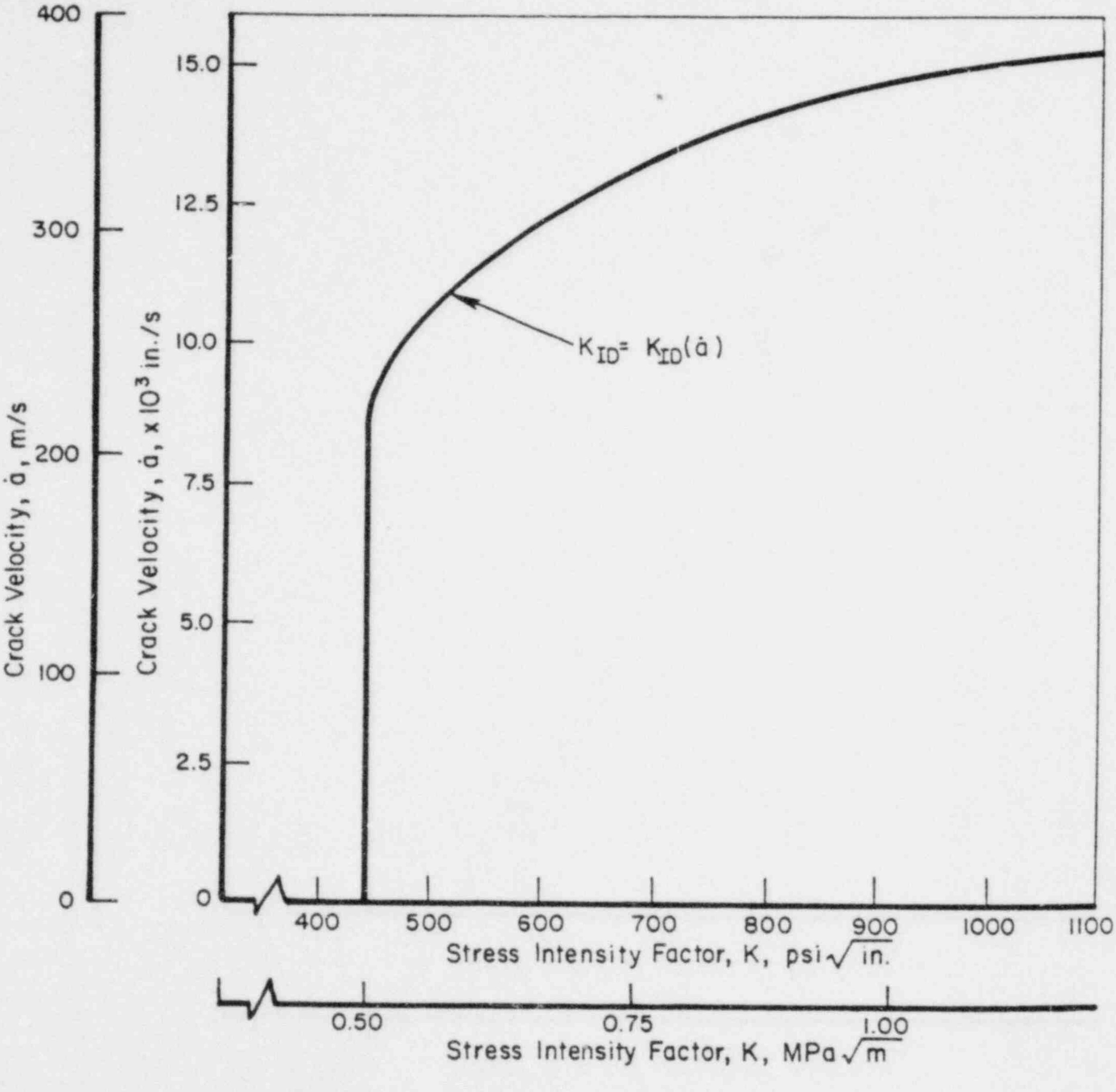


FIGURE 1-2. THE $\dot{a}$-K RELATION FOR HOMOLITE 100 FROM EXPERIMENTS CONDUCTED BY THE UNIVERSITY OF MARYLAND

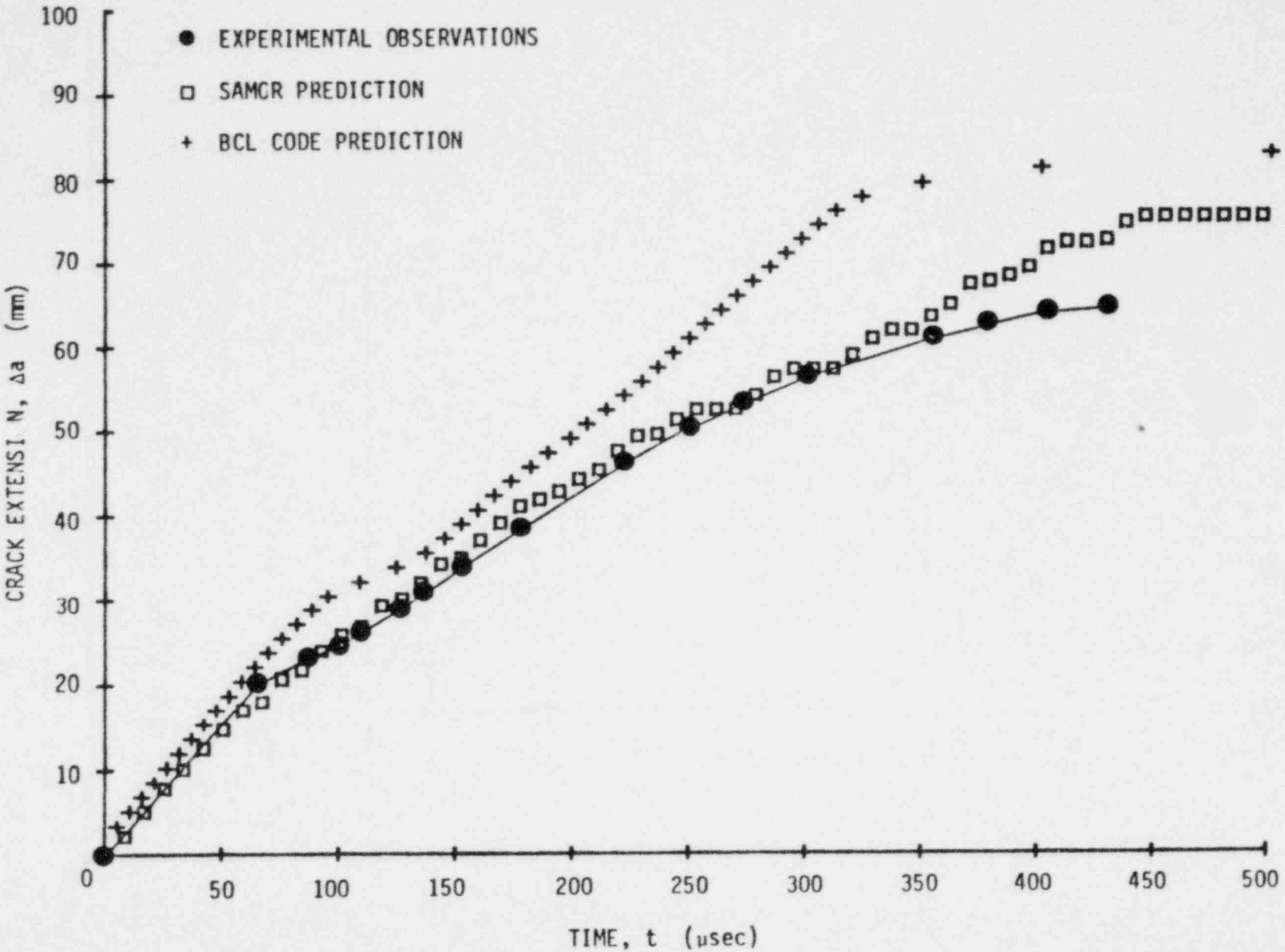


Fig.1-3a. Observed and Predicted Crack Extension as a Function of Time for Test P-9

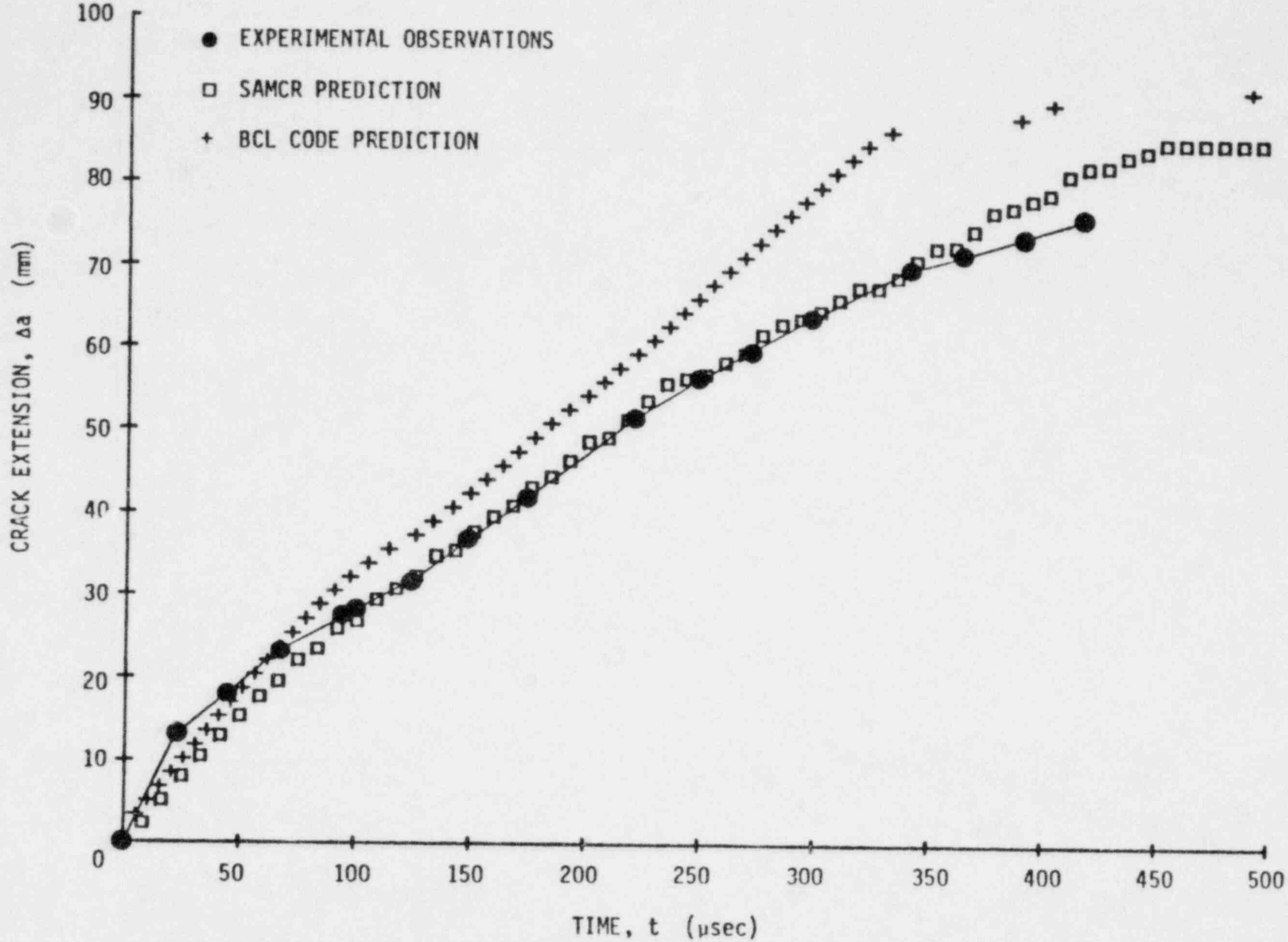


Fig. 1-3b. Observed and Predicted Crack Extension as a Function of Time for Test P-7

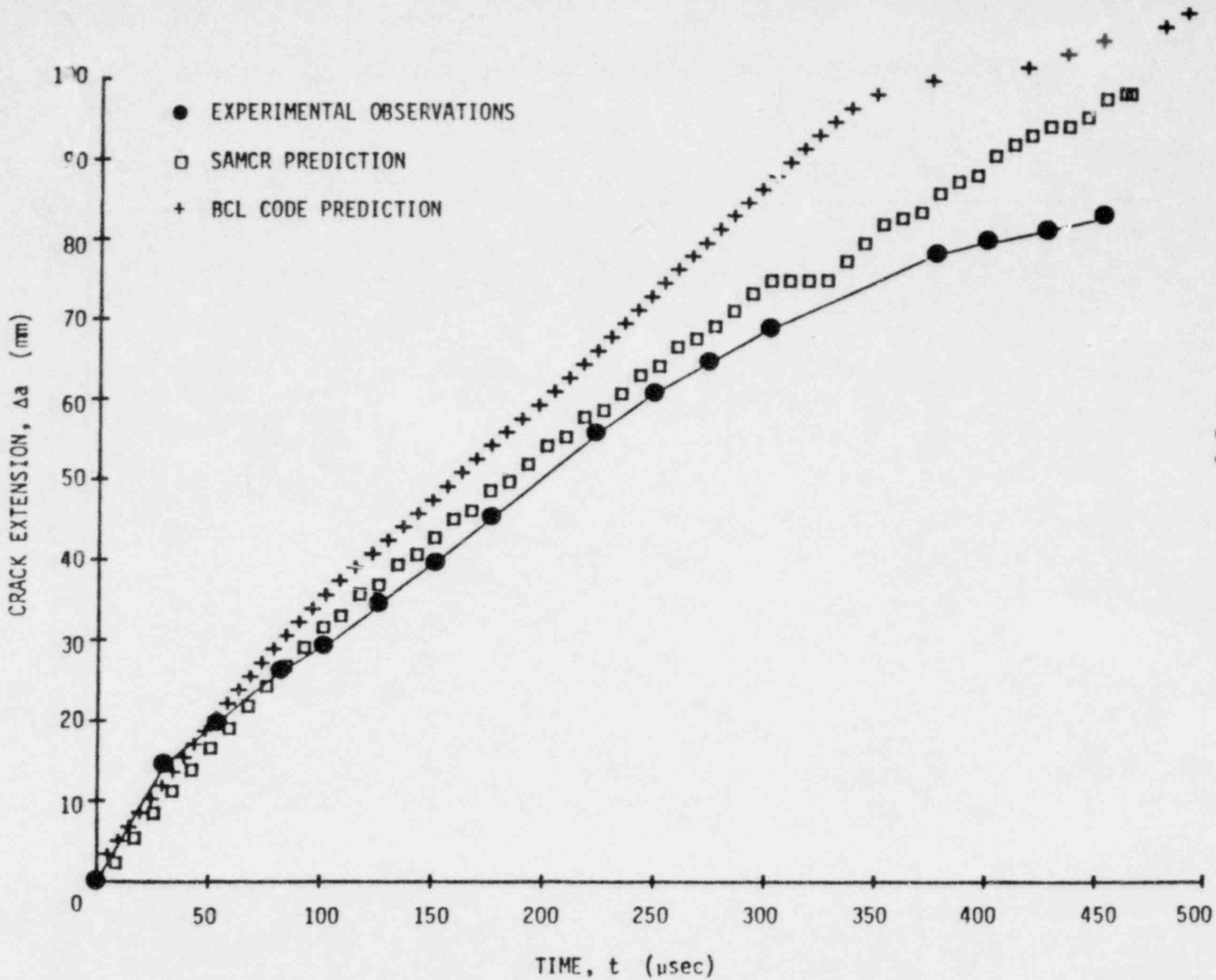


Fig.1-3c Observed and Predicted Crack Extension as a Function of Time for Test P-10

TABLE 1-1. COMPARISON OF MEASURED CRACK EXTENSION WITH THE PREDICTIONS OF BCL AND UNIVERSITY OF MARYLAND CODES AND A QUASI-STATIC ANALYSIS

Total Number	Pin Displacement mm	K_Q MPa $M^{1/2}$	Total Crack Extension, mm			
			Measured	Dynamic Calculation BCL	Dynamic Calculation U. Maryland	Quasi-static Calculation[(a)]
P-9	0.292	0.765	65.0	83.0	77.5	48.3
P-7	0.317	0.834	79.5	91.4	87.4	58.4
P-10	0.368	0.965	86.1	127 [(b)]	100.6	69.2

(a) Using the minimum value from the measured velocity-dependent fracture toughness relation.
(b) Computation predicted no arrest in the specimen.

TABLE 1-2. RATIO OF THE PREDICTED CRACK EXTENSION AT ARREST TO THE EXPERIMENTAL CRACK JUMP LENGTH

Test Number	BCL Prediction	University of Maryland Prediction	Quasi-static Prediction
P-9	1.28	1.19	0.74
P-7	1.15	1.10	0.73
P-10	1.28	1.17	0.80

Of more significance, the difference between the results of a quasi-static crack-arrest prediction and a dynamic prediction were also investigated. Tables 1 and 2 compare the dynamic and quasi-static arrest lengths with the experimentally measured values. The quasi-static predictions were determined from the relation

$$h\ (a_r/w) = \frac{K_a}{K_Q}\ h\ (a_o/w) \quad , \qquad (1\text{-}1)$$

where a_o and a_r, respectively, are the initial and final crack lengths, K_a is the minimum dynamic fracture toughness value (for Homolite 100, K_a = 0.5 $MPam^{1/2}$, see Figure 1-", K_Q is the initial value of the stress-intensity factor, and h is a geometric function determined for the CT specimen.*
For K_Q values taken from the SAMCR results, a_r was calculated from Equation (1-1) via a graphical procedure shown in Figure 1-4.

The results in Table 1-2 and Figure 1-5 clearly show that the quasi-static analysis significantly underestimates the total crack extension. In the three cases considered here the analysis underestimated the crack jump lengths by 20 to 27 percent. This underestimation results from the fact that the kinetic energy that can be returned to the crack tip in a dynamic event is not accounted for in the quasi-static analysis. Hence, the crack can actually propagate further than a quasi-static analysis would suggest.

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* This function combines the geometry dependence of the stress-intensity factor for compact tension specimens under load control obtained by Srawley (1976) with the compliance determined by Newman (1974).

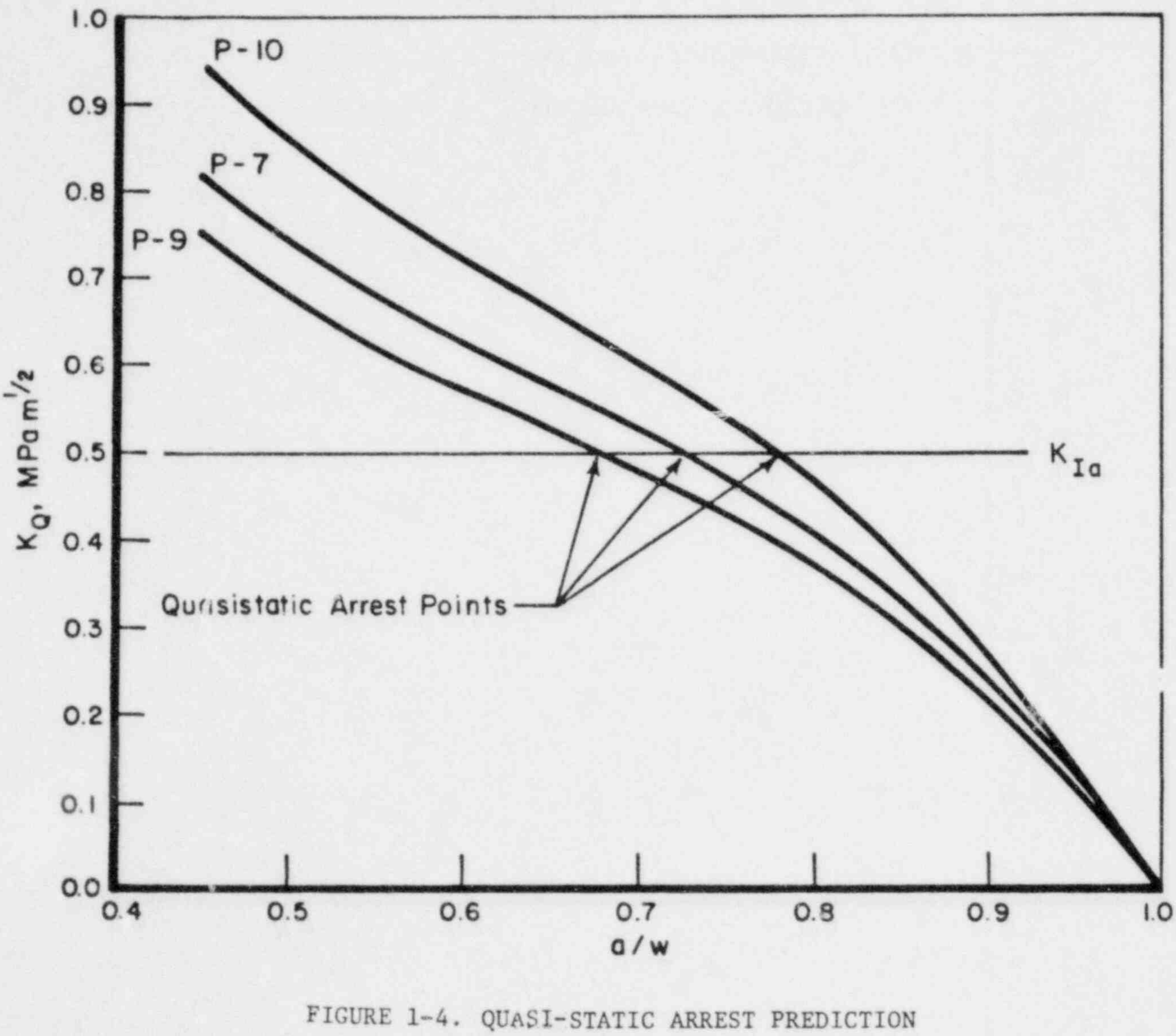

FIGURE 1-4. QUASI-STATIC ARREST PREDICTION

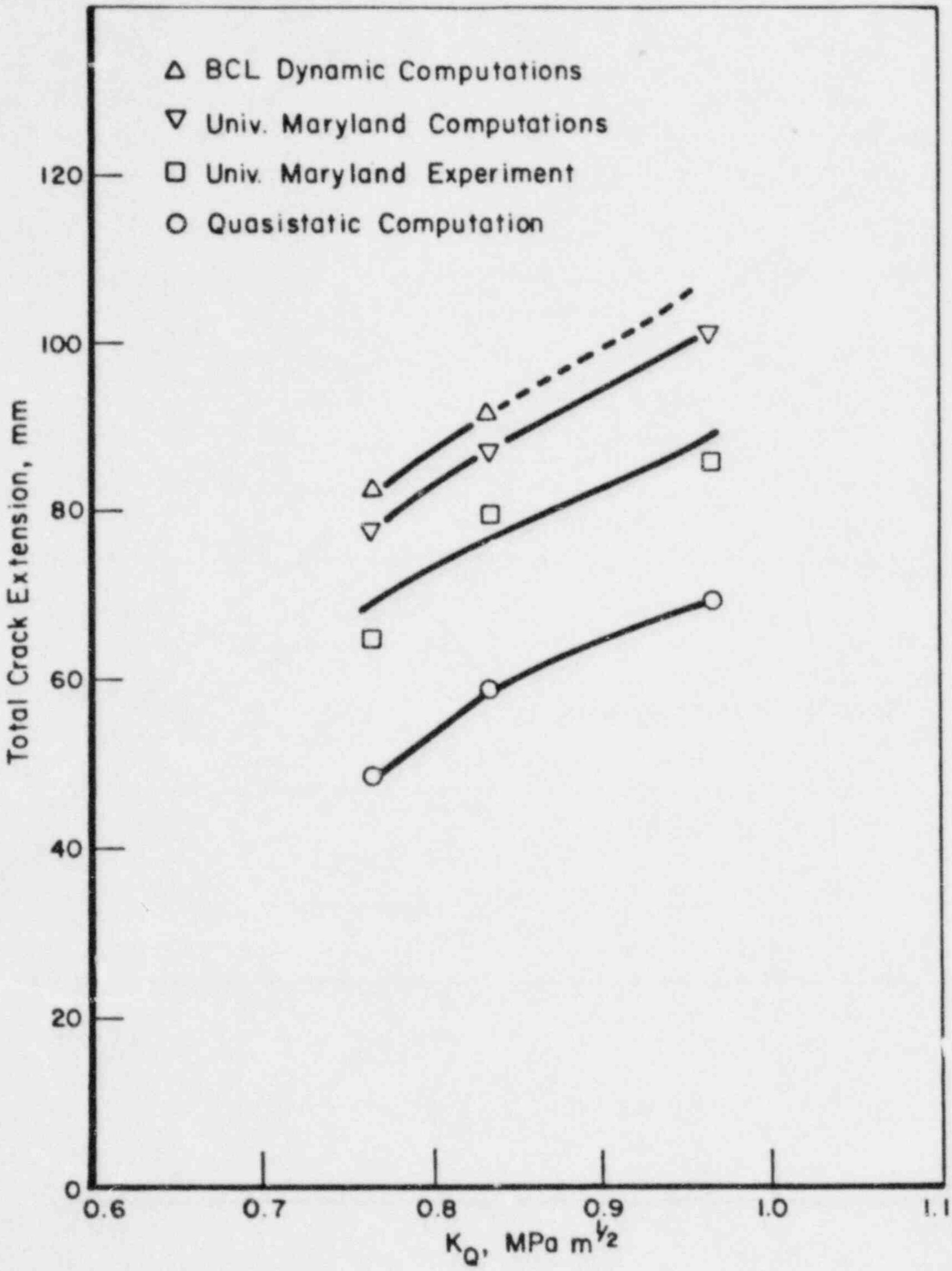

FIGURE 1-5. COMPARISON OF CRACK JUMP LENGTHS FOR HOMOLITE 100 MODIFIED COMPACT TENSION SPECIMENS

1.2. Cooperative Test Program

1.2.1. Initiation Toughness of CTP Steel

Characterization of the A533B steel used in the Cooperative Test Program has been completed with the measurement of K_{IC} values. The test temperatures were 0 C and 23 C, the same as for the crack-arrest (K_{ID} and K_{Ia}) measurements. Because both temperatures are significantly above NDT, the proposed ASTM J-integral method was used. At 23 C, J_{IC} could be obtained from stable-crack-growth behavior. At 0 C, however, unstable cleavage failures were observed in all but one case. In that case, J_{IC} was estimated by taking the area under the load/displacement curve at the onset of unstable crack growth. Table 1-5 tabulates the results, and Figure 1-6 shows the J_R curve for 23 C.

The crack-initiation behavior at 0 C was similar to that of the ORNL A508 in the ductile/brittle transition region, which is discussed in the next section. If the data are considered to be normally distributed, the coefficient of variation is 14 percent (see Table 1-6). This value is close to the degree of scatter in K_{ID} and K_{Ia}. However, some improvements may be possible. Gudas (1979) has shown data that indicate that side grooves markedly reduce the scatter in J_{IC} test measurements. Furthermore, his J_{IC} values for 20 percent-side-grooved specimens lie at the bottom of the scatter band of all specimens (i.e. 0, 10 percent, and 20 percent side-grooved data taken as a whole), a condition that suggests that an element of conservatism is introduced by side grooving. At the same time, the apparent scatter in K_{ID} is found to arise partly from a systematic variation with

TABLE 1-3. CRACK-INITIATION DATA FOR HEAT CTP A533B STEEL

Specimen Number	Test Temperature, C	Area Under Load-Deflection Curve, joules	J, N/mm	Δa, mm	K_{IC}, $MPam^{1/2}$
CTP-100	23	33.1	157.0	0	(c)
CTP-101	23	88.7	409.6	0.73	(c)
CTP-102	23	55.0	254.6	0	(c)
CTP-103	23	129.1	598.3	3.44	(c)
CTP-104	23	104.7	482.0	1.14	(c)
CTP-105	23	279.3	432.4	1.85	(c)
CTP-107	0	21.1	91.7	(a)	146(b)
CTP-108	0	44.2	195.0	(a)	211(b)
CTP-109	0	66.6	315.0	0.90	<268
CTP-110	0	44.4	198.5	(a)	212(b)
CTP-111	0	38.4	169.4	(a)	197(b)
CTP-112	0	41.4	180.4	(a)	202(b)

(a) Catastrophic failure.
(b) Estimated values, see text.
(c) See Figure 2-1.

TABLE 1-4. SUMMARY OF TOUGHNESS DATA OF HEAT CTP

T, C	K_{IC}, $MPam^{1/2}$	K_{ID}, $MPam^{1/2}$	K_{Ia}, $MPam^{1/2}$
0	193 ± 27	123.6 ± 17.1	85.7 ± 12.6
23	310 - 320	138.1 ± 18.2	107 ± 13.3

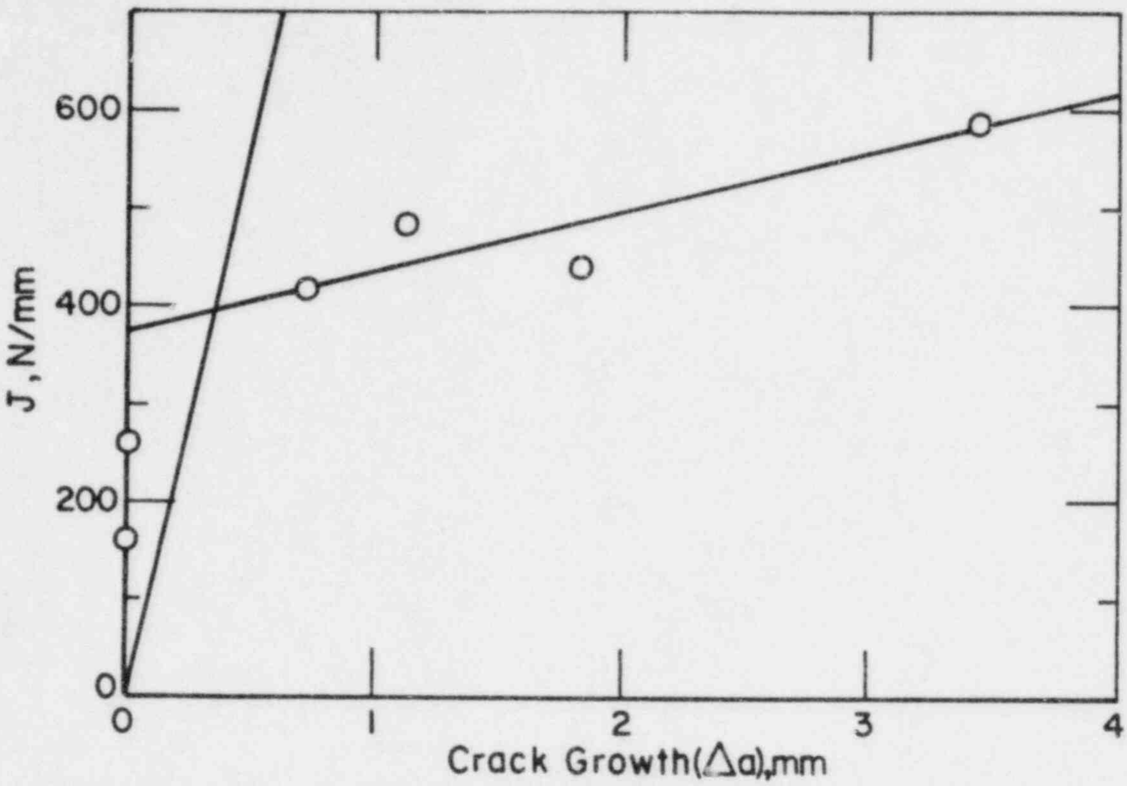

FIGURE 1-6. J_R CURVE FOR COOPERATIVE-TEST-PROGRAM STEEL TESTED AT 23 C

crack velocity, as is discussed in the following section. This leaves unresolved the source of the scatter in K_{Ia}, which appears to be greater than that for the other measures of toughness.

1.2.2. K_{ID}/Velocity Relation for CTP Steel

Examination of the data generated in the Cooperative Test Program reveals a systematic variation of K_D with K_Q, as is illustrated in Figures 1-7 and 1-8. A statistical analysis of these data by Ripling (private communication) showed that a straight-line fit to these data could explain about half of the scatter. His equations, which are indicated by the straight lines on these figures are:

$$\text{At 23 C:}\quad K_D = (37.8 + 0.544\ K_Q) \pm 9.8 \qquad (1\text{-}3a)$$

$$\text{At 0 C:}\quad K_D = (34.2 + 0.50\ K_Q) \pm 6.2\ , \qquad (1\text{-}3b)$$

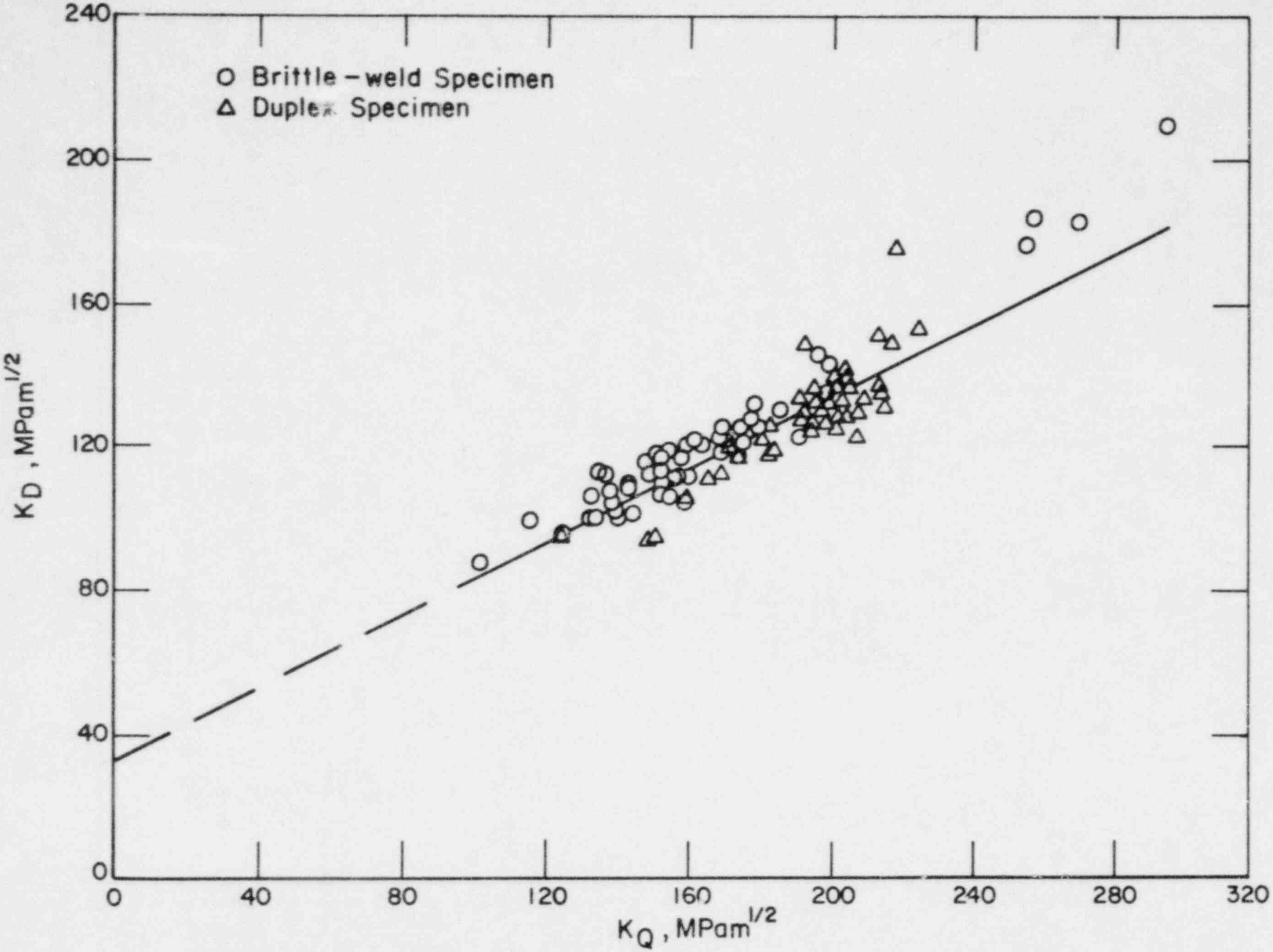

FIGURE 1-7. COOPERATIVE-TEST-PROGRAM K_{ID} DATA; A533B STEEL AT 0 C

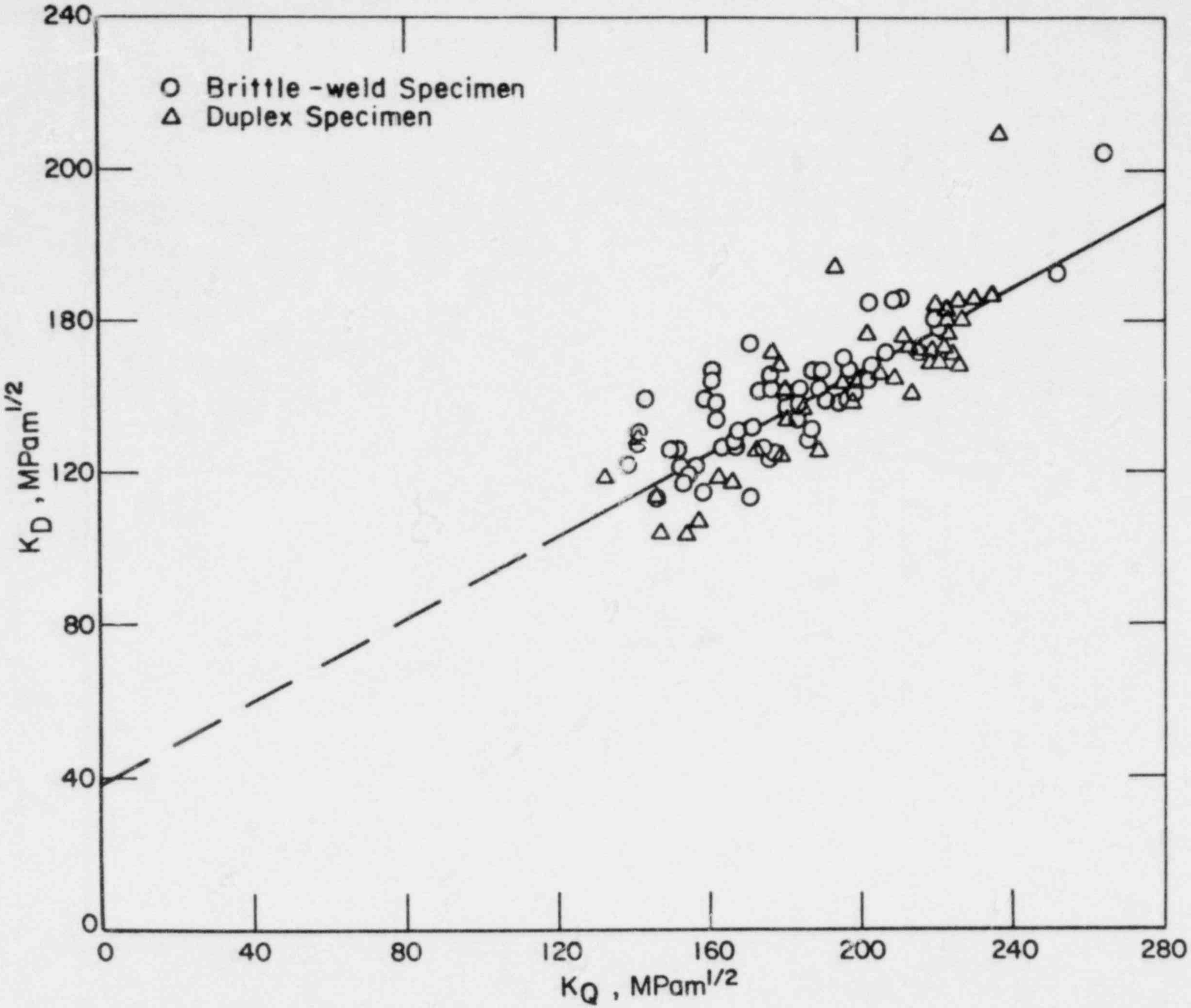

FIGURE 1-8. COOPERATIVE-TEST-PROGRAM K_{ID} DATA; A533B STEEL AT ROOM TEMPERATURE

where the unit of toughness is $MPam^{1/2}$. These equations can be combined with the CT-specimen analyses of Gehlen, et al. (1979) to provide the underlying velocity dependence. Specifically there is a unique relationship between crack velocity and the K_D/K_Q ratio. Figure 1-9 is derived from Figure 10 of Gehlen, et al. (1979). The solid lines represent the range over which the data were available, and the dashed lines are extrapolations based on Equations 1 to 3.

This result indicates that the Cooperative Test Program was carried out at temperatures where the velocity dependence of K_{ID} for this steel is relatively large. Prior to these experiments, the expectation was that K_{ID} would be relatively velocity insensitive (Hahn, et al., 1978a). It would appear that some of the confusion surrounding analysis of the Cooperative Test Program arises from this apparent velocity dependence of K_{ID}.

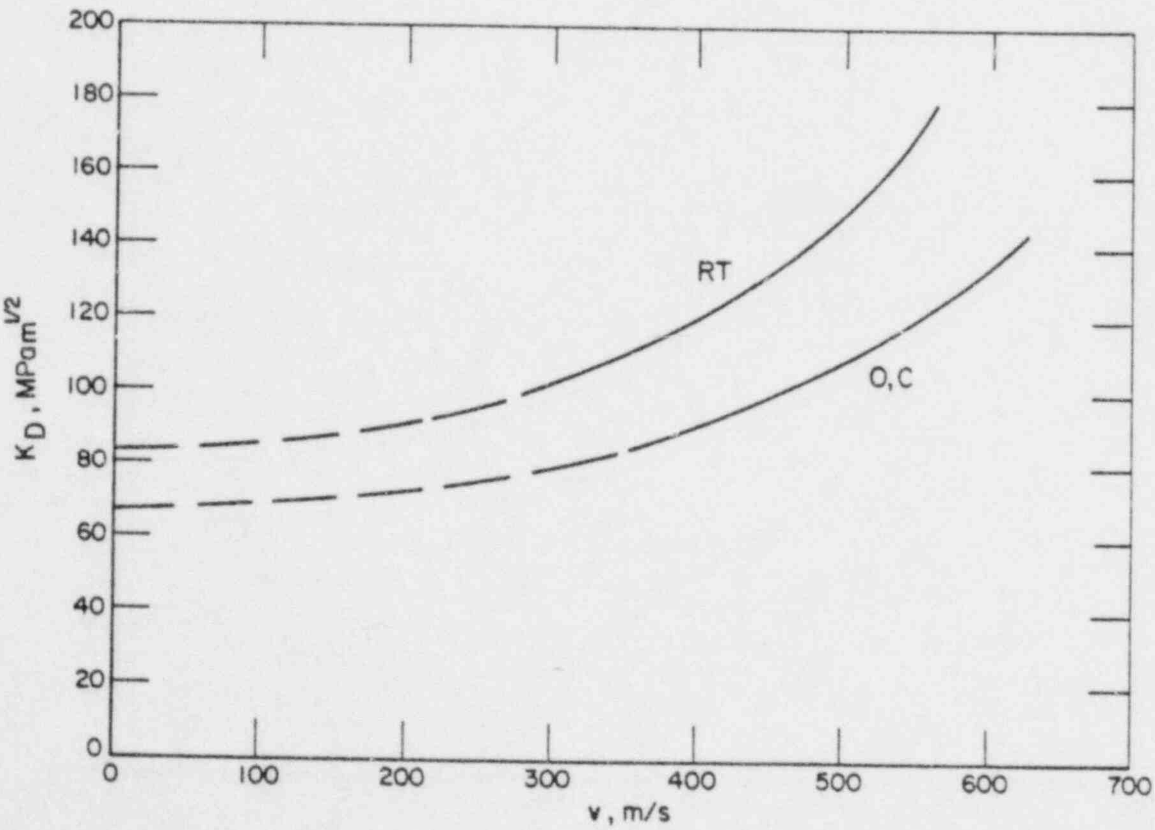

FIGURE 1-9. ESTIMATED K_D/VELOCITY RELATION FOR A533B STEEL (HEAT CTP)

2. HSST SUPPORT ACTIVITIES

2.1. Background

Until recently, there were no data with which to evaluate analyses of long crack jumps under thermal-shock conditions. Experiment TSE-5 carried out at Oak Ridge National Laboratory in August, 1979, provides such information (Cheverton, 1979a, 1979b). Briefly, TSE-5 involved a large cylinder, 991 mm OD x 152 mm wall-thickness x 1220 mm length, heated to 93 C. The inner wall of the cylinder, which contained an axial crack 16 millimeters deep (a/w = 0.10), was quenched using liquid nitrogen. The crack propagated in three distinct jumps (see Table 2-1). Of these, the second jump is of principal interest, because it extended the crack by 64 millimeters.

TABLE 2-1. SUMMARY OF EVENTS FOR THE LONG AXIAL FLAW (TSE-5) (After Cheverton, 1979a)

Initiation-arrest event	1	2	3
Time (Sec)	105	177	205
Crack depth*, (a/w)			
Initiation	0.10	0.20	0.63
Arrest	0.20	0.63	0.80
Temperature, C			
Initiation	-9	-3	79
Arrest	36	82	89
K_{Ic}, $MPam^{1/2}$	79	111	115
K_{Ia}, $MPam^{1/2}$	86	104	92
Duration of experiment, min	30		

* Maximum depth (midlength of TSC-1).

Some material characterization was performed at ORNL. Charpy V-notch impact tests indicated a reference nil-ductility temperature (RT_{NDT}) of 66 C (150 F). However, fracture-toughness (K_{IC}) measurements displayed so much scatter that it has not been possible to use them to derive a transition temperature.

The objectives of the Battelle research in support of TSE-5 are to characterize the crack-arrest behavior of the A508-2 steel used in the experiment and to analyze the thermal-shock results in light of available crack-arrest theories. To this end, part of the prolongation from the ORNL test vessel was provided to us. The steel had been tempered at 613 C (1135 F), which is below the 6.9 C (1200 F) temper specified for A508-2.

Figure 2-1 compares the initiation and arrest stress intensities from TSE-5 with available reference toughness information for pressure-vessel steels. All of the values lie 40-50 $MPam^{1/2}$ above the K_{IR} curve

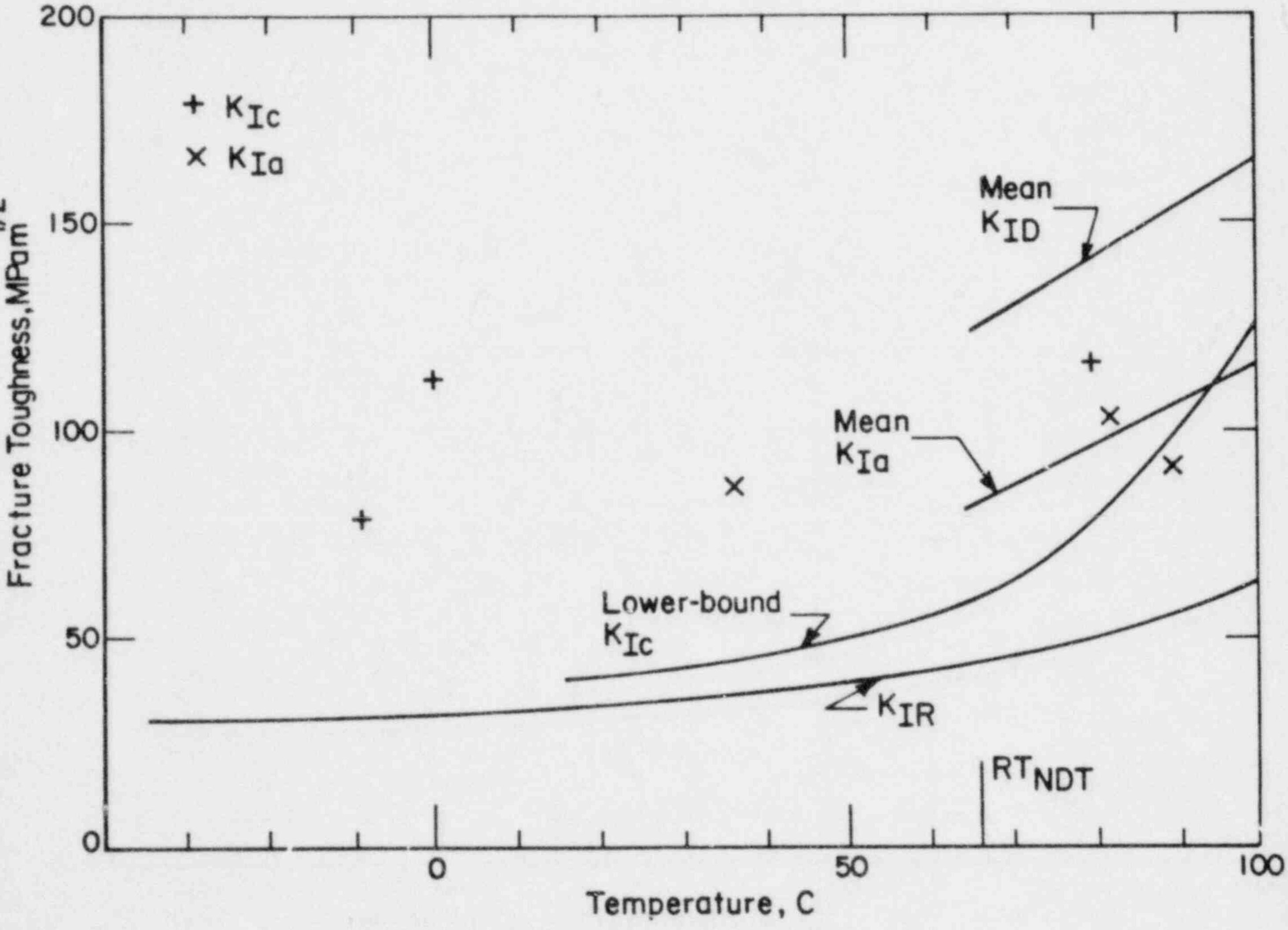

FIGURE 2-1. INITIATION AND ARREST DATA FROM TSE-5 COMPARED WITH VARIOUS REFERENCE CURVES

(paragraph G2110 of the ASME Boiler Code), and the initiation values are in excess of the lower-bound K_{IC} curve (paragraph A4200). The K_{Ia} values for the second and third arrest are in agreement with the BCL K_{Ia} data base, which includes A508 steel (NUREG/CR-0825). The first arrest is in a temperature range below that used for the K_{Ia} data base. Overall, the existing reference curves could not provide sufficient guidance data to predict the test results.

2.2. Crack-Initiation Toughness

Crack-arrest specimens were cut out of the ORNL material to duplicate the crack plane and direction of TSE-5. Figure 2-2 is a schematic

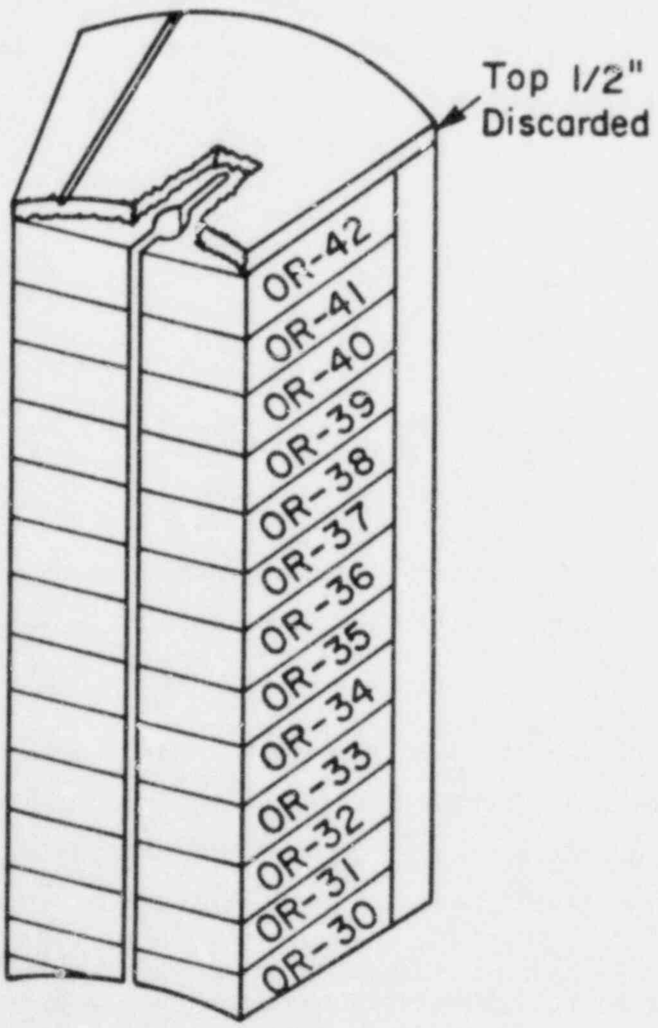

FIGURE 2-2. CUTTING PATTERN FOR PROLONG OF TSE-5 STEEL

diagram of the cutting pattern. The figure is oriented so that the top indicates the steel closest to the test cylinder and the bottom is the end of the prolong. Blocks 30-34 were set aside as not having had a heat treatment representative of that of the test vessel. After the crack-arrest tests were completed, the broken specimen halves were machined into 1T compact specimens of the same orientation for J_{IC} testing. It was possible to cut one J-integral specimen from each broken half of a crack-arrest specimen, and their numbers in Table 2-2 reflect their origin.

TABLE 2-2. CRACK-INITIATION DATA, 1T COMPACT SPECIMENS OF TSE-5 STEEL

Specimen Number	Test Temperature, C	Area Under Load-Deflection Curve, joules	J, N/mm	Δa, mm	K_{IC}, $MPam^{1/2}$
40-1	-7	(a)	(a)	(a)	83[c]
40-2	-7	(a)	(a)	(a)	111[c]
36-1	38	19.39	91.11	(b)	143[c]
36-2	38	17.67	81.03	0	>135
38-1	38	40.45	185.41	(b)	204[c]
38-2	38	27.00	123.83	0	>167
41-1	38	32.54	198.63	(b)	232[c]
41-2	38	43.73	147.88	(b)	182[c]
37-1	82	62.62	287.18	(b)	254[c]
37-2	82	43.73	200.55	0	>212
39-1	82	58.14	274.75	0.53	<249
39-2	82	60.42	290.15	0	>255

(a) Linear elastic load/displacement curves; K_{IC} calculated from load.
(b) Catastrophic fracture.
(c) Estimated values.

The procedures adopted to measure K_{IC} were those adopted by ASTM-E24.01 for J-integral testing. Essentially, four different experimental results were obtained. At -7 C, the load/displacement curves were nearly linear, and the tabulated values were calculated as if the samples were elastic. Although the K_{IC} data reported in the table are invalid according to ASTM E399, it is believed that they are close to the actual values because of the linearity. At 38 C, all specimens exhibited yielding.

In four cases, catastrophic cleavage failure occurred before the specimens could be unloaded. In the other two cases, loading was stopped and the specimens were heat-tinted. No stable crack growth was detected. In both of these cases, the termination points were chosen to be slightly less than the catastrophic failure of the mating sample (e.g., compare Specimens 36-1 and 36-2). The indication is that crack-arrest Sample 36 had lower initiation toughness than did Sample 38, a condition that suggested material inhomogeneity. We have concluded that little, if any, crack growth occurred prior to catastrophic cleavage failure and that those specimens that failed in that manner provided K_{IC} values. These K_{IC} values were calculated from the area under the load/displacement curve using the proposed ASTM J-integral procedures.

Only one instance of stable crack growth was found, and that was at 82 C. Otherwise, the behavior at 82 C resembled that at 38 C. Accordingly, no J_R curves could be obtained.

Overall, the data confirmed the ORNL experience of large scatter in K_{IC} data, particularly in the ductile/brittle transition region. Figure 2-3 compares the Battelle data to the ORNL thermal-shock data. Initiation of the first two jumps in TSE-5 occurred at K_{IC} values close to those found using compact specimens. The third initiation of TSE-5 occurred at a much lower value than for the Battelle tests, and the source of this difference is not yet clear.

2.3. Crack-Arrest Toughness

Because of the limited amount of material provided by ORNL, the crack-arrest-specimen dimensions (152 x 149 x 32 mm) were approximately 3/4 of those of the compact crack-arrest specimens used in the Cooperative Test Program (Hahn, et al., 1978c). Research at Battelle-Columbus (reported by Mager, 1979) suggests that these dimensions should offer no problem for K_{ID} values on the order of 100 $MPam^{1/2}$ or lower. The question of their validity for K_{ID} values on the order of 150 $MPam^{1/2}$ is under investigation in a separate program.

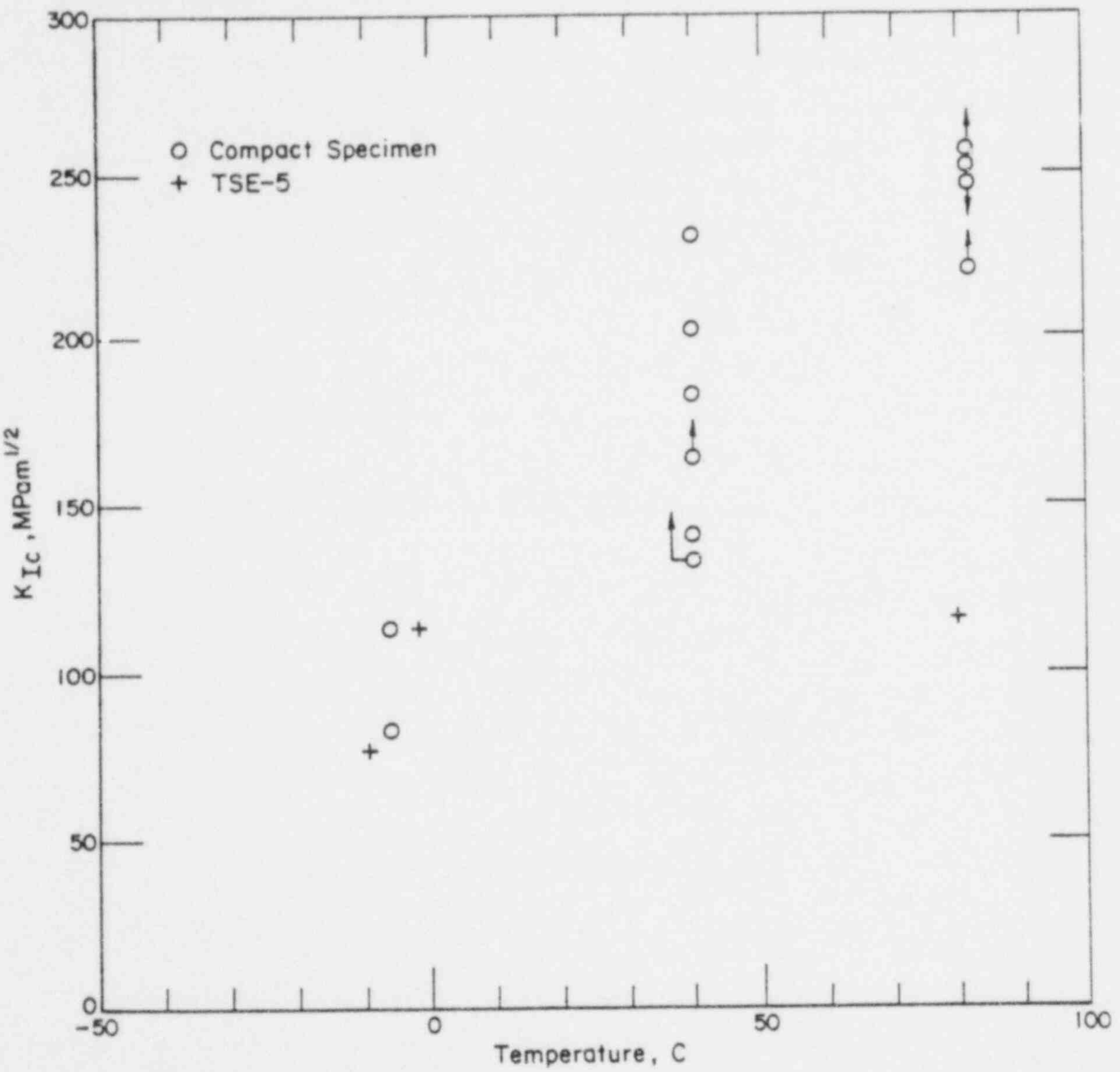

FIGURE 2-3. COMPARISON OF COMPACT-TENSION K_{Ic} DATA WITH THOSE CALCULATED FROM EXPERIMENT TSE-5

As was indicated in Section 2.2, it was possible to fabricate eight specimens from the steel block. The experimental procedures were in accord with practices used for the Cooperative Test Program, with the exception of the means of initiating the crack. A number of participants in that program objected to the precompression prior to initiation. For this reason, cyclic loading, in which the displacement was incrementally increased, was used in the present experiments unless otherwise noted. Target test temperatures were 82 C, which corresponded to the arrest of the second jump in the vessel, and ambient temperature (27 C), which was about 10 C below the arrest of the first jump. (The arrest of the third jump was at a temperature only 7 C higher than that of the second jump.)

Results are given in Tables 2-3 and 2-4. It was not possible to initiate the running cracks at a sufficiently low K_Q level to produce the low crack velocity estimated for the second jump in the vessel (Cheverton, 1979a). It also is believed that the other jumps were essentially static events. For this reason, the K_{ID} and K_{Ia} data may not be representative of the vessel behavior. The values obtained at Battelle are plotted on Figure 2-4, along with the K_{Ia} values deduced from TSE-5. The curves are straight-line interpolations of measurements using compact crack-arrest specimens, the assumed linear temperature dependence being based on a statistical analysis of previous data (Hahn et al., 1978b). The straight lines have the equations:

$$K_{ID} = 91.4 + 0.42\ T \qquad (2\text{-}1A)$$

$$K_{Ia} = 53.8 + 0.46\ T\ , \qquad (2\text{-}1B)$$

where toughness is in $MPam^{1/2}$ and temperature in C. The slopes of both curves are about equal to one another in accord with previous experience, but their absolute values are about half of those for A533B or for A508-2 tempered at a higher temperature. Both K_{ID} and K_{Ia} values obtained at room temperature were closely reproducible, whereas the values at 81-84 C were scattered. The estimates of standard deviation at the higher temperature, while based on only three specimens, were close to 15 percent, as was found on the Cooperative Test Program. Specimen OR-40 is interesting in this respect, because its K_{ID} value was much lower than those of the other two specimens and its fracture surface appearance was much smoother.

TABLE 2-3. CRACK-ARREST DATA FOR ORNL TSE-5 STEEL

Specimen Number	Root Rad., mm	Temperature, C		Displacement, mm		Crack Length, mm	
		T	$T-RT_{NDT}$[(a)]	Initiation	Arrest	Initiation	Arrest
OR-35[(d)]	0.25	26	-40	1.65	(b)	45.1	(b)
-36[(d)]	0.25	27	-39	1.11	(b)	44.8	(b)
-37	0.25	28	-38	0.93	1.05	44.6	107.6
-38	1.40	84	18	(c)	(c)	(c)	(c)
-39	0.66	82	16	1.23	1.30	44.8	101.2
-40	0.25	84	18	0.86	0.93	44.8	93.6
-41	0.25	27	-39	0.89	0.99	44.8	99.9
-42[(d)]	0.25	81	15	0.97	1.05	44.8	80.1

(a) Assuming RT_{NDT} = 66 C (150 F).
(b) Invalid test: crack ran out of side groove.
(c) Stable crack growth.
(d) Precompressed.

TABLE 2-4. CRACK-ARREST TOUGHNESS OF ORNL TSE-5 STEEL

Specimen Number	Temperature, C	Δa/W	$MPam^{1/2}$			Estimated Crack Velocity, m/s
			K_Q	K_{ID}	K_{Ia}	
OR-35	26	(a)	(a)	(a)	(a)	(a)
-36	27	(a)	(a)	(a)	(a)	(a)
-37	28	0.496	162	101	61	670
-38	84	(a)	(a)	(a)	(a)	(a)
-39	82	0.444	214	143	89	615
-40	84	0.384	150	105	78	540
-41	27	0.434	155	104	71	600
-42	81	0.278	170	131	109	430

(a) Invalid test; see Table 2-3.

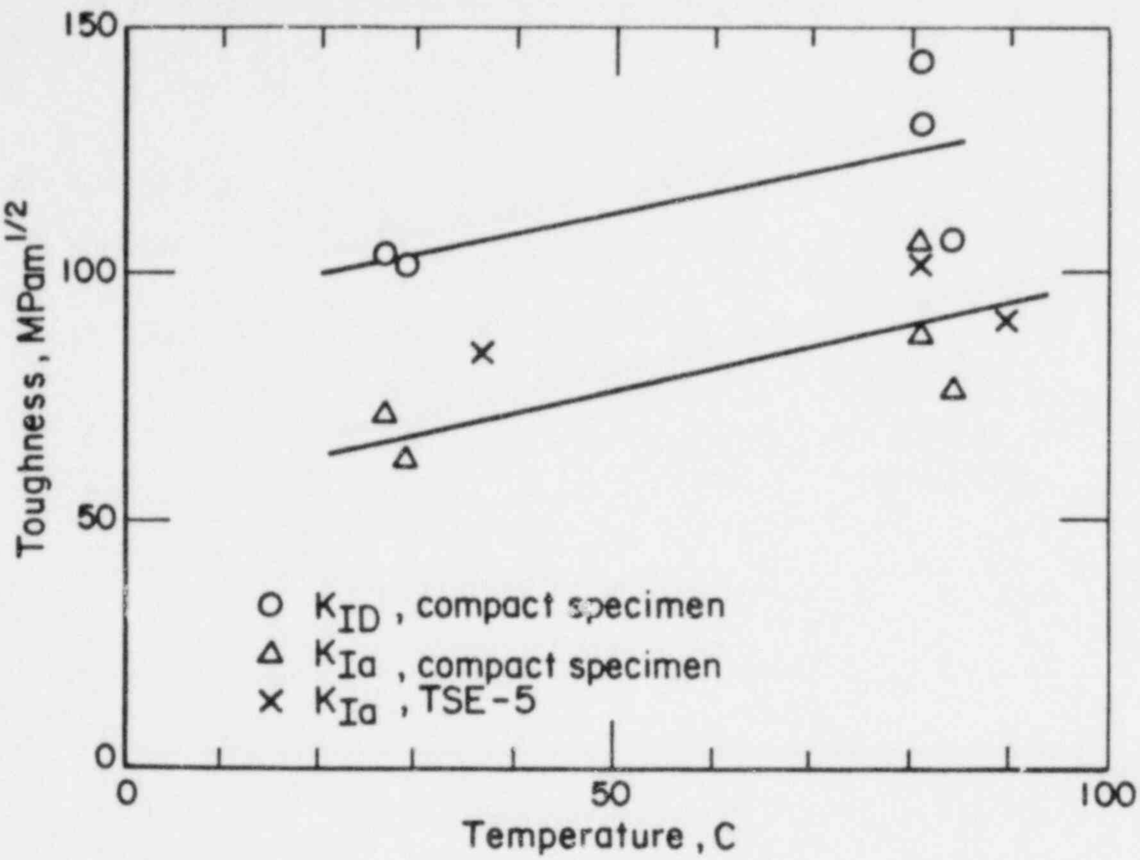

FIGURE 2-4. CRACK-ARREST TOUGHNESS OF TSE-5 MATERIAL

The K_{Ia} values from the TSE-5 experiment also are plotted in Figure 2-4. These are in reasonably good agreement with those obtained in the Battelle crack-arrest tests with compact specimens.

2.4. Analysis of Thermal-Shock Results

The values of K_{ID} and K_{Ia} obtained in this work can be applied to the TSE-5 results. As is shown in Table 2-1, the first and third jumps were quite short and can be assumed to have been approximately static events. The second jump, while extending the crack almost halfway through the vessel, also occurred at modest velocity: Cheverton (1979a) reported that the initial crack speed was ∿180 m/s and decreased continually as the crack progressed.* Thus, it is possible that none of the K_{ID} data reported in the previous section are applicable to TSE-5 because of the greater crack speeds in the Battelle experiments (see Table 2-4).

* More recent evaluation of the data suggests that the speeds may be even lower (Cheverton (1980)).

In this section the experimental and analytical jump lengths in TSE-5 K_{ID} and K_{Ia} are compared.

2.4.1. Static Approach

For the crack to arrest using the static analysis, the K_I stress intensity at some location in the vessel must be less than K_{Ia}. In order to apply this approach, values of K_I and of the temperature distribution were taken from Cheverton (1979a). Values of K_{Ia} were then calculated from Equation (2-1B). Figure 2-5 shows the result for the second jump in TSE-5. The intersection of the K_{Ia} curve with the K_I curve is the predicted arrest point. The actual arrest point was close to the value that would be associated with a K_{Ia} level 15 percent greater than the mean calculated from Equation (2-1B). Table 2-5 shows the results from all three jumps. Since these jumps were all essentially static events, it is not surprising that the results calculated using the static approach yield reasonable predictions.

TABLE 2-5. CRACK ARREST IN TSE-5 (QUASISTATIC ANALYSIS)

		a/w at Arrest	
Jump Number	a/w at Initiation	Actual	Predicted From Static Analysis, mean
1	0.10	0.20	0.30
2	0.20	0.63	0.73
3	0.63	0.80	0.78

2.4.2. Approximate Dynamic Analysis

Since the second jump of the three came closest to being a dynamic event, an approximate dynamic analysis was applied to it. The quasistatic energy-balance analysis (Hahn, et al., 1978c) was used. In this method, all of the elastic energy that is released eventually becomes available to drive the crack. The arrest point is then given by:

$$\int_{a_o}^{a_a} (\mathcal{G} - R)\, da = 0 \quad , \qquad (2-2)$$

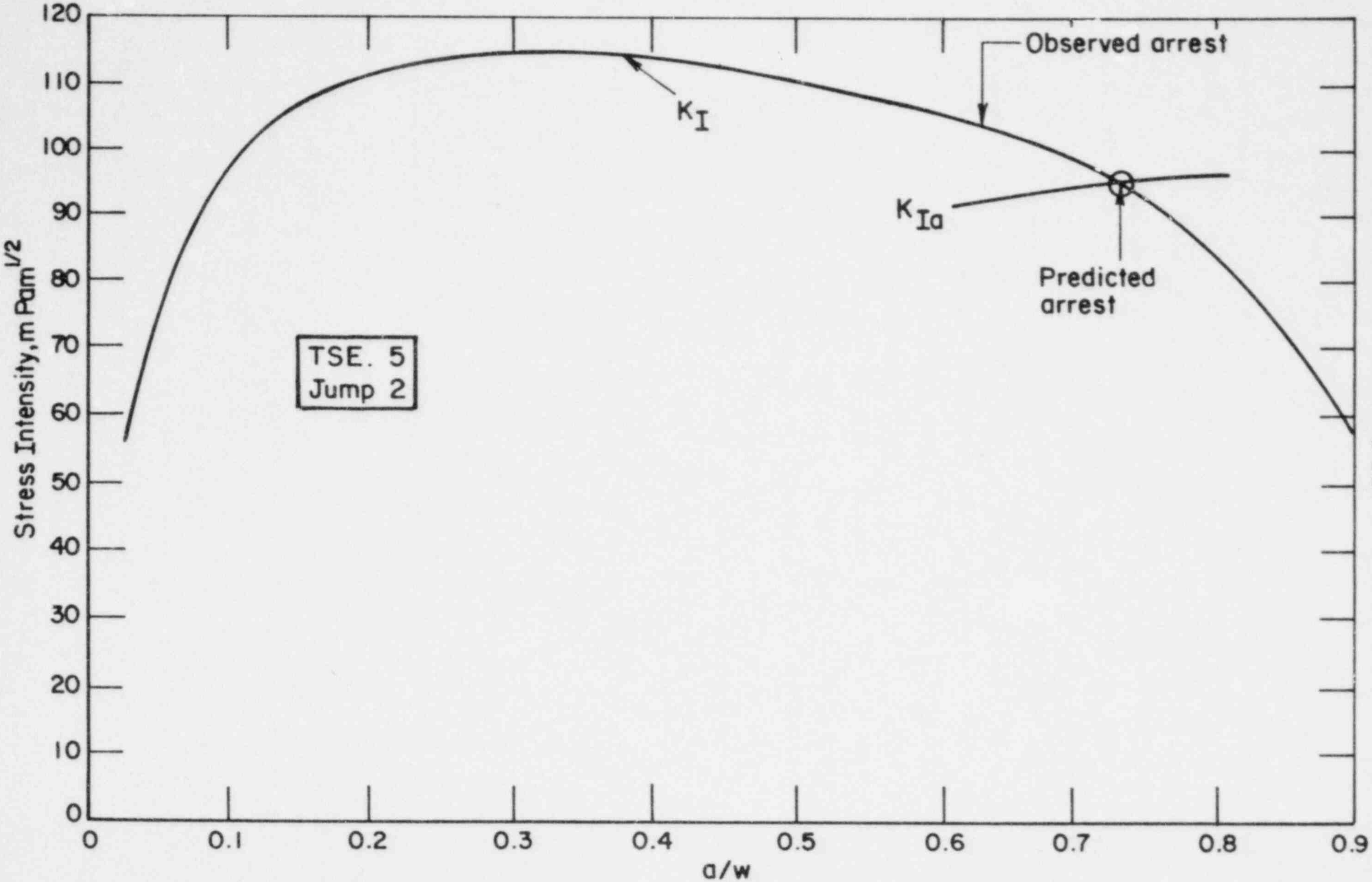

FIGURE 2-5. CRACK ARREST IN TSE-5, QUASISTATIC ANALYSIS

where a is crack length, $\mathcal{G}$ is s.rain-energy-release rate, and $R = K_{ID}^2/E\ (1-\nu^2)$ is the fracture « gy. The limits of integration are initial and arre: crack len. ı. A graphical construction is used to evaluate Equation (2-2), as is illustrated in Figure 2-6. Crack arrest is predicted when the tr aded areas are equal. As is seen in the graph, the expected arrest distance is short of the actual arrest distance. The discrepancy may be the result of the value of K_{ID} used in the calculation being greater than that experienced in the vessel because of the low speed in the vessel, and of the approximate nature of the calculation.

To determine influence of an uncertainty in the measured K_{ID} value the approximate dynamic calculation was repeated using 85% of the average K_{ID} value. In this case the crack arrested at a/w = 0.91. This result gives credence to the idea that the propagating crack toughness values measured on CT specimens may have been too large to represent the values experienced in the thermally shocked cylinder.

Table 2-6 compares the static and approximate dynamic predictions of crack arrest with the vessel behavior. Currently, the full dynamic analysis using the finite-difference technique is being carried out, and preliminary results indicate that its predictions are conservative.

TABLE 2-6. CR.CK ARREST IN TSE-5

(Comparison .f Quasistatic and Dynamic Analyses)

	a/w			Error in Δa/w,
	Initiation	Arrest	Δa/w	percent
Experiment	0.20	0.63	0.43	--
Static analysis	0.20	0.73	0.53	+23
Approximate dynamic analysis using mean K_{ID}	0.20	0.58	0.38	-12
Approximate dynamic analysis using lower found K_{ID}	0.20	0.91	0.71	+65

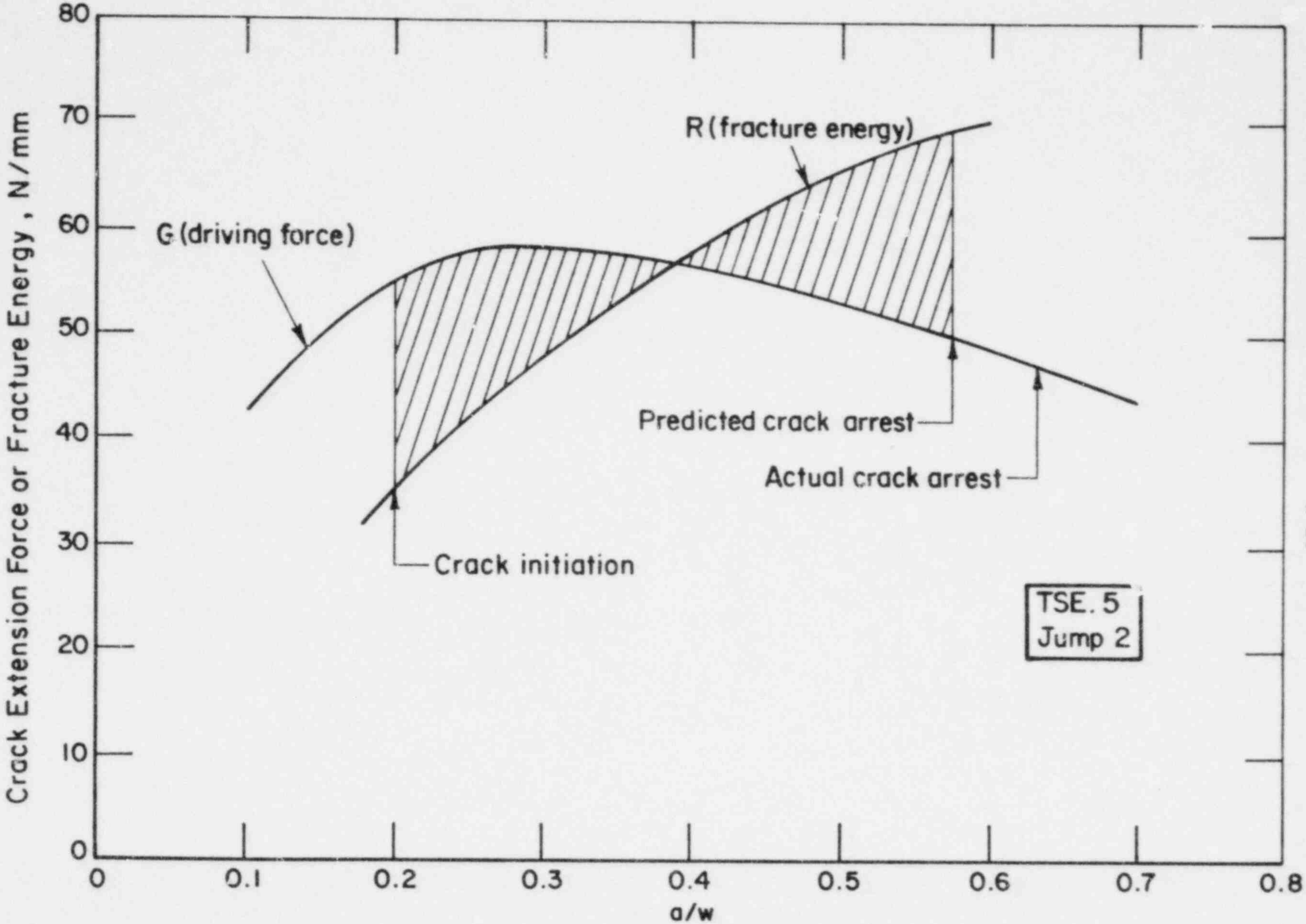

FIGURE 2-6. CRACK ARREST IN TSE-5, APPROXIMATE DYNAMIC ANALYSIS

3. DISCUSSION

The two crack-arrest studies discussed in this report illustrate the strengths and weaknesses of the two approaches to crack arrest. For rapidly propagating cracks, the quasistatic approach is simpler to apply but apparently is less accurate than is the dynamic approach. In the experiments on Homalite 100, the dynamic method provided much better predictions. In that case, the K_{ID} versus velocity curve was well-defined, and a full dynamic analysis was performed. In the case of the thermal-shock experiment, there was not enough test material to provide sufficient characterization of the K_{ID} versus velocity curve over the temperature range of interest. In addition, the dynamic analysis used was only an approximation and the crack velocity was relatively modest. Even so the predicted jump length was reasonably close to the measured one.

It is, of course, premature to make any definite conclusions as to the most suitable approach for predicting crack arrest under thermal-shock conditions. The data base is as yet too small. However, the progress already made in connection with TSE-5 combined with the early results of the fully dynamic analysis provide encouragement that the problem will be resolved.

REFERENCES

Cheverton, R. D. (1979a), "Quick Look Report for Thermal Shock Experiment TSE-5," Oak Ridge National Laboratory (August 14, 1979).

Cheverton, R. D. (1979b), "Behavior of Deep Flaws in a Thick-Wall Cylinder Under Thermal Shock Loading," 7th Water Reactor Safety Meeting, National Bureau of Standards, Gaithersburg, MD.

U.S. Nuclear Regulatory Commission. "Photoelastic Studies of Damping, Crack Propagation, and Crack Arrest in Polymers and 4340 Steel," NUREG/CR-1455, May 1980. Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and the National Technical Information Service, Springfield, VA 22161.

Gehlen, P. C., Hoagland, R. G., and Popelar, C. H. (1979), "A Method for Extracting Dynamic Fracture Toughness from C. T. Tests," Int. J. Fracture, 15, 69-84.

Gudas, J. P. (1979), "Computer Interactive Unloading Compliance Test Method Validation, " 7th Water Reactor Safety Meeting, National Bureau of Standards, Gaithersburg, MD.

Hahn, G. T. , Rosenfield, A. R., Marschall, C. W., Hoagland, R. G., Gehlen, P. C., and Kanninen, M. F. (1978a), "Crack Arrest Concepts and Applications," Fracture Mechanics, edited by N. Perrone, et al., University of Virginia Press, pp. 205-227.

Hahn, G. T., Hoagland, R. G., Lereim, J., Markworth, A. J., and Rosenfield, A. R. (1978b), "Fast Fracture Toughness and Crack Arrest of Reactor Pressure Steel," presented at ASTM Symposium on Crack Arrest Methodology and Applications and to be published in Special Technical Publication 711 in 1980.

Hahn, G. T., Hoagland, R. G., Rosenfield, A. R., and Barnes, C. R. (1978c), "A Cooperative Program for Evaluating Crack-Arrest Testing Methods," idem.

Kalthoff, J. F., (1977-78), "Influence of Dynamic Effects on Crack Arrest," Institute for Feskorpmechanik reports to the Electric Powe Research Institute, Freiberg, Germany.

Mager, T. R., and Marschall, C. W. (1979), "Development of a Crack Arrest Toughness Data Bank for Irradiated RPV Materials," Semiannual Technical Progress Report No. 1 on EPRI RP1326-1.

Newman, J. C., Jr. (1974), "Stress Analysis of the Compact Specimen Including the Effects of Pin Loading," ASTM-STP 560, pp. 105-121.

Strawley, J. E. (1976), "Wide Range Stress Intensity Factor Expressions for ASTM E399 Standard Fracture Toughness Specimens," Int. J. Fracture, 12, 475-476.

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16. ABSTRACT (200 words or less)

Analyses of two kinds of crack arrest experiments have been carried out. The first case was a dynamic finite-difference analysis of tests on a photoelastic material carried out at the University of Maryland. Theory and experiments were shown to be in excellent agreement. The second case was a thermal-shock experiment (TSE-5) carried out by Oak Ridge National Laboratory. Agreement between theory and experiment was not as good here, possibly because the available data base was less detailed and because only an approximate dynamic analysis was carried out.

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