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FRACTURE TOUGHNESS TESTING ON MINIATURE SPECIMENS USING THE ELECTROPOTENTIAL TECHNIQUE

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MASTER

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ABSTRACT

Ferritic steels are currently being considered as fusion first wall candidates because of the relatively low thermal stresses induced during temperature cycles. However, fracture toughness is of concern in this alloy class. Limitations on irradiation space dictate that special techniques be developed for post-irradiation fracture toughness measurements. This study investigates the feasibility of electropotential techniques using single specimens to evaluate fracture toughness. The electropotential technique was applied to obtain continuous crack extension measurements on miniaturized specimens and to trace out J versus Δa curves. The J-integral results obtained from A286 small specimens compare favorably with those obtained from large specimens. Also, the experimental work shows that electropotential and multiple specimen methods produce consistent data in HT-9 in the transition region where crack extension occurs by mixed cleavage and dimpled rupture.

INTRODUCTION

Ferritic steels are candidate first wall materials for fusion reactors because of the relatively low thermal stresses induced during thermal cycling in these materials compared to austenitic materials. However, their fracture behavior is of potential concern to the reactor designer. The materials are expected to undergo a ductile-to-brittle transition around room temperature, and this transition temperature will be elevated by irradiation. Fracture toughness tests can determine the ductile-to-brittle transition temperature as well as provide quantitative fracture toughness data. Because the first wall is expected to be on the order 3 mm thick, and size economy is necessary for irradiation in order to obtain a systematic irradiation environmental variables miniaturized circular compact specimens were used for the test.

J-integral approach was used in this paper. However, in the case of small-scale yielding failure, K_c could be evaluated as a failure parameter. The philosophy in this effort is to obtain R-curve traces of the appropriate measure of crack tip stress intensity in the actual component thickness - at sufficiently low toughness this may be J_{1c} or K_{1c} but most generally are K_c or J_c. The important point is that the measurements will be performed in the actual component thickness so that no penalties for artificially high constraint be taken.

EXPERIMENTAL TECHNIQUE

Test specimens were sectioned from a hot-rolled 12.7 mm strip of A286 superalloy and HT-9 bar stock. The schematic diagrams of A286 miniature compact specimen (3 mm thick) and HT-9 circular compact specimen (2.45 mm thick) are shown in Figure 1(a) and 2(a) respectively. After machining, the A286 test specimens were aged at 760°C for 16 hours. Prior to fracture testing, all test specimens were fatigue precracked using a conventional servo-hydraulic MTS system. The precrack length was 1.5 mm and the maximum stress intensity factor was 28 Mpa $\sqrt{m}$.

Fracture toughness tests were performed at room temperature using an Instron testing machine. The details of the technique utilized to construct multiple specimen J-integral curves on the miniature specimens are given in Reference 1. The values of J were calculated from load vs. load-line displacement curves. After each test, the specimens were heated to 538°C for one hour to heat tint the crack area, and were subsequently broken at room temperature. Crack extensions were measured with a traveling microscope.

The electropotential technique was applied here to obtain continuous crack length measurements during each test. The theory of this technique is described in References 2 and 3. The current input and potential measurement leads were positioned as in Figures 1(b) and 2(b). Crack extension increased the resistance near the crack and hence increased the voltage V_1. The lead positions were chosen to give good sensitivity (large changes in V_1) and reproducibility, based on resistance paper mockups of the specimen lead configuration. During the actual tests, a constant DC current of 15 amps was applied across the specimens. V_1 was recorded using a microvoltmeter.

The values of J were calculated from load versus load-line displacement curves using the following equation[4].

$$J = \frac{2A}{Bb} \qquad (4)$$

where A is the area under load versus load-line displacement curves, B is specimen thickness, and b is unbroken ligament size. Measurement of crack extension was obtained by measuring the maximum distance from the fatigue crack mark to the end of the heat tint mark, Figure 3. On the plot of J versus crack extension Δa, the J_{1c} values are found by construction as the value of the intersection of line $2\sigma_{flow} \times \Delta a$, and the least squares fit line through all points of J versus Δa, where $\sigma_{flow} = (\sigma_{ys} + \sigma_{uts})/2$.

RESULTS AND DISCUSSION

It is known that there is a size effect on the K failure criterion, although the J_{1c} test does not limit the thickness of the test materials as much as the K_{1c} test. For A286, experimental data shows that thickness effects do not appear to be great for fracture toughness measurement using J-integral techniques.(1) The test specimens of A286 used in this work in fact produce plane strain J_{1c} values in agreement with thicker specimens, allowing a convenient reference point for technique verification.

Typical potential changes observed during fracture tests on A286 are shown in Figure 4. The potential changes are plotted against the load-line displacement to provide a measure of crack extension versus sample extension. The voltage curves for this material increase smoothly with a load-line displacement as might be expected for crack growth in a ductile austentic material at low temperature. The dimensionless ratio V_1/V_{1o}, where V_{1o} is the voltage measured for the initial crack length (a_0) after precracking, was used as a parameter to correlate with crack extension.

The calibration for tests done on A286 is shown in Figure 5. Only three tests were done on this material with the limited goal of establishing feasibility of the method by linking to existing J-integral results.(1) A straight line fit to the curve was used for simplicity and emphasis was placed on the region where direct optical crack lengths measurements were available.

The major point to be made with the A286 data is that using the calibration and electropotential measurements for a single specimen, a J versus Δa curve could be derived. Figure 6 shows a comparison of the multiple specimen plot with the electropotential measurements. The electropotential results are within better than 10% of the overall R curve based on all specimens tested, and within 2% of the values for the three specimens actually used for the calibration. The curve from the electropotential measurement was extrapolated back to the crack blunting line to estimate the J_{1c}, and as shown in Figure 6, agreement is very good.

This result proved experimental feasibility for the technique, and the decision was made to obtain a similar set of data on a ferritic material to provide a calibration of the technique on materials where fracture properties are of greatest concern for potential first wall applications. Ferritic alloy HT-9 has been selected for such applications mainly because of lower thermal stresses as well as its excellent swelling resistance and low neutron cross section. The HT-9 test specimen is chosen to be close to the first wall thickness. Circular compact tension specimens were chosen for efficient stacking in EBR-II irradiation using conventional hardware. The calibration curve obtained from potential changes (Figure 7) and corresponding crack extension revealed by heat tint is shown in Figure 8. The multiple specimen J-integral data for HT-9 is compared in Figure 9 with J versus Δa curves derived for single specimens using the electropotential technique. The dotted lines below 0.2 mm crack extension reflect current uncertainty in the calibration at low crack extension. The scatter between the electropotential J-Δa curves mearly reflects the typical specimen-to-specimen variation in the J integral value (+∿10%). The multispecimen method, in contrast, would require a factor of five or more specimens for irradiation testing.

CONCLUSION

The J-integral tests on A286 and HT-9 were performed to demonstrate the electropotential technique for evaluating the fracture toughness of miniature irradiated specimens. It is concluded:

1. The test results of fracture toughness tests on A286 and HT-9 at room temperature using the single specimen electropotential technique agree to within ±5% with those obtained from the multiple-specimen method.

2. The electropotential technique allows instantaneous detection of crack extension rate, and hence can provide, for example, crack initiation and arrest data not available from post-test crack measurements.

3. The single specimen J-integral measurements using the electropotential technique offer the possibility of reducing the number of test specimens required for irradiation testing by a factor of five. This will enable a thorough study of irradiation environmental variables in the limited reactor space available for such tests.

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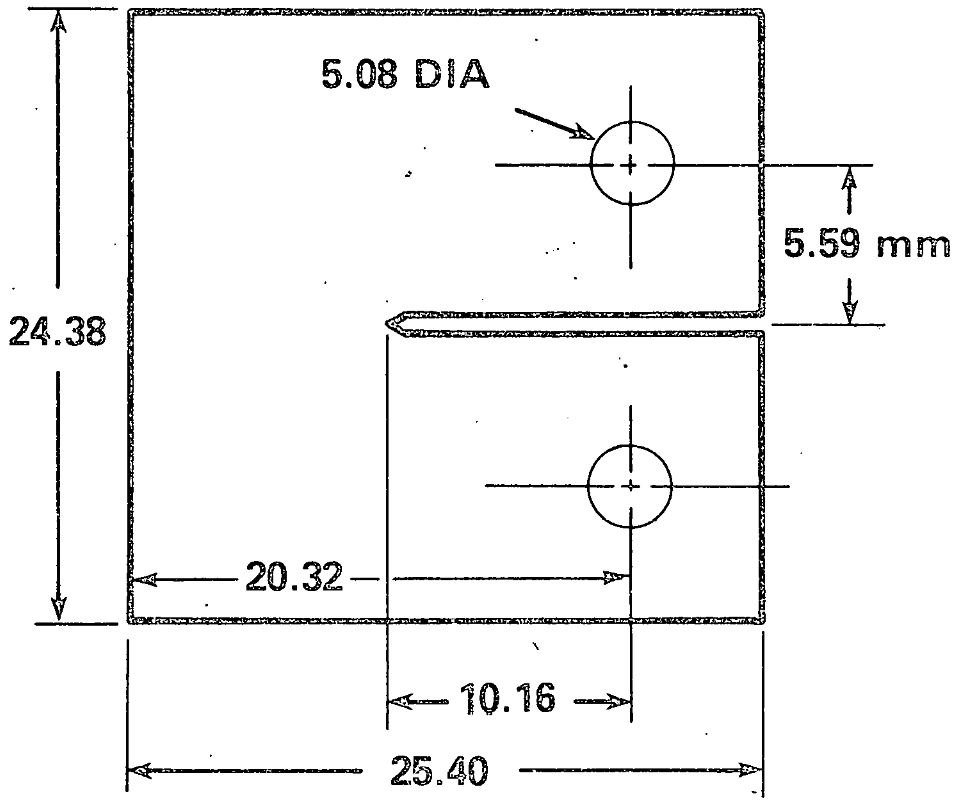
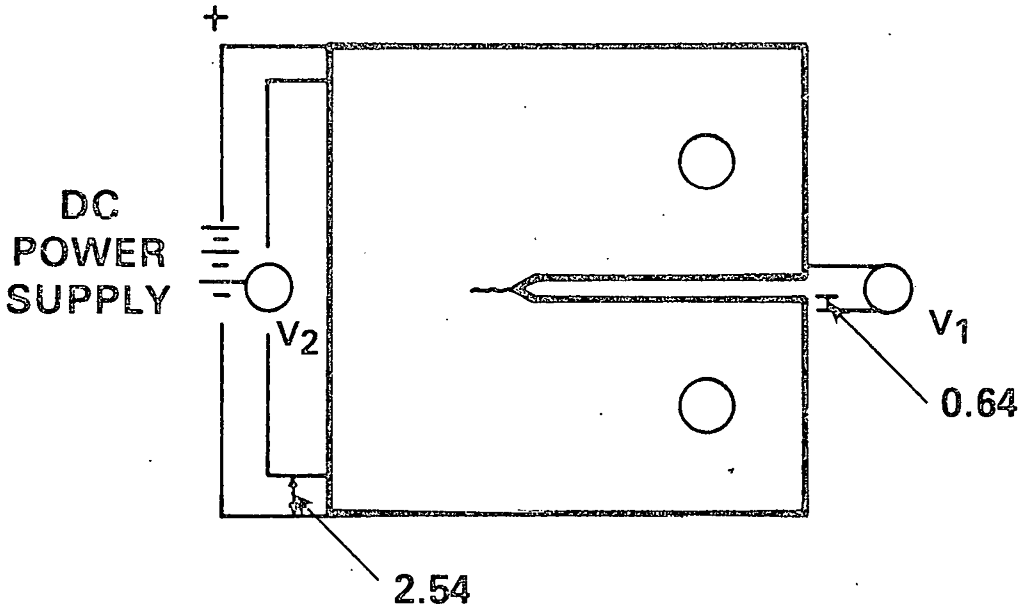
FIGURES

FIGURE 1



(a)



(b)

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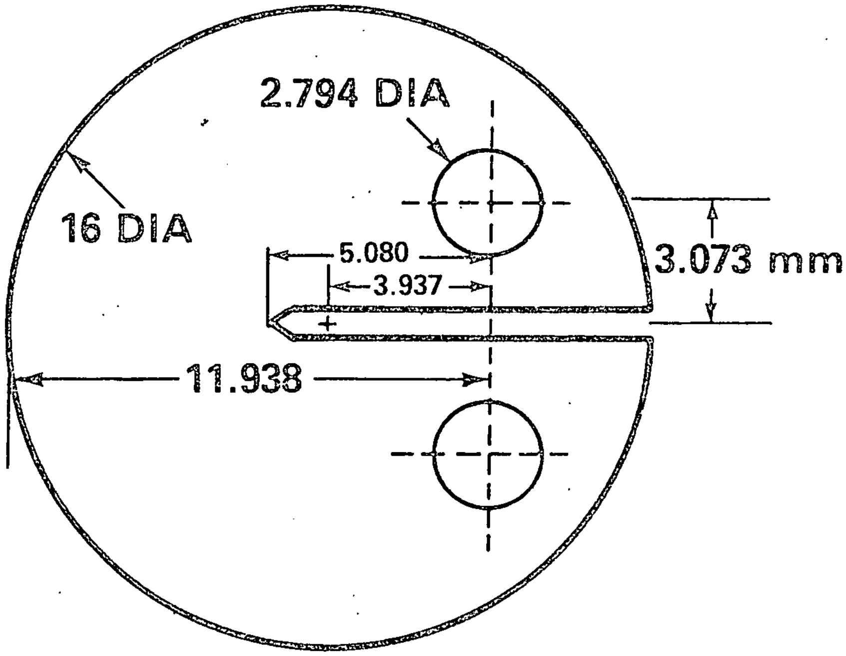
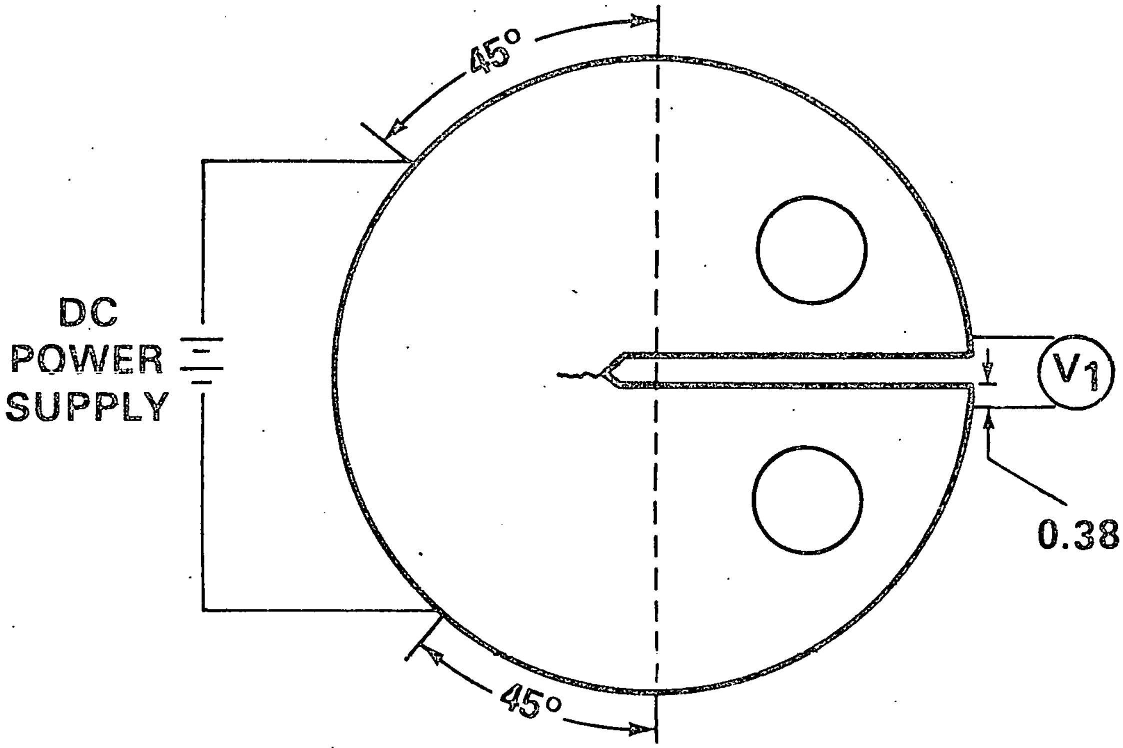
FIGURE 2



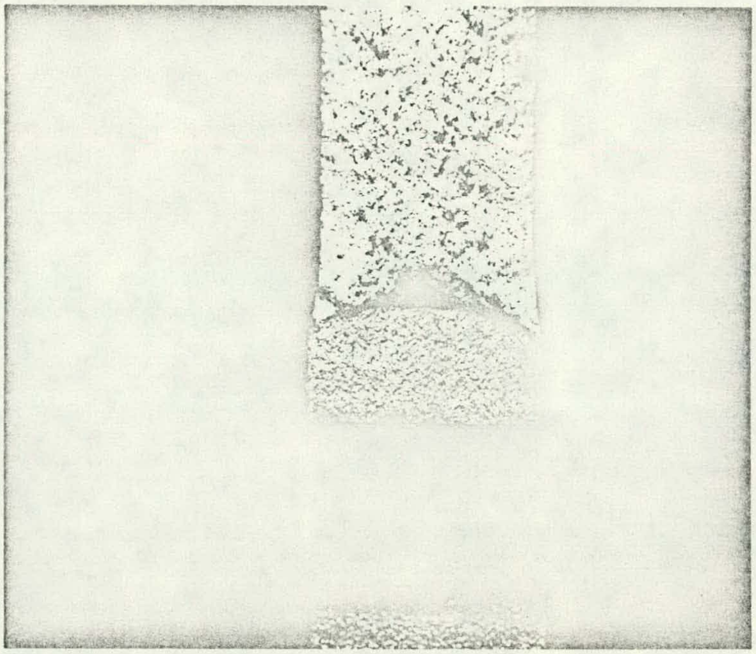
(a)



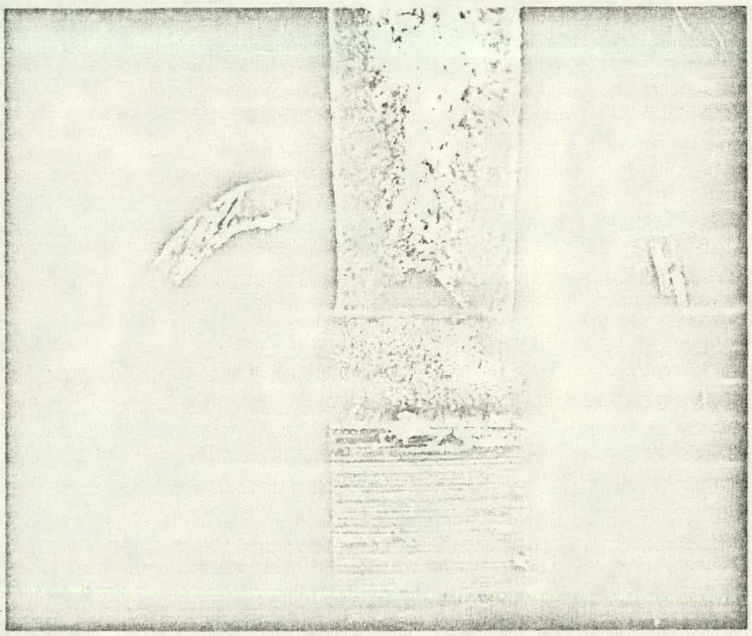
(b)

HEDL 8001-240.7

FIGURE 3

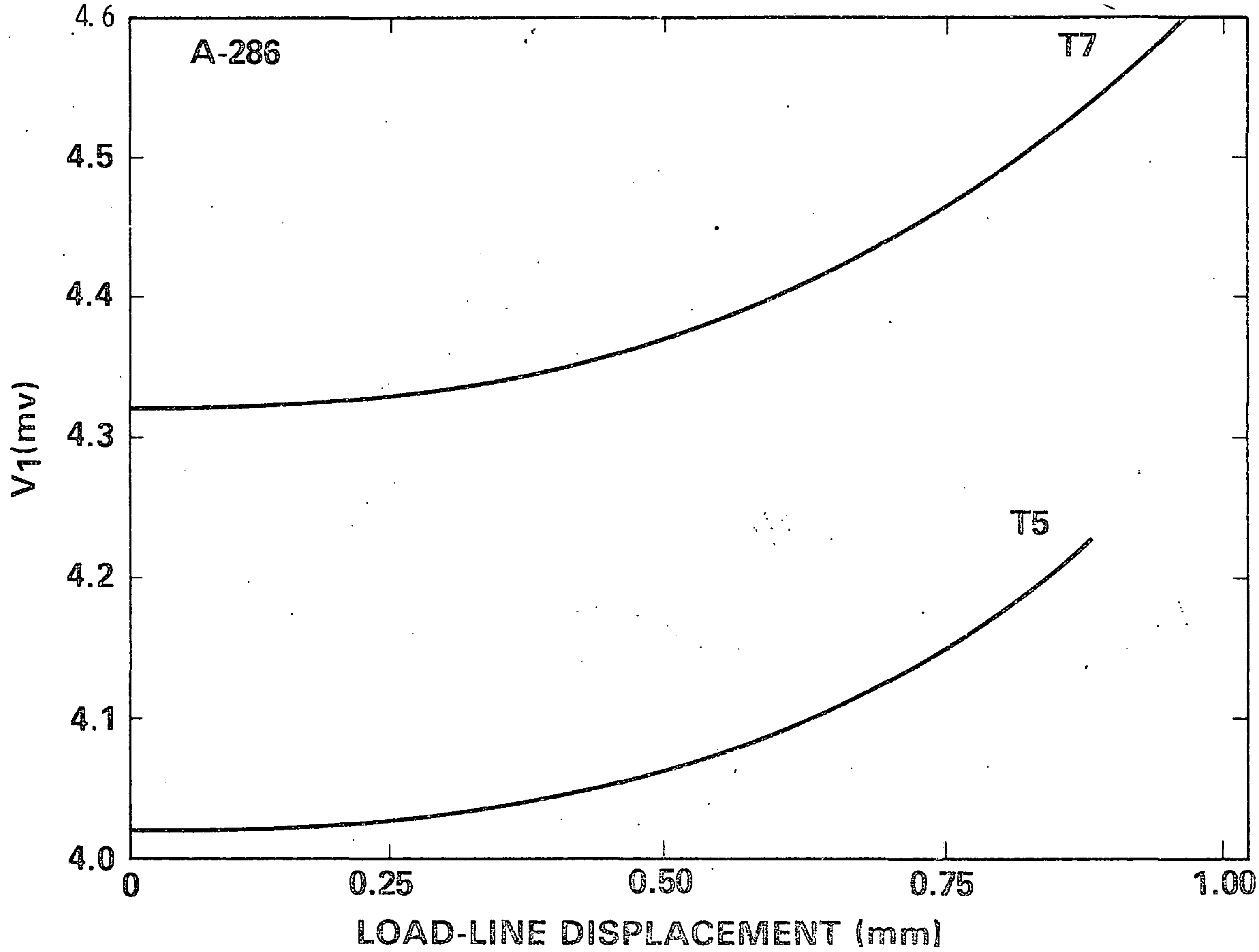


(a) 1 mm

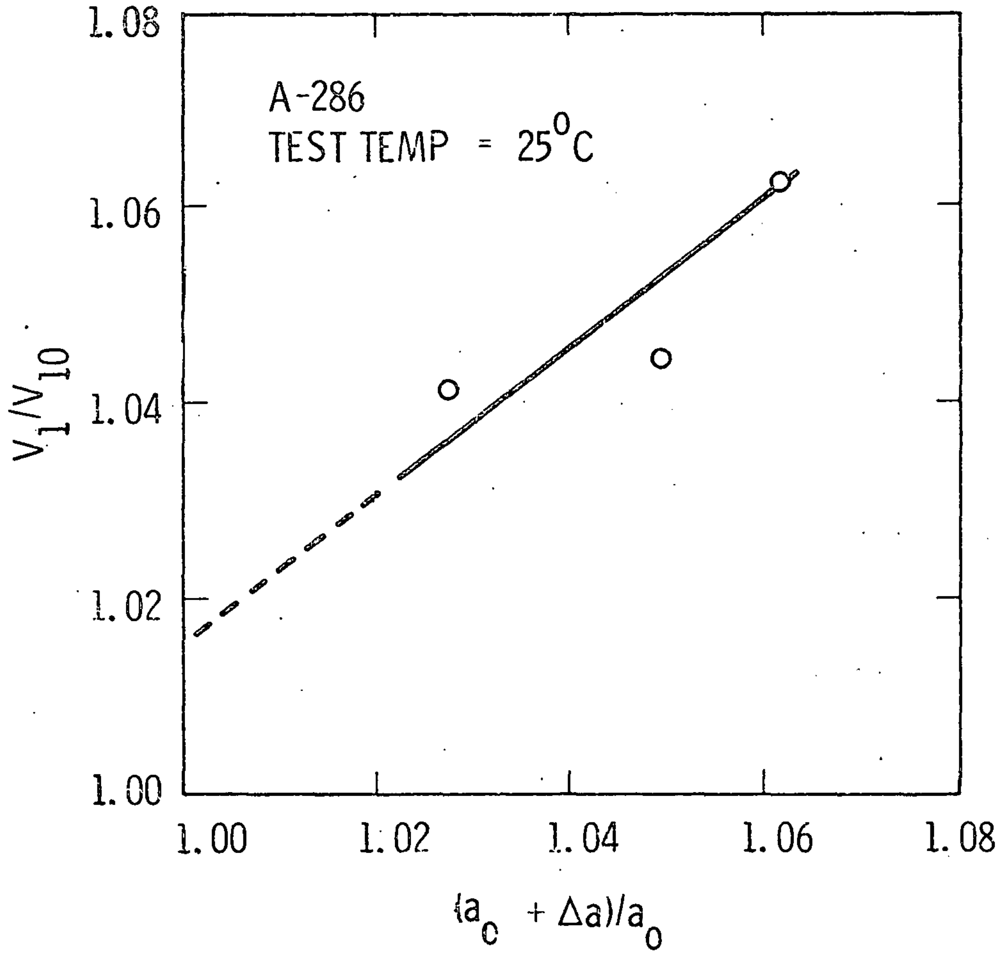


(b) 1 mm

HEDL 8001-240.9



HEDL 8001-240.4



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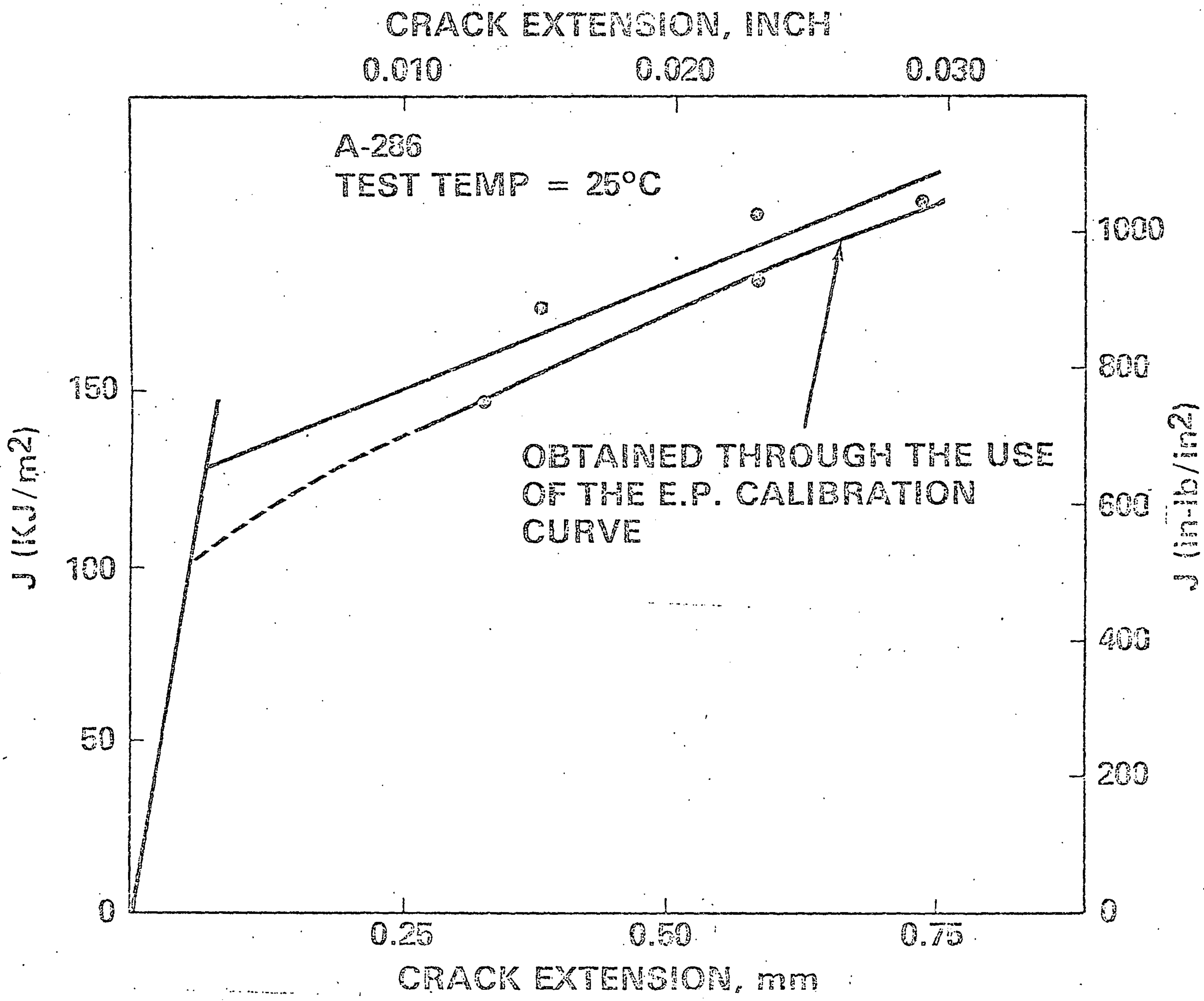

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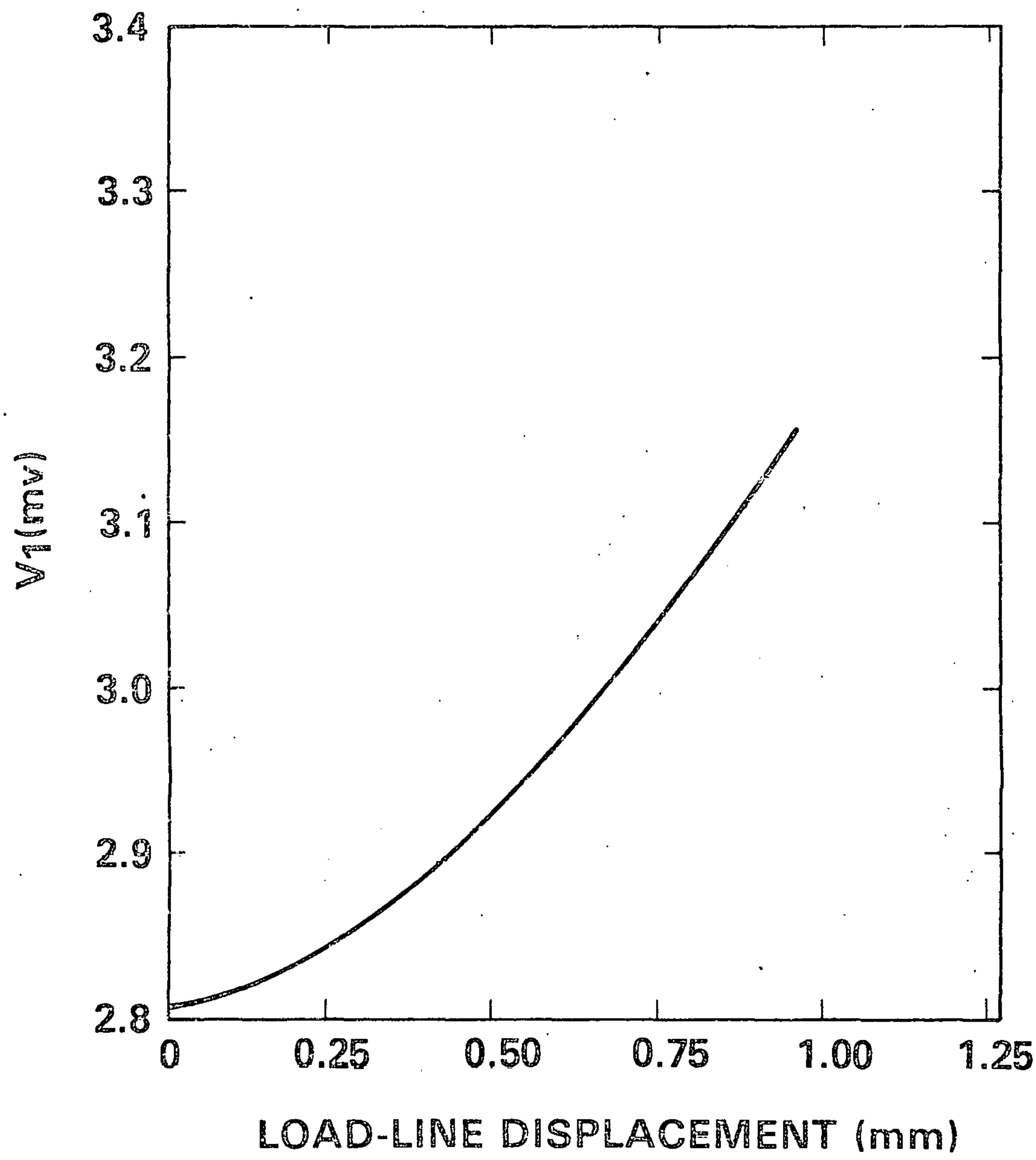
HT-9 CIRCULAR SPECIMEN



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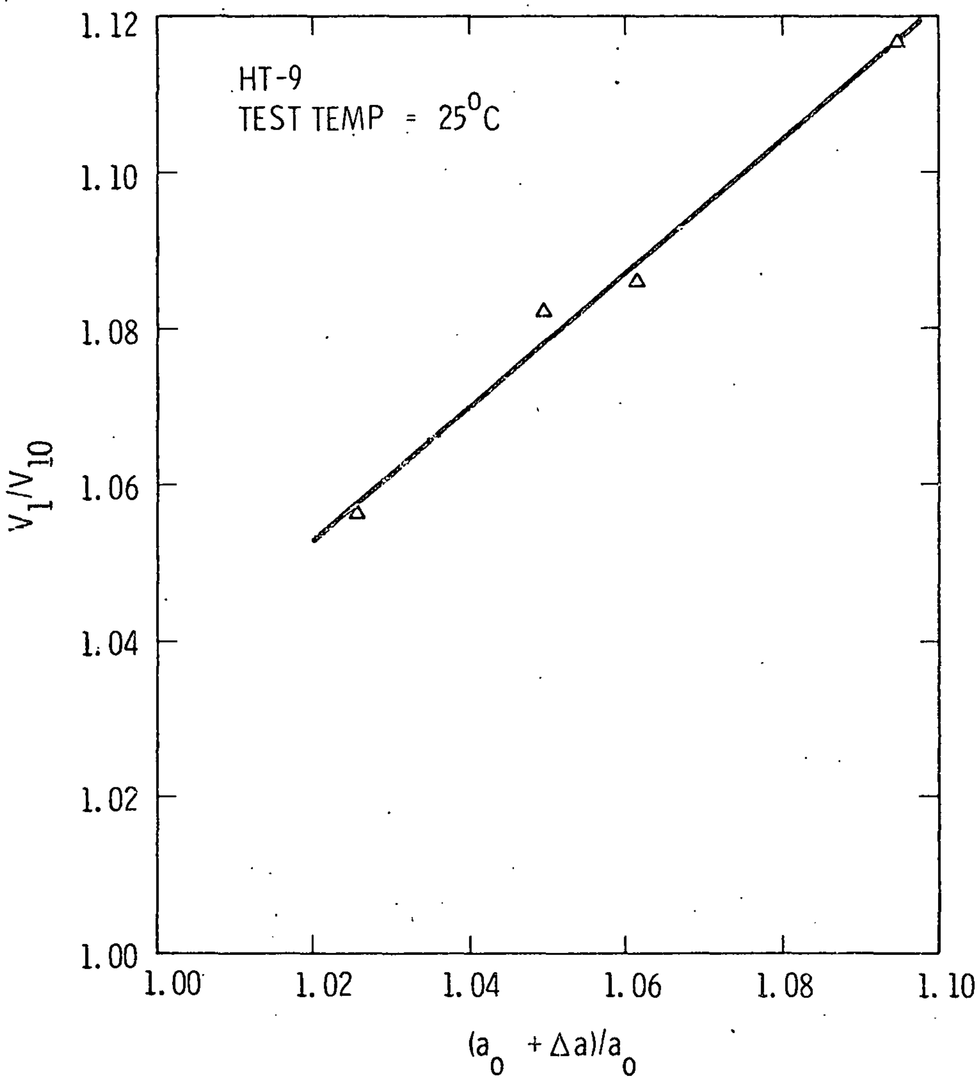

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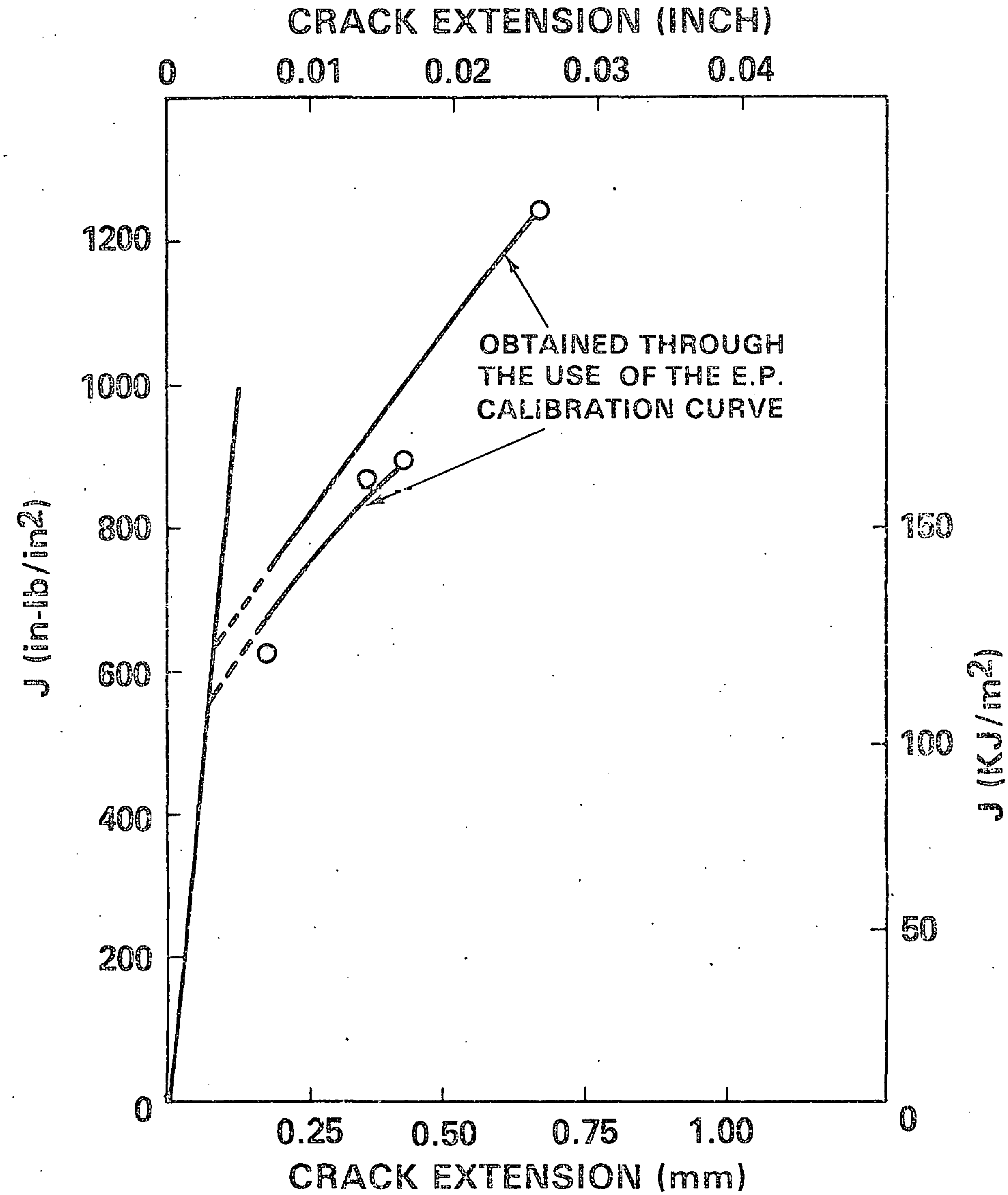
HT-9 0.100 THICK CIRCULAR SPECIMEN (AS RECIEVED CONDITION)



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