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August 25, 1982

Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Attention: Mr. Guy A. Arlotto, Director
Division of Engineering Technology

Dear Sir:

Quick-Look Report on Test of Intermediate Vessel V-8A — Tearing Behavior of Low Upper-Shelf Material

Enclosed are two copies of the Quick-Look Report on Test of Intermediate Vessel V-8A — Tearing Behavior of Low Upper-Shelf Material. This was the twelfth intermediate vessel test in the HSST program and the first such test to investigate the tearing behavior of material of low toughness, like that of irradiated high-copper welds. This was also the first test in which a major objective was to induce and then interrupt a tearing instability.

The objectives were successfully achieved in the test performed on August 11, 1982. Stable tearing (flaw growth with increasing pressure) was observed by ultrasonic instrumentation, and a tearing instability was first indicated by displacement gages at about 140 MPa, a load reasonably within the range of pretest predictions.

As had been hoped, the tearing instability developed at a pressure well below that at which the entire cylinder yields, a condition that would make conclusive data interpretation very difficult. Consequently, this test presents an opportunity, never before realized, for critically evaluating the application of methods of elastic-plastic fracture mechanics to thick-section structures. Further analyses will be predicated on posttest measurements of flaw geometry and material properties.

Copies of this report have been sent to your Materials Engineering Branch.

Sincerely yours,

H E Trammell

H. E. Trammell, Director
Engineering Technology Division

HET:RHB:spf

Enclosure

QUICK-LOOK REPORT ON TEST OF INTERMEDIATE VESSEL V-8A — TEARING BEHAVIOR OF LOW UPPER-SHELF MATERIAL

R. H. Bryan S. E. Bolt
J. G. Merkle G. D. Whitman

Introduction

Intermediate test vessel V-8A was pressure tested hydraulically at 150°C on August 11, 1982, in the twelfth test of a flawed 152-mm-thick steel vessel. The purpose of the test was to investigate the tearing behavior of material having low upper-shelf toughness similar to the toughness of irradiated high-copper seam welds in some existing reactor pressure vessels. A primary objective of the test was to induce and interrupt a tearing instability so as to obtain experimental data by which the application of methods of elastic-plastic fracture mechanics to large structures could be evaluated. This objective was attained.

Test Preparations

Vessel V-8A had previously been tested as vessel V-8 in 1978.[1] It is a cylindrical vessel fabricated of ASTM A533, grade B, class 1 steel plate with the geometry shown in Fig. 1. The original V-8 flaw was removed, and the Babcock and Wilcox Company (B&W) repaired and placed a special seam weld in the vessel as shown in Fig. 2.[2] A cross section of a prototypic weld is shown in Fig. 3. B&W used an automatic submerged arc process with materials and postweld heat treatment selected to produce the desired upper-shelf toughness properties. The tearing resistance properties, (J_R vs crack extension, Δa) of a trial weld produced by this process compared favorably with the resistance of irradiated high-copper welds, as shown in Fig. 4.[3,4] In addition to the seam weld in vessel V-8A, B&W made four full-thickness seam welds with the same procedure and measured the J_R properties. Figure 5 gives the average power-law J_R curves deduced from the data for each seam, and Table 1 gives the average J_{Ic} values and the J_R parameters.

The flaw in vessel V-8A was placed in the special seam weld in the orientation shown in Fig. 2 by first machining a notch to the profile shown in Fig. 6 and then cyclically pressurizing the notch to extend the notch by fatigue. The location of the tip of the fatigue crack during the fatiguing process was determined by ultrasonic measurements as indicated in Fig. 7. Our best estimate of the pretest crack dimensions was that the flaw was 93 mm deep by 280 mm long.

The vessel was instrumented inside and outside with thermocouples and strain gages. Seven ultrasonic transducers were mounted on the inside surface in the plane of the flaw to observe changes in crack depth. Displacement gages were mounted across the mouth of the flaw to provide data for posttest estimates of flaw size at all stages of the test. Figure 8 shows the instrumented vessel in the test cell.

Stress and fracture mechanics analyses were performed by ORNL prior to machining the initial notch, as a basis for selecting an initial flaw geometry, and after flaw sharpening for planning test operation and predicting flaw behavior during the test. Five types of analyses were made. Gross yield pressure of an unflawed cylinder was calculated, and local plastic instability pressure vs crack size was determined. Calculations of J_I vs pressure and Δa were made by two simplified methods: the Raju-Newman equations for linear-elastic conditions and the tangent modulus method for elastic-plastic conditions. Results of these calculations and linear-elastic finite element computations suggested a range of parameters to be considered by three-dimensional, elastic-plastic finite-element analyses using the ADINA-ORVIRT-3D computer programs. Elastic-plastic calculations of J_I vs Δa were compared with the J_R curves to predict the pressures and flaw sizes prior to and at instability.

Pretest fracture mechanics calculations were also received from five organizations outside ORNL, in response to information provided for the purpose. The results of these calculations are summarized in Table 2. The highest estimate is about 7 percent above the final instability pressure, and the lowest estimate is 10 percent less than the initial instability pressure, as given below. These results demonstrate the existence of several methods apparently suitable for performing such calculations.

Test Results

Vessel V-8A was maintained at about 150°C during pressurization. Pressure was increased slowly, as shown in Fig. 9, with intermittent small decrements introduced so as to record the elastic response of crack-opening displacement even after yielding. At about 138 MPa a small seal leak, unrelated to the flaw, caused the pressure to fall to 116 MPa. Upon further pressurization an instability was observed between 135 and 140 MPa for a period of a few minutes. The vessel restabilized when the pressure decreased slightly. Pressure was subsequently increased to about 143 MPa; and the vessel again became unstable, at this time between about 139 and 143 MPa. After several seconds of instability the vessel was depressurized in order to preserve evidence of the final crack geometry for posttest evaluation.

After the test, visual examinations indicated that the initial flaw was, as intended, well sharpened by fatigue along the entire crack front and that the flaw grew in size during pressurization. Tearing appears to be greatest near the ends of the flaw but without much tearing on the outside surface of the vessel (see Fig. 10). Precise measurements of the crack geometry will be made after the weld seam is cut from the vessel.

Crack-mouth-opening displacement (CMOD) vs pressure recorded during the test is shown in Fig. 11 in comparison with values calculated by the ADINA 3D finite-element computer program for several specific flaw shapes. The reason for the measured CMOD values exceeding the calculated values after yielding has yet to be determined. A comparison of the inside and outside circumferential strains 180° from the flaw, as measured and as calculated by the ADINA program, is shown in Fig. 12. These results appear satisfactory.

Summary

The objectives of the intermediate vessel V-8A test were achieved with the successful conduct of the pressure testing of a thick pressure vessel with a large sharp flaw in a region of the vessel having low upper-shelf toughness. A tearing instability developed at about 140 MPa (about twice the design pressure), a pressure in the range of pretest predictions based on elastic-plastic fracture mechanics and measured material properties.

The flaw will be destructively examined to establish accurately the initial and final shapes, test data will be used to estimate intermediate flaw shapes, material from the seam weld will be tested to determine its tearing resistance, and fracture mechanics analyses based upon the post-test measurements will be made.

References

1. R. H. Bryan et al., Test of 6-in.-thick Pressure Vessels. Series 3: Intermediate Test Vessel V-8, ORNL/NUREG-58, Oak Ridge National Laboratory, Oak Ridge, TN, December 1979.

2. H. A. Domian, Vessel V-8 Repair and Preparation of Low Upper-Shelf Weldment, ORNL/Sub/81-85813/1, report prepared for ORNL by the Babcock and Wilcox Company, Alliance, OH, June 1982.

3. P. P. Holz and R. H. Bryan, "Intermediate Test Vessel V-8A," Heavy-Section Steel Technology Program Quart. Prog. Rep. for January–March 1981, ORNL/TM-7822, pp. 97–102, Oak Ridge National Laboratory, Oak Ridge, TN, June 1981.

4. F. J. Loss, "Toughness and Ductile Shelf Properties of Irradiated Low-Shelf Weld Metals," Nuclear Regulatory Commission 8th Water Reactor Safety Research Information Meeting, Gaithersburg, MD, Oct. 27–31, 1980.

Table 1. J-integral average properties of characterization welds at 149°C

Weld	Number of specimens	J_{Ic} (kJ/m²)	Power law parameters[a]	
			C	n
V852	5	70.8	137.9	0.386
V862	6	61.5	134.0	0.451
V882	2	59.0	123.0	0.342
V8102	10	43.2	89.32	0.308

[a] $J = c(\Delta a)^n$ with J in kJ/m² and Δa in mm.

Table 2. HSST Program, Intermediate Test Vessel V-8A Pretest Predictions for Ductile Flaw Instability

Test date: August 11, 1982

Organization	Method	Pressure (MPa)	Pressure (psi)	Outside circumferential strain (%)	Δa (mm)	Δa (in.)
1. Nat. Bureau of Stds., Boulder, CO	Simplified Line Spring	153	22,200	0.126	11.9	0.47
2. ORNL (Merkle)	Tangent Modulus	150	21,700	0.133	10.2	0.40
3. IWM, Freiburg	(not specified)	147.4	21,379		15.0	0.59
4. ORNL (Bass)	ORVIRT	147	21,321		10.0	0.39
5. CERL (UK)	RG	141	20,450		7.0	0.28
6. ORNL (Bryan)	ORVIRT	139	20,160		8.0	0.31
7. AERE (UK)	RG	128	18,560		7.0	0.28
8. Nat. Nuclear (UK)	RG	121	17,550	0.092	6.8	0.27

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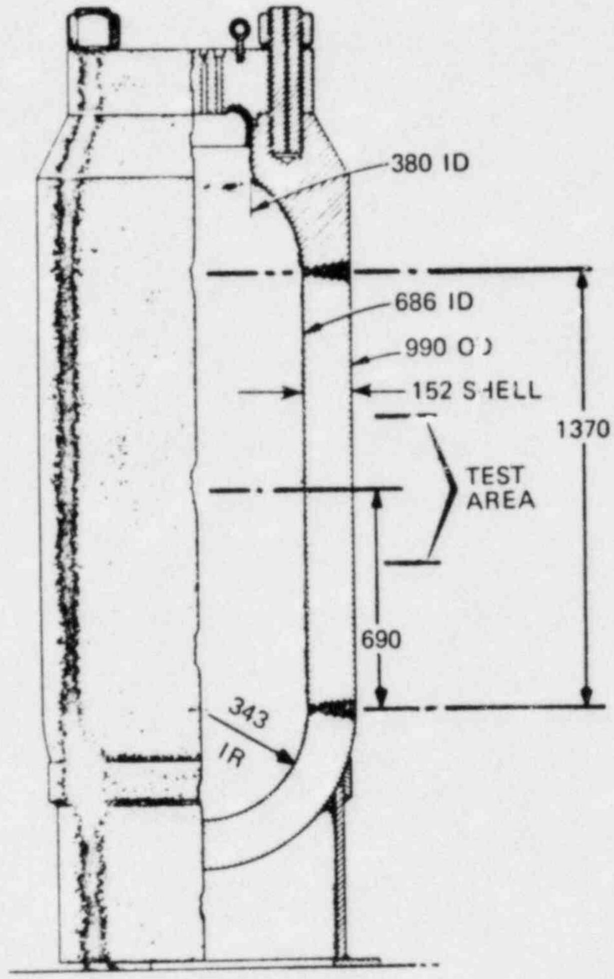

Fig. 1. Irtermediate test vessel geometry.

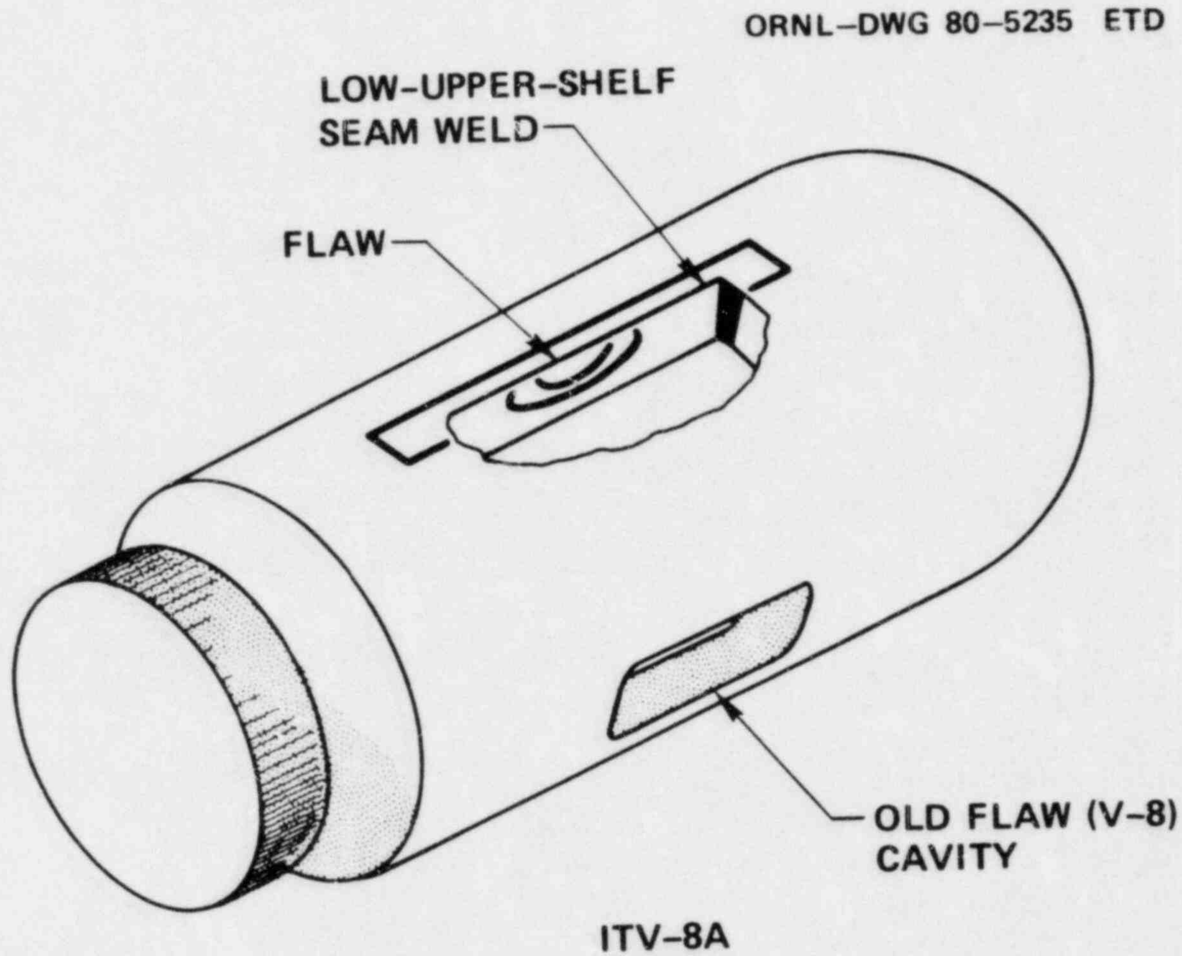

Fig. 2. Schematic view of vessel V-8A.

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Fig. 3. Etched cross section of prototypic weld.

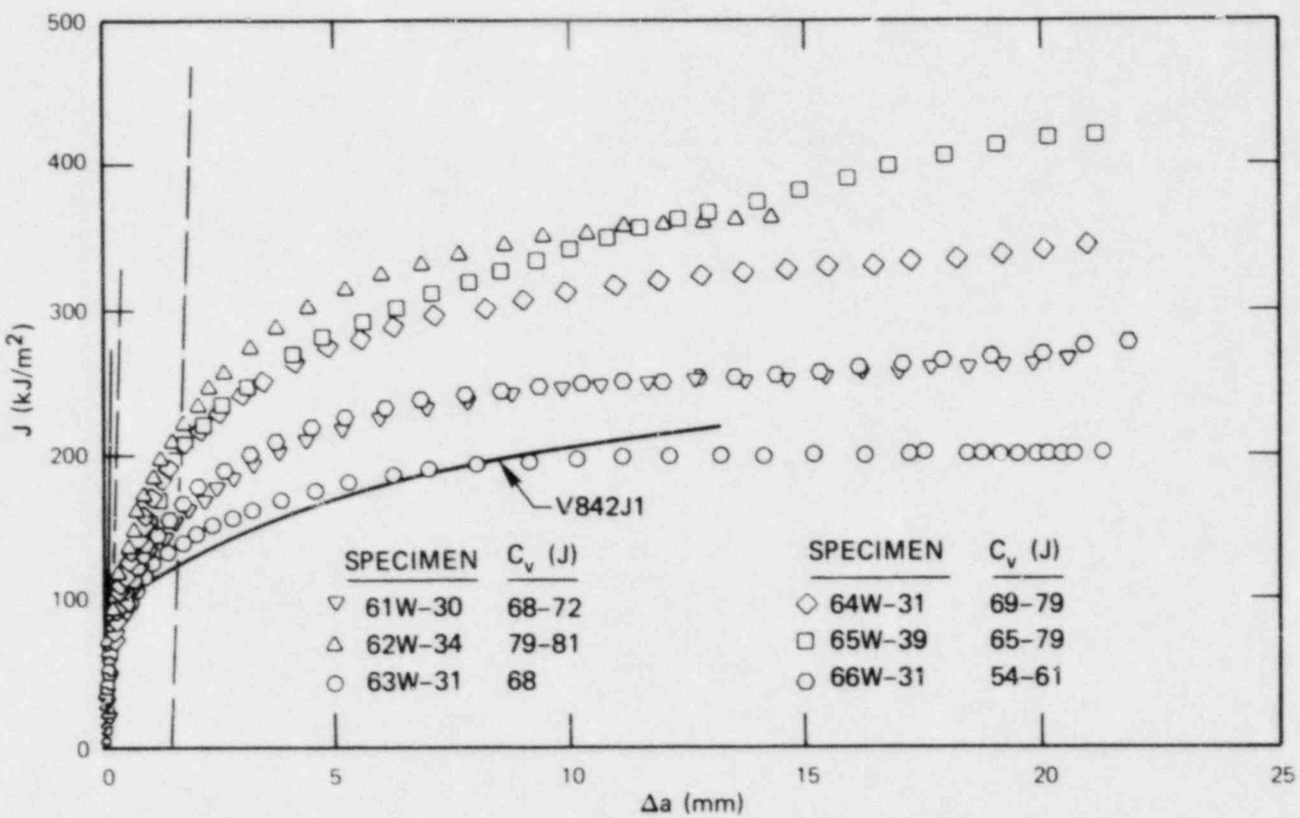

Fig. 4. Comparison of tearing resistance data for the V-8A trial weld and irradiated high-copper welds. Irradiated data are from F. J. Loss (Ref. 4).

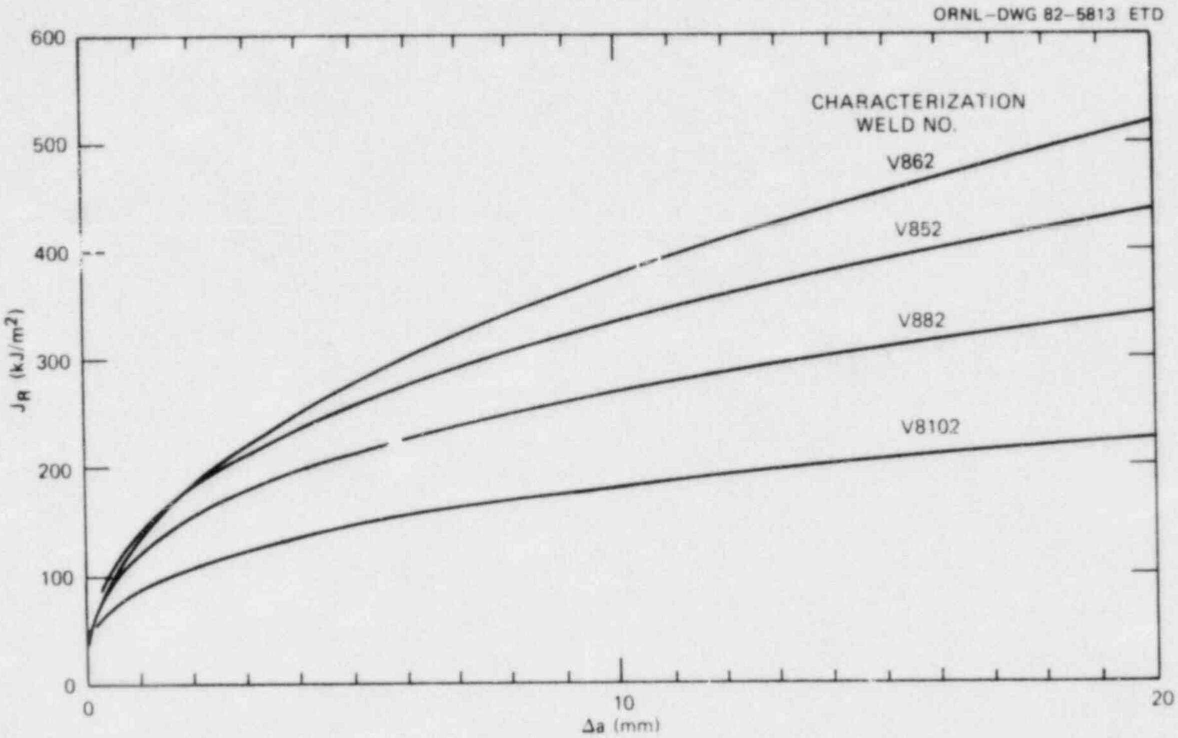

Fig. 5. J_R curves for average power law parameters for each of the four V-8A characterization welds at 149°C. See Table 1 for values of the parameters.

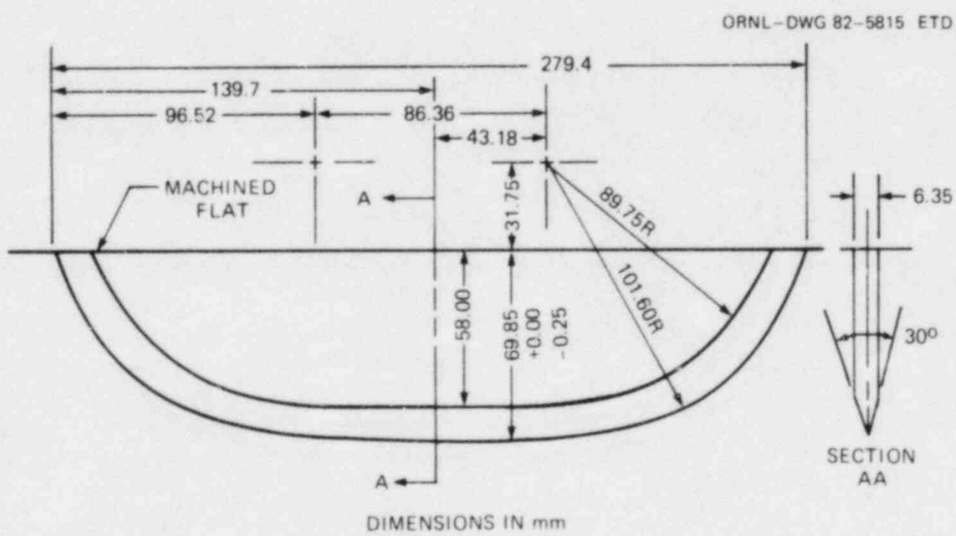

Fig. 6. Configuration of the V-8A machined notch, a sectional view of the radial-axial plane of the vessel that is a plane of symmetry of the flaw.

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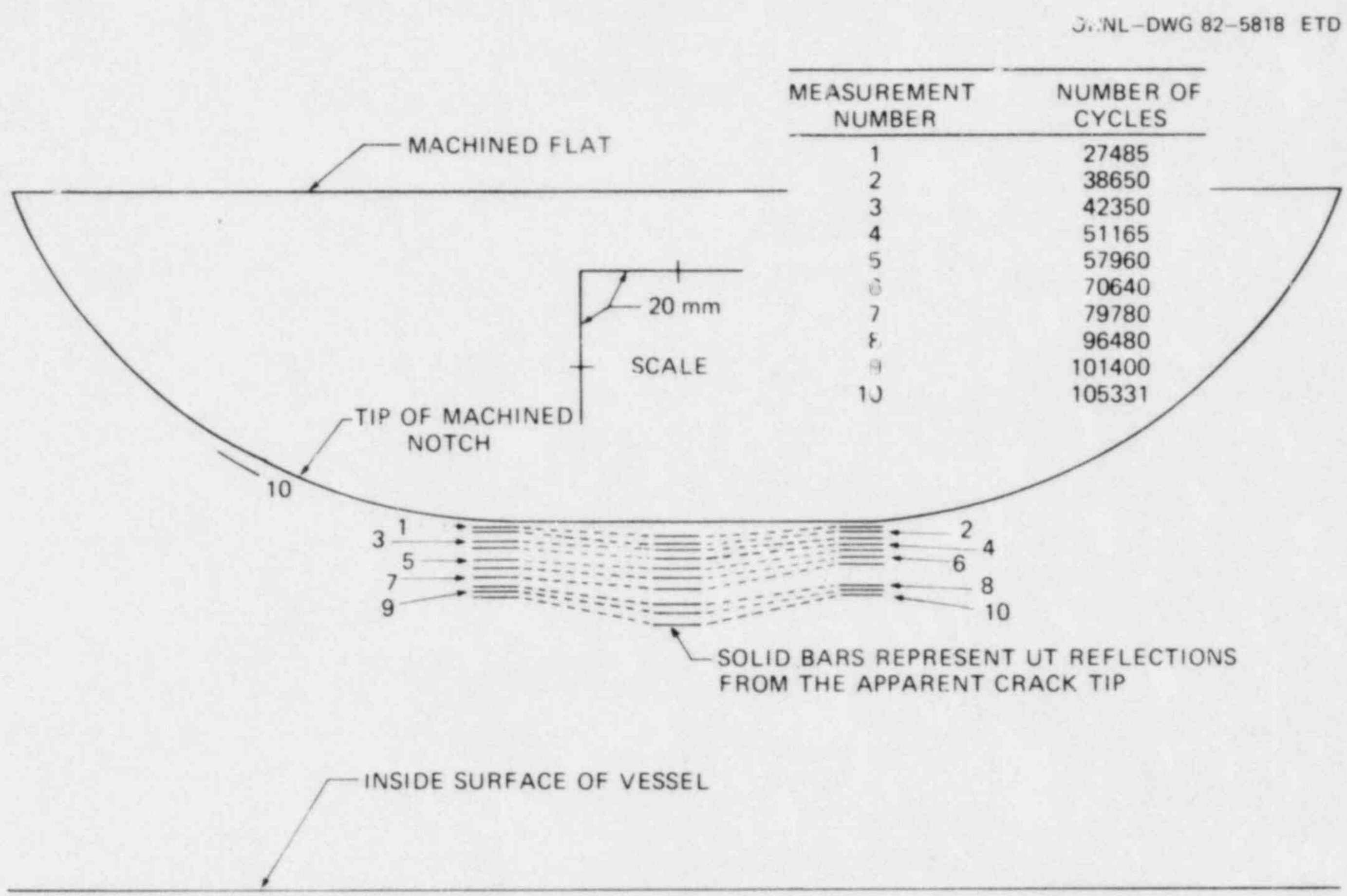

Fig. 7. A scale plot of locations of ultrasonic reflections from the crack tip at several stages of crack growth in the V-8A flaw.

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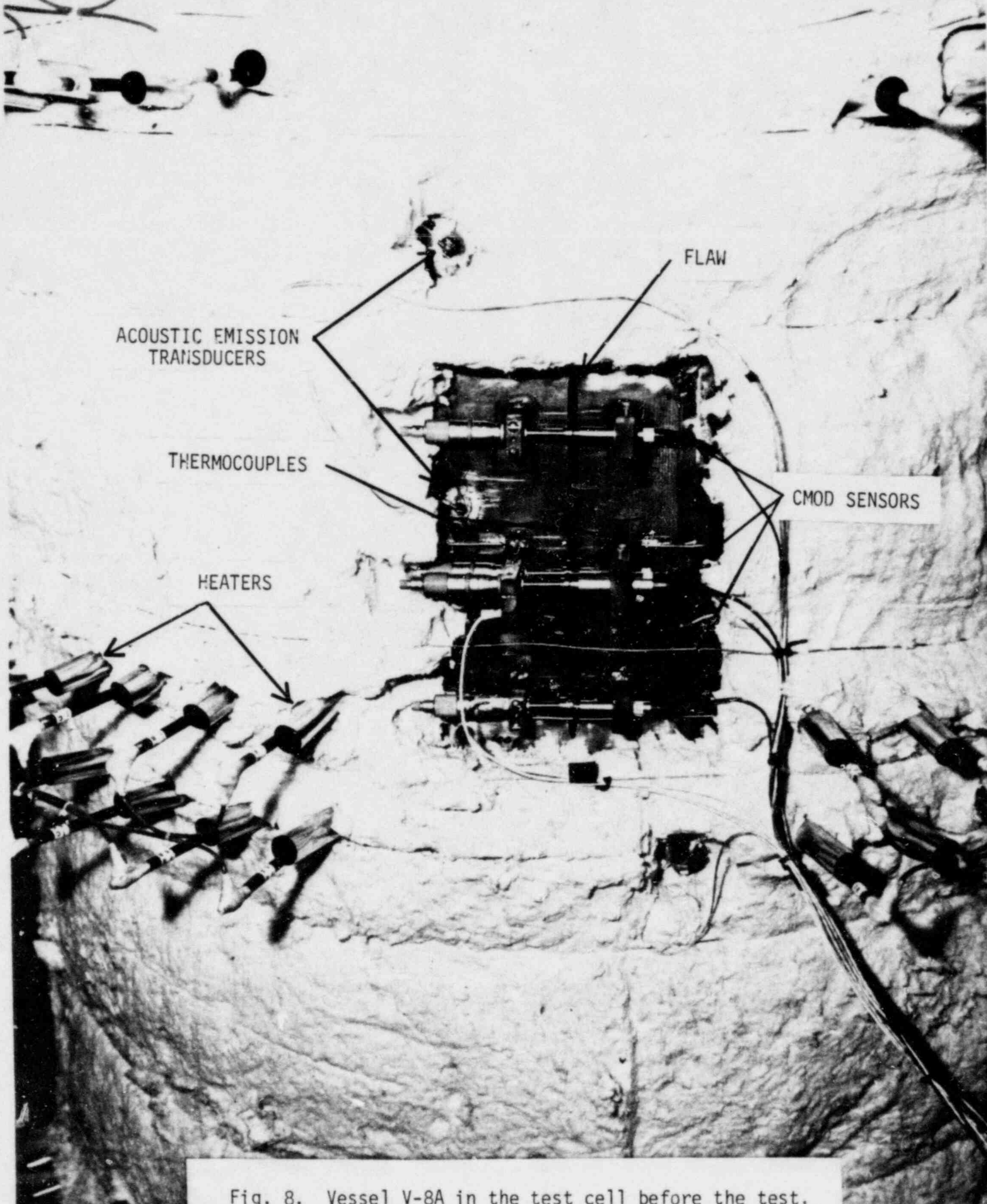

Fig. 8. Vessel V-8A in the test cell before the test.

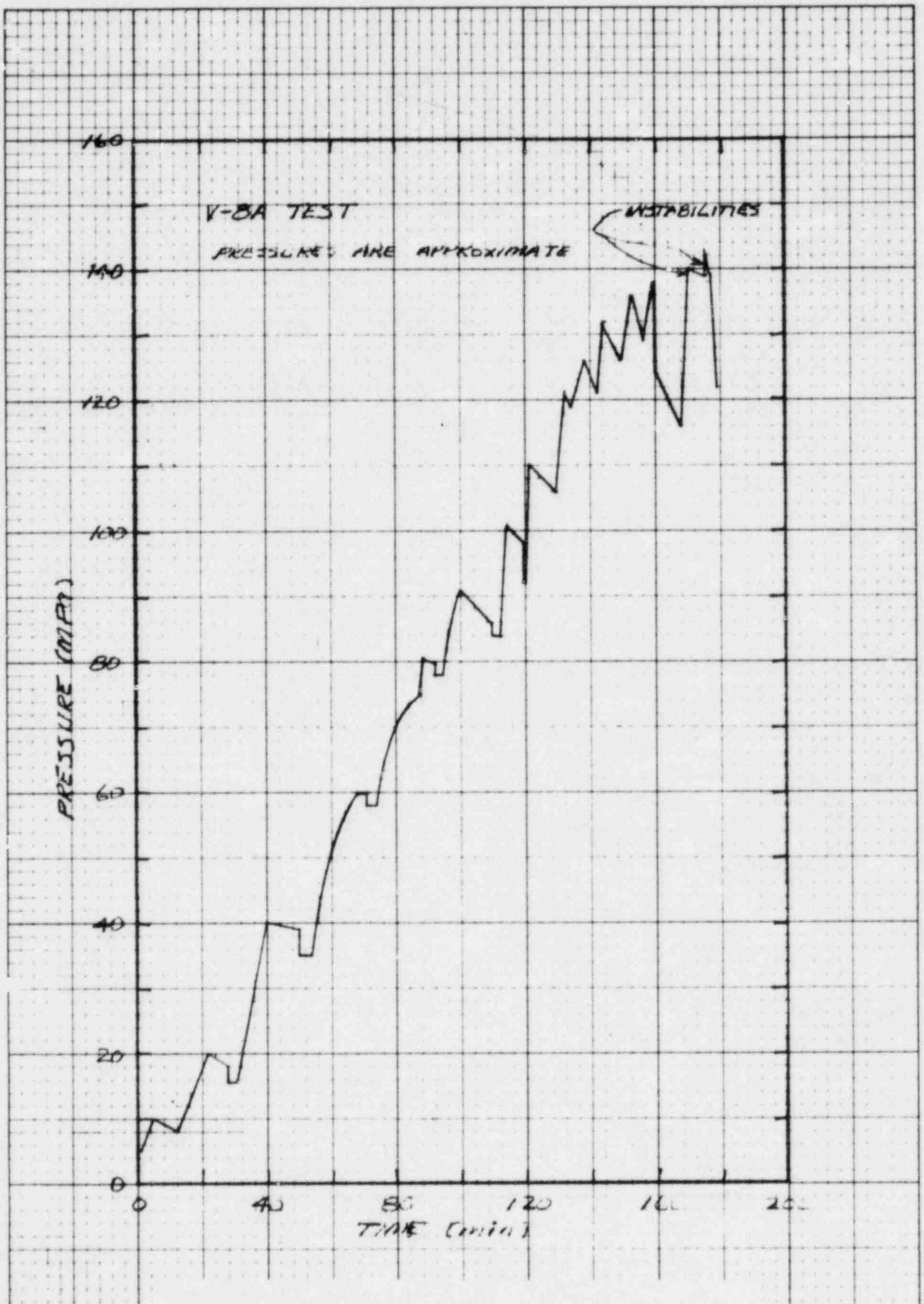

Fig. 9. Pressure vs time in the V-8A test.

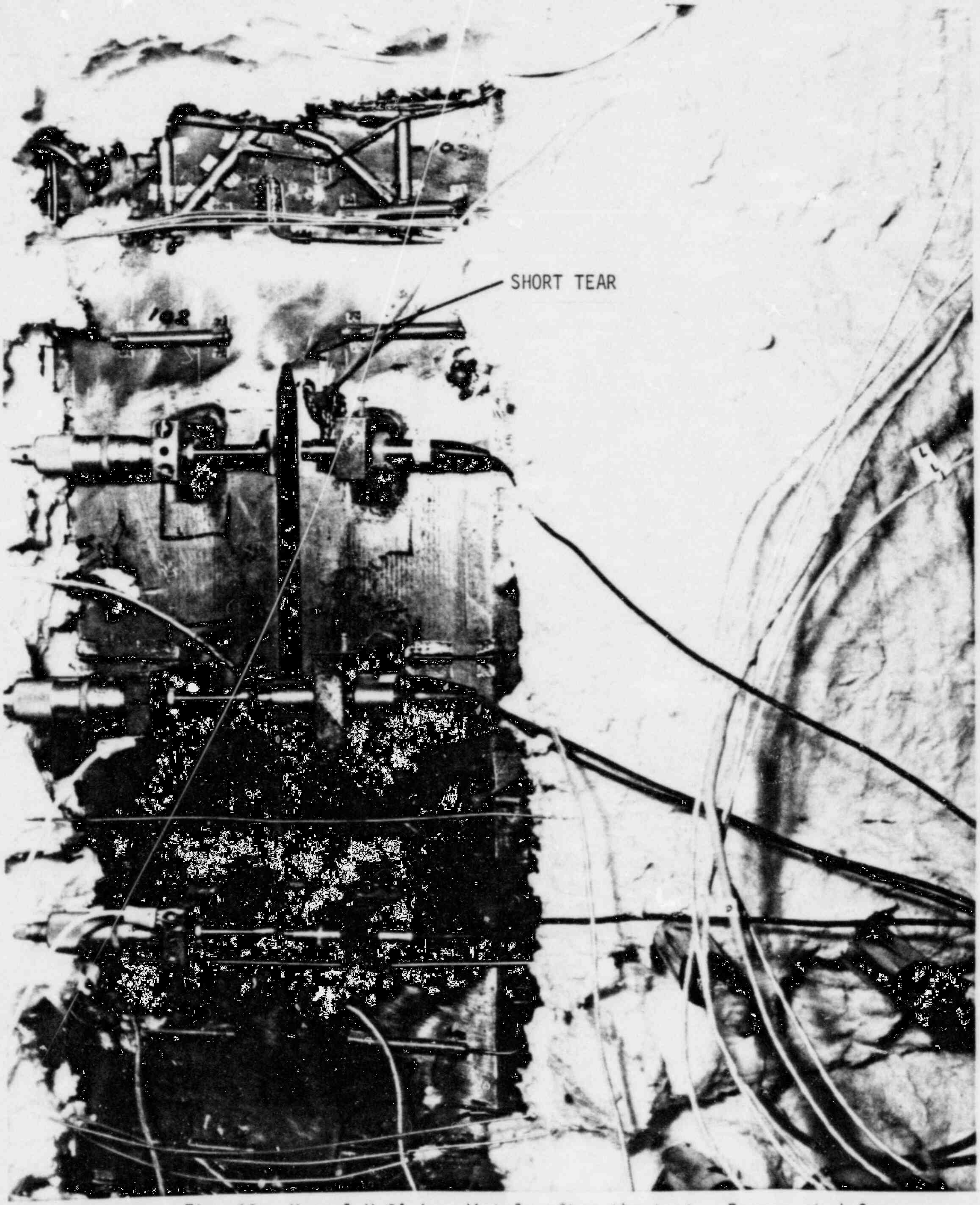

Fig. 10. Vessel V-8A immediately after the test. Permanent deformation at both ends of the flaw and a small surface tear at one end are visible.

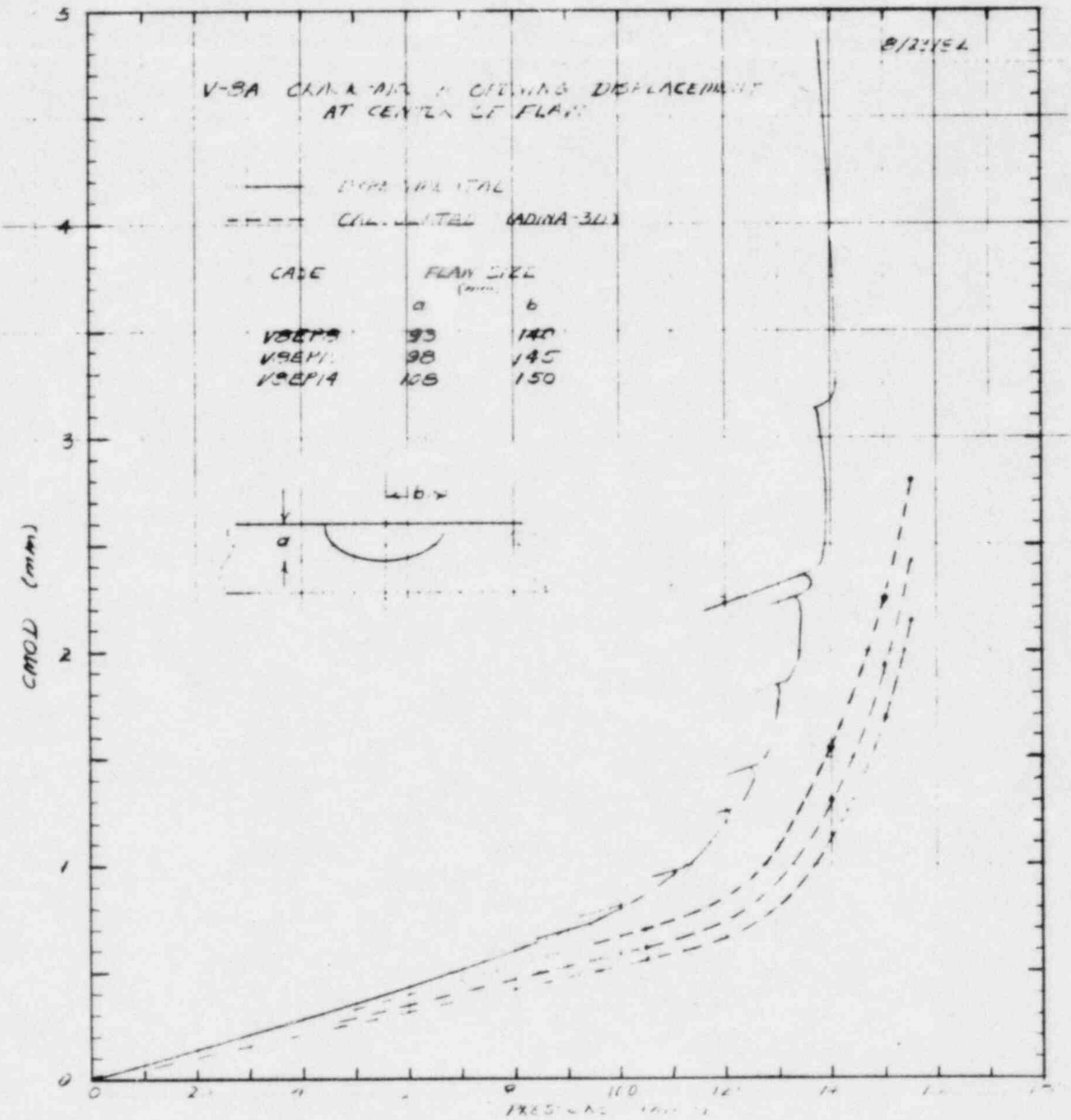

Fig. 11. Crack-mouth-opening displacement (CMOD) vs pressure for vessel V-8A.

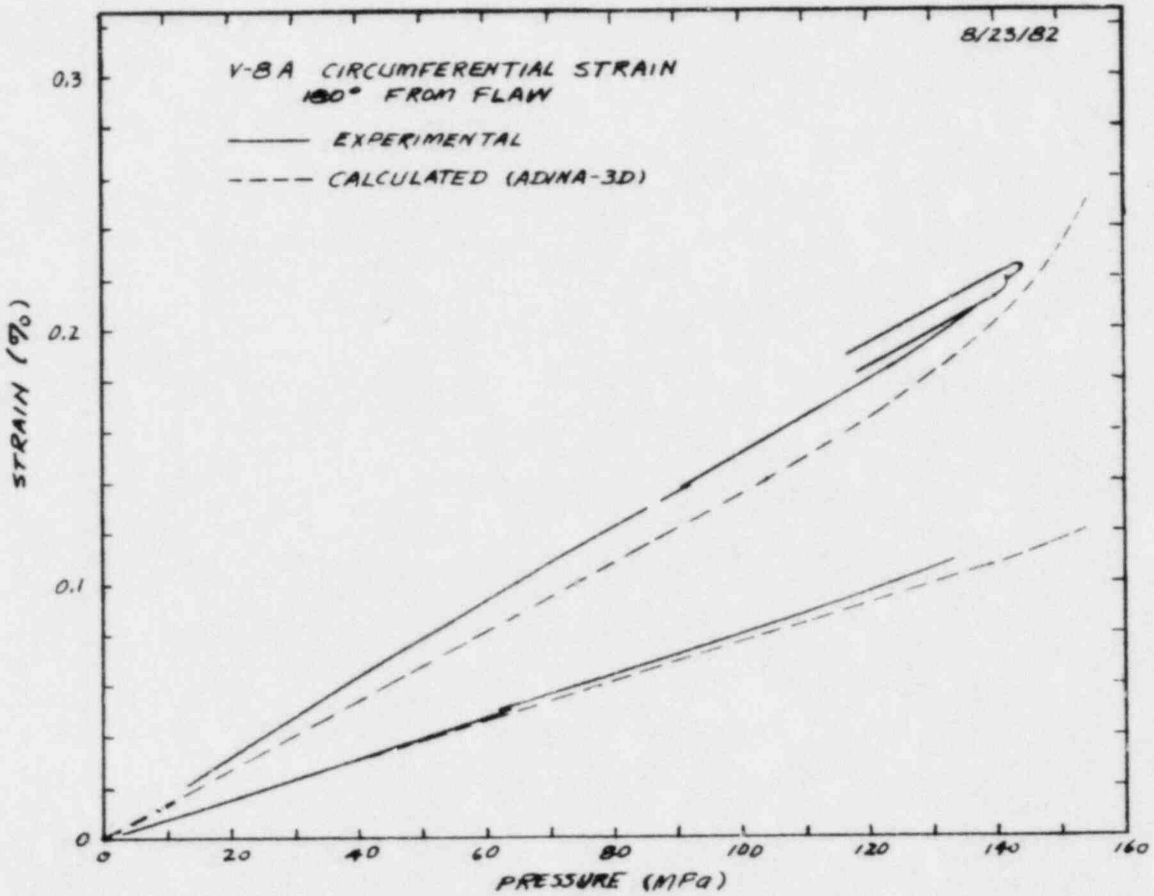

Fig. 12. Circumferential strain in vessel V-8A remote from flaw.

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