HEAVY-SECTION STEEL TECHNOLOGY PROGRAM INTERMEDIATE-SCALE PRESSURE VESSEL TESTS*

R. H. BRYAN, J. G. MERKLE, G. C. SMITH, G. D. WHITMAN

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, U.S.A.

SUMMARY

Eight intentionally flawed thick-walled pressure vessels of ASTM A508 class 2 forging steel or A533, grade B, class 1 steel plate have been pressurized to fracture or leak. Tests of these vessels (990 mm OD, 152 mm wall thickness) permitted the study of fracture behavior of structures under stress states not attainable with conventional testing machines. The test section thickness was chosen in order to provide a test configuration that was essentially full-scale relative to BWR and PWR pressure vessels. Experimental results were used to evaluate and improve methods of fracture analysis that could be used in predicting failure conditions of reactor type pressure vessels.

The test sections of the vessels were of two types: cylindrical and cylindrical with an intersecting nozzle. In every case, one or more sharp surface flaws were introduced in an axial-radial plane. Flaws were located in the outside and inside cylindrical regions, in weld metal and base metal, and at the inside nozzle corners. Test temperatures ranged from 0 °C to 91 °C, covering a range of toughness from transition to static and dynamic upper shelf. The first eight tests were conducted with hydraulic pressurization, which was presumed to adequately sustain loadings for the study of crack initiation. One vessel that leaked without fracturing was repaired and retested pneumatically with an identical flaw to determine whether a sustained and more compliant loading would alter the mode of failure.

Preparation for testing included comprehensive material characterization. Tensile, Charpy, and fracture toughness properties were determined from the vessel cylinder or nozzle prolongations that had undergone the same fabrication history as the test piece. One-seventh-scale models, made from the same material, were flawed and tested with various flaw sizes and at various temperatures.

Results of tests on epoxy and steel models, 152 mm thick flawed tensile specimens, and material property specimens were used to choose specific intermediate vessel test conditions and make predictions of failure conditions. Several different analytical methods were tried; some gave quantitative estimates of pressure, strain, or COD at fracture, while others produced only qualitative information. Of special interest in the evaluation of analytical methods were questions of validity and usefulness of linear elastic fracture mechanics (LEFM). While crack initiation was of principal concern, attempts were also made to predict crack arrest or nonarrest.

Three vessels were tested at temperatures corresponding to the fracture toughness transition. These vessels failed by fractures propagating beyond the test sections. LEFM accurately predicted the strain at fracture of the two cylinders (prior to gross yielding) from which the failure pressure was deduced from the appropriate nonlinear pressure-strain relationship. Tests at upper shelf temperatures involved stable crack growth and plastic instability in the flaw region. These tests resulted in either mixed mode fractures or leak without fracture. The pneumatic sustained load test resulted in a leak without fracture, as had the comparable hydraulic test.

* Work done at Oak Ridge National Laboratory, operated by Union Carbide Corporation for the Energy Research and Development Administration.
This work funded by U.S. Nuclear Regulatory Commission under Interagency Agreements 40-551-75 and 40-552-75.

1. Introduction

Development and validation of methods of analyzing full-scale light-water-cooled reactor pressure vessels containing flaws is a major objective of the Heavy-Section Steel Technology Program. Such methods are an essential tool for the evaluation of the safety of nuclear power plants. It is especially desirable that estimates of the strength of flawed structures be made realistically and quantitatively to ensure adequate margins of safety in the interest of public safety and to avoid unnecessary conservatism in the interest of economy and productivity. The testing of intentionally flawed steel vessels is a necessary part of this development effort. The intermediate-test-vessel (ITV) series of experiments was conceived to provide conditions of size and state of stress similar to those that would obtain in real reactor vessels in normal operation and under accidental conditions. Although ITVs are intermediate in size between laboratory specimens and reactor vessels, they are nearly full size with respect to thickness and are capable of providing conditions of transverse restraint not attainable by other means.

The ITV tests were planned to provide a connection between the fracture behavior observed in small-scale tests and the behavior of full-scale components. When the first two ITVs were tested it was not known whether and within what limits linear elastic fracture mechanics (LEFM) would be a useful analytical method. The general plan for the series was to observe flaw behavior quantitatively under a variety of fracture toughness conditions ranging from low transitional to upper shelf toughness. Some consideration in the early order of tests was given to demonstrating qualitatively that a margin of safety in flawed vessels does exist.

All of the test conditions were selected to be related to some normal or hypothetical abnormal phase of nuclear power plant operation. However, experimental considerations generally dictated the flaw size; and most tests were carried to the ultimate capacity of the testing system or to the point of structural failure. Extremes of temperature and pressure not directly related to any reactor operating condition were used as necessary to obtain quantitative results by which methods of analysis could be decisively evaluated.

The tests performed to date have been primarily concerned with the study of the onset of flaw instability.[1-5] Any method of analysis that is successful in predicting the threshold of instability must be able to relate the geometry of the flaw, structure, and loading to measurable material properties. This usually involves consideration of more than a single fracture criterion. To the extent practicable all of the variables that might have a bearing on flaw behavior were measured during each test: strains near and far from the flaw, crack-opening displacement (COD), crack depth, temperature, and pressure.

In addition to the quantitative results of the tests some important conclusions regarding modes of behavior were reached. Conditions for stable crack growth, mixed mode crack propagation, and leak without break were observed.

2. Description of Intermediate Test Vessels

Ten 150-mm-thick vessels were fabricated to the configurations shown in Fig. 1. The 990-mm-OD by 1370-mm-long test sections were fabricated of ASTM A508, class 2 forgings in vessels V-1 through V-6 and of ASTM A533, grade B, class 1 plate in vessels V-7 through V-10. The nozzles in V-5, -9, and -10 were fabricated of ASTM A508, class 2 forging steel. The test cylinders of forged vessels V-3, -4, and -6 were cut longitudinally and rejoined by submerged-arc welding to provide weld metal sites for emplacement of flaws. The test section of vessel V-6 also contained an intersecting circumferential weld.

The vessels were designed and fabricated in accordance with Section III of the 1968 edition of the ASME Boiler and Pressure Vessel Code. The thickness of the test section was chosen as the minimum adequate for the performance of valid tests of linear elastic fracture mechanics. The length was such that a central flawed region would be unaffected by the discontinuities at the two heads. The diameter of the test section and closure forging were a practical minimum allowing personnel access for inspection, flaw preparation, and instrumentation. The ITV thickness is almost full scale with respect to real reactor vessels. Although design pressures are markedly different, by virtue of the Code definition of allowable stress intensity, the difference between the largest and the smallest principal stresses at design pressure is the same in cylindrical sections of the test vessels and reactor pressure vessels.

3. Test Preparations

Intermediate vessel tests were preceded by intensive preparations to obtain a quantitative basis for predicting failure conditions and for evaluating methods of fracture analysis. Material properties of the test vessels were measured and flawed epoxy and steel models were tested. Tentative test conditions were evaluated by experimental and mathematical analysis to determine the specific test conditions, in terms of flaw size and vessel temperature, likely to produce useful intermediate vessel test results.

4. Material Characterization

Tensile, impact, and fracture toughness properties of the ITVs were determined prior to testing. Prolongations of the test cylinders and nozzle forgings were acquired for this purpose. Thus the material properties were determined for pieces that had experienced the same fabrication history as the vessel test sections up to the time of welding of vessel components together. The variation of properties with depth were measured where practicable.

Charpy impact energy curves were determined as a function of depth and orientation. Results were typical of A508, class 2, and A533, grade B, class 1 materials. NDT temperatures determined by drop-weight tests of shell course material were typically −12°C and −51°C, respectively, for the two materials.

Fracture toughness was estimated from test data from bend tests of precracked Charpy specimens and from tests of 21.6 and 102-mm-thick compact tension (CT) specimens. Data were converted to lower bound K_{Icd} values by the equivalent energy procedure proposed by Witt and Mager.[6] Such calculations have been shown by Merkle and Corten[7] to agree with J-integral calculations, for the same chosen measurement point, for these two specimens. The smaller thickness corresponds to the thickness of 1/7-scale steel model vessels used in this program. Variations of toughness with depth in cylinder wall and temperature were determined for the material in which the flaw would be located.

5. Model Testing

Scale models were used extensively as an aid to planning and interpreting results of tests of the ITVs. Epoxy models, which behave elastically, as well as steel models, which exhibit elastic-plastic behavior, were tested. In each case the model contained machined notches that were sharpened either by fatigue (in epoxy) or by hydrogen-charge cracking of an electron-beam weld placed at the root of the machined notch (in steel). The models were instrumented to provide pressure-strain data up to the time of failure. These data provided a means of qualifying various computational methods for determining the strength of flawed vessels as a function of flaw geometry and toughness. Shape factors needed for application of LEFM were measured in epoxy model tests.

6. Test Vessel Preparation

Sharp flaws of the desired shape and location were necessary to satisfy the assumptions of LEFM and to maximize the chances of successful correlation of experiment and analysis. Flaw geometries for the tests are defined by Fig. 2; and the estimated and actual flaw dimensions are given in Table I. In all cases the actual initial flaw geometry was close enough to the estimated value to meet test objectives; however, the discrepancies were in some instances large enough to affect the strength of the vessel and accuracy of pretest analysis.

Flaw preparation involves two steps: (1) a notch is machined at the desired location to within a few millimeters of the desired final crack tip contour; (2) the machined notch is extended either by fatigue or by a combination of electron-beam (EB) welding and hydrogen-charge cracking.

Vessel V-7 has been tested twice, and it has been repaired for a third test. After each of the V-7 tests the flawed region was repaired by the half-bead welding procedure prescribed in Section XI of the ASME Boiler and Pressure Vessel Code.[8] The flaws for the subsequent tests, designated V-7A and V-7B, were identical to the original V-7 flaw design.

The vessels were extensively instrumented with internal and external strain gages (typically 60 or more), crack-opening-displacement (COD) gages, ultrasonic transducers for monitoring the location of the crack front, acoustic emission sensors, and thermocouples.

7. Test Description

The intermediate vessel tests were performed under the conditions indicated in Table II. Prior to pressurization, the test vessel was brought to the prescribed temperature range. With one exception, the vessels were pressurized hydraulically until a leak or burst developed. Usually pressure was raised in steps of 3 to 30 MPa, depending on the pressure, with pauses in pumping to allow for recording and assessment of data. Vessel V-7A was pressurized pneumatically in an attempt to replicate the hydraulic test of V-7.

8. Discussion of Results

The intermediate vessel tests demonstrated that, large flaws notwithstanding, all of the vessels were capable of yielding in the unflawed region before the onset of fracture. None fractured without approaching or exceeding a condition of through-the-wall yielding remote from the crack. The gross strain behavior of the cylindrical vessels is shown in Fig. 3. The three vessels tested to burst on the static upper shelf went well into the strain-hardening range and the two vessels with nozzles yielded through the thickness. All vessels except V-7 and V-7A, which were only loaded until they leaked, held a pressure of at least 2.7 × design pressure without fracture.

The fracture results are summaried in Table II by toughness regimes. Linear elastic fracture mechanics based on strain[2] accurately predicted the fracture strain, λ_f, (calculated elastically) and the pressure (inferred from the actual or computed pressure-strain curve at λ_f) for V-2 and V-4, which were tested in the toughness transition. These vessels fractured extensively slightly prior to gross section yielding.

Vessels V-1 and V-3 were tested at a temperature (54°C) for which the static fracture toughness was known to be high (above 300 $MN \cdot m^{-3/2}$) but the crack arrest toughness low. Hence crack arrest was not expected. The cracks propagated in a mixed mode fracture beyond the ends of the test sections. Substantial stable crack growth prior to fracture was expected and did occur. LEFM calculations of the critical pressure and strain, taking stable crack growth into account, were quite conservative. The gross section strains at fracture were well beyond yield. Fracture appeared to be related to the attainment of local plastic instability, which was, in turn, dependent upon the extent of stable crack growth. The latter phenomenon must be accounted for quantitatively in an analysis if the method is to be useful for predicting fracture strength after through-the-thickness yielding occurs.

The test of vessel V-6 at 88°C gives further confirmation to the conclusions derived from the V-1 and V-3 tests with respect to crack initiation. At the higher temperature, however, the fracture was a full shear and terminated within the test section. The decreasing load during fracture probably limited the length of the tear.

The test pressure of the vessels with nozzles, V-5 and V-9, exceeded the fracture pressures predicted by LEFM based on strain by a considerable margin. Although the stress is high at the nozzle corner on account of stress concentration, the transverse restraint on the flaw is low. Nozzle corner circumferential strains reached about 6.5 and 8.5% in V-5 and V-9, respectively.

Although pretest analyses underestimated fracture pressures and strains in the vessels with nozzles the test results were predicted qualitatively. Vessel V-5, which was tested at 88°C, did not fracture; the crack grew stably with increasing pressure until a leak developed. Vessel V-9 fractured at about the pressure at which V-5 leaked. Because of the low V-9 test temperature (24°C), the arrest toughness was below the static toughness, and the crack propagated rapidly. The crack had, however, grown stably from a depth of 30 mm to about 50 mm before becoming unstable.

Vessel V-7 contained a very deep flaw (Fig. 2), the size of which was chosen so as to attain failure between design pressure (66.9 MPa) and gross yield pressure. Tests of flawed steel models confirmed the latter to be about 190 MPa. Two modes of failure were possible, a leak-without-burst and burst. Pretest analyses and flaw preparations were made with the intention of demonstrating a leak-without-burst. The V-7 test was carried out hydraulically with the expected result, a leak at 147.2 MPa. Upon depressurization the vessel resealed itself and held a pressure of about 125 MPa.

The vessel was repaired and retested pneumatically with an identical flaw in a virgin region of the vessel. A thin-membrane patch was also welded to the inside surface beneath the flaw so as to allow the pressure to be maintained long after rupture. The sustained-load test, designated V-7A, produced flaw behavior practically identical to that of the first test. Rupture occurred at 144.2 MPa; the crack had grown about 10 mm toward each end but did not propagate.

Crack-opening displacement (COD) was an important measurement in every test. The COD vs pressure behavior of V-7A is somewhat typical of all intermediate vessel tests. During periods of constant or slightly decreasing pressure the COD continued to increase for a time, as shown in Fig. 4. This creeping behavior, which had been suspected as possibly indicating incipient instability, was carefully evaluated after the test of V-7A, which was instrumented for this purpose. The stability of the crack at peak pressure is indicated by the asymptotic behavior of the COD at maximum pressure shown in Fig. 5. The maximum pressure was maintained within 1.1% after rupture occurred.

9. Summary and Conclusions

The tests of intermediate-size vessels with sharp flaws permitted the comparison of experimentally observed behavior with analytical predictions of the behavior of flawed pressure vessels. Fracture strains estimated by LEFM were accurate in the cases in which the flaws resided in regions of high transverse restraint and the fracture toughness was sufficiently low for unstable fracture to occur prior to yielding through the vessel wall (viz V-2 and V-4). When both of these conditions were not present, unstable fracture did occur, always preceded by stable crack growth; and the cylinders with flaws initially less than halfway through the wall attained gross yield prior to burst (viz V-1, V-3, and V-6). Predictions of failure pressure of the vessels with flawed nozzles, based upon LEFM estimates of failure strain, were very conservative.

LEFM calculations of critical load were based upon small-specimen fracture toughness test data. Whenever gross yielding preceded failure, the actual strains achieved were considerably greater than the estimated strains at failure based on LEFM (viz V-1, V-3, V-6, and V-9). In such cases the strength of the vessel may be no longer dependent upon plane-strain fracture toughness but upon the capacity of the cracked section to carry the imposed load stably in the plastic range. Stable crack growth, which has not been predictable quantitatively, is an important factor in elastic-plastic analysis of strength.

The ability of the flawed vessels to attain gross yield in unflawed sections has important qualitative implications on pressure vessel safety margins. The gross yield condition occurs in light-water-reactor pressure vessels at about 2 × design pressure. This loading condition is generally well beyond the allowable normal, upset, and emergency conditions for which reactor pressure vessels may be designed. The intermediate vessel tests that demonstrated a capacity for exceeding this load (viz all except V-2, V-4, and V-7) confirm that the presumed margin of safety is not diminished by the presence of flaws of substantial size, provided that material properties are adequate.

References

[1] DERBY, R. W., et al., Test of 6-Inch-Thick Pressure Vessels, Series 1: Intermediate Test Vessels V-1 and V-2, USAEC Report ORNL-4895, Oak Ridge National Laboratory, February 1974.

[2] BRYAN, R. H., et al., Test of 6-Inch-Thick Pressure Vessels, Series 2: Intermediate Test Vessels V-3, V-4, and V-6, ERDA Report ORNL-5059, Oak Ridge National Laboratory, November 1975.

[3] MERKLE, J. G., et al., Test of 6-Inch-Thick Pressure Vessels, Series 3: Intermediate Test Vessel V-7, ERDA Report ORNL/NUREG-1, Oak Ridge National Laboratory, August 1976.

[4] MERKLE, J. G., et al., Test of 6-Inch-Thick Pressure Vessels, Series 4: Intermediate Test Vessels V-5 and V-9 with Inside Nozzle Corner Cracks, ERDA Report ORNL/NUREG-7, Oak Ridge National Laboratory, to be published.

[5] BRYAN, R. H., et al., Test of 6-Inch-Thick Pressure Vessels, Series 3: Intermediate Test Vessel V-7A, ERDA Report ORNL/NUREG-9, Oak Ridge National Laboratory, to be published.

[6] WITT, F. J., MAGER, T. R., A Procedure for Determining Bounding Values on Fracture Toughness K_{Ic} at Any Temperature, USAEC Report ORNL-TM-3894, Oak Ridge National Laboratory, October 1972.

[7] MERKLE, J. G., CORTEN, H. T., "A J-Integral Analysis for the Compact Specimen, Considering Axial Force as Well as Bending Effects," Journal of Pressure Vessel Technology, ASME, Vol. 96, Series J, No. 4, pp. 286-292, November 1974.

[8] "Rules for Inservice Inspection of Nuclear Power Plant Components," ASME Boiler and Pressure Vessel Code, Section XI, Subsubarticle IWB-4420, 1974 edition with Summer and Winter 1974 Addenda, American Society of Mechanical Engineers, New York.

Table I. Flaw Design for Intermediate-Size Vessels

Vessel	Flaw	Location[a]	Material	Dimensions (mm) Estimated a	Estimated 2b	Actual a	Actual 2b
1		Outside	A508-2	64	206	65	210
2		Outside	A508-2	64	206	64	211
3		Outside	SA Weld	65	210	54	216
4	A[b]	Outside	SA Weld	66	210	75	210
	B	Outside	A508-2	66	204	79	204
5		Inside nozzle corner	A508-2	30			
6	A[b]	Outside	SA Weld	47	129	47	133
	B	Outside	A508-2	44	132	34	132
	C	Inside	SA Weld	45	135	49	135
7		Outside	A533-B1	135	472		
7A		Outside	A533-B1	135	472	139	467
7B		Outside	Sect. XI Weld	140	472		
9		Inside nozzle corner	A508-2	30			

[a]Plane of flaw lies in radial-axial plane of test cylinder (and also of nozzle in V-5 and V-9).

[b]Flaw at which fracture occurred.

Table II. Results of Tests on Intermediate-Size Vessels

Vessel No.	Test temp., (°C)	Fracture toughness K_c, $MN \cdot m^{-3/2}$	Maximum pressure p_f, MPa, and strain λ_f, %, at failure		Mode of failure	Calculated results: LEFM[a] based on strain	Calculated results: Plastic instability	Load factor (p_f/p_d)[b]	Toughness Range
2	0	202	p_f	192	Flat	189		2.87	Transition range
			λ_f	0.19		0.206			
4	24	176	p_f	183	Mixed	181		2.73	
			λ_f	0.168		0.163			
9	24	165–302	p_f	185	Mixed	93–127		2.77	
			λ_f	1.05[c]		0.070–0.096[c]			
1	54	342	p_f	199	Mixed	190	206[d]	2.96	Static upper shelf
			λ_f	0.92		0.345			
3	54	357	p_f	214	Mixed	190	217[d]	3.19	
			λ_f	1.45		0.398			
6	88	405	p_f	220	Shear	190	232[d]	3.28	Static and dynamic upper shelf
			λ_f	2.0		0.479			
5	88	265	p_f	183	Leak	132		2.74	
			λ_f	0.25[c]		0.100[c]			
7	91	331	p_f	147.2	Leak	143	132	2.20	
			λ_f	0.12		0.109			
7A	88	331	p_f	144.2	Leak			2.16	
			λ_f	0.110					

[a] Linear elastic fracture mechanics.

[b] p_d, design pressure = 66.9 MPa.

[c] Outside circumferential strain 180° from nozzle.

[d] Assuming 15% stable crack growth.

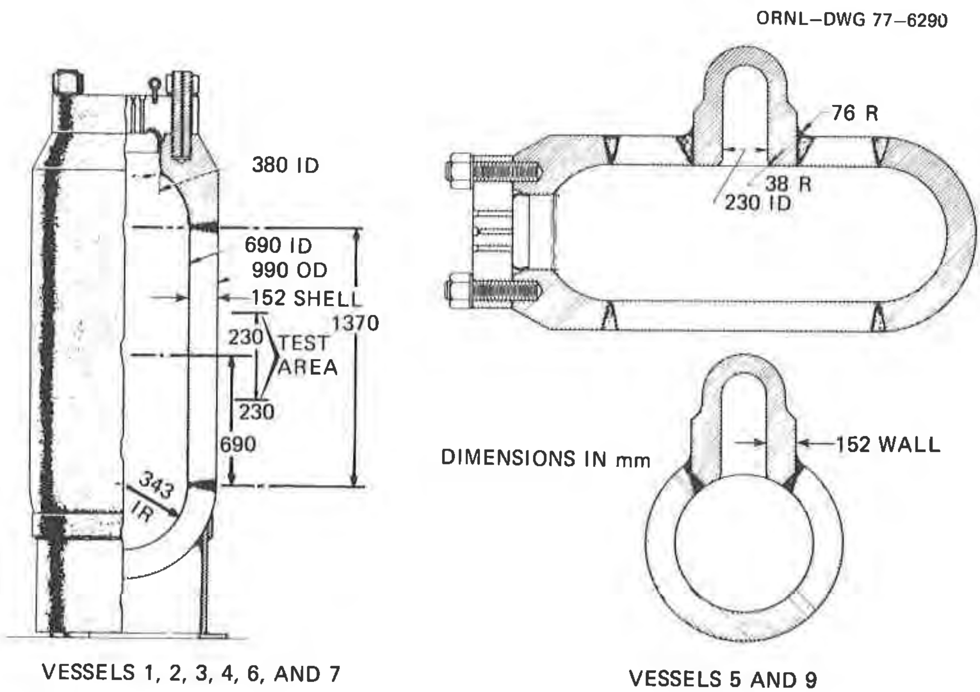

Fig. 1. Intermediate test vessel typical cross sections.

ORNL–DWG 77–6291

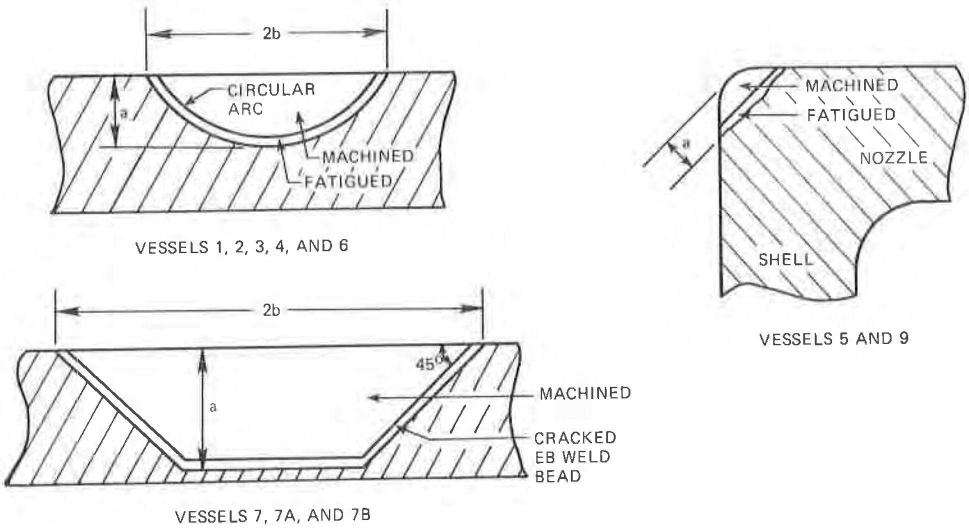

Fig. 2. Flaw geometries for intermediate test vessels.

ORNL–DWG 77–6287

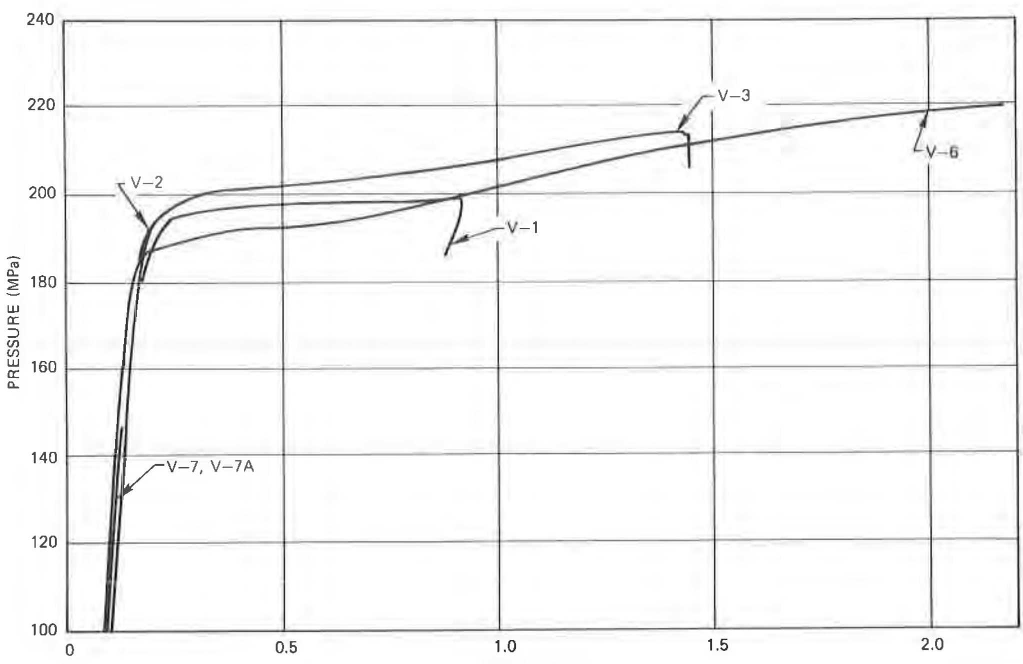

Fig. 3. Outside circumferential strain of cylindrical intermediate test vessels 1, 2, 3, 6, 7, and 7A remote from flaws.

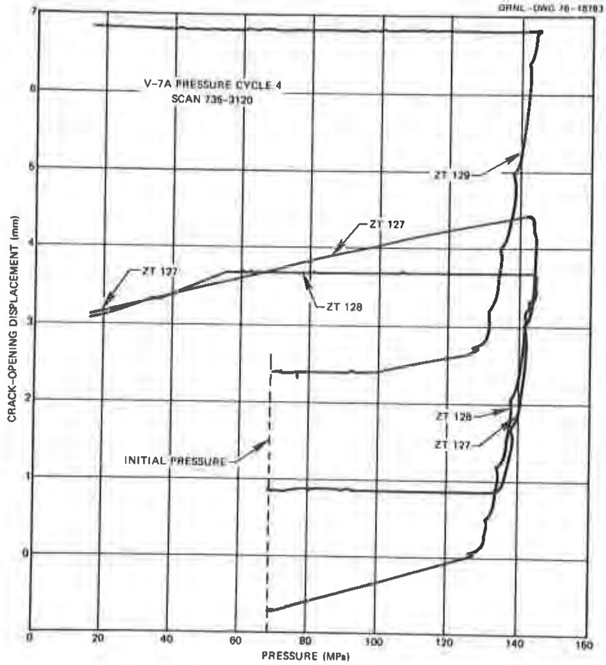

Fig. 4. Crack-opening displacement versus pressure of vessel V-7A during final pressurization cycle.

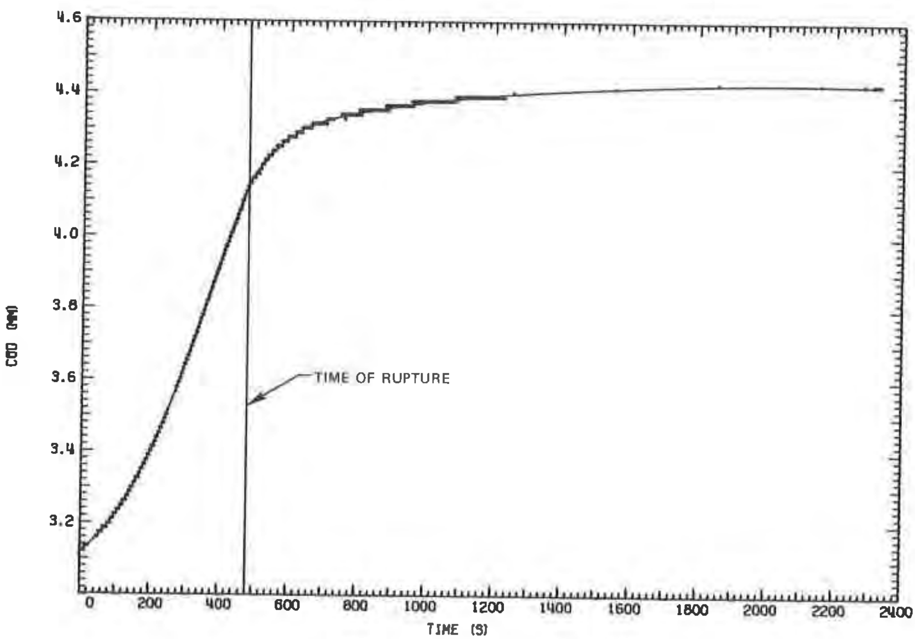

Fig. 5. Crack-opening displacement versus time for vessel V-7A during final period of sustained load.