**Test of 6-in.-Thick Pressure Vessels.
Series 4: Intermediate Test Vessels V-5 and V-9
with Inside Nozzle Corner Cracks**

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ENGINEERING TECHNOLOGY DIVISION

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Foreword

The work reported here was performed mostly at Oak Ridge National Laboratory (ORNL) under sponsorship of the U.S. Nuclear Regulatory Commission's (NRC) Heavy-Section Steel Technology (HSST) Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which G. D. Whitman is manager. The manager for the NRC is E. K. Lynn.

This report is designated Heavy-Section Steel Technology Program Technical Report No. 43. Prior reports in this series are listed below.

1. S. Yukawa, *Evaluation of Periodic Proof Testing and Warm Prestressing Procedures for Nuclear Reactor Vessels*, HSSTP-TR-1, General Electric Company, Schenectady, N Y. (July 1, 1969).
2. L. W. Loechel, *The Effect of Section Size on the Transition Temperature in Steel*, MCR-69-189, Martin Marietta Corporation, Denver, Colo. (Nov. 20, 1969).
3. P. N. Randall, *Gross Strain Measure of Fracture Toughness of Steels*, HSSTP-TR-2, TRW Systems Group, Redondo Beach, Calif. (Nov. 1, 1969).
4. C. Visser, S. E. Gabrielse, and W. VanBuren, *A Two-Dimensional Elastic-Plastic Analysis of Fracture Test Specimens*, WCAP-7368, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (October 1969).
5. T. R. Mager, F. O. Thomas, and W. S. Hazelton, *Evaluation by Linear Elastic Fracture Mechanics of Radiation Damage to Pressure Vessel Steels*, WCAP-7328 (Rev.), Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (October 1969).
6. W. O. Shabbits, W. H. Pryle, and E. T. Wessel, *Heavy Section Fracture Toughness Properties of A 533 Grade B Class 1 Steel Plate and Submerged Arc Weldment*, WCAP-7414, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (December 1969).
7. F. J. Loss, *Dynamic Tear Test Investigations of the Fracture Toughness of Thick-Section Steel*, NRL-7056, U.S. Naval Research Laboratory, Washington, D.C. (May 14, 1970).
8. P. B. Crosley and E. J. Ripling, *Crack Arrest Fracture Toughness of A 533 Grade B Class 1 Pressure Vessel Steel*, HSSTP-TR-8, Materials Research Laboratory, Inc., Glenwood, Ill. (March 1970).
9. T. R. Mager, *Post-Irradiation Testing of 2 T Compact Tension Specimens*, WCAP-7561, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (August 1970).
10. T. R. Mager, *Fracture Toughness Characterization Study of A 533, Grade B, Class 1 Steel*, WCAP-7578, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (October 1970).
11. T. R. Mager, *Notch Preparation in Compact Tension Specimens*, WCAP-7579, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (November 1970).
12. N. Levy and P. V. Marcal, *Three-Dimensional Elastic-Plastic Stress and Strain Analysis for Fracture Mechanics, Phase I: Simple Flawed Specimens*, HSSTP-TR-12, Brown University, Providence, R.I. (December 1970).
13. W. O. Shabbits, *Dynamic Fracture Toughness Properties of Heavy Section A 533 Grade B, Class 1 Steel Plate*, WCAP-7623, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (December 1970).
14. P. N. Randall, *Gross Strain Crack Tolerance of A 533-B Steel*, HSSTP-TR-14, TRW Systems Group, Redondo Beach, Calif. (May 1, 1971).

15. H. T. Corten and R. H. Sailors, *Relationship Between Material Fracture Toughness Using Fracture Mechanics and Transition Temperature Tests*, T&AM Report 346, University of Illinois, Urbana, Ill. (Aug. 1, 1971).
16. T. R. Mager and V. J. McLoughlin, *The Effect of an Environment of High Temperature Primary Grade Nuclear Reactor Water on the Fatigue Crack Growth Characteristics of A 533 Grade B Class 1 Plate and Weldment Material*, WCAP-7776, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (October 1971).
17. N. Levy and P. V. Marcal, *Three-Dimensional Elastic-Plastic Stress and Strain Analysis for Fracture Mechanics, Phase II: Improved Modeling*, HSSTP-TR-17, Brown University, Providence, R.I. (November 1971).
18. S. C. Grigory, *Six-Inch-Thick Flawed Tensile Tests, First Technical Summary Report, Longitudinal Specimens 1 through 7*, HSSTP-TR-18, Southwest Research Institute, San Antonio, Tex. (June 1972).
19. P. N. Randall, *Effects of Strain Gradients on the Gross Strain Crack Tolerance of A 533-B Steel*, HSSTP-TR-19, TRW Systems Group, Redondo Beach, Calif. (May 1, 1972).
20. S. C. Grigory, *Tests of Six-Inch-Thick Flawed Tensile Specimens, Second Technical Summary Report, Transverse Specimens Numbers 8 through 10, Welded Specimens Numbers 11 through 13*, HSSTP-TR-20, Southwest Research Institute, San Antonio, Tex. (June 1972).
21. L. A. James and J. A. Williams, *Heavy Section Steel Technology Program Technical Report No. 21, The Effect of Temperature and Neutron Irradiation Upon the Fatigue-Crack Propagation Behavior of ASTM A533, Grade B, Class 1 Steel*, HEDL-TME-72-132, Hanford Engineering Development Laboratory, Richland, Wash. (September 1972).
22. S. C. Grigory, *Tests of Six-Inch-Thick Flawed Tensile Specimens, Third Technical Summary Report, Longitudinal Specimens Numbers 14 through 16, Unflawed Specimen Number 17*, HSSTP-TR-22, Southwest Research Institute, San Antonio, Tex. (October 1972).
23. S. C. Grigory, *Tests of Six-Inch-Thick Flawed Tensile Specimens, Fourth Technical Summary Report, Tests of One-Inch-Thick Flawed Tensile Specimens for Size Effect Evaluation*, HSSTP-TR-23, Southwest Research Institute, San Antonio, Tex. (June 1973).
24. S. P. Ying and S. C. Grigory, *Tests of Six-Inch-Thick Tensile Specimens, Fifth Technical Summary Report, Acoustic Emission Monitoring of One-Inch and Six-Inch-Thick Tensile Specimens*, HSSTP-TR-24, Southwest Research Institute, San Antonio, Tex. (November 1972).
25. R. W. Derby et al., *Test of 6-Inch-Thick Pressure Vessels. Series I: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).
26. W. J. Stelzman and R. G. Berggren, *Radiation Strengthening and Embrittlement in Heavy Section Plates and Welds*, ORNL-4871 (June 1973).
27. P. B. Crosley and E. J. Ripling, *Crack Arrest in an Increasing K-Field*, HSSTP-TR-27, Materials Research Laboratory, Glenwood, Ill. (January 1973).
28. P. V. Marcal, P. M. Stuart, and R. S. Bettes, *Elastic-Plastic Behavior of a Longitudinal Semi-Elliptical Crack in a Thick Pressure Vessel*, Brown University, Providence, R.I. (June 1973).
29. W. J. Stelzman, *Characterization of HSST Plates 01, 02, and 03* (in preparation).
30. D. A. Canonico, *Characterization of Heavy Section Weldments in Pressure Vessel Steels* (in preparation).
31. J. A. Williams, *The Irradiation and Temperature Dependence of Tensile and Fracture Properties of ASTM A533, Grade B, Class 1 Steel Plate and Weldment*, HEDL-TME 73 75, Hanford Engineering Development Laboratory, Richland, Wash. (August 1973).

32. J. M. Steichen and J. A. Williams, *High Strain Rate Tensile Properties of Irradiated ASTM A533 Grade B Class 1 Pressure Vessel Steel*, HEDL-TME 73-74, Hanford Engineering Development Laboratory, Richland, Wash. (July 1973).
33. P. C. Riccardella and J. L. Swedlow, *A Combined Analytical-Experimental Fracture Study*, WCAP-8224, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa. (October 1973).
34. R. J. Podlasek and R. J. Liber, *Final Report on Investigation of Mode III Crack Extension in Reactor Piping*, Battelle Columbus Laboratories, Columbus, Ohio (May 1974).
35. T. R. Mager et al., *Interim Report on the Effect of Low Frequencies on the Fatigue Crack Growth Characteristics of A533 Grade B Class 1 Plate in an Environment of High-Temperature Primary Grade Nuclear Reactor Water*, WCAP-8256, Westinghouse Electric Corporation, Pittsburgh, Pa. (December 1973).
36. J. A. Williams, *The Irradiated Fracture Toughness of ASTM A533, Grade B, Class 1 Steel Measured with a Four Inch Thick Compact Tension Specimen*, HEDL-TME 75-10, Hanford Engineering Development Laboratory, Richland, Wash. (January 1975).
37. R. H. Bryan et al., *Test of 6-in.-thick Pressure Vessels, Series 2: Intermediate Test Vessels V-3, V-4, and V-5*, ORNL-5059 (November 1975).
38. T. R. Mager, S. E. Yanichko, and L. R. Singer, *Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material*, WCAP-8456, Westinghouse Electric Corporation, Pittsburgh, Pa. (December 1974).
39. J. G. Merkle, G. D. Whitman, and R. H. Bryan, *An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water Reactor Pressure Vessel Safety*, ORNL/TM-5090 (November 1975).
40. J. G. Merkle et al., *Test of 6-in.-thick Pressure Vessels, Series 3: Intermediate Test Vessel V-7*, ORNL NUREG-1 (August 1976).
41. J. A. Davidson, L. J. Cheschini, R. P. Shogan, and G. V. Rao, *The Irradiated Dynamic Fracture Toughness of ASTM A533, Grade B, Class 1 Steel Plate and Submerged-Arc Weldment*, WCAP-8775, Westinghouse Electric Corp., Pittsburgh, Pa. (October 1976).
42. R. D. Cheverton, *Pressure Vessel Fracture Studies Pertaining to a PWR LOCA-ECC Thermal Shock: Experiments TSE-1 and TSE-2*, ORNL NUREG TM-3 (September 1976).

Copies of these reports may be obtained from Laboratory Records Department, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tenn. 37830.

Test of 6-in.-Thick Pressure Vessels. Series 4: Intermediate Test Vessels V-5 and V-9 with Inside Nozzle Corner Cracks

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Abstract

This report describes failure testing of two 99-cm-diam (39-in.), 15.2-cm-thick (6-in.) steel pressure vessels, each containing one flawed nozzle. Vessel V-5 was tested at 88°C (190°F) and failed by leaking without fracturing after extensive stable crack growth. Vessel V-9 was tested at 25°C (75°F) and failed by fracturing. Material properties measured before the tests were used for pretest and posttest fracture analyses. Test results supported by analysis indicate that inside nozzle corner cracks are not subject to plane strain under pressure loading. The preparation of inside nozzle corner cracks is described in detail. Extensive experimental data are tabulated and plotted.

1. Introduction

The United States electric power industry began to utilize nuclear power as an economically competitive source of energy during the 1960-1970 decade. Plans were made and construction was started for boiling-water reactor (BWR) and pressurized-water reactor (PWR) nuclear generating stations in increasing numbers. The international energy shortage has increased the need to effectively utilize these types of nuclear power plants.

With the competitive commercialization of BWRs and PWRs, the predominant capacity ratings of these plants increased to about 1100 MW(e) with an attendant need for larger, thicker reactor pressure vessels. As a direct result of the expected increase in plant generating capacity and component size, the Advisory Committee on Reactor Safeguards (ACRS) issued a letter to the U.S. Atomic Energy Commission (USAEC) in December 1965 concerning reactor system containment safety.¹ Concerning pressure vessel safety, the letter stated that additional research on methods of stress analysis and nondestructive examination, on irradiation effects on pressure vessel steels, and on methods for evaluating the effects of flaws on vessel integrity should be undertaken in order to ensure that structural safety margins would be maintained as vessel sizes increased. The Heavy-Section Steel Technology (HSST) Program was instituted by the USAEC as a result of this recommendation. Direct technical management of the program was assigned to the Oak Ridge National Laboratory (ORNL). Sponsorship of the program is presently assigned to the Reactor Safety Research (RSR) Division of the U.S. Nuclear Regulatory Commission (USNRC).

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The HSST program was instituted during a period of industrial change, to complement investigations initiated by the industry of thick-section vessels for water-cooled nuclear reactor service. The program is especially concerned with developing the information necessary for assessing the influence of flaws on the safety and serviceability of the thick-section components of reactor pressure vessels. The program has developed data on the characteristics of plates, welds, and forgings in terms of mechanical properties, toughness, inherent flaws, and homogeneity. A major objective is to develop methods by which better estimates can be made of the effects of flaws on the service life and strength of vessels.

Methods of analysis as well as experimental methods are being developed for the fracture evaluation of structures. A wide variety of specimen types and sizes have been tested under a wide range of loading conditions. Considerable progress has been made in understanding the behavior of flawed structures and in applying the results of tests of small specimens to the analysis and evaluation of large structures. The importance of the size of test specimens and structures in the proper characterization of behavior has been demonstrated in many parts of the program. Confidence in methods of safety analysis can be attained only to the extent that theoretical methods have been tested by experiment with appropriately sized structures under loading conditions of interest. Consequently, the HSST program includes simulated service tests, of which the intermediate vessel tests are a part. General views of some of the 99-cm-OD (39-in.), 15.2-cm-thick (6-in.) steel pressure vessels used for these tests are shown in Figs. 1.1 and 1.2.

Fig. 1.1. Intermediate test vessel with plain cylindrical test section.

Fig. 1.2. View of intermediate test vessels showing bolted-on closure head used for all vessels and welded-in nozzle used for vessels V-5, V-9, and V-10.

The aim of simulated service testing is to provide, through a series of experiments, a connection between the observed behavior of structures in a laboratory environment and the expected behavior of full-size components under the wide variety of conditions that constitute the actual operating environment. The main effort of this task is to determine, if not already known, which factors or conditions are important and then to carry out tests with the particular combinations of conditions that will contribute significant information on the expected behavior of structures in service. Factors of concern include material properties; flaw location, orientation, shape, size, and sharpness; and loading and environmental conditions. If expense, resources, safety, and time were of no importance, the significance of these factors could be studied under actual service conditions imposed on vessels in a large number of experiments with vessels as large as, or larger than, reactor pressure vessels. Since such an approach is completely impractical, each factor is studied separately or in combination with others on as simple a scale as practicable.

The objective of each simulated service test is to determine the ability of analytical methods to predict actual fracture behavior of a flawed structure under known conditions of material properties and loading. In the planned progression of such tests, analytical methods are confirmed, improved, or their limitations revealed. The testing of intermediate vessels, in conjunction with tests of flawed tensile specimens of similar material and smaller flawed models of the intermediate vessels, permits

consideration of many variables. Thus, the intermediate vessel tests are a part of a structural test program that covers ranges of flaw size, section thickness, temperature, and stress state. The effects of differences in transverse restraint, toughness, plastic strain, biaxiality, and stress concentration can be observed and analyzed.

The original objectives emphasized in the simulated service test were (1) to demonstrate capability to predict the "vessel transition temperature" for a selected crack configuration using the material of interest (ASTM A533, grade B, class 1 plate; ASTM A508, class 2 forging); (2) to demonstrate, for the materials of interest, capability to predict various combinations of load (pressure), temperature, and crack configuration in full-thickness vessels that will not cause fracture, and, finally, a combination that will cause fracture for both frangible and tough fracture conditions.

The intermediate vessel tests have been subdivided into four series:

1. flaws in cylindrical vessels, A508, class 2 forging steel—two vessels (vessels V-1 and V-2);
2. flaws in cylindrical vessels with longitudinal submerged-arc weld seams, A508, class 2 forging steel—three vessels (vessels V-3, V-4, and V-6);
3. flaws in cylindrical vessels with longitudinal submerged-arc weld seams, A533, grade B, class 1 plate steel—two vessels (vessels V-7 and V-8);
4. cylindrical vessels with radially attached nozzles, vessels of A508, class 2 forging steel and A533, grade B, class 1 plate steel; nozzles of A508, class 2 forging steel—three vessels (vessels V-5, V-9, and V-10).

The general objectives of the tests performed in each test series, up to and including the test of vessel V-9, are summarized in Table 1.1.

Table 1.1. Objectives of series 1, 2, 3, and 4 of the intermediate test vessel experiments

Test objectives	Series 1		Series 2			Series 3	Series 4	
	V-1	V-2	V-3	V-4	V-6	V-7	V-5	V-9
Demonstrate strength	✓	✓	✓	✓	✓	✓	✓	✓
Test prediction methods	✓	✓	✓	✓	✓	✓	✓	✓
Compare weld metal and base metal			✓	✓	✓			
Determine effects of flaw size					✓	✓		
Compare performance of inside and outside surface flaws					✓			
Observe mode and extent of crack propagation in the dynamic upper-shelf range of temperature					✓	✓	✓	
Observe behavior of flaw in region of stress concentration (nozzle corner)							✓	✓

The report² on the first test series contains a comprehensive description of the pertinent factors considered in the design of the vessels and construction of the test facility and those leading to the tests of series 1, as well as a documentation of test results and fracture predictions. Emphasis is placed on providing the test results in such a manner that they form a resource for any investigators interested in the problems of fracture. The report³ on series 2 tests documents comprehensive information on the characteristics of the three test vessels, their material properties, the conditions of testing, and the results so as to facilitate further analysis. A third report⁴ documents the testing of vessel V-7, which was tested in series 3. Vessel 7 had the same cylindrical geometry as the five vessels of the first two series, but it contained a flaw that was much larger and deeper than those of any other vessel tested. The test was preceded by tests of 1/4-scale steel models of V-7 and by analyses, the results of which, when taken together, indicated that the mode of failure would be the rupture of the thin ligament along the base of the flaw. Vessel V-7 failed as predicted, the test being necessarily terminated by the leakage of the pressurizing fluid. The vessel as a structure and the flaw itself remained stable throughout the test. These reports also describe the use of fracture toughness measurements based on equivalent-energy concepts. These measurements and the investigations of crack growth by tests of both large tensile specimens and model vessels provided the bases for analytical predictions of rupture conditions.

This report covers the testing of intermediate test vessels V-5 and V-9, both of which contained inside nozzle corner flaws about 3.05 cm (1.2 in.) deep. Vessel V-5, which was tested first at 88°C (190°F), was the first intermediate test vessel to develop a leak without a fracture. Vessel V-9 was tested later at 24°C (75°F) in order to develop a fast running fracture from the nozzle corner flaw. Both vessels reached almost identical maximum pressures, corresponding to the onset of through-thickness yielding in the cylindrical region of the vessels. Large plastic strains were measured at the inside nozzle corners opposite both flaws.

Following these tests, a summary report⁵ and a paper⁶ were prepared, describing all the foregoing test results and their significance with respect to reactor pressure vessel safety. Tables 1.2 and 1.3, taken from Refs. 5 and 6, show the test conditions and a comparison of measured and calculated conditions at failure for each vessel. The methods designated in Table 1.3 as LEFM based on strain and plastic instability are described in detail in Refs. 2 through 4.

After the test of vessel V-9, vessel V-7 was retested pneumatically, with the original flaw repaired and a new identical flaw placed in the vessel at a different location. This test, designated as test V-7A,

Table 1.2. Intermediate vessel test conditions^a

Vessel No.	Flaw size (in.)		Test temperature (°F)	K_{IC} , fracture toughness (ksi√in.)	Flaw description	
	<i>a</i>	<i>2b</i>			Location	Material
2	2.53	8.30	32	184	Outside	A508-2
4	3.00	8.25	75	160	Outside	Weld
9	1.20	Nozzle	75	150-275	Inside	A508-2 (nozzle)
1	2.56	8.25	130	311	Outside	A508-2
3	2.11	8.50	130	325	Outside	Weld
6	1.87	5.25	190	369	Outside	Weld
5	1.20	Nozzle	190	241	Inside	A508-2 (nozzle)
7	5.30	18.6	196	301	Outside	A533-B

^aConversion factors: 1 in. = 2.54 cm; °C = $\frac{5}{9}$ (°F - 32); 1 ksi√in. = 1.0988 MN·m^{-3/2}.

Table 1.3. Intermediate vessel test results

Vessel No.	p_f , maximum pressure (ksi) and λ_f , strain (%) at failure	Mode of failure	Calculated results		p_f/p_d , ^b load factor	Remarks ^c
			LE based on strain ^d	Plastic instability		
2	p_f 27.9 λ_f 0.194	Flat	27.4 0.206		2.87	Transition range
4	p_f 26.5 λ_f 0.168	Mixed	26.4 0.163		2.75	
9	p_f 26.9 λ_f 1.05 ^d	Mixed	13.5-18.4 0.070-0.096 ^d		2.77	
1	p_f 28.8 λ_f 0.92	Mixed	27.5 0.345	29.9 ^e	2.96	Static upper shelf
3	p_f 31.0 λ_f 1.47	Mixed	27.5 0.398	31.5 ^e	3.19	
6	p_f 31.9 λ_f 2.0	Shear	27.5 0.479	33.7 ^e	3.28	Static and dynamic upper shelf
5	p_f 26.6 λ_f 0.25 ^d	Leak	19.1 0.100 ^d		2.74	
7	p_f 21.4 λ_f 0.12	Leak	20.8 0.109	19.1	2.20	

^aLinear elastic fracture mechanics.^b p_d , design pressure = 9.71 ksi.^cConversion factor: 1 ksi = 6.8948 MPa.^dOutside circumferential strain 180° from nozzle.^eAssuming 15% stable crack growth as suggested in Ref. 2.

provided experimental results virtually identical to those obtained from vessel V-7, except for the maintenance of pressure following leakage from the flaw. This test is described in a forthcoming report.

As described in Chapter 5 of this report, the results of fracture tests in the elastic range of small epoxy models of the intermediate test vessels with flawed nozzles^a provided data that were an indispensable part of the pretest fracture analyses for vessels V-5 and V-9. Testing of small-scale steel models also continued to provide useful pretest information. All the test results obtained from the small-scale steel models of the intermediate test vessels are summarized in tabular form in Ref. 9.

All the intermediate test vessels were loaded by internal pressure. Thermal shock tests on thick-walled steel cylinders containing continuous and finite-length sharp inside surface flaws have also been conducted in the HSST program. The first two of these tests are described in Ref. 10. Taken as a whole, the tests described above provide a quantitative basis for developing and evaluating methods of fracture safety analysis for reactor pressure vessels under a wide range of geometric, material, and loading conditions.

REFERENCES

1. *Nucleonics* 24(1), 17-18 (January 1966).
2. R. W. Derby et al., *Test of 6-in.-thick Pressure Vessels. Series I: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).

3. R. H. Bryan et al., *Test of 6-in.-thick Pressure Vessels. Series 2: Intermediate Test Vessels V-3, V-4, and V-6*, ORNL-5059 (November 1975).
4. J. G. Merkle et al., *Test of 6-in.-thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7*, ORNL NUREG-1 (August 1976).
5. J. G. Merkle, G. D. Whitman, and R. H. Bryan, *An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water-Reactor Pressure Vessel Safety*, ORNL TM-5090 (November 1975).
6. J. G. Merkle, G. D. Whitman, and R. H. Bryan, "Relation of Intermediate-Sized Pressure-Vessel Tests to LWR Safety," *Nucl. Safety* 17(4), 447-63 (July-August 1976).
7. R. H. Bryan, G. C. Smith, and J. G. Merkle, *Test of 6-in.-thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7A*, ORNL NUREG-9 (to be published).
8. R. W. Derby, "Shape Factors for Nozzle Corner Cracks," *Exp. Mech.* 12(12), 580-84 (December 1972).
9. G. D. Whitman, *Quart. Prog. Rep. on Reactor Safety Programs Sponsored by the NRC Division of Reactor Safety Research for April-June 1975*, ORNL TM-5021, Vol. II (September 1975).
10. R. D. Cheverton, *Pressure Vessel Fracture Studies Pertaining to a PWR LOC-A-ECC Thermal Shock: Experiments TSE-1 and TSE-2*, ORNL NUREG TM-31 (September 1976).

2. Description of Vessels

DESIGN PROCUREMENT AND FABRICATION

The intermediate test vessels were procured under two separate contracts with the Taylor Forge Division of the Gulf and Western Products Company. Vessel V-5 was procured under the first contract, along with vessels V-1 through V-6, and it was the only vessel in the first group fabricated to have a radial nozzle in the cylindrical shell.

Vessels V-9 and V-10, which were procured in the second group of vessels designated V-7 through V-10 under the second contract, were also designed and fabricated with a radial nozzle configuration geometrically identical to the earlier vessel V-5. Other than logistics and legal requirements, the feature that distinguished the first from the second group of vessels was the utilization of ASTM A508, class 2 forging material for the cylindrical shells of the first group and ASTM A533, grade B, class 1 plate material for the cylindrical shells of the second group. Configuration, material, and fabrication requirements for the two groups of vessels were otherwise identical. All three nozzles were fabricated from ASTM A508, class 2 forging steel. The objectives sought in the design of both groups of vessels included (1) a cylindrical shell thickness comparable to that of light-water reactor (LWR) vessels; (2) special head and closure designs to give reasonable assurance that these components would not fail prior to rupture due to a sharp test flaw intentionally placed in the cylindrical shell or, in the case of vessels V-5, V-9, and V-10, in the shell-nozzle intersection region; and (3) achievement of economy by competitive lump-sum bidding.

The general physical features of vessels V-5, V-9, and V-10 are shown in Fig. 2.1. Machined dimensions of the nozzles for vessels V-5, V-9, and V-10 prior to welding into the cylindrical shell are shown in Fig. 2.2.

Design and procurement activities for vessels V-1 through V-10 were described in detail in Refs. 1 through 3; hence, only the principal features of these activities, as they apply to vessels V-5 and V-9, are summarized here.

The radial nozzle configuration for vessels V-5, V-9, and V-10 was chosen, on the basis of judgment, to provide a representative situation with respect to the interaction of a flaw with a complex stress state. At the time the first intermediate test vessel contract was let, existing and planned LWR pressure vessels were being designed with nozzles having D_m/d ratios (ratios of shell mean diameter to nozzle inside diameter) varying from 3 to 6. A D_m/d ratio of 4 was therefore selected for intermediate test vessels V-5, V-9, and V-10. In addition, the dimensions governing reinforcement, inside nozzle corner radius, and outside fillet radius were chosen near the midrange of the values permitted by paragraph N-462 of Section III of the 1968 ASME Code. Since LWR pressure vessel nozzle corners typically have stress concentration factors of about 2.8, an experimental study by Derby⁴ and an analytical study by Krishnamurthy⁵ were performed to determine if this design objective had been met. These studies both indicated a stress concentration factor of approximately 3.0 for the chosen nozzle design.¹ The configuration selected was therefore considered to be adequately representative of LWR vessel nozzles. The experimental data obtained from vessels V-5 and V-9 subsequently provided valuable additional information about the stress concentration factor of the nozzles, as discussed in Chapter 5.

In the procurement of the first six vessels, the vendor, Taylor Forge Division of Gulf and Western Products Co., was permitted, for economy, the option of utilizing either ASTM A508, class 2 forgings or ASTM A533, grade B, class 1 steel plate in the fabrication of the cylindrical shells. Also, under this purchase order an option was requested to permit procurement of four extra hemispherical head and

Fig. 2.1. Intermediate test vessel with 22.86-cm-ID (9-in.) test nozzle (1 in. = 2.54 cm).

access closure subassemblies. By this option, four head subassemblies were obtained that subsequently, under the second purchase order, became component parts of vessels V-7 through V-10. In the purchase order for vessels V-7 through V-10, only plate material conforming to ASTM A533, grade B, class I was permitted in the fabrication of the cylindrical shells in order to obtain data for both forging and plate forms that comprise the reference materials for the current generation of LWR vessels. The second purchase order further provided that the shell courses could be made by using either one or two longitudinal submerged-arc welds and one or two shell segments per vessel. The vendor elected to make the shell courses for each vessel from a single shell segment with a single longitudinal weld seam.

Fig. 2.2. Nozzle for vessels V-5, V-9, and V-10 (1 in. = 2.54 cm).

Taylor Forge sublet the fabrication of the radial nozzle for vessel V-5 to Lenape Forge Co. and the nozzles for vessels V-9 and V-10 to the Midvale Heppenstall Co. None of the work performed by the nozzle subcontractors was audited by ORNL because of temporary funding shortages.^{2,3}

The nozzle vendors reported the following results of chemical analyses of the nozzles for vessels V-5, V-9, and V-10:

Vessel No.	Forging No.	Test No.	Composition (wt %)										Grain size
			C	Mn	P	S	Si	Cr	Ni	Mo	V	Cu	
V-5	R837G	Q2Q23W	0.19	0.73	0.008	0.014	0.21	0.26	0.78	0.69	0.04		Ladle 10
			0.207	0.72	0.005	0.017	0.23	0.26	0.86	0.65	0.05		Check 10
V-9 & V-10		BV3778	0.18	0.66	0.009	0.009	0.22	0.35	0.76	0.64	0.01	0.15	

As reported by Lenape, the nozzle for vessel V-5 was forged, bored slightly undersize as shown in Fig. 2.3, and heat treated by normalizing, austenitizing, quenching, and tempering. Specifically, the

Fig. 2.3. Location of test specimens from nozzle forging for vessel V-5.

forging was heat treated as follows:

Normalized at $889 \pm 14^\circ\text{C}$ ($1650 \pm 25^\circ\text{F}$) for 7 hr and air cooled.

Austenitized at $889 \pm 14^\circ\text{C}$ ($1650 \pm 25^\circ\text{F}$) for 7 hr and water quenched.

Tempered at $717 \pm 14^\circ\text{C}$ ($1290 \pm 25^\circ\text{F}$) for 7 hr and air cooled.

The test material was stress relieved by heating from 333°C (600°F) at a rate of about 39°C/hr (70°F/hr) maximum to $625 \pm 14^\circ\text{C}$ ($1125 \pm 25^\circ\text{F}$) and holding for 30 hr. The material was control-cooled to 333°C (600°F) at about 47°C/hr (85°F/hr) and then cooled to ambient temperature in air.

According to Midvale-Heppenstall, the following fabrication procedures were used to make the nozzles for vessels V-9 and V-10:

1. The original blank was forged into a single 58.10-cm-diam ($22\frac{7}{8}$ -in.) by 211.46-cm-long ($83\frac{1}{2}$ -in.) piece. This forging was then cut into two pieces, one 102.87 cm ($40\frac{1}{2}$ in.) long and the other 69.85 cm ($27\frac{1}{2}$ in.) long. [Note that this accounts for only 172.72 cm (68 in.)—approximately 38.1 cm (15 in.) is unaccounted for.]

2. Each nozzle forging was machined prior to heat treatment. The ID bore and the OD were 21.59 cm ($8\frac{1}{2}$ in.) and 55.88 cm (22 in.), respectively, when heat treating was done. After heat treating, a solid 15.24-cm-long (6-in.) by 55.88-cm-diam (22-in.) buffer was removed from the top (opposite the bored end) prior to obtaining material for Charpy testing.

3. Figure 2.4 shows the nozzle forging from which the test specimens were taken. The Charpy V (C_v) test blanks were oriented in the axial direction. The test material was removed from the $\frac{1}{4}T$ location of the 15.24-cm-thick (6 in.) nozzle wall.

The results of the vendors' room-temperature tensile tests and Charpy V-notch impact tests for the nozzle forgings for vessels V-5, V-9, and V-10 are given in Tables 2.1 and 2.2, respectively.

Taylor Forge qualified three welding procedures for the intermediate vessels: (1) WP-379, an all-submerged-arc procedure for welding longitudinal seams; (2) WP-380, a combination submerged-arc and shielded-metal-arc procedure for welding circumferential seams; and (3) WP-381, an all shielded-metal-arc procedure for attaching the nozzles and for repair welding. Joint preparations for these three procedures are shown in Fig. 2.5. The vendor's data on the room-temperature tensile tests and Charpy V-notch impact tests for these weld qualifications are given in Table 2.3. After fabrication, Taylor Forge hydrostatically tested vessel V-5 to a pressure of 86.19 MPa (12,500 psi). Because of the need to

Table 2.1. Vendors' results of room-temperature tensile tests^a

Vessel No.	Ultimate tensile strength (psi)	Yield strength (psi)	Reduction in area (%)	Elongation (%)
V-5	90,875	70,750	56.9	24.0
	84,270	64,792	60.6	23.5
V-9	90,000	69,000	72.3	27.0
	91,000	72,000	71.9	27.0

^aConversion factor: 1 psi = 6895 Pa.

Fig. 2.4. Location of vendor's test specimens from nozzle forging for vessels V-9 and V-10 (1 in. = 2.54 cm).

Table 2.2. Vendors' results of Charpy V tests^a

Vessel No.	Orientation ^b	Test temperature [°C (°F)]	Charpy V impact energy (ft-lb)	Fracture appearance, shear, %	Lateral expansion (in.)
V-5	C	-12.2 (10)	52	50	0.045
	C	-12.2 (10)	44	50	0.039
	C	-12.2 (10)	41	40	0.036
	C	-12.2 (10)	47	50	0.040
	C	-12.2 (10)	41	40	0.039
	C	-12.2 (10)	29	30	0.029
V-9	L	-12.2 (10)	49	16	0.017
	L	-12.2 (10)	77	33	0.025
	L	-12.2 (10)	50	15	0.018
	L	-12.2 (10)	30	10	0.013
	L	RT RT	126	65	
	L	RT RT	127	65	

^aConversion factors: 1 ft-lb = 1.356 J; 1 in. = 25.4 mm.

^bL = longitudinal; C = circumferential.

Fig. 2.5. Joint preparations for Taylor Forge welding procedures (1 in. = 2.54 cm).

Table 2.3. Vonder's tensile and impact properties^a of weld qualification pieces of vessels V-5, V-9, and V-10

Location ^b	Tensile strength (ksi)	Yield strength (ksi)	Reduction in area (%)	Elongation (%)	C _v impact energy at -12.2°C (+10°F) (ft-lb)	Percent ductile fracture	Lateral expansion (mils)
WP-379							
Weld, $\frac{1}{8}$ T	85	71.5	62.5	28			
Base metal, $\frac{1}{8}$ T					36-40-45	30-40-40	25-28-34
HAZ, $\frac{1}{8}$ T					43-47-49	50-50-50	34-41-38
Weld, $\frac{1}{8}$ T					90-96-97	80-80-80	66-57-70
Weld, $\frac{1}{8}$ in. from bottom surface					77-84-74	80-95-80	53-53-52
WP-382							
Weld, $\frac{1}{8}$ T	81.5	69.4	64.9	28			
Base metal, $\frac{1}{8}$ T					37-55-40	21-25-25	29-41-46
HAZ, $\frac{1}{8}$ T					48-57-62	41-40-50	40-45-49
Weld, $\frac{1}{8}$ T					87-92-92	90-80-70	66-63-68
Weld, $\frac{1}{8}$ in. from top surface					84-91-95	80-80-80	66-73-74
WP-381							
Weld, $\frac{1}{8}$ T	95.3	84.8	70.8	29			
Base metal, $\frac{1}{8}$ T					78-78-68	40-40-40	56-56-51
HAZ, $\frac{1}{8}$ T					86-96-128	60-60-90	62-75-64
Weld, $\frac{1}{8}$ T					75-73-85	70-70-80	60-57-65
Weld, $\frac{1}{8}$ in. from bottom surface					76-72-70	80-80-80	65-62-61

^aConversion factors: 1 ksi = 6.895 MPa, 1 ft-lb = 1.356 J, 1 in. = 25.4 mm, 1 mil = 0.0254 mm.

^b $\frac{1}{8}$ T means a distance equal to $\frac{1}{8}$ of the thickness measured from the top surface. Other values (e.g., $\frac{1}{8}$ T) have the same basis (HAZ = heat-affected zone; C_v = Charpy V).

repair a rejectable flaw that was discovered after the hydrotest, vessel V-5 received two subsequent stress-relief heat treatments at 621°C (1150°F) for a total of 12 hr after hydrotesting. Vessel V-9 was hydrotested after fabrication to a pressure of 82.74 MPa (12,000 psi). No repairs or heat treatments were applied to vessel V-9 after hydrotesting. Other fabrication and inspection information is given in Refs. 2 and 3.

MATERIALS CHARACTERISTICS

The prolongations from the nozzles of vessels V-5 and V-9 were subdivided by Stelzman of ORNL⁸ to obtain test specimens for determining tensile, Charpy V-notch impact, and lower-bound fracture toughness data, and by Mager et al. of Westinghouse Electric Corp.⁹⁻¹¹ to obtain static and dynamic fracture toughness data. These data were used for estimating fracture criteria and for predicting failure conditions prior to rupturing the vessel as had been done for the previous tests. These estimates are described in detail in Chapter 5. The ORNL tensile and Charpy V-notch specimens were taken from locations in the prolongations corresponding to locations of interest in the nozzles, using the orientations defined in Fig. 2.6. The detailed cutting plans for the ORNL specimens taken from the nozzle forging prolongations are given in Table A.1 for vessel V-5 and in Table A.2 for vessel V-9.

Due to an oversight by the vendor, the prolongation test disk for vessel V-5 shown in Fig. 2.3 was not shipped with the vessel but was mistakenly machined for other purposes to form a punch. Figure 2.7 shows the skewed doughnut shape of the prolongation as machined to form the punch and as finally received by ORNL. Also shown in Fig. 2.7 is the assignment of test material from the final shape to Westinghouse and to ORNL.

Fig. 2.6. Specimen orientation notation for HSST intermediate vessel materials showing tensile, Charpy V-notch, and drop-weight specimens.

Fig. 2.7. As-received shape of prolongation of nozzle of vessel V-5 and material assignment.

Tensile and Charpy V-Notch Impact Data

Vessel V-5 nozzle material

Figures 2.8 and 2.9 show the tensile results for vessel V-5 nozzle material obtained at ORNL from C-oriented 0.452-cm-diam (0.178-in.) tensile (MT) specimens tested at a temperature of 93.3°C (200°F) and a strain rate of 0.016 min⁻¹. The axial test results at 14.61 cm (5.75 in.) (0.96T) in the 15.24-cm-thick (6-in.) wall shown in Fig. 2.8 indicate that the yield and ultimate tensile strengths increase along the length of the nozzle in the direction of the vendor's room-temperature specimens and as the end of the forging to be flawed is approached. The radial distribution of strengths indicates that both the yield and ultimate strengths increase from the inner surface to at least the 0.4T position and that the reduction in area appears to reach a maximum at the 1/4T position. The vendor's 24.4°C (75°F) test data listed in Table 2.1 are included in Figs. 2.8 and 2.9, since a scarcity of test specimens prevented a more detailed study. The tensile data obtained by ORNL for the vessel V-5 nozzle material are listed in Table A.4. No Charpy V-notch impact or drop weight data were obtained from the nozzle prolongation for vessel V-5 because of the scarcity of material.

Fig. 2.8. Tensile yield and ultimate stress data for intermediate vessel V-5 nozzle material at 93.3° C (200° F) using C-oriented subsize tensile specimens (1 ksi = 6.895 MPa; 1 in. = 2.54 cm).

Vessel V-9 nozzle material

As shown in Fig. 2.4, the nozzle test prolongation for vessel V-9 came from a less than ideal test location and in a form different from the nozzle cross section. Figure 2.3 shows that the same was true for vessel V-5. The nozzle blank had been rough bored prior to the heat treatment before the final machining and thereby had presented both an inner and outer surface during the quench. At this stage, the prolongation was still attached to the nozzle cylinder in the form of a solid cylinder (a disk after separation) opposite the end to be flawed. Therefore, material that came from a radial position in the disk corresponding to the nozzle inside surface would tend to behave like nozzle midthickness material due to the absence of the inner surface bore. The vendor's test specimens were taken from the nozzle 1/4T position (outer surface = OT) and adjacent to the closed end of the nozzle. Both the vendor's tensile and Charpy V specimens were axially oriented (A and AC), as opposed to the circumferentially oriented (C and CA) specimens tested at ORNL. Two test temperatures were used by the vendor, namely room temperature and 10° F. The vendor's room-temperature results (see Tables 2.1 and 2.2) indicated yield and ultimate strength ranges of 475.7 MPa (69 ksi) to 496.4 MPa (72 ksi) and 620.5 MPa (90 ksi) to 627.4 MPa (91 ksi), and Charpy V energies of 170.8 J (126 ft-lb) to 172.2 J (127 ft-lb). At -12.2° C (10° F), Charpy V values ranged from 40.68 J (30 ft-lb) to 104.4 J (77 ft-lb).

Fig. 2.9. Percent elongation and reduction in area data for intermediate vessel V-5 nozzle material at 93.3°C (200°F) using C-oriented subsize tensile specimens (1 in. = 2.54 cm).

The nozzle prolongation of vessel V-9 was investigated at ORNL both axially along the 10.16-cm (4-in.) length and radially between the radial boundaries of the 15.24-cm (6-in.) nozzle wall. An axial hardness traverse at the 1T depth location indicated no significant axial variation and a Rockwell hardness range of B90 to B92. The axial variations of tensile properties are shown in Fig. 2.10. The increase in the outer surface results (0.04T) suggest that the vendor may have reversed the disk orientation during stamping. The radial variations of tensile properties, shown in Fig. 2.11, indicate high strengths at the outer surface and lower but constant strengths in the central and inner surface regions for reasons previously discussed. Ductility appears to remain constant through the 15.24-cm (6-in.) wall thickness. The slight decrease in elongation near the inner surface location appears to be due to experimental scatter, since no other reason for the deviation is apparent. Comparison with the vendor data indicates that the stress values for both A and C orientations are equivalent but that the total elongation and reduction of area values are higher for the A orientation. The effect of temperature on

Fig. 2.10. Tensile properties of intermediate vessel V-9 nozzle material using circumferentially orientated subsize tensile specimens, ASTM A508, class 2 forging steel [1 ksi = 6.895 MPa; 1 in. = 25.4 mm; °C = $\frac{5}{9}(\text{°F} - 32)$].

Fig. 2.11. Tensile properties of intermediate vessel V-9 nozzle material using circumferential / oriented subsize¹ tensile specimens, ASTM A508, class 2 forging steel [1 ksi = 6.895 MPa; 1 in. = 25.4 mm; °C = $\frac{5}{9}(\text{°F} - 32)$].

the tensile properties is shown in Fig. 2.12. The tensile data obtained at ORNL for the vessel V-9 nozzle material are listed in Table A.5.

The Charpy V impact results from CA and CT* specimens from the nozzle prolongation of vessel V-9 are shown in Figs. 2.13 and 2.14 and are listed in Table 2.4. A comparison with the vendor's results for AC specimens indicates that the upper-shelf values for the AC orientation are higher and that the transition temperature range is the same or lower than for the CA orientation. A comparison of the results of the CT- and CA-oriented tests (see Fig. 2.13) indicates that the fracture resistance is greater for a crack propagating in the through-the-thickness direction than in the axial direction.

*A CT-oriented Charpy V-notch specimen is one having its longitudinal axis aligned in the circumferential (C) direction and in which the notch extends in the thickness (T) direction (see Fig. 2.6). The thickness (T) direction is identical to the radial (R) direction, as shown in Fig. 2.6.

Fig. 2.12. Tensile properties of intermediate vessel V-9 nozzle material using circumferentially oriented subsize tensile specimens, ASTM A508, class 2 forging steel [1 ksi = 6.895 MPa; 1 in. = 25.4 mm; °C = $\frac{1}{2}(\text{°F} - 32)$].

Table 2.4. Charpy V impact properties of intermediate vessel V-9 nozzle material using (CT-oriented specimens from the 0.297 depth location and (CA-oriented specimens from the 0.627 depth location in the 15.24-cm (6-in.) wall thickness of A508, class 2 forging steel

Specimen No.	Specimen orientation	Test temperature (°C) (°F)	Impact energy (J) (ft-lb)	Lateral expansion (mm)
9V-11	CT	65.6 (+150)	98	0.070
9V-23	CT	121.1 (+250)	124	0.071
9V-33	CT	17.8 (60)	36	0.029
9V-45	CT	10 (-50)	94	0.069
9V-56	CT	45.6 (+50)	29	0.022
9V-37	CA	45.6 (+50)	16.5	0.014
9V-05	CA	121.1 (+250)	98	0.064
9V-49	CA	17.8 (60)	47	0.042
9V-66	CA	37.8 (100)	74	0.061
9V-15	CA	10 (-50)	59.5	0.049
9V-27	CA	65.6 (+150)	87	0.066

^aConversion factors: 1 in. = 25.4 mm, 1 ft-lb = 1.3558 J.

Fig. 2.13. Charpy V impact properties of intermediate vessel V-9 nozzle material, 15.24-cm-thick (6-in.) wall, ASTM A508, class 2 forging steel.

Fig. 2.14. Lateral expansion values obtained from Charpy V impact tests on intermediate vessel V-9 nozzle material, 15.24-cm-thick (6-in.) wall, ASTM A508, class 2 forging steel.

Fracture Toughness

Vessel V-5 nozzle material

Data on static lower-bound fracture toughness (K_{Icd}) for vessel V-5 nozzle material from CA- and CT-oriented precracked Charpy V-notch specimens obtained by Stelzman at ORNL are shown in Fig. 2.15. An attempt was made to determine the sensitivity of K_{Icd} to either depth or axial position, but the sampling was insufficient to support any conclusions. It can only be said that between -73.3 and 93.3°C (-100 and 200°F), the K_{Icd} upper shelf is between $159.3\text{ MN}\cdot\text{m}^{-3/2}$ ($145\text{ ksi}\sqrt{\text{in.}}$) and $219.8\text{ MN}\cdot\text{m}^{-3/2}$ ($200\text{ ksi}\sqrt{\text{in.}}$); that the upper shelf begins below -17.8°C (0°F); and that there is no apparent dependence of K_{Icd} on whether the fracture propagates axially (CA) or radially (CT) within the portion of the nozzle forging tested. The static lower-bound fracture toughness data obtained at ORNL for the vessel V-5 nozzle material from precracked Charpy V-notch specimens are listed in Table A.1.

Fig. 2.15. Lower-bound fracture toughness values obtained from intermediate test vessel V-5 nozzle material using CA- and CT-oriented precracked Charpy V-notch specimens [$1\text{ ksi}\sqrt{\text{in.}} = 1.0983\text{ MN}\cdot\text{m}^{-3/2}$; $^\circ\text{C} = \frac{5}{9}(^\circ\text{F} - 32)$].

Westinghouse¹¹ obtained eight specimens from the test prolongation of vessel V-5, including six 0.85T CT and two 2T CT specimens, as shown in Fig. 2.16. All specimens were fatigue precracked according to the methods specified by ASTM.¹² A test temperature of 93.3°C (200°F) was specified in order to maximize the accuracy of the fracture toughness estimate in the upper-shelf temperature range with a minimum number of specimens. The test temperature of 93.3°C (200°F) is within the upper-shelf range, where extremely large specimens would be necessary to perform valid fracture toughness testing according to the ASTM-recommended procedure.¹² For this reason, the equivalent-energy concept^{13,14} was used to interpret the data in terms of lower-bound values of the actual fracture toughness. These data are given in Table 2.5.

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Fig. 2.16. Machining of fracture toughness specimens from the nozzle prolongation of HSST vessel V-5 (1 in. = 2.54 cm).

Table 2.5. Fracture toughness results determined from testing 0.851 and 21 compact tension (CT) specimens from HSS1 vessel V-5 nozzle prolongation^a

Specimen No.	Test temperature [°C (°F)]	Crack length (in.)	Maximum load (lb)	Energy to maximum load (in.-lb)	P_{QY} (lb)	Energy to P_{QY} (in.-lb)	K_{ISCC} (ksi√in.)
21 CT specimens (radial orientation)							
V5-1	93.3 (200)	2.060	84,250	4,278.6	15,000	1,050	240.5
V5-2	93.3 (200)	2.060	84,000	3,880.0	15,000	1,050	233.1
0.8501 CT specimens (radial orientation)							
V5-3	93.3 (200)	0.905	9,200	370.8	2,000	80	150.6
V5-4	93.3 (200)	0.872	10,100	834.2	2,000	80	185.0
V5-5	93.3 (200)	0.850	10,400	763.0	2,000	80	181.4
0.8501 CT specimens (axial orientation)							
V5-6	93.3 (200)	0.882	9,900	611.0	2,000	80	165.5
V5-7	93.3 (200)	0.873	10,450	486.0	2,000	70	214.4
V5-8	93.3 (200)	0.900	9,850	555.7	2,000	80	207.4

^aConversion factors: 1 in. = 25.4 mm; 1 lb = 4.4482 N; 1 ksi√in. = 1,055 MN/m^{3/2}; 1 in.-lb = 0.13558 J; 1 lb_f in. = 0.17513 N·m.

Vessel V-9 nozzle material

The radial distribution of the static fracture toughness, K_{ISCC} , from precracked CV- and CT-oriented Charpy specimens obtained by Stelzman¹ from the vessel V-9 nozzle prolongation is shown in Fig. 2.17. No significant difference in K_{ISCC} level due to orientation or through-the-wall depth at room temperature was noted. The effect of temperature on K_{ISCC} is shown in Fig. 2.18. Again, no significant variation due to CV or CT orientation at in., 0.711 and 0.871 depth locations is seen. Also, based upon the limited data at the 0.041 depth shown in Fig. 2.18, it appears that the static fracture toughness will be on the upper shelf at -17.8°C (0°F) for all depths. The static lower-bound fracture toughness data obtained at ORNL for the vessel V-9 nozzle material from precracked Charpy V-notch specimens are listed in Table A.2.

Stelzman¹ also obtained dynamic lower bound fracture toughness (K_{ISCC}) data for CV- and CT-oriented specimens from the vessel V-9 nozzle prolongation at three depth locations; is shown in Fig. 2.19. The K_{ISCC} transition ranges appear to occur at higher temperatures, and the K_{ISCC} upper-shelf values are higher than for the K_{ISCC} data. The difference in upper-shelf levels between K_{ISCC} and K_{ISCC} may not be as great as shown, since it is anticipated that the K_{ISCC} values will rise significantly, particularly in this region, after a correlation between the load-time and load-detection measurements has been established for the laboratory slow-bend machine. Previous results¹ indicate that the K_{ISCC} upper-shelf values should rise about 54.9 MN/m^{3/2} (50 ksi√in.). The dynamic lower-bound fracture toughness data obtained at ORNL for the vessel V-9 nozzle material from precracked Charpy V-notch specimens are listed in Table A.3.

Fig. 2.17. Lower-bound static fracture toughness values obtained from intermediate test vessel V-9 nozzle material using CA- and CT-oriented precracked Charpy V specimens, ASTM A508, class 2 forging steel [1 in. = 25.4 mm; $1 \text{ ksi} \sqrt{\text{in.}} = 1.0988 \text{ MN} \cdot \text{m}^{-1/2}$; $^{\circ}\text{C} = \frac{1}{2} (^{\circ}\text{F} - 32)$].

Fig. 2.18. Lower-bound static fracture toughness values obtained from intermediate test vessel V-9 nozzle material using CA- and CT-oriented precracked Charpy V specimens, ASTM A508, class 2 forging steel [1 in. = 25.4 mm; $1 \text{ ksi} \sqrt{\text{in.}} = 1.0988 \text{ MN} \cdot \text{m}^{-1/2}$; $^{\circ}\text{C} = \frac{1}{2} (^{\circ}\text{F} - 32)$].

Fig. 2.19. Lower-bound static and dynamic fracture toughness values obtained from intermediate test vessel V-9 nozzle material, 15.24-cm-thick (6-in.) wall, ASTM A508, class 2 forging steel [1 in. = 2.54 cm; 1 $\text{ksi}\sqrt{\text{in.}}$ = 1.0968 $\text{MN}\cdot\text{m}^{-3/2}$; $^{\circ}\text{C} = \frac{5}{9}(^{\circ}\text{F} - 32)$].

Westinghouse^{10,11} machined 25 compact tension specimens from selected locations (surface and center regions) in the nozzle prolongation from intermediate vessel V-9. After machining, the twenty-one 0.85T CT, two 1.5T CT, and two 2T CT specimens were precracked according to the methods specified by ASTM.¹² Testing temperatures encompassed the range from -31.7 to 37.8°C (-25 to $+100^{\circ}\text{F}$). The equivalent-energy concept^{13,14} was used to interpret the data in terms of lower-bound values of the actual toughness. The fracture toughness data for the nozzle prolongation material from intermediate pressure vessel V-9 are given in Table 2.6.

A combined plot of the static and dynamic toughness K_{Icd} values measured for the vessel V-9 nozzle material at ORNL and at Westinghouse is shown in Fig. 2.20.

Table 2.6. Fracture toughness results determined from testing 2T, 1.5T, and 0.85T compact tension specimens from vessel V-9 nozzle prolongation^a

Specimen No.	Specimen size (in.)	Test temperature [°C (°F)]	Crack length (in.)	Maximum load (lb)	Energy to maximum load (in.-lb)	P_Q (lb)	Energy to P_Q (in.-lb)	$K_{Ic,d}$ (ksi $\sqrt{\text{in.}}$)
Inner-row specimens (crack root corresponds to the inside surface of the nozzle)								
Surface								
V9A-1	2T	23.9 (75)	2.053	60,500	5,574.3	10,000	47.5	271.0
V9A-2	2T	23.9 (75)	2.060	51,500	1,658.0	10,000	50.0	144.6
V9A-19	0.85T	10 (50)	0.833	11,050	433.4	3,500	21.0	134.0
V9A-21	0.85T	10 (50)	0.860	12,050	783.1	4,000	27.0	190.0
Center region								
V9A-4	1.5T	23.9 (75)	1.577	32,900	1,739.0	7,000	35.0	197.3
V9A-3	1.5T	23.9 (75)	1.570	32,000	1,774.0	7,000	35.0	198.0
V9A-20	0.85T	23.9 (75)	0.857	11,500	967.0	3,500	22.0	204.0
V9A-22	0.85T	23.9 (75)	0.877	10,800	512.1	2,500	11.2	153.3
Middle-row specimens (crack root perpendicular to the inside surface of the nozzle)								
V9A-23	0.85T	23.9 (75)	0.890	11,150	1,049.0	2,000	7.5	220.3
V9A-25	0.85T	23.9 (75)	0.892	11,150	993.6	2,000	7.0	222.6
V9A-24	0.85T	23.9 (75)	0.900	10,950	1,119.0	1,500	4.1	234.5
Outside-row specimens								
Surface								
V9A-5	0.85T	45.6 (110)	0.892	11,300	427.2	3,500	21.0	147.4
V9A-7	0.85T	31.7 (90)	0.868	11,950	728.2	3,500	22.0	151.0
V9A-9	0.85T	17.8 (65)	0.860	11,200	514.0	3,500	23.6	144.0
V9A-11	0.85T	17.8 (65)	0.893	11,600	872.0	3,500	16.0	209.2
V9A-13	0.85T	3.9 (35)	0.862	11,500	806.5	4,000	29.6	185.0
V9A-15	0.85T	10 (50)	0.853	11,900	993.1	3,500	22.0	205.5
V9A-17	0.85T	37.8 (100)	0.867	11,100	831.0	2,000	7.5	188.0
Center region								
V9A-6	0.85T	45.6 (110)	0.867	11,700	661.0	3,000	15.0	178.0
V9A-8	0.85T	31.7 (90)	0.893	8,200	128.0	2,000	7.0	80.1
V9A-12	0.85T	3.9 (35)	0.882	11,600	1,087.0	3,000	16.0	228.5
V9A-16	0.85T	10 (50)	0.850	11,800	517.0	3,500	21.0	150.4
V9A-14	0.85T	23.9 (75)	0.852	11,600	650.4	4,000	28.0	167.5
V9A-10	0.85T	23.9 (75)	0.873	11,250	1,059.6	3,000	16.5	217.1
V9A-18	0.85T	37.8 (100)	0.885	11,200	864.0	4,000	29.0	201.5

^aConversion factors: 1 in. = 25.4 mm; 1 lbf = 4.4482 N; 1 ksi $\sqrt{\text{in.}}$ = 1.0388 MN $\text{m}^{-3/2}$; 1 ft-lb = 1.3558 J; 1 lbf/in. = 0.17513 N/mm.

Fig. 2.20. Static and dynamic K_{IC} values for vessel V-9 nozzle material [1 in. = 2.54 cm; 1 ksi $\sqrt{\text{in.}}$ = 1.0988 MN $\text{m}^{-1/2}$; $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$].

REFERENCES

1. R. W. Derby et al., *Test of 6-in.-thick Pressure Vessels. Series I: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).
2. C. E. Childress, *Fabrication and Mechanical Test Data for Acceptance of the First Six 6-in.-thick Intermediate Test Vessels of the Heavy-Section Steel Technology Program*, ORNL/TM-4351 (October 1973).
3. C. E. Childress, *Fabrication and Mechanical Test Data for the Four 6-in.-thick Intermediate Test Vessels Made from Steel Plate for the Heavy-Section Steel Technology Program*, ORNL/TM-5074 (January 1976).
4. R. W. Derby, "Shape Factors for Nozzle Corner Cracks," *Exp. Mech.* 12(12), 580-84 (December 1972).
5. N. Krishnamurthy, *Three-Dimensional Finite Element Analysis of Thick-Walled Vessel-Nozzle Junctions With Curved Transitions*, ORNL/TM-3315 (Mar. 24, 1971).
6. W. J. Stelznan, "Characterization of Intermediate Test Vessel Materials," *HSST Program, Semiannual Prog. Rep. Aug. 31, 1973*, ORNL-4971, pp. 66-70.
7. W. J. Stelznan, "Characterization of Intermediate Test Vessels," *Quart. Prog. Rep. Reactor Safety Programs Sponsored by the Division of Reactor Safety Research for April-June 1974*, ORNL/TM-4655, Vol. II, pp. 56-66.
8. W. J. Stelznan, "Characterization of Intermediate Test Vessels," *Quart. Prog. Rep. Reactor Safety Programs Sponsored by the Division of Reactor Safety Research for July-September 1974*, ORNL/TM-4729, Vol. II, pp. 51-52.
9. T. R. Mager et al., "Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Materials," *HSST Program Semiannual Prog. Rep. Aug. 31, 1973*, ORNL-4971, pp. 74-80.
10. T. R. Mager et al., "Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material," *Quart. Prog. Rep. Reactor Safety Programs Sponsored by the Division of Reactor Safety Research for April-June 1974*, ORNL/TM-4655, Vol. II, pp. 66-69.
11. T. R. Mager et al., *Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material*, HSSTP-TR-38 (WCAP-8456), Westinghouse Electric Corp., Pittsburgh, Pa. (December 1974).
12. *Tentative Method of Test for Plane-Strain Fracture Toughness of Metallic Materials*, ASTM E399-70T, American Society for Testing and Materials, 1970.
13. F. J. Witt, *A Procedure for Determining Bounding Values on Fracture Toughness K_{Ic} at Any Temperature*, Paper 13, HSST 5th Annual Information Meeting, Oak Ridge National Laboratory, March 1971.
14. F. J. Witt and T. R. Mager, *A Procedure for Determining Bounding Values on Fracture Toughness K_{Ic} at Any Temperature*, ORNL/TM-3894 (October 1972).
15. R. G. Berggren and W. J. Stelznan, "Notch-Bend Properties of Irradiated Steels," *Quart. Prog. Rep. Reactor Safety Programs Sponsored by the Division of Reactor Safety Research for April-June 1974*, ORNL/TM-4655, Vol. II, pp. 42-49.

3. Flaw Preparation

BACKGROUND

The basic shape of an experimental flaw must be produced by machining. Thereafter, specific procedures must be developed and perfected for sharpening the flaw. The first two HSST program intermediate tensile specimens had semielliptical notches that were machined using the electrical discharge machining (EDM) process. Attempts were first made to develop a stress corrosion procedure to initiate sharp cracks at the root of an EDM notch. Procedures involving maintaining the specimen at 121°C (250°F) under a static tensile load and pouring ammonium nitrate (NH_4NO_3) into the notch were investigated. However, tests of compact tension specimens with notches sharpened by this process indicated that the static load required to generate the crack was too great; that is, yielding at the tip of the crack at the temperature at which the crack was generated affected the load required to cause specimen failure in the transition temperature range and lower. Therefore, the first two intermediate tensile specimens were tested with unsharpened notches. The next two specimens were tested with cracks successfully sharpened by bending fatigue; this procedure, however, could not be applied to surface cracks in test pressure vessels.¹

We next investigated a method of sharpening a premachined part-circular notch cavity with high, locally applied cyclic pressure.² The notch was filled with hydraulic oil, and the opening was sealed with a rubber O-ring and a clamp plate, as shown in Fig. 3.1. The notch cavity was then connected to a pumping system and subjected to cyclic loading. In effect, the hydraulic oil acts like a wedge that is continually pushed into the notch and then removed. This system was successfully employed to grow sharp elliptically shaped crack fronts by fatigue in the intermediate tensile specimens, as illustrated in Fig. 3.2. Following the successful application of fatigue crack sharpening by cyclic notch pressure to the

Fig. 3.1. Sealing and clamping arrangement for local fatigue device (1 in. = 2.54 cm).

Fig. 3.2. Fatigue sharpened crack front in an intermediate tensile specimen.

remaining intermediate tensile specimens, the same procedure was successfully applied to the sharpening of external surface cracks in the first five intermediate test vessels.³⁴ For the sharpening of an inside surface flaw, the first of which was placed in vessel V-6, it was found necessary to replace the clamped-on seal block with a welded-on seal block.³⁵ The same cyclic pumping system, known as a "pump-dump" system, was used for both methods of notch sealing. This system is illustrated in Fig. 3.3, and a detailed description and operating instructions for the pump-dump system are given in Appendix E.

The successful sharpening of a flaw on the interior wall of vessel V-6 provided the basic background information required to guide the development of procedures for growing the inside nozzle corner flaws in vessels V-5 and V-9, using welded-on inside nozzle corner seal blocks. However, the task of developing a reliable procedure for growing an interior nozzle corner flaw presented considerable additional mechanical, welding, detection, and pumping problems. A number of inside nozzle corner mockups were built and employed to develop and test sawing methods, weld boss configuration, weld penetration for adequate weld attachment, and high-pressure pump-fatiguing and ultrasonic depth-testing techniques, and to develop operational and test procedure standards for the work. Quality assurance and quality control procedures were developed and utilized for all the tasks. The following specific procedure standards were issued:

Code 10563 HSST Program, IVT Crack Preparation Facilities

- A. Test Procedure Safety Equipment Mobility Test
- B. Welder Qualification Test for Interior Nozzle Corner Weld-On Bosses
- C. Verification Test for Preheating Procedure
- D. Welding Procedure for Interior Nozzle Corner Weld-On Bosses
- E. Sealing Procedure for Interior Nozzle Corner Weld-On Bosses
- F. Preparations for Mounting Transducers for Nozzle Corner Ultrasonic Monitoring

High-pressure pump-fatiguing tasks were performed in accordance with the pump operating instructions given in Appendix E.

VESSEL SUPPORT STAND AND EQUIPMENT

Welding and instrumentation work inside the vessels was facilitated by the vessel support stand and elevator lift, both of which are shown in Fig. 3.4. A number of safety precautions were incorporated into this facility to ensure safe entry into the vessel by a welder fully clothed with a heat-resistant, flameproof suit and attached wristlets, as shown in Figs. 3.5 and 3.6. Other special precautions included the elimination of any electrical shock hazards from the vessel, supporting structure, and protective clothing; two-way phone communications; continuous monitoring by personnel stationed specifically for that purpose; protected insulated nylon rope for wristlets to retain the welder's hands vertically upward to permit rapid assisted evacuation, if required; nonhazardous internal tank lighting; and controlled air circulation in the vessel to prevent asphyxiation.

NOTCH SAWING TEMPLATE AND WELD BOSS DESIGN

Figure 3.7 shows the final notch sawing template and weld boss pieces. The slitting fixture was contoured to match the nozzle curvature and was then tack welded to the nozzle corner to guide a 0.65-mm-thick (25-mil) sawblade for a slot about 20 mm (0.80 in.) deep at the center of the slot. A template

Fig. 3.3. Cyclic pressure pumping system for notch sharpening by fatigue; shown for inside surface flaw sharpening in a vessel cylinder; similar arrangement used for inside nozzle corner flaws (1 psi = 6895 Pa).

Fig. 3.4. Vessel support stand and elevator lift.

Fig. 3.5. Worker enters vessel V-5.

Fig. 38. Welder entering vessel.

PHOTO 4297-73

Fig. 3.7. Weld boss and sawing template fixtures used in preparing and sharpening the flaws in intermediate test vessels V-5 and V-9.

was then fitted to the presawed area for trimming five 0.13-mm (5-mil) stainless steel shim inserts, which were then placed in the notch to reduce oil volume before aligning the weld boss cover. Tabs placed beforehand on the shims served to properly align the weld boss over the slot, while interior fixturing supported the boss for weld tacking and root-pass operations.

ASTM A533, grade B, class 1 plate was selected for the weld boss material to match the vessel steel and the vessel manufacturer's weld electrode selection (E8018) used for welding the nozzle forgings to the vessels. Care was taken to retain planar coordinates for the weld block orientation to match that of the vessel wall.

Development trials indicated the need for considerable weld penetration for the weld-boss-to-nozzle attachment in order to ensure fatigue crack growth in the plane of and beyond the sawed slot rather than through the outer edges of the weld joint. Figure 3.8 represents the final cross section of the flaws grown in the nozzle corners of both vessels V-5 and V-9. Both vessel flaws appeared to be generally similar, of nonuniform or irregular depth, and with nearly identical amounts of visible fatigue crack growth on the inside surfaces of the nozzle and vessel. The 11.7-mm (0.45-in.) fatigue crack growth dimension shown in Fig. 3.8 is based on posttest measurements; the other dimensions shown in the figure are pretest estimates. For a visible external fatigue crack of approximately 16.5 mm (0.65 in.) on the horizontal and vertical surfaces of the inside nozzle, or approximately 11.7 mm (0.46 in.) in the plane of the sawed nozzle slot, boss blocks beveled for welding to provide double those distances for weld deposit fill proved adequate. In earlier trials with separate pump oil inlet and outlet connectors, fabricated from bar-shaped stock and with single-unit dual-connector weld boss units of smaller size, oil cracks developed through the weld metal edges before we were able to achieve the desired "pumped-flaw" depth.

Four weepholes were precision machined into each weld boss block, as shown in Figs. 3.9 and 3.10, to establish a leak passage for the pumped oil when the fatigue crack had grown to a length of approximately 12.7 mm ($\frac{1}{2}$ in.) beyond the bottom of the presawed notch in the vicinity of the notch midpoint. The weld boss holes served as fixtures for aligning and guiding the drilling of the weephole passage extensions into the nozzle. For each vessel, two holes were drilled until the hole intercept depth was reached. Four holes were available in the weld boss (see Fig. 3.10) in case drills should break, but these holes provided only questionable fatigued flaw-depth confirmations. Oil traces were noted, in the case of vessel V-5, at an actual fatigue crack depth, observed later, that was slightly less than the originally intended 12.7 mm (0.5 in.) at the notch midpoint shown in Fig. 3.10. Oil leaked from one of the monitor holes in vessel V-9 shortly after pumping was started, and the monitor passage had to be plug-welded to seal off a crack that had grown from near the invert of the weld boss oil inlet connection into the weephole passage. The entire crack was found to have formed within the weld boss block, external to the boss-to-nozzle weld. Therefore, depth estimates of nozzle corner flaws had to be based upon ultrasonic measurements made from the outside surface of the nozzle, directly opposite the crack.

The cyclic loading applied to the notches was about 172 MPa (25,000 psi) oil pressure for approximately 225,000 cycles, each cycle requiring four pump strokes. Under ideal operating conditions, the system can average about 50 to 52 cycles per hour.

WELD BOSS INSTALLATION AND REMOVAL

Welder qualification certifications were held on mockups to prepare the welder for working in the special clothing within confined spaces and to demonstrate that all required welding operations could be performed.

Fig. 3.8. Cross section of inside nozzle corners showing flaws in intermediate test vessels V-5 and V-9 (1 in. = 25.4 mm).

Fig. 3.10. Weephole design used for weld bosses in intermediate test vessels V-3 and V-9 (1 in. = 25.4 mm).

PHOTO 4000-74

Fig. 3.11. Mirror view of weld boss with pumping attachment for flaw sharpening on intermediate test vessel V-5.

Local preheating of the weld boss and the adjacent nozzle and vessel walls controlled boss and wall temperatures for the boss weld-on process to within a range of 177°C (350°F) to 288°C (550°F). Vessel surface temperatures were also monitored and controlled not to exceed 316°C (600°F). Electrical Calrod heating, occasionally supplemented by manual torch flame heating to the vessel's exterior surface, was used along with an insulation blanket liner within the vessel. The preheat was controlled and monitored via thermocouples. Postwelding temperature was maintained between 323°C (450°F) and 288°C (550°F) for 2 hr and gradually reduced thereafter. E-8018 filler rod was used for the root pass, which was made by the gas-tungsten arc process with a specially shaped torch tip to reach the entire periphery of the pass. The vessels were allowed to cool down for liquid dye-penetrant testing of the root passes before proceeding with renewed preheat and additional gas-tungsten arc passes and finally with manual metal arc passes using E-8018 weld wire specifically procured for this purpose. Interpass temperature was controlled to 288°C (550°F). The completed welds were again checked with liquid dye-penetrant. Figure 3.11 shows the completed vessel V-5 weld boss and cyclic pressure connection, which was photographed with the aid of a mirror in the vessel.

Flame-cutting techniques were used for the removal of the weld bosses from the vessel interiors. Oxyacetylene torch gouging followed "crack-sharpening" operations, with the vessels placed horizontally and preheated locally by torch to about 177°C (350°F). The flame-cut surfaces were kept a minimum of 3.2 mm ($\frac{1}{8}$ in.) from the inside surfaces of the vessel. The remainder of the protruding metal was then removed by hand grinding to 6.35×10^{-3} mm (250- μ in.) finishes in order to have the finished surfaces conform to within 1.6 mm ($\frac{1}{16}$ in.) of the true position of the inside surface.

ULTRASONIC TRANSDUCER MOUNTING

Shallow weld pads were joined to the circular external nozzle fillet contour of both vessels V-5 and V-9 to provide a plane perpendicular to the plane of the flaw and parallel to the root of the sawcut. Each pad served as a base for a sleeve that positioned and housed an ultrasonic transducer, as shown in Fig. 4.10 for vessel V-9, during the pretest stages of installation at the K-25 facility test cell. The transducer crystals transmitted information on the depth of the flaw center during flaw pump cycling operations and served to terminate pumping upon reaching an approximately 30.5 mm (1.2 in.) center flaw depth, or about 10.2 mm (0.4 in.) growth in depth beyond the sawcut. Actual posttest measurements at the exact flaw center indicated slightly lesser depths [about 7.6 mm (0.3 in.)] but showed an irregular fatigue flaw depth contour to establish 30.5 mm (1.2 in.) as the average center depth. Fig. 4.10 also shows some of the acoustic-emission sensors mounted near the nozzle.

REFERENCES

1. S. C. Grigory, *Tests of 6-in.-thick Flawed Tensile Specimens; First Technical Summary Report, Longitudinal Specimens Numbers 1 Through 7*, HSSTP-TR-18, Southwest Research Institute (June 1972).
2. A. A. Abbatiello and R. W. Derby, *Notch Sharpening in a Large Tensile Specimen by Local Fatigue*, ORNL/TM-3925 (November 1972).
3. R. W. Derby et al., *Test of 6-inch-thick Pressure Vessels. Series 1: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).
4. R. H. Bryan et al., *Test of 6-inch-thick Pressure Vessels. Series 2: Intermediate Test Vessels V-3, V-4, and V-6*, ORNL-5050 (November 1975).

4. Test Facilities and Experimental Data

TEST FACILITY

The test site for intermediate test vessels V-5 and V-9 was the same as that used for previously reported vessel tests.¹⁻³ The criteria for site selection and design along with a detailed description of the facility are given in Ref. 1. The site is located at a decommissioned power plant adjacent to the Oak Ridge Gaseous Diffusion Plant (ORGDP). At this site, the vessels were hydraulically pressurized to failure in a concrete cell, which was converted from an old steam turbine foundation. A sectional view of the test pit is shown in Fig. 4.1, and an overhead view of vessel V-5 in the test pit is shown in Fig 4.2.

The test facility is capable of controlling vessel temperatures from -18 to 177°C (0 to 350°F) and vessel pressure to 345 MPa ($50,000\text{ psi}$). Figure 4.3 is a schematic flow diagram of the test

Fig. 4.1. Sectional view of test pit for intermediate test vessel (1 in. = 2.54 cm).

Fig. 4.2. Overhead view of vessel V-5 in test pit before testing.

facility. Cylindrical Panelcoils are mounted on the vessel for controlling temperature; Fig. 4.4 shows the layout of the Panelcoils on vessel V-5. Vessel V-9 was tested at ambient temperature and required no heating or cooling.

PREPARATIONS FOR TESTING

Vessel Preparation

After the vessels were flawed, as described in Chapter 3, they were transported to another Y-12 facility of the Engineering Technology Division for instrumentation.¹ After all of the inside and part of the outside instrumentation was installed, the heads were attached and the vessels were sealed. They were then moved to the test site and installed in the test pit for completion of the instrumentation, as shown in Fig. 4.5 for vessel V-9. At this point the heating coils were installed on vessel V-5, as shown in Fig. 4.6. Instrumentation lead wires were connected with the control room, and, in the case of vessel V-5, insulation was applied to the vessel. The vessels were then ready to be filled with demineralized water and connected to the pressurization lines. During the filling operation and while the vessels were being brought to the test temperature, installation of television, acoustic emission, and ultrasonic monitoring equipment was completed. After final checks on all recording equipment, the vessels were ready to test.

Fig. 4.3. Schematic flow diagram of test facility for intermediate test vessel (1 gpm = 6.309 m³/sec; 1 psi = 6895 Pa; 1 in. = 25.4 mm; 1 gal = 3.79 liters).

Fig. 4.4. Panelcoil design for intermediate test vessel V-5.

Fig. 4.5. View of intermediate test vessel V-9 in test pit prior to pressurization.

Fig. 4.6. View of intermediate test vessel V-5 in test pit before test; Paneloids are in place, but thermal insulation has not yet been installed.

Instrumentation

Six types of measurements were made on vessels V-5 and V-9. The location of strain gages, thermocouples, crack-opening displacement (COD) gage, and ultrasonic sensors are shown in Fig. 4.7. Internal pressure was measured and acoustic emissions were monitored. The acoustic-emission sensor locations and data are reported in Appendix D.

Fifteen Chromel-Alumel thermocouples were used to monitor vessel temperature and ensure the adequacy of the prescribed test conditions in the regions of interest. Multipoint Brown (Honeywell) recorders were used to record temperatures.

The inner and outer surfaces were instrumented with 90 strain gages. Two types of strain sensors were used: Micromasurements type EP-08-250-120 and Ailtech weldable type SG-125. The Micromasurements foil gages are made from annealed constantan foil on a flexible polyimide back and are used primarily where large strains are to be encountered. They were installed using M-Bond 200 (Eastman 910) cement. The Ailtech weldable gages utilize Nichrome elements encapsulated in stainless steel with MgO insulation. They are spot welded in place and have MgO-insulated stainless steel integral leads. The gage qualification and installation procedures were presented in Refs. 1 and 2. A Datum System 70 computer-controlled data-acquisition system (DAS) and portable BLH strain indicators were used to record the strain data. A complete tabulation of strains is given in Appendix C.

The COD measurement was accomplished by means of a special clip gage consisting of an Omega spring with strain gages mounted on the surfaces giving a signal that is precalibrated in terms of the crack opening. Figures 4.8 and 4.9 show the clip gage in place before and after the vessel V-5 test. The permanent COD is apparent from a comparison of these two photographs.

As in the previous tests, two completely independent systems were used to monitor pressure. A closed-circuit television system was used to directly view a conventional Bourdon pressure gage mounted near the high-pressure pump. This was a backup for a more precise system that consisted of a strain-gage-based pressure transducer, a signal-conditioning system, and an L&N recorder. After calibration at a standards laboratory, this device is accurate to ± 1.72 MPa (250 psi) in a range of 207 MPa (30,000 psi).

Scanning closed-circuit television systems were also utilized for general surveillance of the test pit and pressurization equipment. A close-up view of the outer surface opposite the flaw was recorded by means of video tape during the test.

Acoustic emissions were monitored during these tests by Dunegan Endevco and Southwest Research Institute. Their reports are included in Appendix D.

Crack growth in both vessels was monitored by means of an ultrasonic pulse-echo system. Figure 4.10 shows the ultrasonic sensor mounted on a block in the fillet of the nozzle-to-shell intersection of vessel V-9. Also shown are some of the acoustic-emission sensors and strain gages.

TEST PROCEDURES AND RESULTS

Vessel V-5 was tested at a temperature of 88°C (190°F). It was loaded in 13.8-MPa (2000-psi) pressure increments to 82.7 MPa (12,000 psig) and then in 6.89-MPa (1000-psi) increments to 179 MPa (26,000 psig). The pressure at maximum load was 183 MPa (26,600 psig). Vessel V-9 was tested at a temperature of 24°C (75°F). It was loaded in 6.89-MPa (1000-psi) increments to 152 MPa (22,000 psig) and then in 3.45-MPa (500-psi) increments to maximum load at 185 MPa (26,900 psig).

INSIDE SURFACE INSTRUMENTATION LAYOUT

OUTSIDE SURFACE INSTRUMENTATION LAYOUT

INSTRUMENTATION AT ENDS OF FLAW

DETAIL "B"
INSIDE NOZZLE RADIUS
INSTRUMENTATION

OUTSIDE NOZZLE FILLET INSTRUMENTATION

LEGEND
— STRAIN GAGE
⊗ THERMOCOUPLE
00 COD GAGE

NOTE:
ALL VIEWS ARE FROM OUTSIDE OF VESSEL EXCEPT DETAIL "A" WHICH IS FACING FLAW FROM INSIDE

Fig. 4.7. Strain gage and thermocouple layout for intermediate test vessels V-5 and V-9.

Fig. 4.8. Vessel V-5 crack-opening displacement (COD) gage and mirror image before test.

Fig. 4.9. Vessel V-5 crack-opening displacement (COD) gage and mirror image after test.

Fig. 4.10. Close-up view of exterior nozzle region of vessel V-9 before test, showing ultrasonic crystal for measuring crack depth and acoustic-emission sensors.

Vessel V-5

For vessel V-5, stable crack growth was obtained up to maximum load; at maximum load a leak without break (i.e., no fast running crack) was obtained. The failure, or leak, was innocuous and was indicated only by the loss of pressure under continued pumping and by mist in the test space, as seen on the TV monitor. Repressurizing under direct visual observation, as shown in Fig. 4.11, revealed that the leak was located in the nozzle fillet radius immediately adjacent to the ultrasonic transducer weld pad. A general exterior posttest view of vessel V-5 is shown in Fig. 4.12, and a close-up exterior view of the leak region is shown in Fig. 4.13.

Posttest examination of the interior of vessel V-5 showed that no significant correction was needed in the pretest description of the flaw. The flaw appears to have extended in a flat ductile tearing mode through to the exterior surface, making the small opening on the outside nozzle fillet shown in Fig. 4.13. There are shear lips extending approximately 15.24 cm (6 in.) from either end of the flaw in the barrel and nozzle sections on the inside surface of the vessel.

Figure 4.14 shows pressure vs circumferential strain for gage 89, which is located on the outside surface at the cylinder equator 180° away from the nozzle centerline. Figure 4.15 shows pressure vs strain for gage 24, which is located on the internal nozzle corner radius opposite the flaw. The influence of the high stress concentration is evident. Figure 4.16 shows pressure vs circumferential strain for gage 73, which is located in the nozzle external fillet radius opposite the flaw and in the plane of the flaw. Figure 4.17 shows pressure vs circumferential strain for gage 119, which is located near the junction of the flaw side nozzle external fillet radius and the cylinder external surface in line with the flaw. Figure 4.18 shows the measurement of crack-opening displacement vs pressure, as recorded on X-Y-Y plotter II.

Table 4.1 presents data and commentary on the crack growth monitored by Klindt and Baker of the ORNL Inspection Engineering Department. Evidently, crack growth was initiated at a pressure level of approximately 124 MPa (18,000 psig).

Figure 4.19 shows the variation of pressure with time during the testing of vessel V-5. Note that below ~124 MPa (~18,000 psi), pressure remained about constant with time when pumping was stopped for the reading of gages, but above 124 MPa (18,000 psi), the pressure decayed slightly when pumping was stopped, probably due to continued yielding and stable crack growth. Leaking commenced at 110 min from the start of the test, and continued pumping would not raise the pressure. The last small peak in the pressure-time diagram, at ~125 min, was produced by restarting the pumps in order to reopen the leak and take the photograph shown in Fig. 4.11.

Vessel V-9

In vessel V-9, failure at 185 MPa (26,900 psig) was extensive and frangible; crack propagation occurred both above and below the nozzle in the cylinder of the vessel. Missiles were generated from the nozzle cap material. Figure 4.20 shows a general posttest view of vessel V-9, and Fig. 4.21 shows a close-up view of the fractured nozzle.

In general, the strains at failure or maximum load for vessel V-9 equaled or exceeded those for vessel V-5. Figure 4.22 shows plots of circumferential strain vs pressure for the outside nozzle fillet radius away from the flaw for vessels V-5 and V-9. Figure 4.23 shows plots of outside circumferential strain remote from the nozzle vs pressure for vessels V-5 and V-9, and Fig. 4.24 shows plots of the inside nozzle corner circumferential strain vs pressure for both vessels V-5 and V-9. Figure 4.25 shows the crack-opening displacement vs pressure for vessel V-9.

Fig. 4.11. Photograph of leak in flawed nozzle region of vessel V-5; the arrow points to two small water jets.

Fig. 4.12. Overall view of vessel V-5 after testing to a condition of leak without fracture at 88°C (190°F); arrow shows location of leak.

PHOTO 4101-74

Fig. 4.13. Closeup view of leak point adjacent to ultrasonic base block on nozzle of vessel V-5 (arrow shows flaw penetration to surface).

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Fig. 4.14. Pressure vs outside circumferential strain, test of intermediate vessel V-5 at 88°C (190°F) (1 psi = 6895 Pa).

Fig. 4.15. Pressure vs inside uncracked nozzle corner circumferential strain, test of intermediate vessel V-5 at 88°C (190°F) (1 psi = 6895 Pa).

ORNL-DWG 74-8833

Fig. 4.16. Pressure vs outside uncracked nozzle region circumferential strain, test of intermediate vessel V-5 at 88°C (190°F) (1 psi = 6895 Pa).

ORNL-DWG 74-6934

Fig. 4.17. Pressure vs outside cracked nozzle region circumferential strain, test of intermediate vessel V-5 at 88°C (190°F) (1 psi = 6895 Pa).

Fig. 4.18. Pressure vs crack-opening displacement (COD), test of intermediate vessel V-5 at 88°C (190°F) (1 psi = 6895 Pa; 1 in. = 25.4 mm).

Fig. 4.19. Pressure history of intermediate test vessel V-5 (1 ksi = 6.8948 MPa).

Fig. 4.20. View of intermediate vessel V-9 after test.

Fig. 4.21. Close-up view of fractured nozzle in vessel V-9; test temperature was 24°C (75°F).

Fig. 4.22. Pressure vs outside uncracked nozzle region circumferential strain for intermediate test vessels V-5 and V-9 (1 psi = 6895 Pa).

ORNL-DWG 74-10474

Fig. 4.23. Pressure vs outside circumferential strain in vessel cylinder for intermediate vessels V-5 and V-9 (1 psi = 6895 a).

Fig. 4.24. Pressure vs inside uncracked nozzle corner circumferential strain for intermediate test vessels V-5 and V-9 (1 psi = 6895 Pa).

Fig. 4.25. Crack-opening displacement (COD) vs pressure for intermediate vessel V-9, tested at 24°C (75°F) (1 psi = 6895 Pa; 1 in. = 25.4 mm).

Table 4.1. Ultrasonic monitoring of crack growth for vessel V-5*

Pressure (ksi)	Comments
0	Initial setup shows a weep-hole indication at 7.6 in. depth, a notch at 8.35 in., and a back surface corner at 9.0 in.
4	There is no indication of a crack.
6	There is no indication of a crack.
8	A fatigue crack tip is visible at 8.1 in.
10	The signal at 8.1 in. is now slightly higher in amplitude.
12-17	There is very little change in crack tip position, but the amplitude of this signal is becoming progressively greater.
18	There is a small signal at 8.0 in., which is apparently due to tearing and a small amount of crack growth.
19	The crack front signal at 7.8 in. is increasing in amplitude.
21	The crack signal is now at 7.7 in.
22	The crack signal is now at 7.6 in. and has blended into the weep hole.
23	There is little change from 22 ksi.
24	The crack signal is now at 7.4 in. and has moved past the weep hole.
25	The crack signal is now at 7.2 in.
25.9	The crack signal is now at 6.5 in. and is a slowly moving signal (small incremental tearing is taking place).
26.5	The crack signal is now at 6.0 in. and still slowly moving.
26.4	The crack signal is now at about 2.5 in., just to the right of the anomalous signal at 2.2 in.
26.0	The crack signal is now hidden in the anomalous signal.
25.9	
25.5	
6	A leak has occurred, and the crack signal is now located at 1.6 in. from the front surface.

*Conversion factors: 1 ksi = 6.895 MPa; 1 in. = 2.54 cm.

Figure 4.26 shows the setup and the experimental data on crack growth obtained by the ORNL Inspection Engineering Department by ultrasonic monitoring of vessel V-9. The fatigue crack, which was 5.59 mm (0.22 in.) deep, became detectable at a pressure level of 12.1 MPa (1750 psig). No crack extension was detectable from this point until a pressure level of 145 MPa (21,000 psig) was reached. The crack extended slowly, obtaining a depth of 17.8 mm (0.7 in.) at 185 MPa (26,850 psig) shortly before failure. No intermediate data were obtained between this point and failure.

During the test of vessel V-9, a comparative plot was made showing the inside nozzle corner strains measured by strain gage 24 on vessels V-5 and V-9, the pressure-strain curve predicted by the MARC-3D elastic-plastic finite-element computer program (see Ref. 21 in Chapter 5), and the predicted point of initial yielding based on elastic calculations made by the SAFE-3D finite-element computer program (see Ref. 10 in Chapter 5). This plot, which is shown in Fig. 4.27, indicates that both vessels V-5 and V-9 produced nearly identical nozzle corner pressure-strain curves, and that the analytically predicted values of nozzle corner strain were significantly lower than the measured values.

Fig. 4.26. Ultrasonic setup and experimental crack depth data for intermediate vessel V-9 (1 in. = 25.4 mm; 1 ksi = 6.895 MPa).

Fig. 4.27. Comparison of calculated and measured nozzle corner strain values, up to 2.8% strain, for vessels V-5 and V-9.

The experimental strain data obtained from vessels V-5 and V-9 are listed in tabular form in Appendix C. Plots of a considerable portion of the strain data obtained from vessel V-9 are contained in Appendix F.

REFERENCES

1. R. W. Derby et al., *Test of 6-in.-thick Pressure Vessels. Series 1: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).
2. R. H. Bryan et al., *Test of 6-in.-thick Pressure Vessels. Series 2: Intermediate Test Vessels V-3, V-4, and V-6*, ORNL-5059 (November 1975).
3. J. G. Merkle et al., *Test of 6-in.-thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7*, ORNL/NUREG-1 (August 1976).

5. Fracture Analysis Methods and Results

BACKGROUND

The choice of an inside nozzle corner crack lying in the plane containing both the nozzle and the vessel axes (the longitudinal plane) as a test configuration was based on existing experimental data¹⁻³ indicating that such cracks can form by low-cycle fatigue due to excessive cyclic pressure and can also lead to fast fracture at low temperatures if they grow by fatigue to a critical size. During the early planning stages of the HSST program, hypothetical calculations were made by Lubahn⁴ for a pressure vessel with an inside nozzle corner crack. These calculations considered the increase (above elastically calculated values) of both the applied strain at the nozzle corner and the strain tolerance for a flaw at that location due to local yielding. However, the effects of local yielding were known to be complex and a consistent hypothesis concerning these effects was not expected to emerge until after the test results had been obtained. Therefore, subsequent fracture strength calculations were based largely, but not entirely, on elastic-plastic estimates of nozzle corner strain combined with linear elastic fracture mechanics (LEFM) estimates of fracture strain.

An early attempt to estimate the elastic stress-intensity factor for a nozzle corner crack was made by Yukawa.⁵ He used the known solutions for a through crack emanating from a circular hole in a flat plate under uniaxial and equibiaxial tension^{6,7} with a crack-shape reduction factor based on the ratio of the stress-intensity factor for a corner crack⁸ to that for a through edge crack in a rectangular bar under uniform tension. Embley⁹ has since shown that this method of calculation should be modified to include the additional effects of vessel internal pressure on the crack faces themselves in order to avoid underestimating the value of K_I . This feature of the problem will be discussed later in more detail.

PRELIMINARY CALCULATIONS AND EXPERIMENTS

Following the design of the nozzles used in intermediate test vessels V-5, V-9, and V-10 (described in Chapter 2), a combined analytical and experimental effort was undertaken to better define the expected behavior of flawed and unflawed vessels with nozzles under test conditions. The analytical effort consisted of an elastic three-dimensional finite-element analysis by Krishnamurthy¹⁰ for a slightly idealized version of the actual nozzle-to-cylinder intersection region, but not including the test crack, which had not yet been designed. The results of this analysis are described in detail in Ref. 10 and summarized in Ref. 11. The most important result of Krishnamurthy's finite-element analysis¹⁰ was that the estimated elastic stress-concentration factor for the inside nozzle corner under internal pressure loading and based on the average vessel hoop stress was 2.98. This value, which was obtained by extrapolating finite-element stress values to the inside surface of the nozzle corner, was judged to be within the range of typical values intended to be achieved by the nozzle design.

The experimental work, which was carried on at ORNL concurrently with the finite-element calculations, consisted of tests to fracture of two different sizes of epoxy model pressure vessels containing a single radial nozzle with one fatigue-sharpened inside nozzle corner crack in the longitudinal plane. The methods and materials used for producing these vessels are described in Ref. 12. The results of the fracture tests were given in terms of the LEFM shape factor for a nozzle corner crack expressed as a function of the nominal vessel hoop stress and the ratio of the crack depth to the effective nozzle radius, using the equation¹¹

$$C_n = K_{IC} / \sigma_h \sqrt{\pi a} \quad (1)$$

where the nominal vessel hoop stress is given by

$$\sigma_h = p(r_i / t) \quad (2)$$

and where p is internal pressure, r_i is inside vessel cylinder radius, and t is vessel cylinder thickness. As originally suggested in Ref. 14 and shown in Fig. 5.1, the crack depth a is defined as the distance to the crack tip measured from the inside nozzle corner along the line bisecting the angle between the inside surface tangents to the nozzle and the cylinder. The effective nozzle radius is the perpendicular distance from the nozzle axis to the point on the inside nozzle corner from which the crack depth is measured. Thus, the effective nozzle radius is given by

$$r_e = r_n + (1 - 1/\sqrt{2})r_c \quad (3)$$

Fig. 5.1. Nozzle corner crack dimensions.

where r_e is effective nozzle radius, r_n is inside radius of the nozzle beyond the transition, and r_c is radius of curvature of the inside nozzle corner in the longitudinal plane. The fracture toughness K_{Ic} of the epoxy model material was determined separately by fracture testing beams with fatigue-sharpened cracks manufactured from the tested vessel pieces.

The dimensions of the two series of epoxy model pressure vessels with nozzles are listed in Table 5.1, and a general view of the models is shown in Fig. 5.2. The small thick-walled epoxy models were

Table 5.1. Dimensions of epoxy models with nozzles

Model	Inside radius [cm (in.)]	Wall thickness [cm (in.)]	Nominal nozzle radius [cm (in.)]	Nozzle wall thickness [cm (in.)]
Small, thick-walled	4.32 (1.70)	1.80 (0.71)	1.29 (0.507)	1.22 (0.48)
Large, thinner wall	6.83 (2.69)	1.50 (0.59)	2.36 (0.93)	1.42 (0.56)

Fig. 5.2. Epoxy model pressure vessels with nozzles.¹¹

approximately geometrically similar to the intermediate test vessels with nozzles. A closeup posttest view of an epoxy vessel nozzle corner crack is shown in Fig. 5.3, and the fracture mechanics test results for the models are summarized graphically in Fig. 5.4. Additional experimental strain measurements were made with strain gages located on and near the unflawed inside nozzle corners, as described in Ref. 13 and summarized in Ref. 11. These strain measurements gave a value of 2.79 for the experimentally determined elastic stress-concentration factor of the inside nozzle corner for the small thick-walled epoxy model vessels.

An additional series of fracture experiments was conducted with epoxy model pressure vessels without nozzles and containing moderately deep and deep external surface cracks in order to compare the stress-intensity factor values obtained by the model fracturing technique with existing approximate analytical solutions.¹⁵ The comparison was judged to be satisfactory, thus supporting the shape-factor values obtained from the fracture tests on the epoxy models with inside nozzle corner flaws.

In addition to providing a direct basis for the design of the flaws in intermediate test vessels V-5 and V-9, the epoxy model nozzle corner flaw test data were also used by the Pressure Vessel Research Committee (PVRC), in conjunction with other analytical results, as a basis for a proposed approximate elastic method of fracture analysis for nozzle corner cracks in vessels loaded by internal pressure.¹⁴

The nozzle corner crack shape-factor data presented in Ref. 14 are shown in Fig. 5.5. The epoxy model test data and the curve for the flat-plate (analytical) model shown in Fig. 5.5 are the same as those shown in Fig. 5.4. The flat-plate curve was calculated for a through crack emanating from a hole in a flat plate, without the reduction for crack shape used in Ref. 5, although a reduction factor of some magnitude less than 1.0 was still thought to exist. The finite-element results shown in Fig. 5.5 were based on crack-front average values of the elastic strain energy release rate calculated by Gilman and Rashid¹⁶ for a postulated three-dimensional boiling-water reactor (BWR) inside nozzle corner crack configuration. The finite-element curve was recommended in Ref. 14 for application to actual reactor vessels, primarily because typical reactor vessel cylinder dimensions had been used in the calculations. The reason why the epoxy model vessel experimental values exceeded the analytically estimated values was not apparent at the time Ref. 14 was written, but, as mentioned earlier, Embley⁹ showed that the effects of vessel internal pressure acting on the crack surfaces are probably responsible for most of the difference. These effects would not be as significant for actual reactor pressure vessels as they are for the intermediate test vessels because actual reactor vessels have proportionally thinner walls relative to their radii and therefore lower pressures for identical stress levels.

TEST TEMPERATURE SELECTION AND FLAW DESIGN

Vessel V-5

The test temperature for intermediate test vessel V-5 [88°C (190°F)] was selected to provide dynamic upper-shelf fracture toughness conditions for the first intermediate vessel nozzle corner crack test. The flaw size in vessel V-5 was chosen using the method of LEFM based on strain, as described below, and on the basis of the nozzle corner crack-sharpening experiments described in Chapter 3. The LEFM portion of the calculations was based on Derby's tests of an epoxy model vessel with a nozzle corner crack.¹¹ Combining Eqs. (1) and (2) and rearranging gives

$$p_f^*/K_{II} = 1/C_n(r, t)\sqrt{\pi a}, \quad (4)$$

where p_f^* is elastically calculated failure pressure and C_n is obtained from the curve for the small thick-walled epoxy vessels shown in Fig. 5.4. Referring to the design dimensions of the intermediate test vessel

Fig. 5.3. Closeup of nozzle corner crack in epoxy model pressure vessel after fracture test.

Fig. 5.4. Summary of experimental results obtained from ORNL nozzle corner crack epoxy model pressure vessel fracture tests.¹¹

Fig. 5.5. Estimates of stress-intensity factors for flaws at a nozzle corner.¹⁴

nozzles shown in Fig. 2.1, $r_n = 11.43$ cm (4.5 in.) and $r_i = 3.81$ cm (1.5 in.). Thus, from Eq. (3), $r_z = 12.55$ cm (4.94 in.). Since $(r_i/t) = 2.25$, Eq. (4) becomes

$$p_i^*/K_t = 1.398C_s\sqrt{a}. \quad (5)$$

In order to consider values of a/r_z less than 0.2, it was necessary to extrapolate the small thick-walled epoxy vessel curve shown in Fig. 5.4 toward an intercept on the vertical axis. This was done by assuming that the intercept value should be $1.1K_t$, where K_t is the elastic stress-concentration factor of the nozzle corner. Using the value of $K_t = 2.79$ obtained experimentally from the epoxy models, the intercept value was estimated to be 3.07, which slightly exceeds the intercept value of the curve for the flat-plate model shown in Fig. 5.5. The resulting calculated curve of Eq. (5) is shown in Fig. 5.6.

For preliminary calculations, a first approximation to the inside nozzle corner pressure-vs-strain curve was constructed by combining an estimate of the initial slope of the curve based on the elastic stress-concentration factor determined from the epoxy model tests with an estimate of the ideally plastic limit pressure of the nozzle-to-cylinder intersection region. The initial slope of the curve was determined by estimating the pressure at which initial yielding would occur at the inside nozzle corner, based on a maximum shear stress yield criterion. In the elastic range, the maximum principal strain is given by

$$\epsilon_1 = [\sigma_1 - \nu(\sigma_2 + \sigma_3)]/E, \quad (6)$$

where E is Young's modulus and ν is Poisson's ratio. For the inside nozzle corner,

$$\sigma_1 = K_t p(r_i/t) \quad (7)$$

and

$$\sigma_3 = -p. \quad (8)$$

Based on the data obtained by Pickett and Grigory,² the intermediate principal stress at an inside nozzle corner under internal pressure loading is nearly zero. Therefore, it was assumed that

$$\sigma_2 = 0. \quad (9)$$

At initial yield,

$$\sigma_1 - \sigma_3 = \sigma_Y \quad (10)$$

and

$$p = p_{Yn}. \quad (11)$$

Thus, combining Eqs. (6) through (10) gives at initial yield

$$\epsilon_1 = \frac{\sigma_Y}{E} \left[\frac{1 + \nu/K(r_i/t)}{1 + 1/K(r_i/t)} \right]. \quad (12)$$

Fig 5.6. Curve for estimating stress intensity factors for nozzle corner cracks in intermediate test vessels.

With $K_I = 2.79$, $(r/t) = 2.25$, and $\nu = 0.3$, Eq. (12) reduces to

$$\epsilon_i = 0.904(\sigma_i/E) \quad (13)$$

The pressure at initial yield is calculated by combining Eqs. (7), (8), (10), and (11):

$$p_{yn} = \sigma_Y [K(r/t) + 1] \quad (14)$$

Since material property data for the nozzle forging material were not available when these preliminary calculations were made, it was assumed that $\sigma_y = 483 \text{ MPa}$ (70 ksi). Consequently, from Eq. (13), with $E = 20.7 \times 10^4 \text{ MPa}$ ($3 \times 10^4 \text{ ksi}$), the nozzle corner strain at initial yield is 0.211%; from Eq. (14), the initial yield pressure p_{y0} is 66.3 MPa (9.62 ksi).

The ideally plastic limit pressure of the nozzle-to-cylinder intersection region was estimated roughly by using the computer program SCHRØ 6, which was written to calculate upper bounds to the limit pressures for thin-cylinder-to-cylinder intersection regions.¹⁷ Since the intermediate test vessels have thickness-to-diameter ratios considerably greater than those for which the computer program was intended, the calculated result was considered to be only a rough approximation (on the high side) for the pressure at which nozzle corner strains may become large. The calculated upper-bound limit pressure for the intermediate test vessel nozzle-to-cylinder junctions was 339 MPa (49.2 ksi). The fact that this pressure was an overestimate was obvious because it exceeds the burst pressure of an unflawed cylinder of intermediate test vessel geometry, which is 262 MPa (38.0 ksi) as determined by a small unflawed steel model burst test.¹⁸ Nevertheless, this calculated limit pressure was used for purposes of estimating a first approximation to the pressure-strain curve.

In the first approximate pressure-strain curve estimate, it was assumed that the nozzle corner strain at the onset of gross yielding in the nozzle intersection region (i.e., at the upper-bound limit pressure) was equal to the strain at the onset of strain hardening in a uniaxial tensile test, which is about 1.2%. Furthermore, it was assumed that between the initial and the gross yield pressures, the pressure and strain differences between the gross yield and the current values can be related by a power law equation having the form $y = Ax^n$. At the initial yield pressure, the slope of the power law transition curve was made equal to the elastically calculated slope of the pressure-strain curve. The resulting pressure-strain curve estimate is shown in Fig. 5.7. Although this curve later proved to be a rather inaccurate first approximation to the actual experimental curve, it still served its purpose satisfactorily in the flaw size selection process.

Since actual toughness data for the nozzle forging material of vessel V-5 were not available when the flaw size was chosen, it was assumed that the plane strain fracture toughness would lie between 330 and 385 $\text{MN}\cdot\text{m}^{-3/2}$ (300 and 350 $\text{ksi}\sqrt{\text{in.}}$) based on the static upper-shelf toughness data^{11,19} already obtained for vessels V-1, V-3, and V-6. Calculations were then made using the curve shown in Fig. 5.6 to find the flaw size corresponding to an elastically calculated failure pressure equal to the gross yield pressure of the vessel cylinder. These calculations are summarized in Table 5.2. The gross yield pressure

Table 5.2. Elastically calculated failure pressures for intermediate test vessels with inside nozzle corner cracks

a , flaw depth [cm (in.)]	p_f^* [MPa (ksi)]	
	For $K_{Ic} = 330 \text{ MN}\cdot\text{m}^{-3/2}$ (300 $\text{ksi}\sqrt{\text{in.}}$)	For $K_{Ic} = 385 \text{ MN}\cdot\text{m}^{-3/2}$ (350 $\text{ksi}\sqrt{\text{in.}}$)
0.64 (0.25)	343 (49.8)	401 (58.1)
1.27 (0.50)	248 (36.0)	290 (42.0)
1.91 (0.75)	213 (30.9)	249 (36.1)
2.54 (1.00)	203 (29.4)	229 (33.2)
3.81 (1.50)	184 (26.7)	215 (31.2)
5.08 (2.00)	177 (25.7)	206 (29.9)
6.35 (2.50)	170 (24.7)	199 (28.8)
7.62 (3.00)	163 (23.6)	190 (27.5)

Fig. 5.7. Preliminary estimate of intermediate test vessel nozzle corner pressure-strain curve.

of the vessel cylinder was estimated from the equation

$$p_{cyl} = 1.04\sigma_y \ln(r_o/r_i) \quad (15)$$

where the factor 1.04 is an empirical factor based on previously obtained steel model and intermediate vessel test data, and the remainder of the equation is based on the Tresca (maximum shear stress) yield criterion. For $\sigma_y = 483 \text{ MPa}$ (70 ksi), $r_o = 49.53 \text{ cm}$ (19.5 in.), and $r_i = 34.29 \text{ cm}$ (13.5 in.), the estimated gross yield pressure of the vessel cylinder was 184 MPa (26.7 ksi); as indicated in Table 5.2, for a toughness of $330 \text{ MN}\cdot\text{m}^{-1/2}$ (300 ksi $\sqrt{\text{in.}}$), the calculated flaw depth corresponding to an elastically calculated failure pressure of 189 MPa (26.7 ksi) was 3.31 cm (1.50 in.). Consequently, the target flaw

configuration chosen for the flaw-sharpening experiments discussed in Chapter 3 was a circular arc with a chord 2.54 cm (1 in.) deep from the nozzle corner and with a maximum crack depth of 3.81 cm (1.50 in.). Since the approximate pressure-strain curve shown in Fig. 5.7 is still nearly linear at a pressure of 184 MPa (26.7 ksi), no refinements were made to the previous LEFM calculations. However, a three-dimensional elastic-plastic finite-element analysis of the nozzle-to-cylinder intersection region was undertaken, as described below. Furthermore, in order to control the crack-sharpening process and to provide more accurate input for pretest predictions, the actual flaw depth in vessel V-5 was estimated by means of ultrasonic measurements made from the outside surface of the vessel before the test, as described in Chapter 3.

Vessel V-9

The flaw depth in vessel V-9 was intended to be, and for all practical purposes was, the same as the flaw depth in vessel V-5. The test temperature for vessel V-9 [24°C (75°F)] was selected on the basis of fracture toughness data indicating that the dynamic fracture toughness might exceed the static fracture toughness above this temperature and thus inhibit the occurrence of the desired fast running fracture. The test temperature selection for vessel V-9 is discussed in more detail below in conjunction with the pretest calculations for vessel V-9.

PRETEST ANALYSIS FOR VESSEL V-5

Finite-Element Calculations

Since only a rough approximation to the nominal inside nozzle corner pressure-strain curve was available when the flaw size for vessel V-5 was chosen, a three-dimensional elastic-plastic finite-element stress analysis of an intermediate vessel nozzle region was undertaken to provide a better basis for making pretest predictions of failure conditions. This same problem would have been approached experimentally for an outside surface flaw. However, methods were not developed for mounting strain gages inside, or for installing instrumentation lead wires through, the small 1/4-scale steel models of the intermediate test vessels. The computer program for analyzing the nozzle corner region was developed by the MARC Analysis Research Corporation²⁰ under a Union Carbide Corporation Nuclear Division (UCCND) subcontract. The resulting calculated pressure-strain curves for the unflawed nozzle corner are shown in Fig. 5.8 along with the analytical first approximation given in Fig. 5.7. Details of the finite-element method used for analyzing the unflawed nozzle region are described in Ref. 21, which also contains elastic stress-intensity factor results for nozzle corner cracks obtained after both vessels V-5 and V-9 were tested. The latter results will be discussed in conjunction with the other posttest calculations.

Fracture Toughness Estimate

The static initiation fracture toughness of the nozzle forging material in vessel V-5 was measured by Stelzner²² at ORNL using precracked Charpy V-notch (PCCV) specimens and by Westinghouse^{23,24} using 2.16-cm-thick (0.85-in.) and 5.08-cm-thick (2.00-in.) compact specimens. The toughness data obtained at 93°C (200°F) that were available before the test of vessel V-5 are listed in Table 5.3. These and additional PCCV specimen test data that were obtained after the test of vessel V-5 are listed in Tables A.1 and 2.5. Differences of generally minor significance exist between the toughness values for the Westinghouse specimens listed in Table 2.5 and those listed in Table 5.3, because the specimen load-deflection data were reanalyzed by Westinghouse after the originally transmitted test results (Table 5.3)

Fig. 5.8. Estimates of pressure vs maximum strain curve for intermediate test vessel V-5 at the inside nozzle corner region (not considering the flaw); $\sigma_f = 483 \text{ MPa}$ (70 ksi).

Table 5.3. Lower-bound equivalent-energy static fracture toughness properties for nozzle material of intermediate test vessel V-5 at 93°C (200°F)^a

Specimen No	Thickness (cm)	Type of specimen	Orientation	Distance in from outside surface (cm)	K_{Icd} ($\text{MN}\cdot\text{m}^{-3/2}$)	$1/d$ (cm^{-1})	$(\frac{K_{Icd}}{K_{Icd}^2})^2$
ORNL specimens ²³							
SV-005	1.00	PCCV	CT	11.74	159	1.00	1.000
SV-004	1.00	PCCV	CA	10.24	182	1.00	0.763
SV-003	1.00	PCCV	CT	8.89	205	1.00	0.601
SV-002	1.00	PCCV	CA	7.49	220	1.00	0.546
Westinghouse specimens ^{23,24}							
V5-3	2.16	CT	CT		176	0.463	0.822
V5-4	2.16	CT	CT		201	0.463	0.628
V5-5	2.16	CT	CT		221	0.463	0.521
V5-6	2.16	CT	CA		210	0.463	0.577
V5-7	2.16	CT	CA		237	0.463	0.451
V5-8	2.16	CT	CA		245	0.463	0.423
V5-1	5.08	CT	CT		253	0.197	0.397
V5-2	5.08	CT	CT		259	0.197	0.378

^aConversion factors: $1 \text{ cm} = 0.394 \text{ in}$; $1 \text{ MN}\cdot\text{m}^{-3/2} = 0.9101 \text{ ksi}\sqrt{\text{in}}$

were used for the pretest analysis of vessel V-5. The toughness corresponding to a thickness of 15.24 cm (6.0 in.) was estimated by means of the plot of $(K_{Icm}/K_{Icd})^2$ vs $1/d$ shown in Fig. 5.9, in which the normalizing value of K_{Icm} is $159 \text{ MN}\cdot\text{m}^{-3/2}$ ($145 \text{ ksi}\sqrt{\text{in.}}$). The empirical basis for this method of extrapolation is discussed in Ref. 25. The estimated value of $(K_{Icm}/K_{Icd})^2$ (from Fig. 5.9) is 0.362, which leads to a value of $K_{Icd} = 265 \text{ MN}\cdot\text{m}^{-3/2}$ ($241 \text{ ksi}\sqrt{\text{in.}}$).

Fig. 5.9. Estimate of fracture toughness at 93°C (200°F) for the 6-in.-thick nozzle in HSST program intermediate test vessel V-5; $K_{Icm} = 159 \text{ MN}\cdot\text{m}^{-3/2}$ ($145 \text{ ksi}\sqrt{\text{in.}}$).

Flaw Size Estimate

The flaw depth estimate used in the pretest analyses of vessel V-5 was based on ultrasonic measurements made from the outside surface of the vessel in the plane of the crack, as described in Chapter 3. The ultrasonically based pretest estimate of the flaw geometry is shown in Fig. 3.8, from which it was estimated that the flaw depth was 3.05 cm (1.2 in.).

Table of Pretest Analysis Data

Prior to the test of vessel V-5, the available material properties and dimensional data, other than the estimate of K_A given previously, that were known to be required for various methods of fracture analysis were compiled and are summarized in Table 5.4. Note that no drop-weight tests were performed on vessel V-5 material and that the only Charpy V-notch impact tests performed on vessel V-5 material were those conducted at -12.2°C ($+10^\circ\text{F}$) by the vessel fabricator (see Chapter 2).

Table 5.4. Data for pretest fracture analysis of intermediate test vessel V 5

Material	A508, class 2 forging steel, base metal
Nil ductility temperature (NDT)	-12°C ($+10^\circ\text{F}$) (assumed, based on V-1 data)
Test temperature	88°C ($+190^\circ\text{F}$)
Expected fatigue-sharpened flaw depth at inside nozzle corner ^a	3.05 cm (1.2 in.)
Tensile properties of nozzle material at 93°C (200°F) ^b	
Yield stress	425 MPa (61.6 ksi)
Ultimate stress	553 MPa (80.2 ksi)
Strain at maximum load	8.9%
Total elongation	16.8%
Gage length	3.175 cm (1.250 in.)
Reduction in area	68.3%
Original specimen diameter	0.4509 cm (0.1775 in.)
Tensile properties of cylinder material ^c	
Yield stress	500 MPa (72.5 ksi)
Ultimate stress	654 MPa (94.8 ksi)
Nozzle dimensions ^d	
Inside radius	11.43 cm (4.5 in.)
Thickness	15.24 cm (6.0 in.)
Cylinder dimensions ^e	
Inside radius	68.58 cm (27.0 in.)
Thickness	15.24 cm (6.0 in.)
Charpy V-notch impact energy at 88°C (190°F)	No data

^aSee Fig. 3.8.

^bSpecimen 5V-202 (see Table A.4).

^cVendor's room-temperature data.

^dSee Figs. 2.1 and 2.2.

^eSee Fig. 2.1.

Graphical Estimate of Fracture Strain
(estimate prepared by J. G. Merkle, ORNL)

Before any analytical calculations were made for vessel V-5, the failure conditions for the previously tested vessels (V-1, V-2, V-3, V-4, and V-6) were examined by plotting the product of the failure strain times the square root of the flaw size vs the fracture toughness. The values of failure strain, flaw size, and fracture toughness used for constructing this plot were those listed in Tables 1.2 and 1.3, except that a value of $K_{Ic} = 220 \text{ MN}\cdot\text{m}^{-3/2}$ ($200 \text{ ksi}\sqrt{\text{in.}}$) was used for vessels V-2 and V-4, based on the equivalent-energy pretest calculations for those two vessels.^{11,19} The resulting plot is shown in Fig. 5.10, which indicates that $\lambda_f\sqrt{a} = 0.09\% \sqrt{\text{m}}$ ($0.565\% \sqrt{\text{in.}}$) for $K_{Ic} = 265 \text{ MN}\cdot\text{m}^{-3/2}$ ($241 \text{ ksi}\sqrt{\text{in.}}$). With $a = 3.05 \text{ cm}$ (1.2 in.), the estimated failure strain is 0.516%; then with the use of the elastic-plastic finite-element pressure-strain curve shown in Fig. 5.8, the pressure corresponding to a strain of 0.516% is determined to be 159 MPa (23.0 ksi).

Linear Elastic Fracture Mechanics (LEFM) Based on Strain

K_{Ic} estimate based on ORNL epoxy model fracture data
(analysis performed by J. G. Merkle, ORNL)

The curve in Fig. 5.6 was used to obtain an estimated value of $p_f^*/K_{Ic} = 0.058 \text{ cm}^{-1/2}$ ($0.093 \text{ in.}^{-1/2}$) using the ultrasonically measured flaw depth of 3.05 cm (1.2 in.). Combining this estimate with the

Fig. 5.10. Graphical pretest estimate of strain tolerance for nozzle corner flaw in intermediate test vessel V-5.

fracture toughness estimate of $K_{Ic} = 265 \text{ MN}\cdot\text{m}^{-1/2}$ ($241 \text{ ksi}\sqrt{\text{in.}}$) leads to an elastically calculated failure pressure of $p_f^* = 154 \text{ MPa}$ (22.4 ksi). Dividing this pressure by the initial slope of the finite-element pressure-strain curve shown in Fig. 5.8, which is $447 \text{ MPa}\cdot\epsilon^{-1}$ ($64.84 \text{ ksi}\cdot\epsilon^{-1}$), gives an elastically calculated failure strain of 0.346% . The corresponding failure pressure read from the finite-element curve shown in Fig. 5.8 is 132 MPa (19.1 ksi).

K_I estimate based on Fig. A5-1 of WRC-175

(analysis performed by C. Buchalet, Westinghouse PWR Systems Division)

This analysis followed the same basic procedure as the preceding one, except that the K_I estimate was based on the finite-element curve shown in Fig. 5.5 (which is Fig. A5-1 of Ref. 14) and the crack depth was estimated from Fig. 3.8 as 3.18 cm (1.25 in.). For vessel V-5, the value of r_c (determined previously) is 12.55 cm (4.94 in.). Thus, using $a = 3.18 \text{ cm}$ (1.25 in.) and $a/r_c = 0.253$ and reading the finite-element curve shown in Fig. 5.5 somewhat inexactly gives $K_{II} \sigma_n \sqrt{\pi a} = 1.59$. Using Eq. (2) and $a = 3.18 \text{ cm}$ (1.25 in.) gives $p_f^*/K_{Ic} = 0.088 \text{ cm}^{-1/2}$ ($0.141 \text{ in.}^{-1/2}$), and for $K_{Ic} = 265 \text{ MN}\cdot\text{m}^{-1/2}$ ($241 \text{ ksi}\sqrt{\text{in.}}$), $p_f^* = 234 \text{ MPa}$ (34.0 ksi). Next, using a graphical estimate of the initial tangent to the finite-element pressure-strain curve shown in Fig. 5.8, one obtains the elastically calculated failure strain of 0.53% ; then, reading from the pressure-strain curve at this value of strain, one obtains an estimated failure pressure of 161 MPa (23.4 ksi). (This same method of analysis was also applied to vessel V-9, and the results for both vessels are shown graphically in Fig. 5.28.)

K_I estimate based on a two-dimensional finite-element analysis

(analysis performed by C. Buchalet, Westinghouse PWR Systems Division)

This analysis was identical in principle to the preceding two analyses, but the value of K_I was estimated from an approximate manipulation of the finite-element analysis results^{2b} for a continuous longitudinal crack in a cylinder with a radius-to-thickness ratio of 10; the curves are shown in Fig. 5.11. With reference to Fig. 5.11 and with the assumption of a linearly varying nominal stress distribution with an inside nozzle corner stress-concentration factor of 2.0, the crack centerline stress distribution is represented by the expression

$$\sigma = \sigma_n(2 - x/t), \quad (16)$$

where x is the radial distance from the inside surface. The thickness here is taken as 21.59 cm (8.5 in.), which is approximately $\sqrt{2}$ times the cylinder wall thickness. In reference to the equations given in Fig. 5.11, for a continuous inside surface longitudinal crack in a cylinder subject to a linearly varying nominal stress distribution,

$$\sigma = A_0 + A_1 x, \quad (17)$$

and

$$K_I^c = \sqrt{\pi a} [A_0 F_1 + (2a/\pi) A_1 F_2], \quad (18)$$

where the superscript c designates a continuous crack. From a comparison of Eqs. (16) and (17), it

Fig. 5.11. Stress-intensity magnification factors for longitudinal crack in cylinder ($r/t = 10$).²⁶

follows that

$$A_0 = 2\sigma_h \quad (19)$$

and

$$A_1 = -\sigma_h/t. \quad (20)$$

Then, for $a = 3.18$ cm (1.25 in.) and $t = 21.59$ cm (8.5 in.), a/t is approximately 0.15; from the curves shown in Fig. 5.11, $F_1 = 1.225$ and $F_2 = 1.1$. Thus, by using Eq. (2) with $(r/t) = 2.25$, Eqs. (19) and (20), and the values of a , t , F_1 and F_2 given above, Eq. (18) gives

$$K_1^C/p = 16.66 \sqrt{\text{cm}} \quad (10.45 \sqrt{\text{in.}}). \quad (21)$$

The stress-intensity factor K_I for a semielliptical surface crack is estimated by applying a crack shape reduction factor to Eq. (21), so that

$$K_I = K_I' \times R^x, \quad (22)$$

where, for a linearly varying nominal stress distribution,^{27,28}

$$R^x = \frac{A_0/\Phi_1 + (A_1/\Phi_2)x}{A_0 + (A_1/2)x}, \quad (23)$$

The values of Φ_1 and Φ_2 for the deepest point of a semielliptical crack are obtained from Fig. 5.12, which is based on the analytical solution for a complete elliptical crack buried in an infinite elastic solid.²⁹ Using a flaw major axis length, $2b$ (scaled from Fig. 3.8) of 9.65 cm (3.80 in.), then $a/2b = 0.33$; and from Fig. 5.12, one obtains $\Phi_1 = 1.3$ and $\Phi_2 = 2.17$. Entering the above values into Eq. (23) gives $R^x = 0.76$, and therefore, from Eqs. (21) and (22), after substituting p_f^* for p and K_h for K_I ,

$$K_h/p_f^* = 12.65 \sqrt{\text{cm}} (7.94 \sqrt{\text{in.}}). \quad (24)$$

Fig. 5.12. Shape factors at the positive end of the semiminor axis of an elliptical crack in an infinite body under an arbitrary stress profile; applied by approximation to the deepest point of a semielliptical surface crack.^{27,28}

For $K_{IC} = 265 \text{ MN}\cdot\text{m}^{-3/2}$ (241 ksi $\sqrt{\text{in.}}$), solving Eq. (24) for the elastically calculated failure pressure gives $p_f^* = 210 \text{ MPa}$ (30.4 ksi). Then, by using the graphically estimated initial tangent to the finite-element pressure-strain curve shown in Fig. 5.8, one obtains the elastically estimated failure strain of 0.47% and, reading from the same pressure-strain curve at this value of strain, the estimated failure pressure of 154 MPa (22.4 ksi).

The Tangent Modulus Method (analysis performed by J. G. Merkle, ORNL)

Since the preceding analyses indicated that some yielding would occur in the nozzle corner region before fracture, calculations were made for vessel V-5 by the tangent modulus method of elastic-plastic fracture analysis (the details of the method are explained in Appendix H of Ref. 19). For this method of analysis, the fracture criterion is expressed in terms of a notch ductility factor, which is related to the fracture toughness by the equation¹⁹

$$\epsilon_f \sqrt{\rho} = (20 \lambda_f / \sqrt{\pi}) (K_{IC} / S_f) , \quad (25)$$

where ϵ_f is notch root strain at fracture, ρ is effective notch root radius, λ_f is tensile yield strain, S_f is tensile yield stress, and K_{IC} is fracture toughness. The yield stress of the nozzle material at 93°C (200°F) is 425 MPa (61.6 ksi) (see Table 5.4), and thus the yield strain is 0.205%. Substituting this value of λ_f into Eq. (25) and assuming that $K_{IC} = K_{IC}$ gives

$$\epsilon_f \sqrt{\rho} = 2.32 \times 10^{-2} (K_{IC} / S_f) . \quad (26)$$

In addition, for $K_{IC} = 265 \text{ MN}\cdot\text{m}^{-3/2}$ (241 ksi $\sqrt{\text{in.}}$), $K_{IC} / S_f = 6.23 \sqrt{\text{cm}}$ (3.91 $\sqrt{\text{in.}}$).

Analysis for frangible conditions

For an initially conservative calculation, it was first assumed that frangible behavior would occur. Under these conditions, the tangent modulus method reduces to the method of LEFM based on strain, except for the assumption of uniaxial nominal stress conditions. For frangible conditions, the failure strain is given by¹⁹

$$\lambda_f = \epsilon_f \sqrt{\rho} / 2C \sqrt{a} \sqrt{E/E_t} , \quad (27)$$

where λ_f is failure strain, a is flaw depth, E is elastic modulus, E_t is the tangent modulus of the strain-hardening branch of the stress-strain curve, and C is the LEFM shape factor based on the surface stress at the location of the flaw. It has been shown¹⁹ that a satisfactory approximation for the term $\sqrt{E/E_t}$ is

$$\sqrt{E/E_t} = 10 , \quad (28)$$

and this relationship was therefore used in the development of Eq. (25). The shape factor based on the local stress can be determined either by dividing the value obtained from Fig. 5.4 by the elastic stress-concentration factor K_t or by modifying Eq. (4) to read

$$C = \frac{1}{K_t (p_f^* / K_{IC}) (r_i / t) \sqrt{\pi a}} \quad (29)$$

Using Eq. (29) with $K_t = 2.79$ and the values of (p_f^*/K_A) , (r/t) , and a given previously gives $C = 0.883$, which is based on the peak nozzle corner stress in the elastic range. Then, by using Eqs. (26) and (28), Eq. (27) gives a failure strain estimate of

$$\lambda_f = \frac{(2.32)(3.91)}{(2)(0.883)\sqrt{1.2(10)}} = 0.469\% .$$

Finally, the failure pressure corresponding to a strain of 0.469% from the finite-element curve shown in Fig. 5.8, is 154 MPa (22.3 ksi).

Analysis for transition conditions

A more realistic assumption was used next; namely, the nozzle corner fracture strain was assumed to lie between the yield strain and the strain at the onset of strain hardening. Also, in recognition of the existence of a steep strain gradient in the nozzle corner region, the local fracture strain for the flaw in vessel V-5 was estimated by the tangent modulus equation for a flaw subject to bending in the transition range of strain. For the above two conditions, the sum of the elastic and transition range increments of the notch ductility factor¹⁹ is given by

$$2\sqrt{\lambda_f \lambda_T} - \lambda_T = \epsilon_f \sqrt{\rho} / 2C \sqrt{a \sqrt{E/E_s}} . \quad (30)$$

Since the right sides of Eqs. (27) and (30) are identical, it follows that

$$2\sqrt{\lambda_f \lambda_T} = 0.469 + 0.205 = 0.674\%$$

and, therefore, that $\lambda_f = 0.554\%$. Finally, the failure pressure corresponding to a strain of 0.554% from the finite-element curve shown in Fig. 5.8, is 164 MPa (23.8 ksi).

The Equivalent-Energy Method

Estimate based on finite-element calculations of the nozzle corner pressure-strain curve (analysis performed by J. G. Merkle, ORNL)

One procedure for applying the equivalent-energy method¹⁰ is a direct extension of LEFM based on the assumption that the area under the load-vs-local-strain curve for the flaw location continues to vary inversely with flaw size at failure in the postyield range. The governing equation for this approach is²³

$$K_{Icd} = 2\pi C^2 a U E' , \quad (31)$$

where K_{Icd} is the fracture toughness for the thickness of interest, C is the LEFM shape factor based on the local stress, U is the area under the load-vs-local-strain curve for the flaw location, and E' is the initial slope of the same curve. For convenience, the local stress is assumed to remain proportional to the pressure, and Eq. (31) is rewritten in terms of the pressure and the local strain to give

$$K_{Icd} = 2\pi C^2 \rho a U M , \quad (32)$$

where C_p is the LEFM shape factor based on pressure, M is the initial slope of the pressure-vs-nozzle-corner-strain curve, and U is redefined as the area under the same curve. Since the LEFM shape factor based on local stress is already known from the preceding analysis ($C = 0.883$), the shape factor based on pressure can be determined by writing

$$C_p p = C \sigma_{\max} \quad (33)$$

Using Eq. (7) with $\sigma_1 = \sigma_{\max}$ gives

$$C_p = CK(r/t) \quad (34)$$

therefore,

$$C_p = (0.883)(2.79)(2.25) = 5.54$$

Rearranging Eq. (32) gives

$$U = K_{td}^2 / 2\pi C_p^2 \rho M \quad (35)$$

The pressure and strain increments corresponding to the first three load increments of the finite-element analysis²⁰ used to plot the curve shown in Fig. 5.8 are listed in Table 5.5. Also listed in the table are the total values of U at the end of each load increment; these values are plotted vs pressure in Fig. 5.13. Using the first load increment values of pressure and strain, which define the end of the elastic range, one obtains a value for M of 447 MPa-%⁻¹ (64.84 ksi-%⁻¹). Therefore, from Eq. (35), the predicted value of U at failure is given by

$$U = \frac{(6.89)(2.41)^2 \times 10^3}{(2)(\pi)(5.54)^2(1.2)(6.484)} = 26.68 \text{ MPa}\cdot\% \text{ (3.87 ksi}\cdot\%)$$

From the curve shown in Fig. 5.13, the failure pressure at this value of U is 134 MPa (19.4 ksi), and from the pressure-strain curve shown in Fig. 5.8, the predicted nozzle corner strain at failure is 0.36%.

Table 5.5. Pressure, nozzle corner strain increment, and total energy values for the first three load increments of a finite-element elastic-plastic stress and strain analysis of intermediate test vessel 7-5

Load increment	Initial pressure [MPa (ksi)]	Final pressure [MPa (ksi)]	Strain increment (%)	Total energy [MPa·% (ksi·%)]
0	0 (0)	97.9 (14.2)	0.219	10.76 (1.56)
1	97.9 (14.2)	117 (17.0)	0.065	17.72 (2.57)
2	117 (17.0)	138 (20.0)	0.095	29.85 (4.33)

Fig. 5.13. Pressure-energy curve used for equivalent-energy analysis of vessel V-5.

Estimate based on steel model test data
(analysis performed by F. J. Witt, ORNL)

Another procedure for applying the equivalent-energy method involves the calculation of a shape factor from scale-model test data, as described in Appendix G of Ref. 19. This shape factor is calculated from model test data by rearranging Eq. (35) to read

$$C_p = K_{II,II} \sqrt{2\pi a U M} \quad (36)$$

where the value of $K_{II,II}$ used in the equation is the fracture toughness of the flawed region of the model. For analyzing a geometrically similar prototype, both the value of $K_{II,II}$ applicable to the flawed region of the prototype and the value of C_p determined from the model by Eq. (36) are entered into Eq. (35), thus determining the value of U at failure. The values of pressure and strain at fracture of the prototype are then determined by finding the point on the prototype pressure-strain curve where the area under the curve is equal to the computed value of U .

One scale model of vessel V-5 was tested prior to the test of vessel V-5. This model, which was designated nozzle model I, is shown in Fig. 5.14. Since only outside surface strain gages were used on the 1/2-scale steel models, these equivalent-energy calculations had to be based on exterior strain data instead of strain data at the inside nozzle corner opposite the flaw. Because of the lack of inside surface strain gages, it was originally planned to use the model data to confirm the accuracy of the elastic-plastic analysis discussed previously and then to use the analytically calculated inside nozzle corner pressure-strain curve for the vessel V-5 calculations. However, the experimental strain data from nozzle model I did not confirm the finite-element calculations (experimental strains considerably exceeded calculated strains),²¹ and therefore the vessel V-5 calculations had to be based on model test data alone.

Nozzle model I was fabricated from material taken from the cylindrical prolongation of vessel V-4. The material used to make the nozzle in nozzle model I was originally located near the outside surface of the prolongation. No toughness data were obtained for vessel V-4 outside surface base metal above 38°C (100°F). However, after a comparison was made between the toughness data for vessel V-4 base metal at a depth from the outside surface of 1.52 cm (0.6 in.), as shown in Fig. 5.15, and the outside surface

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Fig. 5.14. Nozzle model I before test.

Fig. 5.15. Fracture toughness K_{Ic} values vs temperature for intermediate test vessel V-4 base metal [$1 \text{ ksi}\sqrt{\text{in.}} = 1.0988 \text{ MN}\cdot\text{m}^{-1/2}$; $^{\circ}\text{C} = ^{\circ}\text{F} - 32$; $1 \text{ in.} = 2.54 \text{ cm}$].

toughness data for vessels V-1 and V-2, as shown in Fig. 5.16, it was judged that the value of $K_{Ic,0.85}$ for the nozzle material of the model at 88°C (190°F) should be about $233 \text{ MN}\cdot\text{m}^{-1/2}$ ($212 \text{ ksi}\sqrt{\text{in.}}$).

The flaw in nozzle model I was intended to have a depth of about 0.53 cm (0.21 in.). Before the nozzle was welded into the model cylinder, the flaw was prepared at an inside nozzle corner by machining, electron-beam welding, and hydrogen-charge cracking. After flawing and fabrication by welding, the model was stress relieved at 621°C (1150°F) for 1 hr, as discussed in Appendix B. It was instrumented with exterior surface strain gages according to the plan shown in Fig. B.2. It was then hydraulically pressurized at 88°C (190°F) to a maximum pressure of 246 MPa (35.7 ksi), at which leakage commenced, due to the inside nozzle corner flaw having grown by stable tearing to reach the

Fig. 5.16. Lower-bound static fracture toughness for vessels V-1 and V-2 from 0.85T compact tension specimens, circumferential orientation¹¹ [1 ksi√in. = 1.0988 MN·m^{-3/2}; °C = $\frac{5}{9}$ (°F - 32); 1 in. = 2.54 cm].

outside surface near the nozzle-to-cylinder weld. The vessel continued to retain a lower pressure of about 243 MPa (35.3 ksi) for a period of time during which some of the strain values continued to increase as additional stable tearing of the flaw took place. The experimental strain data obtained from nozzle model I are listed in Table B.1 of Appendix B. Posttest photographs of the model are shown in Figs. 5.17 and 5.18. Note the extent of flaw penetration to the outside surface and the large amount of crack opening that occurred at the inside surface due to the stable tearing of the flaw. Posttest measurements of flaw depth indicated that the original depth of the flaw was between 0.622 cm (0.245 in.) and 0.686 cm (0.270 in.).

The locations on the model for which experimental pressure-strain data were plotted for the purpose of determining an equivalent-energy shape factor (C_p) were the locations of strain gages 4 and 7 (see Fig. B.2). Both gages were located on the outside surface in the nozzle-to-cylinder intersection region and both measured strains across the plane of the crack. Since strains recorded by both gages were nearly identical, a single curve was drawn to represent the data (see Fig. 5.19). When the area under this curve up to a selected failure strain of 1.04% was measured, the pseudoelastic failure pressure, at which the area under the pseudoelastic linear pressure-strain diagram would be the same, was found to be 1503 MPa (218 ksi). This pseudoelastic failure pressure can also be calculated by means of the bilinear approximation to the pressure-strain diagram shown by the dashed curve in Fig. 5.19 using the

Fig. 5.17. Posttest photograph of nozzle model 1, outside view.

equation¹⁹

$$\eta_f^* = p_f \sqrt{1 + (p_f/p_1 + 1)(\lambda_{mf}/\lambda_{mf} - 1)} \quad (37)$$

where p_f and λ_{mf} are the coordinates of the "knee" of the bilinear curve for the model and p_1 and λ_{mf} are

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Fig. 5.18. Posttest photograph of nozzle model 1, inside view.

Fig. 5.19. Pressure-strain curves for strain gages 4 and 7 on nozzle model I.

the coordinates of the end point of the same curve. For the bilinear curve shown in Fig. 5.19, $p_y = 199$ MPa (28.8 ksi), $p_f = 259$ MPa (37.5 ksi), $\lambda_{ny} = 0.04\%$, and $\lambda_{nf} = 1.04\%$. Entering these values into Eq. (37) gives $p_f^* = 1503$ MPa (218 ksi), which agrees with the value determined by measuring areas under the actual pressure-strain curve. Since the value of U is related to p_f^* by

$$U = (p_f^*)^2 / 2M. \quad (38)$$

it follows, by substituting Eq. (38) into Eq. (36), that

$$C_p = K_{hd} / p_f^* \sqrt{\pi a}. \quad (39)$$

Using the values given previously, Eq. (39) thus gives

$$C_p = 212/218\sqrt{0.245\pi} = 1.1$$

The next step in the analysis was to estimate the fracture toughness of the full section thickness for the vessel V-5 nozzle material at the test temperature. This estimate was based on equivalent-energy toughness values obtained from precracked Charpy V-notch specimens and from 0.85T and 2T compact specimens. At the time these calculations were made, two PCCV specimens (specimens 5V-003 and 5V-005) had been tested at 93°C (200°F). Averaging the toughness values in Table A.1 for these two specimens, based on crosshead displacement, gives $K_{K1CV} = 184 \text{ MN}\cdot\text{m}^{-3/2}$ (167 ksi√in.). Next, reference is made to Fig. 2.15 and Table 5.3, which present the results of tests of three 0.85T compact specimens with a radial (CT) orientation (specimens V5-3, V5-4, and V5-5) at 93°C (200°F). Reanalyzing the experimental data for specimen V5-4 gives a value of $K_{K10.85T} = 231 \text{ MN}\cdot\text{m}^{-3/2}$ (210 ksi√in.). Averaging this value with that listed in Table 5.3 for the same specimen and then averaging the resulting value with those listed in Table 5.3 for the other two specimens gives $K_{K10.85T} = 204 \text{ MN}\cdot\text{m}^{-3/2}$ (186 ksi√in.). Finally, averaging the toughness values given in Table 5.3 for 2T CT specimens V5-1 and V5-2 gives $K_{K2} = 256 \text{ MN}\cdot\text{m}^{-3/2}$ (233 ksi√in.).

To estimate the toughness corresponding to a section thickness of 15.24 cm (6.0 in.), it was assumed that the volumetric energy ratio¹⁹

$$S_{m,d} = (d/m)(K_{Km}/K_{Kd})^2 \quad (40)$$

can be extrapolated as a linear function of thickness based on the 2T CT data and either the PCCV or the 0.85T CT data. In Eq. (40), m and d are two different thicknesses. It has been shown²⁵ that toughness estimates based on this assumption can be developed graphically by means of the type of plot shown in Fig. 5.20, where for convenience m has been chosen as the thickness of the specimen with the lowest toughness, so that $K_{Km} = 184 \text{ MN}\cdot\text{m}^{-3/2}$ (167 ksi√in.). Figure 5.20 was thus constructed using the following values:

d (cm (in.))	K_{Kd} ($\text{MN}\cdot\text{m}^{-3/2}$ (ksi√in.))	$(K_{Km}/K_{Kd})^2$
1.00 (0.394)	184 (167)	1.000
2.16 (0.85)	204 (186)	0.806
5.08 (2.0)	256 (233)	0.514

Projecting straight lines through the 2T CT point from both the PCCV and the 0.85T CT points to the line corresponding to $d = 15.24 \text{ cm}$ (6.0 in.) and then averaging the two resulting toughness estimates gives $K_{K6} = 289 \text{ MN}\cdot\text{m}^{-3/2}$ (263 ksi√in.).

The failure conditions for vessel V-5 were estimated by rewriting Eq. (39) to read

$$p_f^* = K_{Kd}/C_p\sqrt{\pi a} \quad (41)$$

Although the flaw in nozzle model I was slightly larger than required for geometric similitude, it was still assumed that $C_p = 1.1$ for a flaw depth of 3.05 cm (1.2 in.). Thus, using the values given above, Eq. (40)

Fig. 5.20. Fracture toughness estimate for nozzle material in vessel V-5; $K_{Iem} = 184 \text{ MN} \cdot \text{m}^{-3/2}$ (167 l.si $\sqrt{\text{in.}}$).

leads to

$$p_f^* = (6.89)(263) / 1.1 \sqrt{1.2\pi} = 848 \text{ MPa (123 ksi)}.$$

The remainder of the calculations for vessel V-5 were actually based on measured areas under the nonlinear pressure-strain curve shown in Fig. 5.19. However, substantially the same result can be obtained analytically by using the bilinear approximation to the pressure-strain curve shown by the

broken line in Fig. 5.19. The elastic-plastic portions of the curves shown in Fig. 5.19 were lowered by 12.4 MPa (1.8 ksi) to allow for the difference in yield stress between the model and the prototype nozzle materials. Thus, the parameters of the adjusted bilinear approximation to the model pressure-strain curve are $p_Y = 186$ MPa (27.0 ksi), $p_I = 246$ MPa (35.7 ksi), $\lambda_{mY} = 0.0384\%$, and $\lambda_{mI} = 1.04\%$. The local failure strain (see Ref. 19) can be estimated from

$$\lambda_f = \lambda_{mY} + (1/q) \{ \sqrt{1 + q[2(U/p_Y) - 1]} - 1 \} \quad (42)$$

where

$$q = \frac{p_I/p_Y - 1}{\lambda_{mI} - \lambda_{mY}} \quad (43)$$

$$U = (p_Y^*)^2 / 2M \quad (38)$$

and

$$M = p_Y \lambda_{mY} \quad (44)$$

From Eq. (44), $M = 4847$ MPa-% (703 ksi-%) and, from Eq. (38), $U = 74.19$ MPa-% (10.76 ksi-%). Using Eq. (43) gives $q = 0.3217\%^{-1}$. Consequently, Eq. (42) gives

$$\lambda_f = 0.0384 + (1/0.3217) \{ \sqrt{1 + 0.3217[2(10.76/27.0) - 0.0384]} - 1 \} = 0.397\%.$$

The failure pressure is estimated from¹⁹

$$\begin{aligned} p &= p_Y [1 + q(\lambda_f - \lambda_{mY})] \\ &= (6.89)(27.0)[1 + 0.3217(0.397 - 0.0384)] \\ &= 208 \text{ MPa (30.1 ksi)}. \end{aligned} \quad (45)$$

Thus failure was estimated to occur at a pressure of about 207 MPa (30 ksi), which corresponds to a calculated outside circumferential strain in the cylindrical region of the vessel, remote from the nozzle, of about 1.4% (see Fig. 5.21).

POSTTEST ANALYSES FOR VESSEL V-5

The Equivalent-Energy Method (analysis performed by F. J. Witt, ORNL)

Figure 5.22 shows that the circumferential strain normal to the crack plane on the outside surface of the nozzle in vessel V-5 at maximum pressure was close to the value of 0.397% predicted by the pretest equivalent-energy analysis, although the maximum pressure was less than predicted. The area under the pressure-strain curve at maximum pressure should also be reasonably close to the predicted value. For convenience, this area will be calculated by using the bilinear approximation to the measured pressure-strain curve represented by the dashed curve shown in Fig. 5.22. The parameters of the bilinear curve are $p_Y = 172$ MPa (25.0 ksi), $p_I = 187$ MPa (27.1 ksi), $\lambda_{mY} = 0.06\%$, and $\lambda_{mI} = 0.33\%$. The area under the

Fig. 5.21. Calculated pressure vs outside circumferential strain for cylindrical region of intermediate test vessel (1 ksi = 6.8948 MPa).

Fig. 5.22. Pressure vs outside circumferential strain data from gage 73 on intermediate test vessel V-5 tested at 88°C (190°F).

bilinear curve is given by

$$U = p_Y \lambda_{mY} / 2 + (p_Y + p_I) (\lambda_I - \lambda_{mY}) / 2. \quad (46)$$

Thus, from Eq. (46), $U = 53.6 \text{ MPa}\cdot\%$ (7.78 ksi·%), which is 72% of the predicted value.

The Stress-Concentration Method
(analysis performed by W. H. Irvine, UKAEA)

This method of analysis, which was applied previously to vessels V-1 and V-2, is described in Ref. 11. Briefly, crack extension is assumed to take place when the force originally carried by the crack area plus an additional area bordering the crack front of width S in the uncracked structure produces a stress equal to the ultimate tensile stress when carried by the additional area of width S alone. The width of the additional area S is considered to be a material property and is empirically related to the material ductility and the Charpy V-notch impact energy by the equations¹¹

$$S = 1.30\alpha(\text{CVN}/\sigma_Y)^{1/3} \quad (47)$$

and

$$\alpha = (\epsilon_t/20.76)^2. \quad (48)$$

In Eqs. (47) and (48), CVN is Charpy V-notch impact energy (ft-lb), σ_Y is yield stress (ksi), and ϵ_t is total elongation in a tensile test (%) when the specimen gage length is four times the square root of the specimen cross-sectional area. For other gage lengths, Ref. 11 gives a conversion formula for elongation values, which is

$$\epsilon_{t2} = \ln \{ 1 + (L_{n1}/L_{n2})(e^{e_{t1}} - 1) - [(L_{n1}/L_{n2}) - 1](e^{e_t} - 1) \} , \quad (49)$$

where ϵ_t is tensile necking strain, L_{n1} and L_{n2} are the two gage lengths, and ϵ_{t1} and ϵ_{t2} are the two corresponding total elongations expressed as decimals. Using the values of ϵ_{t1} , L_{n1} and e_t given in Table 5.4, Eq. (49) gives $\epsilon_{t2} = 24\%$. Thus, Eq. (48) gives $\alpha = 1.34$. Since no CVN impact energy data were obtained for vessel V-5 material at 88°C (190°F), it was assumed that CVN = 136 J (100 ft-lb), so that Eq. (47) gives $S = 5.23$ cm (2.06 in.). For calculations, it was assumed for simplicity that $S = 5.08$ cm (2.0 in.).

As an approximation, the nozzle corner crack front was treated as a straight line perpendicular to the nozzle corner diagonal and intersecting both the nozzle and the cylinder inside surfaces at equal distances of 6.73 cm (2.65 in.) from the point of intersection of the inside surface tangents, based on Fig. 3.8. The corresponding crack depth, based on an inside nozzle corner radius of curvature of 3.81 cm (1.50 in.), is 3.18 cm (1.25 in.). The crack area AC was calculated to be 19.55 cm² (11.50 in.²). (A detail sketch of this flaw geometry, which was also used later for the analysis of vessel V-9, is given in Fig. 5.27. Note, however, that the flaw depth given does not agree exactly with the one just determined because the crack front was not perfectly straight.) Applying the failure criterion

$$\sigma_n(AC TZ) = \sigma_{gu}(AC + ACTZ) , \quad (50)$$

which does not include the effects of pressure acting on the crack faces, gives

$$\sigma_{gu} = \sigma_n(AC TZ) / (AC + ACTZ) , \quad (51)$$

where σ_{gu} is the gross average stress over $AC + ACTZ$ in the absence of the crack and σ_n is the ultimate

tensile stress. Table 5.4 shows that σ_u is approximately 552 MPa (80 ksi), so that from Eq. (51), $\sigma_{pm} = 436$ MPa (63.3 ksi). Since σ_{pm} slightly exceeds the yield stress [425 MPa (61.6 ksi)], failure was expected to occur at the gross yield pressure of the cylinder (reasoning, apparently, that a properly designed nozzle intersection region would not have a gross yield pressure less than that of the plain cylindrical region). The gross yield pressure of the plain cylindrical region was estimated from

$$p_r = \frac{\sigma_r}{(r_i/t)} \quad (52)$$

which gives $p_r = 189$ MPa (27.4 ksi) as the estimated failure pressure.

Linear Elastic Fracture Mechanics Based on Strain (analysis presented in Ref. 31)

The PVRC Ad Hoc Group on Toughness Requirements, which prepared WRC Bulletin 175 (Ref. 14), has also prepared a draft report concerning toughness criteria for regions of stress concentration.¹¹ This report contains descriptions of several proposed methods of elastic-plastic fracture analysis supplemented by calculations for some of the intermediate test vessels by several of the proposed methods. For the LEFM method based on strain, the analysis of vessel V-5 is identical to the previously described Westinghouse pretest analysis based on a value of K_I determined by the method described in Ref. 14.

Modified WRC-175 Method (analysis presented in Ref. 31)

An approximate method of elastic-plastic fracture analysis was suggested in Ref. 14 (WRC-175), based on the assumption that the actual fracture stress decreases linearly with flaw size between the ultimate tensile stress at zero flaw size and the yield stress at a flaw size that can be calculated by LEFM. This method also incorporates the assumptions that the elastically calculated strain is a good estimate of the actual strain and that the actual stress can be estimated by reducing the elastically calculated stress by an amount proportional to the estimated plastic strain. However, trial calculations made by this method showed that it could be unconservative when stresses are nearly or completely statically determinate. Consequently, the step of reducing the elastically calculated stress to a lower value was eliminated in Ref. 31. The modified method was then used to calculate a critical flaw size for vessel V-5 at the measured failure pressure of 183 MPa (26.6 ksi). The average membrane stress near the nozzle corner, in the plane of the flaw, was estimated by averaging the stress indices given for this region in Section III, Subsection NB, Table 3338.2(C)-1 of the ASME code for nuclear vessels.¹² The average membrane stress near the nozzle corner, σ'_{mp} , was then calculated from

$$\sigma'_{mp} = \sigma_{mp}(l_i + l_o)/2 \quad (53)$$

where σ_{mp} is the average of the elastically calculated inside and outside surface stresses in the cylindrical region of the vessel. For an intermediate test vessel,¹³

$$\sigma_{mp} = 2.84p - 0.5p = 2.34p \quad (54)$$

Thus, by using Eq. (54), Eq. (53) gives

$$\begin{aligned}\sigma_{mp} &= (6.89)(26.6)(2.34)(3.1 + 1.2)^2 \\ &= 924 \text{ MPA (134 ksi)}\end{aligned}$$

Because σ_{mp} exceeds the ultimate tensile stress, the calculated critical flaw size is negative and thus the modified WRC-175 method is not useful for this problem.

The Strain Tolerance Method (analysis presented in Ref. 31)

This method of estimating fracture strains in the inelastic range is an extension of Randall's gross strain approach,¹¹ in which the fracture strain for a given flaw size and temperature is estimated by means of an experimentally based fracture analysis diagram plotted in terms of strain. Such a diagram was constructed by first drawing a strain tolerance-vs-temperature curve for a flaw depth of 6.10 cm (2.40 in.) based on the experimental data obtained from the intermediate tensile test specimens,¹⁴ as shown in Fig. 5.23. Then, by using the test data from the smaller gross strain tension specimens,¹¹ temperature shifts due to flaw size were calculated by assuming that the temperature for failure at a given strain level varies inversely with the square root of the flaw size. Failure temperatures for specific strains

Fig. 5.23. Strain tolerance data from flawed intermediate tensile test specimens tested by Southwest Research Institute.¹¹

were thus calculated empirically from³¹

$$T_{0.5} = 154 - 116/\sqrt{a}, \quad (55)$$

$$T_{1.0} = 160 - 96/\sqrt{a}, \quad (56)$$

and

$$T_{2.0} = 166 - 83/\sqrt{a}, \quad (57)$$

where flaw size is in inches, temperature is in degrees Fahrenheit, and the subscripts indicate percent strain at fracture. The resulting strain tolerance diagram is shown in Fig. 5.24. The upper end points of the curves shown in the figure were determined by estimating the gross section strain at tensile instability following stable crack growth as a function of flaw size, based on the gross strain³¹ and intermediate tensile specimen³⁴ test data. In the case of vessel V-5, using Fig. 5.24, a test temperature of 88°C (190°F), and a flaw size of 3.05 cm (1.20 in.) results in an estimated strain tolerance of 3.3% and the conclusion that net section plastic instability should precede failure. Although no estimate of failure pressure is given in Ref. 31, the pressure corresponding to a nozzle corner strain of 3.3% from the experimental curve for vessel V-5 shown in Fig. 4.15, is 177 MPa (25.7 ksi).

Fig. 5.24. Strain tolerance curves for A533, grade B, class 1 steel from the HSST program as a function of temperature and flaw size.³¹

Stress-Concentration Factor Calculations

Since the measured strains at the inside nozzle corner opposite the flaw in vessel V-5 exceeded the pretest estimates made by all methods (elastic finite element, strain gaged epoxy models, and elastic-plastic finite element), calculations of the experimental elastic stress-concentration factor were made for a pressure near the nozzle corner yield pressure. The equations involved are

$$\sigma_1 = [E(\epsilon_1 + \nu\epsilon_2) - \nu(1 + \nu)p] / (1 - \nu^2) \quad (58)$$

$$\sigma_2 = [E(\epsilon_2 + \nu\epsilon_1) - \nu(1 + \nu)p] / (1 - \nu^2) \quad (59)$$

and, from Eq. (7),

$$K_t = (\sigma_1/p) \cdot (r_i/r) \quad (60)$$

For $E = 20.7 \times 10^4$ MPa (3×10^4 ksi) and $\nu = 0.3$, and with ϵ_1 and ϵ_2 expressed in percent and p in ksi, Eqs. (58) and (59) can be written as

$$\sigma_1 = 329.67\epsilon_1 + 98.90\epsilon_2 - 0.4286p \quad (61)$$

$$\sigma_2 = 329.67\epsilon_2 + 98.90\epsilon_1 - 0.4286p \quad (62)$$

The ϵ_1 value is recorded by gage 24 and ϵ_2 by gage 25 (see Fig. 4.7). Referring to Table C.1, at a pressure of 27.6 MPa (4 ksi), $\epsilon_1 = 0.1444\%$ and $\epsilon_2 = -0.0340\%$. Thus, using Eqs. (61), (62), and (60),

$$\sigma_1 = 293.2 \text{ MPa (42.53 ksi)} \quad (63)$$

$$\sigma_2 = 9.4 \text{ MPa (1.36 ksi)} \quad (64)$$

and

$$K_t = 4.73 \quad (65)$$

These calculations indicate that the actual value of K_t for the intermediate test vessel nozzles exceeds 4 and that the state of stress at the inside nozzle corner is nearly uniaxial rather than nearly plane strain. In consideration of the importance of these findings, it was planned to acquire a greater amount of nozzle corner strain data from the test of vessel V-9 at pressures less than the initial yield pressure of the nozzle corner. The data would facilitate the inclusion of both a more accurate estimate of the nozzle corner elastic stress-concentration factor and a realistic appraisal of transverse restraint effects in methods of fracture analysis proposed for nozzle corner cracks. However, since sufficient data of this type were not available before the test of vessel V-9, the calculations were based on substantially the same set of assumptions used for vessel V-5. It was recognized that the accuracy of these calculations might be limited if the strain data just discussed from vessel V-5 were correct.

PRETEST ANALYSES FOR VESSEL V-9

Selection of Test Conditions

Since upper-shelf conditions conducive to large amounts of stable crack growth and eventual leakage without rupture had clearly existed in the test of vessel V-5, it was decided to test vessel V-9 with a flaw of the same size and at a temperature low enough for fast fracture to occur but high enough for crack arrest to be possible, if dictated by the interaction between crack size, toughness, and stress conditions. In principle, such a combination of events would be most likely to occur at a temperature below the upper-shelf range at which the static initiation and crack arrest fracture toughnesses are about equal. Therefore, preliminary LEFM calculations were made to determine if crack arrest could be expected, assuming that $K_{Ia} = K_{Ic}$. Based on the posttest crack-sharpening ultrasonic measurements made of the flaw depth in vessel V-9, as summarized in Fig. 3.8, the flaw depth was estimated to be 3.05 cm (1.2 in.), the same as that in vessel V-5. Consequently, for initial crack extension, the same relationship between p and K_I obtained from Fig. 5.6 and used for vessel V-5 was applied to vessel V-9:

$$K_I/p = 1/0.093 = 10.75 \quad (63)$$

A through crack in the cylinder was analyzed for considering the possibility of crack arrest in the cylindrical region of the vessel near the nozzle. The crack had a total length equal to the inside radius of the nozzle plus the distance from the nozzle axis to a point on the inside surface of the cylinder, at which the nominal stress had decreased to a value about 10% above that for the cylinder without a nozzle. The nominal inside surface stress in a plain intermediate test vessel cylinder¹¹ is $2.84p$. Therefore, a value 10% higher for $p = 6.89$ MPa (1000 psi) is 21.54 MPa (3124 psi); from Fig. 5.25b, this value occurs¹² about 36.83 cm (14.5 in.) from the nozzle axis. Thus, the total crack length to be considered was about 48.26 cm (19.0 in.). Since a through crack with a total length of 47.30 cm (18.62 in.) had already been considered¹³ in the analysis of vessel V-7, the previous analysis was used here also for convenience. Neglecting the plastic zone size correction used previously, the value of K_I is given by¹⁴

$$K_I = \sqrt{1.1 M_h \sigma_h \sqrt{\pi a}} \quad (64)$$

For the assumed crack,¹⁵ $M_h = 1.45$, $a = 23.65$ cm (9.31 in.), and by using Eq. (2), Eq. (64) gives $K_I/p = 18.51$. Since this value exceeds the value of 10.75 computed for extension of the initial nozzle corner flaw, crack arrest without the aid of a pressure drop was not considered likely in vessel V-9 for $K_{Ia} = K_{Ic}$.

At the time the preceding calculations were made, the only toughness-vs-temperature data available for vessel V-9 were the PCCV static initiation toughness data for the nozzle material shown in Fig. 2.18 and the PCCV dynamic initiation toughness data previously obtained¹⁶ for vessel V-7 (Fig. 5.26). The latter data were considered tentatively applicable to the cylinder of vessel V-9 because the cylinders of vessels V-7 and V-9 were fabricated from the same heat of steel,^{15,16} as discussed in Chapter 2. A comparison of the static and dynamic fracture toughness data given in Figs. 2.18 and 5.26 showed that for the dynamic toughness not to exceed the static toughness, a test temperature below 0°C (32°F), at which plain water could not be used as the pressurizing fluid, would probably be required. Therefore, it was decided to test at 24°C (75°F), a temperature at which some stable crack growth but eventual fast fracture could still reasonably be expected. Furthermore, this test temperature provided the practical advantage of not having to heat or cool the vessel for an indoor test in August and also matched the previous test temperature of vessel V-4.

Fig. 5.25. Circumferential stress contours (σ_θ) on longitudinal section ($\theta = 0^\circ$) for an intermediate test vessel; $p = 6.895$ MPa (1000 psi) (Ref. 10); 1 in. = 2.54 cm.

Fig. 5.26. Dynamic fracture toughness values measured with CA-oriented precracked Charpy V-notch specimens of vessel V-7 material.²³ [1 ksi√in. = 1.0988 MN·m^{1/2}; °C = °F - 32].

Table of Pretest Analysis Data

The test temperatures for the 0.85T, 1.5T, and 2T compact specimens of vessel V-9 nozzle material tested by Westinghouse²⁴ were selected on the basis of a tentative vessel test temperature of 24° C (75° F). The results of all the toughness tests performed on vessel V-9 material are summarized in Fig. 2.20, which shows considerable scatter in the toughness data and overlapping of the scatter bands for the dynamic and static toughness values at the test temperature. The other material and geometry data applicable to vessel V-9 are summarized in Table 5.6. The instrumentation used for vessels V-9 and V-5 was the same (Chapter 4).

Linear Elastic Fracture Mechanics Based on Strain (analysis performed by J. G. Merkle, ORNL)

An examination of the fracture toughness data for the vessel V-9 nozzle material listed in Table 2.6 revealed no consistent effect of specimen location on the 0.85T CT static initiation fracture toughness

**Table 5.6. Data for pretest fracture analysis of RSST program
intermediate test vessel V-9**

Nozzle material	A508, class 2 forging steel, base metal
Nozzle NDT temperature	-12°C (+10°F) (assumed, based on V-1 data)
Vessel test temperature	24°C (+75°F)
Expected fatigue-sharpened flaw depth at inside nozzle corner ^a	3.05 cm (1.2 in.)
Tensile properties of nozzle material at 24°C (75°F) ^b	
Yield stress	474 MPa (68.8 ksi)
Ultimate stress	609 MPa (88.3 ksi)
Strain at maximum load	9.0%
Total elongation	18.1%
Gage length	3.175 cm (1.250 in.)
Reduction in area	70.3%
Original specimen diameter	0.4509 cm (0.1775 in.)
Tensile and drop-weight NDT properties of cylinder material (A533, grade B, class 1 steel) ^c	
Yield stress	475 MPa (68.9 ksi)
Ultimate stress	574 MPa (83.3 ksi)
Total elongation	28%
Gage length	5.08 cm (2.0 in.)
NDT temperature	-51°C (-60°F)
Nozzle dimensions ^d	
Inside radius	11.43 cm (4.5 in.)
Thickness	15.24 cm (6.0 in.)
Cylinder dimensions	
Inside diameter	68.58 cm (27.0 in.)
Thickness	15.24 cm (6.0 in.)
Charpy V-notch impact energy of nozzle material ^d at 24°C (75°F)	90.8 J (67 ft-lb)

^aSee Fig. 3.8.

^bSpecimen 9V-213 (see Table A.5).

^cAverage of fabricator's data (see Ref. 36, p. 12). Tensile properties at room temperature.

^dSee Fig. 2.2.

values. Furthermore Fig. 2.20 shows no consistent effect of specimen size on the static initiation fracture toughness at 24°C (75°F) because (1) the 1.5T CT specimens gave values near the middle of the static toughness range, (2) both greater and lesser values were obtained from smaller specimens, and (3) the minimum and maximum values were both obtained from the 2T CT specimens. Consequently, it was decided to make static initiation calculations for three toughness values covering the full range of the values measured at 24°C (75°F): 159 MN·m^{-1/2} (145 ksi√in.), 220 MN·m^{-1/2} (200 ksi√in.), and 298 MN·m^{-1/2} (271 ksi√in.). Because the steepest part of the dynamic fracture toughness transition curve occurs at 24°C (75°F) and the range of dynamic values extends from below to above the range of static values, both stable crack growth and "popins" were considered possible.

Since the crack size and the geometry for vessels V-5 and V-9 were the same, it followed, based on the epoxy model vessel test data, that

$$p_f^0 = 0.093 K_k \quad (65)$$

However, since the finite-element estimate of the pressure-strain curve for vessel V-5 given in Fig. 5.8 was not accurate with respect to the experimental curve shown in Fig. 4.15, it was decided to base the calculations for vessel V-9 on the curve obtained experimentally from vessel V-5. By scaling, the slope of the initial tangent to the curve shown in Fig. 4.15 is given by

$$M = 164 \text{ MPa-}\epsilon\%^{-1} \text{ (23.8 ksi-}\epsilon\%^{-1}) \quad (66)$$

and the estimated failure strain is computed from

$$\lambda_f = p_f^0 / M \quad (67)$$

The estimated failure pressure is the pressure corresponding to λ_f , as read from the pressure-strain curve shown in Fig. 4.15. Thus, by using Eqs. (65) and (67) and Fig. 4.15, the following conditions at crack initiation were estimated for vessel V-9:

K_k [MN-m ^{-3/2} (ksi√in.)]	p_f^0 [MPa (ksi)]	λ_f (%)	p_f [MPa (ksi)]
159 (145)	93.1 (13.5)	0.6	93.1 (13.5)
220 (200)	128 (18.6)	0.8	108 (15.6)
298 (271)	174 (25.2)	1.1	127 (18.4)

POSTTEST ANALYSES FOR VESSEL V-9

The Stress-Concentration Method (analysis performed by W. H. Irvine, UKAEA)

These calculations were based on a refinement of the analysis method used for vessel V-5, incorporating both the effects of pressure acting on the crack faces and an assumed relationship between the uncracked nozzle region stress distribution and the gross average stress acting over the depth of the crack plus the plastic zone of width S . When a crack face pressure term is added to the right side of Eq. (50), the failure criterion becomes

$$\sigma_n(ACTZ) = p_f(AC) + \sigma_{pn}(AC + ACTZ) \quad (68)$$

Equation (68) is rearranged to give an estimate of σ_{pn} , the gross average stress in the uncracked nozzle region over the depth $(a + S)$, which is

$$\sigma_{pn} = \frac{\sigma_n(ACTZ/AC) - p_f}{1 + ACTZ/AC} \quad (69)$$

Note that the value of σ_{pm} now depends on a preliminary estimate of the failure pressure p_f . The estimated value of σ_{pm} is related to the stress distribution in the uncracked nozzle region by the method described graphically in Fig. 5.27, which shows the calculated results for vessel V-9. Following a suggestion by Krishnamurthy,¹⁰ the variation of the elastically calculated stress in the uncracked nozzle region along the bisector of the nozzle intersection angle in the longitudinal plane, which is also the crack centerline of the cracked nozzle, is represented empirically by

$$\sigma_H = \sigma_0 e^{-\mu x} \quad (70)$$

where x is distance from the inside nozzle corner. For the intermediate test vessels, Krishnamurthy¹⁰ estimated values of μ ranging from 0.175 to 0.211, depending on the fineness of the finite-element mesh. The value of μ used for this analysis was 0.178. As shown in Fig. 5.27, the curve of $\sigma_H(x)$ is truncated at the yield stress, and the area under the $\sigma_H(x)$ curve between $x=0$ and $x=(a+S)$ is then set equal to $\sigma_{pm}(a+S)$. By integration, the result is

$$d = \frac{\ln(\sigma_0/\sigma_Y)}{\mu} \quad (71)$$

where d is the value of x at which the nominal stress reaches the yield stress. For $d \leq (a+S)$, (σ_0, σ_Y) is

Fig. 5.27. Nozzle intersection region stress distribution used for fracture analysis of intermediate test vessel V-9 by the stress-concentration method.

determined from

$$\ln(\sigma_n/\sigma_T) = (\sigma_n/\sigma_T)e^{-\mu(a+S)} + (\sigma_{gr}/\sigma_T)(a+S) - 1, \quad (72)$$

which can be solved easily by successive approximation. Once the value of (σ_n/σ_T) is known, p_f can be calculated from the equation

$$p_f = \frac{\int_0^l \sigma_n dx}{\sigma_T l} p_T, \quad (73)$$

where p_T is computed from Eq. (52). Before calculating p_f , the condition $d \leq (a+S)$ should be checked to ensure the applicability of the following equations. The value of the numerator in Eq. (73) is determined by

$$\int_0^l \sigma_n dx = \sigma_{gr}(a+S) + (\sigma_n/\mu)[e^{-\mu(a+S)} - e^{-\mu l}], \quad (74)$$

where l is the value of x at the outside surface of the nozzle intersection region. Thus, by combining Eqs. (74) and (73), the value of p_f is given by

$$p_f = \{(\sigma_{gr}/\sigma_T)[(a+S)/l] + [(\sigma_n/\sigma_T)/\mu l][e^{-\mu(a+S)} - e^{-\mu l}]\} p_T. \quad (75)$$

The value of S was determined by the same procedure used for vessel V-5. Referring to the tensile elongation data given in Table 5.6, the total tensile elongation for a specimen with a gage length equal to four times the square root of the specimen cross-sectional area, as computed from Eq. (49), is 26.2%. Next, from Eq. (48), $\alpha = 1.593$. Then, using $CVN = 90.8 \text{ J}$ (67 ft-lb) as given in Table 5.6, Eq. (47) gives $S = 5.26 \text{ cm}$ (2.07 in.). The crack area is the same as for vessel V-5, so that referring to Fig. 5.27,

$$AC = (A^2/2) - r^2[1 - (\pi/4)] = 19.55 \text{ cm}^2 (3.03 \text{ in.}^2). \quad (76)$$

However, the area of the crack tip zone of width S is slightly greater than that for vessel V-5 because of the slight increase in the value of S . For the straight crack front assumed, as shown in Fig. 5.27,

$$ACTZ = LS + S^2 = 77.68 \text{ cm}^2 (12.04 \text{ in.}^2). \quad (77)$$

Using Eq. (69), with $\sigma_n = 476 \text{ MPa}$ (69 ksi), values of σ_{gr} were calculated for three different assumed failure pressures, as shown below

p_f [MPa (ksi)]	σ_{gr} [MPa (ksi)]
103 (15.0)	465 (67.5)
138 (20.0)	452 (65.5)
172 (25.0)	452 (65.5)

A value of $\sigma_{gr} = 462 \text{ MPa}$ (67.0 ksi) was then assumed for further calculations. Then, using an assumed value of $\sigma_T = 476 \text{ MPa}$ (69 ksi), Eq. (72) was solved by successive approximations to give $(\sigma_n/\sigma_T) = 1.483$.

Thus, from Eq. (71), $d = 5.61$ cm (2.21 in.), which is less than $(a + S)$ as assumed. The gross yield pressure was calculated from Eq. (52) as $p_Y = 211$ MPa (30.67 ksi). Therefore, using the previously determined values and assuming that $a = 3.05$ cm (1.2 in.) and $t = 22.86$ cm (9.0 in.), Eq. (75) gave $p_f = 144.6$ MPa (20.97 ksi). This value p_f could have been used to calculate a new value of σ_m , and the entire calculation repeated, but this refinement was not considered necessary.

Linear Elastic Fracture Mechanics Based on Strain (analysis presented in Ref. 31)

This estimate, which was performed by the same method used in Ref. 31 for vessel V-5, is described graphically in Fig. 5.28. The nozzle corner pressure-strain curve used was the finite-element estimate shown in Fig. 5.8, despite the fact that this curve tends to overestimate pressure as a function of strain, as indicated by the experimental curves shown in Fig. 4.27. Two extreme toughness values were assumed. These are listed in Table I.2, taken from Ref. 37, and approximate the values given in Table 2.6 for the two 2T CT specimens of vessel V-9 material tested by Westinghouse.³⁴ The resulting estimated failure conditions for vessel V-9 are:

K_{Ic} [MN-m ^{-3/2} (ksi√in.)]	p_f [MPa (ksi)]	λ_f (%)
165 (150)	128 (18.6)	0.33
302 (275)	170 (24.6)	0.61

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Fig. 5.28. Estimate of failure pressure for intermediate test vessels V-5 and V-9, with nozzle corner flaws, by the method of LEFM based on strain.³¹

Modified WRC-175 Method (analysis presented in Ref. 31)

Since the measured failure pressure of vessel V-9 was slightly above the failure pressure of vessel V-5, the elastically estimated maximum stress in the unflawed nozzle corner region of vessel V-9 at failure also exceeds the ultimate tensile stress. Thus, this method, as previously explained, is not useful for calculating a critical flaw size.

The Strain Tolerance Method (analysis presented in Ref. 31)

This method was also applied to vessel V-5, as discussed previously. The predicted nozzle corner strains at failure for both vessels V-5 and V-9 are shown in Fig. 5.24. The predicted nozzle corner strain at failure for vessel V-9 is 1.25%. Although no estimate of failure pressure is given in Ref. 31, the pressure corresponding to a nozzle corner strain of 1.25% (from the experimental curve for vessel V-9 shown in Fig. 4.24) is 148 MPa (21.5 ksi).

Stress-Concentration Factor and Principal Stress Calculations from Experimental Data

Since the elastic stress-concentration factor calculated from the experimental data for vessel V-5 at a pressure of 27.6 MPa (4.0 ksi) considerably exceeded the pretest estimates, strain readings from vessel V-9 were taken at several closely spaced values of low pressure to determine the elastic stress-concentration factor and the intermediate principal stress at the nozzle corner with greater certainty. Before the onset of yielding, the principal stresses were calculated from Eqs. (61) and (62). After yielding, but prior to the onset of strain hardening, the principal stresses at the nozzle corner were calculated by using the Tresca (maximum shear stress) yield criterion. Thus, the maximum principal stress is given by

$$\sigma_1 = \sigma_r + \sigma_1 \quad (78)$$

where

$$\sigma_1 = -p \quad (79)$$

Since there is no plastic strain in the direction of the intermediate principal stress, which in this case is the direction tangential to the nozzle corner in the plane of the crack, it follows that

$$\sigma_2 = E\epsilon_2 + \nu(\sigma_1 + \sigma_1) \quad (80)$$

The experimental strain data for the unflawed nozzle corner of vessel V-9 are listed in Table C.3. The value of ϵ_1 was measured by strain gage 24 and ϵ_2 was measured by gage 25. The resulting values of the principal stresses and the elastic stress-concentration factor calculated for selected pressures between 6.89 MPa (1.0 ksi) and 75.8 MPa (11.0 ksi) are listed in Table 5.7. For pressures equal to or better than 75.8 MPa (11.0 ksi), the value of σ_2 calculated from Eq. (80) is a higher compressive stress than the pressure, indicating that for these conditions $\sigma_2 = \sigma_1 = -p$, which is a so-called "corner" yield condition. The value of the elastic stress-concentration factor is consistently close to or greater than 4, thus supporting the value calculated previously for vessel V-5. The value of σ_2 is consistently small and, after

Table 5.7. Principal stress and elastic stress-concentration factor values at the inside unflawed nozzle corner of intermediate test vessel V-9, calculated from experimental strain data

Pressure [MPa (ksi)]	Stress (MPa)			Remarks	K_t
	σ_1	σ_2	σ_3		
6.9 (1.0)	63	0.4	-6.9	Elastic	4.05
13.8 (2.0)	134	3.5	13.8	Elastic	4.33
34.5 (5.0)	302	6.2	34.5	Elastic	3.89
55.2 (8.0)	419	9.9	-55.2	Yield	
68.9 (10.0)	405	-47.8	-68.9	Yield	
75.8 (11.0)	399	-75.8	75.8	Yield (corner)	

yielding, eventually becomes compressive and equal to the vessel internal pressure. Thus the existence of a partial restraint condition around the nozzle corner flaw border, similar to the one existing in a surface cracked uniaxial tensile specimen,¹⁹ is indicated.

Summary of Pretest and Posttest Calculations

The pretest and posttest calculations for vessels V-5 and V-9 are summarized in Table 5.8. All the estimated nozzle corner strains at failure for both vessels were low, most of them by a wide margin. All but two of the estimated failure pressures were also low, again mostly by a considerable margin. The two most accurate estimates were those made by the stress-concentration and the strain tolerance methods

Table 5.8. Pretest and posttest calculations for vessels V-5 and V-9

Method of analysis	Vessel V-5		Vessel V-9	
	P_f [MPa (ksi)]	λ_f (%)	P_f [MPa (ksi)]	λ_f (%)
Pretest estimates^a				
Graphical estimate	159 (23.0)	<u>0.52</u>		
LEFM based on strain				
K_t estimate from epoxy data	132 (19.1)	<u>0.35</u>	93-127 (13.5-18.4)	<u>0.6-1.1</u>
K_t estimate from WRC-175	161 (23.4)	<u>0.53</u>		
K_t estimate from finite-element analysis	154 (22.4)	<u>0.47</u>		
Tangent modulus method				
Frangible	154 (22.3)	<u>0.47</u>		
Transition	164 (23.8)	<u>0.55</u>		
Equivalent-energy method				
Based on finite-element p - λ curve	134 (19.4)	0.36		
Based on steel model data	207 (30.0)	1.4		
Test results				
	<u>183 (26.6)</u>	<u>6.5</u>	<u>185 (26.9)</u>	<u>8.4</u>
Posttest calculations^a				
Stress-concentration method	<u>189 (27.4)</u>		<u>145 (21.0)</u>	
LEFM based on strain	161 (23.4)	<u>0.53</u>	128-170 (18.6-24.6)	<u>0.33-0.61</u>
Modified WRC-175 method	(Not applicable)		(Not applicable)	
Strain tolerance method	177 (25.7)	<u>3.30</u>	148 (21.5)	<u>1.25</u>
Additional posttest calculations for partial restraint conditions (See Table 5.10)				

^aUnderlined values were determined by the method indicated; other values were determined from the calculated values and an estimate of the pressure-strain curve.

for vessel V-5. Almost all the methods that gave low estimates shared the common assumption of plane strain fracture toughness conditions, which was not made for the two most accurate estimates. This fact, combined with the knowledge that the intermediate principal stress at the inside nozzle corner is small and eventually becomes compressive after yielding, implies that the assumption of plane strain conditions around a nozzle corner crack may be neither necessary nor desirable. In addition, the general overconservatism of the methods directly based on LEFM for nozzle corner cracks also led to additional efforts to confirm or improve the calculations of both K_I and nozzle corner strain made previously. These more recent development efforts are described in the next section of this chapter.

ADDITIONAL EXPERIMENTS AND CALCULATIONS

Stress-Intensity Factor Estimates and Data

Effects of pressure in the crack

Since the LEFM-based estimates of nozzle corner strain at failure for vessels V-5 and V-9 were all low, as shown by Fig. 4.27, the possibility was considered that the nozzle corner crack shape-factor values used for these estimates were too high, especially those based on the epoxy model fracture data.¹¹ However, the three more recent independent developments discussed below all tend to confirm the shape-factor values used for analysis.

An analysis by Embley⁹ shows that the difference between the shape-factor curves in Fig. 5.4 for the intermediate test vessels, one based on the epoxy model fracture data¹¹ and the other based on a flat-plate analysis,¹⁴ is mostly due to the effects of pressure in the crack; these are included in the epoxy model vessel test data but not in the flat-plate analysis. The solutions for a single through crack extending from a circular hole in a flat plate under uniaxial and equibiaxial remote tensile stress fields are available.⁷ Embley⁹ reasoned that the free body diagram of the hole and the crack configuration can be developed by superposing two cases as shown in Fig. 5.29. Furthermore, case B is pure hydrostatic compressive loading, which contributes nothing to the value of K_I . In addition, case A can be represented as the sum of two cases. The first is a case of remote uniaxial tension, perpendicular to the crack plane, of magnitude $\sigma_h/2$; the second is a case of remote equibiaxial tension of magnitude $\sigma_h/2 + p$. Therefore, using Eq. (2), the value of K_I is given by

$$K_I = \sigma_h \sqrt{\pi a} [F_C/2 + (1/2 + 1/r)F_B] \quad (81)$$

where F_C and F_B are the single crack coefficients for uniaxial and equibiaxial loading, respectively, given in Ref. 7. Figure 5.30 shows curves computed by Eq. (81) for the reactor pressure vessel configuration considered by Gilman and Rashid¹⁶ and the two epoxy model vessels tested by Derby.¹³ It is clear from the figure that the major differences between previous shape-factor estimates for nozzle corner cracks are resolved by considering the effects of pressure in the crack⁹ and that the accuracy of the epoxy model test results for application to the intermediate test vessels is confirmed.

Three-dimensional finite-element analysis

A three-dimensional, elastic-plastic, finite-element analysis of the flawed nozzle region in vessel V-5, including the pressure loading on the crack faces, was performed using the MARC-3D program.²¹ Although the computed surface strains were generally less than those measured experimentally near the nozzle, the maximum value of K_I on the crack front in the elastic range agreed well with the values

Fig. 5.29. Superposition diagram for crack extending from hole in flat-plate model.⁹

Fig. 5.30. Stress-intensity factor estimates for nozzle corner cracks based on model of a flat plate with a circular hole; includes effects of pressure acting on the crack surfaces.⁹

obtained experimentally for the same geometry from the epoxy model fracture tests.¹¹ For a vessel internal pressure of 35.2 MPa (5.1 ksi), the maximum calculated value of K_I was $69.0 \text{ MN}\cdot\text{m}^{-1/2}$ ($62.8 \text{ ksi}\sqrt{\text{in.}}$). Thus, using Eqs. (1) and (2), the shape factor based on the nominal hoop stress is given by

$$C_n = \frac{K_I}{p(r_1/t)\sqrt{\pi a}} = \frac{62.8}{(5.1)(2.25)\sqrt{1.2\pi}} = 2.82 \quad (82)$$

For $a/r_2 = 1.2/4.94 = 0.24$, Fig. 5.4 shows that this value is only slightly greater than the values obtained experimentally from the epoxy models at similar values of a/r_2 . Furthermore, referring to Fig. 5.30, this value is less than 4.5% higher than the value estimated for the small thick-walled epoxy models of the intermediate test vessels by Embley's flat-plate analysis.⁹

Three-dimensional frozen stress photoelastic data

Experiments were also performed by Smith, Jolles, and Peters,¹² using the frozen stress photoelastic technique, on six epoxy models with flawed nozzles identical in design to the epoxy models tested by Derby.¹¹ Their results, which are summarized in Fig. 5.31, also show good agreement with Derby's data, although their shape-factor values tend to be somewhat less for shallow cracks. Nevertheless, there is no indication of differences between the two sets of data large enough to account for the differences between the predicted and measured nozzle corner strains at failure in vessels V-5 and V-9. Therefore, the overconservatism of the LEFM-based failure strain estimates for nozzle corner cracks is more likely due to causes other than gross errors in the K_I estimates. Prominent among these other causes is the nonexistence of plane strain conditions around the crack front, as mentioned previously.

Fig. 5.31. Stress-intensity factor data for small thick-walled epoxy vessels with nozzle corner cracks measured by stress freezing photoelasticity.¹⁰

Analytical Estimates of the Elastic Stress-Concentration Factor

The fact that the values of the elastic stress-concentration factor calculated from the experimental data for both vessels V-5 and V-9 considerably exceeded the expected values raised questions with regard to the accuracy of such estimates, both for the intermediate test vessels and for actual reactor pressure vessels. Apparently, the finite-element method¹¹ underestimated K_t because of problems related to mesh size, element stiffness, and the presence of a steep strain gradient in the region of maximum stress. The strain gage data from the epoxy models¹¹ underestimated K_t because either the gage location was offset from the location of the peak strain or the gage length exceeded the distance over which the strain was a maximum. The resulting uncertainty regarding the accuracy of elastic stress-concentration

factor values did not affect the previously discussed estimates of K_t because the methods for estimating the two parameters were independent. However, the uncertainty regarding K_t values did bear on the expected accuracy of low-cycle fatigue and inelastic pressure-strain curve estimates because both types of estimates are based partly on the value of the elastic stress-concentration factor.¹¹

Fortunately, a practical explanation of the problem described above can be found by using the analytical work of Van Dyke,¹⁹ who obtained solutions for the stresses around a circular hole in an infinite shallow cylindrical shell loaded by remote axial tension, internal pressure, or torsion. In these solutions, the stresses around the hole were found to be functions of a curvature parameter β , defined by

$$\beta^2 = r^2 \sqrt{12(1 - \nu^2)} / 8r_m t, \quad (83)$$

where r is hole radius, r_m is cylinder midthickness radius, and t is cylinder thickness. For relatively small values of β , the membrane stress at the hole under internal pressure loading is given approximately by^{19,20}

$$K_t = \sigma_{\theta\theta} / \sigma_{\theta\theta} = 3/2 + \cos 2\theta + \pi\beta^2 [1 + (5/4) \cos 2\theta] + \dots, \quad (84)$$

where $\sigma_{\theta\theta}$ is the average hoop stress (σ_h) and θ is the position angle measured around the hole from the longitudinal plane of the cylinder. Equation (84) is shown plotted in Fig. 5.32 along with the results of a

Fig. 5.32. Stresses around the perimeter of a circular hole in a shallow cylindrical shell under internal pressure for small β .¹⁹

more complete series solution³⁹ for the stresses around a circular hole in a cylindrical shell under internal pressure loading. For the purposes of this discussion, the approximation given by Eq. (84) will be considered sufficiently accurate for estimating values of K_t .

For $\theta = 0$, Eq. (84) reduces to³⁹

$$K_t = \sigma_{\theta\theta}/\sigma_x = 2.5 + 9\pi\beta^2/4, \quad (85)$$

and for $r_m = \infty$, Eq. (83) gives $\beta^2 = 0$ and then Eq. (85) reduces to $K_t = 2.5$, which is the correct solution for a hole in a flat plate under 2:1 biaxial tension.⁴¹ When Eq. (85) is applied to an intermediate test vessel with a nozzle and to the same nozzle in the so-called reference calculational model³⁷ which represents a typical PWR reactor pressure vessel, one obtains the results shown in Table 5.9. The stress-concentration factor for the intermediate test vessel nozzle is given by $K_t = 4.16$, which agrees with the measurements made on vessel V-9. Furthermore, because of the lower value of β , the stress-concentration factor for the same nozzle in a typical reactor pressure vessel is given by $K_t = 2.71$, which agrees with expectations based on a considerable amount of engineering experience. Thus, the strain measurements made on the intermediate test vessel nozzles are supported by analysis, and, furthermore, the results do not reflect adversely on the nozzle designs used for reactor pressure vessels.

Table 5.9. Stress-concentration factor estimates for identical nozzles in an intermediate test vessel and a reference calculational model of typical PWR vessel design

Term	Intermediate test vessel with nozzle	Reference calculational model of PWR vessel
Nozzle mean radius r	19.05 cm (7.5 in.)	19.05 cm (7.5 in.)
Cylinder mean radius r_m	41.91 cm (16.5 in.)	229.24 cm (90.25 in.)
Cylinder thickness t	15.24 cm (6.0 in.)	21.59 cm (8.5 in.)
β	0.489	0.174
K_t	4.16	2.71

Pressure-Strain Curve Estimates

If the critical strain in a nozzle corner region containing a flaw is defined as the peak strain that could exist at the same nozzle corner without a flaw, at the failure pressure, and this strain is calculated directly in terms of the flaw size and the fracture toughness, an accurate estimate of the unflawed nozzle corner pressure-strain curve is required to determine the corresponding failure pressure. In the previous discussions, it was pointed out that attempts to calculate the elastic-plastic pressure-strain curves of the intermediate test vessel nozzle regions by the finite-element method have not been very successful so far. Therefore, it was considered worthwhile to attempt to develop one or more semiempirical equations for estimating nozzle corner pressure-strain curves. As pointed out by Randall,¹¹ the initial slope of a pressure-strain curve should be determined by the elastic stress-concentration factor of the nozzle and by the ratio of the intermediate principal stress at the nozzle corner to the pressure. As demonstrated in the previous discussions, both these quantities can now be estimated with considerable accuracy. The experimental data obtained from vessels V-5 and V-9 showed that the nozzle corner pressure-strain

curves of both vessels became nearly horizontal at the gross yield pressure of the vessel cylinders. This behavior is consistent with the assumption that nozzle design by the area replacement method serves to prevent the gross yield pressure of the nozzle intersection region from becoming less than the gross yield pressure of the cylindrical region of the vessel without a nozzle. Based on these considerations, it was hypothesized that the primary variables controlling the shape of the elastic-plastic pressure-strain curve should be the initial slope M and the ratio of the vessel internal pressure to the gross yield pressure of the vessel cylinder $p/p_{G,Y}$. The initial slope of the pressure-strain curve was estimated by assuming that the intermediate principal stress at the inside nozzle corner was compressive and equal to the pressure, so that the initial elastic strain is given by

$$\lambda^E = \frac{K_i p(r_i/t) + 2\nu p}{E} \quad (86)$$

The value of M is determined by rearranging Eq. (86) to give

$$M = \frac{p}{\lambda^E} = \frac{L}{K_i(r_i/t) + 2\nu} \quad (87)$$

For $E = 2068 \text{ MPa} \cdot \epsilon^{-1}$ ($300 \text{ ksi} \cdot \epsilon^{-1}$), $K_i = 4.16$, and $\nu = 0.3$, Eq. (87) gives $M = 208 \text{ MPa} \cdot \epsilon^{-1}$ ($30.12 \text{ ksi} \cdot \epsilon^{-1}$). The gross yield pressure of the vessel cylinder,

$$p_{G,Y} = 1.04 \sigma_Y \ln(r_o/r_i) \quad (15)$$

was estimated from Eq. (15). From Table 5.4, the yield stress of the vessel V-5 cylinder material at room temperature was 500 MPa (72.5 ksi); from Table 5.6, the yield stress of the vessel V-9 cylinder material at room temperature was 475 MPa (68.9 ksi). Therefore, assuming test temperature yield stresses of $\sigma_Y = 476 \text{ MPa}$ (69.0 ksi) for both vessel cylinders and using $r_o/r_i = 1.17$, Eq. (15) gives $p_{G,Y} = 182 \text{ MPa}$ (26.4 ksi).

Next, two semiempirical equation forms, each based on a single assumption, were developed. The first assumption was that the slope of the pressure-strain curve is related to its initial slope and to the pressure by

$$dp/d\lambda = M(1 - p/p_{G,Y}) \quad (88)$$

Integrating Eq. (88) gives

$$p = p_{G,Y}(1 - e^{-M\lambda/p_{G,Y}}) \quad (89)$$

or, by rearranging Eq. (89),

$$\lambda = \frac{p_{G,Y}}{M} \ln \frac{1}{1 - p/p_{G,Y}} \quad (90)$$

Thus, for the intermediate test vessel nozzle corners, substituting the values of M and $p_{G,Y}$ determined from Eqs. (87) and (15) into Eq. (89) gives

$$p = 26.4(1 - e^{-1.141\lambda}) \quad (91)$$

where p is in ksi and λ is in percent. Equation (91) is shown plotted in Fig. 5.33, which demonstrates that it fits the data from vessel V-5 with remarkable accuracy.

The next assumption investigated was based on plotting the ratio p/λ vs p using the data for vessel V-9 listed in Table C.3. This plot is shown in Fig. 5.34, from which it was deduced that the relationship between the two parameters might be approximated by an ellipse having the equation

$$(p/M\lambda)^2 + (p/p_{cr})^2 = 1. \quad (92)$$

Rearranging Eq. (92) gives

$$p = \frac{p_{cr}}{\sqrt{1 + (p_{cr}\lambda/M)^2}}. \quad (93)$$

or alternately,

$$\lambda = \frac{(p/M)}{\sqrt{1 - (p/p_{cr})^2}}. \quad (94)$$

Again, for the intermediate test vessel nozzle corners, substituting the values of M and p_{cr} obtained from Eqs. (87) and (15) into Eq. (93) gives

$$p = \frac{26.4}{\sqrt{1 + (0.8755 \lambda)^2}}. \quad (95)$$

Equation (95) is shown plotted in Fig. 5.33, which demonstrates that it fits the data from vessel V-9 with equally remarkable accuracy. Thus, it appears that either or both of the simple semiempirical expressions discussed above can be used to obtain good estimates of elastic-plastic, nozzle corner, pressure-strain curves for use in elastic-plastic fracture strength calculations.

Elastic-Plastic Fracture Analyses for Nozzle Corner Cracks under Conditions of Partial Transverse Restraint

In the preceding discussions, it was established that the intermediate principal stresses at the inside nozzle corners of vessels V-5 and V-9 were initially small and eventually became compressive after yielding. Under these conditions, which approximate uniaxial tension, it was shown in Appendix E of Ref. 19 that plane strain conditions do not exist for a surface crack oriented normal to the maximum principal tensile stress. Furthermore, for these same conditions, Appendix H of Ref. 19 showed that the Irwin β_{tr} correction can be used to estimate the increase in the effective fracture toughness due to less than full transverse restraint. Therefore, the measured conditions at final failure in vessels V-5 and V-9 were used to calculate the plane strain fracture toughness required to produce the measured failure conditions, neglecting any increases in crack dimensions due to stable crack growth but considering the increase in the effective fracture toughness due to less than full transverse restraint by means of the Irwin β_{tr} correction. These calculations were made by both the method of LEFM based on strain and by the tangent modulus method. The test conditions and material properties used in these calculations, as well as the resulting estimated fracture toughness values, are shown in Table 5.10.

Fig. 5.33. Comparison of calculated and measured nozzle corner pressure-strain curves for intermediate test vessels V-5 and V-9.

Fig. 5.34. Plot of pressure divided by strain vs pressure for the measured pressure vs nozzle corner strain data from intermediate test vessel V-9.

Table 5.10. Test conditions, material properties, and calculated fracture toughness values for vessels V-5 and V-9

	Vessel V-5	Vessel V-9
Test temperature	88°C (190°F)	24°C (75°F)
Nozzle yield stress σ_y	425 MPa (61.6 ksi)	474 MPa (68.8 ksi)
Crack depth a	3.05 cm (1.2 in.)	3.05 cm (1.2 in.)
Nozzle corner failure strain λ_f	6.5%	8.4%
Measured fracture toughness K_{Ic}	265 $\text{MN}\cdot\text{m}^{-3/2}$ (241 $\text{ksi}\cdot\sqrt{\text{in.}}$)	159 $\text{MN}\cdot\text{m}^{-3/2}$ (145 $\text{ksi}\cdot\sqrt{\text{in.}}$) 220 $\text{MN}\cdot\text{m}^{-3/2}$ (200 $\text{ksi}\cdot\sqrt{\text{in.}}$) 298 $\text{MN}\cdot\text{m}^{-3/2}$ (271 $\text{ksi}\cdot\sqrt{\text{in.}}$)
Calculated fracture toughness K_{Ic}		
LEFM based on strain	278 $\text{MN}\cdot\text{m}^{-3/2}$ (253 $\text{ksi}\cdot\sqrt{\text{in.}}$)	326 $\text{MN}\cdot\text{m}^{-3/2}$ (297 $\text{ksi}\cdot\sqrt{\text{in.}}$)
Tangent modulus method	197 $\text{MN}\cdot\text{m}^{-3/2}$ (179 $\text{ksi}\cdot\sqrt{\text{in.}}$)	226 $\text{MN}\cdot\text{m}^{-3/2}$ (206 $\text{ksi}\cdot\sqrt{\text{in.}}$)

^aCalculations based on the assumption of partial transverse restraint conditions.

Linear elastic fracture mechanics based on strain

The calculations for the vessels by the method of LEFM based on strain were performed as follows. Using the value of the failure strain given in Table 5.10, the value of K_I , σ_T was calculated from the result of combining Eqs. (65) and (67), which is

$$K_I/\sigma_T = M\lambda_f/0.093\sigma_T. \quad (96)$$

Referring to Appendix H of Ref. 19, the parameter β , was calculated from

$$\beta = \frac{(K_I/\sigma_T)^2}{2a}. \quad (97)$$

and the ratio K_I/K_h was then calculated from

$$K_I/K_h = 1.058\beta^{1/4}. \quad (98)$$

which applies when β is large.¹⁹ The value of K_h was then calculated by dividing the value obtained from Eq. (96) by that obtained from Eq. (98) and multiplying the result by the yield stress. The value of M used in Eq. (96) was the value obtained previously from Eq. (87), which was based on the calculated value of $K_I = 4.16$.

From the results given in Table 5.10, it can be seen that the calculated toughness value for vessel V-5 is only slightly greater than the measured value and that the calculated toughness value for vessel V-9 is only slightly greater than the maximum measured value. These results imply that this method of calculation provides a slightly conservative method for estimating failure strains for nozzle corner flaws. Since the initial flaw size was used in these calculations, it also appears that when using this method it may not be necessary to increase the flaw size to account for stable crack growth, even though considerable stable crack growth can be expected to occur in the upper-shelf temperature range.

The tangent modulus method

The calculations made for the vessels by the tangent modulus method were performed as follows. The LEFM shape factor was calculated from Eq. (29) using the calculated value of $K_I = 4.16$ and the initial crack size of 3.05 cm (1.2 in.), giving $C = 0.592$. Because of the steep strain gradient in the nozzle corner region, the tangent modulus method equations for bending given in Appendix H of Ref. 19 were used to calculate the notch ductility factor. Since the experimentally measured failure strains were both in the strain-hardening range, the notch ductility factor increments were calculated from the equations given below.¹⁹

For the elastic range,

$$\Delta\epsilon\sqrt{\rho} = 2C\sqrt{a}\sqrt{E/E_s}\lambda_T. \quad (99)$$

For the transition range,

$$\Delta\epsilon\sqrt{\rho} = 4C\sqrt{a}\sqrt{E/E_s}(\sqrt{\lambda_s\lambda_T} - \lambda_T). \quad (100)$$

For the strain-hardening range,

$$\Delta\epsilon\sqrt{\rho} = 2C\sqrt{a} \{ \sqrt{\lambda_1(\lambda_1 + \lambda_2)} - \sqrt{\lambda_2(\lambda_1 + \lambda_2)} + \lambda_2 \ln[(\sqrt{\lambda_1} + \sqrt{\lambda_1 + \lambda_2})(\sqrt{\lambda_2} + \sqrt{\lambda_1 + \lambda_2})] \} \quad (101)$$

where

$$\lambda_2 = \sigma_T/E_s - \lambda_1 \quad (102)$$

For both vessels, the value of the strain-hardening tangent modulus E_s was taken as 20.7 MPa-%⁻¹ (3.0 ksi-%⁻¹), so that Eq. (28) still holds, and the value of the strain at the onset of strain hardening λ_1 was taken as 1.2%. The total value of $\epsilon\sqrt{\rho}$ was calculated by adding the values obtained from Eqs. (99), (100), and (101), and the value of K_I/σ_T was then obtained by rearranging Eq. (25) to read

$$K_I/\sigma_T = (\sqrt{\pi} \cdot 20\lambda_1)\epsilon\sqrt{\rho} \quad (103)$$

The value of K_{II} was then calculated by using Eqs. (97) and (98) as discussed previously.

The results given in Table 5.10 show that the calculated toughness value for vessel V-5 is somewhat less than the measured value but that the calculated toughness value for vessel V-9 is close to the midrange measured value. These results indicate that when using this method for estimating nozzle corner crack strain tolerances, some allowances for stable crack growth should be made if it is to be expected in order to avoid unconservative results. This conclusion agrees with the results of calculations made previously by the tangent modulus method.¹⁹

REFERENCES

1. L. F. Kooistra and M. M. Lemcoe, "Low Cycle Fatigue Research on Full-Size Pressure Vessels," *Welding J.* 41(7), 297s-306s (July 1962).
2. A. G. Pickett and S. C. Grigory, "Prediction of the Low Cycle Fatigue Life of Pressure Vessels," *Trans. ASME, Ser. C, J. Basic Eng.* 89, 858-70 (December 1967).
3. G. D. Whitman, G. C. Robinson, and A. W. Savolainen (Eds.), *Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors*, ORNL-NSIC-21 (December 1967).
4. J. D. Lubahn, "A Hypothetical Pressure Vessel Problem," Enclosure (6) to Minutes of the Fifth Meeting of the HSST Program Planning Committee, held at the Oak Ridge National Laboratory, Sept. 11-12, 1967 (unpublished).
5. S. Yukawa, *Evaluation of Periodic Proof Testing and Warm Prestressing Procedures for Nuclear Reactor Vessels*, HSSTP-TR-1 (July 1, 1969).
6. O. L. Bowie, "Analysis of an Infinite Plate Containing Radial Cracks Originating from the Boundary of an Internal Circular Hole," *J. Math. Phys.* 35 (1956).
7. P. C. Paris and G. C. Sih, "Stress Analysis of Cracks," pp. 30-83 in *Fracture Toughness Testing and Its Applications*, ASTM STP 381, American Society for Testing and Materials, 1965.
8. F. W. Smith, "Stress Intensity Factors for a Semi-Elliptical Surface Flaw," *Structural Development Research Memorandum No. 17*, Boeing Company, Seattle, Wash., August 1966.

9. G. T. Embley, "Stress Intensity Factors for Nozzle Corner Flaws," Knolls Atomic Power Laboratory, Schenectady, New York, draft dated July 1974 (to be published).
10. N. Krishnamurthy, *Three-Dimensional Finite Element Analysis of Thick-Walled Vessel-Nozzle Junctions with Curved Transitions*, ORNL-TM-3315 (Mar. 24, 1971).
11. R. W. Derby et al., *Test of 6-Inch-Thick Pressure Vessels. Series 1: Intermediate Test Vessels V-1 and V-2*, ORNL-4895 (February 1974).
12. A. A. Abbatiello, R. W. Derby, and T. A. King, "Producing Epoxy Model Pressure Vessels for Fracture Tests," *Exp. Mech.* 11(1), 46-48 (January 1971).
13. R. W. Derby, "Shape Factors for Nozzle Corner Cracks," *Exp. Mech.* 12(12), 580-84 (December 1972).
14. PVRC Ad Hoc Group on Toughness Requirements, "PVRC Recommendations on Toughness Requirements for Ferritic Materials," *WRC Bulletin 175*, Welding Research Council, August 1972.
15. R. W. Derby, "Experimentally Determined Shape Factors for Deep Part-Through Cracks in a Thick-Walled Pressure Vessel," pp. 482-91 in *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, American Society for Testing and Materials, 1973.
16. J. D. Gilman and Y. R. Rashid, "Three-Dimensional Analysis of Reactor Pressure Vessel Nozzle," Paper G 2.6, presented at the First International Conference on Structural Mechanics in Reactor Technology, Berlin, Germany, Sept. 20-24, 1971.
17. J. Schroeder and B. K. Roy, "Upper Bounds to Limit Pressures of Branch-Pipe Lateral Connections. Part I: Bounds for Branch Pipe Diameter Ratios Smaller Than 0.7," ASME Paper 71-PVP-43, presented at the ASME Pressure Vessels and Piping Conference, San Francisco, Calif., May 10-12, 1971.
18. R. W. Derby, "Fracture Studies of Model Pressure Vessels Made of Nuclear Grade Steel," Paper No. G 6.6, Volume G, Part 4, *Proceedings of the First International Conference on Structural Mechanics in Reactor Technology, Berlin, Germany, Sept. 20-24, 1972*.
19. R. H. Bryan et al., *Test of 6-in.-thick Pressure Vessels. Series 2: Intermediate Test Vessels V-3, V-4, and V-6*, ORNL-5059 (November 1975).
20. H. J. Bellucci, "Three-Dimensional Elastic-Plastic Stress and Strain Analyses for Fracture Mechanics," pp. 3-5 in *HSST Program Quart. Prog. Rep. April-June 1974*, ORNL-TM-4655, Vol. II (August 1974).
21. H. J. Bellucci, "Three-Dimensional Elastic-Plastic Stress and Strain Analyses for Fracture Mechanics: Complex Geometries," ORNL Sub 3821-1, MARC Analysis Research Corporation, Palo Alto, Calif. (November 1975).
22. W. J. Stelzman, "Characterization of Intermediate Test Vessel Materials," pp. 66-74 in *HSST Program Semiannual Progress Report for Period Ending August 31, 1973*, ORNL-4971 (July 1974).
23. T. R. Mager, S. Yanichko, and L. R. Singer, "Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material," pp. 74-79 in *HSST Program Semiannual Progress Report for Period Ending August 31, 1973*, ORNL-4971 (July 1974).
24. T. R. Mager, S. E. Yanichko, and L. R. Singer, *Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material*, WCAP-8456 (December 1974).
25. J. G. Merkle, "Analytical Applications of the J-Integral," pp. 264-80 in *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, American Society for Testing and Materials, 1973.

26. C. B. Buchalet and W. H. Bamford, "Stress Intensity Factor Solutions for Continuous Surface Flaws in Reactor Pressure Vessels," pp. 385-402 in ASTM STP 590, American Society for Testing and Materials, 1976.
27. C. Buchalet, "Fracture Prevention for Reactor Vessels. Part I: Proposed Fracture Analysis Method for Complex Geometries and Loadings" (draft), Westinghouse Electric Corporation, Pittsburgh, Pa., June 1973.
28. C. B. Buchalet and W. H. Bamford, "Method for Fracture Mechanics Analysis of Nuclear Reactor Vessels Under Severe Thermal Transients," ASME Paper 75-WA/PVP-3, presented at the ASME Winter Annual Meeting, Houston, Tex., Nov. 30-Dec. 4, 1975.
29. R. C. Shah and A. S. Kobayashi, "Stress Intensity Factor for an Elliptical Crack Under Arbitrary Normal Loading," *Eng. Fract. Mech.* 3, 71-96 (1971).
30. F. J. Witt, "The Application of the Equivalent Energy Procedure for Predicting Fracture in Thick Pressure Vessels," pp. 163-67 in *Practical Applications of Fracture Mechanics to Pressure Vessel Technology*, Institution of Mechanical Engineers, London, 1971.
31. PVRC Ad Hoc Group on Toughness Requirements, "PVRC Recommendations on Prevention of Fracture at Gross Structural Discontinuities," (draft report dated Aug. 10, 1976, with revisions dated Sept. 10, 1976).
32. ASME Boiler and Pressure Vessel Code, Section III, Division I, "Nuclear Power Plant Components," 1974 edition.
33. P. N. Randall and J. G. Merkle, "Effects of Crack Size on the Gross-Strain Crack Tolerance of A-533 B Steel," *ASME Eng. Ind.* 92(3), 935-41 (August 1972).
34. S. C. Grigory, "Testing the Six-Inch Thick Flawed Tensile Specimen for the Heavy Section Steel Technology Program," *Nucl. Eng. Des.* 17 (1), 161-69 (August 1971).
35. J. G. Merkle et al., *Test of 6-Inch-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7*, ORNL NUREC-1 (August 1976).
36. C. E. Childress, *Fabrication and Mechanical Test Data for the Four 6-Inch-Thick Intermediate Test Vessels Made from Steel Plate for the Heavy Section Steel Technology Program*, ORNL-TM-5074 (January 1976).
37. J. G. Merkle, G. D. Whitman, and R. H. Bryan, *An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water-Reactor Pressure Vessel Safety*, ORNL-TM-5090 (November 1975).
38. C. W. Smith, M. Jolles, and W. H. Peters, *Stress Intensities for Nozzle Cracks in Reactor Vessels*, VPI-E-76-25 (also ORNL Sub 7015-1) (November 1976).
39. P. Van Dyke, "Stresses about a Circular Hole in a Cylindrical Shell," *Office of Naval Research Contract NONR 1866 (02), Technical Report No. 21*, Div. of Engr. and Applied Physics, Harvard University, Cambridge, Mass., Sept. 1964 [see also *AIAA J.* 3(9), 1733-42 (1965)].
40. F. Sellars, "A Note on the Correlation of Photoelastic and Steel Model Data for Nozzle Connections in Cylindrical Shells," pp. 35-39 in *WRC Bulletin 139*, Welding Research Council, April 1969.
41. W. Griffel, *Handbook of Formulas for Stress and Strain*, Frederick Ungar Publishing Co., New York, 1966.

6. Results and Conclusions

Intermediate test vessels V-5 and V-9 contained carefully prepared and sharpened 3.05-cm-deep (1.2-in.) inside nozzle corner cracks. Vessel V-5 was tested first, at 88°C (190°F), and was the first intermediate test vessel to fail by leaking without fracturing. Vessel V-9 was tested later at 25°C (75°F) and failed by fast fracturing, as intended.

Material property values, including fracture toughness, were obtained for the nozzle materials of vessels V-5 and V-9 before the vessels were tested. The fracture toughness data were obtained from small notched beams and compact specimens, using the equivalent-energy calculation procedure. This procedure is known to give results substantially identical to a *J*-integral calculation for the same load-displacement reference point for these two specimens.

Procedures were successfully developed for placing fatigue-sharpened surface flaws in the inside nozzle corners of test pressure vessels. The preparation of these flaws involved welding seal blocks over the notch opening inside the vessel under difficult conditions, with the vessel preheated for welding.

Fatigue flaw sharpening was accomplished using a cyclic hydraulic pressure in the notch of about 172 MPa (25,000 psi). Approximately 225,000 pressure cycles were required to produce about 1.17 cm (0.46 in.) of fatigue crack growth. The cycling rate was about 50 cph.

During fatigue crack sharpening, flaw depth was monitored ultrasonically from the outside surface of the nozzle directly opposite the notch. Detailed procedures for flaw preparation are described in Chapter 3 and Appendix E.

Vessels V-5 and V-9 were instrumented with inside and outside surface strain gages and thermocouples. Crack depths were recorded continuously as a function of pressure by means of ultrasonic transducers placed on the nozzle corner outside surfaces directly opposite the flaws. Crack extension was also monitored externally by acoustic-emission sensors. Crack-opening displacement (COD) was measured by means of specially designed clip gages mounted across the notches inside the vessel.

Large inside surface CODs occurred before failure in both tests. The COD at failure was about 3.68 cm (1.45 in.) for vessel V-5 and about 2.54 cm (1.0 in.) for vessel V-9. Vessel V-5 failed by leakage without fracturing, following extensive stable crack growth, and vessel V-9 failed by fast fracture after some stable crack growth. Both vessels reached the gross yield pressure of their cylindrical regions before failure.

The inside unflawed nozzle corner strain at failure was 6.5% for vessel V-5 and 8.4% for vessel V-9.

The experimentally measured inside nozzle corner pressure-strain curves for vessels V-5 and V-9 were nearly identical, but the experimentally measured strains considerably exceeded pretest calculated values.

Epoxy model fracture data were used by ORNL for estimating the stress-intensity factor of the inside nozzle corner cracks in vessels V-5 and V-9 as a function of pressure. Subsequent independent calculations and photoelastic experimental data substantiated the epoxy model fracture data and revealed the importance of considering the effect of internal crack face pressure, especially for relatively thick-walled vessels.

Pretest estimates of the inside nozzle corner elastic stress-concentration factor for vessels V-5 and V-9, based on strain gage readings from the small epoxy fracture models and a three-dimensional elastic finite-element analysis, were approximately 2.8. Strain data from vessels V-5 and V-9 indicated an actual value exceeding 4.0. Posttest calculations agreed with the measured value, but also indicated that the elastic stress-concentration factor for the same nozzle in a reactor pressure vessel would still be about 2.7; the difference is due to the difference in the ratios of the cylinder radius to the nozzle radius.

Numerous pretest and posttest fracture analyses were made for both vessels V-5 and V-9. All the estimated nozzle corner strains at failure for both vessels were low (most by a wide margin), especially those based on LEFM and the assumption of full transverse restraint. The two most accurate estimates avoided assuming a plane strain constraint condition along the leading edge of the crack, a condition that experimental strain data imply does not exist for a crack at the inside nozzle corner. Subsequent calculations made by both the method of LEFM based on strain and the tangent modulus method, using the Irwin β_K correction to estimate the increase in the effective fracture toughness due to less than full transverse restraint, provided estimates of fracture toughness that agreed well with the pretest measured values.

Two simple semiempirical equations were found to fit the measured inside nozzle corner pressure-strain curves quite accurately. Both equations are based on the estimated value of the elastic stress concentration factor and the cylinder gross yield pressure.

Detailed tabulations and plots of material property data, small model and intermediate test vessel strain data, and a discussion of acoustic-emission results are included in the report.

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The writers wish to express thanks to all who participated in the preparation and testing of vessels V-5 and V-9. H. D. Curtis directed the test facility preparations at K-25; T. A. King applied the instrumentation to the vessels; T. M. Cate was responsible for data system operations; W. A. Bird was responsible for the remote TV system; and S. P. Baker and K. K. Klindt operated the ORNL acoustic-emission and ultrasonic systems.

Appendix A
Material Properties of the Nozzle
Prolongations of Vessels V-8 and V-9

Material Properties of the Nozzle Prolongations of Vessels V-5 and V-9

Properties of the base metal of the nozzle prolongations of vessels V-5 and V-9 were determined by W. J. Stelzman of the Metals and Ceramics Division of Oak Ridge National Laboratory and by T. R. Mager, S. E. Yanichko, and L. R. Singer of the Westinghouse Electric Corporation.*¹ This appendix presents the raw data obtained by Stelzman and shown previously in curve form in Chapter 2. All the Westinghouse data are presented in Chapter 2.

Stelzman tested precracked Charpy V-notch specimens taken from the nozzle prolongations of the vessels to obtain K_{Ic} and K_{IIc} values. The locations of the specimens in the nozzle prolongations of vessels V-5 and V-9 are shown in Figs. A.1 and A.2, and their orientations are as defined in Fig. 2.6. Tables A.1 through A.3 give the data and fracture toughness values determined from these

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Fig. A.1. Cutting plan for segment VSA of nozzle prolongation of vessel V-5.

Table A.1. Fracture toughness (K_{Ic}) of nozzle prolongation of vessel V-5 from slow-bend (0.100 in./min) tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lb_f = 4.4482 N
1 ft-lb = 1.3558 J 1 lb_f/in. = 0.17513 N/mm
1 ksi√in. = 1.0988 MN·m^{3/2}

Specimen No.	Depth ^a	Specimen orientation	Test temperature [°C (°F)]	Average crack data ^b				Load (lb)		Deflection (in.)		Energy (ft-lb)		Slope of linear load-displacement curve (10 ⁶ lb/in.)	Lateral expansion (mils)	K_{Ic} (ksi√in.)	
				a (in.)	w/a (in.)	a/w	W/W ₀	Maximum	Start of fracture	Fracture arrest	Maximum load	Start of fracture	Maximum load			Start of fracture	From crosshead motion
SV-003	0.68	CT	93.3 (200)	0.2183	0.1757	0.554	3.20	1210		0.080		6.7	8.28	33	188	216	
SV-005	0.49	CT	93.3 (200)	0.1984	0.1955	0.504	2.69	1385		0.074		4.9	9.34	29	145	165	
SV-007	0.96	CT	0 (32)	0.2011	0.1930	0.510	2.75	1375		0.070		6.6	9.39	34	171	196	
SV-012	0.49	CT	54.4 (130)	0.1825	0.2114	0.463	2.37	1505		0.057		5.8	10.26	30	145	165	
SV-013	0.39	CT	-45.6 (-50)	0.1884	0.2056	0.478	2.48	1690	1560	0.077	0.127	8.9	9.60	27	181	208	
SV-015	0.21	CT	-73.3 (-100)	0.1915	0.2024	0.486	2.55	1420	175	0.028			2.4	10	97	108	
SV-016	0.86	CT	-17.8 (-6)	0.1359	0.2581	0.345	1.71	2370		0.081		12.7	11.34	43	163	186	
SV-018	0.58	CT	23.9 (75)	0.2000	0.1950	0.506	2.71	1285		0.070		6.2	8.13	34	151	172	
SV-009	0.77	CT	22.8 (73)	0.2103	0.1837	0.534	2.98	1210		0.072		6.1	8.61	30	171	196	
SV-021	0.96	CT	-73.3 (-100)	0.2076	0.1864	0.527	2.91	1050	230	0.020			1.2	5	75	82	
SV-023	0.77	CT	-17.8 (-6)	0.2016	0.1924	0.512	2.77	1370		0.067		6.1	9.00	35	164	188	
SV-025	0.58	CT	93.3 (200)	0.2159	0.1781	0.548	3.13	1095		0.067		5.2	8.73	27	167	191	
SV-026	0.49	CT	-73.3 (-100)	0.2081	0.1858	0.528	2.92	1375	135	0.037			2.9	3	114	128	
SV-027	0.86	CT	93.3 (200)	0.2157	0.1783	0.547	3.11	1135		0.076		6.0	8.88	29	180	207	
SV-002	0.77	CA	93.3 (200)	0.1945	0.2005	0.492	2.60	1435		0.093		9.5	9.99	31	201	232	
SV-004	0.58	CA	93.3 (200)	0.2017	0.1933	0.511	2.76	1225		0.076		6.8	8.70	33	167	191	
SV-006	0.39	CA	45.6 (-50)	0.1928	0.2022	0.488	2.56	1580	210		0.170		9.24	30	178	204	
SV-008	0.86	CA	0 (32)	0.2001	0.1948	0.507	2.72	1390		0.082		8.0	9.00	38	182	209	
SV-011	0.58	CA	54.4 (130)	0.1989	0.1956	0.504	2.69	1350		0.066		6.1	8.99	37	157	179	
SV-014	0.30	CA	-73.3 (-100)	0.1517	0.2428	0.385	1.90	1910	100		0.030		3.2	11	77	84	
SV-017	0.77	CA	-17.8 (-6)	0.1878	0.2063	0.477	2.48	1570		0.091		10.2	9.90	41	197	227	
SV-019	0.49	CA	23.9 (75)	0.1986	0.1959	0.503	2.68	1355		0.090		8.7	10.41	37	202	233	
SV-001	0.86	CA	-73.3 (-100)	0.2018	0.1932	0.511	2.76	1290	220		0.023	1.6	8.46	10	80	88	
SV-010	0.68	CA	22.8 (73)	0.1995	0.1947	0.506	2.71	1290		0.056		4.9	8.61	34	139	158	
SV-020	0.30	CA	-17.8 (-6)	0.2006	0.1926	0.510	2.75	1295		0.060		5.4	8.58	33	149	170	
SV-022	0.86	CA	-73.3 (-100)	0.1959	0.1989	0.496	2.63	850	200		0.015	0.8	9.18	4	56	59	
SV-024	0.68	CA	93.3 (200)	0.2006	0.1944	0.508	2.73	1355		0.065		5.6	9.00	29	153	175	
SV-028	0.77	CA	93.3 (200)	0.2003	0.1947	0.507	2.76	1355		0.082		7.9	8.46	34	176	202	

^aFracture of wall thickness (6 in.) from outside.

^bDimension a is the average of six measurements.

Table A.2. Fracture toughness (K_{Ic}) of nozzle prolongation of vessel V-9 from slow-bend (0.100 in./min) tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lb_f = 4.4482 N
 1 ft-lb = 1.3558 J 1 lb_f/in. = 0.17513 N/mm
 1 ksi√in. = 1.0988 MN·m^{-3/2}

Specimen No.	Depth ^a	Specimen orientation	Test temperature °C (°F)	Average crack data ^b				Load (lb)		Deflection (in.)		Energy (ft-lb)		Slope of linear displacement curve (10 ³ lb/in.)	Lateral expansion (mil)	K_{Ic} (ksi√in.)	
				a (in.)	b (in.)	a/w	b/w	Start of fracture	Maximum	Maximum load	Start of fracture	Maximum load	Start of fracture			From crosshead motion	From specimen deflection
9V-056	0.04	CA	20.0 (68)	0.2295	0.1655	0.581	3.69		1030		0.058		4.1	7.20		159	182
9V-070	0.125	CT	20.0 (68)	0.2082	0.1851	0.529	3.10		1260		0.070		6.1	8.49		177	203
9V-071	0.21	CA	20.0 (68)	0.2167	0.1782	0.549	3.30		1195		0.066		5.2	7.92		167	191
9V-072	0.29	CT	20.0 (68)	0.3127	0.0807	0.795	10.76		270		0.058		1.08	2.76		147	167
9V-073	0.37	CA	20.0 (68)	0.2117	0.1833	0.536	3.16		1255		0.069		5.9	7.86		170	195
9V-074	0.46	CT	20.0 (68)	0.2041	0.1897	0.518	2.99		1320		0.067		5.9	8.70		169	194
9V-075	0.62	CA	20.0 (68)	0.2275	0.1676	0.576	3.62		1070		0.073		5.3	7.20		176	202
9V-076	0.71	CT	20.0 (68)	0.2052	0.1887	0.521	3.02		1320		0.068		6.1	8.22		169	194
9V-077	0.79	CA	20.0 (68)	0.2178	0.1772	0.531	3.33		1160		0.062		4.8	8.04		163	186
9V-078	0.87	CT	20.0 (68)	0.2071	0.1848	0.526	3.06		1295		0.064		5.5	8.40		164	188
9V-079	0.96	CA	20.0 (68)	0.2220	0.1730	0.562	3.45		1130		0.067		5.0	7.86		171	196
9V-082	0.04	CT	37.8 (100)	0.2037	0.1908	0.516	2.97		1355		0.063		5.9	8.85		169	194
9V-083	0.04	CT	7.2 (45)	0.2099	0.1837	0.533	3.14		1305		0.066		5.9	8.70		178	204
9V-020	0.04	CT	-6.7 (20)	0.2069	0.1879	0.524	3.05		1380		0.065		6.0	8.46		171	196

^aFraction of wall thickness (6 in.) from outside.

^bDimension a is the average of six measurements.

Table A.3. Fracture toughness ($K_{I,da}$) of nozzle prolongation of vessel V-9 from dynamic-bend tests of precracked Charpy V-notch specimens

Conversion factors: 1 in. = 25.4 mm 1 lbf = 4.4482 N
 1 ft-lb = 1.3558 J 1 lbf/in. = 0.17513 N/mm
 1 ksi $\sqrt{\text{in.}}$ = 1.0988 MN $\cdot \text{m}^{-3/2}$

Specimen No.	Depth ^a	Specimen orientation	Test temperature [°C (°F)]	Average crack data ^b				Energy (ft-lb)		Slope of linear load-displacement curve (10 ⁻³ lb/in.)	Lateral expansion (mils)	$K_{I,da}$ (ksi $\sqrt{\text{in.}}$)	
				a (in.)	w-a (in.)	a/w	$\sqrt{a/w}$	Maximum load	Start of fracture			From crosshead motion	From specimen deflection
9V-017	0.79	CA	93.3(200)	0.2015	0.1941	0.509	2.91	6.6		49.5			415
9V-029	0.79	CA	-17.2 (0)	0.2120	0.1836	0.536	3.16		0.66	49.5			142
9V-039	0.79	CA	37.8(100)	0.2148	0.1808	0.543	3.24	8.9		34.4			446
9V-051	0.79	CA	10 (50)	0.2036	0.1895	0.520	3.01		0.33	37.7			84
9V-059	0.79	CA	23.9 (75)	0.2035	0.1913	0.515	2.96		1.80	39.1			196
9V-019	0.96	CT	10 (50)	0.2020	0.1919	0.512	2.93			24.7			43
9V-041	0.96	CT	37.8(100)	0.1994	0.1954	0.505	2.87		3.50				191
9V-065	0.46	CT	37.8(100)	0.2213	0.1730	0.561	3.44	4.2		19.4			275
9V-085	0.46	CT	55.6(150)	0.2129	0.1821	0.539	3.19	6.9		23.5			320
9V-047	0.46	CT	10 (50)	0.2258	0.1692	0.572	3.57		0.43	18.9			80
9V-013	0.46	CT	21.1 (70)	0.2064	0.1868	0.525	3.05	7.6		24.8			332
9V-004	0.46	CT	121.1(250)	0.2216	0.1720	0.563	3.46	5.9		20.1			298
9V-025	0.46	CT	15.6 (60)	0.2139	0.1816	0.541	3.21		0.43	26.5			85
9V-026	0.54	CA	10 (50)	0.2180	0.1770	0.552	3.33		1.70	24.6			169
9V-036	0.54	CA	55.6(150)	0.2120	0.1834	0.536	3.17	6.8		27.3			340
9V-014	0.54	CA	121.1(250)	0.2179	0.1776	0.551	3.32	6.8		23.0			319
9V-048	0.54	CA	21.1 (70)	0.2116	0.1835	0.536	3.16		4.10	20.2			226
9V-012	0.37	CT	21.1 (70)	0.2180	0.1752	0.554	3.36	6.5		25.1			340
9V-034	0.37	CT	15.6 (60)	0.2149	0.1801	0.554	3.25	7.9		25.4			363
9V-057	0.37	CT	-17.8 (0)	0.2154	0.1786	0.547	3.28		0.12	25.8			46
9V-003	0.37	CA	26.7 (80)	0.2065	0.1891	0.522	3.03	7.5		23.0			313
9V-024	0.37	CA	37.8(100)	0.2145	0.1809	0.542	3.23	7.7		25.1			353
9V-046	0.37	CA	17.8 (0)	0.2121	0.1829	0.537	3.17		0.12	29.9			47

^aFraction of wall thickness (6 in.) from outside.

^bDimension a is the average of six measurements.

Not recorded

Not determined

Fig. A-2. Cutting plan for segment V9B of nozzle prolongation of vessel V-9; individual specimen characteristics are listed in Table A-6.

specimens. When the slow-bend tests were made, the specimen deflection was obtained from the crosshead motion; consequently, conservative (low fracture toughness) values were obtained. These results were available at the time of the vessel tests. Subsequently, the system was changed, and static specimen deflection is presently being measured directly. By correlating the results obtained by both methods, Stelzman found that the static toughness data accumulated to date are sufficient to determine corrections for K_{Ic} data up to $137 \text{ MN}\cdot\text{m}^{-3/2}$ ($125 \text{ ksi}\sqrt{\text{in.}}$). This correlation is shown in Fig. A.3. The adjusted static values in Tables A.1 and A.2 are included in the tabulation under the heading "From specimen deflection." It should be noted that deflections for the adjusted values are taken from the correlation given in Fig. A.3, of which the portion above the data points shown is an assumed linear fit to the data.

The value of K_{Ic} is calculated in accordance with the expression given in ASTM E-399-72 for bend specimens,² with the load P_Q being given the value E_{m1} prescribed by the equivalent-energy method,

$$P_Q = \sqrt{2kE_{m1}},$$

where k is the slope of the linear portion of the load-deflection curve and E_{m1} is the area under the curve up to maximum load. The dimensional parameters shown in Tables A.1 through A.3 are

Fig. A.3 Comparison of static fracture toughness as computed from deflectometer measurements and crosshead motion. (1 in. = 25.4 mm; 1 ksi√in. = 1.0988 MN·m^{1/2})

defined in ASTM E-399-72. The span length was 40 mm (1.576 in.) for all specimens; the width and thickness of the specimens were nominally 10 mm (0.394 in.), but actual measurements were used in calculating K_{Icd} .

The dynamic K_{Id} values listed in Table A.3 were obtained from techniques current at the time of the tests (1974) and therefore do not incorporate subsequent improvements in dynamic fracture toughness procedures.

The tensile properties determined by Stelzman and the dynamic fracture toughness measurements of the nozzle prolongations of vessels V-5 and V-9 are given in Tables A.4 and A.5, respectively. Locations of these specimens are also shown in the tables, and their orientations are as defined in Fig. 2.6.

The characteristics and test conditions for all the specimens taken from the vessel V-9 prolongation and tested at ORNL are given in Table A.6.

Table A-4. Tensile properties of V-5 nozzle forging material
from subsize tensile specimens ($\dot{\epsilon} = 0.016/\text{min}$)^a

Specimen No.	Orientation	Relative depth, d/b	Relative axial length	Test temperature (°C (°F))	Stress (ksi)				Elongations in 1.250 in. (%)		Reduction of area
					Upper yield	Lower yield	Ultimate	True fracture	Uniform	Total	
5V-200	C		0.909	93.3(200)		63.5	80.8	176	8.5	16.4	70.3
5V-201	C	0.958		93.3(200)		60.7	78.6	150	8.8	15.3	62.5
5V-202	C	0.677		93.3(200)		61.6	80.2	155	8.9	16.8	68.3
5V-203	C	0.395		93.3(200)	64.9	64.1	82.0	148	8.6	15.9	59.6
5V-204	C		0.091	93.3(200)	58.9	58.3	77.3	Tear	10.0	16.0	60.4

^aConversion factors: 1 in. = 25.4 mm; 1 ksi = 6.8948 MPa.

Table A.5. Tensile properties of V-9 nozzle forging material from subsize tensile specimens ($\dot{\epsilon} = 0.016/\text{min}$)^a

Specimen No.	Orientation	Relative depth, d/b	Relative axial length	Test temperature [°C (°F)]	Stress (ksi)			Elongation in 1.250 in. (%)		Reduction of area
					Upper yield	Lower yield	Ultimate	Uniform	Total	
9V-200	C	0.04	0.37	22.2 (72)		73.0	91.2	9.1	18.1	69.1
9V-204	C	0.96	0.37	22.2 (72)		69.7	89.6	9.8	19.1	67.1
9V-205	C	0.96	1.37	22.2 (72)		69.9	89.4	9.0	16.7	67.4
9V-206	C	0.04	1.87	22.2 (72)		75.4	93.8	8.8	18.1	71.3
9V-207	C	0.96	2.37	22.2 (72)	69.5	68.7	88.9	8.8	17.7	67.0
9V-211	C	0.04	3.37	22.2 (72)	77.0	76.8	94.7	8.6	16.8	69.0
9V-212	C	0.29	3.37	22.2 (72)	70.1	69.7	89.2	9.3	17.6	67.4
9V-213	C	0.54	3.37	22.2 (72)	69.4	68.8	88.3	9.0	18.1	70.3
9V-214	C	0.79	3.37	22.2 (72)	69.5	69.1	89.4	9.6	18.5	67.4
9V-215	C	0.96	3.37	22.2 (72)	68.9	68.1	88.9	8.0	14.8	63.0
9V-208	C	0.46	2.87	-45.6 (-50)	74.7	73.9	96.4	10.6	19.1	65.2
9V-209	C	0.54	2.87	93.3 (200)	65.7	65.4	83.8	8.0	15.1	66.9
9V-210	C	0.62	2.87	-17.8 (0)		70.7	93.2	9.5	18.8	65.5
9V-216	C	0.54	3.87	-73.3 (-100)	81.9	78.8	101.0	11.4	21.2	65.3

^aConversion factors: 1 in. = 25.4 mm; 1 ksi = 6.8948 MPa.

Table A.6. Characteristics of individual specimens taken from segment V9B

Row letter ^a	Radial position number ^a	Test temperature [°C (°F)]		Orientation	Specimen number				Spec blank
					Tensile	Charpy-V	K _{ICd}	K _{ICd}	
A	1	20	(68)	C	9V-200				
A	2								9V-001
A	3								9V-002
A	4	b		C	9V-201				
A	5	204.4	(400)	CA				9V-003	
A	6	121.1	(250)	CT				9V-004	
A	7	b		C	9V-202				
A	8	121.1	(250)	CA		9V-005			
A	9	93.3	(200)	CA			9V-006		
A	10	b		C	9V-203				
A	11	-31.7	(-25)	CT			9V-007		
A	12	20	(68)	C	9V-204				
B	1	-31.7	(-25)	CT			9V-008		
B	2								9V-009
B	3								9V-010
B	4	65.6	(150)	CT		9V-011			
B	5	204.4	(400)	CT				9V-012	
B	6	21.1	(70)	CT				9V-013	
B	7	121.1	(250)	CA				9V-014	
B	8	10	(50)	CA		9V-015			
B	9	-31.7	(-25)	CA			9V-016		
B	10	93.3	(200)	CA				9V-017	
B	11	93.3	(200)	CT			9V-018		
B	12	10	(50)	CT				9V-019	
C	1	-6.7	(20)	CT			9V-020		
C	2								9V-021
C	3								9V-022
C	4	121.1	(250)	CT		9V-023			
C	5	37.8	(100)	CA				9V-024	
C	6	15.6	(60)	CT				9V-025	
C	7	10	(50)	CA				9V-026	
C	8	65.6	(150)	CA		9V-027			
C	9	51.7	(125)	CA			9V-028		
C	10	-17.8	(0)	CA				9V-029	
C	11	-45.6	(-50)	CT			9V-030		
C	12	20	(68)	C	9V-205				
D	1	20	(68)	C	9V-206				
D	2								9V-031
D	3								9V-032
D	4	-17.8	(0)	CT		9V-033			
D	5	21.1	(70)	CT				9V-034	
D	6	65.6	(150)	CT				9V-035	
D	7	65.6	(150)	CA				9V-036	
D	8	-45.6	(-50)	CA		9V-037			
D	9	-45.6	(-50)	CA			9V-038		
D	10	37.8	(100)	CA				9V-039	
D	11	-1.1	(30)	CT			9V-040		
D	12	37.8	(100)	CT				9V-041	
E	1	37.8	(100)	CT			9V-042		
E	2								9V-043
E	3								9V-044
E	4	10	(50)	CT		9V-045			
E	5	-17.8	(0)	CA				9V-046	

Table A.6 (continued)

Row letter ^a	Radial position number ^a	Test temperature [°C (°F)]	Orientation	Specimen number				Spare blank
				Tensile	Charpy-V	K _{Icd}	K _{Idd}	
E	6	10 (50)	CT				9V-047	
E	7	21.1 (70)	CA				9V-048	
E	8	-17.8 (0)	CA		9V-049			
E	9	21.1 (70)	CA			9V-050		
E	10	1 ^b (50)	CA				9V-051	
E	11	51.7 (125)	CT			9V-052		
E	12	20 (68)	C	9V-207				
F	1	7.2 (45)	CT			9V-053		
F	2							9V-054
F	3							9V-055
F	4	-45.6 (-50)	CT		9V-056			
F	5	-17.8 (0)	CT				9V-057	
F	6	-45.6 (-50)	C	9V-208				
F	7	93.3 (200)	C	9V-209				
F	8	-17.8 (0)	C	9V-210				
F	9	-17.8 (0)	CA			9V-058		
F	10	23.9 (75)	CA				9V-059	
F	11	-73.3(-100)	CT			9V-060		
F	12	c	CT					9V-061
G	1	20 (68)	C	9V-211				
G	2							9V-062
G	3							9V-063
G	4	20 (68)	C	9V-212				
G	5	c					9V-064	
G	6	20 (68)	CT				9V-065	
G	7	20 (68)	C	9V-213				
G	8	37.8 (100)	CA		9V-066			
G	9	-73.3(-100)	CA			9V-067		
G	10	20 (68)	C	9V-214				
G	11	c	CT			9V-068		
G	12	20 (68)	C	9V-215				
H	1	20 (68)	CA			9V-069		
H	2	20 (68)	CT			9V-070		
H	3	20 (68)	CA			9V-071		
H	4	20 (68)	CT			9V-072		
H	5	20 (68)	CA			9V-073		
H	6	20 (68)	CT			9V-074		
H	7	-73.3(-100)	C	9V-216				
H	8	20 (68)	CA			9V-075		
H	9	20 (68)	CT			9V-076		
H	10	20 (68)	CA			9V-077		
H	11	20 (68)	CT			9V-078		
H	12	20 (68)	CA			9V-079		

^aSee Fig. A.2 for position in nozzle prolongation. Row letters A through H, respectively, correspond to positions 0.953 cm (3/8 in.), 2.223 cm (7/8 in.), 3.493 cm (1 3/8 in.), 4.763 cm (1 7/8 in.), 6.033 cm (2 3/4 in.), 7.309 cm (2 7/8 in.), 8.573 cm (3 3/8 in.), 9.843 cm (3 7/8 in.) from quenched end of test pieces. Radial position numbers 1 through 12, respectively, correspond to depths measured from OD of 0.64 cm (0.25 in.), 1.91 cm (0.75 in.), 3.18 cm (1.25 in.), 4.45 cm (1.75 in.), 5.72 cm (2.25 in.), 6.99 cm (2.75 in.), 8.26 cm (3.25 in.), 9.53 cm (3.75 in.), 10.80 cm (4.25 in.), 12.07 cm (4.75 in.), 13.34 cm (5.25 in.), 14.61 cm (5.75 in.).

^bUntested.

^cBad test.

REFERENCES

1. T. R. Mager, S. E. Yanichko, and L. R. Singer, *Fracture Toughness Characterization of HSST Intermediate Pressure Vessel Material*, WCAP-8456, Westinghouse Electric Corp. (December 1974).
2. ASTM E-399-72, "Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," *ASTM Standards*, Part 31, 1973.

Appendix B

Nozzle Model 1 Design, Fabrication, Instrumentation, and Test Data

Nozzle Model I Design, Fabrication, Instrumentation, and Test Data

This appendix presents information regarding the design, fabrication, instrumentation, and testing of nozzle model I, which is the only small-scale steel model with a flawed nozzle thus far tested in the HSST program. Figure B.1 illustrates the design of the model, including the type and location of the fabrication welds. The inside nozzle corner flaw was machined and sharpened by electron-beam welding and hydrogen charging before the nozzle was welded into the vessel. The heads were then welded to the cylinder. The following welding and heat-treatment procedures were used for model fabrication.

1. The filler metal was type E-9018.
2. Root passes were made by gas-tungsten arc with filler rod.
3. Subsequent passes were made by gas-tungsten arc or shielded-metal arc.
4. The model was preheated before welding to 121–260°C (250–500°F). The specified interpass temperature was 260°C (500°F).

Fig. B.1. Fabrication drawing for nozzle model I.

5. The root and final passes were inspected by dye penetrant in accordance with ASTM Standard E-165.

6. Precautions were taken to avoid hydrogen contamination of weld metal.

7. Immediately after welding, the model was placed in a stress-relieving furnace, heated to a temperature of $621^{\circ}\text{C} \pm 14^{\circ}$ ($1150^{\circ}\text{F} \pm 25^{\circ}$) at a maximum rate of 55.5°C/hr (100°F/hr), and held at that temperature for 1 hr. The model was then furnace cooled to 316°C (600°F) at a maximum rate of 55.5°C/hr (100°F/hr), and then air cooled to room temperature.

8. After stress relieving, the model was inspected by radiography. Neither cracks nor lack of fusion were acceptable. Porosity indications were judged according to the charts given in Appendix VI to Section III of the 1971 ASME Boiler and Pressure Vessel Code.

Figure B.2 shows the location and numbering of the strain gages mounted on the vessel. Strain gages 13 through 19 were 3.18 mm (1/8 in.) EP-08 gages and were mounted with Eastman 910 cement on a 200-grit surface. The other 12 gages were 0.79 mm (0.031 in.) EP-08 gages and were mounted by the same procedure. The test results for nozzle model I are listed in Table B.1, and they are also discussed in Chapter 5.

Fig. B.2. Strain gage layout for nozzle model I.

Table B.1. Pressure-strain data from nozzle model 1 (vessel V-4 prolongation)

See Fig. 8.2 for gage locations
 Test temperature: 88°C (190°F)
 Flaw depth: 6.86 mm (0.27 in.)
 Flaw location: inside nozzle corner
 Test date: August 1, 1973

Pressure surge (psi)	Pressure drop (psi)	Strain (in/in) at gage No. -																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0		10	20	2	10	0	20	10	20	20	10	0	0	0	0	10	0	0	0	20
4,000		210	140	20	100	50	20	90	20	130	200	20	50	60	60	270	240	240	230	250
8,000		310	230	10	170	80	20	150	20	260	340	20	90	100	90	410	430	420	420	420
12,000		560	350	10	251	110	30	220	10	380	510	20	130	140	130	620	640	640	630	640
14,000		650	420	0	261	120	50	240	0	450	600	30	130	140	130	730	760	750	740	750
16,000		720	470	-30	290	120	60	250	-20	510	660	40	130	180	160	810	830	840	840	840
18,000		790	520	-40	300	120	80	260	-40	580	720	50	120	200	180	910	930	940	930	940
20,000		870	580	-80	310	100	90	260	-70	630	780	70	110	220	190	1,000	1,070	1,060	1,050	1,030
4,000		0	30	-60	-70	30	-30	20	-40	130	140	50	-60	10	0	20	40	40	40	30
8,000		160	150	-50	100	10	70	80	-40	270	300	60	30	100	90	210	240	240	230	220
12,000		340	250	-50	180	50	80	150	-50	400	470	60	60	120	120	400	440	440	430	420
20,000		520	360	-60	320	100	80	270	-60	630	790	70	110	220	200	990	1,060	1,020	1,050	1,020
22,000		870	580	-70	940	110	110	280	-110	670	850	80	90	230	200	1,090	1,210	1,210	1,200	1,120
23,000		990	620	-120	340	130	130	280	-140	590	890	90	80	230	190	1,160	1,310	1,220	1,310	1,180
24,000		990	640	-150	360	70	130	280	-140	590	890	90	80	200	160	1,230	1,440	1,450	1,440	1,350
25,000		1,050	650	-210	390	50	140	280	-160	720	940	110	50	200	160	1,330	1,610	1,650	1,650	1,550
26,000		1,160	650	-210	450	30	160	300	-200	750	1,030	140	20	140	80	1,390	1,610	1,650	1,650	1,550
26,000	100	1,430	710	-210	560	20	170	350	-170	850	1,260	200	-40	0	-110	1,490	1,880	2,080	1,890	1,490
26,000		1,680	730	-200	580	30	170	370	-150	870	1,220	200	-40	-50	-160	1,570	1,960	2,250	1,960	1,520
26,000		1,500	750	-180	600	30	160	380	-130	890	1,230	200	-40	-90	-200	1,530	2,090	2,340	2,020	1,530
26,500	100	1,530	780	-170	630	30	160	410	-130	960	1,260	200	-50	-140	-280	1,600	2,160	2,460	2,230	1,600
26,500		1,580	810	-120	650	30	150	420	-80	1000	1,270	210	-30	-200	-340	1,640	2,320	2,890	2,410	1,640
27,000	200	1,690	860	-60	730	40	150	480	0	1,130	1,310	220	-60	-350	-520	1,780	3,000	3,540	2,850	1,870
27,000		1,730	880	-40	760	40	130	510	10	1,170	1,310	210	-50	-400	-580	1,840	3,130	3,730	3,050	2,030
27,000	100	1,860	880	-30	770	40	130	520	20	1,200	1,330	210	-50	-440	-620	1,870	3,300	3,930	3,280	2,200
27,000		1,980	880	0	800	50	120	540	40	1,240	1,350	200	-50	-500	-670	1,960	3,610	4,290	3,700	2,310
27,000		2,030	890	10	810	50	120	550	50	1,260	1,350	190	-40	-530	-700	2,100	3,680	4,560	4,050	2,380
27,500	300	2,050	910	20	830	50	110	560	50	1,260	1,400	190	-40	-540	-710	2,160	4,070	4,760	4,270	2,630
27,500		2,130	910	50	860	60	100	610	60	1,320	1,460	190	-40	-660	-820	2,440	4,940	5,680	5,240	2,680
27,500		2,220	910	50	900	70	90	640	70	1,350	1,420	180	-30	-700	-860	2,570	5,150	5,860	5,460	2,770

Table B.1 (continued)

Pres- sure ^a (psi)		Pressure drop ^b (psi)		Strain (mm/m) ^c at gage No. --																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
28,000	500	2,720	950	50	1,010	100	50	750	150	1490	1,490	150	-20	-930	-1120	3,040	6,060	6,780	6,420	3,070	
28,000		2,910	1,000	60	1,060	110	30	800	190	1570	1,520	130	10	-1,050	-1220	3,210	6,410	7,120	6,770	3,180	
28,500	500	3,340	1,160	90	1,210	160	40	940	290	1690	1,640	70	30	-1,470	-1520	3,790	7,810	8,530	8,220	3,630	
28,500	400	3,740	1,250	110	1,250	180	-70	1,000	320	1730	1,690	40	40	-1,670	-1630	3,980	8,170	8,890	8,570	3,750	
28,500	200	3,830	1,310	120	1,290	190	-80	1,030	350	1750	1,740	20	60	-1,800	-1680	4,110	8,350	9,070	8,750	3,840	
29,000		4,080	1,480	140	1,390	240	-130	1,130	420	1810	1,840	-40	80	-2,250	-1850	4,520	9,130	9,850	9,520	4,060	
29,200		4,520	1,750	220	1,510	280	-200	1,290	500	1860	2,030	-110	120	-2,820	-2200	5,190	10,950	11,730	11,390	4,780	
29,600		5,340	2,230	310	1,730	360	-300	1,530	610	1930	2,370	-230	170	-3,720	-2610	6,400	12,850	13,660	13,280	5,660	
30,000	700	5,680	2,410	320	1,810	380	-330	1,610	630	1950	2,550	-280	200	-3,960	-2720	6,680	13,260	14,070	13,680	5,900	
30,500	400	6,730	3,020	410	1,960	460	-470	1,850	705	2040	3,040	-420	260	-6,900	-3250	8,000	15,710	16,580	16,140	7,120	
31,000	400	7,160	3,240	420	2,020	490	-470	1,960	770	2100	3,280	-470	290	-5,100	-3380	8,110	16,180	17,070	16,620	7,400	
31,400	400	8,870	4,190	530	2,160	600	620	2,340	880	2280	4,160	-670	390	-6,170	-4140	10,340	19,650	20,640	20,110	9,200	
32,000	400	11,090	5,300	600	2,490	720	-780	2,880	950	2540	5,460	900	510	-7,120	-4870	12,590	22,830	24,430	23,810	11,240	
32,600	400	13,060	6,230	660	2,960	820	-910	3,350	1010	2780	6,710	-1090	620	-7,770	-5380	14,470		27,570	26,870	17,940	
33,100	400	15,070	7,120	710	3,540	900	-1020	3,870	1040	3000	8,010	1260	700	-8,100	-5810	16,300		30,740	29,960	16,640	
33,500	500	16,840	7,880	760	4,090	990	-1120	4,350	1070	3190	9,200	1410	780	-8,730	-6150	18,000		33,690		16,230	
33,600	200	19,090	8,840	870	4,900	1060	-1230	4,950	1120	3450	10,750	1580	900	-9,210	-6560	20,120		36,140		18,230	
34,100	300	21,910	9,950	960	5,880	1180	-1360	5,650	1160	3720	14,640	1770	1100	-9,650	-6940	22,470				22,460	
34,500	600		10,850	1030	6,690	1290	-1470	6,180	1180	3960	16,770	1900	1280	-9,920	-7200	24,650				22,350	
34,700			11,600	1090	7,340	1370	-1570	6,660	1230	4140	15,520	-2000	1460	-10,160	-7420	26,430				24,280	
35,000	500		13,190	1270	8,740	1580	-1820	7,760	1380	4540	18,300	-2180	1860	-10,580	-7850	30,330				28,030	
35,000	500		14,370	1410	9,870	1760	-2050	8,610	1500	4830	20,500	-2350	2180	-10,780	-8120	33,190				30,820	
34,500			14,410	1410	9,900	1750	-2070	8,640	1490	4820	20,550	-2360	2200	-10,790	-8120	33,260				30,880	
35,700	1000		15,600	1520	11,070	1950	-2320	9,560	1630	5100	22,770	-2620	2550	-10,910	-8320	36,070				33,670	
35,200	600		1610	12,550	2190	-2670	10,810	1840	5430			-3050	2980	-10,970	-8490	40,380				37,860	
37,300	700		1680	14,080	2460	-2880	12,210	2100	5170	13,600	3590	3520	3520	-10,810	-8500	43,000				40,940	
37,300	600		1620	15,230	2650	-3030	13,400	2270	5220	13,500	4070	3960	3960	-10,550	-8410		out			44,350	
35,100				17,550	3020	-3080	16,520	2760	4230	13,460	5250	5200	5200	9,270	-7820					48,800	
33,500	0			19,800			20,950												open	37,400	
		7,170	open	1070	16,400	6290	1620	19,550	920	1910	13,480	-7860	5780	1,110	-3130	1,450	5,210	13,110			

^a 1 psi = 6.8948 kPa.^b If plastic deformation occurs after a pressure is achieved, the pressure reduces by the amount shown; such information was not always recorded.^c To convert microstrain to percent strain, move decimal point four places to left.^d Unplugged heaters @ $P = 34,100$ psi.^e Failed by leaking.

Appendix C
Intermediate Vessel Test Data

BLANK PAGE

Channel
No.

	2000	4000	6000	8000	10,000	12,000	13,000	14,000
26	-7500917E+03	-1444393E+04	-224563E+04	-3030139E+04	-3022239E+04	-5140723E+04	-5003122E+04	-6553014E+04
26	-2652960E+03	-5160375E+03	-7505524E+03	-1002232E+04	-1241902E+04	-1493523E+04	-1621250E+04	-1760704E+04
27	-363549E+03	-6095975E+03	-102777E+04	-1361857E+04	-1600039E+04	-2220033E+04	-2421079E+04	-2621079E+04
29	-4302310E+03	-8409400E+03	-1263599E+04	-1693909E+04	-2120409E+04	-2595970E+04	-2867171E+04	-3226795E+04
30	-645033E+03	-125573E+04	-2106400E+04	-2992961E+04	-3903730E+04	-5233225E+04	-5974091E+04	-6836797E+04
31	-3281820E+03	-6367123E+03	-9356109E+03	-1240917E+04	-1661000E+04	-2020106E+04	-2204911E+04	-2404911E+04
32	-326340E+03	-5056101E+03	-8607400E+03	-1137020E+04	-1493909E+04	-1833496E+04	-1904012E+04	-1904012E+04
37	-2756193E+03	-4437701E+03	-6819111E+03	-9000040E+03	-1116217E+04	-1332379E+04	-1436533E+04	-1546502E+04
63	-9400510E+02	-1920906E+03	-3704327E+03	-3726705E+03	-4445456E+03	-5566708E+03	-5997930E+03	-6507550E+03
73	-4491200E+02	-9559714E+02	-1308632E+03	-1796762E+03	-2285013E+03	-2650004E+03	-2792796E+03	-2929504E+03
89	-1171002E+02	-2363134E+02	-3650815E+02	-4550490E+02	-5702760E+02	-6796450E+02	-7204701E+02	-7812011E+02
8	-1670307E+02	-2417140E+02	-3124607E+02	-3871308E+02	-4647498E+02	-5430370E+02	-6303703E+02	-7363007E+02
9	-1740993E+02	-2574362E+02	-3450004E+02	-4105794E+02	-4853969E+02	-5729072E+02	-6713652E+02	-7843652E+02
10	-1572129E+02	-2055652E+02	-2640091E+02	-3251446E+02	-3917059E+02	-4645421E+02	-5436427E+02	-6290009E+02
11	-5095485E+01	-6000000E+01	-6800000E+01	-7595485E+01	-8390970E+01	-9186455E+01	-9981940E+01	-10777425E+01
12	-6870000E+02	-1218400E+03	-1807940E+03	-2456452E+03	-3167939E+03	-3913639E+03	-4673110E+03	-5436427E+03
13	-1631004E+03	-3222054E+03	-4400917E+03	-5502452E+03	-6400427E+03	-7212143E+03	-7919601E+03	-8538152E+03
14	-1521004E+03	-3047252E+03	-4075126E+03	-4894503E+03	-5640917E+03	-6320670E+03	-6939665E+03	-7497369E+03
15	-2350193E+02	-5502452E+02	-7075162E+02	-8600232E+02	-1018000E+02	-1186059E+02	-1363099E+02	-1547070E+02
16	-4519072E+02	-9632775E+02	-1316650E+02	-1631004E+02	-1904813E+02	-2240284E+02	-2633424E+02	-3074030E+02
17	-1120714E+02	-2024116E+02	-2920991E+02	-3851717E+02	-4780277E+02	-5706491E+02	-6713652E+02	-7812011E+02
18	-1041535E+02	-2003071E+02	-2849484E+02	-3670336E+02	-4426839E+02	-5207004E+02	-6013560E+02	-6863750E+02
19	-7074501E+02	-1257703E+02	-1847252E+02	-2515407E+02	-3040000E+02	-3617004E+02	-4235193E+02	-4904144E+02
20	-1416916E+02	-2770070E+02	-4205446E+02	-5502452E+02	-6779007E+02	-7919601E+02	-9186455E+02	-10477425E+02
21	-3026340E+01	-5915130E+01	-8803924E+01	-1177132E+02	-1444045E+02	-1666222E+02	-1921481E+02	-2207840E+02
22	-7800440E+02	-1395266E+02	-2003071E+02	-2829033E+02	-3619301E+02	-4426839E+02	-5207004E+02	-6013560E+02
23	-6200517E+02	-1130490E+02	-1631004E+02	-2220033E+02	-2852960E+02	-3425177E+02	-4019181E+02	-4634930E+02
25	-1827600E+02	-3399739E+02	-5244981E+02	-7400659E+02	-9845400E+02	-1242517E+02	-1519181E+02	-1804500E+02
28	-2350193E+02	-3733070E+02	-5409900E+02	-7800440E+02	-1057162E+02	-1363099E+02	-1698509E+02	-2057070E+02
33	-2731574E+02	-4093252E+02	-6005401E+02	-8236200E+02	-1102191E+02	-1363099E+02	-1698509E+02	-2057070E+02
34	-2240284E+02	-3409000E+02	-4895000E+02	-6640000E+02	-8660711E+02	-1089948E+02	-1363099E+02	-1698509E+02
35	-2397497E+02	-3677004E+02	-5003700E+02	-6640000E+02	-8660711E+02	-1089948E+02	-1363099E+02	-1698509E+02
36	-3733070E+02	-5409900E+02	-7800440E+02	-1057162E+02	-1363099E+02	-1698509E+02	-2057070E+02	-2434930E+02
38	-1700440E+02	-2731574E+02	-3733070E+02	-5409900E+02	-7800440E+02	-1057162E+02	-1363099E+02	-1698509E+02
39	-2310091E+02	-3409000E+02	-4895000E+02	-6640000E+02	-8660711E+02	-1089948E+02	-1363099E+02	-1698509E+02
46	-5000323E+01	-1234000E+02	-1804747E+02	-2371230E+02	-2944900E+02	-3519900E+02	-4105794E+02	-4647498E+02
41	-2077714E+02	-3959471E+02	-5802060E+02	-7918053E+02	-1018000E+02	-1240284E+02	-1493909E+02	-1760704E+02
42	-3332183E+02	-7252390E+02	-1060217E+02	-1352674E+02	-1644900E+02	-1937355E+02	-2234126E+02	-2534930E+02
43	-2791331E+02	-4704250E+02	-6913670E+02	-9136700E+02	-1137962E+02	-1363099E+02	-1698509E+02	-2057070E+02
44	-2320000E+04	-2232562E+04	-2491170E+04	-2775512E+04	-3016675E+04	-3287430E+04	-3566615E+04	-3847800E+04
45	-1293671E+02	-2587362E+02	-3803007E+02	-4950070E+02	-6135372E+02	-7367920E+02	-8646615E+02	-9981940E+02
50	-1272075E+02	-1920155E+02	-2800206E+02	-3644420E+02	-4501956E+02	-5386800E+02	-6290009E+02	-7247070E+02
59	-9900550E+02	-2018911E+02	-3019404E+02	-3970090E+02	-4970674E+02	-5987280E+02	-6939665E+02	-7919601E+02
60	-1130062E+02	-2291306E+02	-3411597E+02	-4400447E+02	-5465111E+02	-6578197E+02	-7730803E+02	-8934853E+02
61	-3920215E+02	-8624650E+02	-1274700E+02	-1666092E+02	-2136517E+02	-2633424E+02	-3163099E+02	-3733070E+02
62	-1803290E+01	-2685975E+01	-3528194E+01	-4420044E+01	-5386800E+01	-6320670E+01	-7307004E+01	-8334930E+01
64	-3500509E+02	-5190519E+02	-6879970E+02	-8585273E+02	-1030857E+02	-1219022E+02	-1417070E+02	-1634930E+02
65	-9606590E+02	-1960100E+02	-2884207E+02	-3783000E+02	-4723860E+02	-5684131E+02	-6673400E+02	-7704930E+02
66	-2256124E+02	-4429044E+02	-6528733E+02	-8604874E+02	-1070219E+02	-1287791E+02	-1511243E+02	-1740704E+02
68	-2273725E+02	-3320444E+02	-4711941E+02	-6364874E+02	-8249100E+02	-1030857E+02	-1247070E+02	-1474930E+02
70	-1540450E+02	-2294341E+02	-3290995E+02	-4364070E+02	-5540470E+02	-6820510E+02	-8200510E+02	-9680510E+02
71	-1760050E+02	-2587362E+02	-3803007E+02	-4950070E+02	-6135372E+02	-7367920E+02	-8646615E+02	-9981940E+02
72	-7030100E+02	-1445221E+02	-2109243E+02	-2753736E+02	-3437205E+02	-4120662E+02	-4804126E+02	-5487590E+02
74	-5077807E+02	-7421411E+02	-1036414E+02	-1330991E+02	-1626490E+02	-1923080E+02	-2219670E+02	-2516260E+02
75	-1855353E+02	-2752060E+02	-3573991E+02	-4402037E+02	-5230991E+02	-6060000E+02	-6890000E+02	-7720000E+02
76	-1249921E+03	-2519173E+03	-3710705E+03	-4902037E+03	-6112499E+03	-7367920E+03	-8646615E+03	-9981940E+03
77	-1249921E+03	-2519173E+03	-3710705E+03	-4902037E+03	-6112499E+03	-7367920E+03	-8646615E+03	-9981940E+03
79	-1581932E+03	-3085744E+03	-4530966E+03	-5956059E+03	-7401801E+03	-8866633E+03	-1035091E+03	-1184091E+03
80	-8903013E+02	-1816293E+02	-2675614E+02	-3515405E+02	-4394257E+02	-5230991E+02	-6060000E+02	-6890000E+02
81	-1757070E+02	-3449000E+02	-5003700E+02	-6640000E+02	-8660711E+02	-1089948E+02	-1363099E+02	-1698509E+02
82	-1542072E+02	-2680214E+02	-3852115E+02	-5003700E+02	-6640000E+02	-8660711E+02	-1089948E+02	-1363099E+02
83	-1249921E+03	-2480313E+03	-3652115E+03	-4806307E+03	-5995119E+03	-7147991E+03	-8300863E+03	-9453735E+03
84	-1191332E+03	-2302664E+03	-3456815E+03	-4570020E+03	-5722290E+03	-6815900E+03	-7923761E+03	-9047672E+03
85	-2343003E+02	-5273100E+02	-7616711E+02	-9569714E+02	-1230391E+02	-1425600E+02	-1620809E+02	-1816018E+02
86	-1230391E+02	-2421244E+02	-3554445E+02	-4667677E+02	-5761350E+02	-6815900E+02	-7923761E+02	-9047672E+02
87	-1210062E+02	-2402194E+02	-3515405E+02	-4628017E+02	-5761350E+02	-6815900E+02	-7923761E+02	-9047672E+02
90	-1210062E+02	-2421244E+02	-3554445E+02	-4667677E+02	-5761350E+02	-6815900E+02	-7923761E+02	-9047672E+02
91	-1230391E+02	-2460738E+02	-3593525E+02	-4724267E+02	-5878519E+02	-6999175E+02	-8140000E+02	-9290000E+02
92	-1230391E+02	-2460738E+02	-3593525E+02	-4724267E+02	-5878519E+02	-6999175E+02	-8140000E+02	-9290000E+02
93	-1171002E+02	-2363134E+02	-3650815E+02	-4550490E+02	-5702760E+02	-6796450E+02	-7204701E+02	-7812011E+02
94	-1132742E+02	-2265440E+02	-3320105E+02	-4355150E+02	-5429348E+02	-6444440E+02	-7493316E+02	-8577222E+02
96	-1953003E+02	-4002507E+02	-5722611E+02	-7401801E+02	-9112272E+02	-1084102E+02	-1267000E+02	-1450000E+02
97	-1210062E+02	-2402194E+02	-3515405E+02	-4628017E+02	-5761350E+02	-6815900E+02	-7923761E+02	-9047672E+02
98	-1210062E+02	-2421244E+02	-3554445E+02	-4667677E+02	-5761350E+02	-6815900E+02	-7923761E+02	-9047672E+02
99	-1054621E+02	-2092943E+02	-3085744E+02	-4075126E+02	-5069987E+02	-6060000E+02	-7050000E+02	-8040000E+02
100	-1054621E+02	-2092943E+02	-3085744E+02	-4075126E+02	-5069987E+02	-6060000E+02	-7050000E+02	-8040000E+02
101	-5273100E+02	-1132122E+02	-1620993E+02	-2070183E+02	-2597496E+02	-3124805E+02	-3632805E+02	-4140805E+02
102	-1015561E+03	-2050653E+03	-3027154E+03	-3996190E+03	-4921557E+03	-5800410E+03	-6719109E+03	-7637808E+03

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Table C.1. Prototype strain data from U-S test (computer output)

Stress (mm./in.) at rupture (psi) (Mean diameter tension)

15,000	16,000	17,000	18,000	19,000	20,000	21,000	22,000	23,000	24,000	25,000	26,000	27,000	28,000	29,000	30,000	31,000	32,000	33,000	34,000	35,000	36,000	37,000	38,000	39,000	40,000	41,000	42,000	43,000	44,000	45,000	46,000	47,000	48,000	49,000	50,000	51,000	52,000	53,000	54,000	55,000	56,000	57,000	58,000	59,000	60,000	61,000	62,000	63,000	64,000	65,000	66,000	67,000	68,000	69,000	70,000	71,000	72,000	73,000	74,000	75,000	76,000	77,000	78,000	79,000	80,000	81,000	82,000	83,000	84,000	85,000	86,000	87,000	88,000	89,000	90,000	91,000	92,000	93,000	94,000	95,000	96,000	97,000	98,000	99,000	100,000
15000	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000	26000	27000	28000	29000	30000	31000	32000	33000	34000	35000	36000	37000	38000	39000	40000	41000	42000	43000	44000	45000	46000	47000	48000	49000	50000	51000	52000	53000	54000	55000	56000	57000	58000	59000	60000	61000	62000	63000	64000	65000	66000	67000	68000	69000	70000	71000	72000	73000	74000	75000	76000	77000	78000	79000	80000	81000	82000	83000	84000	85000	86000	87000	88000	89000	90000	91000	92000	93000	94000	95000	96000	97000	98000	99000	100000

Table C.2. Pressure-strain data from V-5 test
(manual readout from BLH boxes)

Pressure (psi)	Strain (in./in.) at gage No. —										(Plus denotes tension)	
	118	119	117	116	105	106	107	108	109	110	111	112
0	0	0	0	0	+10	0	0	0	0	0	+10	0
2,000	+100	+20	+100	+130	+110	+620	+750	+70	+420	+600	+260	+280
4,000	+190	+40	+180	+230	+180	+1,190	+1,400	+170	+790	+1,130	+490	+520
6,000	+290	+50	+260	+330	+260	+1,760	+2,060	+300	+1,160	+1,820	+690	+750
8,000	+380	+50	+330	+440	+350	+2,340	+2,750	+420	+1,560	+2,570	+920	+990
10,000	+470	+60	+410	+540	+410	+2,950	+3,520	+510	+1,960		+1,140	+1,220
12,000	+560	+70	+490	+640	+770	+4,070	+4,930	+1,070	+2,410		+1,370	+1,460
13,000	+600	+60	+530	+690	+1,020	+4,580	+5,710	+1,520	+2,640		+1,480	+1,570
14,000	+640	+50	+570	+730	+1,310	+5,140	+6,510	+1,940	+2,920		+1,590	+1,680
15,000	+670	+50	+620	+770	+1,590	+5,700	+7,330	+2,360	+3,270		+1,700	+1,790
16,000	+700	+40	+670	+830	+1,860	+6,310	+8,160	+2,760	+3,670		+1,820	+1,910
17,000	+740	+20	+720	+880	+2,160	+6,980	+9,080	+3,180	+4,130		+1,940	+2,030
18,000	+760	0	+760	+920	+2,480	+7,700	+10,060	+3,660	+4,630		+2,050	+2,150
19,000	+790	-40	+820	+960	+2,830	+8,510	+11,190	+4,180	+5,210		+2,180	+2,290
20,000	+820	-80	+880	+1,020	+3,260	+9,510	+12,540	+4,830	+5,870		+2,360	+2,480
21,000	+850	-140	+930	+1,080	+3,740	+10,660	+14,110	+5,570	+6,650		+2,540	+2,670
22,000	+910	-210	+1,000	+1,170	+4,350	+12,100	+16,080	+6,490	+7,620		+2,760	+2,910
23,000	+1,030	-300	+1,080	+1,290	+5,110	+13,950	+18,580	+7,640	+8,880		+3,030	+3,150
24,000	+1,260	-410	+1,160	+1,430	+6,140	+16,460	+21,930	+9,160	+10,520		+3,320	+3,430
25,000	+1,600	-560	+1,270	+1,610	+7,790	+20,610	+27,390	+19,890	+13,130		+3,700	+3,790
25,900	+1,940	-790	+1,410	+1,870	+10,830	+28,460	+37,480	+26,460	+17,970		+4,380	+4,470
26,500	+2,220	-1,050	+1,600	+2,210	+14,780		+50,750	+32,910			+5,490	+5,630
26,600	+3,030						+68,760					
26,550	+4,090				+24,170		+78,400					
26,450					+28,580		+92,780					+7,850
26,400	+5,290	-1,520	+2,490	+2,560			+109,280	+60,420				+8,050
26,250	+9,040	-1,030	+2,940	+2,570	+32,460							
	+11,400											
	+13,230											
	+12,550	+970	+2,890	+1,760								

Channel
No.

	1200	2200	3200	4200	5000	6200
24	- 3133127E+03	- 6646516E+03	- 9053440E+03	- 1215462E+04	- 1500945E+04	- 1796979E+04
26	- 1266315E+03	- 2786052E+03	- 3799070E+03	- 5120577E+03	- 6331841E+03	- 7566563E+03
27	- 1677481E+03	- 3671749E+03	- 5001732E+03	- 6679013E+03	- 8296324E+03	- 9900961E+03
29	- 2267642E+03	- 4907114E+03	- 6774955E+03	- 9180780E+03	- 1179724E+04	- 1370039E+04
30	- 3790090E+03	- 9622093E+03	- 1370753E+04	- 1900970E+04	- 2409185E+04	- 2964231E+04
32	- 1550909E+03	- 3323600E+03	- 4590224E+03	- 6141629E+03	- 7629540E+03	- 9117530E+03
37	- 1297115E+03	- 2657600E+03	- 3544942E+03	- 4405367E+03	- 5729450E+03	- 6774215E+03
63	- 4713593E+02	- 1060991E+03	- 1446822E+03	- 1901510E+03	- 2404434E+03	- 2907703E+03
73	- 3780134E+02	- 8193119E+02	- 1103004E+03	- 1449905E+03	- 1827996E+03	- 2174729E+03
97	- 5018379E+02	- 1243786E+02	- 1685004E+03	- 2269417E+03	- 2780130E+03	- 3324193E+03
9	- 2270906E+02	- 5052667E+02	- 6661942E+02	- 9180780E+02	- 1170747E+03	- 1360704E+03
8	+ 5305442E+02	+ 1100004E+03	+ 1503309E+03	+ 2121070E+03	+ 2590414E+03	+ 3134626E+03
10	- 5061642E+02	- 1137076E+02	- 1502500E+02	- 2009420E+02	- 2627353E+02	- 3133906E+02
11	- 6011730E+02	- 1233970E+02	- 1677547E+02	- 2216052E+02	- 2753971E+02	- 3270044E+02
13	- 7595826E+02	- 1614220E+02	- 2120943E+02	- 2734215E+02	- 3355664E+02	- 3862217E+02
14	+ 4439400E+02	+ 8562600E+02	+ 1203770E+03	+ 1582094E+02	+ 1931939E+02	+ 2311532E+02
15	- 2524020E+02	- 5048305E+02	- 6323165E+02	- 7914711E+02	- 9172523E+02	- 1043090E+02
16	- 3154947E+02	- 6676036E+02	- 9357068E+02	- 1064710E+03	- 1290946E+02	- 1423578E+02
17	+ 5064640E+02	+ 1013346E+03	+ 1424773E+03	+ 1962789E+03	+ 2374559E+03	+ 2912271E+03
18	- 7265944E+02	- 1548248E+02	- 2056279E+02	- 2722570E+02	- 3322678E+02	- 3829229E+02
19	+ 3169375E+02	+ 6022608E+02	+ 8068091E+02	+ 1171362E+03	+ 1425021E+03	+ 1773270E+03
20	- 4743312E+02	- 1170340E+03	- 1582615E+03	- 2152736E+03	- 2640839E+03	- 3102073E+03
21	- 6326430E+02	- 1484982E+02	- 2057322E+02	- 2756235E+02	- 3450362E+02	- 4083533E+02
22	+ 5300006E+02	+ 1077457E+02	+ 1520240E+02	+ 2026104E+03	+ 2470032E+03	+ 2976585E+03
23	- 2210135E+02	- 6003561E+02	- 7900052E+02	- 1076360E+03	- 1392410E+03	- 1645093E+03
25	+ 7921280E+02	+ 1584339E+02	+ 2185140E+02	+ 2964183E+02	+ 3578167E+02	+ 4306136E+02
28	+ 1585309E+02	+ 3170945E+02	+ 5067939E+02	+ 6964734E+02	+ 7600732E+02	+ 9018069E+02
33	- 6016320E+02	- 1297910E+02	- 1772835E+02	- 2374341E+02	- 2975897E+02	- 3514109E+02
34	- 1107538E+02	- 2405160E+02	- 3260387E+02	- 4400446E+02	- 5444895E+02	- 6450000E+02
35	- 138047E+03	- 3570944E+02	- 4888013E+02	- 6489044E+02	- 7895669E+02	- 9090731E+02
36	- 1570500E+02	- 3774387E+02	- 4736453E+02	- 6311577E+02	- 7853597E+02	- 9001979E+02
38	- 6273735E+02	- 1880036E+02	- 2210350E+02	- 3482367E+02	- 5059708E+02	- 6492099E+02
39	- 1106666E+03	- 2403414E+03	- 3227854E+03	- 4137130E+03	- 512362E+03	- 625440E+03
40	- 4705078E+02	- 8795137E+02	- 1069390E+02	- 1381917E+02	- 1697225E+02	- 1980314E+02
41	- 8169748E+02	- 1792958E+02	- 2421855E+02	- 3271077E+02	- 4080221E+02	- 4867579E+02
42	- 1241564E+02	- 4072452E+02	- 5032626E+02	- 6405060E+02	- 7895597E+02	- 9064877E+02
43	- 1131718E+02	- 2453727E+02	- 3186435E+02	- 4497371E+02	- 5560774E+02	- 6626220E+02
44	- 1100544E+03	- 2421625E+03	- 3102530E+03	- 4403173E+03	- 5472692E+03	- 6501800E+03
45	- 697980E+02	- 1416701E+02	- 1910612E+02	- 2516213E+02	- 3176141E+02	- 3762339E+02
46	- 1562709E+02	- 3764010E+02	- 5032626E+02	- 6919506E+02	- 8796497E+02	- 1068395E+02
58	- 6599220E+02	- 1477373E+02	- 1981518E+02	- 2673574E+02	- 3333537E+02	- 3994072E+02
60	- 5973217E+02	- 1320708E+02	- 1792802E+02	- 2453308E+02	- 3082211E+02	- 3648300E+02
61	- 2825878E+02	- 6400394E+02	- 9121273E+02	- 1195201E+02	- 1509205E+02	- 1792390E+02
62	- 4092647E+02	- 9754420E+02	- 1321012E+02	- 1792802E+02	- 2233614E+02	- 2673927E+02
64	- 1195268E+02	- 2579257E+02	- 3522698E+02	- 4780050E+02	- 6007735E+02	- 7297402E+02
65	- 4717590E+02	- 1006482E+02	- 1352463E+02	- 1855702E+02	- 2284654E+02	- 2842105E+02
66	- 8490674E+02	- 1855584E+02	- 2516213E+02	- 3428340E+02	- 4309020E+02	- 5115557E+02
68	- 8488174E+02	- 1823900E+02	- 2516213E+02	- 3396080E+02	- 4182972E+02	- 4969330E+02
70	- 6599720E+02	- 1414476E+02	- 1910612E+02	- 2579117E+02	- 3207372E+02	- 3836557E+02
71	- 1570070E+02	- 3771808E+02	- 534953E+02	- 6919506E+02	- 880493E+02	- 1073721E+02
72	- 9382674E+02	- 2829546E+02	- 4090399E+02	- 5063149E+02	- 6492318E+02	- 7872950E+02
74	- 6752496E+01	- 2516528E+02	- 3146955E+02	- 4412755E+02	- 5660641E+02	- 6814301E+02
75	- 5151662E+02	- 1197113E+02	- 1638412E+02	- 2174850E+02	- 2710117E+02	- 3264000E+02
76	- 6411778E+02	- 1480732E+02	- 2048116E+02	- 2742212E+02	- 3403533E+02	- 4085480E+02
77	- 2837332E+02	- 6614890E+02	- 8821383E+02	- 1197748E+02	- 1512565E+02	- 1796254E+02
79	- 6617740E+02	- 1449807E+02	- 2017191E+02	- 2742212E+02	- 3372607E+02	- 4097500E+02
80	- 5044755E+02	- 1101300E+02	- 1513158E+02	- 2048779E+02	- 2553361E+02	- 3057702E+02
81	- 9402824E+01	- 2516148E+02	- 3772201E+02	- 5158346E+02	- 6929333E+02	- 8505399E+02
82	- 6929547E+02	- 1480980E+02	- 2079893E+02	- 2773732E+02	- 3466830E+02	- 4128779E+02
83	- 5661305E+02	- 1228078E+02	- 1732419E+02	- 2332456E+02	- 2798708E+02	- 3466092E+02
84	- 5352203E+02	- 1165666E+02	- 1638466E+02	- 2208377E+02	- 2773236E+02	- 3277575E+02
85	- 6210392E+02	- 1401892E+02	- 2827532E+02	- 4097559E+02	- 5349237E+02	- 5979646E+02
86	- 5978744E+02	- 1228301E+02	- 1701121E+02	- 2300937E+02	- 2835888E+02	- 3371751E+02
87	+ 3792346E+01	+ 3792346E+01	+ 3792346E+01	+ 3792346E+01	+ 3792346E+01	+ 3792346E+01
90	+ 6940056E+01	+ 6940056E+01	+ 6940056E+01	+ 6940056E+01	+ 6940056E+01	+ 6940056E+01
91	- 5671347E+01	- 1197561E+01	- 1670381E+01	- 2269417E+01	- 2805148E+01	- 3341011E+01
92	- 1579571E+02	- 3670051E+02	- 5064917E+02	- 6936330E+02	- 8829675E+02	- 1060554E+02
93	- 5674788E+02	- 1197905E+02	- 1607259E+02	- 2206372E+02	- 2742650E+02	- 3278312E+02
94	- 535053E+02	- 1165931E+02	- 1575708E+02	- 211818E+02	- 2615912E+02	- 3120253E+02
96	- 9340746E+01	- 2136872E+02	- 3140517E+02	- 4097559E+02	- 5367009E+02	- 6292646E+02
97	- 5660765E+02	- 1228024E+02	- 1669322E+02	- 2237897E+02	- 2806090E+02	- 3408411E+02
98	- 5668382E+02	- 1228786E+02	- 1701605E+02	- 2300937E+02	- 2836373E+02	- 3407527E+02
99	- 6615218E+02	- 1449555E+02	- 1985417E+02	- 2679137E+02	- 3360836E+02	- 3991260E+02
100	- 4415115E+02	- 1060616E+02	- 1418672E+02	- 1922701E+02	- 2422735E+02	- 2886653E+02
101	- 2200953E+02	- 553087E+02	- 6929153E+02	- 9140700E+02	- 1197257E+02	- 1417906E+02
102	- 4412100E+02	- 1040115E+02	- 1386849E+02	- 1859661E+02	- 2395532E+02	- 2836830E+02

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Table C.3 (continued)

Channel No.	Stress (ksi./in.) at pressure (psi) (Stress denotes tension)									
	23,00	23,500	24,000	24,500	25,000	25,500	26,000	26,500	26,850	
24	-1660830E+05	-1847639E+05	-2114311E+05	-2401442E+05	-3009959E+05	-4028230E+05	-5785049E+05	-7374501E+05	-7962995E+05	
26	-5787652E+04	-6566181E+04	-7731649E+04	-9289011E+04	-1174005E+05	-1521952E+05	-2115916E+05	-2645291E+05	-2842707E+05	
27	-8065030E+04	-1000753E+05	-1168280E+05	-1389532E+05	-1730737E+05	-2237803E+05	-3105636E+05	-4168208E+05	-4168208E+05	
29	-1700954E+05	-1444747E+05	-1662209E+05	-1947693E+05	-2404223E+05	-3070182E+05	-4275523E+05	-5359919E+05	-5765200E+05	
30	-9900749E+05	-1058014E+06	-1058014E+06	-1058014E+06	-1358092E+06	-1058178E+06	-1058146E+06	-1058146E+06	-1058092E+06	
32	-1059691E+05	-1134990E+05	-1207550E+05	-1292330E+05	-1645804E+05	-2120747E+05	-2822946E+05	-3356711E+05	-3635144E+05	
37	-2260423E+04	-2731904E+04	-3193935E+04	-3767954E+04	-4480420E+04	-5367743E+04	-6466352E+04	-7809602E+04	-9404222E+04	
63	-1307115E+04	-1465725E+04	-1575815E+04	-1726795E+04	-1962702E+04	-2337743E+04	-2868557E+04	-3356711E+04	-3635144E+04	
73	-9614018E+03	-1078005E+04	-1230003E+04	-1410435E+04	-1695623E+04	-2052094E+04	-2521780E+04	-3007005E+04	-3109933E+04	
97	-1311094E+04	-1399616E+04	-1519145E+04	-1662619E+04	-1806420E+04	-2160837E+04	-2646496E+04	-3209191E+04	-3357790E+04	
8	-8990465E+03	-9022312E+03	-8705515E+03	-7597633E+03	-5096529E+03	-1360110E+03	+2629191E+03	+1315045E+03	+1103290E+03	
9	+1700272E+04	+2029410E+04	+2562659E+04	+3314707E+04	+4463482E+04	+6747065E+04	+1031520E+05	+1612517E+05	+1612517E+05	
10	-1041575E+04	-1280304E+04	-1665301E+04	-2235124E+04	-3314715E+04	-5026552E+04	-7809911E+04	-1012517E+04	-1012517E+04	
11	-6748362E+03	-4386482E+03	-3093510E+03	-3545408E+03	-3825374E+03	-5666536E+03	-9497540E+03	-1234704E+03	-1234704E+03	
13	-1301220E+04	-1665267E+04	-2282722E+04	-3245078E+04	-5040173E+04	-7905749E+04	-1258211E+05	-1608000E+05	-1608000E+05	
14	+1349008E+04	+1614707E+04	+2039122E+04	+2660970E+04	+3745394E+04	+5395208E+04	+8156044E+04	+1029319E+05	+1029319E+05	
15	-7027035E+03	-6774264E+03	-5950558E+03	-4019087E+03	-2207425E+03	-5099200E+03	+1070323E+04	+1196476E+04	+1196476E+04	
16	-1152247E+04	-1202952E+04	-1231460E+04	-1206110E+04	-1082644E+04	-8609642E+03	-5475184E+03	-6108408E+03	-6108408E+03	
17	+1640068E+04	+1917573E+04	+2415707E+04	+3096312E+04	+4236055E+04	+5977051E+04	+9210258E+04	+1463902E+05	+1463902E+05	
18	-1205976E+04	-1478343E+04	-1900008E+04	-2790545E+04	-4232722E+04	-6572548E+04	-1090811E+05	-1463902E+05	-1463902E+05	
19	+6706277E+03	+6363909E+03	+6522899E+03	+6648845E+03	+6712164E+03	+6966144E+03	+8200932E+03	+9910636E+03	+9910636E+03	
20	-4621410E+03	-4241816E+03	-3708210E+03	-3040285E+03	-4420199E+03	-5697890E+03	-8579058E+03	-1230192E+04	-1230192E+04	
21	-1794835E+04	-1592420E+04	-2035705E+04	-2694172E+04	-3075072E+04	-3752728E+04	-5422261E+04	-7253139E+04	-7253139E+04	
22	+1599087E+04	+1883001E+04	+2330381E+04	+2972809E+04	+4077807E+04	+5759288E+04	+9093211E+04	+1201553E+05	+1201553E+05	
23	-943827E+03	-9560577E+03	-9465489E+03	-8959044E+03	-7661005E+03	-5697807E+03	-2183415E+03	+2772508E+03	+2772508E+03	
25	+6408352E+04	+7104444E+04	+8127555E+04	+9520007E+04	+1196402E+05	+1528931E+05	+2180519E+05	+3417277E+05	+3417277E+05	
28	-1548280E+04	-1779290E+04	-2077022E+04	-2421978E+04	-2906369E+04	-3587261E+04	-4441578E+04	-5417277E+04	-5417277E+04	
33	-6008957E+03	-5951893E+03	-4179078E+03	-2375768E+03	-3767583E+03	-4242798E+03	-4780641E+03	-5073405E+03	-5073405E+03	
34	-3100301E+03	-2311092E+03	-2323822E+03	-2375768E+03	-3164401E+03	-4309965E+03	-5172719E+03	-5417277E+03	-5417277E+03	
35	-6610418E+03	-7002127E+03	-7544802E+03	-8145441E+03	-8434669E+03	-8278723E+03	-7823185E+03	-7949474E+03	-7949474E+03	
36	-1100301E+03	-2974740E+03	-2815350E+03	-2468196E+03	-1613308E+03	+6040581E+02	+6398056E+03	+1658355E+03	+1658355E+03	
38	-1993491E+03	-1962310E+03	-1961830E+03	-1899902E+03	-1867331E+03	-1930149E+03	-1328040E+03	-6003991E+02	-6003991E+02	
39	-2200149E+04	-2190690E+04	-2171674E+04	-2140043E+04	-2117881E+04	-2193837E+04	-2412799E+04	-3165835E+04	-3165835E+04	
40	-6288572E+03	-6678778E+03	-6761367E+03	-7107346E+03	-7704996E+03	-8182517E+03	-8276849E+03	-1701544E+04	-1701544E+04	
41	-1902919E+04	-1950002E+04	-1994119E+04	-2028718E+04	-2053881E+04	-2113671E+04	-2189185E+04	-2362261E+04	-2362261E+04	
42	-3551190E+03	-3458312E+03	-3301040E+03	-3049408E+03	-2388865E+03	-1628856E+02	-4532975E+03	+1031867E+04	+1031867E+04	
43	-2307378E+04	-2453371E+04	-2535513E+04	-2711296E+04	-3255456E+04	-4715116E+04	-7082883E+05	-1674620E+05	-1674620E+05	
44	-3008901E+04	-3351190E+04	-3950624E+04	-4891107E+04	-6369953E+04	-8369953E+04	-1042052E+05	-2380950E+05	-2380950E+05	
45	-6321157E+03	-4937542E+03	-1721535E+03	+3177626E+03	+6637598E+03	+3789556E+02	-6667172E+03	-959288E+03	-959288E+03	
58	-540831E+03	-5597814E+03	-6064291E+03	-7327800E+03	-9498147E+03	-1166805E+04	-1789483E+04	-1336702E+04	-1336702E+04	
59	-1823202E+04	-1912359E+04	-2016158E+04	-2145121E+04	-2456519E+04	-3064829E+04	-4510850E+04	-6260471E+04	-6260471E+04	
60	-516113E+04	-560993E+04	-6706792E+04	-8463364E+04	-12132570E+04	-16648327E+04	-2417285E+04	-3183883E+04	-3183883E+04	
61	-1298264E+04	-1321030E+04	-1409102E+04	-1402812E+04	-1145213E+04	-7013670E+03	-7853965E+02	+8812211E+02	+8812211E+02	
62	-128343E+03	-1369425E+03	-1443788E+03	-1569905E+03	-1748095E+03	-2148512E+03	-3173975E+03	-400614E+04	-400614E+04	
64	-3990494E+04	-4243185E+04	-4551437E+04	-4859689E+04	-510818E+04	-5614884E+04	-7404726E+04	-9552670E+04	-9552670E+04	
65	-1453253E+04	-1572709E+04	-1764500E+04	-2053960E+04	-2576101E+04	-3362627E+04	-4360907E+04	-596301E+04	-596301E+04	
66	-3560767E+04	-4126781E+04	-4906488E+04	-6287692E+04	-8426832E+04	-11404188E+05	-1842055E+05	-2221615E+05	-2221615E+05	
68	-2506948E+04	-2673570E+04	-2915768E+04	-3327819E+04	-4183376E+04	-5400893E+04	-7804126E+04	-9999276E+04	-9999276E+04	
70	-1792794E+04	-1893452E+04	-2072741E+04	-2305503E+04	-2846517E+04	-3859449E+04	-5108249E+04	-6215272E+04	-6215272E+04	
71	-5850261E+03	-6259134E+03	-7139855E+03	-8492389E+03	-9719107E+03	-1251891E+04	-1525550E+04	-1462597E+04	-1462597E+04	
72	+3167047E+02	+4105144E+02	+3167047E+02	+1568694E+02	+1575329E+02	-4400877E+03	-9802166E+03	-1292300E+04	-1292300E+04	
74	-3056491E+03	-3277699E+03	-3655627E+03	-4475510E+03	-5452671E+03	-6740510E+03	-7648181E+03	-8510239E+03	-8510239E+03	
75	-1497201E+04	-1541323E+04	-1585465E+04	-1654800E+04	-1768276E+04	-2266361E+04	-3391711E+04	-4425527E+04	-4425527E+04	
76	-2170083E+04	-2288171E+04	-2420809E+04	-2597280E+04	-2959775E+04	-3892931E+04	-5781157E+04	-7728951E+04	-7728951E+04	
77	-1115821E+04	-1169395E+04	-1207237E+04	-1197764E+04	-1046467E+04	-7091748E+03	-3771581E+02	+2900420E+03	+2900420E+03	
79	-2052110E+04	-2193866E+04	-2370492E+04	-2638317E+04	-3155267E+04	-4104254E+04	-5932586E+04	-8085201E+04	-8085201E+04	
80	-1311382E+08	-1355430E+08	-1421712E+08	-1500428E+08	-1661187E+08	-2042714E+08	-2824484E+08	-3814093E+08	-3814093E+08	
81	-4423005E+03	-4570056E+03	-5231740E+03	-5799387E+03	-6083079E+03	-6713319E+03	-7751577E+03	-9794358E+03	-9794358E+03	
82	-1091275E+04	-2206441E+04	-2657282E+04	-3224580E+04	-4356195E+04	-5957736E+04	-8020703E+04	-1337444E+05	-1337444E+05	
83	-1370998E+04	-1424630E+04	-1467633E+04	-1538115E+04	-164640E+04	-1761682E+04	-2046727E+04	-2477008E+04	-2477008E+04	
84	-1191439E+04	-1251332E+04	-1367968E+04	-1550785E+04	-1998387E+04	-3130101E+04	-48227364E+04	-7016241E+04	-7016241E+04	
85	-1796931E+03	-2047947E+03	-2519959E+03	-3151193E+03	-4538131E+03	-7595156E+03	-1364756E+04	-179977E+04	-179977E+04	
86	-1260712E+04	-1330096E+04	-1412022E+04	-1522377E+04	-1711505E+04	-2096071E+04	-2420757E+04	-3621896E+04	-3621896E+04	
87	+2649881E+02	+2780960E+02	+2965111E+02	+3531367E+02	+3216153E+02	+3280341E+02	+4225144E+02	+4477008E+02	+4477008E+02	
90	+2964226E+02	+3157111E+02	+3279456E+02	+3846130E+02	+3530924E+02	+3596485E+02	+4225144E+02	+4477008E+02	+4477008E+02	
91	-1279782E+04	-1355392E+04	-1446834E+04	-1560280E+04	-1717887E+04	-2102531E+04	-2509177E+04	-3064599E+04	-3064599E+04	
92	-2069290E+03	-2837269E+03	-2900813E+03	-2963355E+03	-3057919E+03	-				

Table C.3 (continued)

Strain (in./in.) at pressure (psi) (Vibram monomer tension)

	23,500	24,000	24,500	25,000	25,500	26,000	26,500	26,950	27,400	27,850	0
E+05	-184.7630E+05	-2114.3110E+05	-2401.4420E+05	-2689.590E+05	-2977.738E+05	-3265.886E+05	-3554.034E+05	-3842.182E+05	-4130.330E+05	-4418.478E+05	-4706.626E+05
E+04	-656618E+04	-773264E+04	-889910E+04	-1006556E+04	-1123202E+04	-1239848E+04	-1356494E+04	-1473140E+04	-1589786E+04	-1706432E+04	-1823078E+04
E+03	-1800073E+03	-2166200E+03	-2532327E+03	-2898454E+03	-3264581E+03	-3630708E+03	-3996835E+03	-4362962E+03	-4729089E+03	-5095216E+03	-5461343E+03
E+02	-1447472E+02	-1662209E+02	-1876946E+02	-2091683E+02	-2306420E+02	-2521157E+02	-2735894E+02	-2950631E+02	-3165368E+02	-3380105E+02	-3594842E+02
E+01	-1050092E+01	-1207530E+01	-1364968E+01	-1522406E+01	-1679844E+01	-1837282E+01	-1994720E+01	-2152158E+01	-2309596E+01	-2467034E+01	-2624472E+01
E+00	-2231908E+00	-2599350E+00	-2966792E+00	-3334234E+00	-3701676E+00	-4069118E+00	-4436560E+00	-4804002E+00	-5171444E+00	-5538886E+00	-5906328E+00
E-01	-1446572E-01	-1573015E-01	-1700458E-01	-1827901E-01	-1955344E-01	-2082787E-01	-2210230E-01	-2337673E-01	-2465116E-01	-2592559E-01	-2720002E-01
E-02	-1070005E-02	-1230005E-02	-1390005E-02	-1550005E-02	-1710005E-02	-1870005E-02	-2030005E-02	-2190005E-02	-2350005E-02	-2510005E-02	-2670005E-02
E-03	-1399616E-03	-1519616E-03	-1639616E-03	-1759616E-03	-1879616E-03	-1999616E-03	-2119616E-03	-2239616E-03	-2359616E-03	-2479616E-03	-2599616E-03
E-04	-2022312E-04	-2142312E-04	-2262312E-04	-2382312E-04	-2502312E-04	-2622312E-04	-2742312E-04	-2862312E-04	-2982312E-04	-3102312E-04	-3222312E-04
E-05	-2879610E-05	-3009610E-05	-3139610E-05	-3269610E-05	-3399610E-05	-3529610E-05	-3659610E-05	-3789610E-05	-3919610E-05	-4049610E-05	-4179610E-05
E-06	-1200504E-06	-1260504E-06	-1320504E-06	-1380504E-06	-1440504E-06	-1500504E-06	-1560504E-06	-1620504E-06	-1680504E-06	-1740504E-06	-1800504E-06
E-07	-4336402E-07	-4536402E-07	-4736402E-07	-4936402E-07	-5136402E-07	-5336402E-07	-5536402E-07	-5736402E-07	-5936402E-07	-6136402E-07	-6336402E-07
E-08	-1665267E-08	-1725267E-08	-1785267E-08	-1845267E-08	-1905267E-08	-1965267E-08	-2025267E-08	-2085267E-08	-2145267E-08	-2205267E-08	-2265267E-08
E-09	-1616707E-09	-1676707E-09	-1736707E-09	-1796707E-09	-1856707E-09	-1916707E-09	-1976707E-09	-2036707E-09	-2096707E-09	-2156707E-09	-2216707E-09
E-10	-6774266E-10	-6974266E-10	-7174266E-10	-7374266E-10	-7574266E-10	-7774266E-10	-7974266E-10	-8174266E-10	-8374266E-10	-8574266E-10	-8774266E-10
E-11	-1200504E-11	-1260504E-11	-1320504E-11	-1380504E-11	-1440504E-11	-1500504E-11	-1560504E-11	-1620504E-11	-1680504E-11	-1740504E-11	-1800504E-11
E-12	-1937373E-12	-2007373E-12	-2077373E-12	-2147373E-12	-2217373E-12	-2287373E-12	-2357373E-12	-2427373E-12	-2497373E-12	-2567373E-12	-2637373E-12
E-13	-1470363E-13	-1530363E-13	-1590363E-13	-1650363E-13	-1710363E-13	-1770363E-13	-1830363E-13	-1890363E-13	-1950363E-13	-2010363E-13	-2070363E-13
E-14	-6363000E-14	-6563000E-14	-6763000E-14	-6963000E-14	-7163000E-14	-7363000E-14	-7563000E-14	-7763000E-14	-7963000E-14	-8163000E-14	-8363000E-14
E-15	-4241816E-15	-4341816E-15	-4441816E-15	-4541816E-15	-4641816E-15	-4741816E-15	-4841816E-15	-4941816E-15	-5041816E-15	-5141816E-15	-5241816E-15
E-16	-1502420E-16	-1552420E-16	-1602420E-16	-1652420E-16	-1702420E-16	-1752420E-16	-1802420E-16	-1852420E-16	-1902420E-16	-1952420E-16	-2002420E-16
E-17	-1003001E-17	-1053001E-17	-1103001E-17	-1153001E-17	-1203001E-17	-1253001E-17	-1303001E-17	-1353001E-17	-1403001E-17	-1453001E-17	-1503001E-17
E-18	-9540577E-18	-9940577E-18	-10340577E-18	-10740577E-18	-11140577E-18	-11540577E-18	-11940577E-18	-12340577E-18	-12740577E-18	-13140577E-18	-13540577E-18
E-19	-7100446E-19	-7300446E-19	-7500446E-19	-7700446E-19	-7900446E-19	-8100446E-19	-8300446E-19	-8500446E-19	-8700446E-19	-8900446E-19	-9100446E-19
E-20	-1770290E-20	-1820290E-20	-1870290E-20	-1920290E-20	-1970290E-20	-2020290E-20	-2070290E-20	-2120290E-20	-2170290E-20	-2220290E-20	-2270290E-20
E-21	-5051093E-21	-5151093E-21	-5251093E-21	-5351093E-21	-5451093E-21	-5551093E-21	-5651093E-21	-5751093E-21	-5851093E-21	-5951093E-21	-6051093E-21
E-22	-2311092E-22	-2361092E-22	-2411092E-22	-2461092E-22	-2511092E-22	-2561092E-22	-2611092E-22	-2661092E-22	-2711092E-22	-2761092E-22	-2811092E-22
E-23	-2002127E-23	-2052127E-23	-2102127E-23	-2152127E-23	-2202127E-23	-2252127E-23	-2302127E-23	-2352127E-23	-2402127E-23	-2452127E-23	-2502127E-23
E-24	-2974760E-24	-3024760E-24	-3074760E-24	-3124760E-24	-3174760E-24	-3224760E-24	-3274760E-24	-3324760E-24	-3374760E-24	-3424760E-24	-3474760E-24
E-25	-1966310E-25	-2016310E-25	-2066310E-25	-2116310E-25	-2166310E-25	-2216310E-25	-2266310E-25	-2316310E-25	-2366310E-25	-2416310E-25	-2466310E-25
E-26	-2190090E-26	-2240090E-26	-2290090E-26	-2340090E-26	-2390090E-26	-2440090E-26	-2490090E-26	-2540090E-26	-2590090E-26	-2640090E-26	-2690090E-26
E-27	-1647027E-27	-1697027E-27	-1747027E-27	-1797027E-27	-1847027E-27	-1897027E-27	-1947027E-27	-1997027E-27	-2047027E-27	-2097027E-27	-2147027E-27
E-28	-1195000E-28	-1245000E-28	-1295000E-28	-1345000E-28	-1395000E-28	-1445000E-28	-1495000E-28	-1545000E-28	-1595000E-28	-1645000E-28	-1695000E-28
E-29	-3430312E-29	-3480312E-29	-3530312E-29	-3580312E-29	-3630312E-29	-3680312E-29	-3730312E-29	-3780312E-29	-3830312E-29	-3880312E-29	-3930312E-29
E-30	-2453371E-30	-2503371E-30	-2553371E-30	-2603371E-30	-2653371E-30	-2703371E-30	-2753371E-30	-2803371E-30	-2853371E-30	-2903371E-30	-2953371E-30
E-31	-3334119E-31	-3384119E-31	-3434119E-31	-3484119E-31	-3534119E-31	-3584119E-31	-3634119E-31	-3684119E-31	-3734119E-31	-3784119E-31	-3834119E-31
E-32	-6937352E-32	-6987352E-32	-7037352E-32	-7087352E-32	-7137352E-32	-7187352E-32	-7237352E-32	-7287352E-32	-7337352E-32	-7387352E-32	-7437352E-32
E-33	-5597814E-33	-5647814E-33	-5697814E-33	-5747814E-33	-5797814E-33	-5847814E-33	-5897814E-33	-5947814E-33	-5997814E-33	-6047814E-33	-6097814E-33
E-34	-1912359E-34	-1962359E-34	-2012359E-34	-2062359E-34	-2112359E-34	-2162359E-34	-2212359E-34	-2262359E-34	-2312359E-34	-2362359E-34	-2412359E-34
E-35	-1600993E-35	-1650993E-35	-1700993E-35	-1750993E-35	-1800993E-35	-1850993E-35	-1900993E-35	-1950993E-35	-2000993E-35	-2050993E-35	-2100993E-35
E-36	-1321030E-36	-1371030E-36	-1421030E-36	-1471030E-36	-1521030E-36	-1571030E-36	-1621030E-36	-1671030E-36	-1721030E-36	-1771030E-36	-1821030E-36
E-37	-1369458E-37	-1419458E-37	-1469458E-37	-1519458E-37	-1569458E-37	-1619458E-37	-1669458E-37	-1719458E-37	-1769458E-37	-1819458E-37	-1869458E-37
E-38	-2431850E-38	-2481850E-38	-2531850E-38	-2581850E-38	-2631850E-38	-2681850E-38	-2731850E-38	-2781850E-38	-2831850E-38	-2881850E-38	-2931850E-38
E-39	-1572700E-39	-1622700E-39	-1672700E-39	-1722700E-39	-1772700E-39	-1822700E-39	-1872700E-39	-1922700E-39	-1972700E-39	-2022700E-39	-2072700E-39
E-40	-4126701E-40	-4176701E-40	-4226701E-40	-4276701E-40	-4326701E-40	-4376701E-40	-4426701E-40	-4476701E-40	-4526701E-40	-4576701E-40	-4626701E-40
E-41	-2673570E-41	-2723570E-41	-2773570E-41	-2823570E-41	-2873570E-41	-2923570E-41	-2973570E-41	-3023570E-41	-3073570E-41	-3123570E-41	-3173570E-41
E-42	-1893452E-42	-1943452E-42	-1993452E-42	-2043452E-42	-2093452E-42	-2143452E-42	-2193452E-42	-2243452E-42	-2293452E-42	-2343452E-42	-2393452E-42
E-43	-6259134E-43	-6309134E-43	-6359134E-43	-6409134E-43	-6459134E-43	-6509134E-43	-6559134E-43	-6609134E-43	-6659134E-43	-6709134E-43	-6759134E-43
E-44	-4105144E-44	-4155144E-44	-4205144E-44	-4255144E-44	-4305144E-44	-4355144E-44	-4405144E-44	-4455144E-44	-4505144E-44	-4555144E-44	-4605144E-44
E-45	-3277699E-45	-3327699E-45	-3377699E-45	-3427699E-45	-3477699E-45	-3527699E-45	-3577699E-45	-3627699E-45	-3677699E-45	-3727699E-45	-3777699E-45
E-46	-1541323E-46	-1591323E-46	-1641323E-46	-1691323E-46	-1741323E-46	-1791323E-46	-1841323E-46	-1891323E-46	-1941323E-46	-1991323E-46	-2041323E-46
E-47	-2280371E-47	-2330371E-47	-2380371E-47	-2430371E-47	-2480371E-47	-2530371E-47	-2580371E-47	-2630371E-47	-2680371E-47	-2730371E-47	-2780371E-47
E-48	-1169395E-48	-1219395E-48	-1269395E-48	-1319395E-48	-1369395E-48	-1419395E-48	-1469395E-48	-1519395E-48	-1569395E-48	-1619395E-48	-1669395E-48
E-49	-2193066E-49	-2243066E-49	-2293066E-49	-2343066E-49	-2393066E-49	-2443066E-49	-2493066E-49	-2543066E-49	-2593066E-49	-2643066E-49	-2693066E-49
E-50	-1755430E-50	-1805430E-50	-1855430E-50	-1905430E-50	-1955430E-50	-2005430E-50	-2055430E-50	-2105430E-50	-2155430E-50	-2205430E-50	-2255430E-50
E-51	-6570054E-51	-6620054E-51	-6670054E-51	-6720054E-51	-6770054E-51	-6820054E-51	-6870054E-51	-6920054E-51	-6970054E-51	-7020054E-51	-7070054E-51
E-52	-2206441E-52	-2256441E-52	-2306441E-52	-2356441E-52	-2406441E-52	-2456441E-52	-2506441E-52	-2556441E-52	-2606441E-52	-2656441E-52	-2706441E-52
E-53	-1426430E-53	-1476430E-53	-1526430E-53	-1576430E-53	-1626430E-53	-1676430E-53	-1726430E-53	-1776430E-53	-1826430E-53	-1876430E-53	-1926430E-53
E-54	-1251322E-54	-1301322E-54	-1351322E-54	-1401322E-54	-1451322E-54	-1501322E-54	-1551322E-54	-1601322E-54	-1651322E-54	-1701322E-54	-1751322E-54
E-55	-2047470E-55	-2097470E-55	-2147470E-55	-2197470E-55	-2247470E-55	-2297470E-55	-2347470E-55	-2397470E-55	-2447470E-55	-2497470E-55	-2547470E-55
E-56	-1330060E-56	-1380060E-56	-1430060E-56	-1480060E-56	-1530060E-56	-1580060E-56	-1630060E-56	-1680060E-56	-1730060E-56	-1780060E-56	-1830060E-56
E-57	-2900940E-57	-2950940E-57	-3000940E-57	-3050940E-57	-3100940E-57	-3150940E-57	-3200940E-57	-3250940E-57	-3300940E-57	-3350940E-57	-3400940E-57
E-58	-3215711E-58	-3265711E-58	-3315711E-58	-3365711E-58	-3415711E-58	-3465711E-58	-3515711E-58				

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Table C.4. Pressure-strain data from V-9 test
(manual readout from BLH boxes)

Pressure (psf)	Strain (in./in.) at gage No. -												(Plus denotes tension)
	120	119	118	117	116	105	106	107	108	109	110	111	
0	+20	+10	0	+10	+10	0	0	0	0	+20	0	+10	+10
1,000	-30	+20	+50	+50	+60	+30	+270	+390	-170	+230	+410	+150	+160
2,000	-60	+20	+110	+100	+130	+30	+550	+820	-360	+470	+920	+310	+300
3,000	-90	+30	+140	+130	+170	-30	+750	+1,120	-420	+650	+1,310	+420	+400
4,000	-120	+30	+190	+180	+230	-50	+1,000	+1,500	-480	+880	+1,800	+560	+540
5,000	-160	+30	+220	+210	+270	-50	+1,230	+1,840	-540	+1,100	+2,280	+690	+650
6,000	-190	+40	+260	+260	+330	-60	+1,470	+2,200	-600	+1,330	+2,810	+820	+780
7,000	-220	+40	+310	+300	+380	-70	+1,720	+2,580	-660	+1,590	+3,360	+950	+910
8,000	-250	+50	+330	+340	+430	-80	+1,960	+2,920	-730	+1,830	+3,900	+1,080	+1,030
9,000	-280	+50	+370	+380	+490	-90	+2,200	+3,280	-800	+2,070	+4,450	+1,200	+1,150
10,000	-310	+50	+410	+430	+540	-100	+2,440	+3,630	-880	+2,330	+5,020	+1,320	+1,270
11,000	-350	+50	+450	+470	+590	-110	+2,700	+4,040	-980	+2,610	+5,640	+1,450	+1,390
12,000	-370	+50	+490	+520	+640	-120	+3,110	+4,670	-1,250	+2,920	+6,330	+1,570	+1,510
13,000	-400	+50	+540	+560	+690	-130	+3,560	+5,350	-1,390	+3,250	+7,120	+1,690	+1,630
14,000	-420	+40	+590	+610	+740	-150	+4,030	+6,070	-1,950	+3,640	+8,040	+1,810	+1,750
15,000	-440	+30	+640	+650	+790	-160	+4,520	+6,810	-2,320	+4,100	+9,060	+1,930	+1,870
16,000	-470	+20	+680	+710	+840	-180	+5,060	+7,610	-2,730	+4,580	+10,130	+2,030	+1,970
17,000	-470	0	+720	+760	+890	-1,000	+5,630	+8,470	-3,160	+5,070	+11,230	+2,130	+2,070
18,000	-490	-40	+750	+820	+930	-1,240	+6,280	+9,440	-3,650	+5,620	+12,470	+2,230	+2,170
19,000	-510	-70	+780	+880	+970	-1,520	+7,010	+10,560	-4,220	+6,240	+13,850	+2,340	+2,280
20,000	-530	-120	+830	+950	+1,010	-1,850	+7,890	+11,880	-4,890	+6,980	+15,490	+2,490	+2,420
21,000	-550	-170	+910	+1,020	+1,060	-2,250	+8,920	+13,440	-5,680	+7,830	+17,350	+2,640	+2,560
22,000	-570	-360	+1,060	+1,100	+1,130	-2,810	+10,360	+15,580	-6,750	+8,960	+19,830	+2,750	+2,690
23,000	-580	-310	+1,170	+1,150	+1,190	-3,160	+11,330	+17,070	-7,480	+9,690	+21,500	+2,770	+2,680
24,000	-590	-380	+1,280	+1,210	+1,260	-3,570	+12,470	+18,820	-8,340	+10,550	+23,770	+2,760	+2,660
25,000	-600	-450	+1,390	+1,270	+1,330	-4,040	+13,560	+20,820	-9,300	+11,470	+25,660	+2,740	+2,630
26,000	-610	-650	+1,530	+1,360	+1,420	-4,680	+15,590	+23,750	-10,710	+12,860	+28,910	+2,710	+2,610
27,000	-670	-770	+1,690	+1,580	+1,550	-5,610	+18,270	+27,190	-13,040	+14,830	+33,880	+2,680	+2,570
28,000	-700	-910	+1,850	+1,690	+1,690	-6,740	+21,670	+32,990		+17,500	+39,920	+2,730	+2,640
29,000	-880	-1,140	+2,170	+1,800	+2,040	-9,090	+28,780	+43,830		+22,400	+53,950	+2,880	+2,840
30,000	-1,050	-1,330	+2,830	+2,620	+2,380	-11,290	+40,570	+61,570		+31,560	+80,700	+4,070	+4,090
31,000			+3,490	+3,560	+3,720	-16,460	+74,500	+77,880		+40,000		+9,170	+8,970
										+45,900			

Appendix D
Acoustic-Emission and Posttest
Ultrasonic Data Obtained from Vessels
V-5 and V-9

I. Acoustic-Emission Monitoring of Intermediate Test Vessels V-5 and V-9 with Nozzles*

INTRODUCTION

In 1971 and 1972, prior to the intermediate vessel tests, Southwest Research Institute (SWRI), in conjunction with Oak Ridge National Laboratory (ORNL), monitored the acoustic emission from 2.54-cm-thick (1-in) and 15.2-cm-thick (6-in.) flawed and unflawed tensile specimens. Acoustic-emission monitoring of the first series of intermediate vessel tests was also performed by SWRI for the vessels without nozzles. The results of these tests were reported previously.¹⁻⁵

SWRI has since been given the prime responsibility for acoustic-emission monitoring of two intermediate test vessels with nozzles (vessels V-5 and V-9). This report presents the acoustic-emission results obtained from vessels V-5 and V-9. Each vessel contained a fatigue-sharpened flaw at an interior surface of the nozzle cylinder intersection. The vessels were tested at temperatures of 88°C (190°F) and 25°C (75°F) in February and August 1974, respectively.

INSTRUMENTATION

Six acoustic-emission sensors were located on the outer surfaces of vessels V-5 and V-9 as shown in Figs. D.1 and D.2, respectively, in a pattern similar to that used for vessels V-1 and V-2. However, the instrumentation used in this series of tests was quite different from that used for the first two vessels. Acoustic-emission data obtained from each sensor were entered into an on-line minicomputer for analysis. The results, which located the emission sources, were graphically displayed in real time on a cathode-ray tube (CRT) screen of the computer, and the number of acoustic-emission events from individual locations were also accumulated at the corresponding locations on the screen as they occurred. This real-time analytical data presentation developed by SWRI is unique. Figure D.3 is a functional diagram of three typical channels. The details of this multichannel acoustic-emission system have been well documented elsewhere.⁶

In addition to the computer data analyses, two conventional data readout devices were used. A digital counter (shown in Fig. D.3) was used to measure counts. A second device, a paper strip-chart recorder, which is calibrated by a standard pulse for the energy measurements of acoustic-emission waves, was also used. This device works in parallel with the digital counter shown in Fig. D.3.

RESULTS

Figure D.4 shows the accumulation of acoustic emission as a function of strain. The strain data were obtained from the gage at the inner surface of the nozzle corner, 180° from the flaw. For both vessels V-5 and V-9, the rapid increase in acoustic emission that takes place just before the vessel yields occurs at a lower vessel pressure in comparison with the case for a flaw in the cylindrical region of a vessel without nozzles. This phenomenon occurs due to the higher stress field in the nozzle area compared to the stress on the vessel wall. The acoustic-emission data of the 88°C (190°F) test are typical for a flaw in a heavy-section steel structure under ductile failure. As shown in

*Part I of Appendix D is a report to ORNL prepared by S. P. Ying, Senior Research Engineer, Southwest Research Institute. The work reported was performed under UCCND Purchase Order 11Y-7333V.

Fig. D.1. Vessel V-5, Southwest Research Institute (SWRI) acoustic-emission transducer locations.

Fig. D.2. Acoustical instrumentation for vessel V-9.

Fig. D.3. Functional diagram of three typical channels of the acoustic-emission system.

Fig. D.4. Cumulative acoustic-emission counts as a function of peak nozzle corner strain for vessels V-5 and V-9 (1 psi = 6.895 Pa).

Fig. D.4, when the strain is greater than 3%, the emission from vessel V-5 tested at 88°C (190°F) increases rapidly until leakage occurs from the flaws. During this period, the strip chart recorded fast acoustic-emission pulses as in the case of the vessel V-1 test (see Fig. 4.32 in Ref. 5). Nevertheless, this indication of high emission rate started earlier and took a longer time before failure occurred at the crack. This implies a slow crack growth.

The acoustic-emission monitoring system is also a good leak-detection device. When leakage started at the flaw, the monitoring system immediately picked up turbulent hydraulic flow noise from the small crack opening.

During a test, the CRT screen of the computer displayed the numbers of acoustic-emission events at individual source locations in cylindrical coordinates of a vessel boundary. The computer data presented in Fig. D.5 were obtained from the test of vessel V-9. The events that were detected from the flaw area are plotted as a function of peak nozzle corner strain in percent. The shape of the

Fig. D.5. Cumulative acoustic-emission events as a function of peak nozzle corner strain for vessel V-9.

curve in Fig. D.5 and the behavior of acoustic emission investigated in terms of the emission events are similar to those shown in Fig. D.4 for the emission counts. (Acoustic-emission counts, also called ringdown counts, are recorded signals due to sound wave oscillations occurring immediately after an acoustic-emission event.)

II. Acoustic-Emission Monitoring of Vessel V-9 by Dunegan/Endevco*

The Dunegan Endevco model 1032 source-location system used during the test of vessel V-9 consisted of two 4-transducer arrays and the control, data processing, and display apparatus necessary to record data for later analysis and to display instantaneously the location of each source. The event number, array number, arrival times, source coordinates, test time, event severity, and vessel pressure were recorded for each event.

The calibration essential to the computation of source coordinates was performed prior to pressurization. A piezoelectric transducer used as a pulsed source was attached to the vessel next to one of the pickup sensors. The time intervals recorded for an input pulse provided the data for calibration of the system.

The arrays of transducers were located on vessel V-9 as shown in Fig. D.6. The transducers were attached to the vessel with plastic tape and a viscous acoustic couplant. The characteristics of the

*Appendix D, Part II is a report to ORNL by M. P. Kelly, Field Test Manager, Dunegan Endevco. The work reported was performed under UCCND Purchase Order 11Y-7328V.

Fig. D.6. Sensor locations for intermediate test vessel V-9 (1 in. = 2.54 cm).

system are given below.

Transducers: 140 kHz resonant frequency, single-ended

Filters: 120 to 240 kHz

Preamplifier gain: 40 dB

Signal conditioner gain: 36 dB

Total system gain: 76 dB

Arrival time resolution: 0.1 μ sec

The acoustic-emission activity (as measured by the number of ringdown counts of the center transducer of the excited array) is shown as a function of pressure in Fig. D.7. The change in slope of the counts-vs-pressure curve between 152 MPa (22,000 psi) and 165 MPa (24,000 psi) is typical of a structure nearing failure and could have been used to predict and prevent catastrophic failure, if necessary.

Hard-copy reproductions of the CRT display of emissions received during the test of V-9 are presented in Figs. D.8 and D.9. During the test, more than 200 events were received from the bottom head closure weld, which is located 69 cm (27 in.) below and parallel to the circumferential centerline of V-9. Although source coordinates were calculated for each of these events, they do not appear on the CRT because they are located a considerable distance, 1.1 m (44 in.), from the center of the array. If the material wave speed is varied, these emissions can be made to appear closer to the

Fig. D.7. Acoustic emission as a function of pressure for intermediate test vessel V-9 (1 psi = 6895 Pa).

Fig. D.8. CRT display of locations of acoustic-emission events detected by array 0 during the entire test of vessel V-9 (1 in. = 2.54 cm).

array and hence displayed on the CRT. Figure D.10 shows the weld emissions for array 0 calculated with a slightly incorrect wave speed.

The weld accounted for significantly more acoustic emissions than were observed for the artificial defect during the acoustic-emission inspection of V-9. Although V-9 actually failed in the nozzle, the emissions emanating from the weld indicate the presence of major weld discontinuities. Figure D.11 represents the weld emission activity (using actual material wave speed) as a function of location along the weld. The monitoring system received no emissions that could be directly related to the artificial defect until approximately 153 MPa (22,250 psi). This correlates very well with the first indication of crack-opening displacement on the gauge. The CRT presentations for the last 125 events recorded [from 175 MPa (25,450 psi) to failure] are shown in Fig. D.12. Only 23 events can be directly attributed to the artificial defect itself. Many of the scattered events in Figs. D.8 and D.9 are probably associated with flaw growth, but were located incorrectly because of errors in the

Fig. D.9. CRT display of locations of acoustic-emission events detected by array 1 during the entire test of vessel V-9.

arrival times at the various transducer locations. This phenomenon is due to the vessel geometry, transducer spacing and placement, and the presence of multiple sound paths.

In an ideal test situation, sensors would be separated by at least five times the vessel thickness in order to minimize the effect of dilatational waves. These alternate paths probably contributed much of the scattered emission received from V-9. The fact that only 23 events could be directly related to the artificial defect substantiates this theory. (NOTE: The acoustic-emission results for vessels V-7 and V-7A also indicate the existence of the problem related to the diameter-to-thickness ratio of the vessels. Actual test results from larger vessels of this material demonstrate much better locational accuracy.⁷

The bottom head closure weld contributed approximately 250 events as compared with 23 emissions directly related to the known flaw. Weld defects, however, typically generate more emissions than do defects of the same magnitude in the parent metal.

Fig. D.10. CRT display of locations of acoustic-emission events detected by array 0. (This display was generated by using an incorrect wave speed.)

The following conclusions can be drawn from the test results:

1. The count-vs-pressure curve for vessel V-9 could have been used to halt pressurization prior to failure had this been desirable. A dramatic change of slope occurred at approximately 172 MPa (25,000 psi).
2. The vessel bottom head closure weld appears to have generated significantly more emissions than did the artificial defect. This weld region should be inspected by an alternate nondestructive testing technique.
3. Only 23 events can be directly attributed to the artificial defect, although much of the scattered emission is probably associated with defect propagation. Multiple sound paths resulting from the diameter-to-thickness ratio of the vessel are probably the cause of inaccurate location of emissions. This problem would not be present in a vessel of this material with a realistic diameter.

Fig. D.11. Distribution of acoustic-emission events along bottom weld (1 in. = 2.54 cm).

III. Posttest Ultrasonic Examination of Vessel V-9

The cylinder-to-hemisphere weld of vessel V-9 was examined ultrasonically by S. P. Baker and R. D. Scofield of the ORNL Inspection Engineering Department after the vessel was removed from the test cell. The weld was about 7.1 cm (2.8 in.) wide at the outside surface of the vessel. In order to include the heat-affected zone as well as the weld itself, the inspection covered the entire girth of the weld out to a distance of about 7.6 cm (3 in.) from either side of the weld centerline. The area was scanned carefully by longitudinal wave ultrasound. Shear wave was used also on the cylindrical side of the weld centerline. This mode was generally not applied on the other side because the curvature of the hemispherical head complicated the interpretation of the indications. The longitudinal weld and the transition-to-shell weld were also scanned without notable indications being found.

Longitudinal wave inspections were performed with a 1.91-cm-diam (3/4-in.) crystal at a frequency of 2.25 MHz. Amplitudes of indications were referenced to the amplitude at the indicated depth given by a distance-amplitude correction curve determined from a calibration block with 3.12-mm-diam (1/8-in.) side-drilled holes. The shear wave inspection was performed with a 45° beam and a 12.7- by 25.4-mm (0.5- by 1-in.) crystal at 2.25 MHz. Calibration was performed as for the longitudinal wave.

The principal results of the inspection are shown in Fig. D.13 along with the Dunegan/Endevco acoustic-emission data. This correlation suggests that the acoustic-emission events attributed to the cylinder-to-hemisphere weld were in fact due mostly to weld imperfections.

Fig. D.12. CRT display of locations of acoustic-emission events between 25,450 psi and failure—(a) array 0; (b) array 1
(1 psi = 6.8948 kPa).

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Fig. D.13. Comparison of on-line acoustic emission data and posttest ultrasonic data for the cylinder-to-hemisphere weld in intermediate vessel V-9.

REFERENCES

1. S. P. Ying, "Acoustic Emission Monitoring of Six-Inch-Thick Flawed Tensile Specimens," HSST 5th Annual Information Meeting, Paper 23, Oak Ridge National Laboratory, March 1971.
2. S. P. Ying, "Acoustic Emission Monitoring of One-Inch-Thick and Six-Inch-Thick Flawed Tensile Specimens," HSST 6th Annual Information Meeting, Paper 15, Oak Ridge National Laboratory, April 1972.
3. S. P. Ying and S. C. Grigory, *Tests of Six-Inch-Thick Tensile Specimens, Fifth Technical Summary Report, Acoustic Emission Monitoring of One-Inch-Thick and Six-Inch-Thick Tensile Specimens*, HSSTP-TR-24, Southwest Research Institute, San Antonio, Tex. (November 1972).
4. S. P. Ying, "Characteristics and Mechanisms of Acoustic Emission under Applied Stress," *Crit. Rev. Solid State Sci.* 4, 85 (1973-74).
5. E. R. Reinhart and S. P. Ying, "Acoustic Emission Monitoring of First Intermediate Vessel Test," *Heavy-Section Steel Technology Program Semiannual Prog. Rep. Aug. 31, 1972*, ORNL-4855, pp. 54-69.
6. S. P. Ying, D. R. Hamlin, and D. Tanneberger, "A Multichannel Acoustic Emission Monitoring System with Simultaneous Multiple Event Data Analyses," *J. Acoust. Soc. Am.* 55, 350 (1974).
7. M. P. Kelly and R. J. Schlamp, "Detecting Structural Degradation by Acoustic Emission," to be published in the Proceedings of the 25th Symposium of the Mechanical Failures Prevention Group, Nov. 3-5, 1976, Gaithersburg, Md.

Appendix E

System Description and Procedures for Sharpening Surface Flaws by Fatigue, Using Cyclic Hydraulic Notch Pressurization

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System Description and Procedures for Sharpening Surface Flaws by Fatigue, Using Cyclic Hydraulic Notch Pressurization

INTRODUCTION

The main factors that affect the pressure generated in a machined notch are compressibility of the fluid, volume of the system, and displacement of the pump. Ideally, one would prefer a perfectly incompressible fluid and a "stiff" system of piping in order to minimize the size of the pump and the power required to generate high pressure. Lower compressibility also diminishes the amount of energy that is dissipated by the system as heat. For example, air is a highly compressible fluid; hence, if air is the working fluid in a "hydraulic system," and if one pump stroke reduces the total volume of the system to half its original volume, the pressure simply doubles. If, on the other hand, the working fluid is water, which is essentially incompressible, and if one pump stroke reduces the total volume to half the original volume, the pressure would be so high that the containment might rupture long before the total system volume was reduced to half. In practice, therefore, since both the fluid and the system are elastic, the peak pressure achieved can be adjusted by the selection of fluid type, total system volume, compliance of the system, and displacement of the pump. For a system of small enough volume and compliance, it is possible to attain the desired maximum pressure with a single pump stroke. With a fixed-displacement pump, it is then practical to adjust system volume so that each pump stroke produces a pressure pulse of the desired magnitude. For systems of small volume, it is not practical to attempt to reach maximum pressure in one stroke. The compliance of gages and the presence of unwanted gas bubbles limits the amount of pressure that can be produced by a single stroke. Also, when the volume is necessarily large because of the size of the flaw, the compressibility of the fluid may be the limiting factor.

One pressure cycle may be accomplished by a single pump stroke, if the conditions are consistent with the factors mentioned above. Otherwise, the pressure cycle must be accomplished by continued pumping to the desired pressure, at which time the fluid is relieved through a dump valve.

Leaks in the packing glands, valve seats, and other components and the temperature and viscosity of the working fluid also affect the performance of the system. Seats of valves or worn contact surfaces on valve stems may leak and thereby cause considerable difficulty in the control of system pressure. The effects of temperature on fluid properties must also be considered. The hydraulic fluid used should have relatively uniform compressibility and viscosity over the range of system operating temperatures encountered.

THE ORNL HIGH-PRESSURE HYDRAULIC PUMPING SYSTEM

Description of System and Components

Our high-pressure hydraulic system consists of a pump, a dump valve, a reservoir, a pressure gage, a variable-volume tubing leg, associated tubing, valves, and the specimen. Figure E.1 illustrates the setup schematically; Fig. E.2 is a photograph of an actual setup, including the ultrasonic inspection apparatus.

The pump is an air-driven, positive-displacement, differential piston pump with an output pressure capacity of 139 MPa (20,000 psi) when driven from a 0.69-MPa (100-psi) air supply. We use

Fig. E.1. Cyclic pressure pumping system for notch sharpening by fatigue. (1 psi = 6895 Pa.)

Fig. E.2 General view of crack-sharpening apparatus being used for an external surface flaw in an intermediate test vessel.

an American Instrument Company single-ended model 46-13720 plunger pump. The dump valve is either an air-driven, positive-displacement, differential piston valve or a pneumatic, diaphragm-operated piston valve, as furnished respectively by the American Instrument Company [model 44-19730, 139 MPa (20,000 psi) "Little Richard" valve] or by the High Pressure Equipment Company [model SD-30, 207 MPa (30,000 psi) HIP "Remarco" valve]. The reservoir is a stainless steel 4-liter beaker, to which the feed lines are soldered. Screens are inserted into the line exit ports to filter the fluid. The pressure gage is a 345-MPa (50,000-psi) Astragage, which is accurate to $\pm 5\%$ of full scale. The variable-volume tubing leg consists of a series of high-pressure autoclave valves connected by short runs of tubing. The tubing is rated for 414-MPa (60,000-psi) service.

System Controls

The system for actuating the pump and the dump valve consists of a count switch, an electric counter, a time-delay relay, two solenoid valves, and an auxiliary counter.

The count switch is a microswitch which contacts a collar on the pump's plunger to count pump strokes (not pump cycles) to allow for coordination of suction and compression pump strokes with a preset count. It is designed to permit a fractional final pump stroke in order to actuate the dump circuit at a predetermined pressure. Fractional stroke adjustment is regulated by shifting the count switch up or down along the length of the plunger.

The counter accumulates the counts transmitted by the count switch and actuates an electric relay whenever the count reaches a number preset on the counter control. The counter is an ITT CE-62-BE-402 unit. Knurled wheels to preset the counter are located inside an interlocked door to prevent inadvertent changing of the preset adjustment. When the number of pump strokes reaches the preset level, the counter automatically resets itself and initiates the next cycle.

The function of the time-delay relay is to prolong the interval between the time that the pump reaches maximum pressure output and the time that the dump valve opens. On a large system, delayed action is necessary to allow the system pressure to peak before the dump valve opens to drop all pressure. The solenoid-controlled valves regulate the air supply to the pump and actuate the dump valve.

An auxiliary counter, which is wired to receive an electrical pulse from the signal that operates the solenoid on the dump valve, is used to count the actual cumulative hydraulic pulses, or cycles, to the specimen.

Additional information on specific system control details are discussed below.

OPERATING INSTRUCTIONS FOR THE ORNL HYDRAULIC PUMP-DUMP SYSTEM

Initial System Startup*

1. Fill the reservoir with No. 10 oil or with an oil-kerosene mixture.
2. Unplug the counter and control-box power-supply cords.

*Use diagram in Fig. E.1 for reference.

3. Open the reservoir isolation valve, the high-point vent valve, all valves on the variable-volume header, the specimen vent valve, and the gage valve.
4. Check the lubricator on the pump's air inlet for an adequate oil supply.
5. Set the reducing valve on the pump's air supply to a low pressure, and then open the hand valve on the pump's air-supply line.
6. Adjust the reducing valve on the pump's air-supply line to deliver air at approximately 83 kPa (12 psig) air.
7. Gradually increase the air pressure to the pump until the pump's piston starts to operate.
8. Set the oil lubricator to deliver about 1 drop per minute.
9. Now run the pump until all air is out of the hydraulic system, and then increase the air pressure to the pump to speed up its operation after the lubricator is properly set.
 - a. Close the high-point vent valve when all air is out of the system up to that point.
 - b. Close the specimen vent valve and all variable-volume header valves when there is no more air in the reservoir.
10. With all valves closed, the system pressure should now start to build up. Observe pressure on the 345-MPa (50,000-psi) Astragage.
11. Now increase the air pressure to the pump to reach the desired system pressure for the specimen.
12. Open the door to the counter control and preset an estimated number of counts.
13. Close the door again and, using the white button, set the counter indicator to zero.
14. Energize the counter controller; plug in the supply cord.
15. Adjust the positioning of the count microswitch until the system begins to count for the desired pressure output. If the first pump stroke is not a downward or suction stroke, unplug the counter and replug it when the count and the stroke are in phase; that is, stroke 1—suction, stroke 2—compression, stroke 3—suction, stroke 4—compression, etc. The count microswitch can also be operated with a pencil to phase counts to strokes, but care must be exercised to prevent mashing one's finger.
16. The gage isolation valve should be shut off when the settings are being made for the desired pressure operation in order to protect the precision gage from chatter.
 - a. The pump may stop when the gage isolation valve is secured because the total system volume is decreased with the gage volume removed. The actual air pressure required to operate the pump may exceed the pressure obtainable from the air supply. **DO NOT INCREASE THE AIR PRESSURE TO THE PUMP AT THIS TIME.** To compensate for the loss of gage volume and to enlarge the volume of the total system, either adjust the valves in parts of the variable-volume header (starting at valve 1) or move the count microswitch down along the pump's plunger attachment until the pump begins to run again. Both operations may be necessary.
 - b. When the pump system pressure ratio has been adjusted, the pulse speed can be increased by increasing the air pressure to the pump. This speed may be further increased by adjusting (turning) the screw on the time-delay relay toward decrease.
17. During operation, continue to check the entire system for leaks. It does not take much of a leak to upset pressure output or system control. All leaks must be sealed at once, followed by readjustments as outlined above.

**Restarts—For Pump Operation of a System
that is Already Set Up, with the Pump-to-System
Pressure Ratio Previously Preset**

1. Adjust count phase as described in items 14 and 15 of the previously detailed procedure.
2. Check oil supply reservoir; refill if necessary.
3. If in doubt, check the system pressure by unplugging the count controller and following the previously detailed procedure described in items 11 through 17.

Troubleshooting

The stem of the dump valve may wear (at a frequency of every 90,000 to 120,000 pump cycles) with repeated seating at pumping pressures in excess of 139 MPa (20,000 psig). The valve will then start to leak. If this should occur, refer to the American Instrument Company's manual for the "Little Richard" dump valve No. 44-19730 or No. 44-19731 for disassembly instructions and information on valve replacement parts.

The pump piston O-rings may wear and start to leak, or other pump problems may be suspected. If so, refer to the American Instrument Company's manual on air-operated piston pumps for liquid service No. 857B.

Appendix F

**Plots of Selected Strain Data
for Vessel V-9**

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