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ACOUSTIC EMISSION MONITORING OF INTERMEDIATE PRESSURE VESSELS TESTED UNDER THE ORNL HEAVY-SECTION STEEL TECHNOLOGY PROGRAM*

MASTER

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ABSTRACT: An overview is presented of ten tests of 15.2-cm-thick steel pressure vessels containing surface cracks. Flaws in the vessels ranged from 31 to 135 mm in depth, and test temperatures ranged from 0 to 91°C. A detailed description of the acoustic emission (AE) monitoring of the most recently completed vessel test, V-7B, and the fatigue crack sharpening of the flaw for test vessel V-8 is also presented. Results obtained during these tests indicate that AE is capable of locating flaws, detecting the onset of flaw growth, and providing an indication of the rate of crack extension (immediacy of fracture).

KEY WORDS: acoustics, emission, pressure vessels, defects, crack propagation, residual stress, failure

Structural integrity of reactor pressure vessels is established by designing and fabricating them in accordance with the applicable ASME Code and Nuclear Regulatory Commission (NRC) requirements for pressure vessels, by inspecting for flaws of significant size, and by evaluating the safety margin available against fracture should flaws exist or develop during operation. The event that must be

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avoided in service is a fracture, without prior warning, in a reactor pressure vessel that can disrupt the safety features of the plant. These vessels are known to possess a large margin of safety against failure under anticipated operating conditions, but the influence of flaws on this margin had not been quantitatively determined for many situations of interest.

The Heavy-Section Steel Technology (HSST) Program was initiated at the Oak Ridge National Laboratory (ORNL) to accelerate investigations of thick-section pressure vessels used in water-cooled reactors. Simulated service tests, referred to as intermediate vessel tests (IVT), have been conducted using a wide variety of specimen types and sizes evaluated under a wide range of loading conditions. Initial objectives emphasized in the simulated service tests were (1) to demonstrate the 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) and (2) to demonstrate, for the materials of interest, the capability to predict various combinations of load (pressure, temperature, and crack configuration in full-thickness walls 152 mm (6 in.) or more which will cause fracture for both frangible and tough fracture conditions. In addition, the simulated service tests provide a connection between the behavior of structures observed in a laboratory environment and the behavior of full-size components under a wide variety of conditions that represent actual operating conditions. Each simulated service test is designed to demonstrate the ability of analytical methods to predict actual fracture behavior of a flawed structure under known conditions of material properties and loading. Thus, as the test series progresses, analytical methods are confirmed, improved, or their limitations revealed.

An associated activity of the IVT series is to demonstrate and evaluate various methods of nondestructive testing for detecting and analyzing flaws and thus preventing catastrophic in-service failure in the unlikely event that conditions would be favorable for such an event to occur. Acoustic emission (AE) is one such technique investigated. AE was utilized to monitor each of the above vessels, and results are contained in the appropriate reference for each test. Results in this paper will be confined only to the two most recently monitored tests: intermediate test vessel V-7B and fatigue crack sharpening of the flaw in intermediate test vessel V-8.

HSST Intermediate Vessel Tests

The intermediate test vessels were fabricated from the same low-alloy steels used for pressurized-water (PWR) and boiling-water reactors (BWR). Sharp flaws of desired size, location, and orientation were produced in each test vessel, which were then loaded by internal pressure. The state of stress achieved in the deliberately flawed regions was similar to that which would exist in a full-scale reactor vessel with a similar flaw. These test vessels were smaller in diameter than the actual reactor pressure vessels, but their wall thicknesses were adequate for providing the required constraint in the neighborhood of the prepared flaw.

Vessel testing was systematically planned so that substantial quantitative results could be derived from each test. Testing conditions were chosen to provide specific data by which analytical methods of predicting flaw growth, and in some cases crack arrest, could be evaluated. Efforts were made to assure that results would be relevant to some aspect of real reactor pressure vessel performance through careful control of material properties, selection of test temperatures, and design of prepared flaws. The use of pressures, and in some cases, temperatures more severe than occur during any condition specified for real reactor pressure vessels was necessary in order to obtain quantitative data by which methods of fracture prediction could be evaluated.

To date, ten tests have been conducted on eight 152-mm-thick (6-in.), 991-mm-diameter (39-in.) steel pressure vessels containing carefully prepared and sharpened flaws. Flaws in these vessels ranged from 31 to 135 mm (1.2 to 5.3 in.) in depth, and test temperatures ranged from 0 to 91°C (32 to 196°F). A summary of the conditions is presented in Table 1. A more detailed description of the tests may be obtained from Refs. 1–5.

AE Monitoring of Intermediate Test Vessel V-7B

Test Background

If a flaw requiring corrective action were to be found in an operating nuclear pressure vessel, there could be considerable safety and economic implications. One possible corrective action would be an in-situ weld repair accomplished by removing material in the region of the flaw and then refilling the resulting cavity with weld metal. If this repair were made in accordance with the provisions of Section XI, Subarticle IWB-4420 of the *ASME Boiler and Pressure Vessel Code*, thermal stress relieving which could lead to serious difficulties associated with thermal expansion and warpage, would not be required after completion of the repair. This raises questions relative to the effects of residual stresses and material toughness levels. Intermediate test vessel V-7B was thus tested at a temperature associated with upper shelf material toughness to provide baseline information on the effect of the weld repair technique.

HSST vessel V-7B was fabricated from ASTM A533, Grade B, Class 1 steel plate. The test vessel had an outside diameter of 991 mm (39 in.) and an inside diameter of 686 mm (27 in.). The region of interest was a flaw formed by hydrogen charging of an electron-beam weld in the heat-affected zone of a previous weld repair. Details of the test vessel and flaw are presented in Figs. 1 and 2, respectively.

Instrumentation

The Trodyne multi-sensor comprehensive data (MSCD) system shown in Fig. 3 was used for acoustic emission monitoring of ITV V-7B while it was being hydraulically pressurized. Each channel of the system consisted of a sensor, preamplifier, and amplifier. The amplified and filtered signals were fed into a processor which derived the individual acoustic emission parameters from the detected signal, stored the data sets and transferred them to the computer, generated control parameters for the entire MSCD system, and performed discrimination functions. These functions consisted of sensor activity detection (establishes reset time to clear system for the next data set), exclusion signals (accepts only valid sensor arrival sequences), and range gate (assures signals are grouped in complete sets within the instantaneous array). The MSCD system measured the magnitude of acoustic emission events as a function of their location, time of occurrence, and parametric value. All derived acoustic emission parameters were processed, stored for off-line analysis, and displayed on the CRT screen in real time as either raw data, activity distribution, or magnitude distribution. Permanent records of the CRT screen contents were obtained during the test as required.

Experimental Procedure

The cylindrical test section of ITV V-7B was instrumented with eight acoustic emission transducers. Six of these transducers were used as active sensors and two were used as slave sensors to lock the system out to events occurring outside the flawed region. Active transducer positioning and location relative to the flaw are presented in Fig. 4. Monitoring of the entire cylindrical section of the vessel could not be accomplished during this test because the heating elements required to obtain the vessel test temperature of 87°C

(190°F) covered most of the surface. Transducers were attached to the vessel by means of epoxy shoes which had been glued to the vessel surface using an elevated-temperature epoxy (Barco Bond MB-100X epoxy adhesive from the Astro Chemical Company). Location of active transducers (1–6) and slave transducers (S1, S2) are shown pictorially in Fig. 5. Coupling between the epoxy shoe and the transducer was provided by a thin layer of Dow Corning 340 silicone heat sink compound. MSCD system specifications during the test were as follows.

Transducers: 250 kHz resonant frequency, single-ended

Filters: 100–400 kHz

Preamplifier gain: 40 dB

Signal conditioner gain:

Channel 1 — 44 dB (84 dB total)
Channel 2 — 47 dB (87 dB total)
Channel 3 — 47 dB (87 dB total)
Channel 4 — 55 dB (95 dB total)
Channel 5 — 43 dB (83 dB total)
Channel 6 — 44 dB (84 dB total)
Channel 7 — 43 dB (83 dB total)
Channel 8 — 56 dB (96 dB total)

Arrival time resolution: 1 μs

Sensor activity constant: 1 ms

Threshold: 400 mV

ΔT range selector: 200 μs

Pressure was monitored throughout the test using a parametric input to the MSCD from a pressure transducer.

Vessel temperature during the test was maintained at approximately 87°C. The V-7B vessel was pressurized hydraulically in two cycles as shown in Fig. 6. Acoustic emission data were obtained during both cycles.

Cycle 1 Test Results

The initial loading cycle consisted of pressurization to 72.4 MPa with intermediate pressure holds at 27.6 MPa and 55.2 MPa for instrument scans. Acoustic emission data were obtained throughout the cycle. A total of 448 valid events were detected during this cycle. Figure 7 presents a histogram of event occurrence for each 3.4 MPa loading interval. A summation of event occurrence and COD gage output as a function of pressure is presented in Fig. 8. Figure 9 presents a summation of event magnitude voltages as a function of elapsed time and pressure. A two-dimensional grid displaying sensor and flaw locations, and events and event magnitudes at the conclusion of the initial pressurization cycle is presented in Fig. 10. In the figure, the 20.3-cm base of the flawed region is noted as a solid line, and the flawed region extending from the base to the vessel outer surface is noted by the dashed line. Each square of the grid where events have been noted contains two numbers: the upper number corresponds to the total number of accepted events and the lower number the summation of the magnitudes of the voltages for the events. The letter after each number is the scaling factor with A representing the number times one and B the number times ten. Regions with the most intense activity have been highlighted in the figure. It can be noted that these regions, with one exception, were adjacent to the flaw, and there appeared to be more activity for the upper part of the flaw than the lower. The one region not adjacent to the flaw showing intense activity corresponds to the position where a 406 by 610 by 1.59 mm (16 by 24 by 1/16 in.) sheet of 304L stainless steel was fillet welded to the inner surface of the vessel to act as a leak-retarding membrane, and this activity may have been associated with a weld defect.

Cycle 2 Test Results

During the second pressurization cycle the vessel was loaded as shown in Fig. 6 until a leak developed through the vessel wall at the base of the flaw. During the test, pressure was intermittently held constant for short intervals while instrument scans were taken. As for the first cycle, AE data were obtained throughout the loading cycle. A total of 931 valid events were detected during this cycle. Figure 11 presents a histogram of event occurrence for each 3.4 MPa of load. Crack opening displacements and summation of accepted events as a function of pressure are presented in Fig. 12. It can be noted that the curves are of the same general shape in that both the displacements and number of events increase rapidly as failure is approached. Figure 13 presents a summation of event magnitude voltages as a function of elapsed time and pressure. A two-dimensional grid display of events and voltage magnitudes as a function of location at conclusion of the second pressurization cycle is shown in Fig. 14. Significant event occurrence by location as a function of pressure interval is presented in Fig. 15 where significant event occurrence is defined to be a grid square in the figure where at least four events or an event with a magnitude greater than 3.0 V has occurred during the pressure interval defined. As noted in the figures, regions of primary activity were adjacent to the flaw.

Conclusions from AE Monitoring of ITV V-7B

The following conclusions may be drawn from acoustic emission monitoring of HSST vessel V-7B.

1. Primary AE activity was adjacent to the flaw. Some activity was noted at a location corresponding approximately to the region where the stainless steel patch was fillet welded to the inner surface of the vessel. Data scatter may be attributable to both specimen geometry and the relatively close proximity of the transducers.

2. Plots of COD gages and summation of events as a function of pressure were geometrically similar.
3. At impending failure, the slope of the summation of events as a function of pressure changed drastically. This potentially provides a technique for monitoring the vessel so that pressurization may be halted prior to failure. As failure was approached, the magnitude of the emissions increased.
4. Results of this test tend to indicate that AE was able to identify regions where significant activity was occurring.

AE Monitoring of Fatigue Crack Sharpening of Flaw for ITV V-8

Test Background

HSST ITV V-8 is a weld-repair type intermediate vessel test. Vessel material and geometry are similar to ITV V-7B except for the flaw, which initially was a part-circular saw cut approximately 50.8-mm deep by 205.7 mm (2 in. by 8.1 in.) at the vessel surface. Even though V-8 is also intended as an evaluation of a particular type of repair weld in a thick-walled pressure vessel, it has a substantially different test objective than V-7B. The test is designed to verify that the residual stresses resulting from a non stress-relieved repair weld are important in the transition temperature region where material toughnesses are well below upper-shelf values. The flaw was thus located in a zone of high residual stress and low toughness. Although ITV V-8 is not scheduled for testing until July 1978, the initial notch has been fatigue sharpened by cyclic hydraulic notch pressurization. Acoustic emission data was taken while the crack was fatigue sharpened; the desired flaw growth was approximately 12.7 mm (0.5 in.).

Experimental Procedure

The hydraulic high-pressure system for pressure cycling the machined notch is shown schematically in Fig. 16. It consisted of a pump, dump valve, reservoir, pressure gage, variable-volume tubing leg, associated tubing and valves, and the specimen. The actual system setup during the fatiguing is shown in Fig. 17. This figure shows the seal block held against a machined flat on the vessel by a tensioning band-jacking studs loading arrangement. Sealing of the block to the vessel was by an O-ring in an oblong configuration around the crack. The pressure intensifier was driven by plant air at approximately 0.69 MPa (100 psig) and provided a single pressure pulse, at low cycling pressures, for each stroke of the intensifier piston. The pressure on the discharge of the intensifier was controlled by manually valving tubing volumes in or out as desired for startup and for compensating for crack growth. Pressure cycling during flaw growth was at a rate of approximately 30 cycles/min with cycle pressure extremes of 0 and 84.1 MPa (12,200 psi). Reference 3 can be consulted for more details on the general procedure.

The multisensor comprehensive data system shown in Fig. 3 was used to monitor the vessel during the fatigue crack sharpening of the part-circular saw cut. Three active sensors positioned as shown in Fig. 18 were used to monitor the test. Coupling between the sensors and eopxy shoes attached to the vessel by five-minute epoxy was provided by a thin layer of PYROGEL. AE system specifications during the test were as follows.

Transducers: 500 kHz resonant frequency, single-ended

Filters: 200–800 kHz

Preamplifier gain:
- Channel 1 — 51 dB (91 dB total)
- Channel 2 — 49 dB (89 dB total)
- Channel 3 — 48 dB (88 dB total)

Arrival time resolution: 1 μs

Sensor activity constant: 1 ms

Threshold: 1.00 V

ΔT range selector: 500 μs

Pressure was monitored throughout the test using a parametric input to the MSCD system.

Test Results and Conclusions

Acoustic emission data were obtained during the 58 637 flaw pressurization cycles required to grow the flaw approximately 12.7 mm (0.5 in.). Monitoring was continuous except for two 15-min intervals occurring at approximately 41 000 and 52 000 cycles when there was a computer power failure necessitating a delay while the system was restarted. (This problem has since been solved by incorporation of a power fail option into the computer.) Figure 19 contains a summary of AE results obtained during the test. Presented in the figure as a function of number of crack pressurization cycles are a histogram of event occurrence (per 1000 cycles), a cumulative total of valid events, and a cumulative total of event voltage magnitudes. Superimposed on the summation of accepted events graph is ultrasonic data which were also obtained during the test so that the extent of flaw growth could be monitored. AE results indicate that 1) there was an incubation period of approximately 33 000 cycles prior to the initiation of flaw growth, 2) flaw growth was erratic as evidenced by periods of lower event activity occurring after high activity periods, and 3) the rate of flaw growth increased as the number of cycles (flaw length) increased.

The following conclusions may be derived from the results of the AE monitoring of the fatigue crack sharpening of the flaw for ITV V-8.

1. AE was capable of monitoring flaw growth by the fatigue crack sharpening process in thick-walled [152.4-mm (6-in.)] pressure vessels.
2. AE data may be utilized in tests of this type to provide an indication of the rate of crack extension (event frequency).

3. AE activity (event frequency) during this test appears to correlate with fatigue crack growth data observed in weldments (incubation period followed by erratic crack growth).[7]

4. Correlation between ultrasonic data obtained during the test and AE results was generally good.

Acknowledgments

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TABLE 1--*Summary of conditions and summary of test results (intermediate vessel tests)*

Vessel No.	Flaw size, mm[a]		Test temperature, deg C	Flaw description		Load factor, p_f/p_d[b]	Mode of failure	Remarks
	a	2b		Location	Material			
1	65.0	209.6	54	Outside	A508-2	2.96	Mixed	Static upper shelf
2	64.3	210.8	0	Outside	A508-2	2.87	Flat	Transition range
3	53.6	215.9	54	Outside	Weld	3.19	Mixed	Static upper shelf
4	76.2	209.6	24	Outside	Weld	2.73	Mixed	Transition range
5	30.5	nozzle	88	Inside	A508-2 (nozzle)	2.74	Leak	Static and dynamic upper shelf
6	47.5	133.4	88	Outside	Weld	3.28	Shear	Static and dynamic upper shelf
7	134.6	464.8	91	Outside	A533-B	2.20	Leak	Static and dynamic upper shelf
7A	134.6	464.8	91	Outside	A533-B	2.15	Leak	Pneumatic loading
7B	134.6	464.8	87	Outside	Repair weld	2.34	Leak	Static upper shelf
8	63.5[c]	205.7[c]	*d*	Outside	Weld	*d*	*d*	Transition
9	30.5	nozzle	24	Inside	A508-2 (nozzle)	2.77	Mixed	Transition range

[a] a = crack depth; b = length of surface penetration.

[b] p_f = maximum pressure; p_d = design pressure = 66.9 MPa.

[c] Nominal dimensions.

[d] Not yet tested.

REFERENCES

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3. J. G. Merkle et al., *Test of 6-In.-Thick Pressure Vessels. Series 4: Intermediate Test Vessels V-5 and V-9 With Inside Nozzle Corner Cracks*, ORNL/NUREG-7 (August 1977).

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).

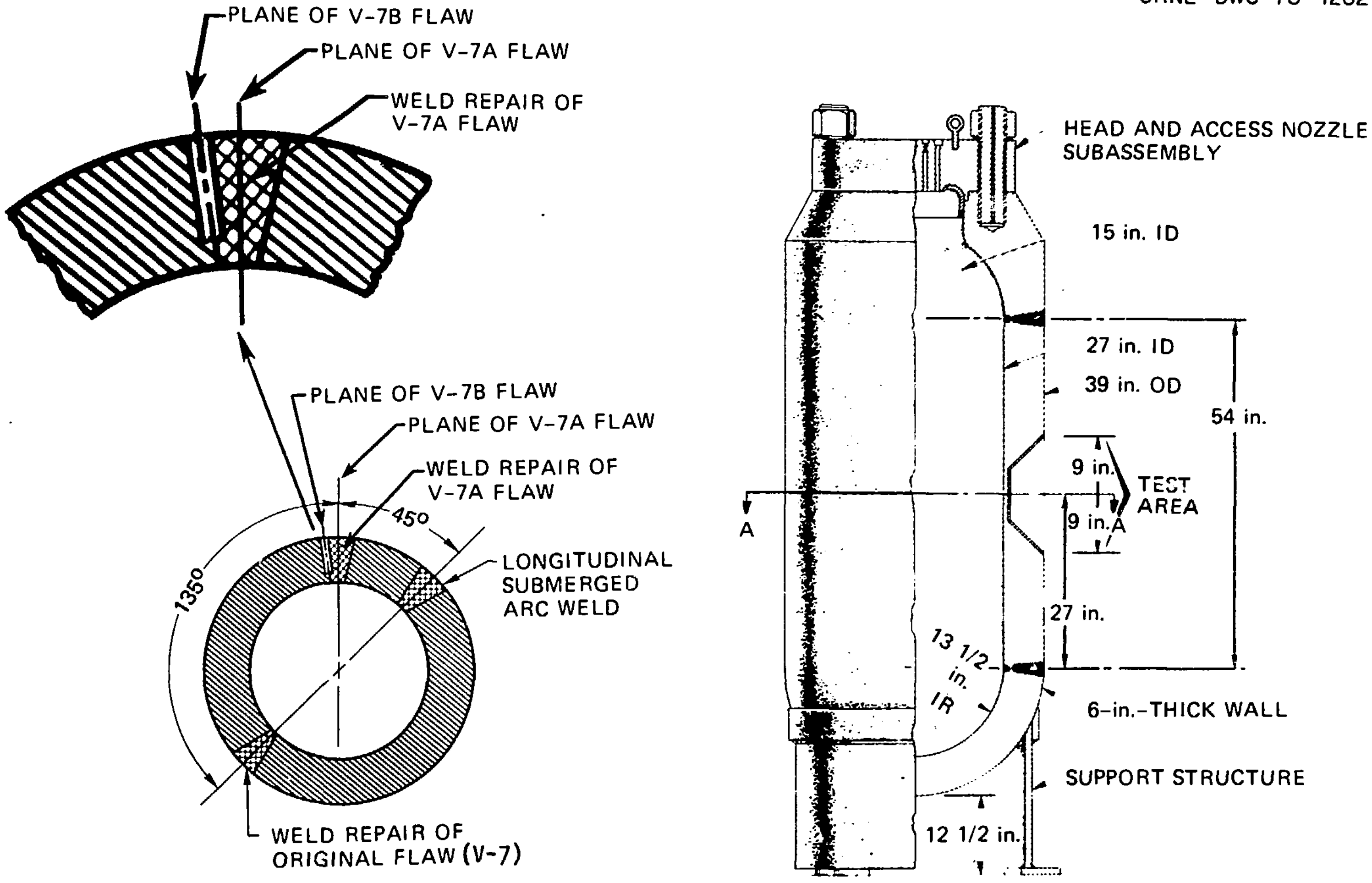
5. R. H. Bryan et al., *Test of 6-In.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7A Under Sustained Loading*, ORNL/NUREG-9 (February 1978).

6. R. H. Bryan et al., *Test of 6-In.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7B*, ORNL/NUREG-38 (to be published).

7. G. D. Whitman, *Heavy-Section Steel Technology Quarterly Progress Report for January–March 1977*, ORNL/NUREG/TM-120, pp. 19–23.

Figure Captions

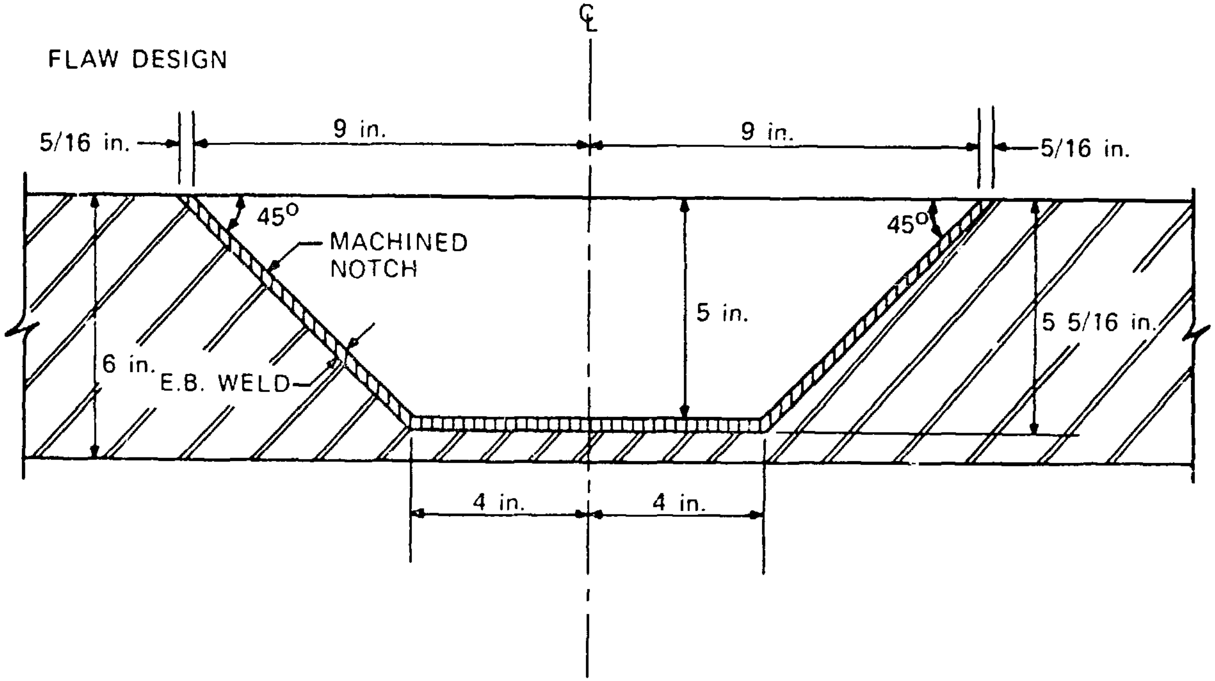
ORNL–DWG 78–1262

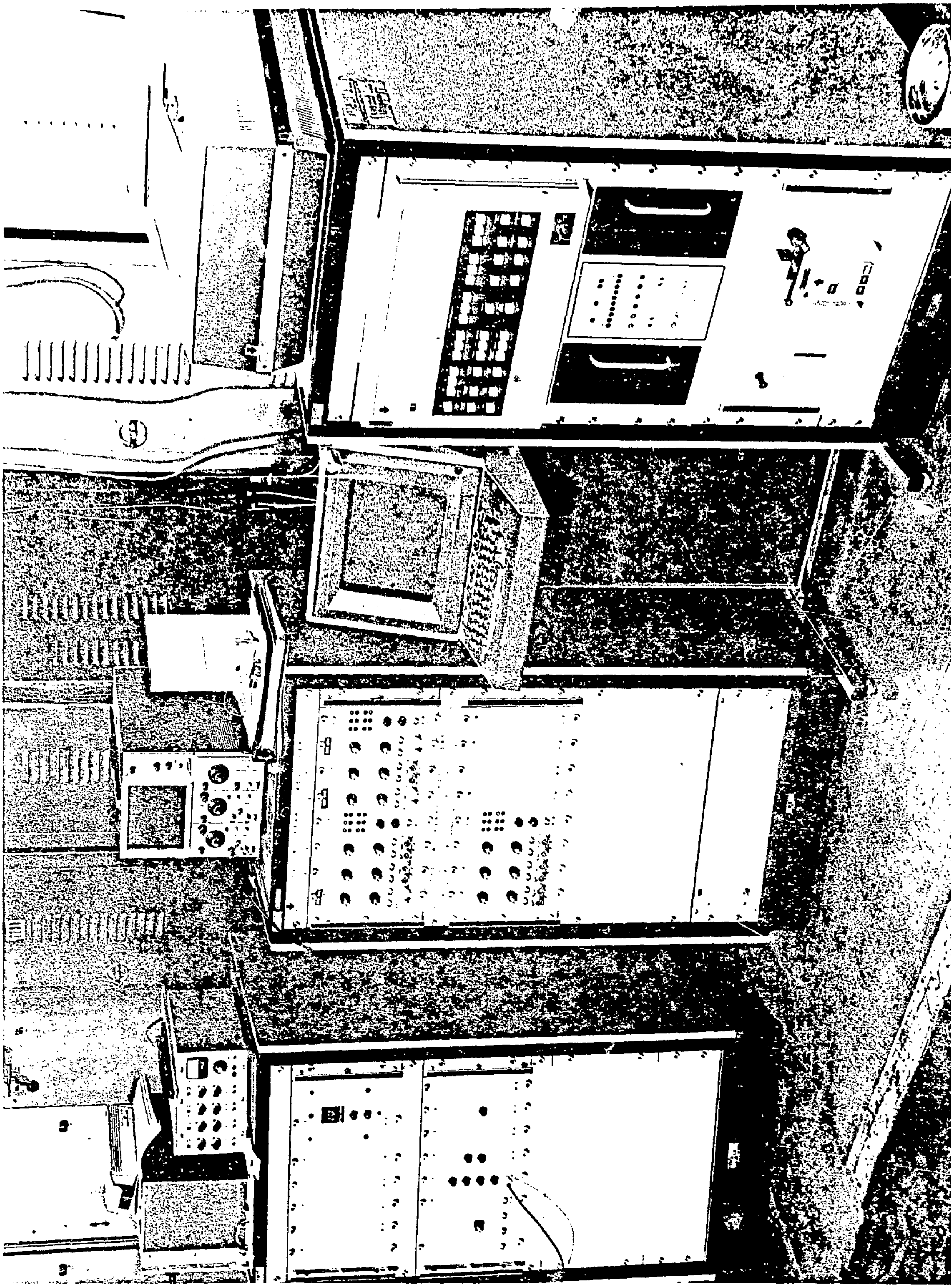


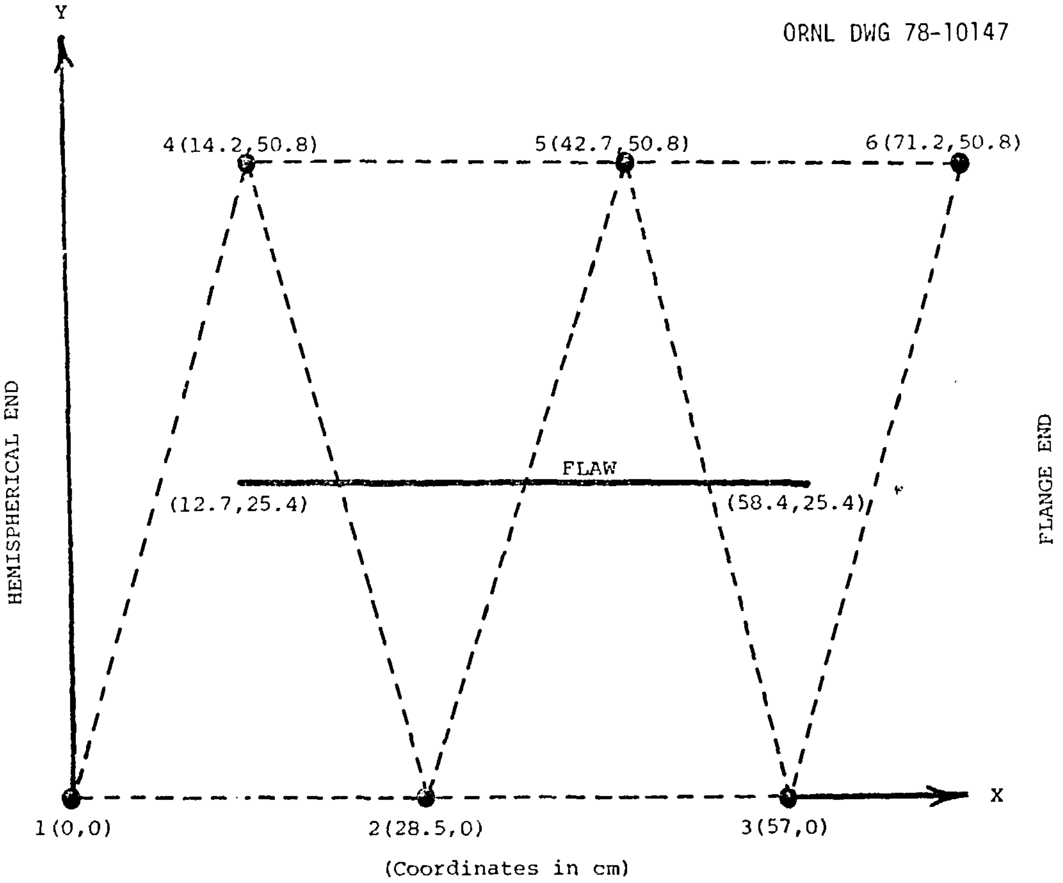
SECTION A-A

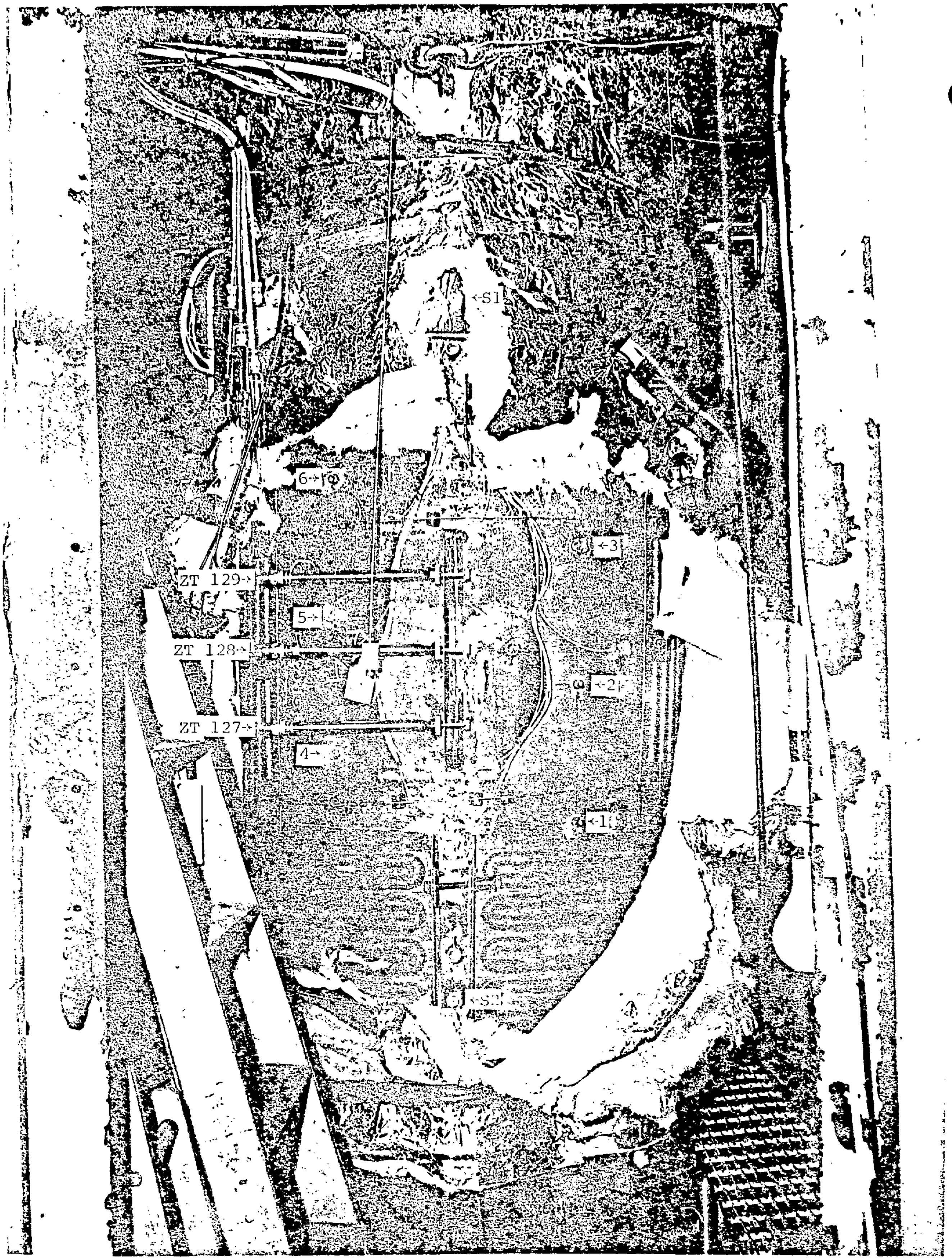
ORNL-DWG 76-7962

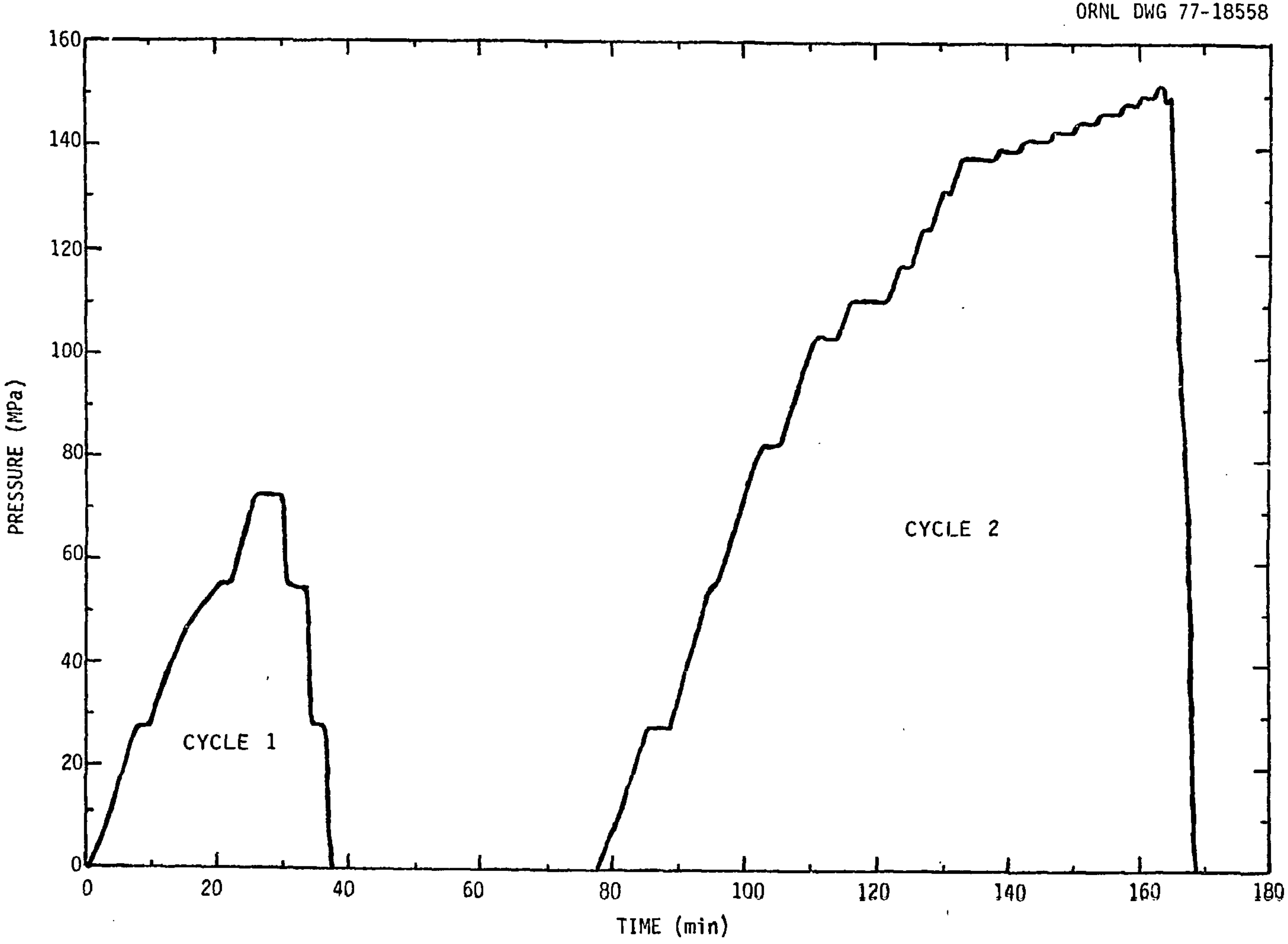
FLAW DESIGN






ORNL DWG 78-10147
Y
X
4(14.2,50.8)
5(42.7,50.8)
6(71.2,50.8)
FLAW
(12.7,25.4)
(58.4,25.4)
HEMISPHERICAL END
FLANGE END
1(0,0)
2(28.5,0)
3(57,0)
(Coordinates in cm)


S1
6
3
ZT 129
5
ZT 128
2
ZT 127
4
1
S2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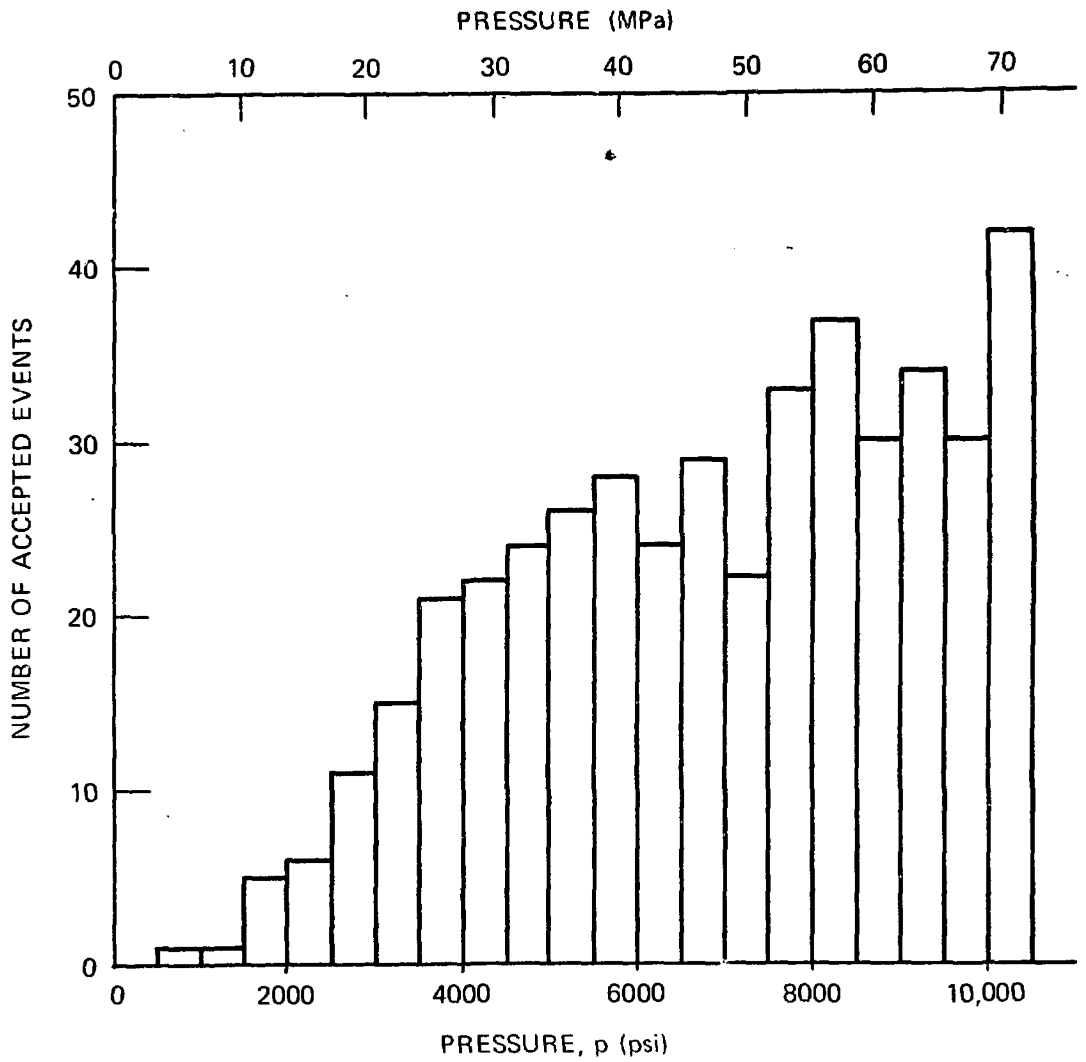
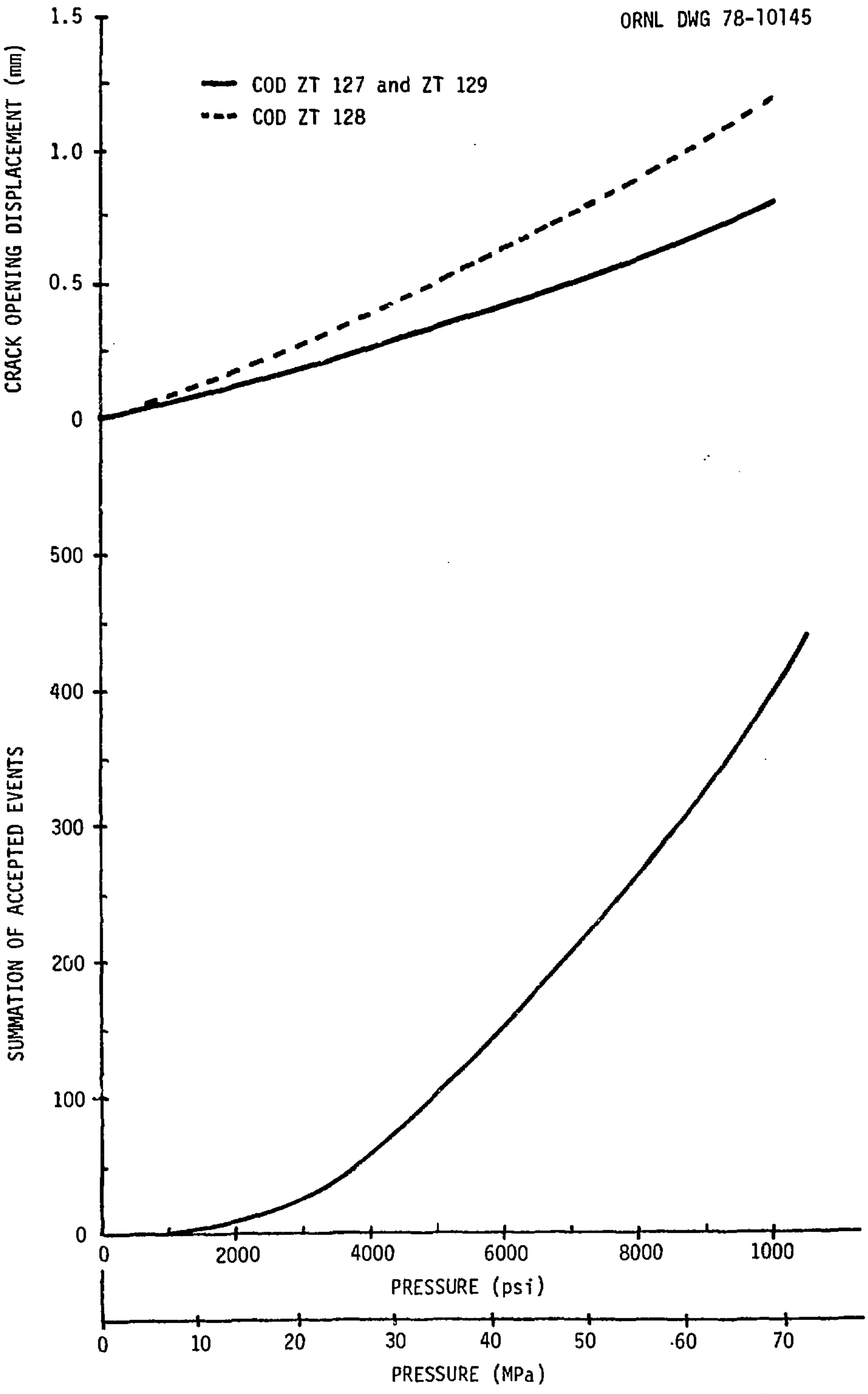
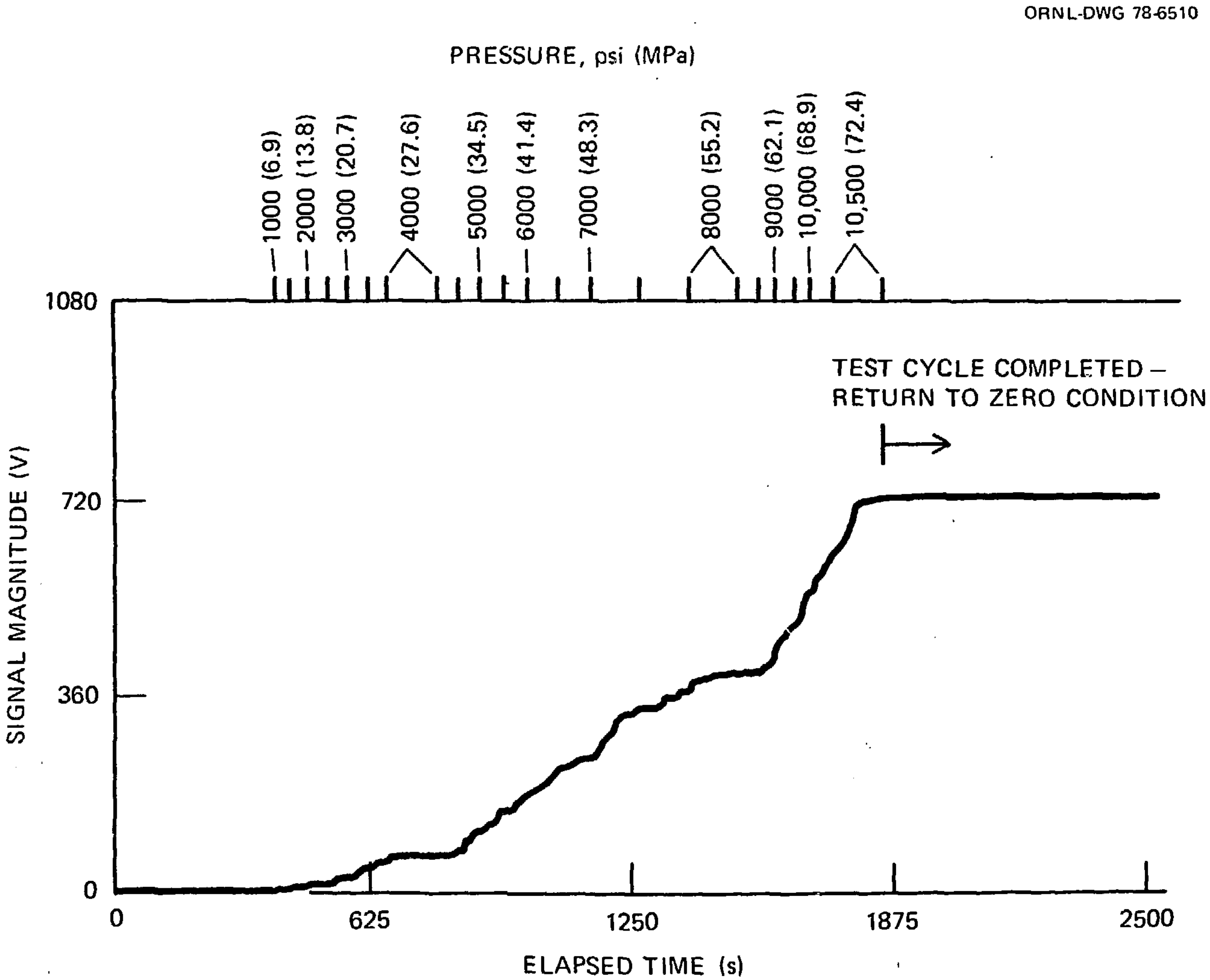
PRESSURE (MPa)
160
140
120
100
80
60
40
20
0
CYCLE 1
CYCLE 2
0
20
40
60
80
100
120
140
160
180
TIME (min)

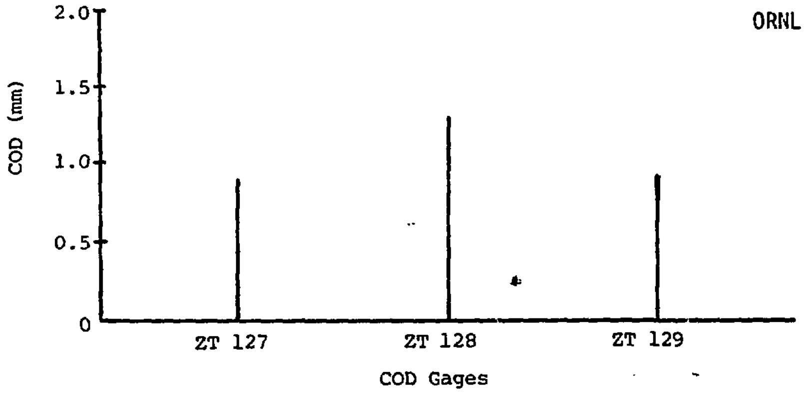
ORNL-DWG 78-6512

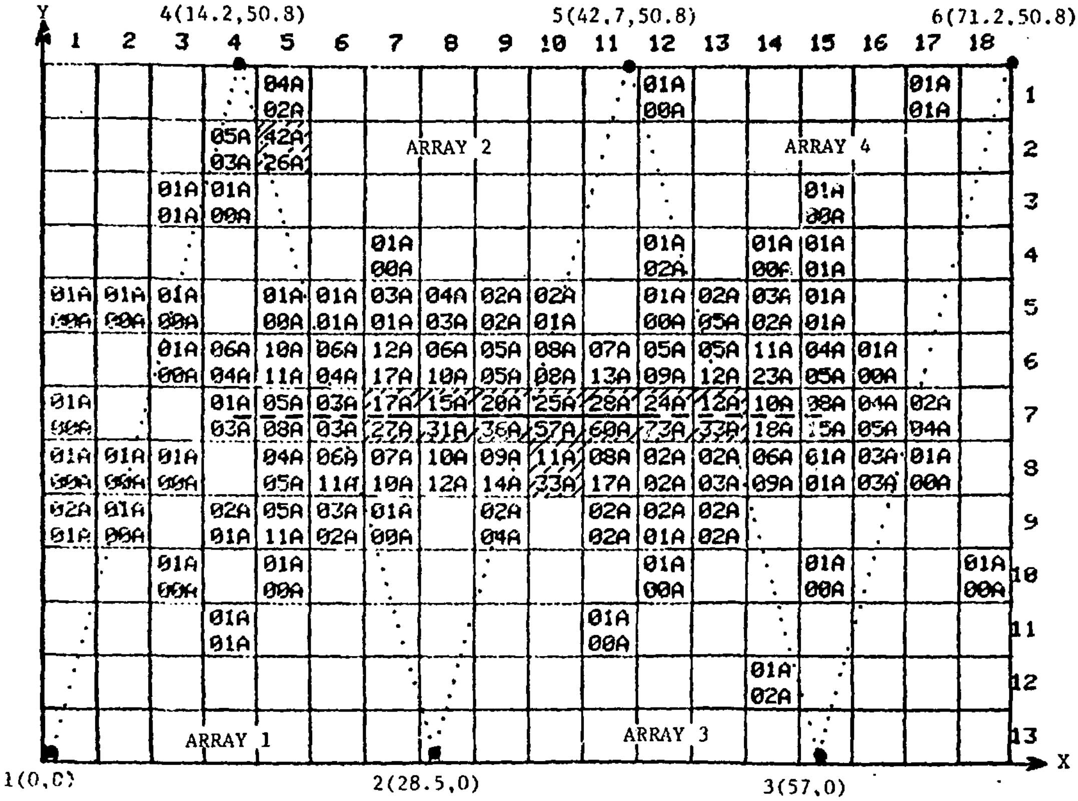



ORNL DWG 78-10145
COD ZT 127 and ZT 129
COD ZT 128
CRACK OPENING DISPLACEMENT (mm)
1.5
1.0
0.5
0
SUMMATION OF ACCEPTED EVENTS
500
400
300
200
100
0
0
2000
4000
6000
8000
1000
PRESSURE (psi)
0
10
20
30
40
50
60
70
PRESSURE (MPa)


ORNL-DWG 78-6510
PRESSURE, psi (MPa)
1000 (6.9)
2000 (13.8)
3000 (20.7)
4000 (27.6)
5000 (34.5)
6000 (41.4)
7000 (48.3)
8000 (55.2)
9000 (62.1)
10,000 (68.9)
10,500 (72.4)
TEST CYCLE COMPLETED –
RETURN TO ZERO CONDITION
SIGNAL MAGNITUDE (V)
1080
720
360
0
0
625
1250
1875
2500
ELAPSED TIME (s)

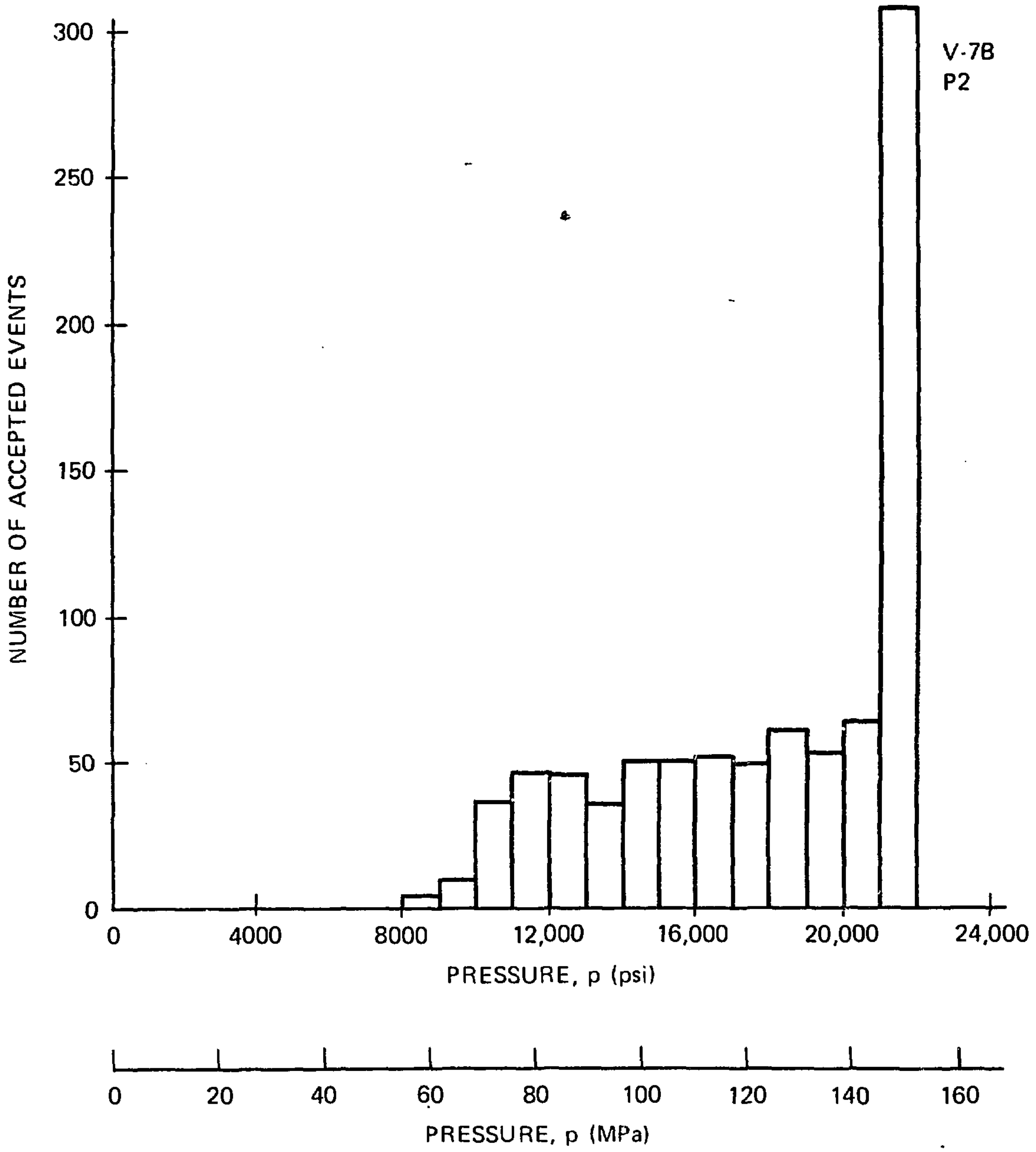
ORNL DWG 78-10148

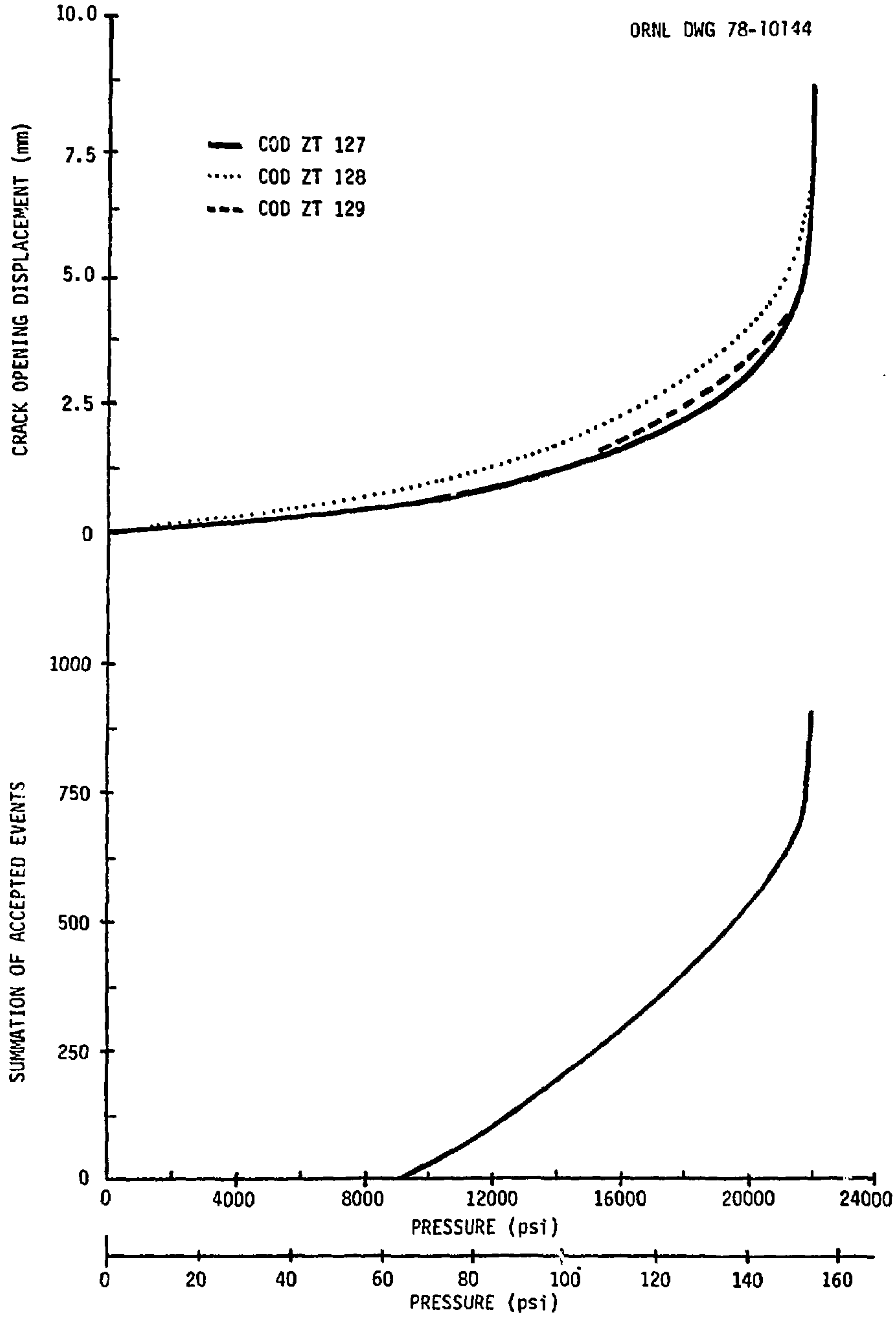


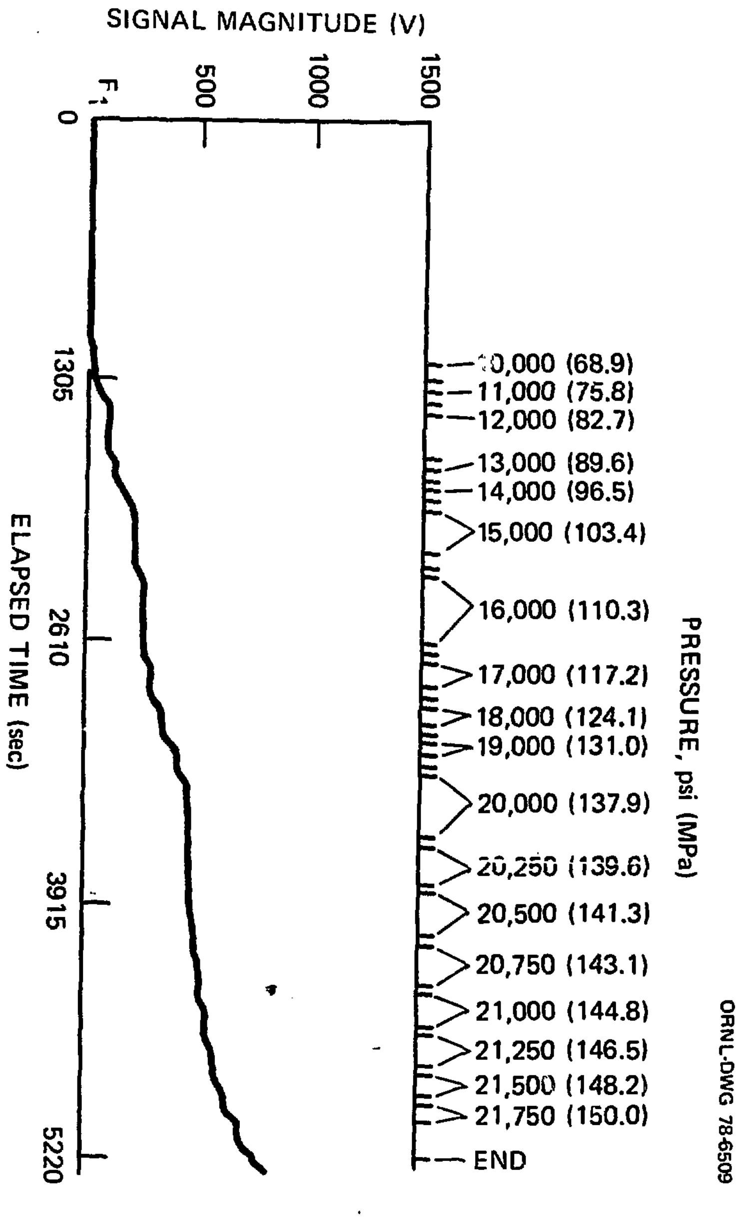


(Coordinates in cm)

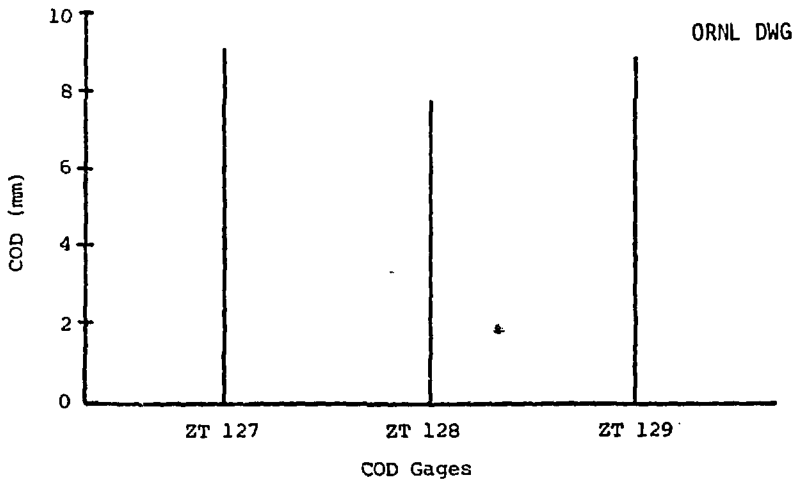
ORNL-DWG 78-6511

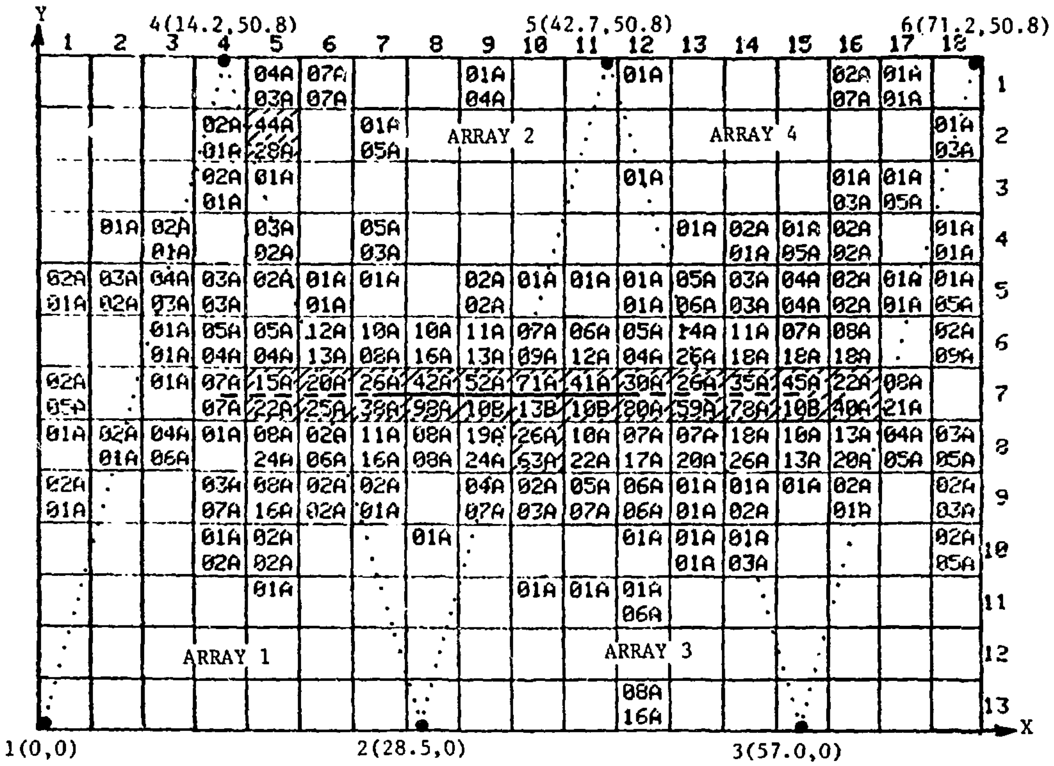



ORNL DWG 78-10144
COD ZT 127
COD ZT 128
COD ZT 129
CRACK OPENING DISPLACEMENT (mm)
10.0
7.5
5.0
2.5
0
SUMMATION OF ACCEPTED EVENTS
1000
750
500
250
0
0
4000
8000
12000
16000
20000
24000
PRESSURE (psi)
0
20
40
60
80
100
120
140
160
PRESSURE (psi)

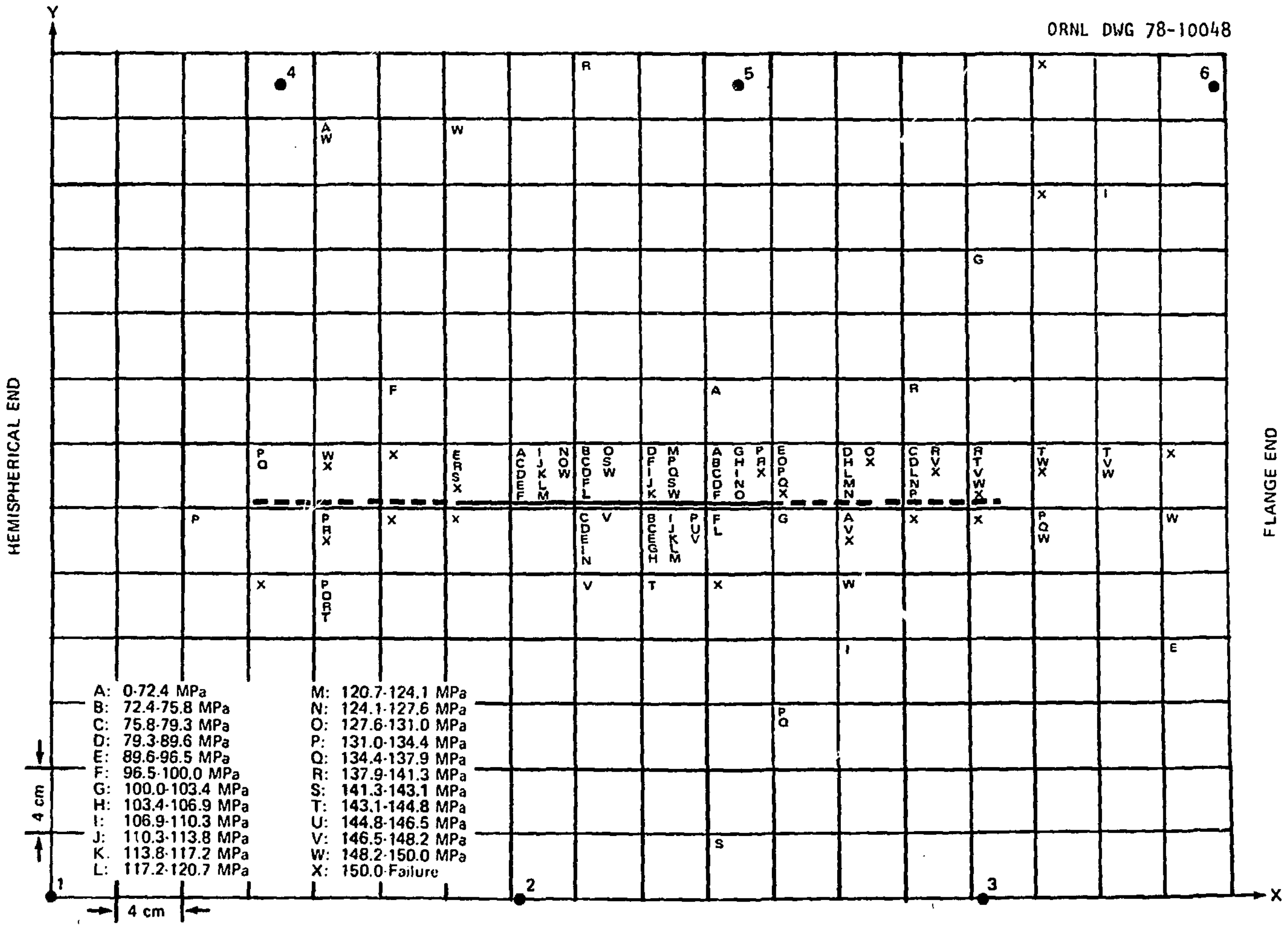

SIGNAL MAGNITUDE (V)
0
500
1000
1500
F1
ELAPSED TIME (sec)
0
1305
2610
3915
5220
PRESSURE, psi (MPa)
10,000 (68.9)
11,000 (75.8)
12,000 (82.7)
13,000 (89.6)
14,000 (96.5)
15,000 (103.4)
16,000 (110.3)
17,000 (117.2)
18,000 (124.1)
19,000 (131.0)
20,000 (137.9)
20,250 (139.6)
20,500 (141.3)
20,750 (143.1)
21,000 (144.8)
21,250 (146.5)
21,500 (148.2)
21,750 (150.0)
END
ORNL-DWG 78-6509

ORNL DWG 78-10149

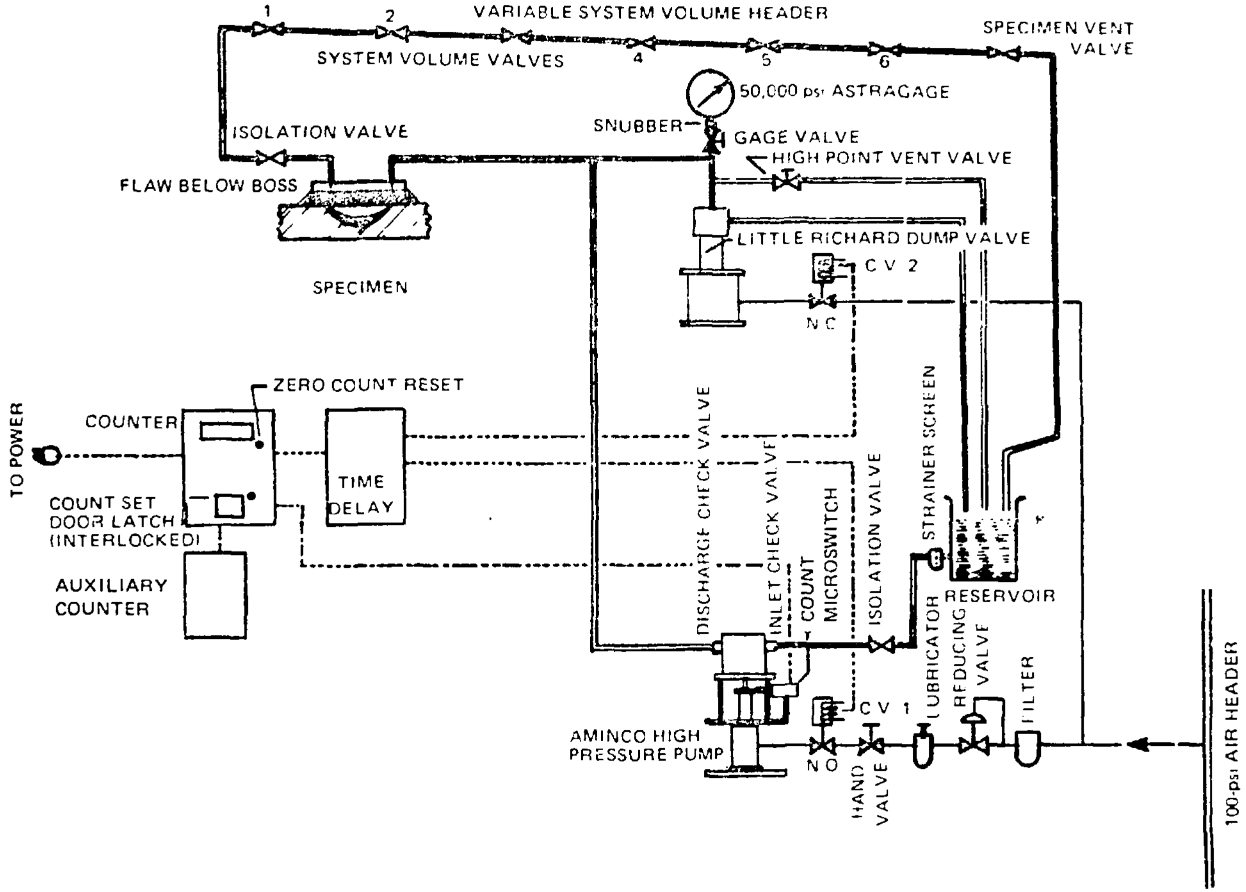


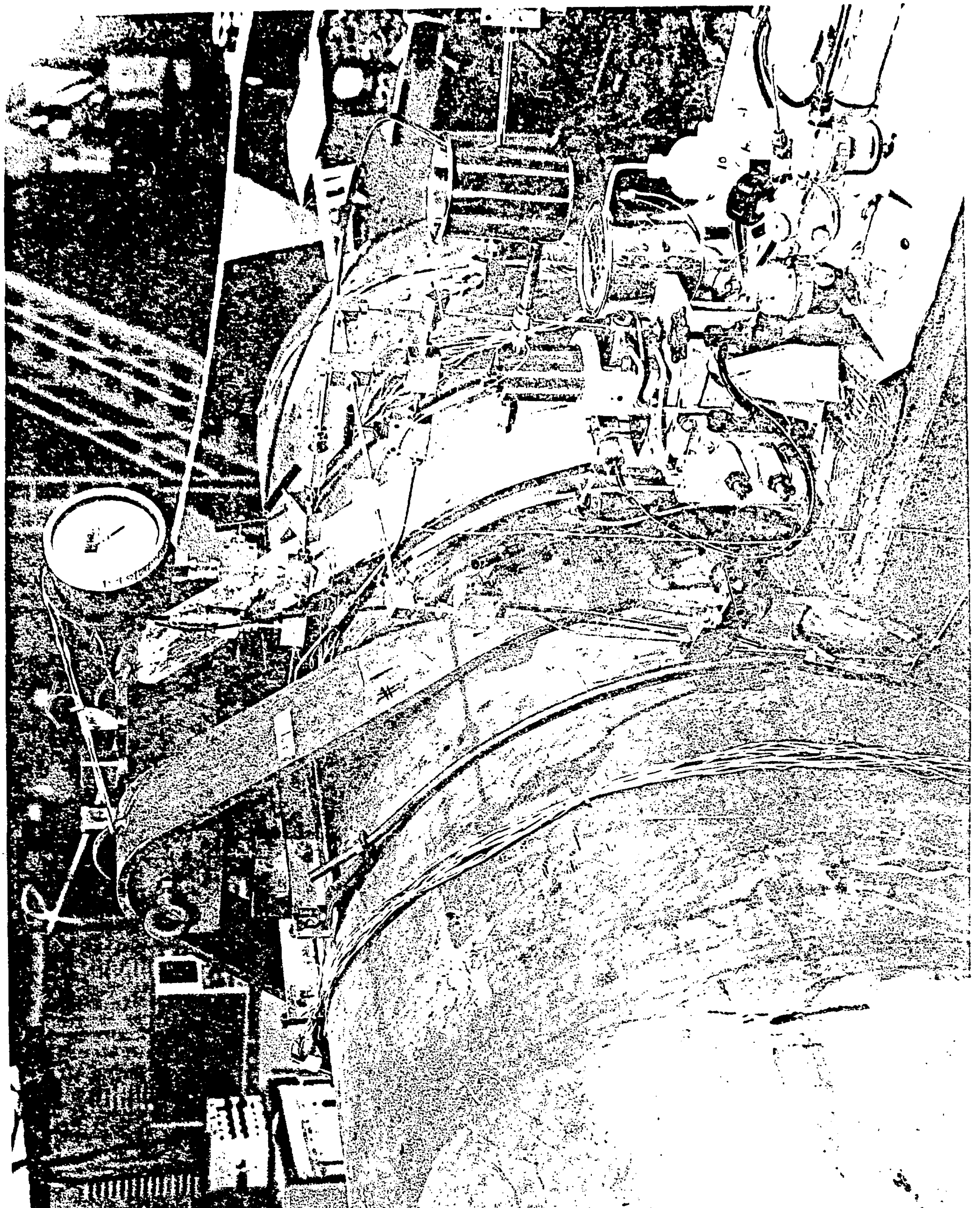


(Coordinates in cm)

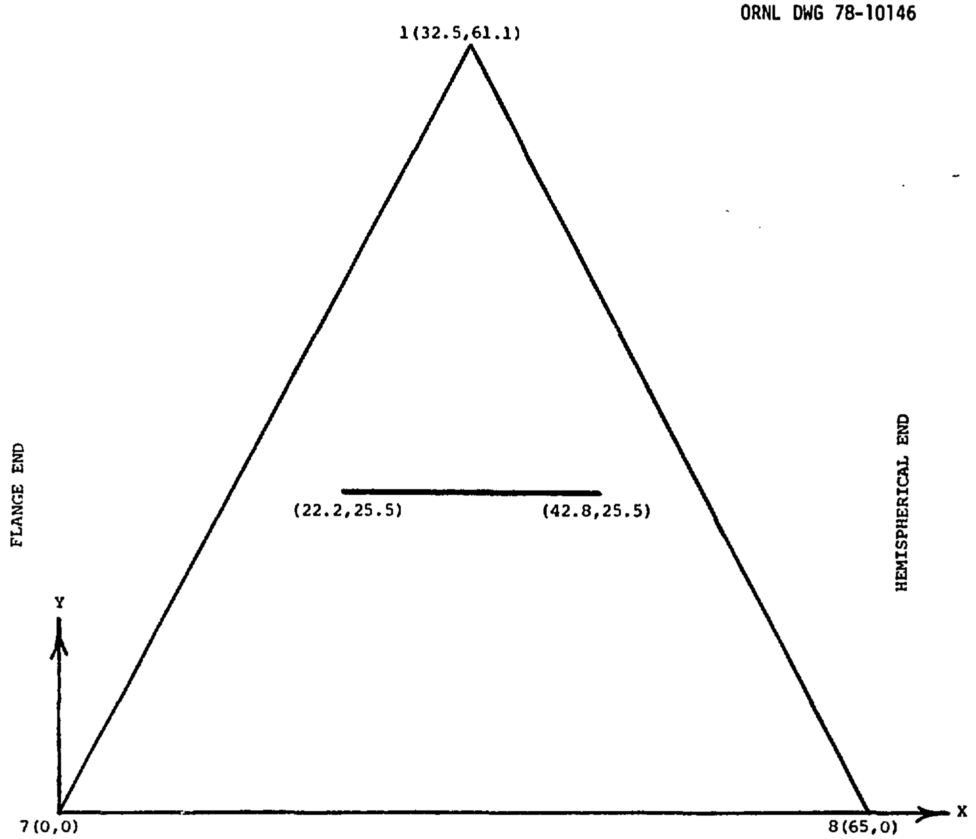

ORNL DWG 78-10048
HEMISPHERICAL END
FLANGE END
A: 0-72.4 MPa
B: 72.4-75.8 MPa
C: 75.8-79.3 MPa
D: 79.3-89.6 MPa
E: 89.6-96.5 MPa
F: 96.5-100.0 MPa
G: 100.0-103.4 MPa
H: 103.4-106.9 MPa
I: 106.9-110.3 MPa
J: 110.3-113.8 MPa
K: 113.8-117.2 MPa
L: 117.2-120.7 MPa
M: 120.7-124.1 MPa
N: 124.1-127.6 MPa
O: 127.6-131.0 MPa
P: 131.0-134.4 MPa
Q: 134.4-137.9 MPa
R: 137.9-141.3 MPa
S: 141.3-143.1 MPa
T: 143.1-144.8 MPa
U: 144.8-146.5 MPa
V: 146.5-148.2 MPa
W: 148.2-150.0 MPa
X: 150.0-Failure
4 cm
4 cm
Y
X

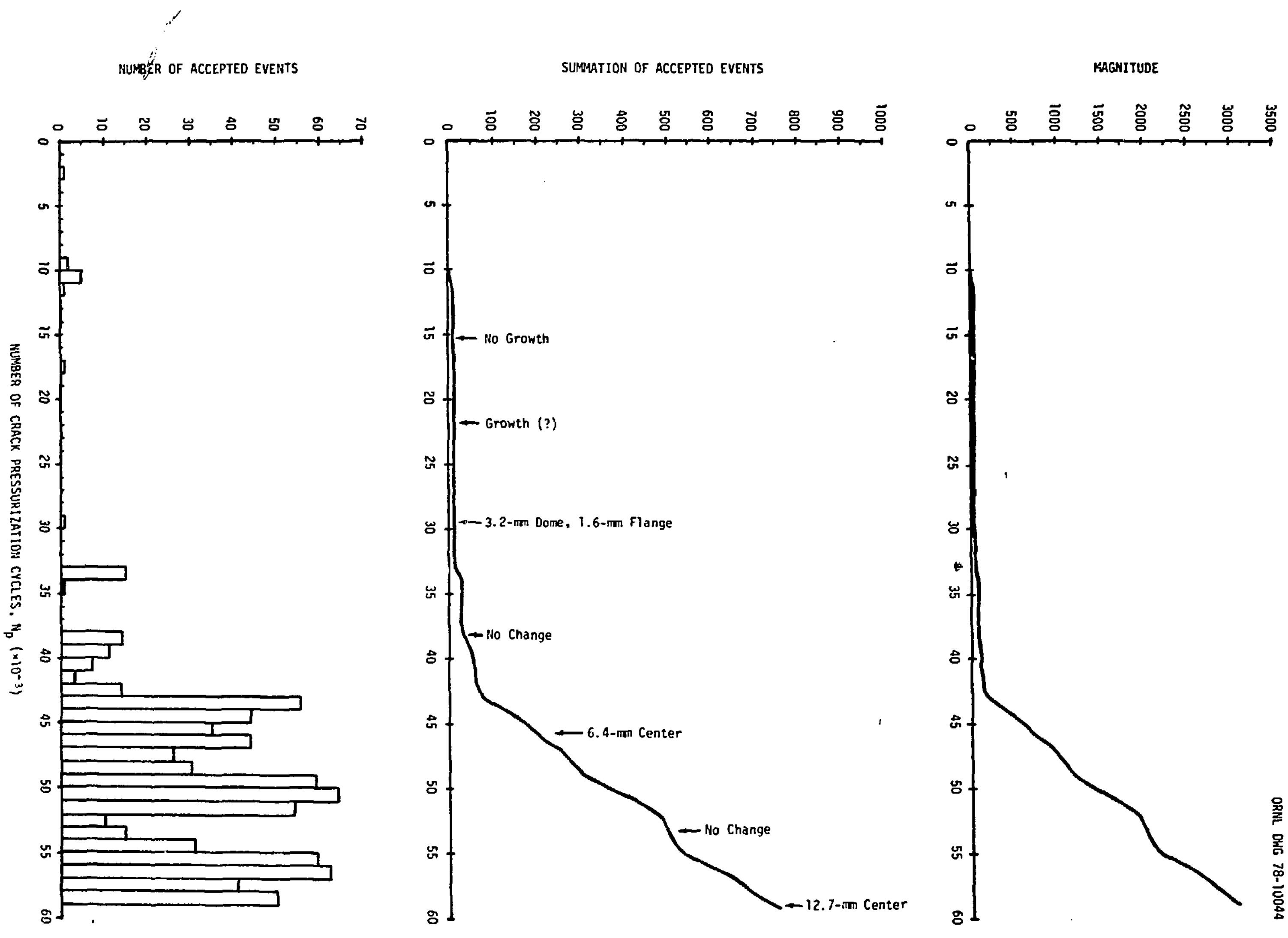
ORNL-DWG 74-8872R





ORNL DWG 78-10146





NUMBER OF ACCEPTED EVENTS
SUMMATION OF ACCEPTED EVENTS
MAGNITUDE
NUMBER OF CRACK PRESSURIZATION CYCLES, N_p (×10⁻³)
No Growth
Growth (?)
3.2-mm Dome, 1.6-mm Flange
No Change
6.4-mm Center
No Change
12.7-mm Center
ORNL DWG 78-10044