Steam Generator Evaluation
Ginna Steam Generator Tube Failure Incident
January 25, 1982
R. E. Ginna Nuclear Power Plant
Docket No. 50-244

Addendum 4
<u>External Tube Loading Test</u>

Revision 1
May 18, 1982

8206010663

ABSTRACT

This report documents the results to date of an external tube loading test conducted by Combustion Engineering, which studies the effects of axial tube loading, tube peening simulation of tube/ loose part interaction, and external pressure experienced by a plugged tube.

An eddy current signal which closely resembled an I.D. defect signal was produced by a tube subjected to axial loading only and a tube was collapsed under the combined loadings of "peening" and external pressure. The collapsed tube geometry closely resembled collapsed tubes observed in the Ginna B-Steam Generator.

GINNA STEAM GENERATOR
EXTERNAL TUBE LOADING TEST

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C.1.0 INTRODUCTION

Subsequent to the Ginna B-Steam Generator tube rupture on January 25, 1982, a comprehensive inspection program was carried out by Rochester Gas and Electric Corporation to ascertain the cause of tube damage. Video examinations revealed that previously plugged tubes in the Number 4 wedge area, immediately outboard of the burst tube, had collapsed and then apparently parted just above the tubesheet. Examination of removed failed tube samples revealed cold working had occurred in the collapsed region of the tubes which ultimately parted due to fatigue. A study of sectioned tube samples clearly established a "domino" like failure progression from peripheral plugged tubes to the active tube which burst. Several foreign objects were discovered on the periphery of the tube bundle, lying on the tubesheet. In addition, video examination discovered other collapsed tubes in the Number 6 wedge area which had not yet parted.

Further examination of the removed tube samples failed to find the I.D. defects which were recorded as the causes for plugging many of the peripheral tubes.

C.2.0 OBJECTIVES

The purpose for performing this test program was to obtain test data which could be used to explain why the tubes adjacent to the burst tube were originally plugged and, once plugged, what caused some of them to collapse during service.

C.2.1 Cause of Eddy Current Indications

Since it was postulated that axial load imposed on the tubes, subsequent to "lock-up" at a support plate, could cause tube deformation, it was planned to imposed axial tube loads on the test tubes based on steam generator transient analysis. Baseline eddy current examinations of the test tubes were compared with data obtained after loading increments.

C.2.2 Cause of Tube Collapse

Previous CE "loose parts" testing experience (Reference C) indicated that the "peening" effect of foreign objects operating in the bundle entrance flow stream could cause cold work and subsequent ovalization of the peripheral tubes. A shot peening simulation of the test tubes was conducted to determine if this effect in combination with external pressure could cause tube collapse.

C.3.0 TEST PARAMETERS

The parameters which were evaluated in this test program were axial load, tube "peening", and external pressure.

C.3.1 Axial Load

Since nearly all of the peripheral plugged tubes were adjacent to tube support plate wedge areas, and eddy current test data suggested some degree of tube "lock-up" in the tube support plates, it seemed reasonable that the tubes in question were subject to axial load during transient operation. Using data from Reference B, the following conditions were considered assuming that lock-up takes place during power operation:

C.3.1.1 Cold feed at hot standby (before plugging); "slug feeding" - tube in compression

C.3.1.2 Power operation (after plugging); tube in tension

C.3.1.3 Worst case (after plugging); zero axial load

C.3.2 Shot Peening

The outward surface of the test tubes was subjected to increments of shot peening which simulated the cold work found to exist on the collapsed Ginna Steam Generator tubes. It was assumed that the cold work accumulated in the generator was caused by the foreign objects recovered from the periphery of the tube bundle. The method of shot peening, which is described in detail in Section 5.0, was developed to simulate the cold work through thickness profile previously found in CE "loose parts" tests (Reference C).

C.3.3 External Pressure

Subsequent to being plugged, tubes will experience external pressure during power operation. The highest external pressure will occur during hot standby conditions when the secondary pressure is near secondary design pressure of 1000 psi. To compensate for the fact that the test is run at room temperature where the tube has higher yield strength than at power operation, a test pressure of 1500 psi is used. This margin also covers any uncertainty relative to the calculated yield point, which is not well defined on the stress-strain curve for Inconel 600 material. Test tubes will be subjected to external pressure after "peening" increments until collapse occurs.

C.4.0 LABORATORY EQUIPMENT

Lab equipment was designed to provide the following capabilities:

(1) Provide tubesheet and first support plate simulation for a single steam generator tube.

(2) Provide means for displacing tube laterally at first support plate location.

(3) Provide means for applying axial load, either tension or compression to the tube and readout in pounds.

(4) Provide means for monitoring axial compression of the tube from tubesheet to first support location and means of measuring amount of tube "bowing".

(5) Provide necessary fixtures such that external pressure may be applied to selected portion of tubing.

(6) Provide means for shot peening of selected portion of tubing within the load frame.

The apparatus designed to provide the above capabilities is described in subsequent sections.

C.4.1 Load Frame

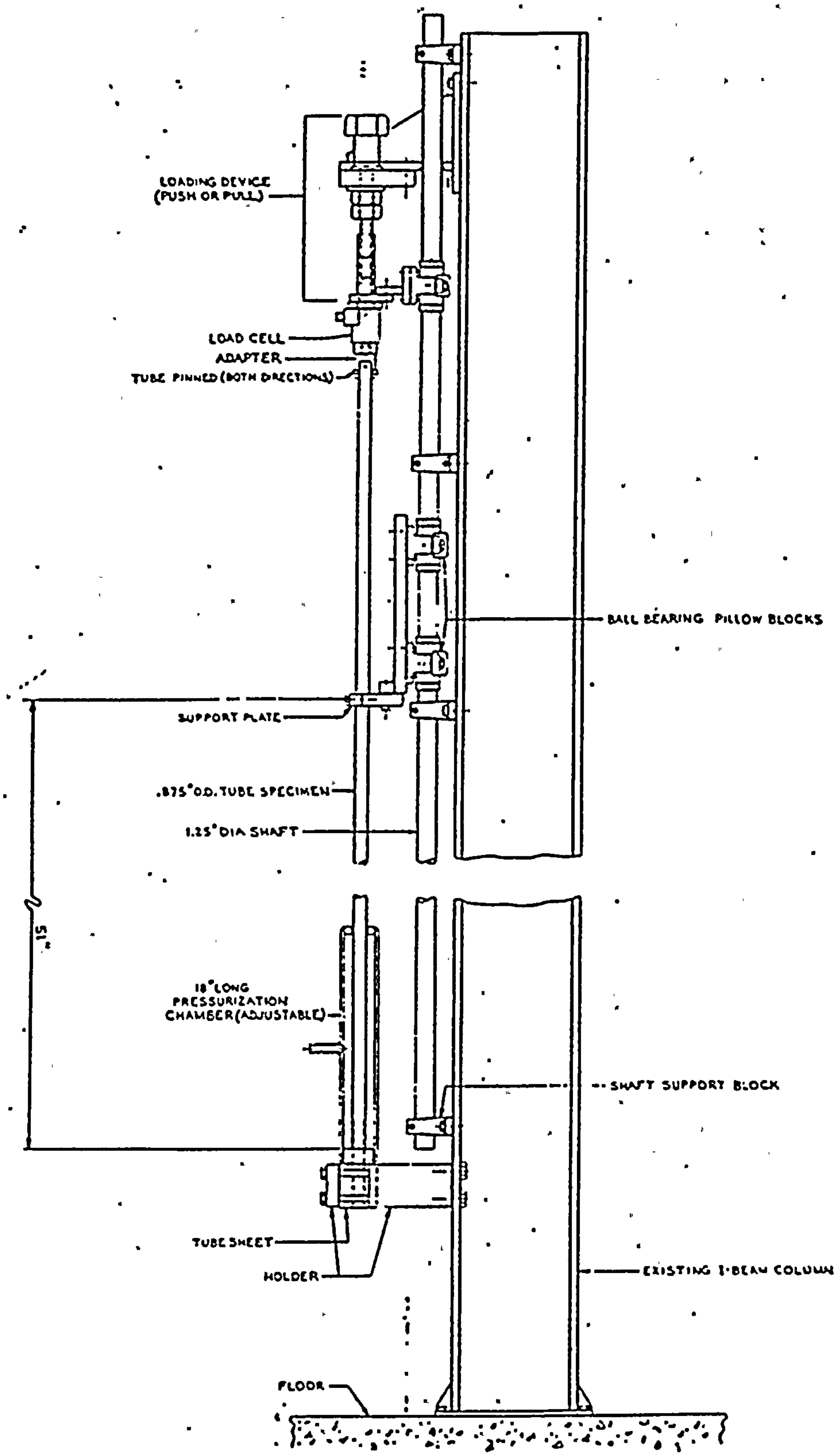
Figure C.4-1 provides an assembly drawing of the load frame. The load frame basically consists of a means of supporting the tube specimen in a vertical position with a simulated tube support, jack screw, load cell, and deflection measuring equipment. A photograph of a side view of the load frame assembly is provided as Figure C.4-2.

C.4.2 Shot Peening Equipment

The shot peening equipment used in the test consisted of a small pressurized air tank which contained the shot material, a regulated pressure air supply, various air flow valves and a 3/4" I.D. delivery hose with appropriate nozzle (1 1/2" x 3/8" Sch 40 pipe for 3/16" steel balls). A rectangular wooden box was constructed to support the tube specimen and position the nozzle relative to the tube for shot peening. The bottom of the box was provided with a tapered transition to collect the ball bearings during the peening operation. A view of fixture for shot peening is shown in Figure C.4-3.

C.4.3 Eddy Current Examination Equipment

A description of this equipment is provided in Section C.7.0.



EXTERNAL TUBE LOADING TEST APPARATUS

COMBUSTION ENGINEERING

FIGURE C.4-1

SIDE VIEW OF LOAD FRAME ASSEMBLY

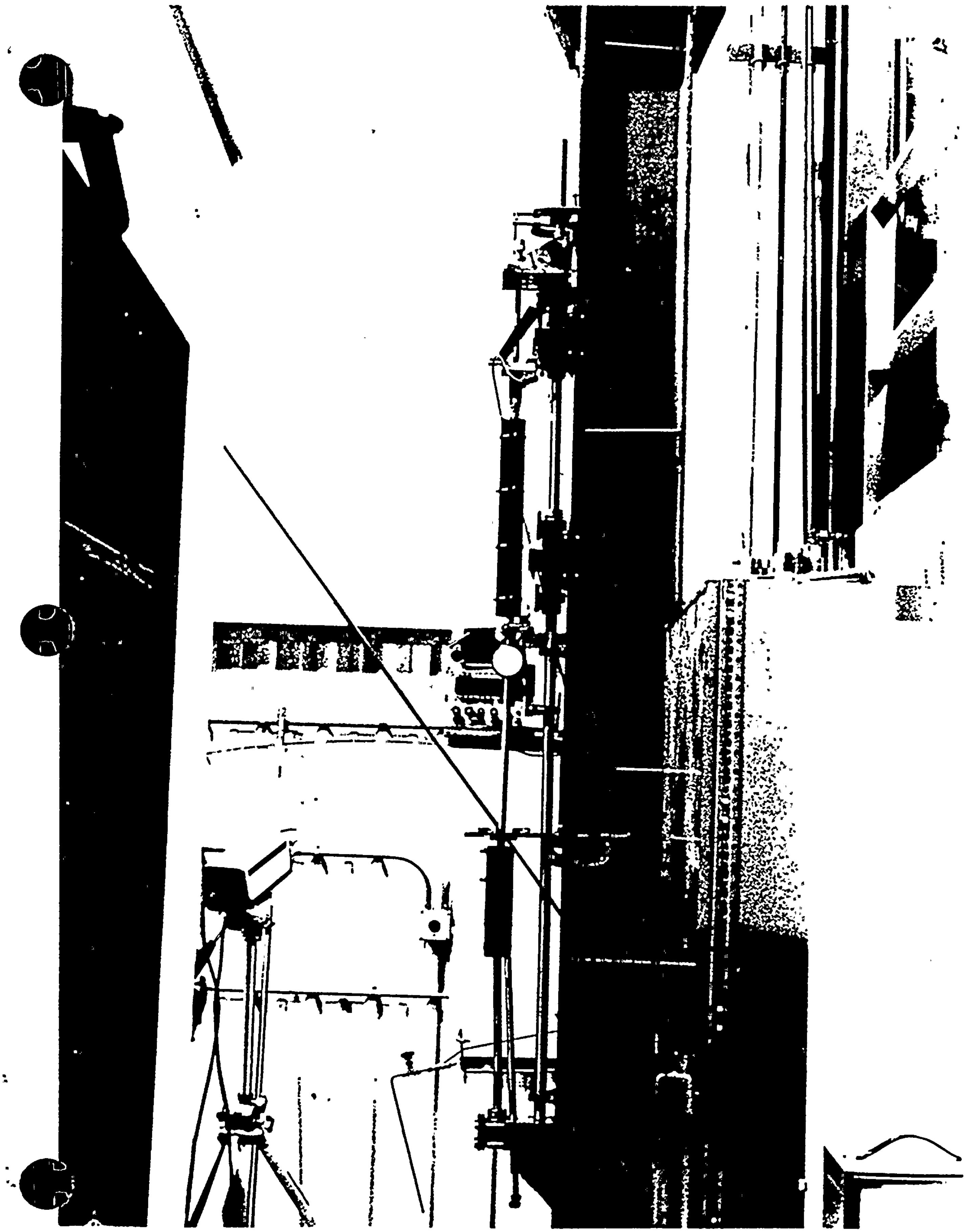


Figure C.4-2

VIEW OF SHOT PEENING FIXTURE

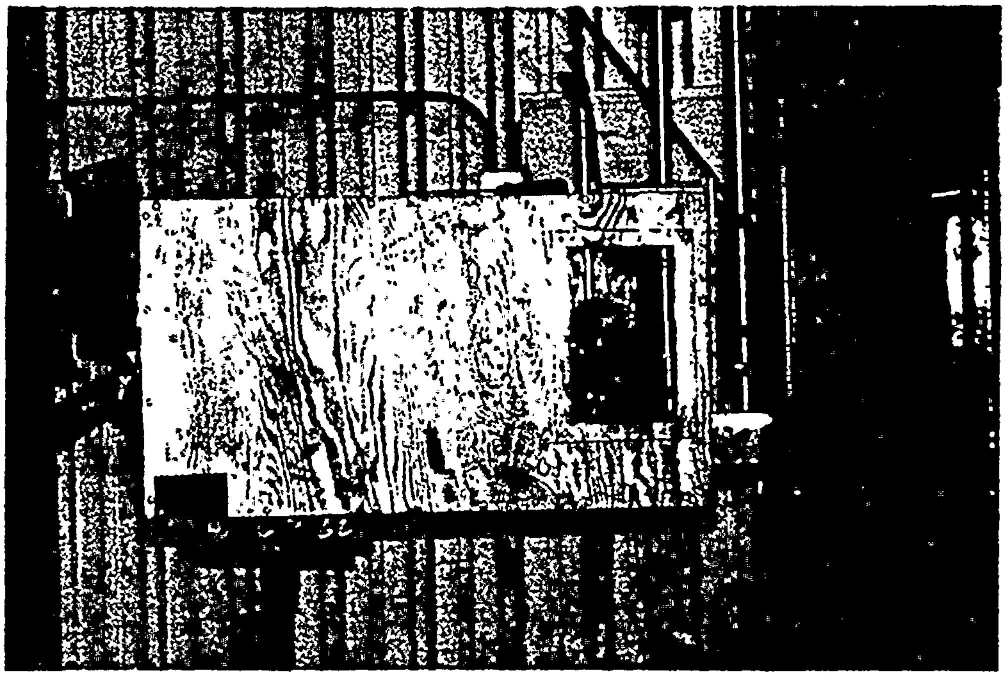


Figure C.4-3

C.5.0 DEVELOPMENT OF SHOT PEENING TECHNIQUE

The objective of the shot peening of the steam generator tube was to simulate the damage caused by loose object impingement on the outside diameter of a tube. The simulation should meet surface damage and metallurgical changes as seen in typical loose object damage.

The characteristic of this damage is presented in References A and B. CE tests pertaining to "loose objects" presented in Reference C were also reviewed. From a review of available data it was noted that prior shot peening tests did not produce a wall hardness profile which matched that of a typical damaged tube subjected to a loose object.

It was therefore decided that to attempt to match the hardness profile of the typical tube, other techniques would have to be used. A preliminary test matrix was written to try various techniques of peening. Preliminary samples were prepared using 3/16" steel balls, #780 shot, and a coarse steel grit (smaller than the #780 shot). Surface appearance showed the 3/16" steel balls most closely resembled the loose object damage.

Therefore, the first samples for hardness testing were made using the 3/16" steel balls with various air pressures and peening durations. The results are shown in Figure C.5-1. The tube samples used were provided by RG&E as purchased from B&W. Tensile properties were confirmed by the Metallurgical Labortory to be 41.3 ksi yield strength, 98.3 ksi tensile strength and 48% elongation. This analysis shows these tubes to be from B&W Heat No. 93396. Tube wall hardness profiles of the virgin tube were also recorded and are shown in Figure C.5-1.

These results show that the 3/16" balls as used with the lab equipment give a hardness profile which closely resembles actual conditions in a tube subjected to impingement by a loose object where the hardness on the OD increases significantly but the hardness at the ID does not basically change.

The 10 psi, 60 sec. and the 20 psi, 30 sec. samples show approximately the same characteristics. Therefore, various combinations of pressure and time may be used to simulate the desired damage.

Hardness vs. Distance Through
Tube Wall for
Shot Peening Tube Samples

Note: All samples made by evenly covering approximately 2" length on one side of the sample

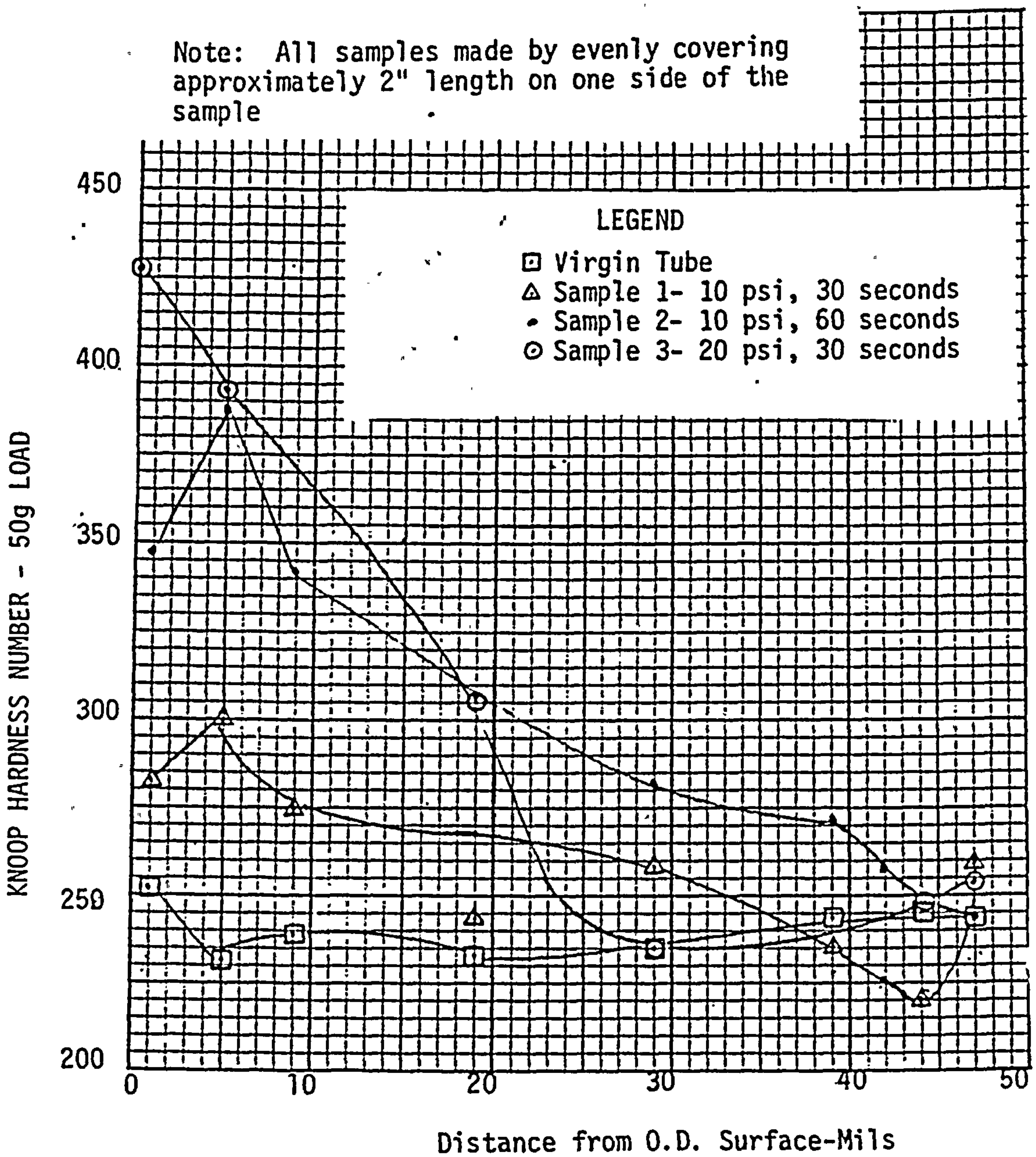


Figure C.5-1

C.6.0 TUBE MECHANICAL TEST RESULTS

C.6.1 General

Inconel 600 steam generator tubes (.875" OD x .050 wall thickness) were provided by Rochester Gas & Electric for this test program. Tensile tests were performed on two tube specimens for reference purposes.

The tube specimens were tested using the load frame and equipment described in Section C.4.0. Specific comments relative to each tube test and the test results are presented in the following sections:

C.6.2 Tube No. 1

This tube was installed in the load frame and initial measurements and eddy current examination performed. Next, the tube was displaced laterally .50 inches as described in Section C.4.0 and an axial compressive load applied to the tube. Axial deformation of .121 inches was applied to the tube (51.8 inch span) and 2,500 pound force was indicated by the load cell.

The diameter of the tube was measured in the 0 to 10 inch distance above the tubesheet and no measurable tube ovality was determined. The tube was then subjected to an external pressure equal to 1500 psig (approximately twice operating pressure). There was no apparent tube deformation or collapse with the application of external pressure.

Eddy current examination of the tube was performed before commencement of the test and after maximum load was applied to the tube. Results of the eddy current examination are discussed in Section C.7.0.

C.6.3 Tube No. 2

Axial loading of tube number one did not result in measurable ovality and consequently the tube did not collapse under external pressure. It was therefore decided that, for test of tube no. 2, lateral restraint of the tube would be provided approximately midway between the tubesheet and the first support so that it would be possible to achieve a higher compressive load on the tube in achieving an axial deformation of approximately .120". A restraint was installed at 29" above the tubesheet and axial load again applied to the tube.

The maximum load applied to the tube was 4,480 pounds at which time axial deformation of the tube was .123 inches. The axial deformation resulted in a maximum "bowing" of the tube of .459 inches at an elevation of 21 inches above the tubesheet. There was no measurable ovality of the tube due to the compressive load. Once again the tube was subjected to external hydrostatic pressure of 1500 psig without any detrimental effect.

Eddy current examination of the tube was performed prior to commencement of the load test and at maximum load. No indications were apparent. The characteristic curvature of the tube during the loading operation is shown in Figure C.6-7.

C.6.4 Tube No. 3

This test was performed in the same manner as tube number one with the exception that a much larger axial deformation of the tube was performed in order to produce a much larger degree of tube "bowing". The tube was installed in the load frame and displaced laterally .50 inch at the support plate. A baseline eddy current examination was then performed of the tube.

An axial compressive load was then applied to the tube such as to achieve a maximum axial deformation of the tube of .622 inches. At each .050 or .100 inch increment, lateral deflection (bowing) of the tube was determined between the tubesheet and the first support plate. As the tube "bowed" the load required for axial deformation reduced from 3,100 pounds at .051 inch axial deformation to 1,130 pounds at .622 inches. The maximum amount of lateral tube deflection was determined to be 3.659 inches at 24 inches above the tubehseet. Eddy current examination of the tube was performed with the tube in the above "bowed" condition and the data is presented in Section C.7.0 of this report.

The compressive load was then removed from the tube and a tensile load applied in an attempt to return the top of the tube to the same elevation that existed prior to the application of compressive load. The dial gages were initialized at the no load condition. A tensile load of 3,800 pounds was subsequently applied to the tube and the dial gages indicated an upward extension of the tube at the vicinity of the support plate of .340 inches. Due to the plastic deformation in the tube the tensile load was not sufficient to eliminate all "bowing" of the tube. At a tensile load of 3,800 pounds the maximum lateral deflection of the tube was .559 inches at 24 inches above the tubesheet. Eddy current examination of the tube was performed with tensile load on the tube. Data is presented in Section 7.0. The tube was again subjected to an external pressure of 1500 psig for approximately 11 inches of the length without any detrimental affect.

C.6.5 Tube No. 4

The eddy current examination data for tube no. 3, at an axial deformation of .630", indicated a phase angle rotation of 11°. This same condition exists in the presence of I.D. defects. However, after consultation with various technical personnel at CE it was recognized that it was probably due to the effect of microscopic "wrinkling" of the tube that was occuring in the region of high plastic deformation (bowing) of the tube. It was then decided that tube No. 4 should be loaded in the same manner as tube No. 3 and more frequent eddy current examinations performed.

Loading operations and tube measurements were made for tube No. 4 in the same manner as tube No. 3 with the exception that eddy current examinations of the tube were performed for each .030 inch increment of axial deformation. This particular tube did not exhibit the same phase angle rotation even at .630 inch deflection. See Section C.7.0 for discussion of eddy current results.

C.6.6 Tube No. 5

Tests of previous tubes with large amounts of tube "bowing" under axial load did not result in significant tube ovality and consequently there was no collapse of the tubes when subjected to external pressure. It was therefore decided to proceed with investigation of the "peening" effect on steam generator tubes while under axial load. The peening procedure that was developed to simulate the effect of a "loose object" is described in Section C.5.0.

A steam generator tube had been previously subjected to approximately one minute of peening using 20 psig air pressure and 3/16" diameter steel balls in the special test fixture used to develop the peening procedure. It was decided to use this tube for the next test to conserve test specimens.

The tube was installed in the load frame with no offset of the support plate. Initial lateral dimensions were acquired to determine the straightness of the tube and check alignment. These measurements indicate that the tube had an initial "bow" of .105" (max) after having been subjected to the initial peening operation. An axial compressive load was next applied to the tube until vertical deformation of the tube indicated .120 inches. This produced a maximum "bowing" of the tube from the installed condition of 1.186 inches at 27 inch elevation. The tube was then unloaded. A permanent axial deformation of the tube of .035 inches was indicated in the unloaded condition.

An axial tensile load of 5,550 pounds was next applied to the tube. This axial deformation of the tube, referenced to the initial installed condition, still indicated a compression of .012 inches. This is apparently due to the "permanent set" existing in the bowed section of the tubing.

The next operation involved peening of the tube for approximately one minute increments and then measuring lateral deflection of the tube and the tube ovality. The peening operation was performed from 3 1/4 inches above the tubesheet to approximately 9 inches above the tubesheet. The tube was peened using 3/16" diameter steel ball bearings with an air pressure of 20 psig. The nozzle was located 1 1/4 inches from the tube during the peening operation. After each peening and measurement interval the tube was again subjected to external hydrostatic pressure of 1500 psig, which compensates for the lower test temperature. After the tube had

been subjected to approximately 27 minutes of peening as described above, the tube ovality in the peened region had increased to 31.3% and the tube collapsed under external pressure slightly below 1500 psig. During each peening operation the vertical tensile load continually was being reduced. The tensile load at the time of collapse of the tube had reduced from 5,500 pounds to 800 pounds.

Photographs of the collapsed tube at the end of the test are provided in Figures C.6-1, C.6-2, and C.6-3. The tube was subsequently sectioned and micro-hardness survey performed at various locations through the wall thickness. Figure C.6-4 provides a view of the cross-section. Figures C.6-5 and C.6-6 provide plots of micro-hardness through the wall thickness at various locations around the tube. It is interesting to note that the hardness across the wall thickness is of the same approximate magnitude as values determine during development of the peening procedure. The range of hardness for 1 minute of peening was comparable to 27 minutes of peening with the 3/16" diameter steel balls. Although the hardness does not appreciably increase as a function of time of peening, the physical distortion of the tube (ovality) does increase. The ovality must be primarily a function of plastic flow during the peening operation.

PHOTOGRAPH OF TUBE SPEC. NO. 5
AFTER COLLAPSE UNDER EXTERNAL PRESSURE

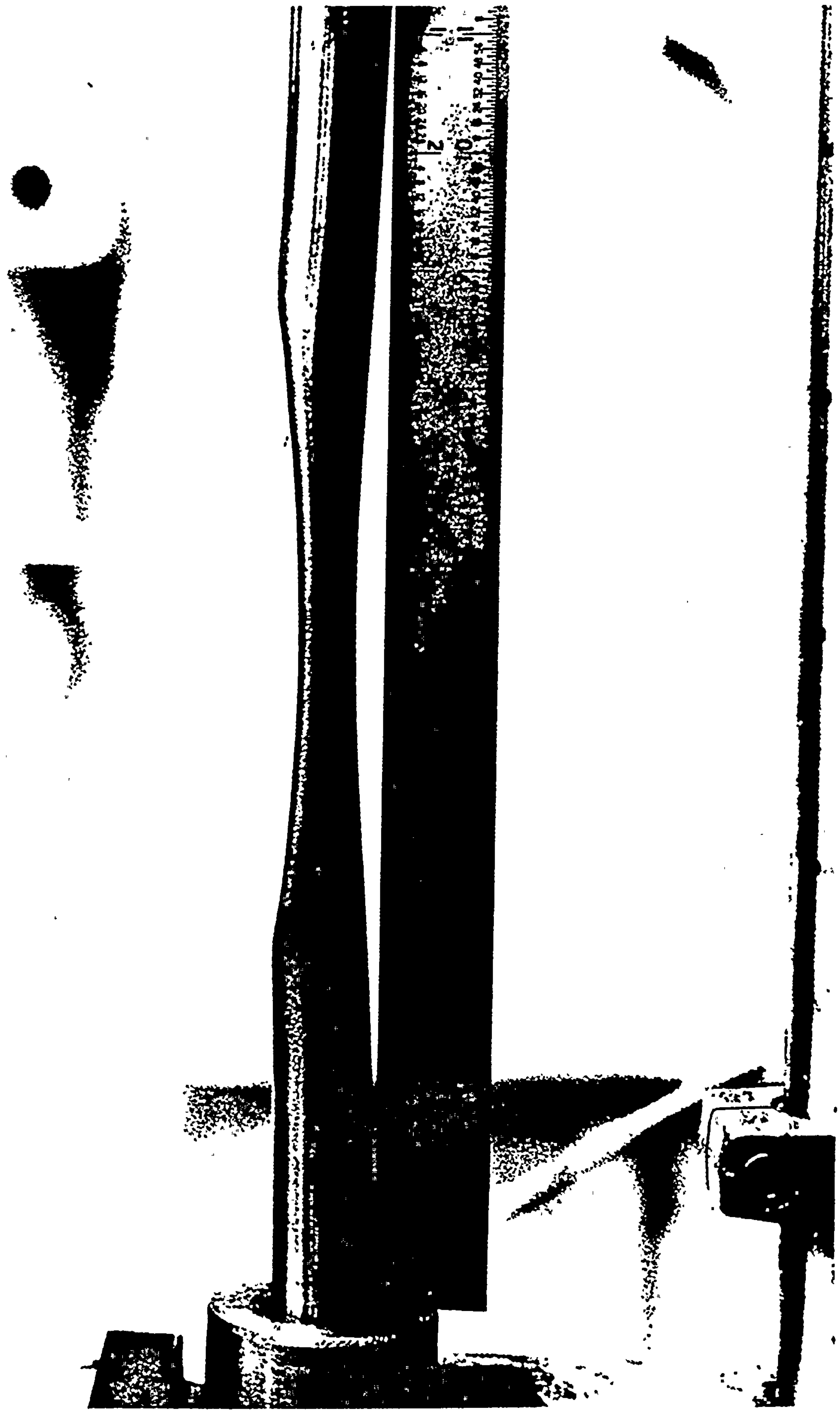


Figure C.6-1

PHOTOGRAPH OF TUBE SPEC. NO. 5
AFTER COLLAPSE UNDER EXTERNAL PRESSURE

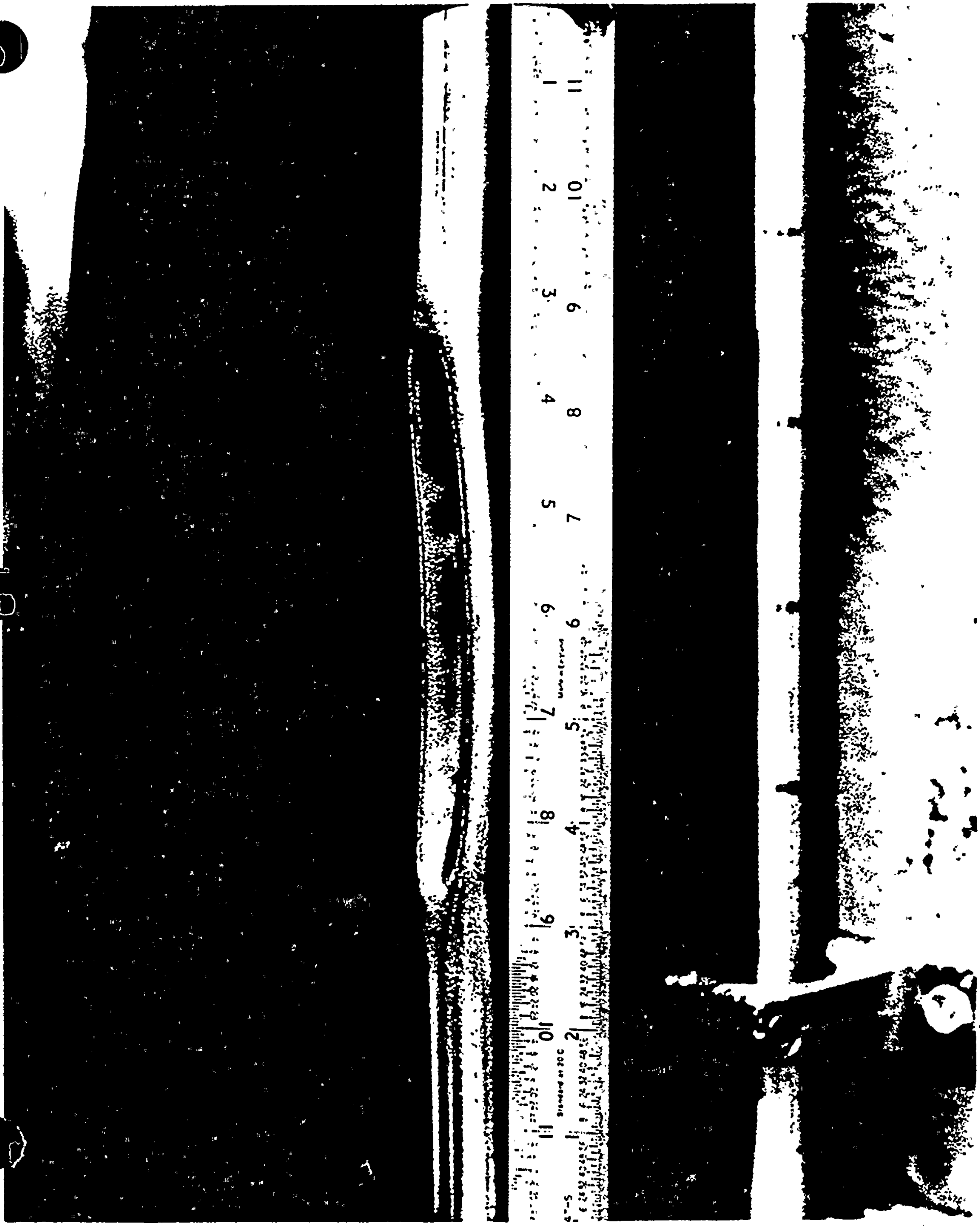


Figure C.6-2

PHOTOGRAPH OF TUBE SPEC. NO. 5
AFTER COLLAPSE UNDER EXTERNAL PRESSURE

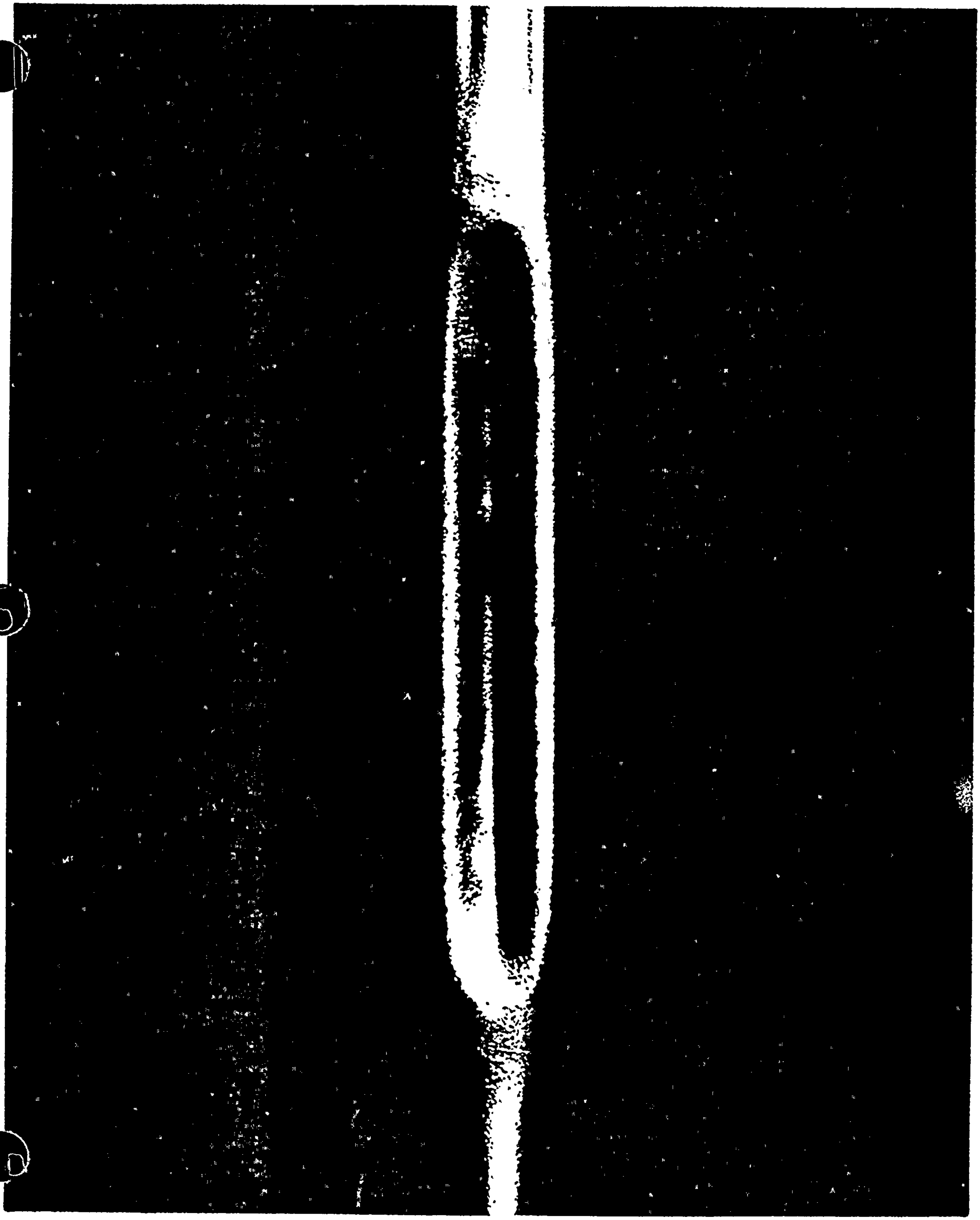
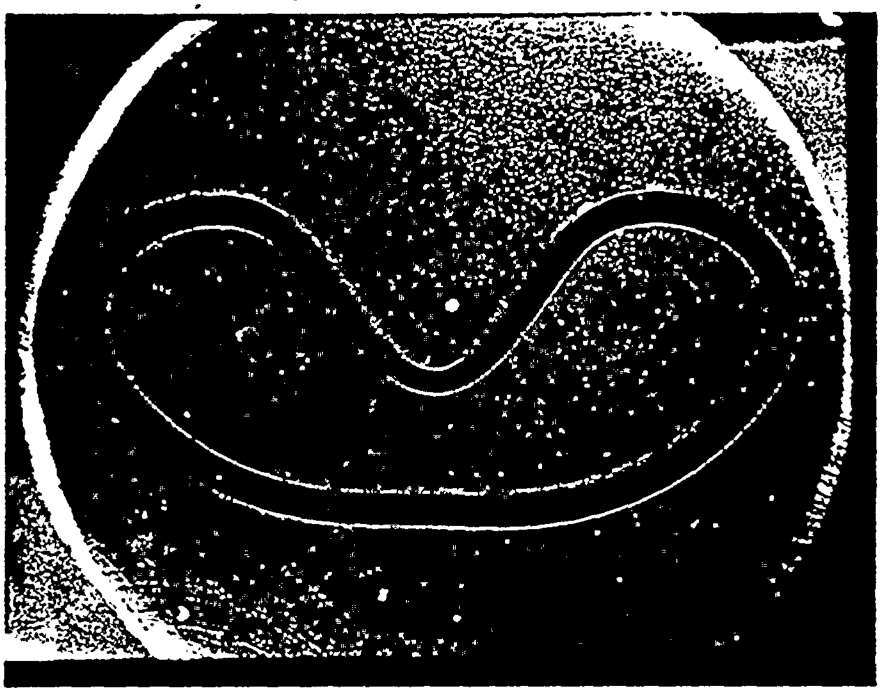


Figure C.6-3

PHOTOGRAPH OF TUBE CROSS SECTION AFTER COLLAPSE UNDER EXTERNAL PRESSURE



PHOTOGRAPH OF UNDAMAGED PORTION OF TUBE

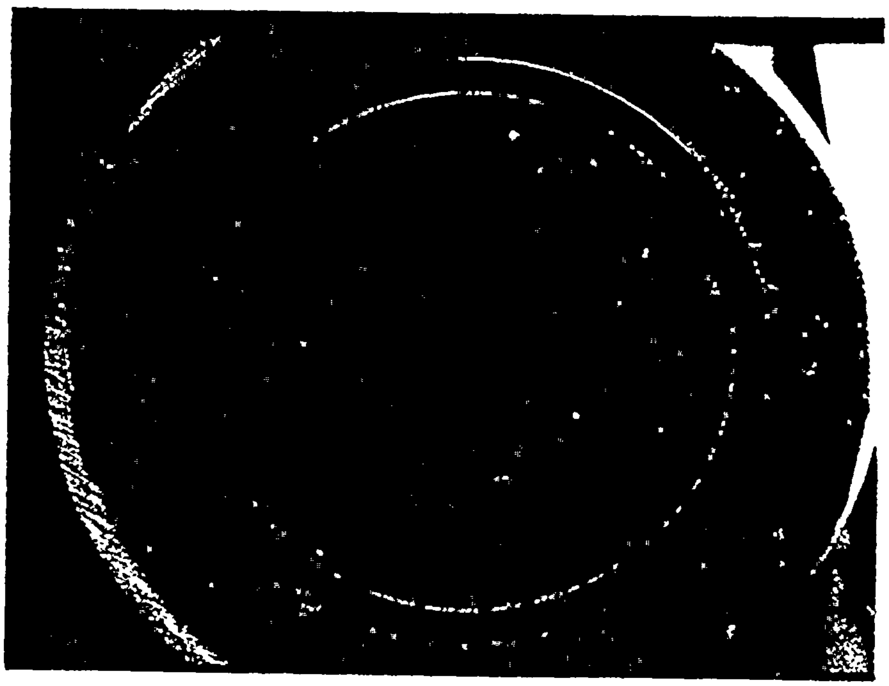
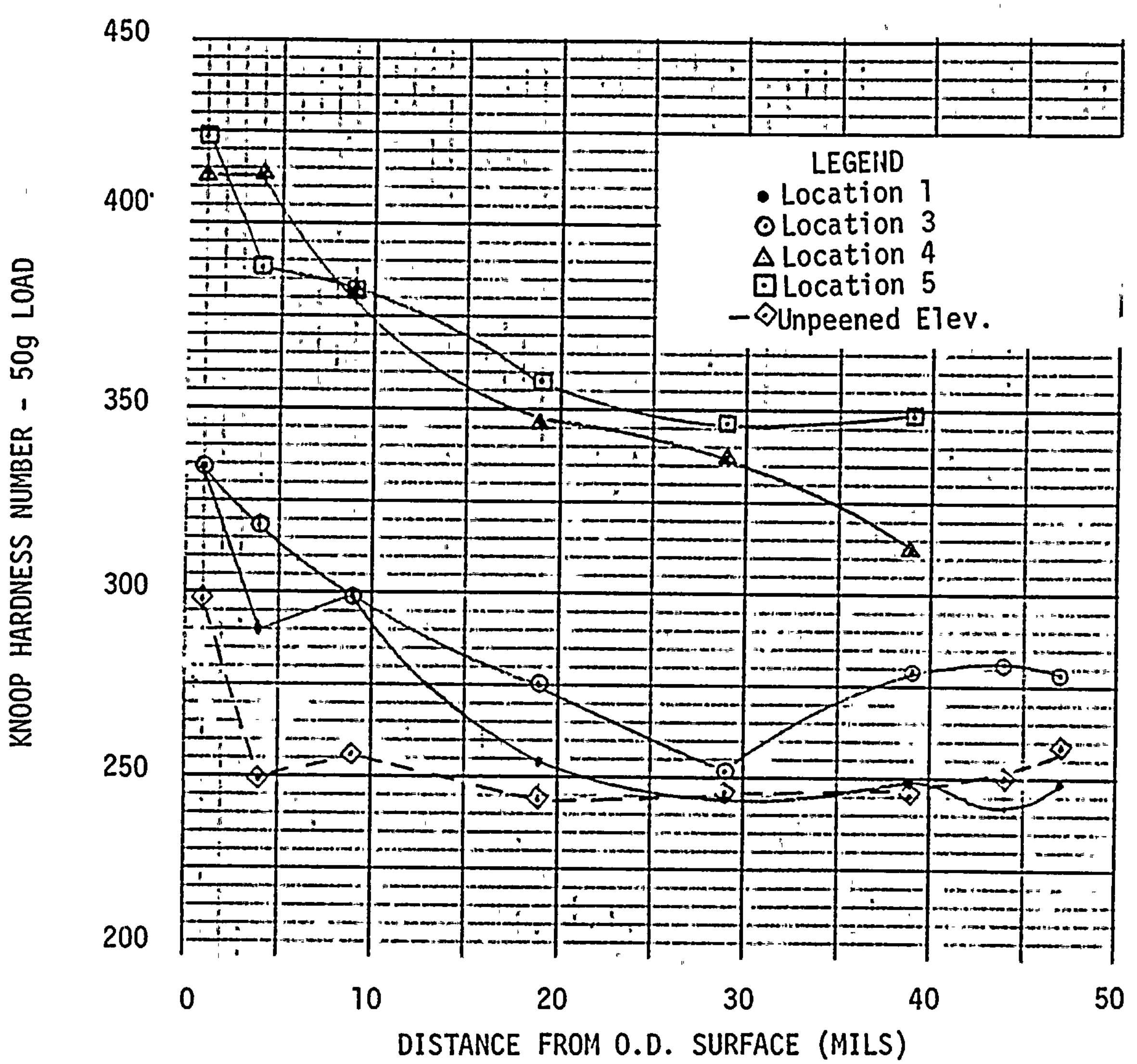
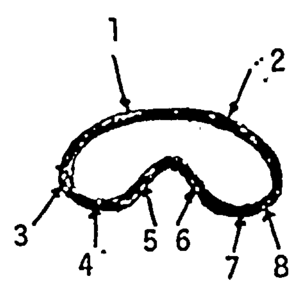


Figure C.6-4

HARDNESS VS. DISTANCE THROUGH TUBE WALL (COLLAPSED TUBE)



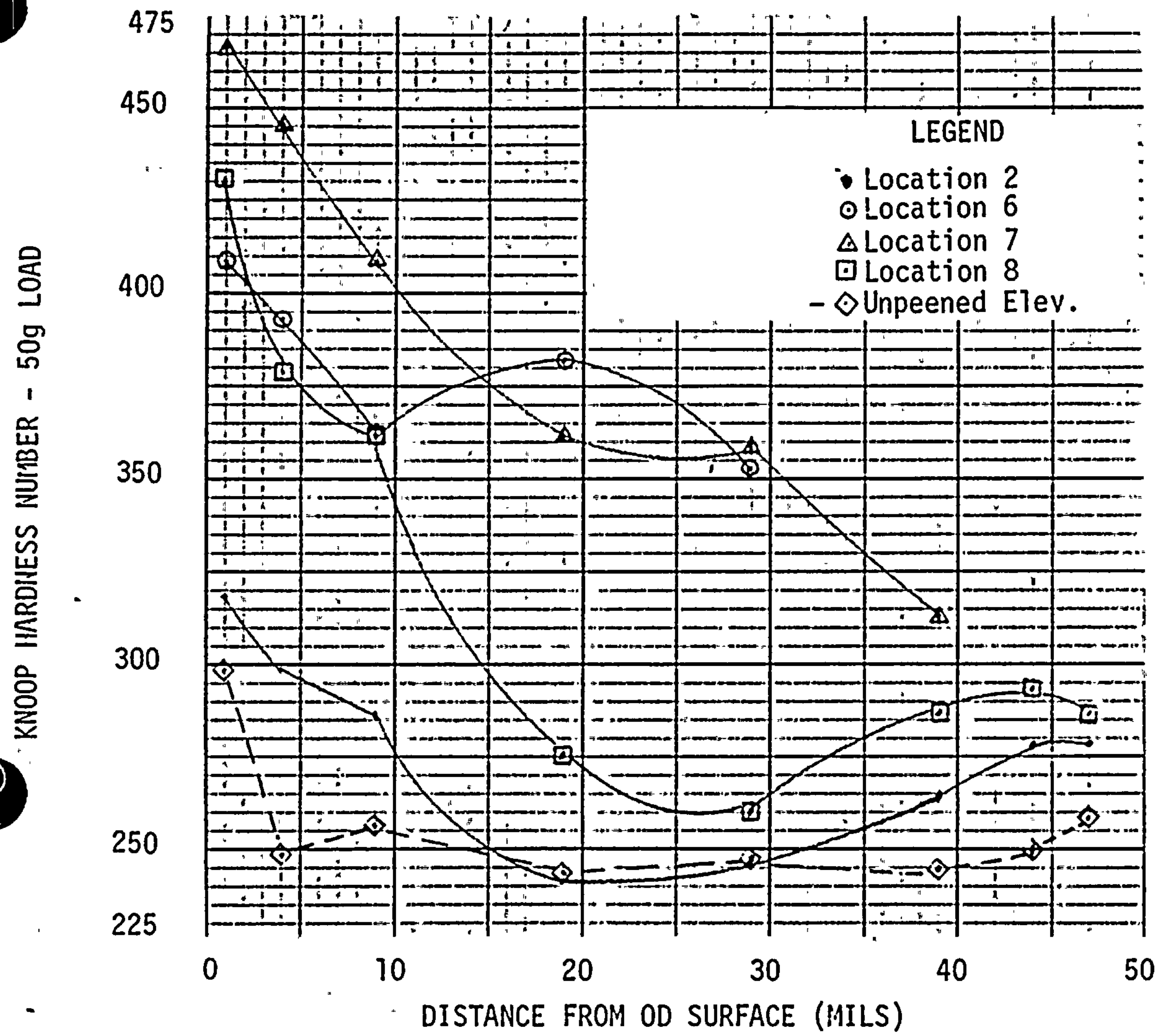
CROSS-SECTION OF COLLAPSED TUBE



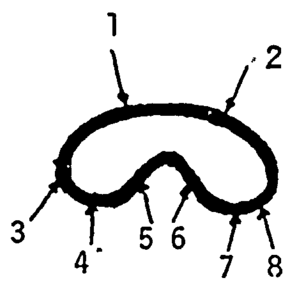
HARDNESS SURVEY LOCATIONS

Figure C.6-5

HARDNESS VS DISTANCE THROUGH TUBE WALL (COLLAPSED TUBE)



CROSS-SECTION OF COLLAPSED TUBE



HARDNESS SURVEY LOCATIONS

Figure C.6-6

CHARACTERIST CURVATURE OF TUBE
SPECIMENS DURING LOADING OPERATIONS

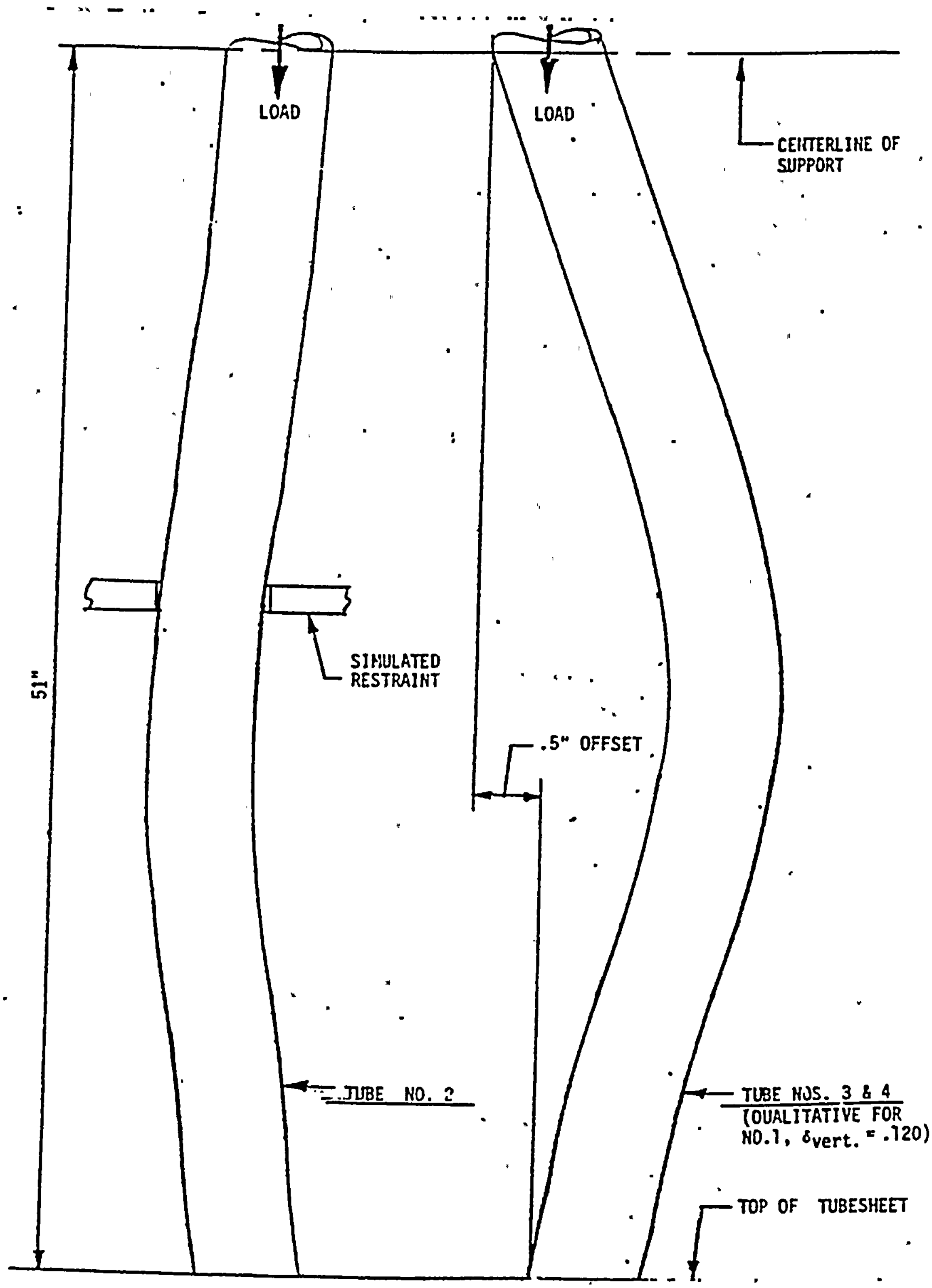


Figure C.6-7

C.7.0 EDDY CURRENT EXAMINATION OF GINNA STEAM GENERATOR EXTERNAL TUBE LOADING TEST

C.7.1 Objectives

The purpose of the eddy current examination of the tube loading test was to determine if mechanical deformation (axial loading, deflection, mechanical peening) would produce eddy current signals which could be interpreted as ID indications.

C.7.2 Eddy Current Equipment and Calibration

The equipment used in the inspection consisted of a Zetec MIZ 12 eddy current instrument with both magnetic tape and strip chart recorders, a Zetec A-720 in. diameter spring-flex probe. The calibration consisted of a certified Section XI standard and an ID pit standard with approximately 20%, 40%, 60% and 80% defects (Figure C.7-1) at a test frequency of 400 KHz. The procedure used in calibration was an attempt to duplicate, as closely as possible, the ISI inspections on the Ginna steam generators in 1976 and 1977. The .052 inch diameter thru wall hole in the Section XI standard was set at approximately 4 volts on the eddy current instrument as specified by Section XI of the ASME code for ISI.

Figures C.7-1 through C.7-8 summarize the results of the eddy current inspection.

C.7.3 Discussion

Eddy current testing showed some differences between baseline examinations and examinations conducted at the various axial loading, peening, and pressurization stages. The signals from tube number 3, for example, could possibly be interpreted as ID indications because of their phase, especially in view of tubes leaking in surrounding areas.

However, an increase in tube noise can cause a rotation of phase, out of noise plane, into ID or OD phase plane thus appearing as a very small ID or OD indication.

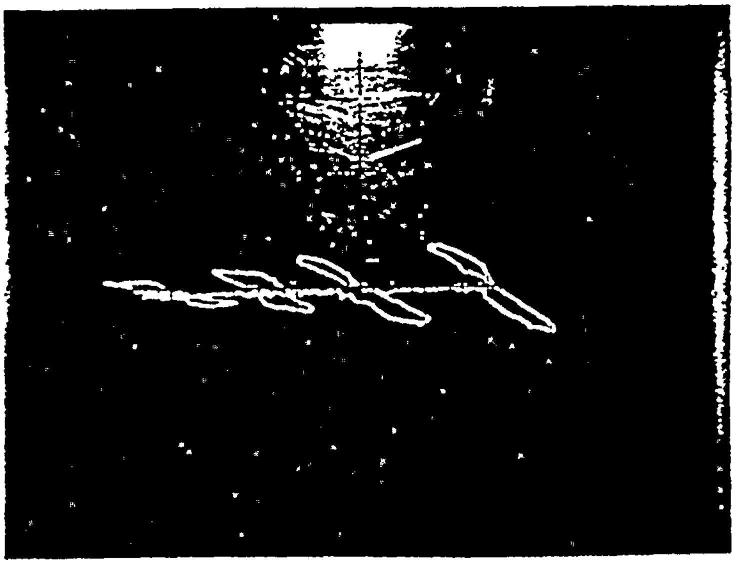
Another phenomenon observed during the eddy current inspection of the subject tubes, particularly the tubes taken to maximum lateral deflection, is dinging at support plate and tubesheet ares. This appears as a depression in the tube both at the top and bottom of the support plate and at the top of the tubesheet. This is caused by the bending action on the tube in the restrained areas as lateral deflection is affected.

Eddy Current Test Intervals and Observations

Tube No.	Testing Interval	Observations
1	Baseline	400 mv uniform background tube noise
1	.120" deflection	1.5 volt signal, 9° phase angle in ID phase angle (Figure C.7.3)
2	.120" deflection	No indications
2	.120" deflection & 1500 psi external pressurization	No indication
3	Baseline	500 mv uniform background tube noise
3	.630" deflection	multiple signals rorated into ID phase plane in area of greatest lateral deflection. (Figure C.7-4) voltage ranges from 1.25 volts to 4 volts phase angles are all 11°
3	.630" deflection	3.25 volt signal, 11° phase angle in ID phase plane aprpoximately 1/2" above tubesheet (Figure C.7-5)
3	3800 lbs tension load	very slight change in voltage of signals both at tubesheet or greatest lateral deflection
4	Baseline	700 mv uniform background tube noise
	every .030 to .630" deflection	No indications (Figure C.7-6)
5	Baseline	300 mv uniform background tube noise (Figure C.7-7)
5	.120" deflection	1.4 volt increase in tube noise over baseline in region of greatest lateral deflection. This tube noise did not rotate up into the ID phase plane
5	Tension load applied	Noise level in area of greatest lateral deflection reduced to 800 mv over background noise. (Figure C.7-8)
5	1500 psi external pressurization	No change (Figure C.7-8)

Figure C.7-1

CALIBRATION STANDARDS @ 400 KHz

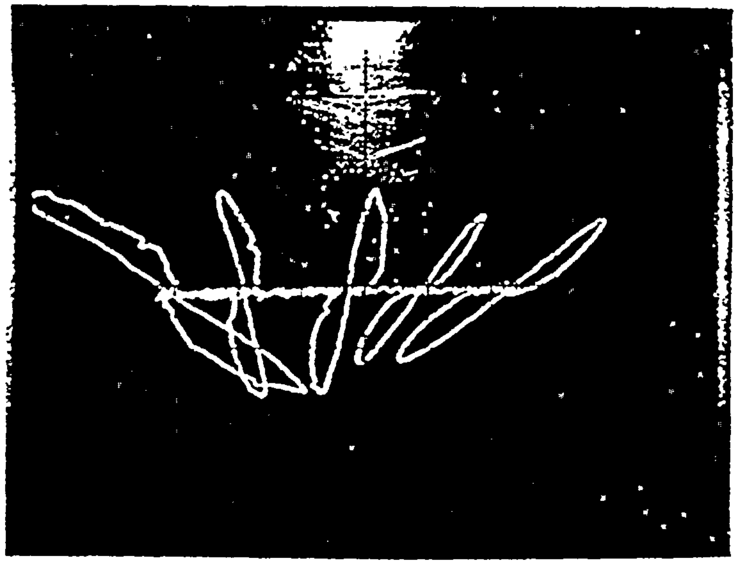


1 Volt/Div - Horizontal & Vertical

ID CALIBRATION

PHASE ANGLES:

20% - 11°
40% - 21°
60% - 29°
80% - 34°

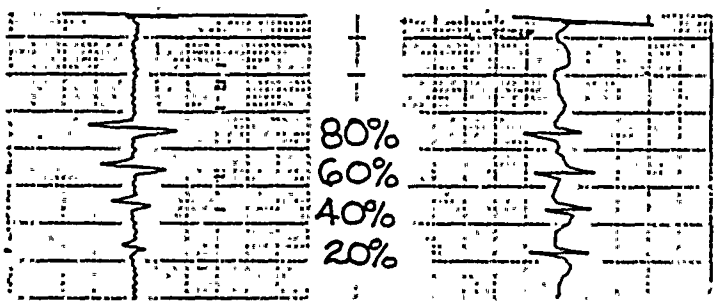


1 Volt/Div - Horizontal & Vertical

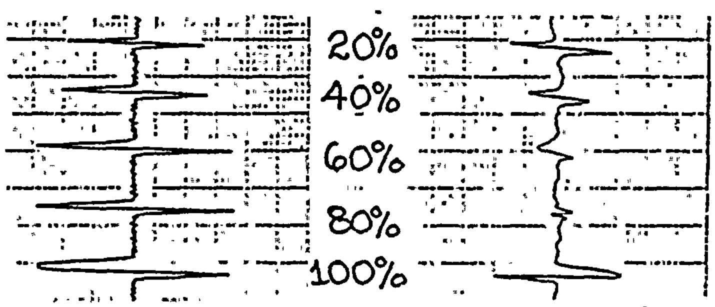
OD SECTION XI CALIBRATION

PHASE ANGLES:

20% - 145°
40% - 130°
60% - 102°
80% - 76°
100% - 36°



100 mv/Div 200 mv/Div

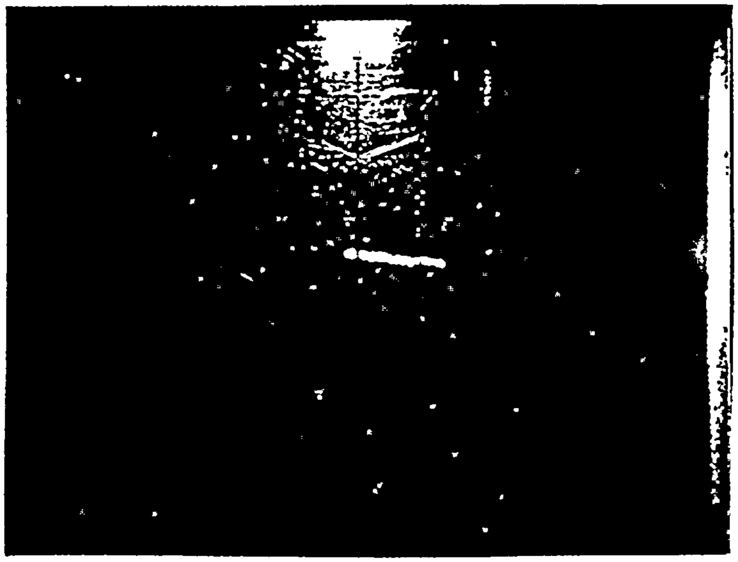


100 mv/Div 200 mv/Div

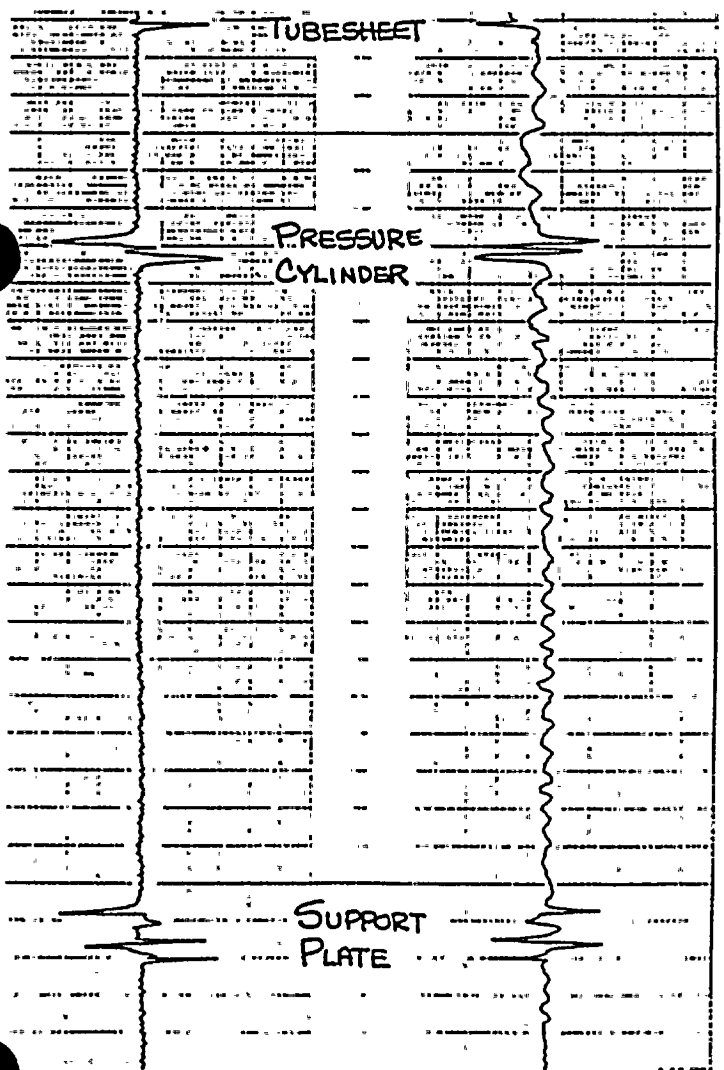
Figure C.7-2

INDICATION IN TUBE NO. 1 @ .120 in. AXIAL DEFLECTION

Area of max. Lateral Deflection.



1 Volt/Div. Both Horiz. & Vertical Phase Angle - 9°



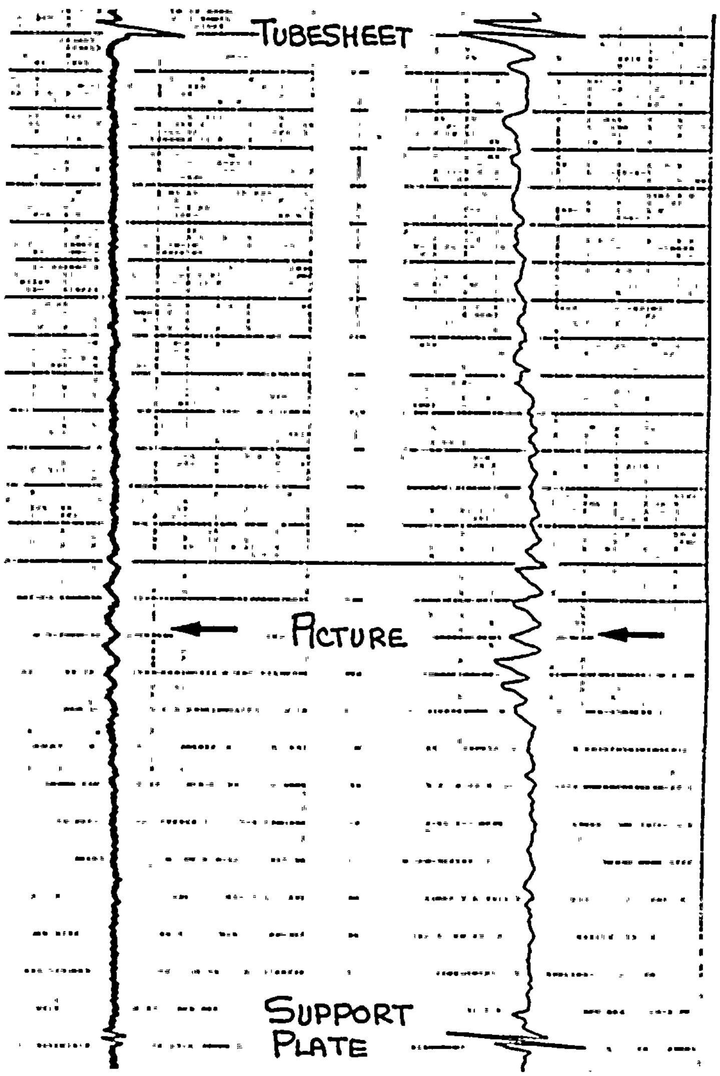
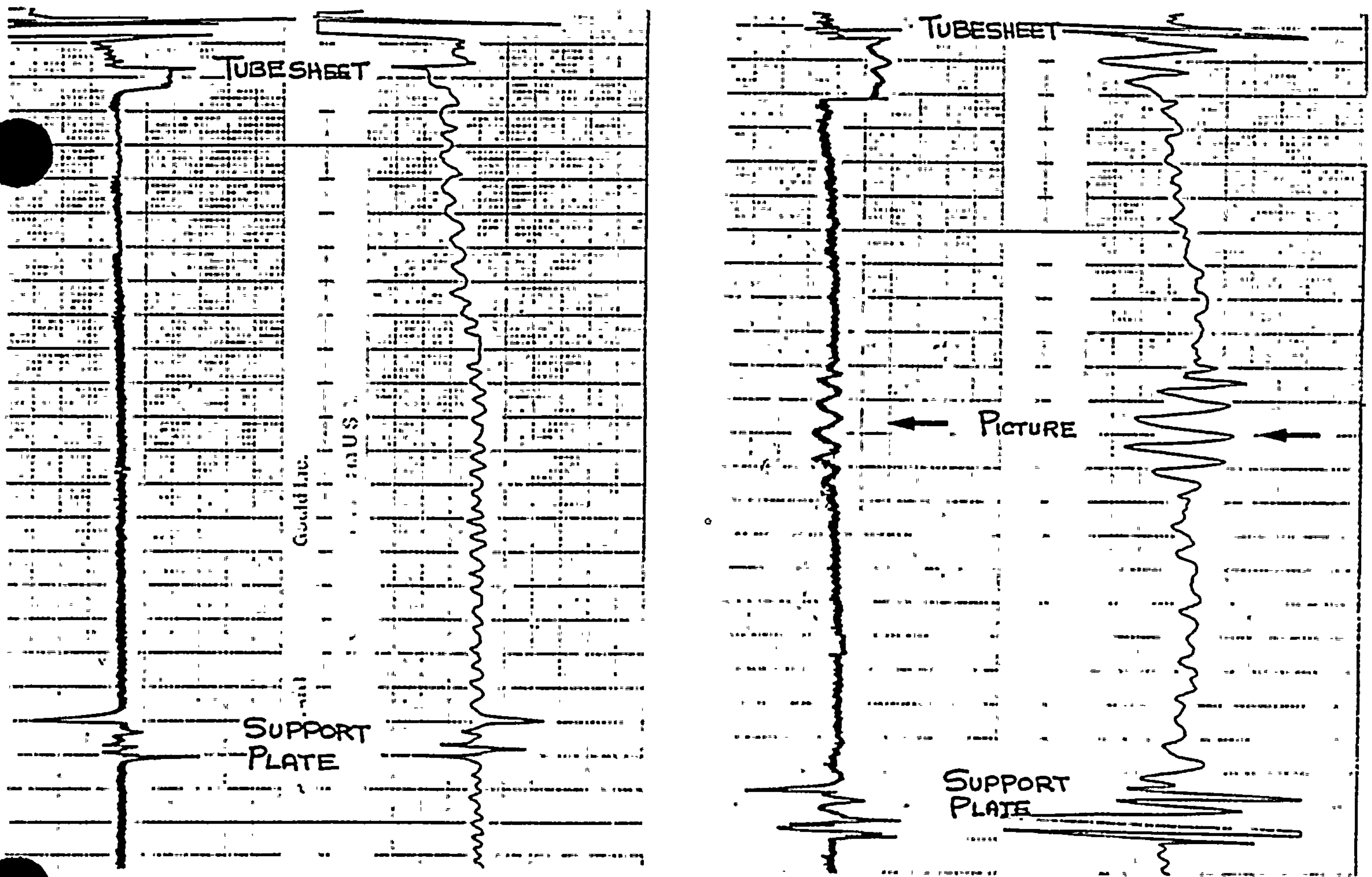


Figure C.7-3

INDICATIONS IN TUBE NO. 3. @ .630 IN. AXIAL DEFLECTION

Area of Max.
Lateral
Deflection

1 Volt/Div. Both
Horz. and Vertical
Phase Angles - 11°



100 mv/Div 200 mv/Div

Baseline

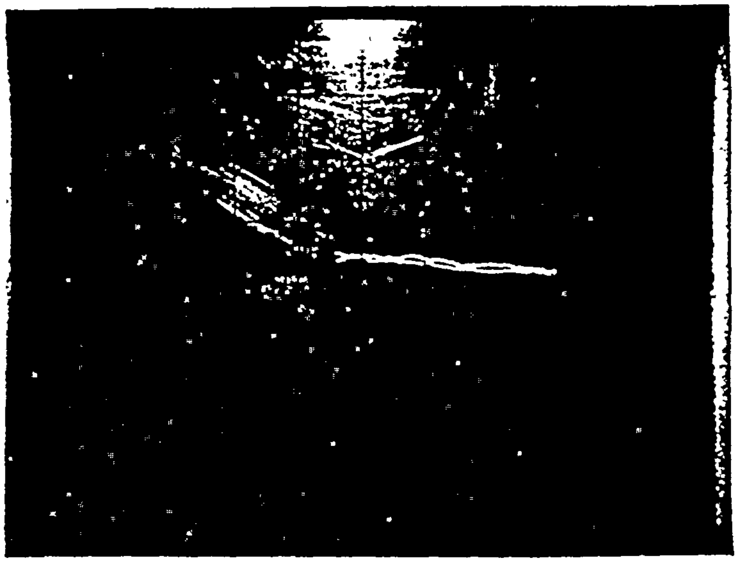
100 mv/Div 200 mv/Div

.630 in. Axial Deflection

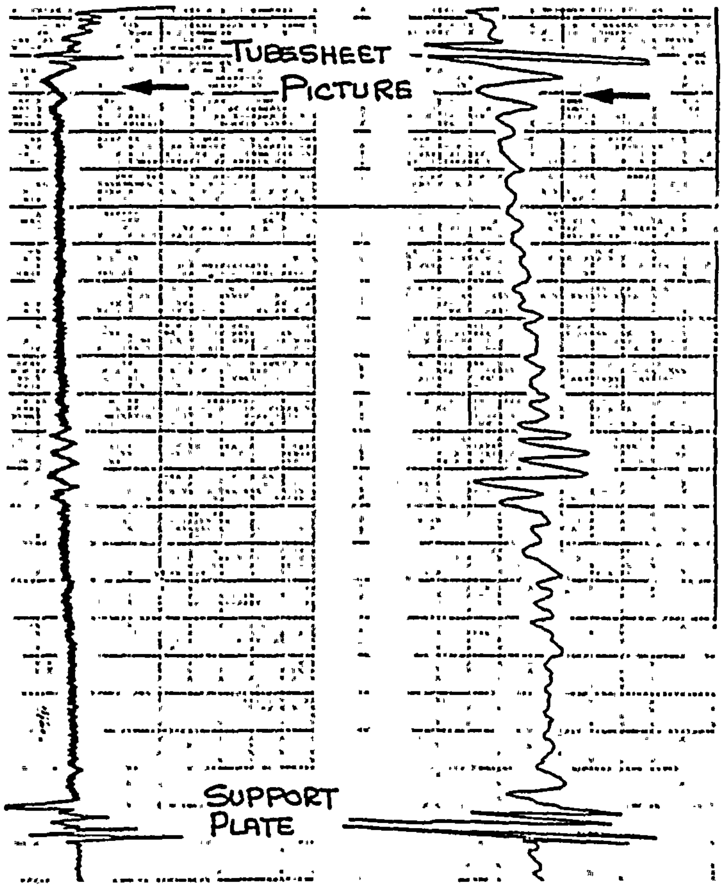
Figure C.7-4

INDICATION IN TUBE NO. 3 @ .630 IN. AXIAL DEFLECTION

Located Approx. 1/2 in. Above Tubesheet.



1 Volt/Div. Both Horizontal & Vertical
Phase Angle - 11°



100 mv/Div
200 mv/Div
.630 in. Axial Deflection

Figure C.7-5

9.0 REFERENCES

A. EPRI NP 1412 Final Report, "Examination of Steam Generator Tube RC45C52 from the Ginna Nuclear Power Plant," May 1980.

B. "Steam Generator Evaluation, Ginna Steam Generator Tube Failure Incident January 25, 1982," submitted by letter dated April 26, 1982 from John E. Maier to Dennis M. Crutchfield, USNRC.

C. CENC 1278, "Investigation of the Effects of a Tube Guide in a San Onofre Steam Generator," December 1976.

D. EPRI NP-2339 Final Report, "Application of an Eddy Current Technique to Steam Generator U-Bend Characterization," April 1982.

E. DE:82007999 Topical Report, "Buckling of the CRBRP Containment Vessel due to Localized Loads," May 1981.

F. "Collapse of Ductile Heat Exchanger Tubes with Ovality Under External Prssure," by A. Lohmeier, N.C. Small, H.J. Bonin and B. Gonnet, 2nd International Conference on SMIRT, Berlin, September 1973.

The explanation of the role which peening plays in tube collapse is not straight forward, but is a function of the cumulative effects of the tube's response to peening. Peening one side of a tube causes plastic flow in both the axial and circumferential directions. Plastic flow in the axial direction results in bowing outward toward the peened surface. Since the tube is constrained, however, by the fixity at the tubesheet, radial contraint at the support plates and possible axial constraint due to tube "lock-up" at the first support plate, bending moments develop which reach a maximum value at the tubesheet. Reference E discusses the effect of a "beam-type" bending moment on the inelastic behavior of a long circular cylinder.

Plastic flow in the circumferential direction, in combination with the bowing and restrained bending effect described above, cause considerable ovality in the tube cross-section in the peened region. Reference F discusses the effect of ovality on the external pressure required for collapse. For example, according to Figure 5 of Reference F, which is based on experimental data using Westinghouse Steam Generator tubing, an ovality of 10% would permit tube collapse at only 40% of the external pressure required to collapse perfectly round tubes. Considerable ovality was observed to occur due to tube peening with 3/16 inch steel balls in the CE test prior to tube collapse.

8.0 CONCLUSIONS

Based on the work performed thus far, which is documented in this test report, significant findings have been realized in the areas of eddy current test results and tube collapse under combined mechanical loadings.

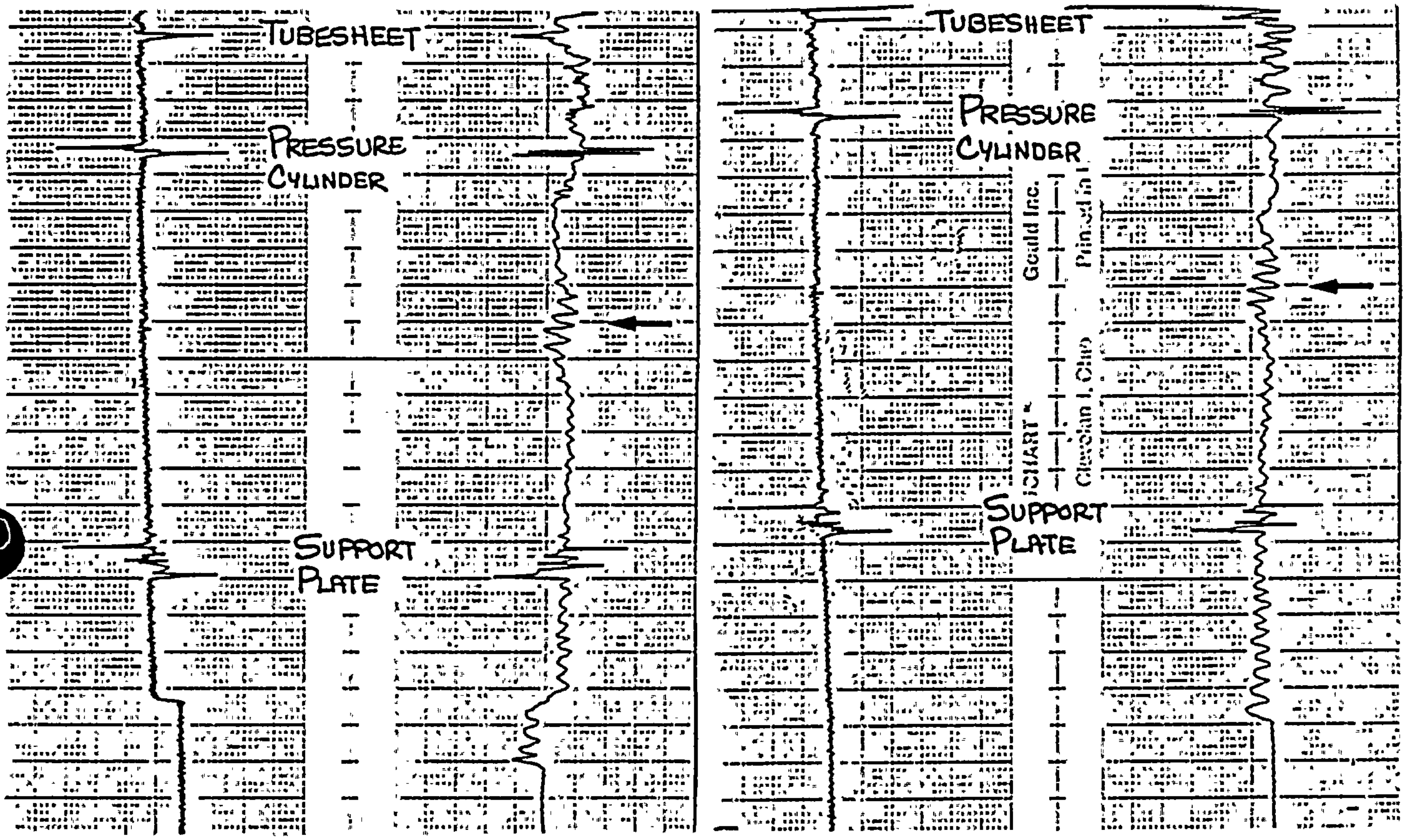
Since no I.D. tube defects have been found in tube samples removed from the Ginna B-Steam Generator, an alternative explanation for the eddy current indications observed, beginning in January 1976 for peripheral tubes, was sought. Samples examined include tube R45C52 which was removed in 1977 and was the subject of an EPRI study (Reference A). More recently a number of tubes have been removed from the Numbers 4 and 6 wedge areas for examination.

Since most tube indications which occurred on the periphery of the tube bundle were located near tube support plate wedge areas, axial loading may have had some influence on the eddy current findings. Thus far in this test, CE has found distinct eddy current signals in 2 of 5 tubes examined which resembled I.D. defect signals and could be directly attributed to axial compressive load. A detailed discussion of these results is contained in Section C.7.0 of this report. Since the indications found in tube No. 1 of this test program were observed after the tube was removed from the test fixture and under no load, it must be concluded that the eddy current signals are related to plastic tube deformation.

The signals observed in this test are similar to those presented in Reference D, Figures 3-9 through 3-12, which were associated with a slight "bulge" near the "opposite transition" of a small radius U-bend tube. The examination of tube R45C52, as documented in Reference A, also revealed a slight "bulged" area. However, since the same axial compressive loading did not always produce the characteristic eddy current signal in the tubes tested, this phenomenon is not yet totally understood. It was the consensus of experienced CE eddy current specialists that the signals observed in this test originally could have been interpreted as shallow depth I.D. indications, given the state-of-the-art of single frequency eddy current testing in 1976 through 1978.

Based on "loose parts" flow testing conducted in 1976 at CE, as documented in Reference C, it was strongly suspected that "peening" of the tubes on the periphery of the bundle played a significant role in tube collapse which was the first step in the process leading to the tube rupture. The first sample "peened", using 3/16 inch diameter steel balls such that the cold work through thickness profile was simulated, did in fact collapse under 1500 psi of external pressure. Section C.6.0 of this report documents the test procedure which led to collapse. Figures C.6-1, C.6-2, and C.6-3 bear a striking resemblence to the collapsed Ginna Steam Generator tubes.

TUBE NO. 5 AFTER TENSION LOAD AND STRAIGHTENING

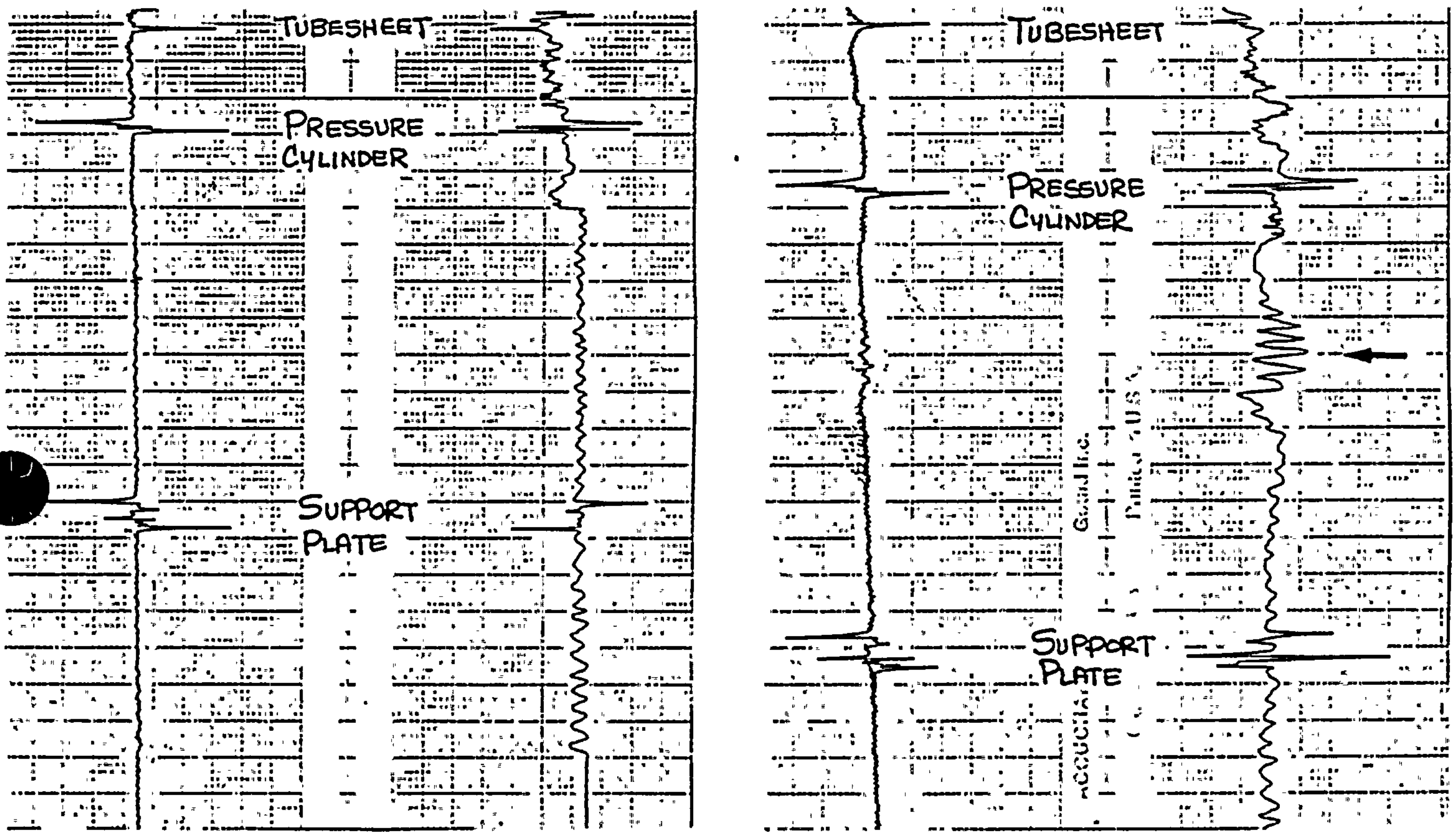


100 mv/Div 200 mv/Div 100 mv/Div 200 mv/Div

Tension Load Applied 1500 psi External Pressure

Figure C.7-8

TUBE NO. 5 BASELINE TO .120 IN. AXIAL DEFLECTION



100 mv/Div 200 mv/Div

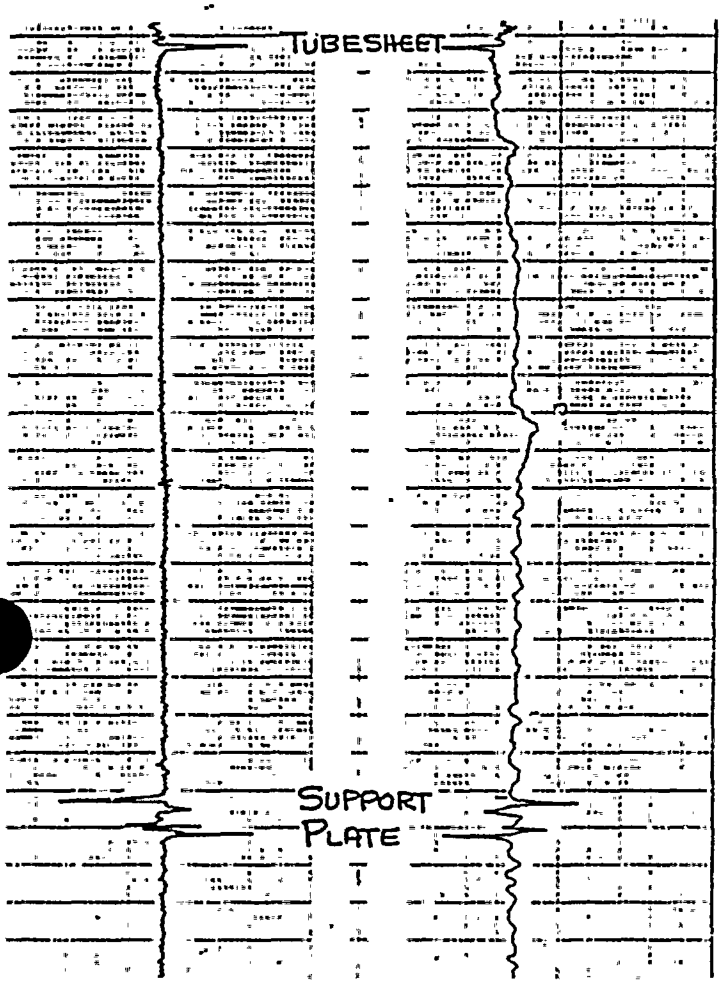
Baseline

100 mv/Div 200 mv/Div

.120 in. Axial Deflection

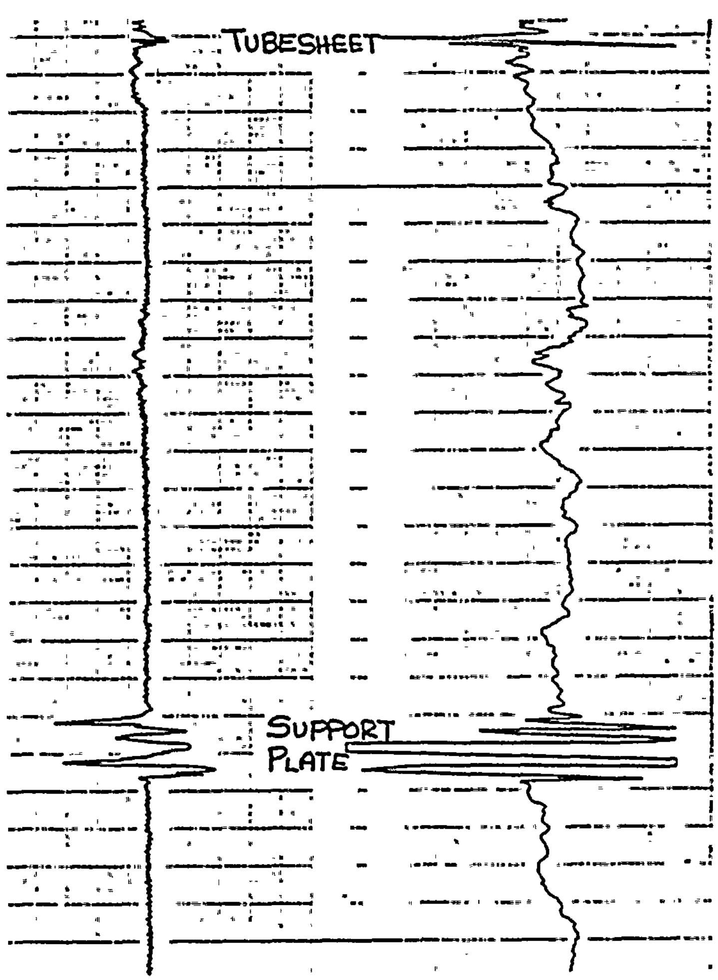
Figure C.7-7

TUBE NO. 4 BASELINE TO .630 IN. AXIAL DEFLECTION



100 mv/Div 200 mv/Div.

Baseline



100 mv/Div 200 mv/div

.630 in. Axial Deflection

Figure C.7-6