TID-5699

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CYCLIC PRESSURE TESTS OF LARGE SIZE PRESSURE VESSELS

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Contract No. AT(30-1)-2140
PROJECT NO. 773-2
Progress Report Number 17

Prepared for

Reactor Development Division
U. S. Atomic Energy Commission

15 March 1960

APPROVED:

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Department of Structural Research

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I. INTRODUCTION

This investigation into the plastic fatigue strength of large size pressure vessels is a part of a general research program on plastic fatigue problems in pressure vessels which is being carried out at several laboratories. The vessels under study at SwRI have a 36 inch I.D. and 2 inch wall thickness, and contain nozzles of several designs and sizes. The overall program includes essentially identical pairs of full size vessels fabricated from A-201, A-302, and T-1 steels.

Stress analysis and fatigue cycling on the No. 1, A-201 vessel have been completed, and fatigue cycling of the second vessel at 2650 psi is in progress. Fabrication of the A-302 vessels is also in progress.

Stress concentration factors determined in the static stress analysis, initial cycling, and results of plastic fatigue tests will be correlated with results of related studies at l'Ecole Polytechnique, Lehigh University, and the University of Illinois.

This report covers the progress in the period from 15 February to 15 March 1960.

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II. PROGRESS DURING REPORT PERIOD

A. No. 1, A-201 VESSEL (With No. 1 Nozzle)

1. Additional Stress Measurements

At the request of the Subcommittee on Reinforced Openings, additional stress data was obtained for Nozzle 3, which is the radial nozzle in the bottom head, in order to make certain that there were no stress peaks in between the points for which stress measurements were made on the outside of the nozzle along the line corresponding to $\alpha = 0°$, or $\alpha = 45°$. Figures 1 and 2 are plots of the principal stresses on the exterior of Nozzle 3 for $\alpha = 0°$ and $\alpha = 45°$, respectively. These curves show both the original curves contained in Progress Report No. 12 and the curves which have been faired in light of the additional data. It is noted that the original peak stress still represents the maximum stress, and that there were no stress peaks in between the origin points. However, the refaired curve does show a somewhat steeper stress gradient than indicated on the original curves.

2. Continuation of Cyclic Testing

Cyclic testing was resumed after making weld repairs on Nozzle 1 at the end of 7223 cycles. At the end of 7516 cycles, a major crack failure occurred, originating at Nozzle 6 on the longitudinal plane in the vicinity of the corner radius and propagating on both sides of the nozzle. Figures 3, 4, and 5 are photographs of the cracked vessel. It should be noted that the

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crack was remote from the longitudinal seam of the vessel. Since the vessel was beyond repair, it was removed from the pit and the second A-201 vessel was prepared for testing.

B. NO. 2, A-201 VESSEL (No. 1 Nozzle Omitted)

1. Check Measurements on Accuracy of Stress Concentration Factors for the Full Size Vessel

In order to rigorously check the accuracy of the value of the stress concentration factor for Nozzle 2 obtained on the No. 1 vessel, Nozzle 2 on the No. 2 vessel was instrumented with foil gages placed in identical locations to those on the No. 1 vessel. Three independent runs were made: two with the Gilmore Strain Plotter which was used to obtain all previous stress data, and one using a Baldwin Strain Indicator of known reliability. The S.C.F.'s computed from these data are summarized in Table I, along with the S.C.F. obtained for the same nozzle on the No. 1 vessel. It is noted that the values obtained from the Gilmore Strain Plotter are in good agreement with the values obtained independently with the Baldwin Strain Indicator. It is also noted that the values obtained from the No. 2 vessel, ranging from 2.8 to 3.0 are considered to be in good agreement with the value of S.C.F. = 3.14, at $\alpha = 0°$ previously obtained from the No. 1 vessel, the agreement being within 6.0% at the point on the corner radius, using the average of the $\alpha = 0°$ values for the No. 2 vessel. This agreement appears especially good in view of the possible fabrication and materials differences between the two vessels. Also, 1/8" rosette gages rather than 1/16" gages were used on the No. 2 vessel, which could also account for the slightly lower value. Six percent is considered within the inherent limits of accuracy of the strain gage technique. The above checks confirm both the accuracy and the repeatability of the stress measuring techniques and instrumentation.

2. Investigation of Effect of Corner Radius on S.C.F.

In Table II is summarized the stress measurements and S.C.F.'s before and after the nozzle radii, for Nozzles 2 and 6, were increased from 1/2 inch to 1 inch in the vicinity of $\alpha = 180°$. It is noted from the data for $\alpha = 0°$, that the effect of grinding at $\alpha = 180°$ had but a negligible effect on the stress distribution at $\alpha = 0°$. Consequently, the values of S.C.F.'s obtained from Nozzle 6 at $\alpha = 0°$ and 180° should be representative of the values which would have been obtained on two individual nozzles, one having a 1/2 inch radius, the other having a 1 inch corner radius all around. It is also noted from Table II that increasing the radius from 1/2 inch to 1 inch decreases the S.C.F. from 2.84 to 2.60, or about 8.5%.

3. Redistribution of Strain Measurements

In order to determine the magnitude of strain redistribution or hysteresis developed during initial cycling at the nominal cyclic test pressure of 2650 psi for the No. 2, A-201 test vessel, electric resistance strain gages were installed on the corner radii of Nozzles 2, 6, and 8, as well as the membrane area of the shell. A 10,000 psi capacity Baldwin pressure transducer, accuracy ± 1/4%, was included in the instrumentation to provide a continuous measurement of pressure. The signals from the strain gages and pressure transducers were recorded on a 12-channel Heiland Visicorder. Figure 6 is a photograph showing the instrumentation set-up.

Figures 7, 8, and 9 are plots of the circumferential corner radius strains for Nozzles 2, 6, and 8 versus cycles. It is noted that the hysteresis loop completely disappears after the application of only one cycle. All subsequent cycles merely retraced the unloading curve for the first cycle - indicating completely elastic action up to the maximum cyclic test pressure of 2650 psi. The strains in the membrane were found, as would be expected, to be completely elastic with no hysteresis loop whatever.

The nominal cyclic test pressure for the redistribution study, and subsequent fatigue cycling, was arrived at on the basis of the pressure required to produce failure in the vessel after 100,000 cycles of loading, as determined from the A-201 Lehigh cantilever beam test results which are plotted in Figure 1 of Progress Report No. 14.

Using a maximum strain concentration factor of 3.7, the limiting membrane stress was established on the basis of the relation

$$\text{Limiting Membrane Stress} = \frac{\text{Strain Range}}{\text{Strain Concentration Factor}} \times \text{Young's Modulus}$$
$$= \frac{.0031}{3.7} \times 30 \times 10^6$$
$$= 25{,}200 \text{ psi}$$

The internal cyclic pressure, corresponding to the above limiting stress was then found from Lamé's formula to be

$$\frac{1000}{9530} \times 25{,}200 = 2650 \text{ psi}$$

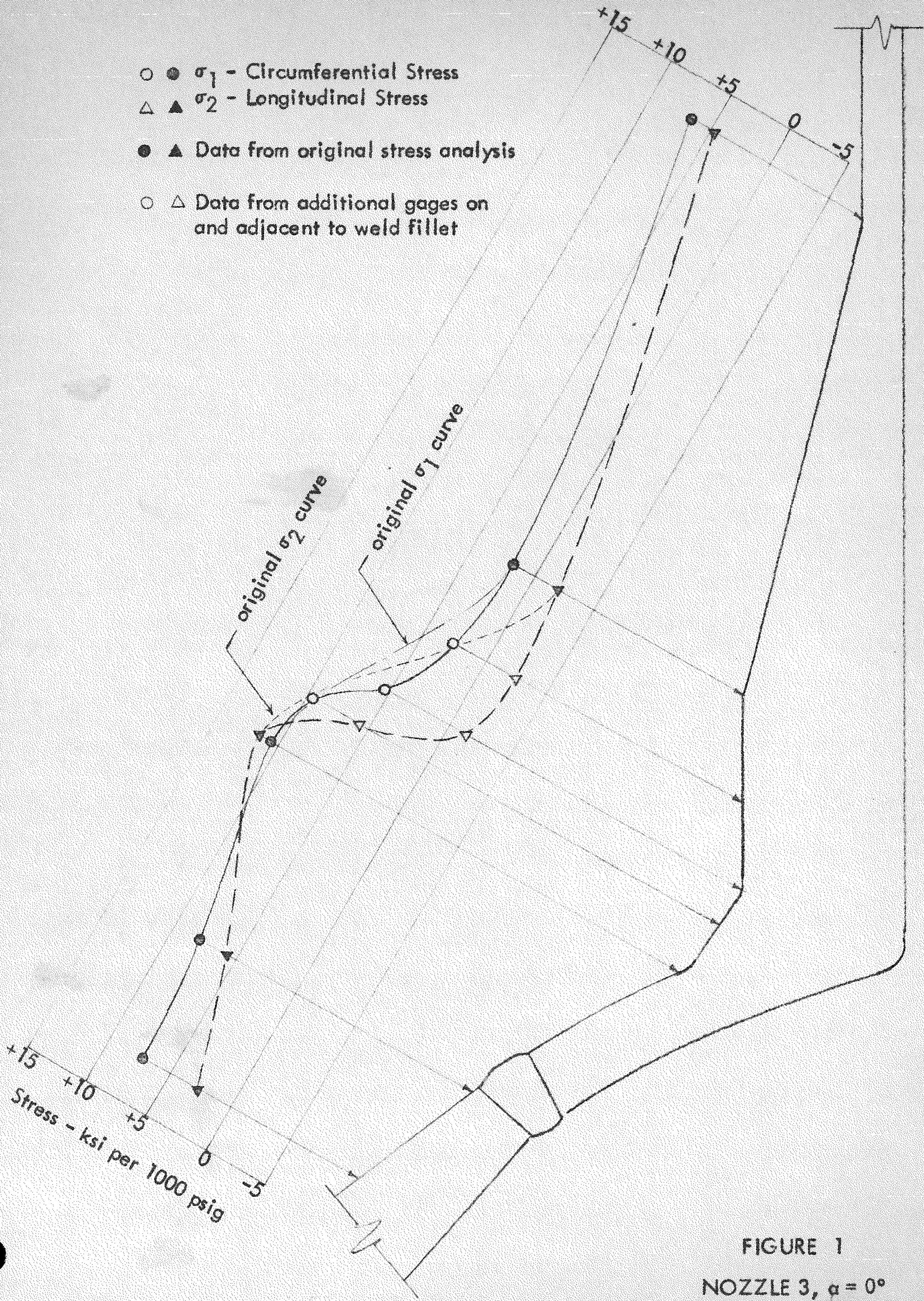

FIGURE 1

NOZZLE 3, $\alpha = 0°$
(Exterior Surface)

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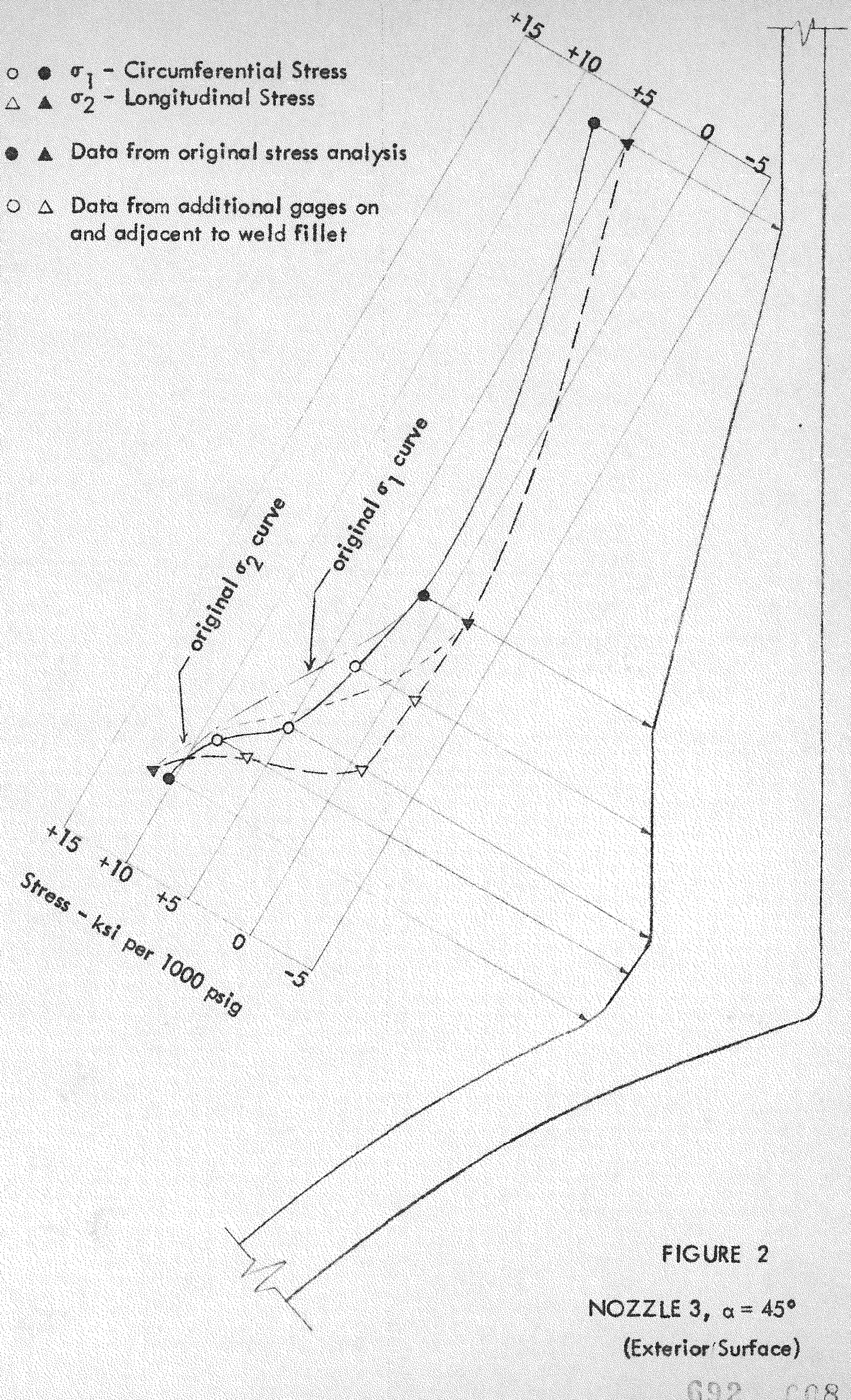

FIGURE 2

NOZZLE 3, α = 45°

(Exterior Surface)

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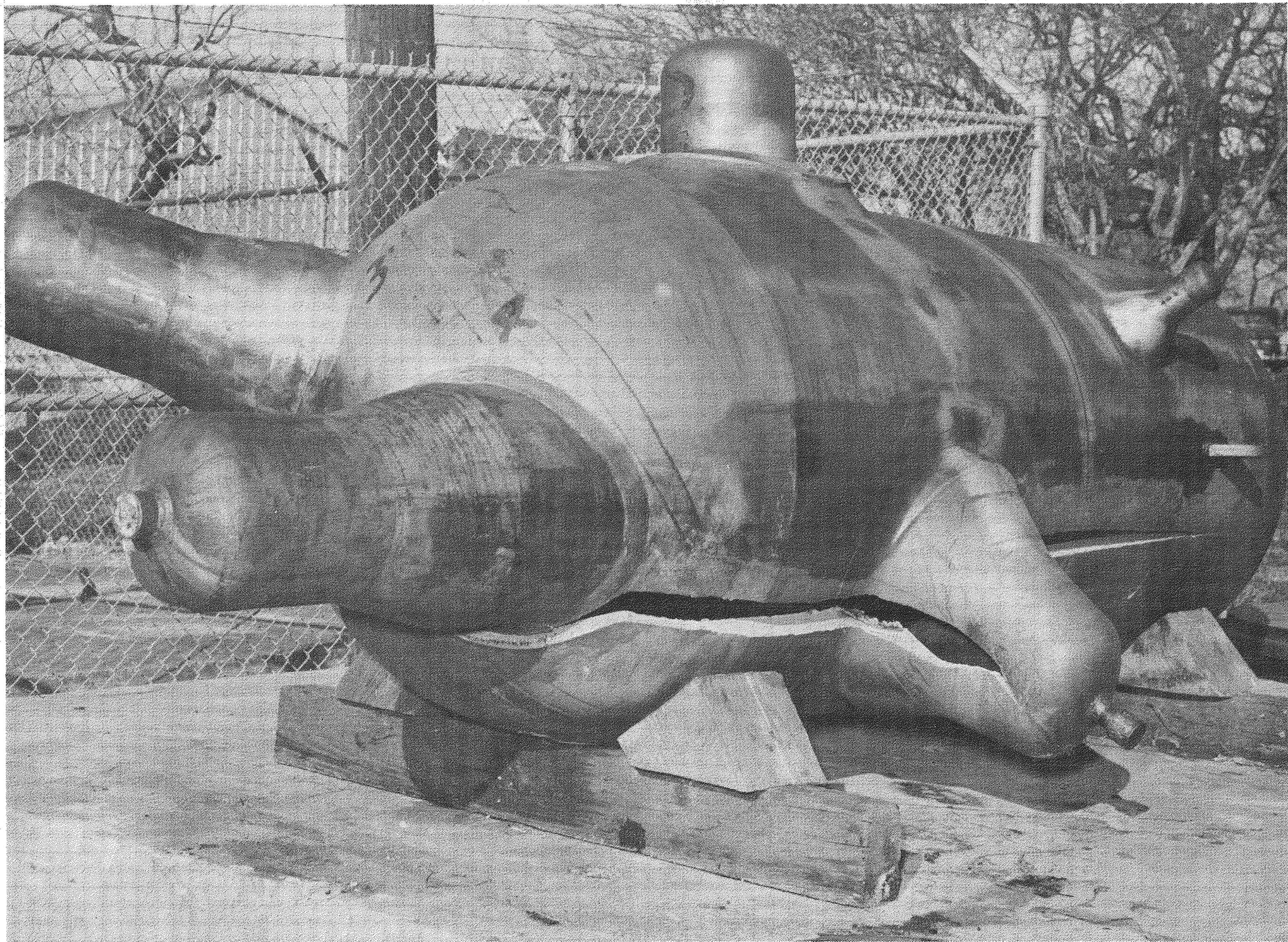

FIGURE 3. Fracture Through Nozzle No. 6 of the No. 1 A-201 Vessel

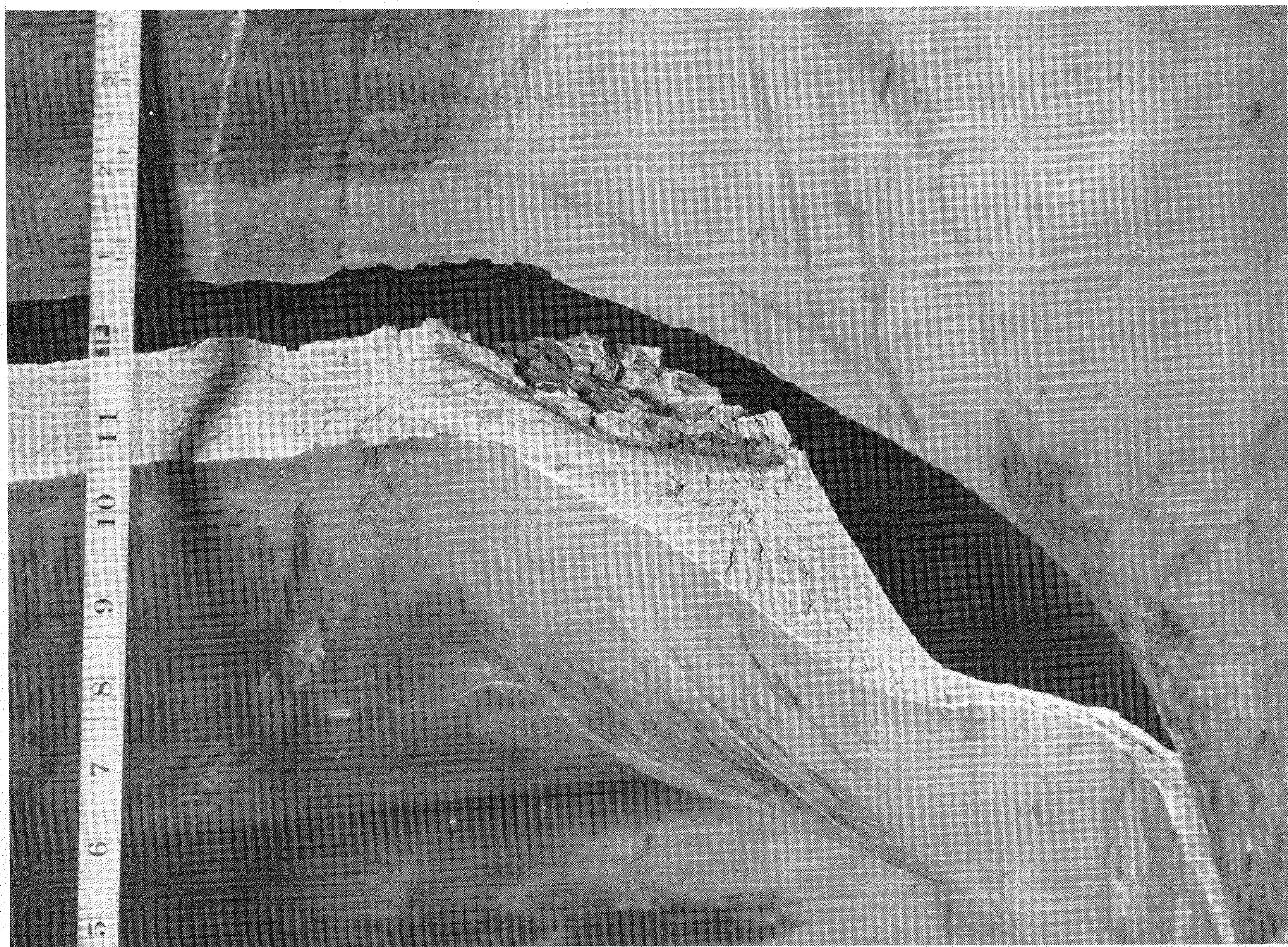

FIGURE 4. Close-up of Fracture, Nozzle No. 6, Showing Weld Repair Zone in Vicinity of Corner Radius

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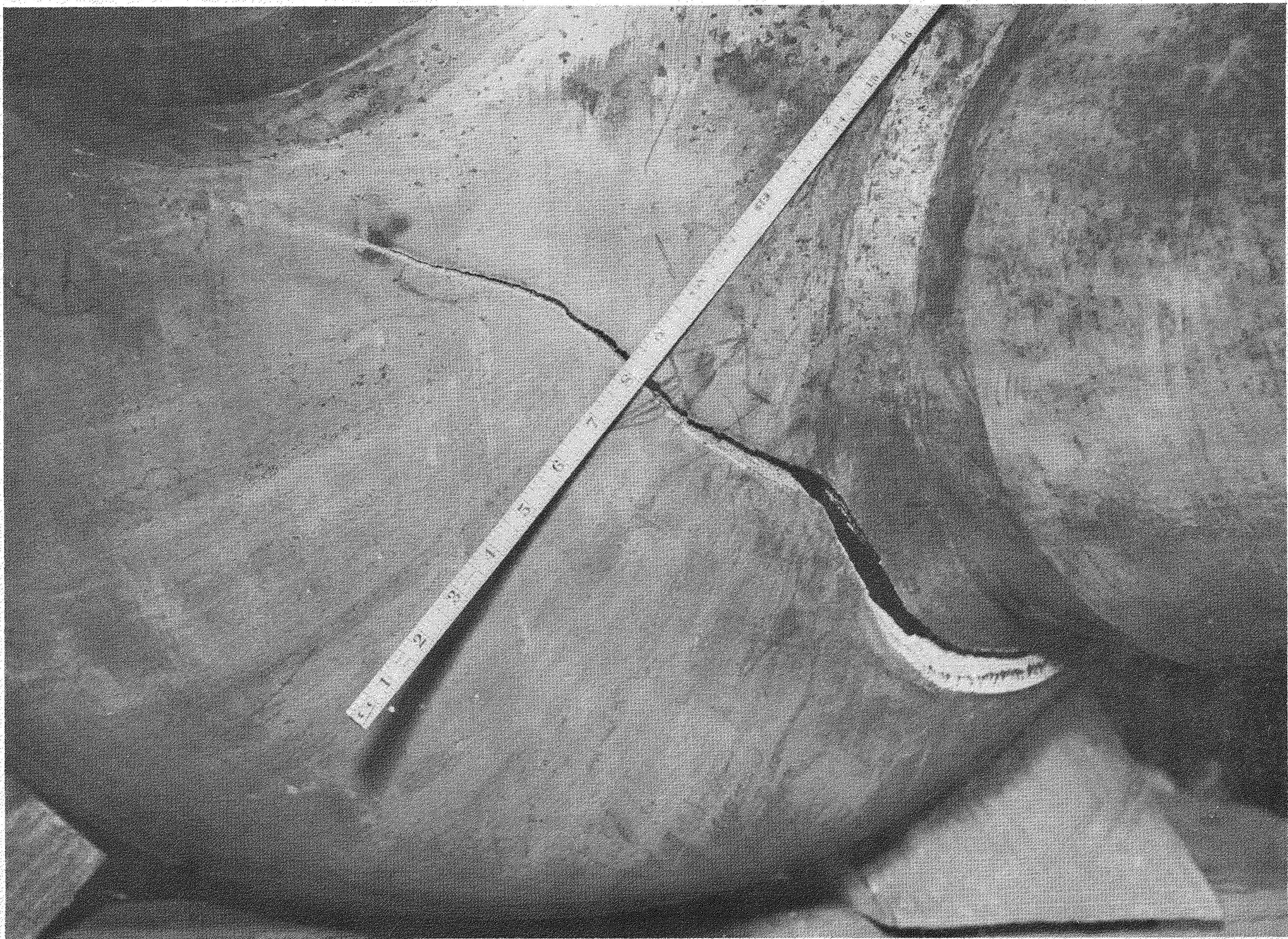

FIGURE 5. Path of Fracture Along Bottom Head in Vicinity of Nozzle No. 4

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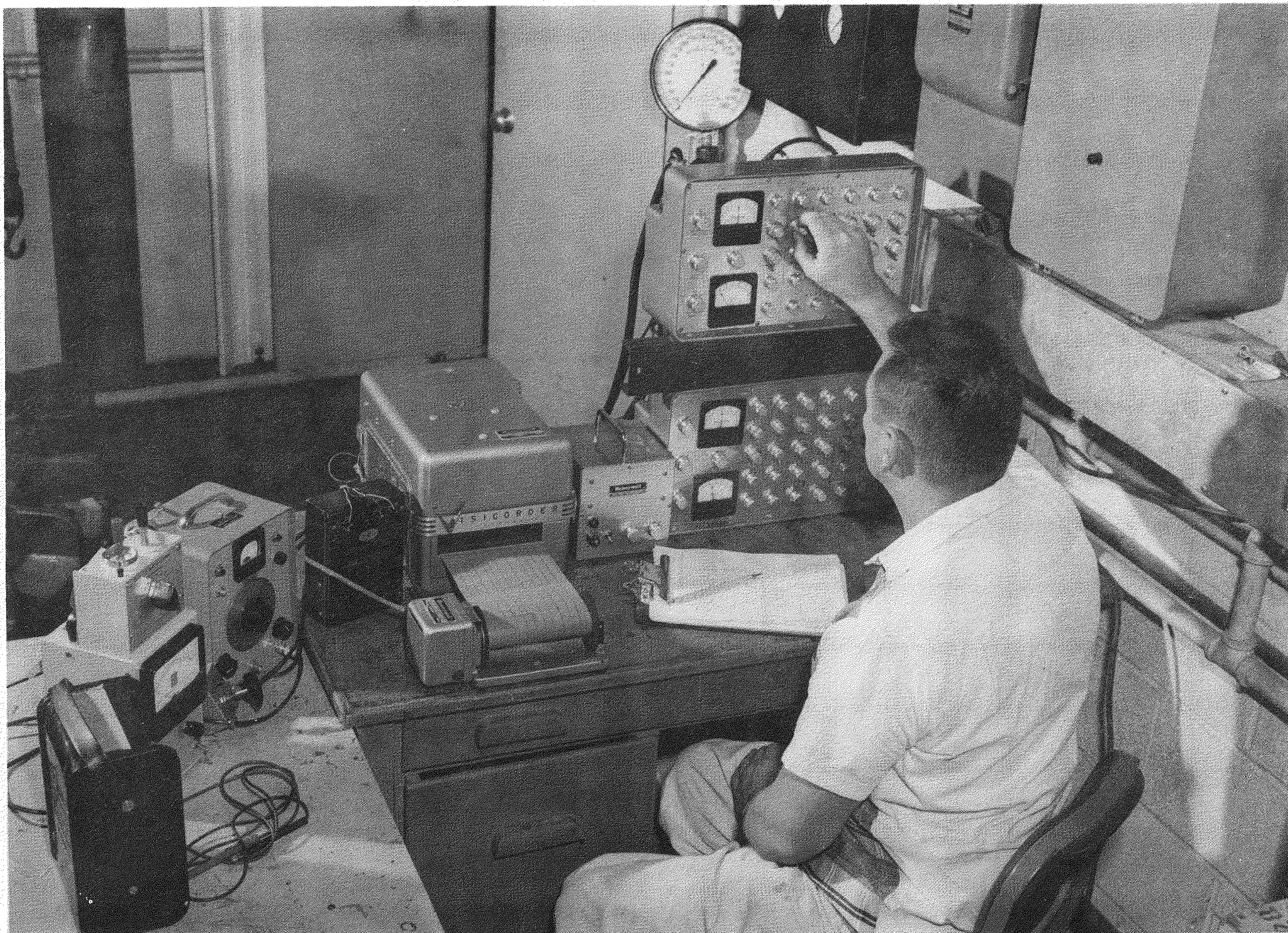

FIGURE 6. Instrumentation for Measurement of Redistribution of Strain (Hysteresis)

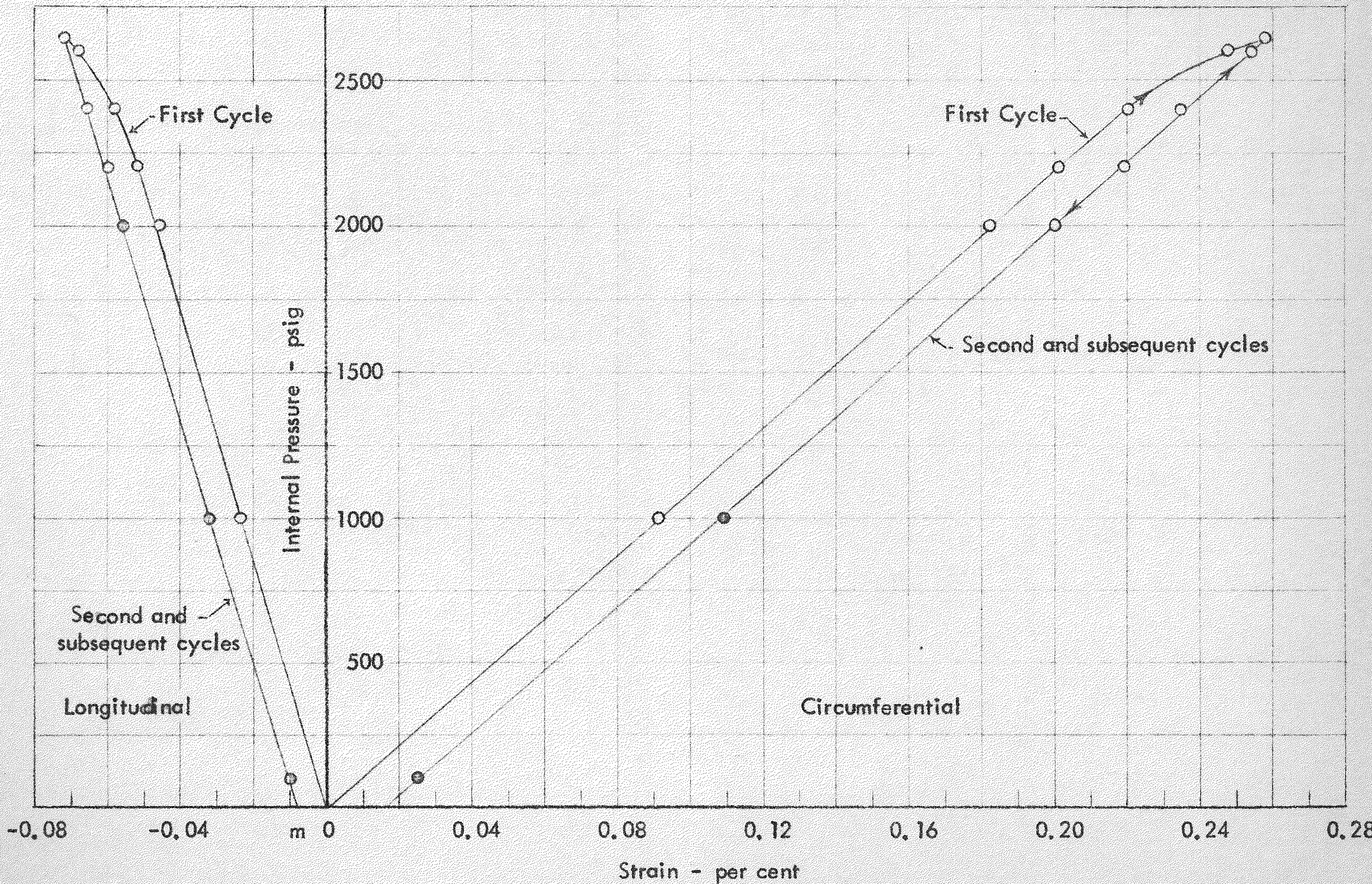

FIGURE 7. Measured Strains on Corner Radius of Nozzle 2 of No. 2, A-201
Test Vessel Cycled to 2650 psig

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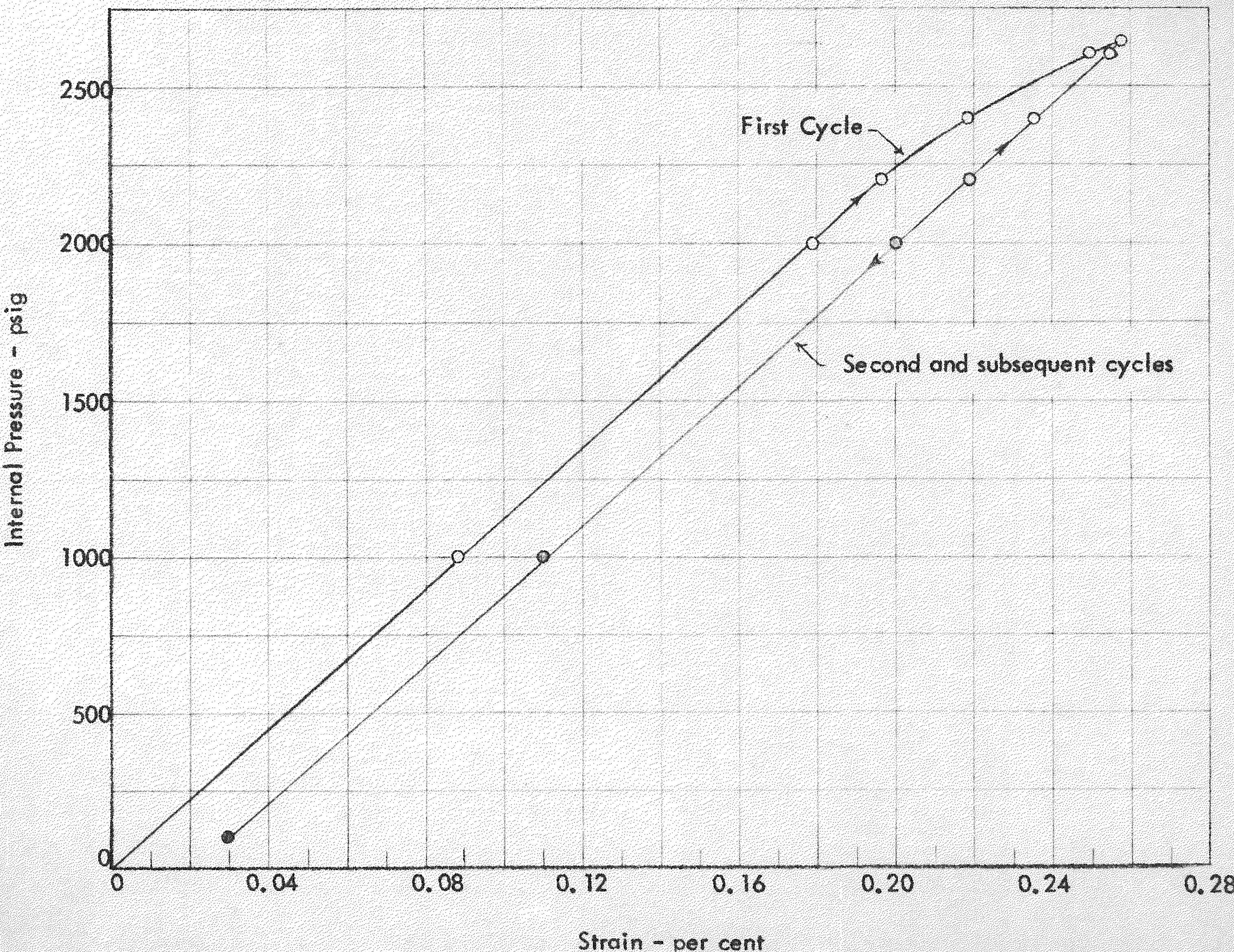

FIGURE 8. Measured Circumferential Strain on Corner Radius of Nozzle 6 of No. 2 A-201 Test Vessel Cycled to 2650 psig

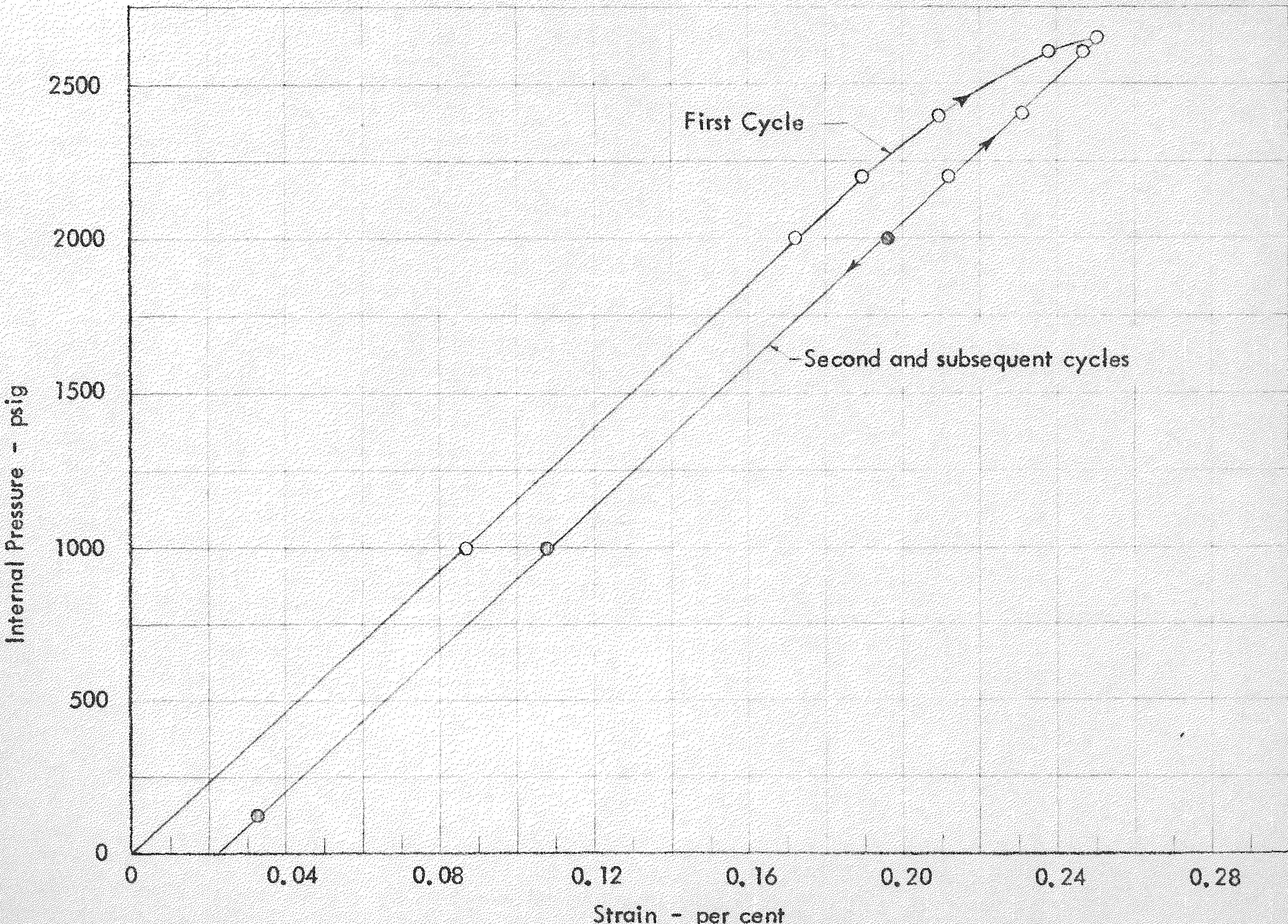

FIGURE 9. Measured Circumferential Strain on Corner Radius of Nozzle 8 of No. 2, A-201 Vessel Cycled to 2650 psig

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TABLE I

COMPARISON OF STRESS DATA -- NOZZLE NO. 2

Instrument	α = 0°				α = 180°		
	Strain (in/in)		Circumferential Stress psi	K_1^*	Strain (in/in)		Circumferential Stress psi
	Circumferential	Longitudinal			Circumferential	Longitudinal	
NO. 2 VESSEL							
Baldwin Strain Indicator	925	-240	28,120	2.96	---	-250	----
Gilmore Strain Plotter Run No. 1	945	-265	28,520	3.00	905	-260	27,270
Gilmore Strain Plotter Run No. 2	930	-235	28,350	2.88	905	-255	27,200
NO. 1 VESSEL							
Gilmore Strain Plotter			29,800				

* $K_1 = \frac{\sigma_{max}}{\sigma_{nom}}$, where σ_{nom} = nominal hoop stress in the shell, and σ_{max} = the maximum principal stress computed from strains measured around the discontinuity.

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TABLE II

EFFECT OD CORNER RADIUS ON FACTOR OF STRESS CONCENTRATION

NOZZLE NO. 6	α = 0°				α = 180°			
	Strain (in/in)		Circum-ferential Stress psi	K_1^*	Strain (in/in)		Circum-ferential Stress psi	K_1^*
	Circumferential	Longitudinal			Circumferential	Longitudinal		
Before Grinding (1/2" Radius all Around)	890	-235	27,030	2.85	890	-235	27,030	2.84
After Grinding (1/2" Radius at α = 0°, 1" Radius at α = 180°)	880	-240	26,710	2.81	835	-225	24,660	2.60

* $K_1 = \frac{\sigma_{max}}{\sigma_{nom}}$, where σ_{nom} = nominal hoop stress in the shell, and σ_{max} = the maximum principal stress computed from strains measured around the discontinuity.

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III. PVRC MEETING IN SAN ANTONIO

On March 14, 1960 a meeting was held in San Antonio, Texas to discuss the nozzle stress concentration factor values obtained at Penn State, University of Illinois, and Southwest Research Institute. Appendix A contains the Minutes of that Meeting.

IV. WORK PENDING

Preparations for cycling the No. 2, A-201 test vessel at 2650 psi are in progress, and fabrication of the A-302 test vessels at Combustion Engineering is under way. This writer will inspect the vessels at the fabricator's plant, prior to the time the heads are welded to the cylindrical shell.

V. FISCAL INFORMATION

Project expenditures through the accounting period ending 12 March 1960 amount to $95,755, leaving a balance of $30,737.

APPENDIX A

" PVRC Meeting at Southwest Research Institute

San Antonio, Texas - March 14, 1960

A meeting was held at the Southwest Research Institute on March 14, 1960, to discuss an apparent discrepancy between test results obtained by Southwest Research Institute and the University of Illinois on tests of reinforced openings in pressure vessels.

Those in attendance at the meeting were:

Prof. C. E. Taylor - University of Illinois
Prof. E. O. Waters - Yale University
Mr. J. L. Mershon - Bureau of Ships
Dr. M. M. Lemcoe - Southwest Research Institute
Mr. J. R. Houstrap - Combustion Engineering
(for Dr. L. W. Smith)
Mr. J. R. Farr - Babock and Wilcox Company
(for Mr. L. F. Kooistra)

Mr. Mershon, the appointed chairman of the meeting, reviewed the facts presented at the meeting of the PVRC Sub-Committee on Reinforced Openings held on February 10 and 11, 1960 in Chicago. At this meeting, the Southwest Research Institute data and the University of Illinois data for a similar nozzle were compared with adjustments for opening size, vessel diameter, and thicknesses in order that the comparison was valid. On the same adjusted nozzle, Southwest Research Institute obtained a K factor of 3.14 while University of Illinois obtained a K factor of 2.28. The two specimens did have different inside corner radii.

Mr. Mershon continued that Prof. Opel at Penn State obtained a K factor of 2.52 for one reading at the center of the inside corner radius on another similar nozzle. Prof. Opel will continue to obtain data so that additional comparisons can be made. Mr. Mershon stated that if all other factors were equal with the inside corner radius being the deciding factor, University of Illinois data should come between the Penn State and the Southwest data.

Dr. Lemcoe then discussed the data obtained by Southwest Research Institute. As shown on the enclosed sheet, data obtained from nozzle #2 on both Vessel #1 and Vessel #2 give a K-factor of about 3.0, but definitely it is not close to 2.5.

Prof. Taylor followed with a review of his test results on the similar nozzle. This data was obtained by the conventional method of freezing the model and analyzing strips cut from the model. With two independent checks, a K-factor of 2.28 and 2.38 was obtained. A third recheck was within 1 - 2%. The very highest K-factor would be 2.40.

Next, a general discussion of the Penn State model took place. The question was asked: Does the inside reinforcement on the Penn State model change the results? If Penn State data were based on the dimensions of the padded section, Prof. Waters stated that the results are approximately 6/5 higher. This would be 2.52 x 6/5 = 3.02, or about the same as the Southwest Research Institute results.

The University of Illinois photoelastic tests were discussed with primary concern directed toward the effect of Poisson's Ratio (which is about 0.5) and the large deformations which occur in pressurizing soft models. The general agreement was that these factors wouldn't appreciably influence the results.

At this point, it was decided to go to the laboratory to observe Vessel #1 which had ruptured through nozzle #6 causing a split in the vessel wall about 2-3 inches wide and about 2 feet long on each side of the nozzle. (Nozzle #6 had been repaired twice before on this vessel to continue the testing). Also, Vessel #2 was observed in the test pit where the two rechecks of K-factor of nozzle #6 had just been completed.

The meeting reconvened, and a listing of the factors which may influence results was made. They were: the size of the inside of the inside corner radius, the effects of multiple openings in one plane around the circumference of the vessel, out-of-roundness, strain gage length and the compatability of method of nozzle attachment on the hard vs. the soft models.

The next to the last item, strain gage length, was discussed with some concern of using a short length gage on material of different grain size. Some information was given regarding testing with different gage lengths with no difference in the results. Therefore, this item was ruled out.

The last item, method of nozzle attachment, was discussed especially by Prof. Taylor regarding the cement used to glue the plastic models. He stated that a small amount of discontinuity in the stress pattern was observed at the joint; however, he felt that this influence was small and could be neglected. Everyone was in agreement.

The individual effects of each of the other three items is not known; and therefore, it was decided to find a way to find the influence of one without the influence of the others. Since it was agreed that inside corner radius was probably the most significant factor, it would be wise to check this item first.

The method agreed upon was to test three nozzles in the same vessel and in the same cross-sectional plane. This will eliminate the effects of out-of-roundness and multiple openings in one plane. Each of the nozzles would have a different inside corner radius.

The specific way to accomplish this was to alter the two SA-302 models to be tested at Southwest Research Institute as follows:

1) On Vessel #3 (the SA-302 vessel with a nozzle #1) - increase the inside corner radius of nozzle #6 from 1/2" to 1".

2) On Vessel #4 (the SA-302 vessel without a nozzle #1) - add a new nozzle #6A which will have an inside corner radius of 1-1/2". This is to be added in the same location that nozzle #1 appears on Vessel #3.

3) On Vessel #4 - nozzle #6 would remain with a 1/2" inside corner radius.

This would result in tests of three nozzles exactly alike except for a 1/2", 1", and 1-1/2" inside corner radius.

Dr. Lemcoe was in agreement that on nozzle #6 of Vessel #2, it would be advisable to put strain gages not only at the corner points but also at the tangent points. This would make a better comparison to the nozzle #6 of Vessel #1.

What would be needed would be another #6 nozzle to be installed in Vessel #4 and additional time to grind larger radii on two #6 nozzles.

Mr. Kooistra was informed over the phone of this proposed change. He was in general agreement with the plans. Therefore, additional funds will have to be obtained as quickly as possible so that another nozzle forging can be obtained from Taylor Forge.

Prof. Taylor discussed some additional data that he had obtained on the photoelastic models.

The meeting was then adjourned.

J. R. FARR "

STRESS DATA

NOZZLE 2 - - FULL SIZE A-201 VESSEL

$\alpha = 0°$ (Longitudinal Plane)

		σ_{max} 2-Dimensional	σ_{max} 3-Dimensional	K_1 2-Dimensional	K_1 3-Dimensional
FROM MEASUREMENTS ON NO. 1 VESSEL		29,840	29,420	3.14	3.13
FROM MEASUREMENTS ON NO. 2 VESSEL (Taken March 9, 1960)	GILMORE STRAIN PLOTTER	28,520		3.0	
	BALDWIN STRAIN INDICATOR	27,270		2.87	