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DYNAMIC COLLAPSE OF STEAM GENERATOR TUBES

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ABSTRACT

Room temperature lateral impact loading tests were performed on 0.875 O.D. x 0.050 inch wall Inconel 600 steam generator tubes under simulated operating conditions. These tests were performed to determine the conditions which would result in the collapse of an externally pressurized tube by lateral impact loads. The test variables include impact load, frequency, and contact surface, external pressure, axial load, length of tube, length of unsupported tube near the impact zone, degrees of tube rotation, geometry of impactor, and pressurizing medium. The test results show that under certain conditions the tube will collapse.

INTRODUCTION

The purpose of this test program was to determine the impact loading conditions which would cause the collapse of a plugged, externally pressurized Inconel 600 generator tube 0.875 inch outside diameter (O.D.) and 0.050 inch nominal wall thickness.

These tests were designed to simulate a foreign object impacting against the wall of a plugged steam generator tube under operating conditions. They were part of a program to verify the method of failure for the collapsed tubes found in the steam generator at the John Ginna Nuclear Power Plant. The theory is that a loose rectangular steel plate, impacting against the tubes for several years, caused the failures.

Many tube loading conditions were tested, however this report will cover only the test conditions which caused collapse of the tubes. The collapse conditions reported herein may not be the only conditions which will cause the tubes to collapse, but they are the only ones found for this size tube in the limited time allowed for this program.

CONCLUSIONS

1. The steam generator tubes will collapse using a series of lateral impact loads over a 40° circumferential surface area two to three inches in axial length.
2. Considerable ovality will occur before collapse occurs.
3. The collapse is dependent on the shape of the impactor.
4. Impact loads less than 525 lbs. and an external pressure of 1000 psig did not cause the tube to collapse.
5. Impact loads concentrated in a small area will cause a fatigue crack in the impact area rather than a collapse.

EXPERIMENTAL

Specimens

The specimens are Inconel 600 steam generator tube with 0.875 in. O.D. and 0.050 in. nominal wall. The test lengths for the dynamic collapse tests were 19.2 in. and 52.0 in. The bench test tubes were 6.0 in. long.

Test Equipment

A. Bench Tests - The 6.0 inch long 0.875 inch O.D. tube specimen was mounted into two - two-inch long V-blocks, one at each end of the tube, with a two-inch space between the V-blocks. The specimen was secured to the V-blocks by a plate and screws. See Figures 3 and 4. The chisel type device, similar to the ones used in the dynamic tests, was installed in the crosshead of a Baldwin universal testing machine which applied the load. The load range was set to 5000 lbs. which has an accuracy of $\pm$ 5 lbs. The diametral measurements were made with a micrometer which is accurate to the fourth decimal place although only the first three places were used.

B. Dynamic Collapse Tube Tests - The dynamic collapse tube test fixture was designed to simulate at room temperature, specific operating conditions of the steam generator and to apply lateral impact loads to the tube specimen. This test fixture has the capability to apply simultaneously to the tube specimen (1) up to 1000 lb. impact load, (2) impact rod travel of 1.5 inches, (3) external pressure up to 2000 psig, and (4) axial tensile load up to 1500 lbs. The test fixture is shown in Figure 1 and photographs 1, 2 and 3. Photograph 3 also shows the instrumentation.

The tube specimen is mounted and sealed inside the 2.00 inch diameter test chamber as shown in Figure 1. If water is required, the test chamber is filled with water from the reservoir and the air is bled off as required. The pressure is applied to the deionizing water reservoir or directly to the test chamber by a high pressure nitrogen gas bottle. A pressure gage mounted on the test chamber shows applied to the external surface of the tube. A hydraulic cylinder applies the impact force and stroke to the impact rod. A hydraulic controller and function generators direct a servovalve which controls the fluid pressure applied to the hydraulic cylinder, and results in a controlled cyclic force.

The force, displacement, and acceleration are measured by a load cell, LVDT and accelerometer respectively. The LVDT and accelerometer are not shown on Figure 1, but are shown in Photograph 1. The signals from these transducers are monitored and recorded on a Nicolet storage scope. The load cell was calibrated before the tests using a reference load cell traceable to N.B.S.

In a servohydraulic system, frequency, load and displacement are interdependent. Raising any one of them to too high a level will limit the level which can be attained by the other two. Also, the piston velocity is a function of both frequency and displacement. Therefore, in these tests frequency and displacement were not held constant, but were varied to produce the specified force and velocity of impact.

Test Procedure

A. Bench Tests

1. Measure initial O.D. and I.D. three inches in from one end, using micrometers
2. Attach the chisel in the crosshead of the Baldwin Tensile Machine.

3. Mount the tube specimen in the V-blocks and position the tube/V-block assembly so that the chisel is centered on the tube in the space between the supports.
4. Initialize crosshead deflection.
5. Increase load by 50 lb.
6. Release load (to zero)
7. Measure the O.D. at the point where the chisel contacted the tube (minor) and O.D. perpendicular to loading point (major).
8. Repeat Steps 5 through 7 for higher loads. The final load will be reached when the minor O.D. is about 0.500 inc.

B. Dynamic Collapse Tests - Prior to each test the specific test parameters were determined and were used where the test procedure calls for "as specified" test requirement.

1. Cut tube to the "as specified" length.
2. Measure and record I.D., O.D., and ovality of the tube in the test section. Mark the end of the tube to indicate the smallest diameter if there is ovality.
3. Adjust spacers to the specified separation, if they are required.
4. Install the tube in the test fixture ensuring the smallest diameter is in line with the impact rod.
5. Install end cap seals and other test fixture hardware.
6. Turn cap screws to provide a hand tight contact with the tube.
7. Align the impact rod to meet the test requirements.
8. Apply water or gas (as specified) external pressure. Check for leaks and eliminate if they exist.
9. Apply axial load if specified.
10. Apply the lateral load, as specified, at various locations on the tube surface over an area approximately two or three inches long (as specified) in the axial direction and roughly forty degrees in the circumferential direction.

RESULTS

The bench test results are listed in Tables 1 and 2 and Figures 3 and 4. Figures 3 and 4 show a curve of all the data points recorded during the bench tests. Tables 1 and 2 list the reductions in diameter for loads up to 1000 lbs. Since we were interested in loads that would result in ovalities around 2%, for a starting point to calculate the initial dynamic impact loads, the remainder of the data is not listed. To determine the effect on the tube, the bench tests were run until the minor diameter decreased to about 0.500 inches. The curves show that the rate of change of the diameter increases rapidly when the load is above 1000 lbs., and with the blunt (1/8 x 1.0) chisel the change in diameter increases very rapidly at loads about 2200 lbs. Figure 5 shows a comparison of the results of the two bench tests. There is very little change in the O.D. 2 until the applied load is over 1000 lbs. in both cases. This implies that the change in the diameter of O.D. 1 is mainly due to local plastic deformation at the point of contact with the chisel. Photo 4 shows the specimen after testing.

The results of dynamic test 1 through 4 are listed in Tables 3 through 6 respectively. In test No. 1 the tube specimen did not collapse using the sharp chisel or the blunt chisels used in the second phase. However, the tube did develop a fatigue crack at the point of impact using the 1/4 x 1/4 point chisel after 22,345 cycles. This test was stopped because of this crack. Photo 5 shows tube conditions after the first four specimens of testing,and Photo 6 shows the crack after the last series of tests.

In dynamic test No. 2, the tube began to collapse during the final two sequences. A collapse is defined as a significant concave deformation occurring on the side of the tube 180° from the area of impacts.

Dynamic test No. 3 was a repeat of test No. 2 except the external pressure was increased to 1500 psig, deionized water; the impact load was decreased 50 lbs. to 600 lbs. and the spacer separation was increased from six to eight inches. The tube collapsed during the third sequence. Dynamic test No. 4 was a repeat of test No. 3, except it was designed to determine the lowest impact load that would cause a collapse. After incrementing the impact load upward from 450 to 525 lbs. for nine total sequences, the tube collapsed.

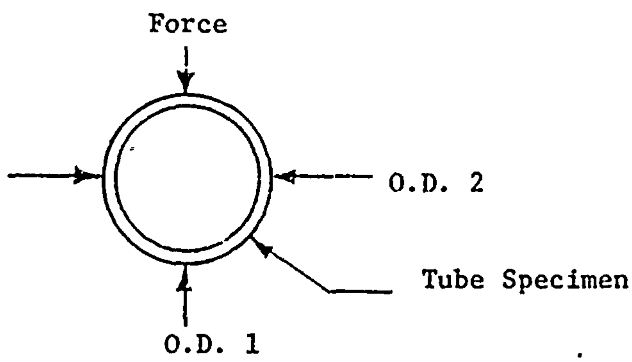
DISCUSSION

Two types of tests were performed - lateral load bench tests and dynamic collapse tube tests. The bench tests were performed to determine a starting impact load for the dynamic tests.

Bench tests were performed using two types of chisel devices - one sharp edge (0.030 inch wide x 1.00 inch long) and the other a blunt edge (0.125 x 1.00). Figure 2 is a sketch of these devices. The sharp edge chisel (0.030 inch wide x 1.0 inch long) simulates a sharp edge of a steel block while the blunt edge chisel (0.125 wide x 1.00 long) is a worn edge. The chisel is installed in the crosshead of the testing machine.

The center of the six inch long tube specimen is marked prior to positioning under the chisel in the testing machine to give a reference point for chisel contact. The load is increased to 50 lbs. then released. The minor (O.D. 1) and major diamters (O.D. 2) are measured with the micrometer and recorded. The load is then incremented by 50 lbs. (for an applied load of 100 lbs.)then released and diametral measurements taken and recorded. This process continues until the minor diameter (O.D. 1) is approximately .500 inch. The percent ovalities are calculated using the following equation.

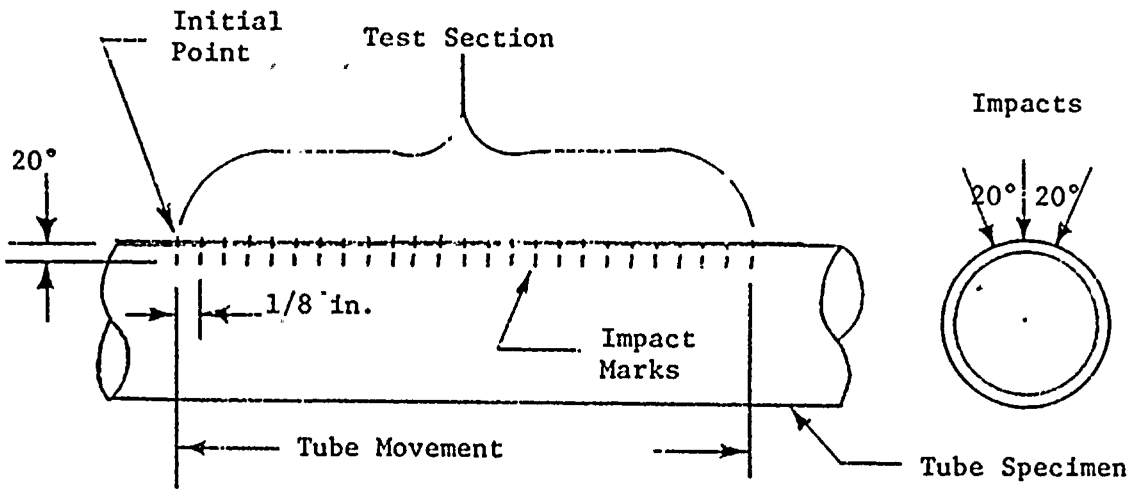
$$\text{Percent Ovality} = \frac{2(\text{O.D. } 2 - \text{O.D. } 1)}{\text{O.D. } 2 + \text{O.D. } 1} \times 100$$



Tables 1 and 2 list the bench test data up to 1000 lbs. load for the sharp and blunt edge chisels, respectively. Figures 3 and 4 are a plot of all the test data for load vs diameters for the sharp and blunt edge chisels, respectively. These tests show that with the sharp edge chisel 550 lbs. is required to get an ovality of 1.09% and 700 lbs. load for 2.14%. For the blunt edge chisel, 1.18% ovality requires 750 lbs. and 2.36% requires 900 lbs. This data was given to the personnel at Westinghouse NTD who calculated a starting load for the dynamic tests.

For the dynamic collapse tube tests the specimen was installed into the test chamber as shown in Figure 1, except, in some tests, two spacers were added to reduce the tube bending and place the tube in the shell mode. Figure 6 is a sketch showing the spacer installed on a tube specimen. The nominal diametral clearance between the spacer and tube is .005 inch, and .010 inch diametral clearance between the spacers and the I.D. of the test chamber. The through holes and clearances allow water or gas to pass. The diametral clearances between the spacers and the test chambers are required for installation. The space between the spacers was two to four inches, depending on the test.

The dynamic tests consist of a series of impact loads applied 0.25 inches apart starting at the beginning of the test section and continuing to the end of the test section. The impactor is then offset axially 0.125 inches, then the impacts continue at increments of 0.25 inches to the starting point. This procedure results in impact loading every 0.125 inches to an axial line on the surface of the specimen. It should be noted that to transit the test section in this manner, the tube is moved axially while the impactor location is fixed in the test fixture. This series of impacts is repeated for circumferential location of $\pm$ 20° from the initial point in the test section as shown below.



This series of impacts at three axial locations is defined as a sequence. At the end of each sequence the I.D. of the tube is measured in the test section with a Ditester micrometer to determine the minimum diameter in the test section. The O.D. cannot be measured while the specimen is in the text fixture. Therefore the specimen is removed periodically for inspection of the impact surface and measurement of the O.D. The impacts were applied one per second at an impactor travel velocity equivalent to 40 Hz. Tables 3 to 6 are the test data for the four dynamic tests.

The first dynamic test was performed with the sharp chisel, spacers separated by 6.0 inches, 1000 psig argon gas, 600 lb. impact force, a test section of 2.0 inches and an initial ovality of 2.6%. The tube was deformed in a vise with copper plates to obtain the ovality. After completion of four sequences the tube was removed for inspection and removal of the spacers for the next test.

After the inspection, the specimen was reinstalled into the test fixture, the test chamber filled with water and pressurized to 1000 psig, and a 1/2 x 1.0 inch impactor installed. The specimen was positioned so that the impactor struck the tube in the center of the previous test area. After 750 impacts at 600 lbs. load, the specimen was removed for inspection and installation of a 1/4 x 1/4 impactor. The test continued until a crack developed in the specimen at the impact location. A total of 22,345 impacts were recorded with the 1/4 x 1/4 impactor.

The second dynamic test was performed with the blunt (1/8 x 1.0) chisel, spacer separation of 6.0 inches, 1000 psig deionized water (Seq. 1-4); argon gas (Seq. 5-10), 650 lb. impact force, a test section of 2.0 in. and an initial ovality of "0" %. After four sequences the specimen was removed for inspection.

The specimen was reinstalled into the test fixture and testing continued as before. After four more impact sequences (a total of eight) the specimen was again removed for inspection. After inspection the tube was reinstalled and the impacting sequences continued. The tube began to collapse on the ninth sequence. The test was stopped at the end of the tenth sequence,when the minor diamter collapsed to about 0.500 inches. The specimen was removed, inspected, and ovality calculated.

The third dynamic test was performed with the blunt chisel, spacer separation of 8.0 inches, 1500 psig deionized water, 600 lb. impact force, a test section of 3.0 inches and an initial ovality of 2.0%. After three sequences the specimen collapsed. The specimen was removed and inspected.

The fourth dynamic test was performed with the blunt chisel, a spacer separation of 8.0 inches, 1500 psig deionized water, an initial force of 450 lbs., a test section of 3.0 inches, an initial ovality of 2.52%. The test was designed to determine the lower load bound which would cause the specimen to collapse. After four sequences the impact force was increased 50 lbs. to 500 lbs. for two sequences then increased to 525 lbs. for the remainder of the test. The impact loads were increased when there was little or no change in the minor diameter after completion of a sequence. The tube collapsed during the ninth sequence. The tube was removed and inspected.

ACKNOWLEDGEMENTS

I would like to acknowledge the efforts of T. R. Gribbin who assembled the test fixture, instrumentation and performed the tests and also C. C. Long for preparing the report for publication.

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TABLE 1

BENCH TEST - SHARP CHISEL IMPACTOR

Load (Lbs)	O.D.1(in.)	O.D.2(in.)	% Ovality	Remarks
0	.8720	.8720	0	Initial I.D. .7659; Wall = .053
50	↓	↓	↓	
100	↓	↓	↓	
150	↓	↓	↓	
200	.8715	↓	.06	
250	.8710	↓	.11	
300	.8700	↓	.22	
350	.8695	↓	.28	
400	.8690	↓	.34	
450	.8682	↓	.43	
500	.8652	↓	.78	
550	.8630	.8725	1.09	
600	.8620	.8725	1.21	
650	.8585	.8735	1.73	
700	.8550	.8735	2.14	
750	.8535	.8735	2.31	
800	.8480	.8740	3.01	
850	.8432	.8768	3.90	
900	.8385	.8752	4.28	
950	.8271	.8762	5.76	
1000	.8262	.8774	6.01	

TABLE 2

LATERAL LOAD BENCH TEST - BLUNT (1/8 x 1)
CHISEL POINT IMPACTOR

Load (Lbs)	O.D.1 (in.)	O.D.2 (in.)	% Ovality	Remarks
0	.8719	.8719	0	Initial I.D. - .7658; Wall = .053
50				
100				
150				
200				
250				
300				
350				
400	.8715	.8720	.06	
450	.8709		.12	
500	.9702		.20	
550	.8700		.22	
600	.8690		.34	
650	.8678	.8732	.62	
700	.8665	.8735	.80	
750	.8632	.8735	1.18	
800	.8612	.8740	1.47	
850	.8578	.8740	1.87	
900	.8538	.8742	2.36	
950	.8488	.8746	2.99	
1000	.8442	.8759	3.68	

TABLE 3
DYNAMIC COLLAPSE TUBE TEST NO. 1

Specimen: 2609-1-B1

Impact Rod: Chisel with .030 radius tip (sharp point)

Load: 600 lbs.

Pressure: 1000 psig, argon gas (Seq. 1-4); deionized water (for remainder of tests)

Space Separation: 6.0 in.

Sequence: 0°, 20° ccw, 20° cw x 2.0 in. length, .25 in. increments with .125 offset coming back. 10-25 impacts at each location.

Sequence	O.D.	I.D.	% Ovality	Remarks
0	.884/.861	.750	2.6	Preset ovality
1	-	.734	-	
2	-	.711	-	
3	-	.689	-	
4	.9165/.781	.668	16.0	Tube removed for insepction

After completion of above test, the following dynamic tests were run with a 600 lb. load, 1000 psig water.

Impacter	Impacts	I.D.	Remarks
1/2 x 1	750	.642	
1/4 x 1/4	700	.633	Tube removed to change impactors.
1/4 x 1/4	9000	.632	
1/4 x 1/4	12,645	-	Without spacers-specimen developed crack. Test stopped.

Final O.D. = .9278/.7328

Ovality = 23.5%

TABLE 4
DYNAMIC COLLAPSE TUBE TEST NO. 2

Specimen: 2609-1-B-2

Impact Rod: Rectangular point: 1/8" x 1.0" (blunt chisel)

Load: 650 lbs.

Pressure: 1000 psig, deionized water (Seq. 1-4); Air (Seq. 5-10)

Spacer Separation: 6.0 in.

Sequence: 0° ccw, 20° cw x 2.0 in. length, .25 in. increment with .125 offset coming back. 10-25 impacts at each location

Sequence	O.D.	I.D.	% Ovality	Remarks
0	.873/.873	.766	0	Wall - .053
1	-	.7341	-	
2	-	.6953	-	
3	-	.6643	-	
4	.923/.766	.6467	18.5	Tube removed for inspection
Tube Reinstalled: 10-25 axial impacts added at end of each sequence				
5	-	.6093	-	
6	-	.5872	-	
7	-	.5561	-	
8	.9812/.6721	.5463	37.3	Tube removed for inspection
Tube Reinstalled: Sequence - same as 5-8				
9	-	.5201		
10	1.0587/.4851	.3952	74	Tube removed for inspection

Final Test: 5650 axial impacts in center of test section.

Comments: Tube began to deform on back side during sequences 9 and 10.

TABLE 5
DYNAMIC COLLAPSE TUBE TEST NO. 3

Specimen: 2609-1-C-1

Impact Rod: 1/8 x 1.0 inch chisel

Load: 600 lbs.

Pressure: 1500 psig, deionized water

Spacer Separation: 8.0 in.

Sequence: 0°, 20° ccw, 20° cw x 3.0 in. length, .25 in. increment with .125 offset coming back. 10-25 impacts at each location.

Sequence	O.D.	I.D.	% Ovality	Remarks
0	.878/.8605	.756	2	Initial: O.D.=.871; I.D.=.765 Wall = .053, Ovality = 0
1	-	.6914	-	
2	-	.5331	-	
3	1.1925/.3694	-	105	Tube collapsed

TABLE 6
DYNAMIC COLLAPSE TUBE TEST NO. 4

Specimen: 2609-1-C-2

Impact Rod: 1/8 x 1.0 inch chisel point

Pressure: 1500 psig, deionized water

Space Separation: 8.0 in.

Sequence: 0°, 20° ccw, 20° cw x 3.0 in. length, 1/4 in. increment with 1/8 in. offset coming back. 10-25 impacts at each location and in center after completion of sequence.

Sequence	Load	O.D.	I.D.	% Ovality	Remarks
0	0	.8705	.7652	0	Initial diameter
0	0	.881/.859	.7531	2.52	Initial ovality
1	450	-	.7161	-	
2	450	-	.6995	-	
3	450	-	.6851	-	Start using 1/2 in. increments
4	450	-	.6771	-	
5	500	-	.6584	-	Increased load
6	500	-	.6378	-	
7	525	-	.5882	-	Increased load
8	525	-	.5067	-	
9	525	1.1597/.492	.3723	80.8	Tube collapsed. Removed for inspection.

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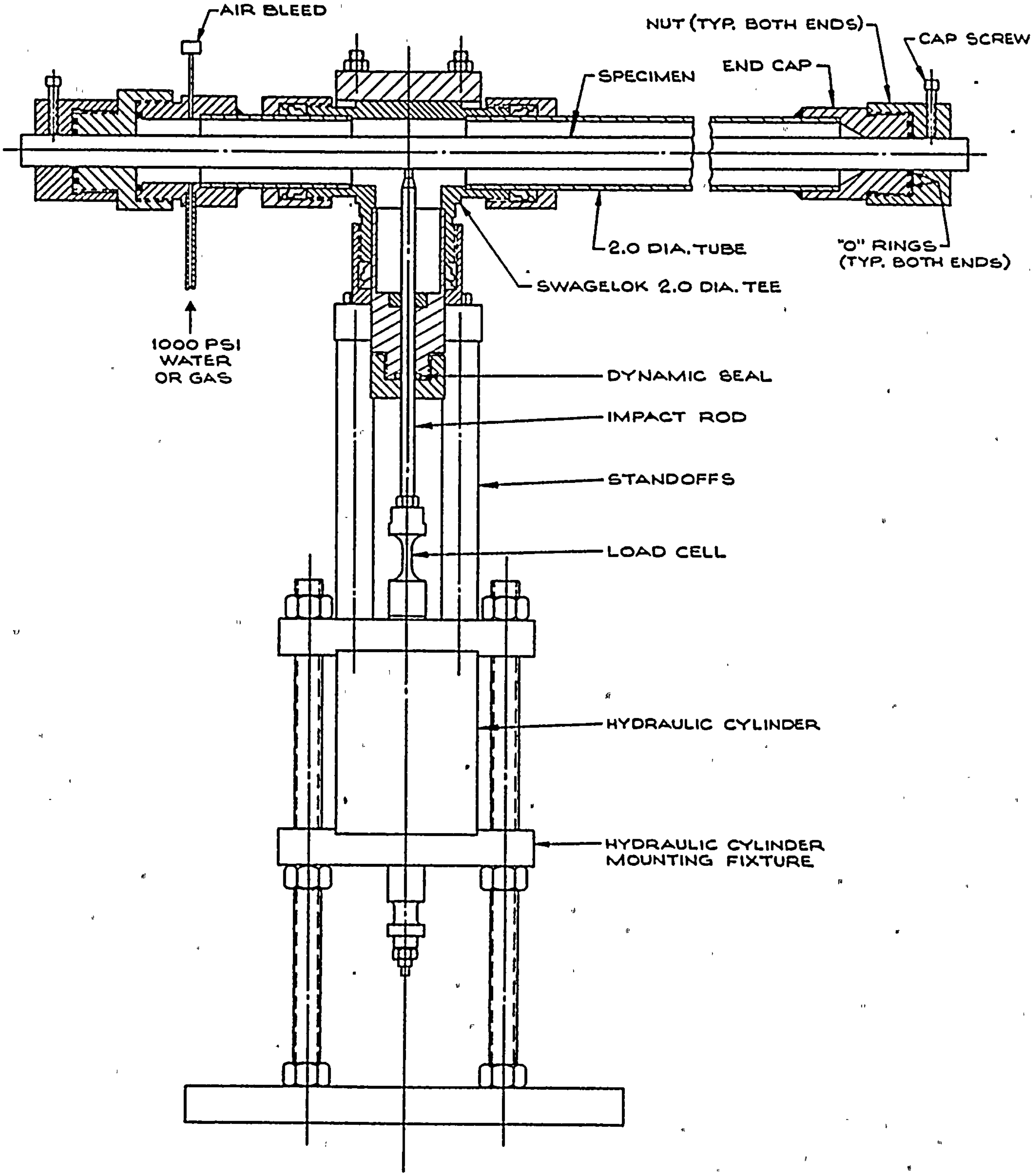
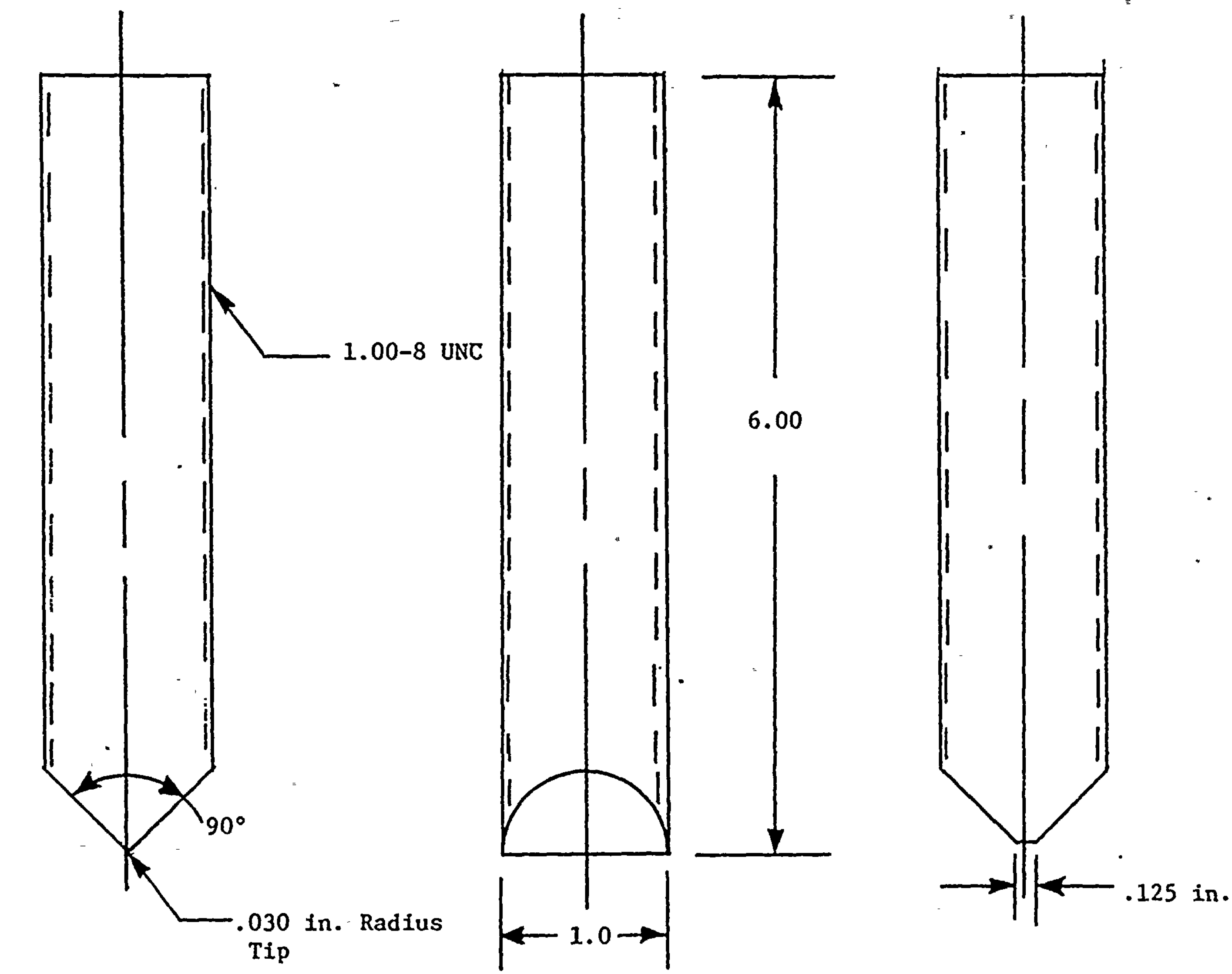


Figure 1 Test Fixture for Dynamic Collapse of Steam Generator Tubes



a. Sharp Edge Chisel   b. Typical Side View   c. Blunt Edge Chisel

Figure 2 Bench Test Chisels

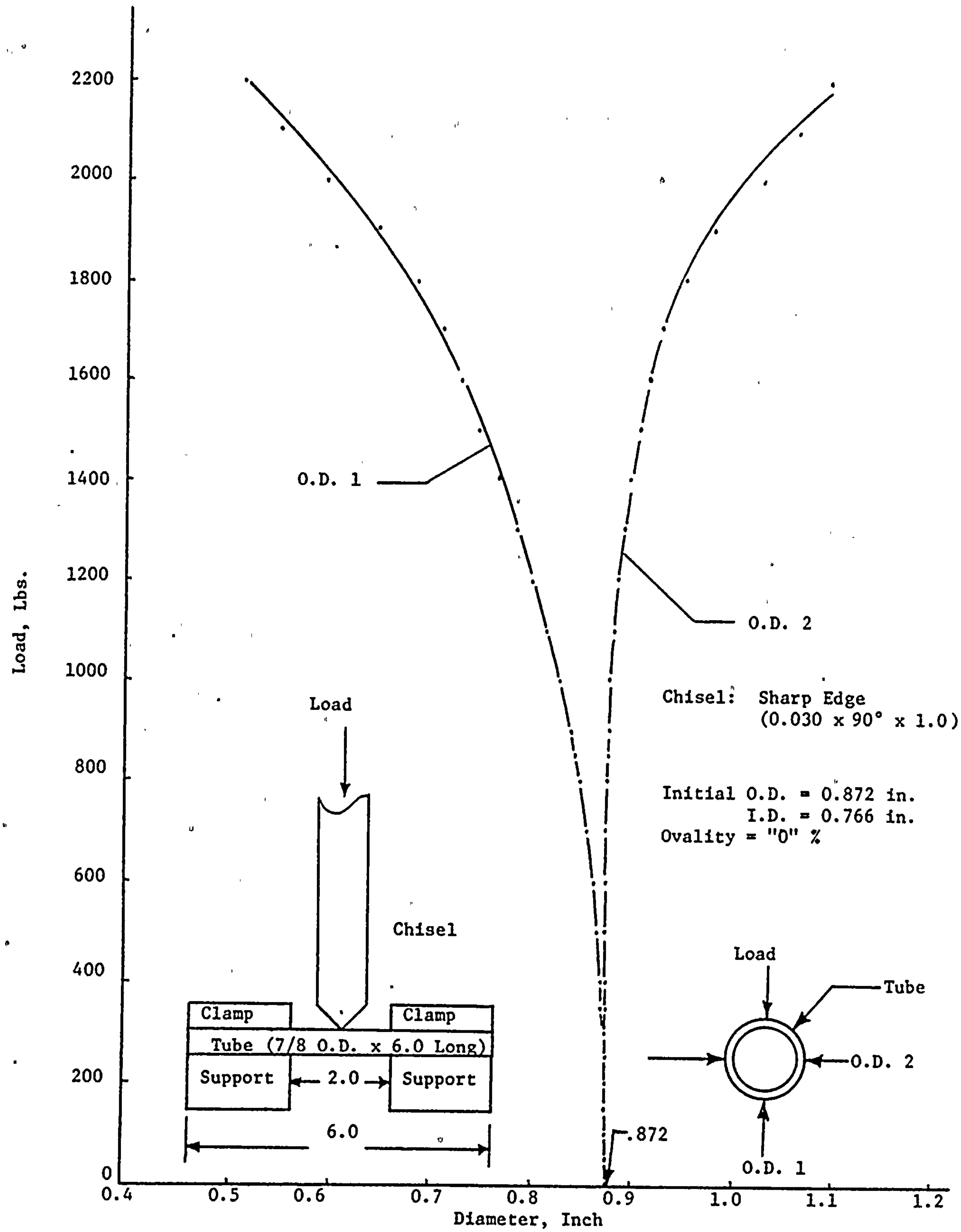


Figure 3 Results of Lateral Load Bench Test with. Sharp Chisel Impactor

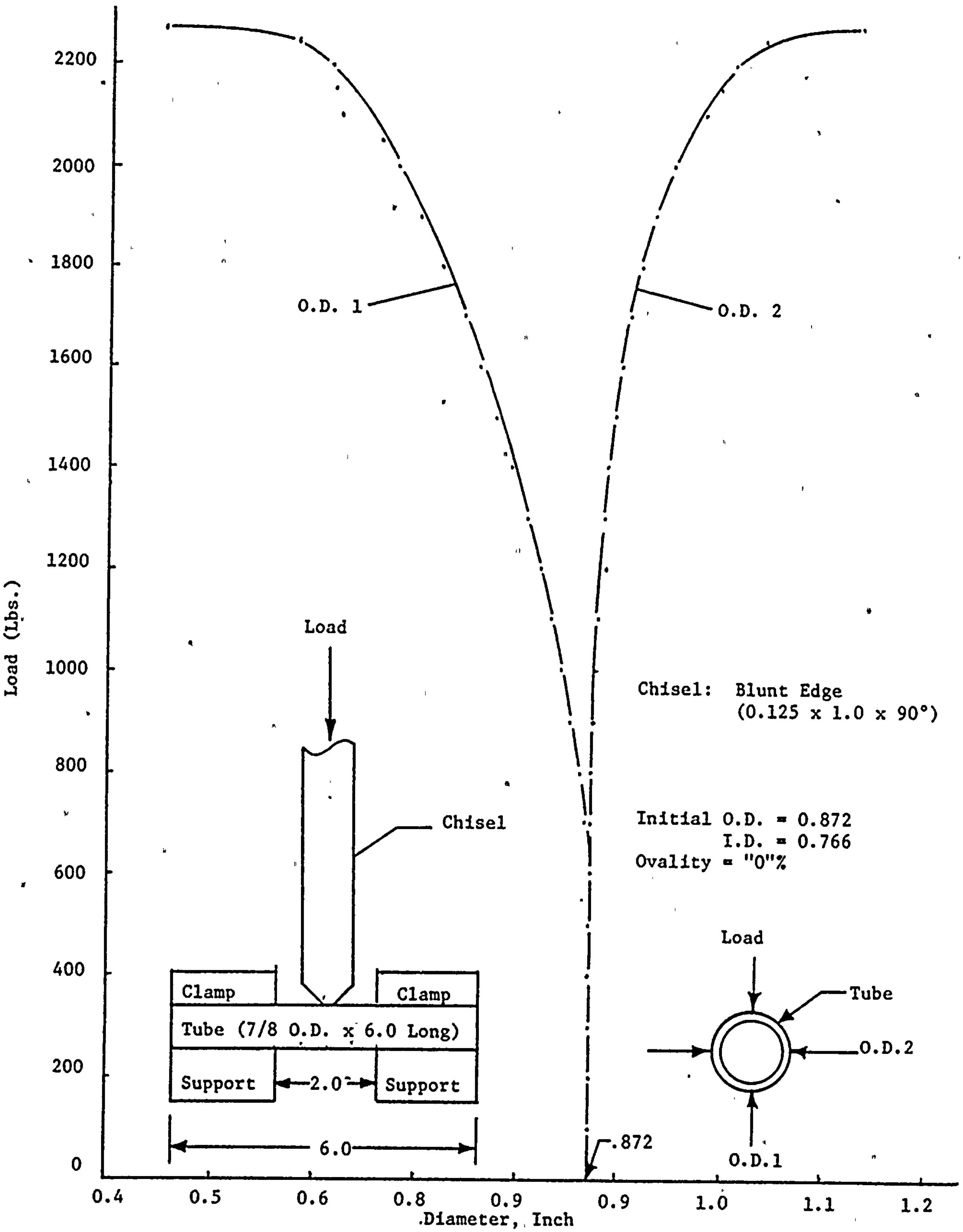


Figure 4 Results of Lateral Load Bench Test with Blunt Chisel Impactor

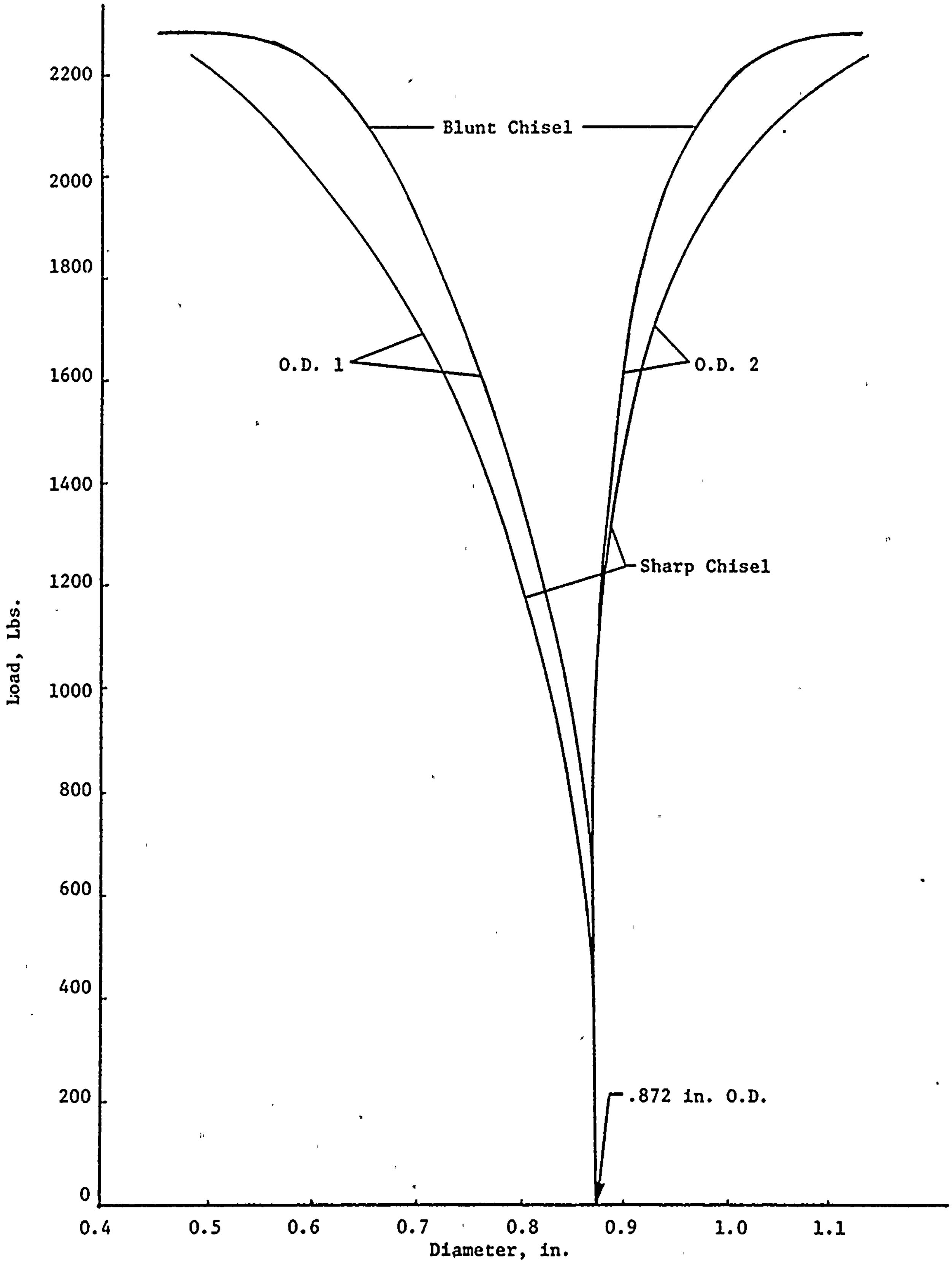


Figure 5 Comparison of Bench Test Results for Sharp and Blunt Chisels

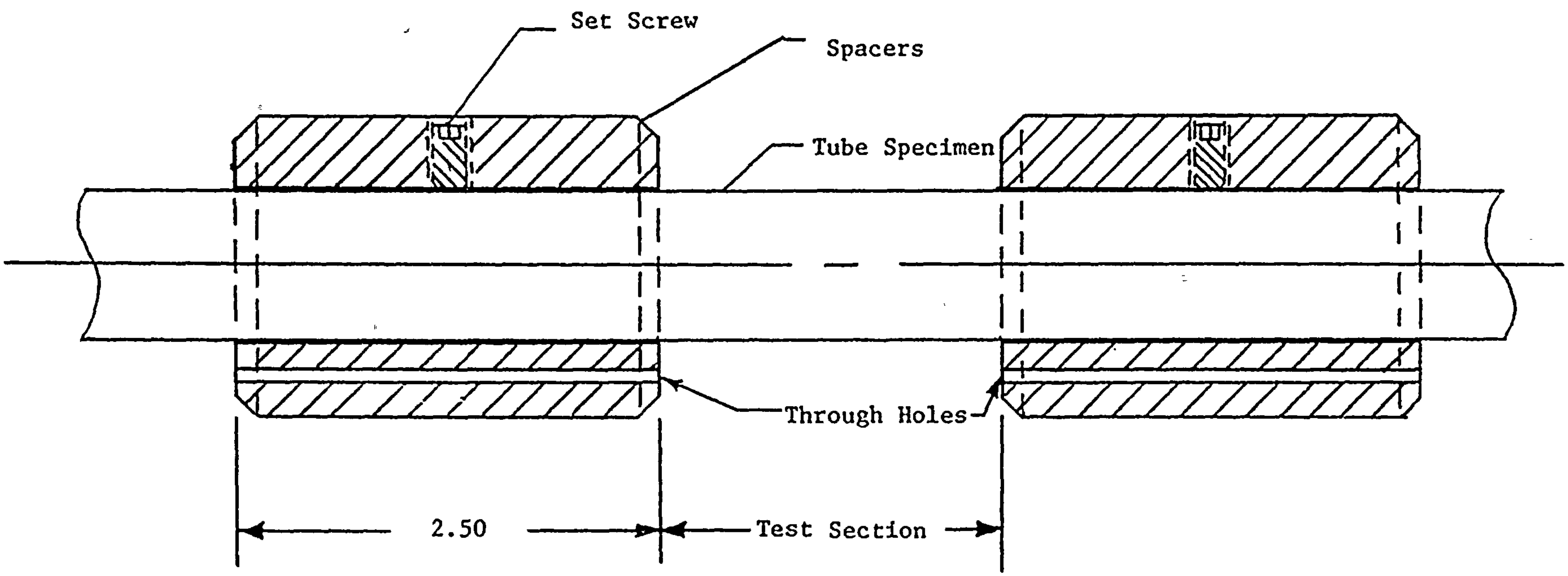
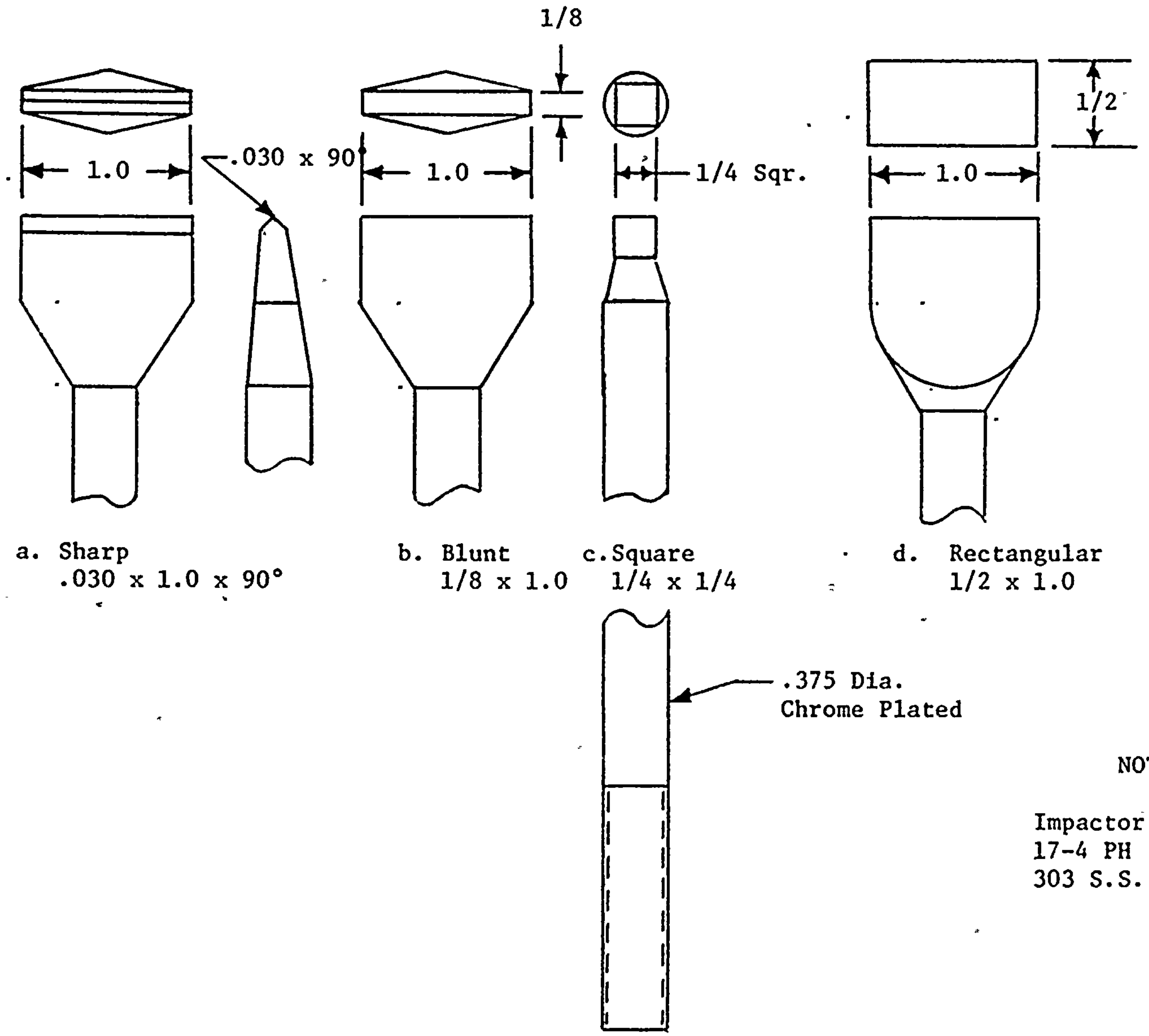


Figure 6 Tube Specimen with Spacers



NOTE:

Impactor Material
17-4 PH (RC 32) and
303 S.S.

Figure 7 Chisels Used in Dynamic Impact Tests

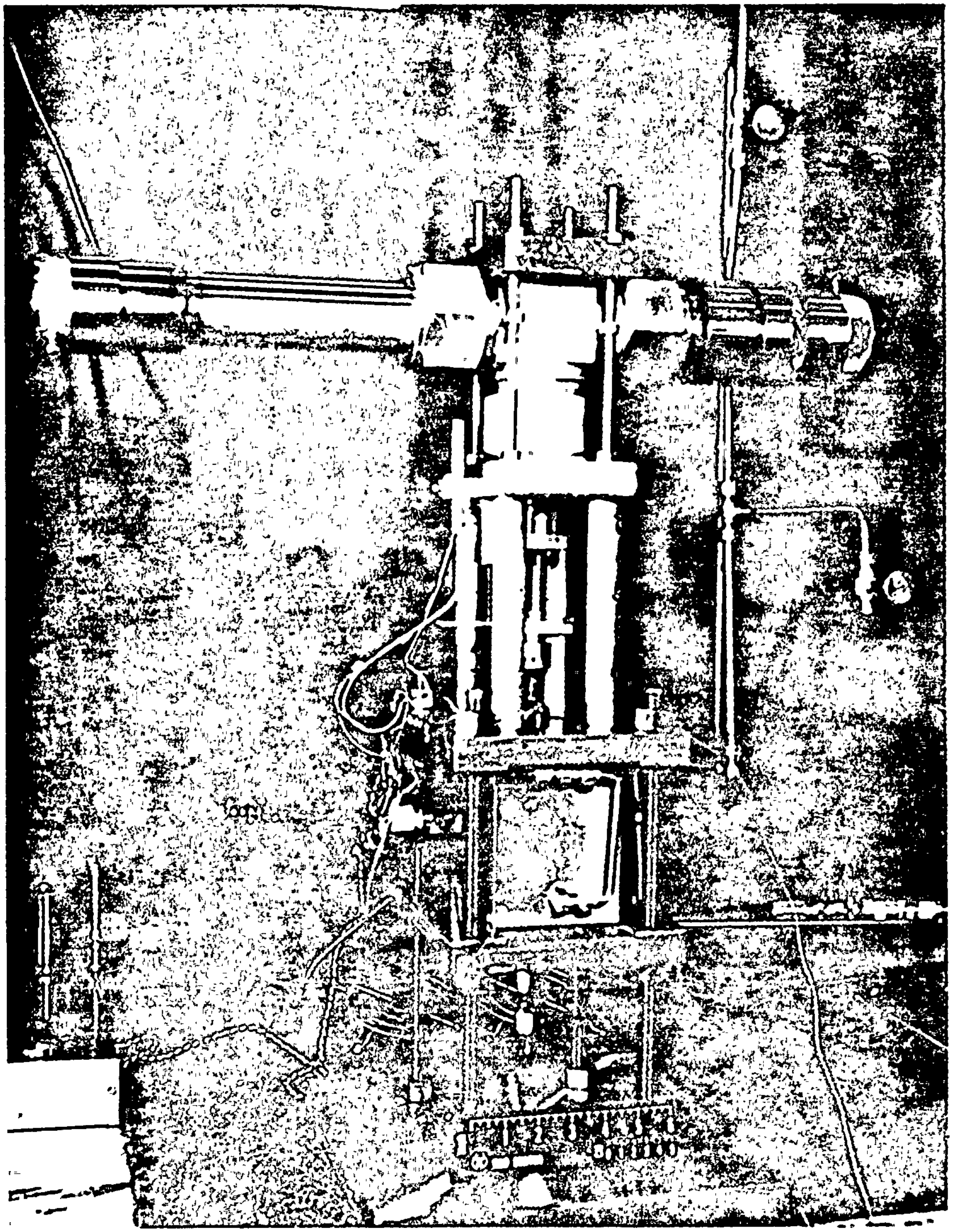


Photo 1 Dynamic Collapse Tube Test Fixture

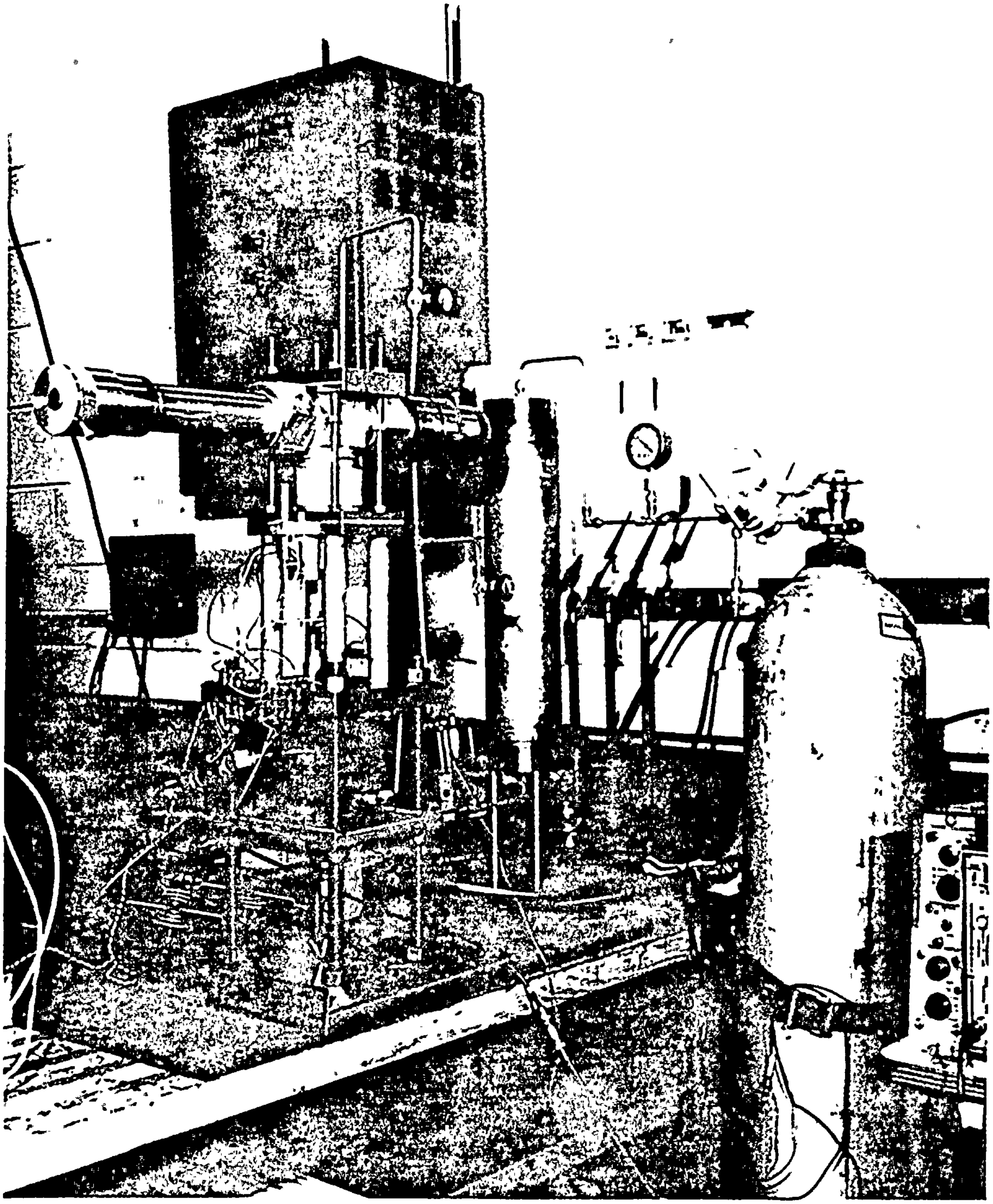


Photo 2 Dynamic Collapse Tube Test Fixture, Water Reservoir, and High Pressure Gas Bottle

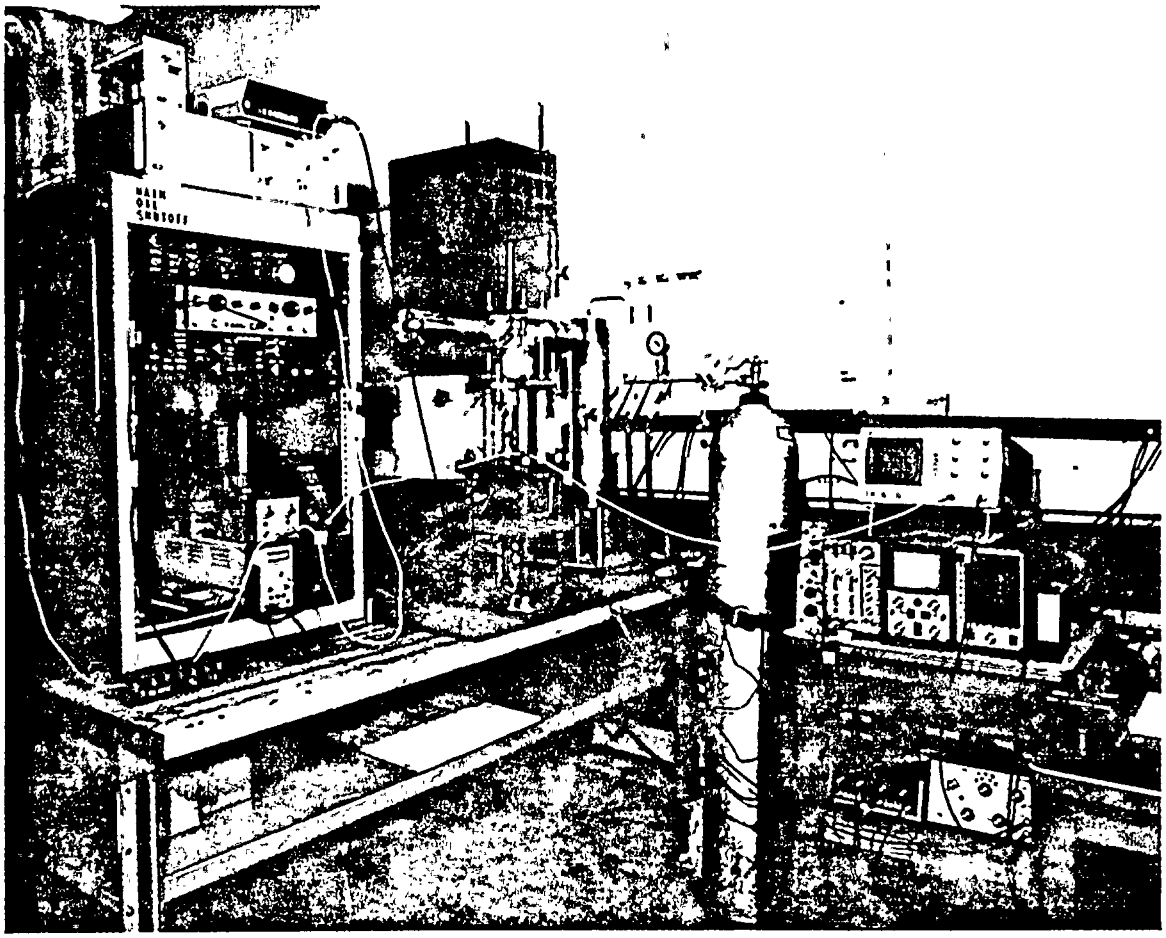
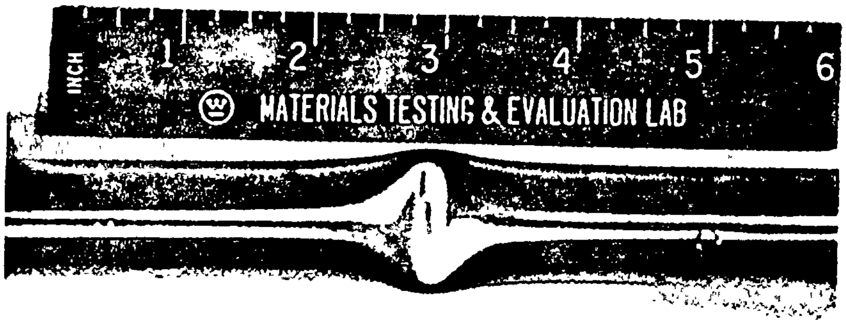
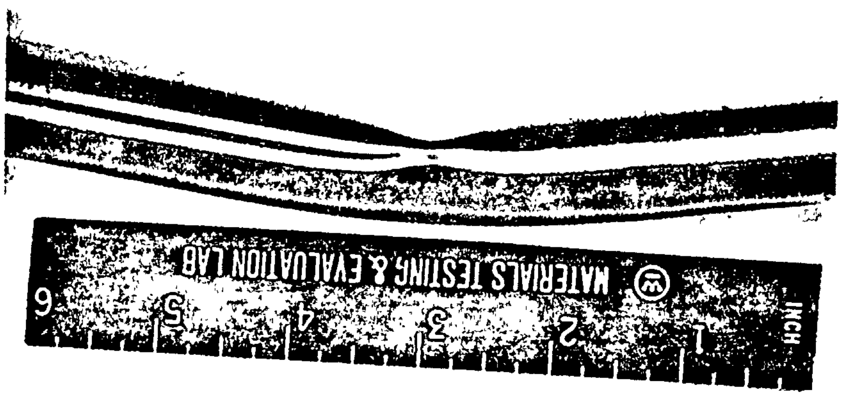


Photo 3 Dynamic Collapse Tube Test System

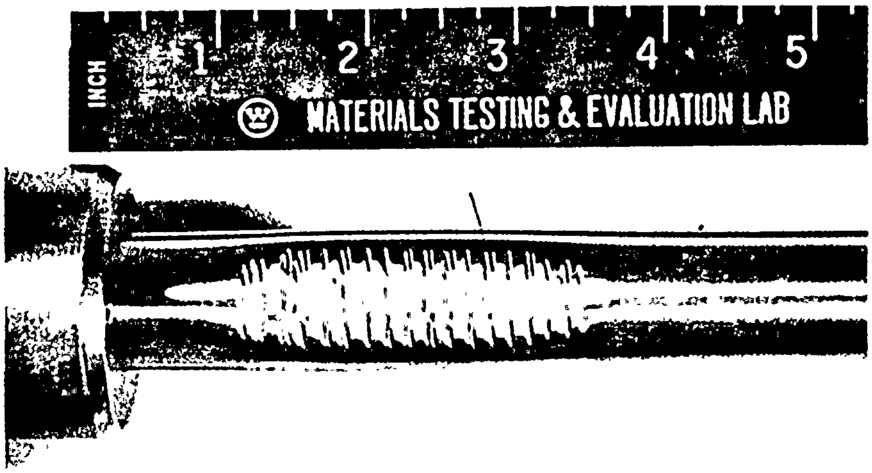


a.



b.

Photo: 4 1/8 x 1.0 in. Chisel Bench Test Specimen After Testing



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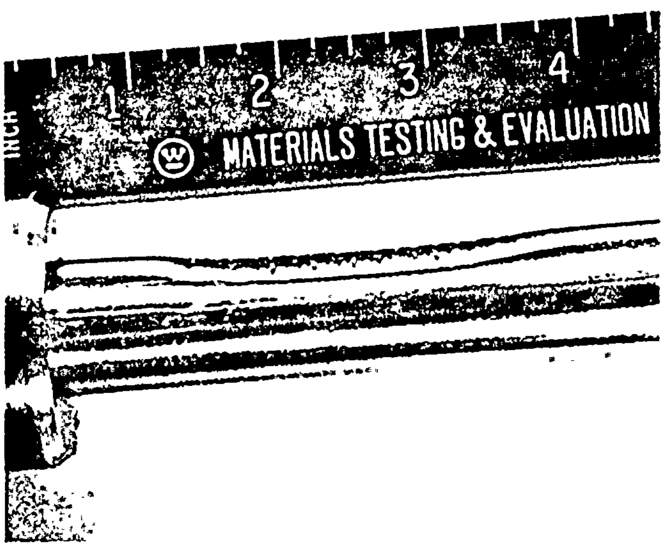
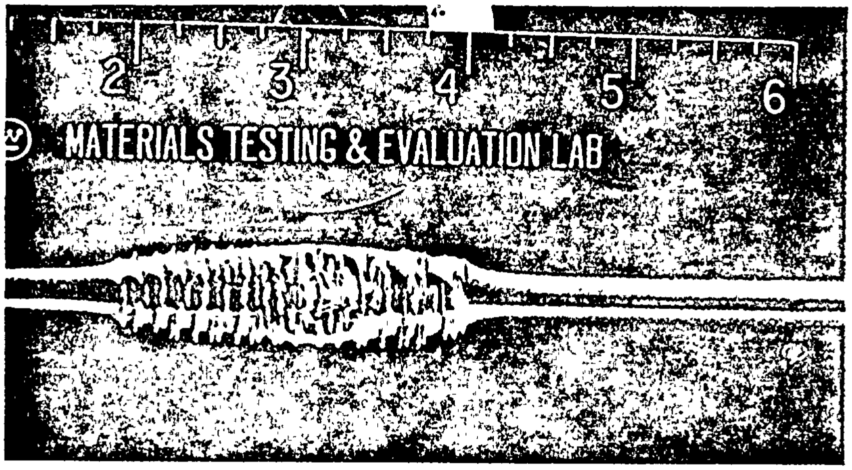
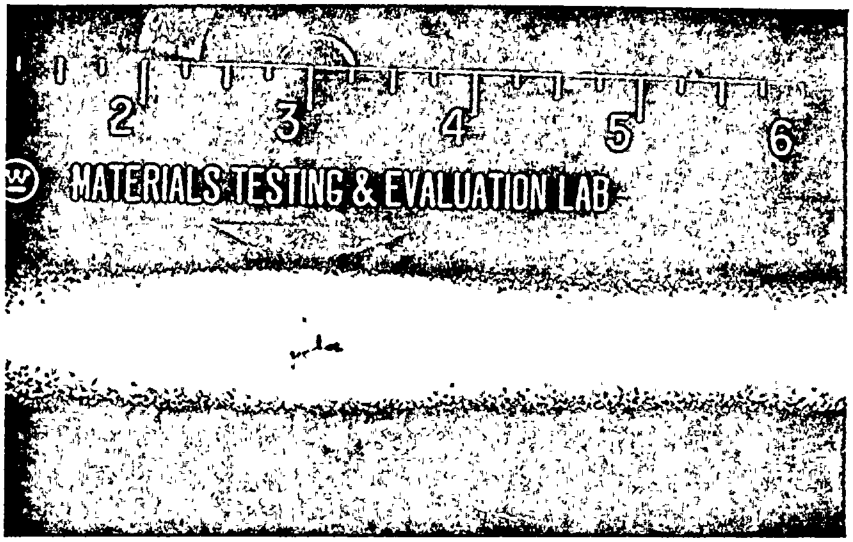


b.

Photo: 5 Sharp Edge Chisel-Tube Specimen After Impact Sequence Tests



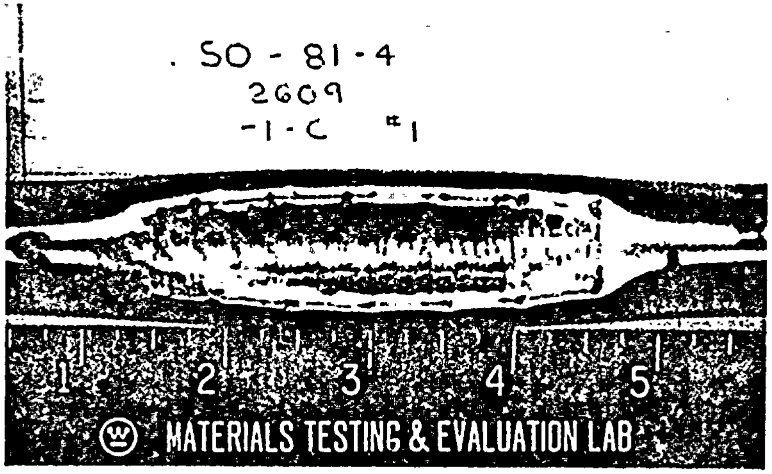
a. Specimen After 1/4 x 1/4 Impactor Tests



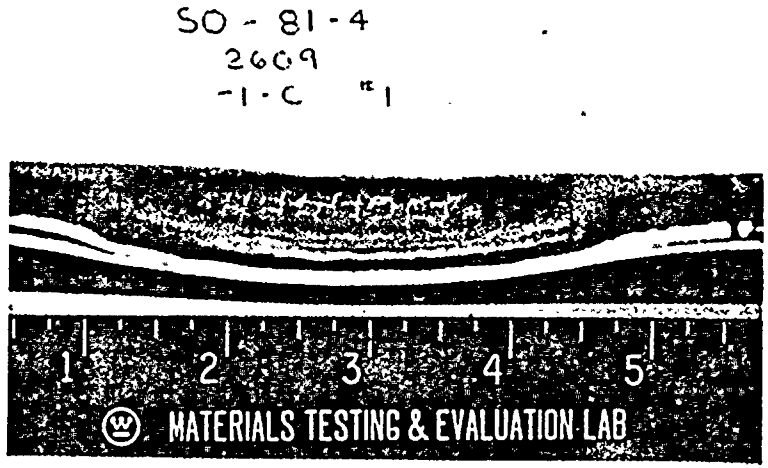
b. Dye Penetrant Test Showing Fatigue Crack

Photo: 6 Sharp Edge Chisel-Tube Specimen After 1/4 x 1/4 Impactor Test - Showing Fatigue Crack

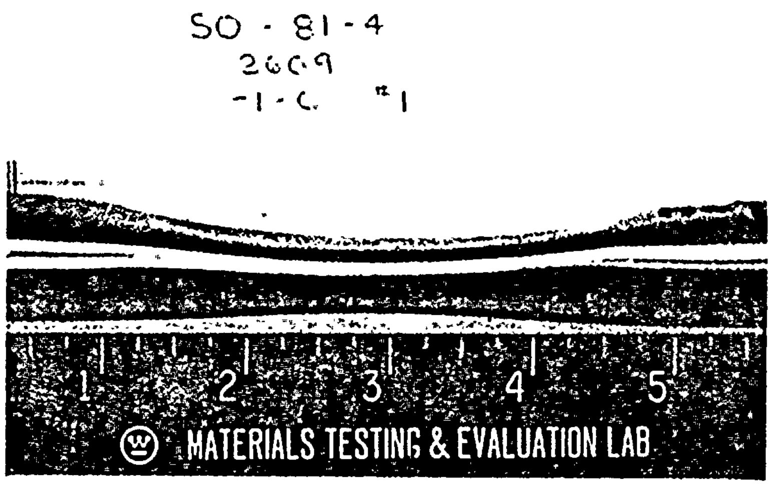
RM-97493



a.



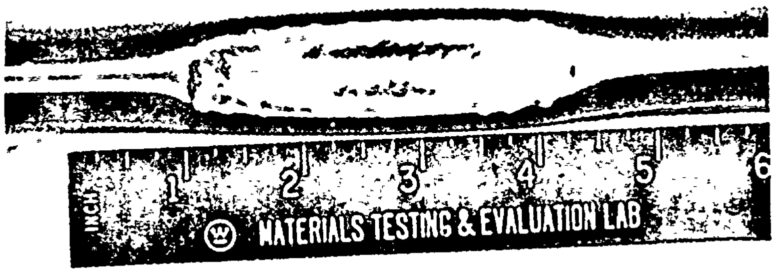
b.



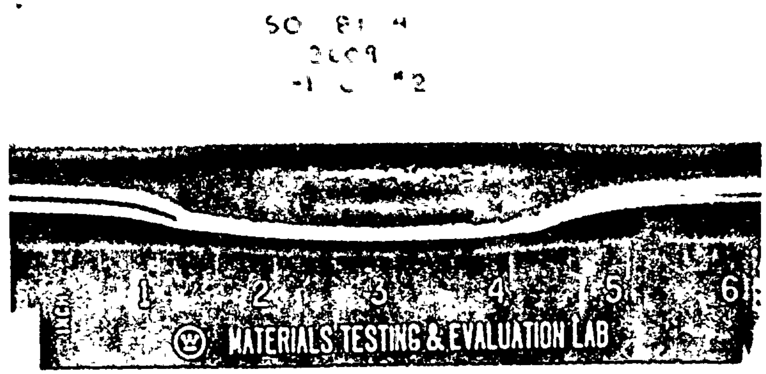
c.

Photo: 7 Dynamic Impact Test No. 3 Tube Specimen After Tests

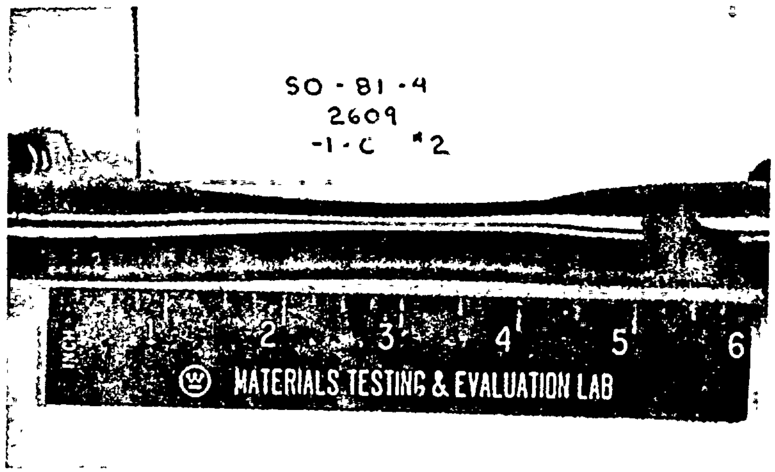
RM-97494



a.



b.



c.

Photo: 8 Dynamic Impact Test No. 4 Tube Specimen After Tests

RM-97495

[illegible]