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**Development of High-Pressure Diaphragms  
for the AEDC Impulse Tunnel**

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Calspan Corporation/AEDC Operations

February 1994

Final Report for Period October 1991 – October 1993

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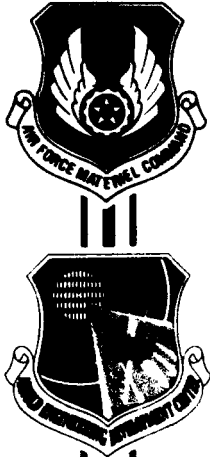
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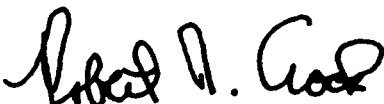
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**PREFACE**

The work reported herein was performed by Arnold Engineering Development Center (AEDC), Air Force Materiel Command (AFMC), under Program Element 65807. The Air Force Program Manager was Capt. P. Zeman, DOT. The work was performed by Calspan Corporation/AEDC Operations, aerospace flight dynamics test support contractor at AEDC, AFMC, Arnold Air Force Base, TN. The work was performed in the Technology and Development Facility (TDF) under AEDC Project Number 0116 during the period October 1, 1991 to October 1, 1993. The manuscript was submitted for publication on February 4, 1994.

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## 1.0 INTRODUCTION

The AEDC Impulse Tunnel (Ref. 1) is a relatively new facility designed to operate at pressures up to 10,000 bars. This operation will require diaphragms with burst pressures up to approximately 6,900 bars. The shock tube is driven by a driver gas compressed by a free piston with use of the powder chamber, pump tube, and high-pressure section of the AEDC impact hypervelocity launcher.

Experience with the hypervelocity launchers in the AEDC ranges has shown that flat burst diaphragms do not open properly above approximately 1,500 bars. This is a result of the required petal thickness as compared to the opening diameter for these flat diaphragms. Petals which are thick compared to the opening diameter typically tear at the corners of the petals. This can result in loss of petals during operation with resultant damage to the facility hardware. Type 304 stainless steel has typically been used for these flat diaphragms because of its combined ductility and strength.

This report documents the development of an impulse tunnel diaphragm design which has been tested at burst pressures up to 6,800 bars.

## 2.0 DESIGN DEVELOPMENT

Consideration of principles for design of high-pressure vessels led to a diaphragm of high-strength material made in a domed or hemispherical shape for burst pressures above 1,500 bars. Recent extension of these design principles has led to development of a diaphragm design with burst pressures up to 6,800 bars (98,000 psi) with full opening characteristics.

The standard design approach for diaphragms for the Range G hypervelocity two-stage launchers has been a flat plate with grooves or scoring on the downstream side to form uniform petals during rupture. This approach has proven to be the least expensive to manufacture. Typically, the material chosen for the flat diaphragms has been type 304 stainless steel rolled plate because of its combination of strength, ductility, and cost. Considerable plastic deformation at the base of the petals is required for the petals to open into a round tube without excessive tearing at the corner of the petal base. Excessive tearing can result in petal loss during opening and possible shock tube damage. The diaphragms currently used in the large two-stage launcher (63.5-mm launch tube) at AEDC typically are of the six-petal design as compared to the more standard approach with four petals. The six petals reduce the tearing and the tendency to lose petals during the launch cycle.

A flat diaphragm design for pressures up to 1,520 bars (22,000 psi) is shown in Fig. 1. Figure 2 is a pretest photo of a flat diaphragm.

The development of the high-strength material shaped diaphragms was an extension of work done by M. D. Prince and J. R. Stewart, circa 1960, in a 40-mm combustion gun at AEDC. Burst pressures up to 3,650 bars were obtained with diaphragms made from heat-treated ASTM 4130 bar stock. This approach was extended to the 3-in. (76.2-mm) size of the Impulse Tunnel shock tube and to burst pressures of 6,800 bars.

The shaped diaphragm is shown in Fig. 3. The design parameters were selected such that changing the remaining metal thickness (RMT) under the crown to change the burst pressure determined the other dimensions. The RMT under the groove at the crown was maintained at 0.77 of the crown thickness ( $T_c$ ). The thickness at the base of the petals ( $T_b$ ) was 1.3  $T_c$ . The outside radius was 2 in. (50.8 mm) to match the cavity opening of the impulse shock tube. The groove was a 30-deg half-angle with a bottom radius of approximately 20 percent of groove depth. The groove depth was constant around the dome. Material was ASTM 4340 round bar stock heat-treated to Rockwell c 34-36. A pretest photo of a shaped diaphragm is shown in Fig. 4.

### 3.0 TEST PROCEDURE

The testing phase for development of the diaphragms was accomplished by use of a gunpowder-driven pressure device as shown in Fig. 5. Design maximum pressure for the device was 7,600 bars. The pressure chamber was adapted from an existing powder chamber with a volume of approximately 2,600 cc (160 in.<sup>3</sup>). Two pressure transducer ports were used to minimize the chance of data loss, should one fail. Ignition of the powder charge was with a U. S. Army electrically actuated M83 primer. The first two tests were with IMR 4198 powder. For the other tests, IMR 4350 was used, since the 4198 burned more rapidly than desired. The bore diameter and length that the diaphragm petals opened into matched the configuration of the Impulse Tunnel, as did the bore downstream of the diaphragm. The powder gas was vented sideways to minimize the recoil of the device. Pressure in the test tank was pumped to 10 torr or less to minimize the blast effects from the charge.

The compression of the driver gas for the piston-driven Impulse Tunnel is a multiply-reflected shock process. The driver gas used is helium. Therefore, it is not possible to fully duplicate with a simple gunpowder-driven device conditions to which the diaphragm is subjected in the Impulse Tunnel. Figure 6 shows the pressure versus time profile for a diaphragm test at 2,930 bars (42,500 psi). Rise time is approximately 2 msec. Effective burst pressure is read as the peak of the curve produced by the pressure transducer. Superimposed on this trace is a pressure versus time profile computed by the method of J. Maus (Ref. 1) for an Impulse Tunnel run with a diaphragm release pressure of 3,100 bars (45,000 psi). Zero on the time scale is the start of the computation. Overall rise times are similar, but the shock pattern is considerably different from the pressure profile of the test rig.

## 4.0 TEST RESULTS

Nineteen tests were made with the diaphragm test device: seven with flat diaphragms, and the remainder with shaped diaphragms. Table 1 summarizes the results. The data are plotted as burst pressure versus the ratio of remaining metal thickness at the crown to the radius of the cavity into which the diaphragm opened ( $RMT/R_i$ ). The results for the shaped 4340 diaphragms with a linear curve fit to the data are presented in Fig. 7. The results for the flat 304SS diaphragms with the same parameters and a linear curve fit are presented in Fig. 8. Based on a limited number of data points, the performance seems to be quite linear with respect to the ratio of  $RMT/R_i$  over a wide pressure range for both types of diaphragms. This will allow simple linear scaling of diaphragms to other tunnel or launcher sizes.

The first series of tests were of six-petal design for both the flat and shaped diaphragms. Figure 9 is a posttest photo of a 1,600-bar release pressure shaped diaphragm. As shown in the figure, the lower burst pressure shaped diaphragms tended to open as a three-petal design, with considerable tearing at the corner of the petals. Full area opening was obtained on all the shaped diaphragms tested to date. Figure 10 is the posttest photo of a 4,560-bar release shaped diaphragm which shows opening of all six petals. After the first manufactured batch of diaphragms was tested, which extended through Test 12, the shaped design was changed to four petals.

The failure mode of the ASTM 4340 material was the classical 45-deg shear mode. As the failure progressed along the groove from crown to base, the failure tended to switch back and forth from one 45-deg plane to the other. With each switch, some material was observed to have been lost from the petals. This phenomenon was more prevalent for the thicker, higher-pressure diaphragms. Figure 11 is a photo of the worst case (burst pressure of 6,160 bars), which clearly shows the ragged edge which was produced.

Loss of pieces of material from the diaphragm can damage both tunnel hardware and test models. A shaped diaphragm (Fig. 12) was fabricated with the grooves inside by the electrical discharge machining process. This diaphragm burst at 6,790 bars. The photo of Fig. 13 shows that the shear reversal was eliminated, but more tearing was produced at the base of the petals.

Two shaped diaphragms were fabricated from 304SS bar stock with the maximum petal thickness that can be used in the Impulse Tunnel without restriction of the flow area. These opened at 3,220 and 3,280 bars with the data points shown in Fig. 7. Figure 14 is a photo of one of these which shows a tensile failure along the grooves and a very low loss of material. Thus, 304SS is a viable material alternative up to approximately 3,300 bars for the shaped diaphragms.

Six flat diaphragms were tested before the calibration runs of the Impulse Tunnel. None of these diaphragms opened completely. Figure 15 is a photo of the 745-bar diaphragm test which shows that two of the three grooves did not fail on one side of the centerline. Figure 16 is a photo of the 1,470-bar diaphragm. Full groove failure was obtained, but full opening was not. It was not known if the Impulse Tunnel, which has a much larger gas reservoir and uses helium instead of powder gas, would produce more or less satisfactory diaphragm opening characteristics. This design was used for the first Impulse Facility run. Figure 17 is a photo of the result, which was obviously less than satisfactory. The design was then changed to four petals and a high ratio of  $RMT/T_c$  (0.70). A view from upstream of the diaphragm with a burst pressure of 1,400 bars from an Impulse Facility run is shown in Fig. 18. Full opening was obtained, but severe tearing is visible at the corners of the petals. Thus, it appears that there is not a large margin between full opening characteristics and loss of petals for flat diaphragms for pressures near 1,400 bars.

In the past, flat diaphragms have typically been fabricated from rolled, annealed plate stock. To expedite the fabrication of the flat diaphragms for the test device, some of the diaphragms were fabricated from round bar stock. A different grain structure should be expected under the grooves for the two different material sources. Records of which were made from plate and which were made from bar stock were not kept.

Most of the flat diaphragms from the test device appeared to fail in tension, whereas the diaphragms from the actual tunnel runs appeared to fail in the 45-deg shear mode. This difference in diaphragm opening characteristics is, at present, unresolved.

A flat diaphragm made from Rc 34-36 ASTM 4340 was tested (No. 13, Table 1) to determine if it was possible to significantly extend the operational range of flat diaphragms. This diaphragm opened at 2,620 bars, but lost all of the petals during the opening process. This approach was then deemed unsatisfactory and was abandoned.

## 5.0 SUMMARY

Shaped diaphragms may be fabricated for burst pressures up to 6,800 bars when they are made of high-strength material. A nearly linear relationship between the burst pressure and the nondimensional ratio of the remaining metal thickness under the groove to the radius of the cavity opening allows linear scaling of the results to different size facilities for both the flat and shaped diaphragms. Grooves on the inside of the hemispherical shape can be used to reduce the tendency for particles to be ejected during the opening process, although at an increase in fabrication cost. The four-petal design gave more satisfactory opening characteristics than the six-petal model.

Flat plate diaphragms with four petals have been used successfully up to 1,400 bars in the Impulse Tunnel. Severe tearing at the base of the petals at this condition indicates that this is near the maximum operating pressure for flat diaphragms made from 304SS. Contrary to experience with the two-stage hypervelocity launchers in Range G, six-petal diaphragms do not work satisfactorily in the Impulse Tunnel.

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1. Maus, J. R., Laster, M. L., and Hornung, H. G. "The G-Range Impulse Facility, A High Performance Free Piston Shock Tunnel." AIAA-92-3946, AIAA 17th Aerospace Ground Testing Conference, July 6-8, 1992, Nashville, TN.

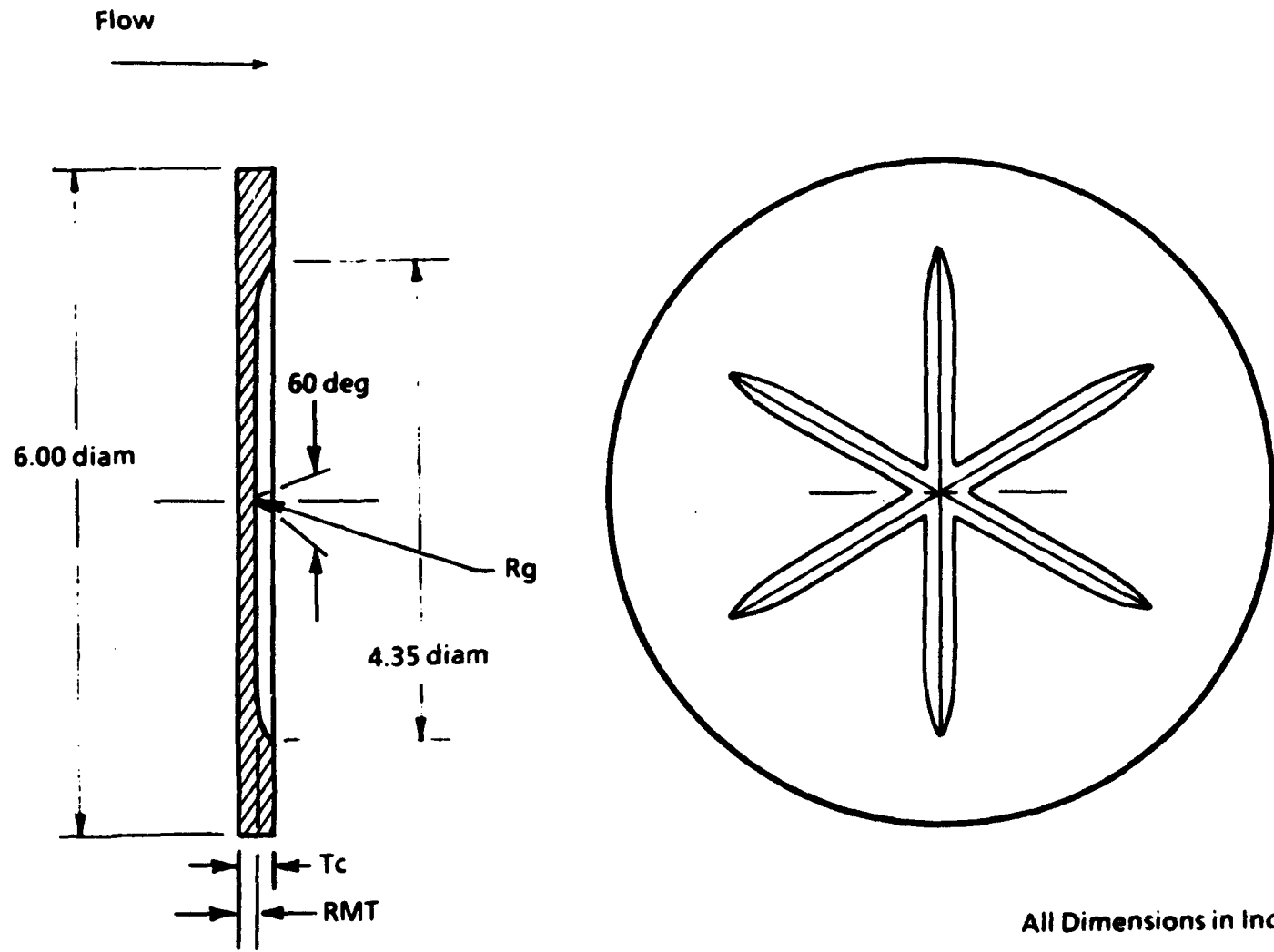


Figure 1. Flat Diaphragm dimensions.

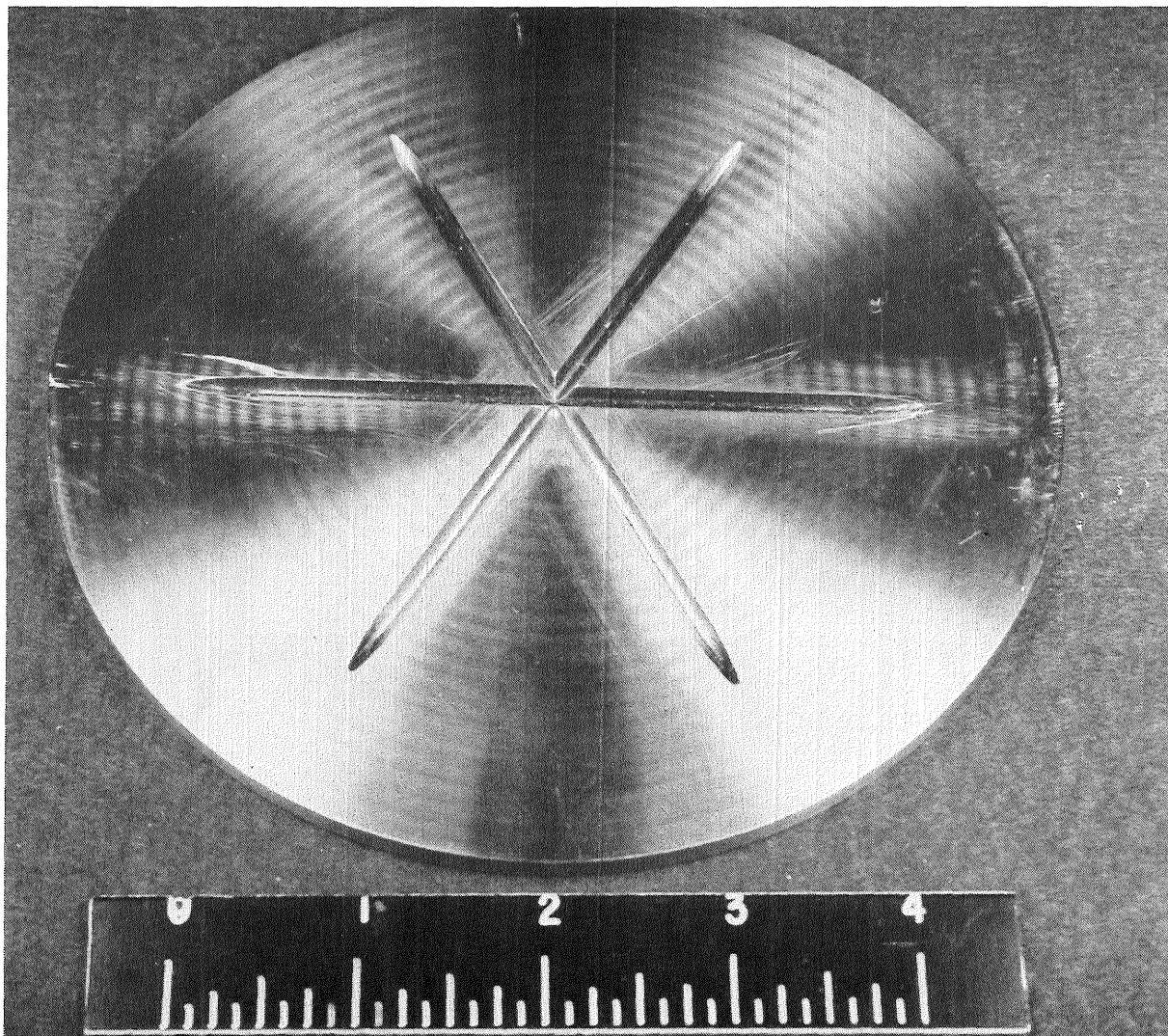


Figure 2. Pretest photo of flat diaphragm.

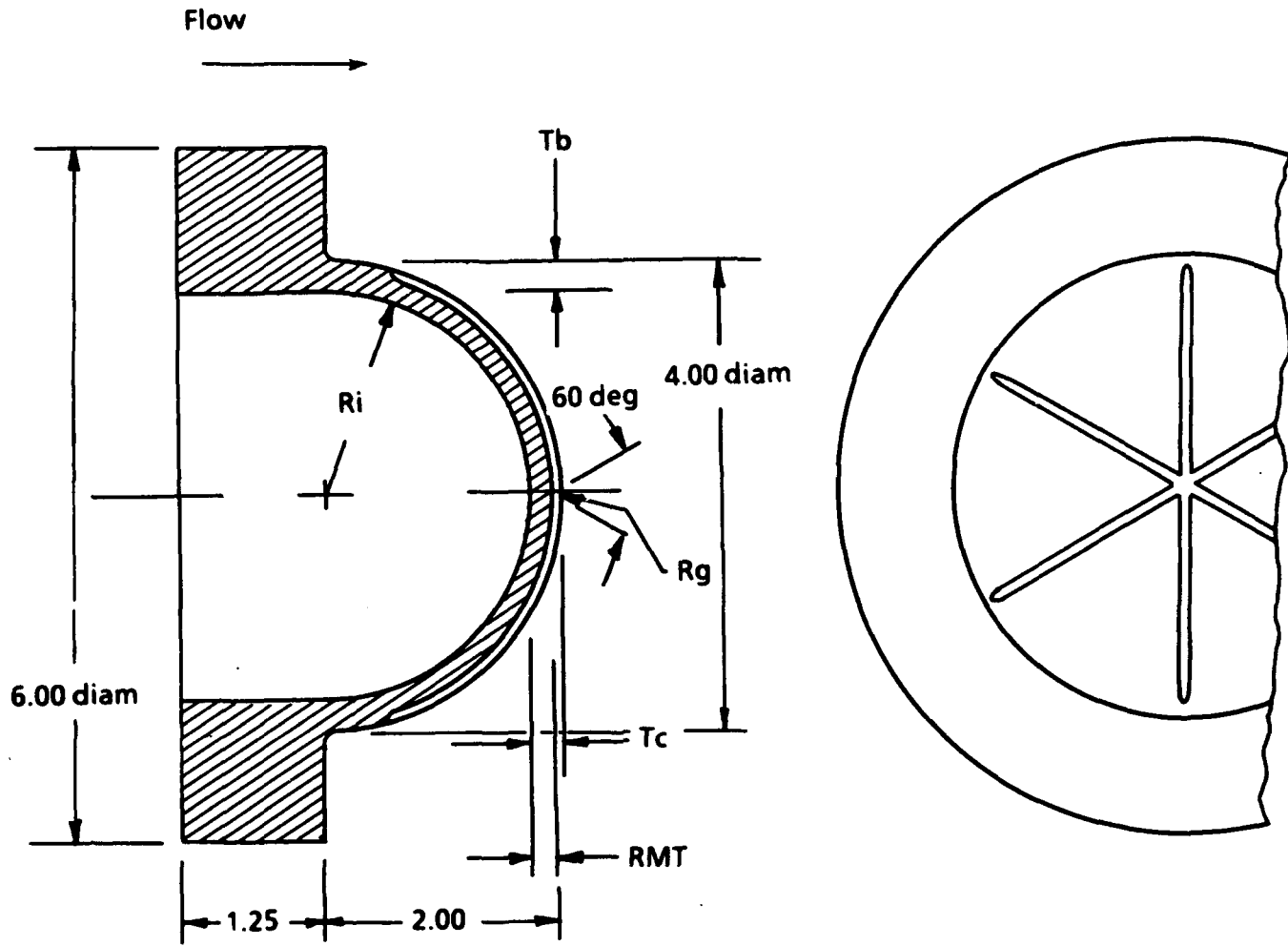


Figure 3. Shaped diaphragm dimensions.

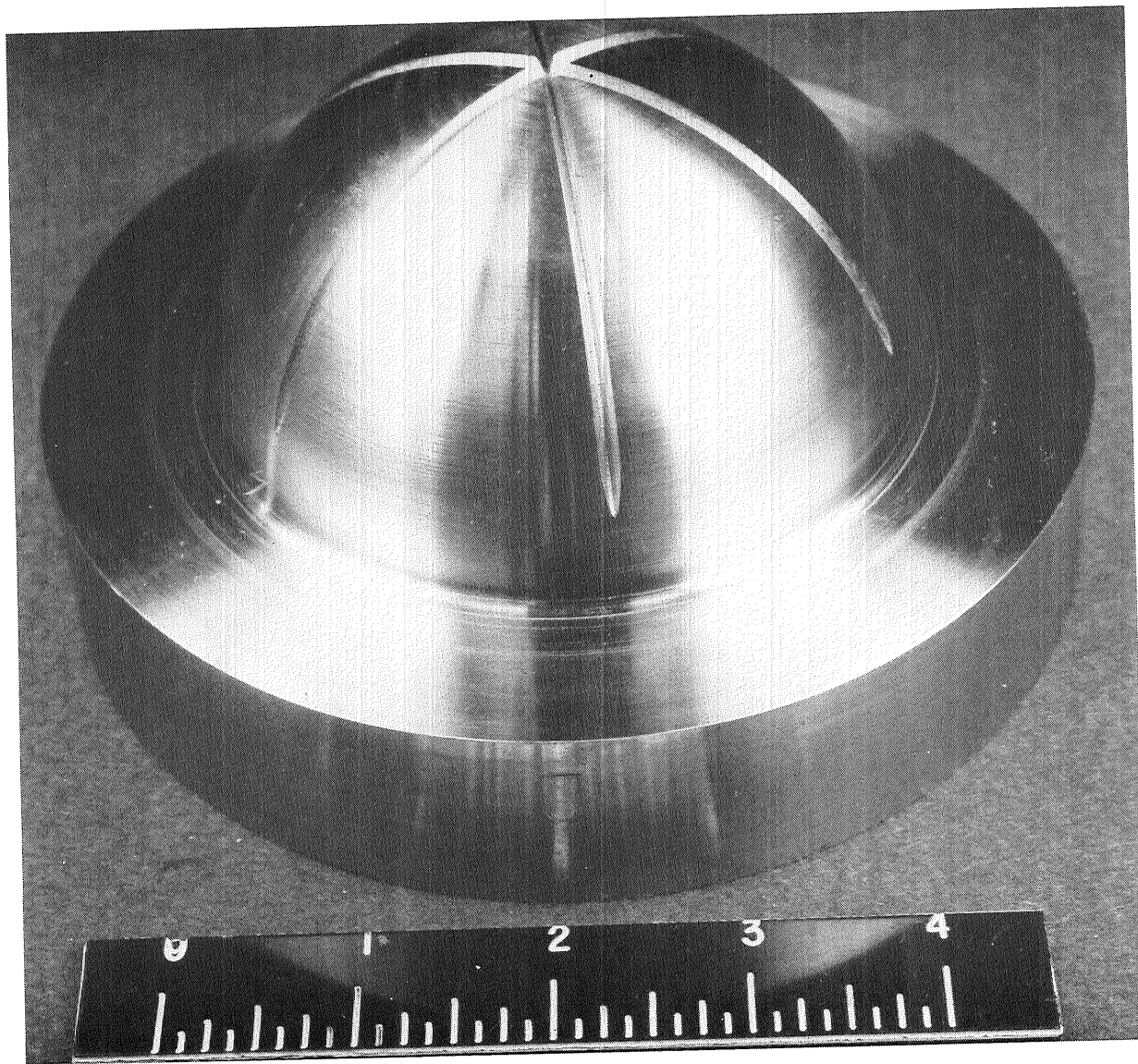


Figure 4. Pretest photo of shaped diaphragm.

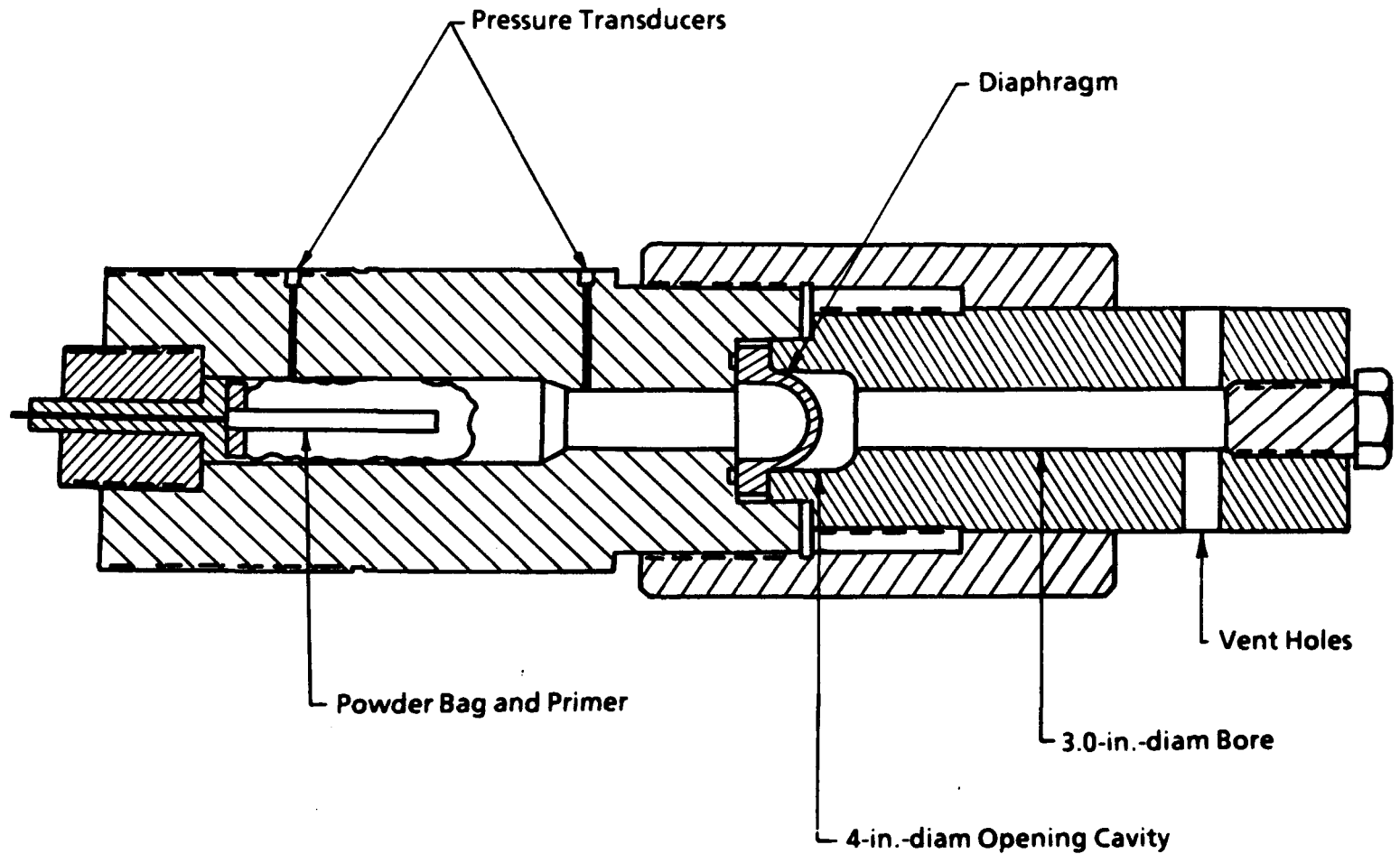


Figure 5. Diaphragm test device.

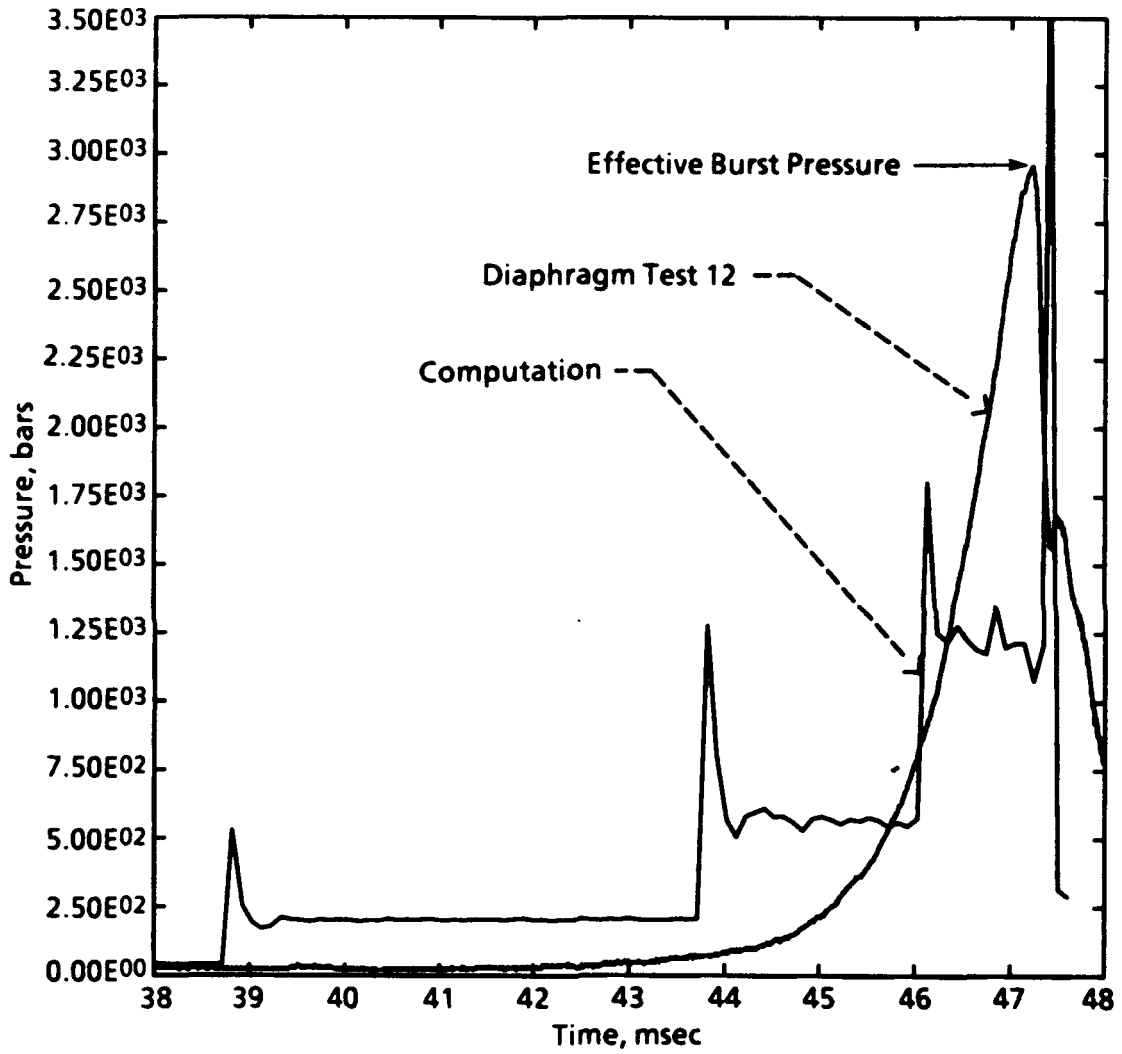


Figure 6. Pressure versus time for test device and impulse tunnel.

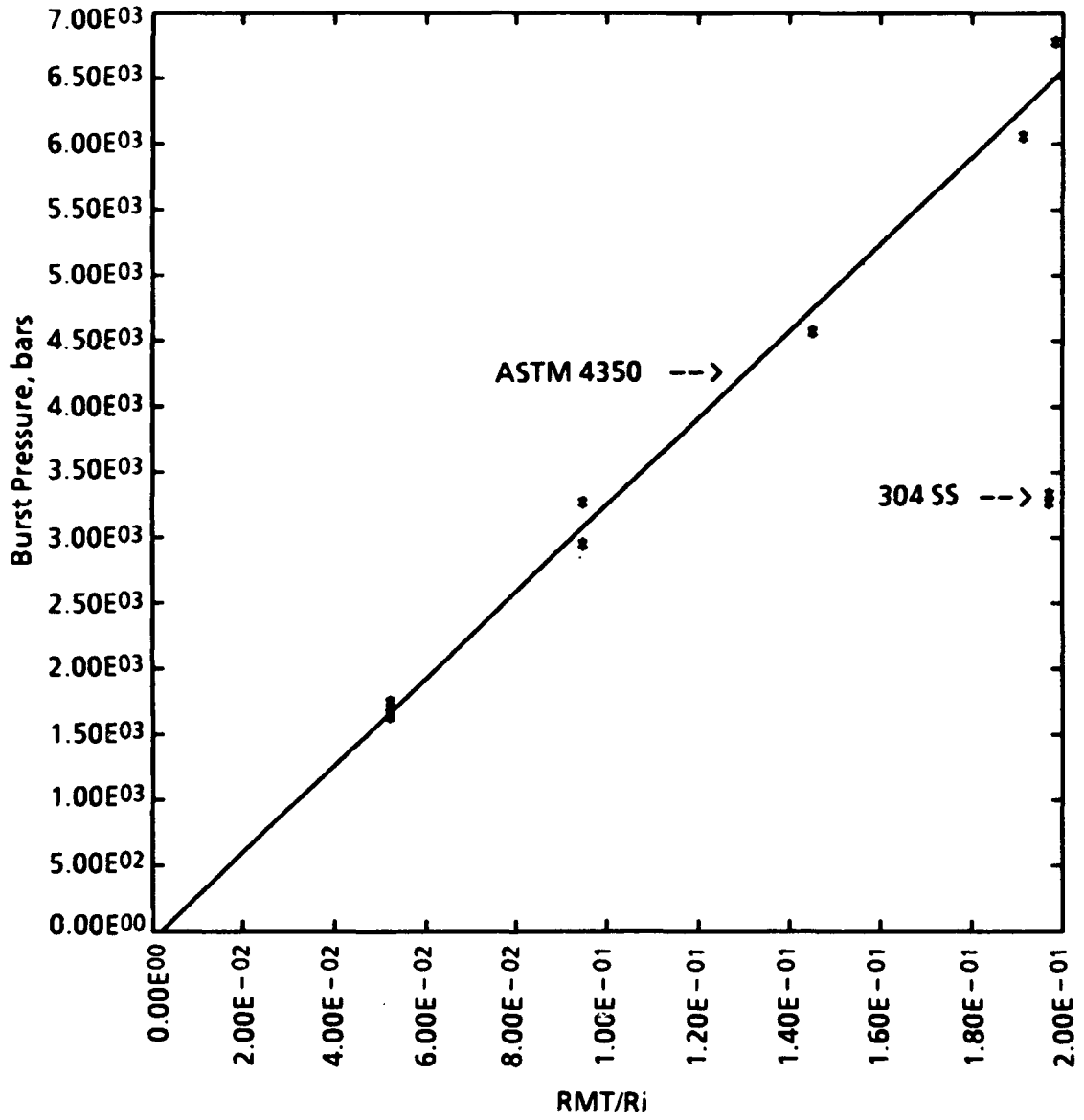


Figure 7. Burst pressure versus RMT/Ri for shaped diaphragms.

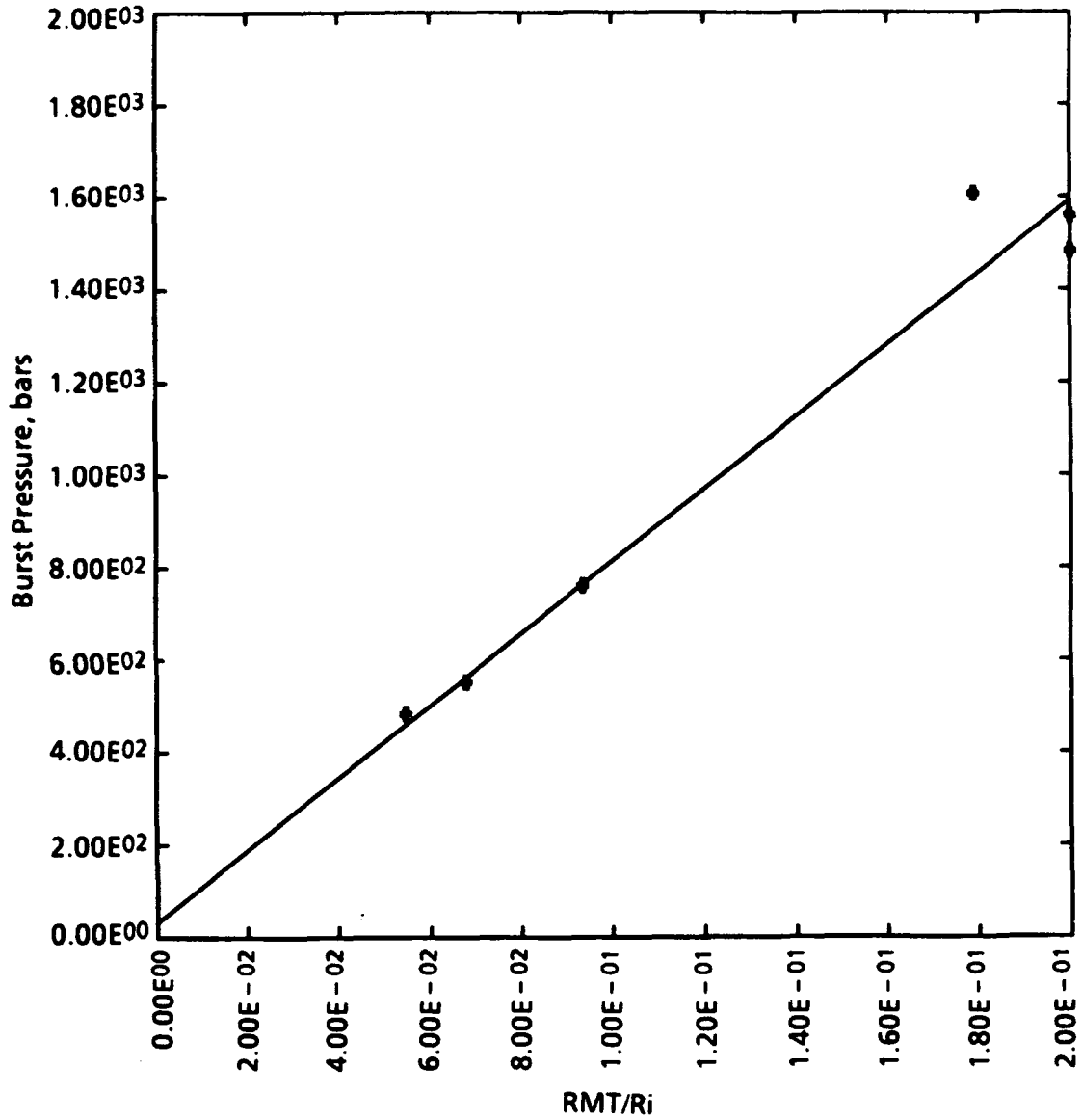
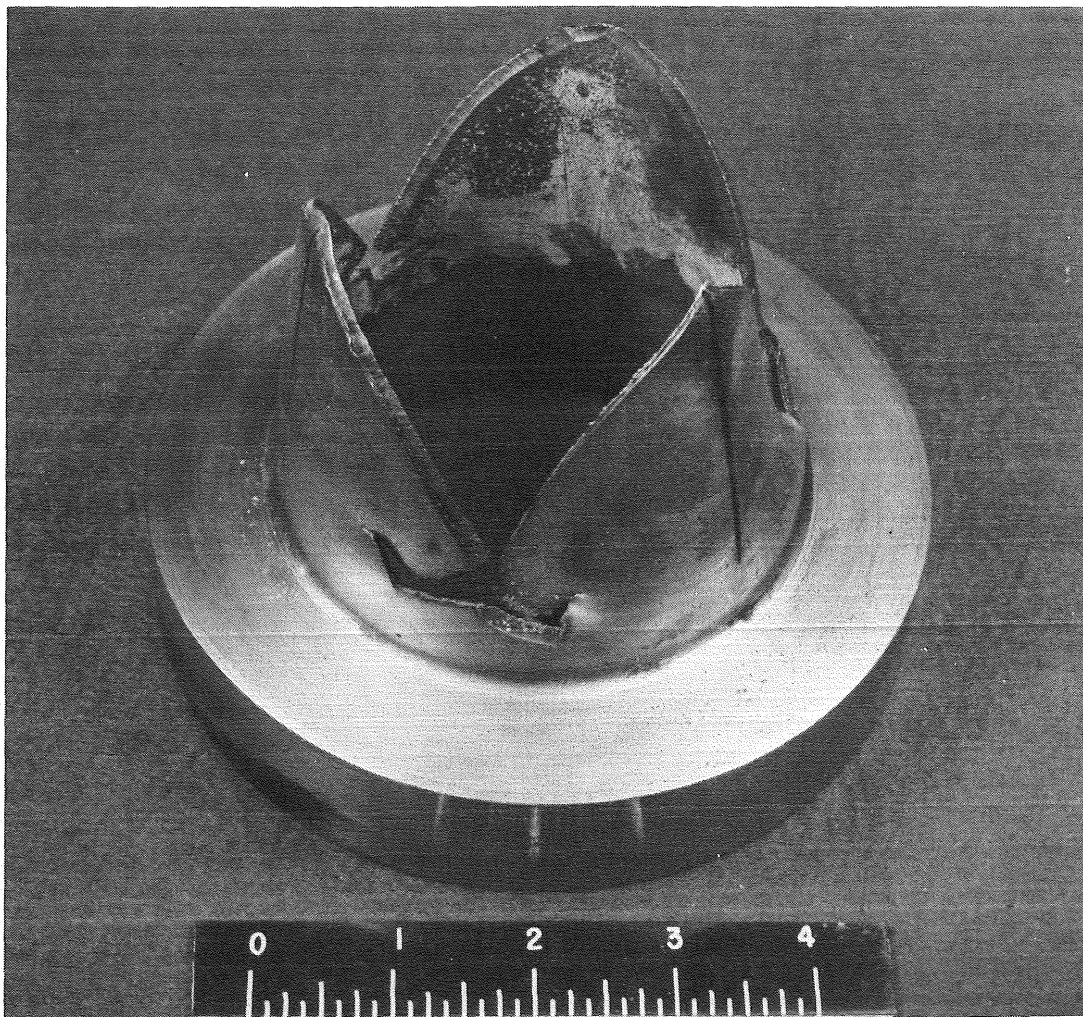
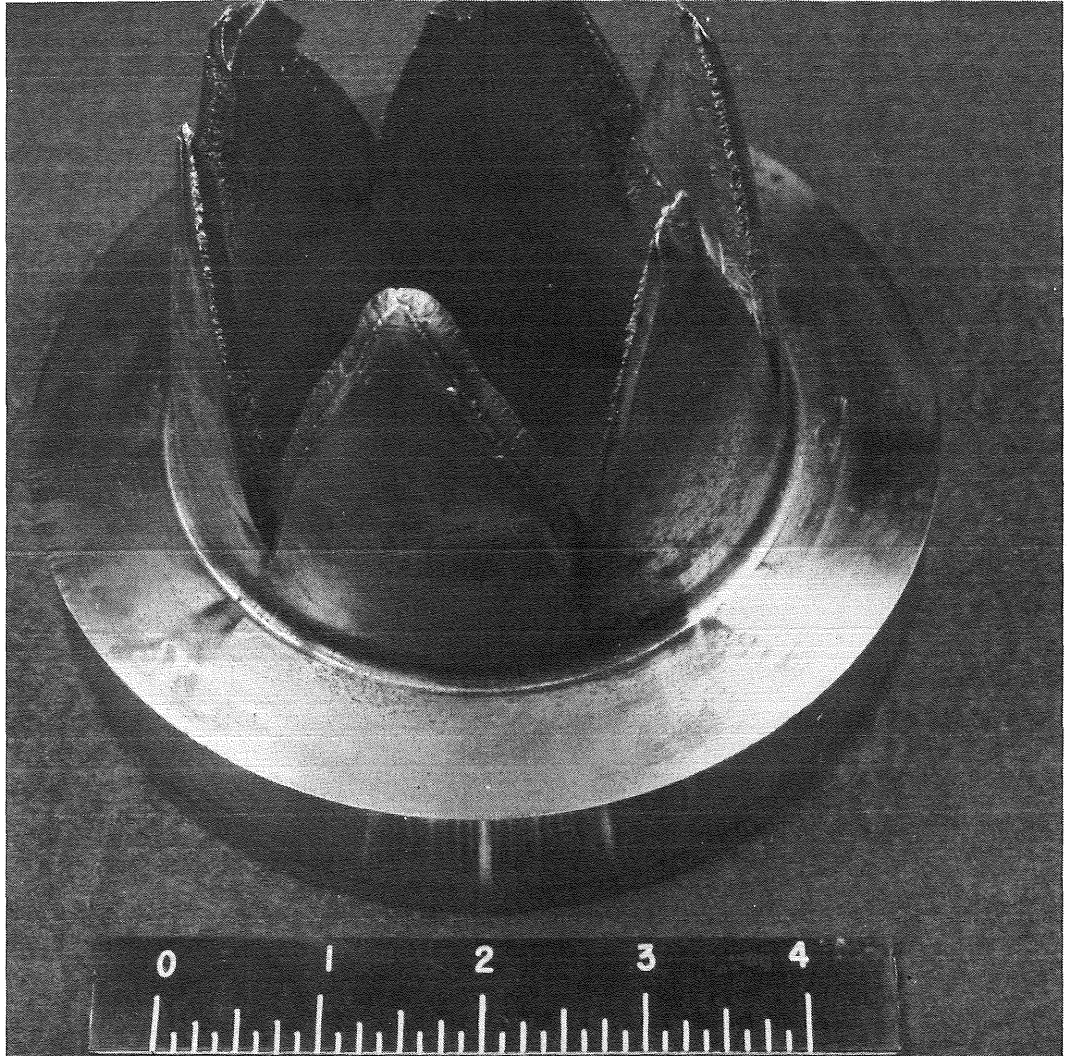


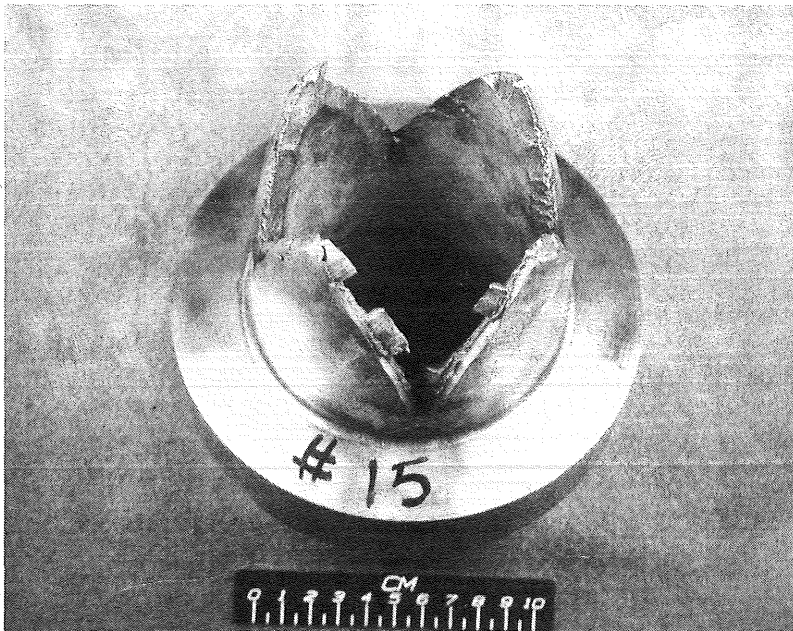
Figure 8. Burst pressure versus RMT/Ri for flat diaphragms.



**Figure 9. Posttest photo of shaped diaphragm, Test No. 3, 1,610 bars.**



**Figure 10. Posttest photo of shaped diaphragm, Test No. 9, 4,560 bars.**



**Figure 11. Posttest photo of worst case ragged edge, shaped diaphragm, Test No. 15, 6,160 bars.**

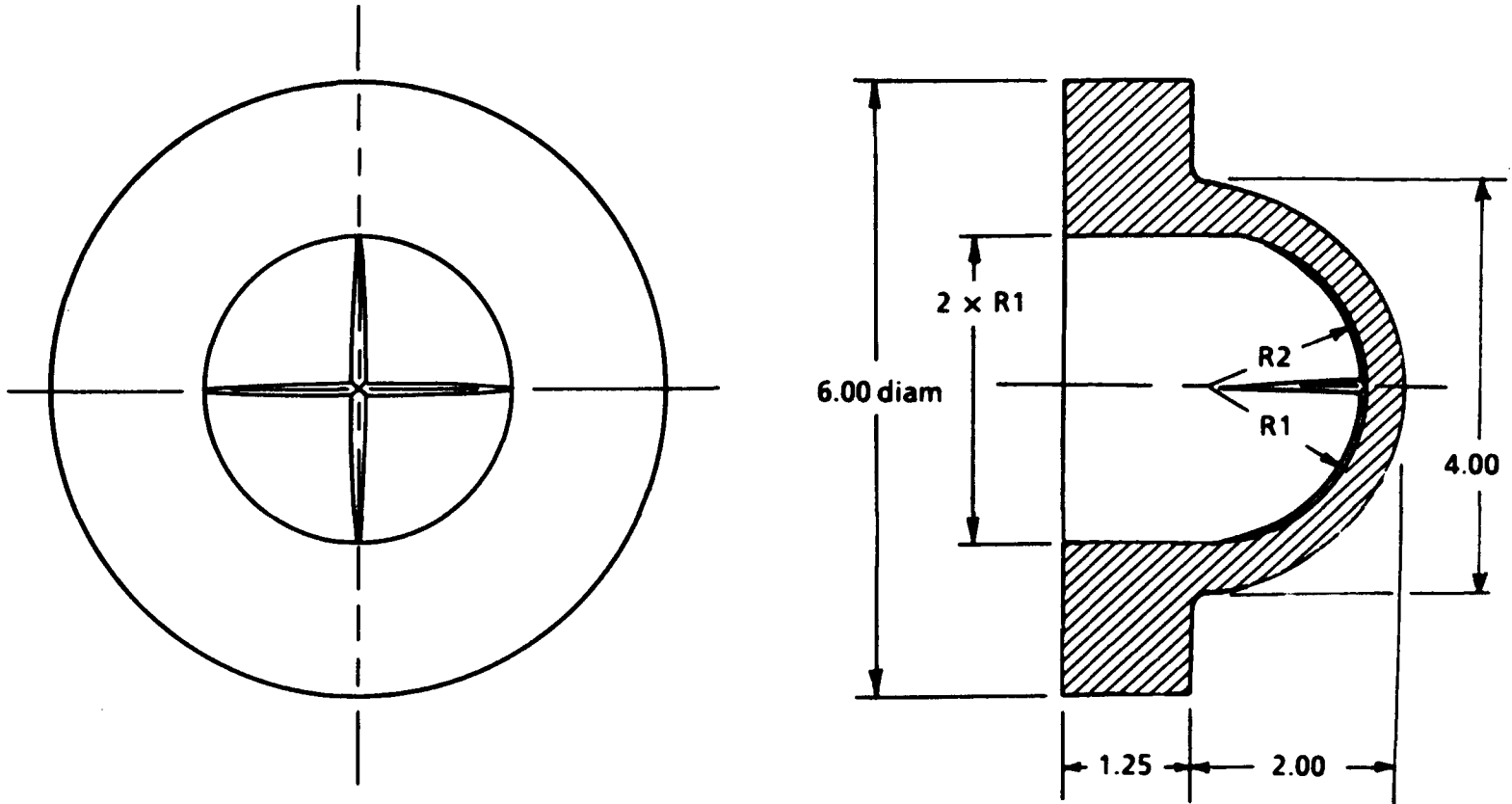
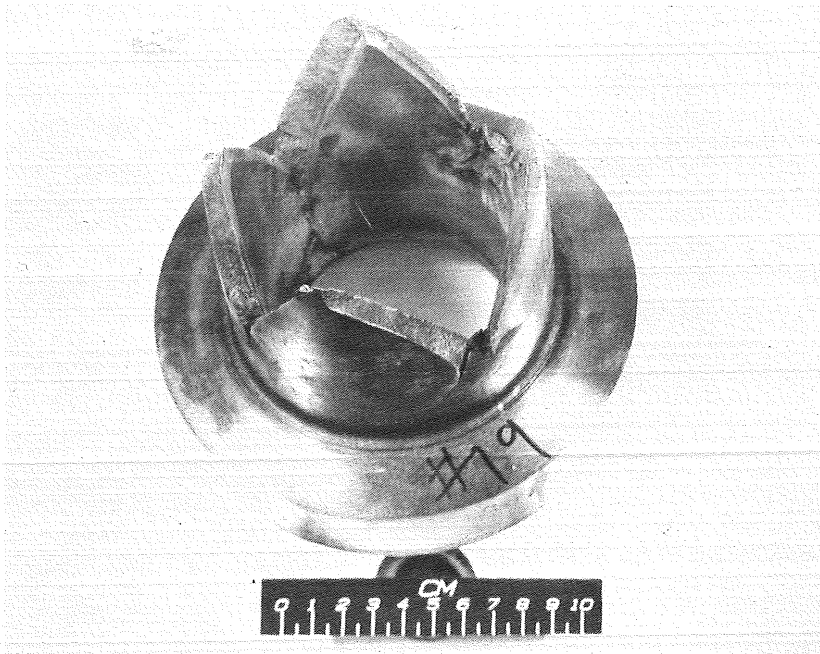


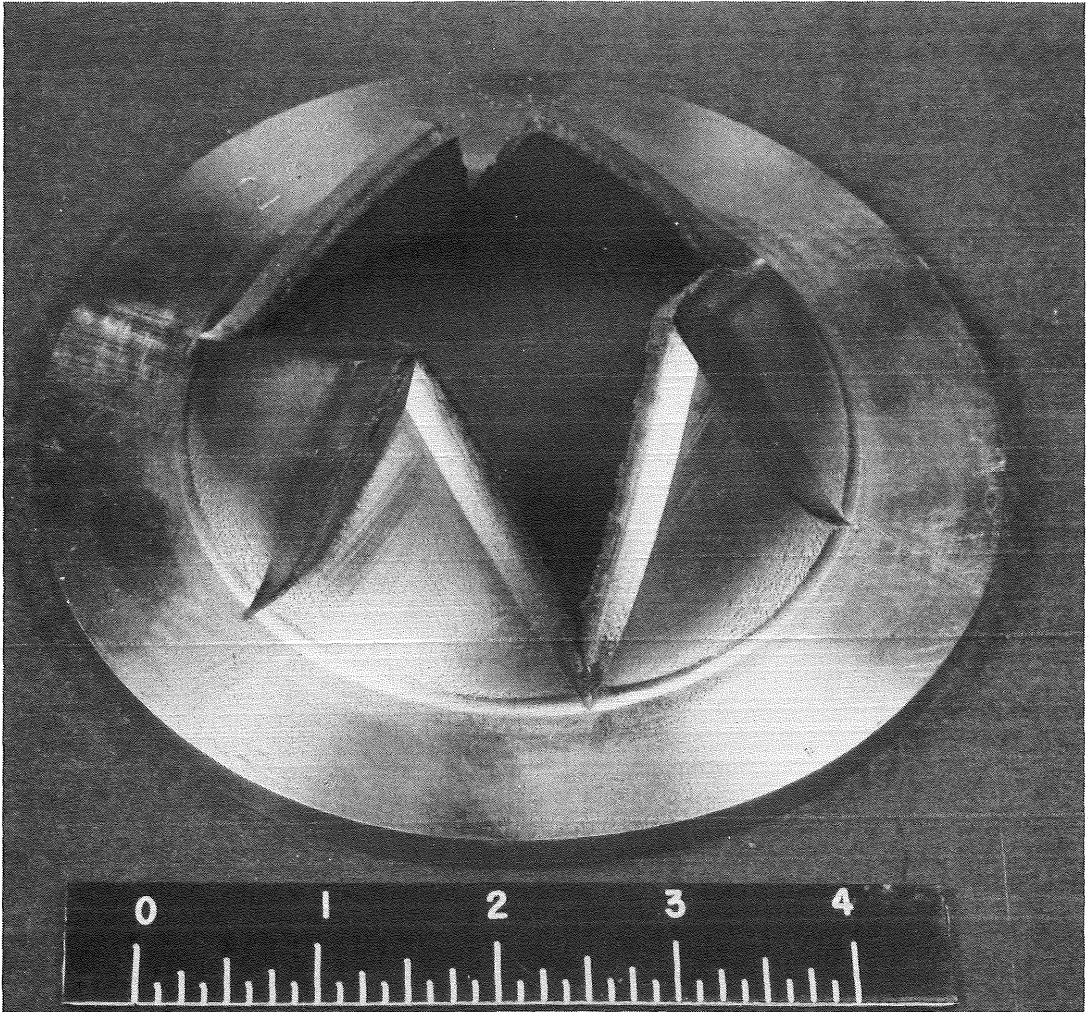
Figure 12. Inside groove-shaped diaphragm dimensions.



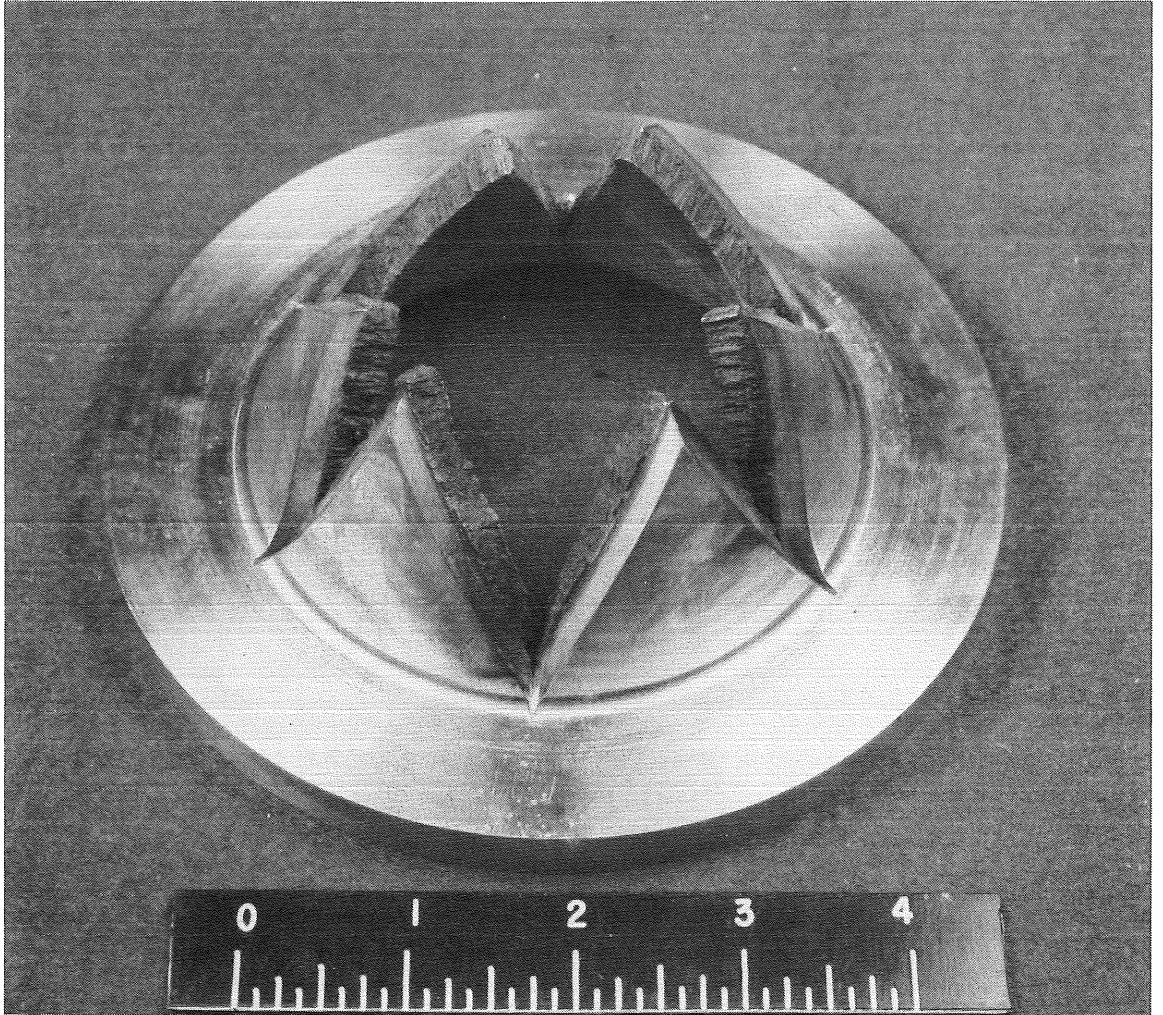
**Figure 13. Posttest photo of inside groove shaped diaphragm, Test No. 18, 6,790 bars.**



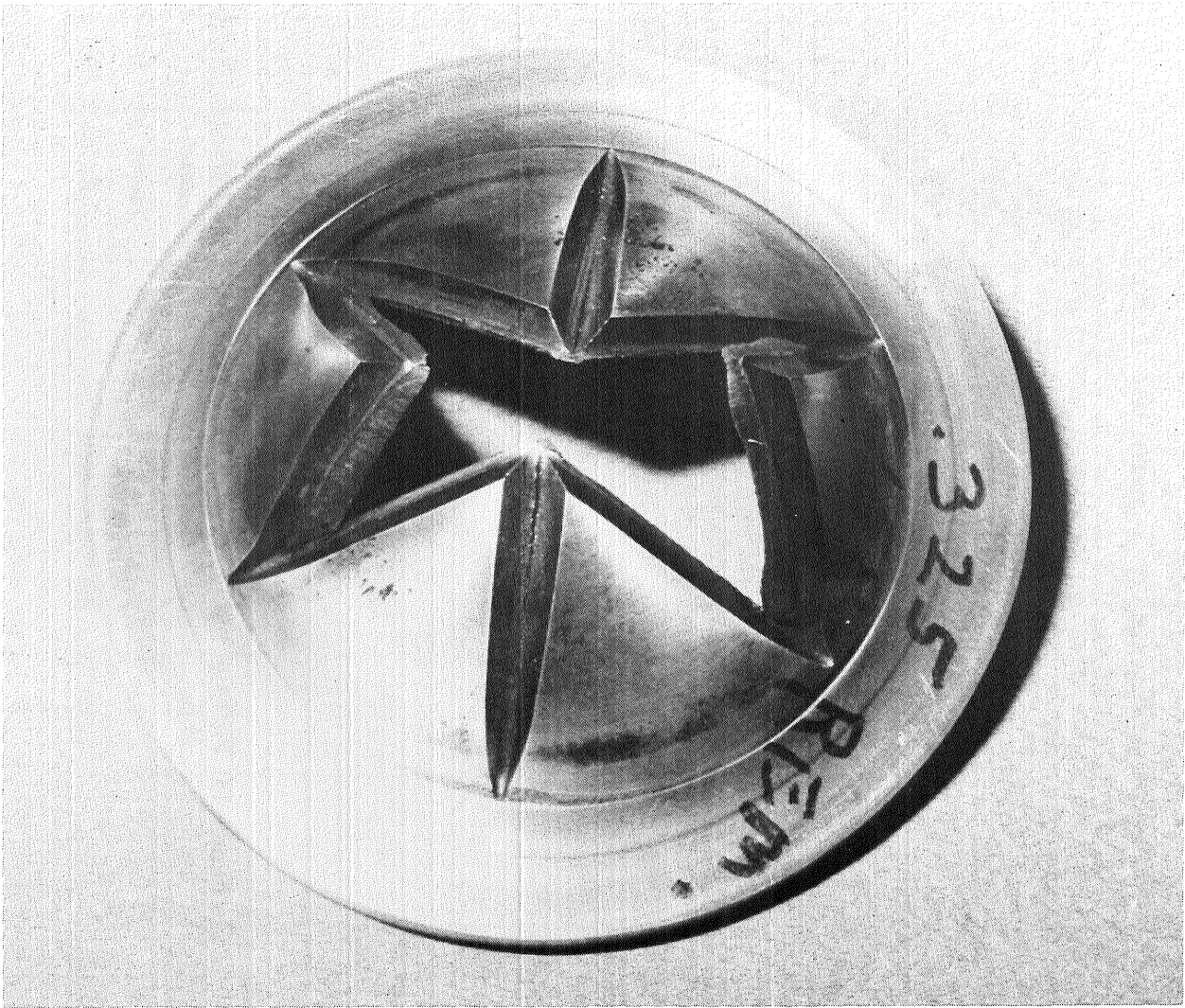
**Figure 14. Posttest photo of 304SS shaped diaphragm, Test No. 17, 3,280 bars.**



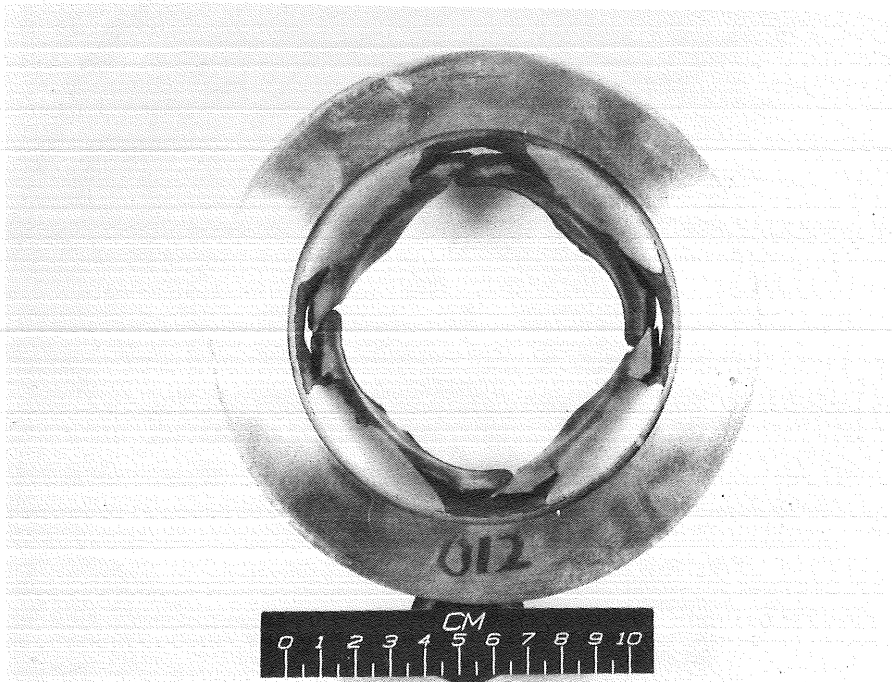
**Figure 15. Posttest photo of flat diaphragm, Test No. 2, 745 bars.**



**Figure 16. Posttest photo of flat diaphragm, Test No. 6, 1,470 bars.**



**Figure 17. Post-run photo of first Impulse Facility run diaphragm.**



**Figure 18. Post-run photo of impulse diaphragm, 1,400 bars.**

**Table 1. Test Results — Diaphragm Test Device**

Test No.	Diaphragm Type	No. of Petals	Measured, Press, bars	Powder Chg, gm	Material	RMT/Tc	RMT/Ri
1	Flat	6	538	200	304 SS	0.6	0.067
2	Flat	6	745	300	304 SS	0.49	0.093
3	Shaped	6	1,610	400	4340	0.77	0.051
4	Shaped	6	3,220	600	4340	0.77	0.0938
5	Shaped	6	4,560	750	304 SS	0.77	0.1441
6	Flat	6	1,470	400	304 SS	0.70	0.200
7	Shaped	6	1,690	400	4340	0.77	0.051
8	Flat	6	469	200	304 SS	0.35	0.054
9	Flat	6	1,540	400	304 SS	0.70	0.200
10	Shaped	6	1,700	400	4340	0.77	0.051
11	Shaped	6	1,590	400	4340	0.77	0.051
12	Shaped	6	2,940	600	4340	0.77	0.0938
13	Flat	6	2,620	600	4340	0.70	0.200
14	Shaped	4	1,610	400	4340	0.77	0.051
15	Shaped	4	6,160	835	4340	0.77	0.190
16	Shaped	4	3,220	600	304 SS	0.77	0.197
17	Shaped	4	3,280	600	304 SS	0.77	0.197
18	Shaped	4	6,790	835	4340	0.77	0.197
19	Flat	4	1,590	400	304 SS	0.70	0.179