U.S. Department
of Transportation
**Federal Railroad
Administration**

Tank Car Frangible Disc Test

**Office of Research and Development
Washington, D.C. 20590**

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16. Abstract

Tests were performed at the Transportation Test Center to evaluate the performance of various frangible disc designs, with respect to AAR Specification A5.03. Tests were also performed to determine the range of burst pressures and effect of temperature, creep, pressure surge, and corrosives on the burst pressure of one lot per disc design. The designs tested were Lead, Lead with Breather Hole, Stainless Steel, and Composites.

It was found that some disc designs have large variations in burst pressure. Lead discs are prone to creep. All disc burst pressures are affected by temperatures, both hot and cold. Composite discs exhibited some damping when exposed to pressure surge cycles.

It was recommended that new frangible disc designs be qualified through a five part test, similar to the one performed here.

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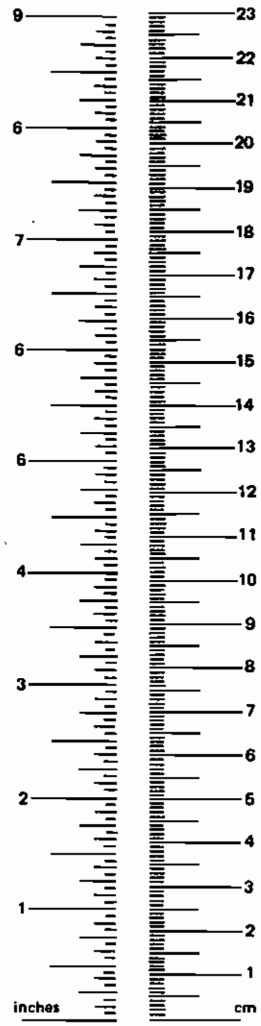
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

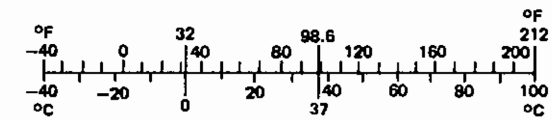
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	16	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286, Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The safe shipment of hazardous materials is an important issue for the U.S. freight railroads. Accidents involving hazardous materials can cause extensive damage and result in serious consequences. In light of these dangers, the Federal Railroad Administration (FRA) has awarded a contract to the Association of American Railroads (AAR) to address the safety of transportation of hazardous materials by rail. One task in this program, Task F, deals with the performance of protective devices such as frangible discs.

A frangible disc acts as a one-time pressure release vent. Some non-pressure tank cars, under Department of Transportation (DOT) classification 103 and 111, are equipped with such vents. The disc separates the contents of the tank car from the outside atmosphere. The disc is designed to rupture at a specific pressure. The rupture of the frangible disc results in the release of internal pressure and reduces the potential for tank failure.

Disc rupture in tank cars, under intended failure modes, may be attributed to several sources. One cause is the large pressure increase due to temperature caused by a fire, perhaps in a derailment situation. The second cause of disc rupture may be the pressure surge created when the car is impacted. This impacting is a common occurrence in railroad yards. The impact of a coupler on the tank itself may also rupture the disc. This may happen during a derailment. Another associated reason for disc rupture is overfilled cars. Undesired disc rupture may be due to the effects of creep, temperature variations, or a corrosive environment on the disc material strength itself. The discs could also fail due to material defects or improper installation.

The AAR requires that disc batches be sampled and tested to insure that appropriate rupture occurs.

2.0 OBJECTIVES

The major objectives of the frangible disc tests were:

1. Determine the rupture pressure distribution when the discs are sampled using the requirement for the qualification of frangible discs as specified by the AAR Manual of Standards and Recommended Practices (A5.03).

2. Determine the pressure at which the disc deformation changed from elastic to plastic, referred to as yield pressure.

3. Determine the effect that temperature has on the rupture of frangible discs.

4. Determine the effect of prolonged exposure to a pressure below the specified rupture pressure of the disc.

5. Determine the effect of a pressure surge or multiple pressure surges on the rupture pressure of a disc.

6. Determine the effect of exposure to corrosive materials on the rupture pressure of frangible discs.

7. Determine how the different types and designs of discs rupture under varying conditions.

3.0 PROCEDURE

Five types of discs, pictured in Figure 3.1, were tested. They were solid lead, lead with a breather hole, a plastic composite, a graphite composite, and a stainless steel design.

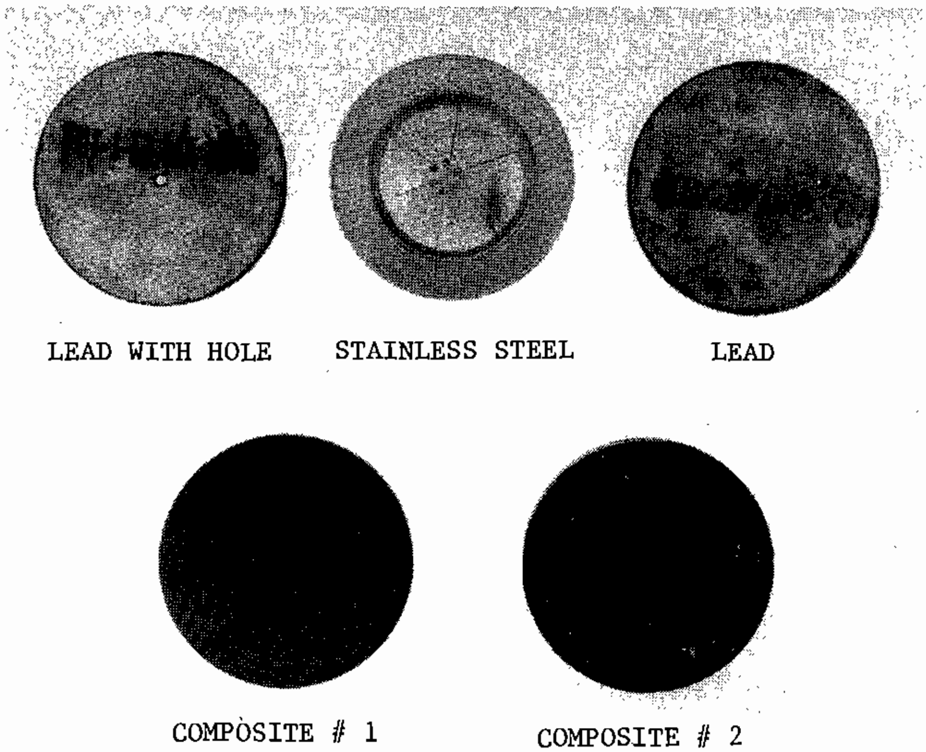

Figure 3.1 Five Types of Frangible Discs Tested.

The thickness of each lead and plastic disc was measured before and after burst testing. The thickness was measured at three locations near the center and three locations around the rim. The average for each was calculated and recorded. A stainless steel disc was taken apart, and the thickness was measured. The average was calculated and recorded. The same was done for a graphite disc. The thickness of each disc was measured after testing with the exception of stainless steel. Only a small number of stainless steel discs were measured after testing because of the destructive nature of the measurement.

The test was broken into six parts which incorporated the seven objectives. A total of 252 discs were tested in the matrix shown in Table 3.1.

TABLE 3.1 FRANGIBLE DISC TEST MATRIX

Test #	Test Description	Lead Mat.	Lead/ Hole	Ryton Comp.	Graph. Comp.	Stain. Steel	Total #/Test
3.1 3.2A 3.2B	Determine range of burst pres.	25 10 10	25 10 10	28 10 10	25 10 10	25 10 10	128 50 50
3.3	Exposure to const. pres.	5		1	1	1	8
3.4A 3.4B	Exposure to pres. surge.	1 2		1 3	1 1	1 1	4 7
3.5	Exposure to corr. env.	1	1	1	1	1	5
Total # of discs per design		54	46	54	49	49	252

3.1 Burst Pressure Test

The purpose of the burst pressure test was to examine the range of burst pressures in a batch of frangible discs. The test specification for determination of burst pressure according to A5.03 in the AAR Specifications for tank cars is as follows:

A5.03 Frangible Discs, other than lead, used in safety vents.

The procedure for the determination of the burst pressure of a frangible disc, including a disc with breather hole, is to test one from each lot of 100 discs or less of the same design *and made from the same piece of material. The test procedure must employ a pressure rise which reaches 50 percent of the rated burst pressure within 2 seconds and then continues at a rate of 1 to 4 psi per second (6.9 to 28 kPa per second) to burst. If the tolerance specified in A5.02(b) is exceeded, 2 additional discs must be tested and both must meet specifications, or the lot must be rejected. Frangible discs must be tested at a temperature between 70-75°F (21.1-23.9°C) unless otherwise specified.*

According to A5.02(b), the permissible tolerance for the burst pressure of a frangible disc must be plus 0 to minus 15 percent.

The test followed the procedure outlined in A5.03. A batch of 25 discs for each disc design was tested. Each disc was subjected to the pressure rise shown in Figure 3.2.

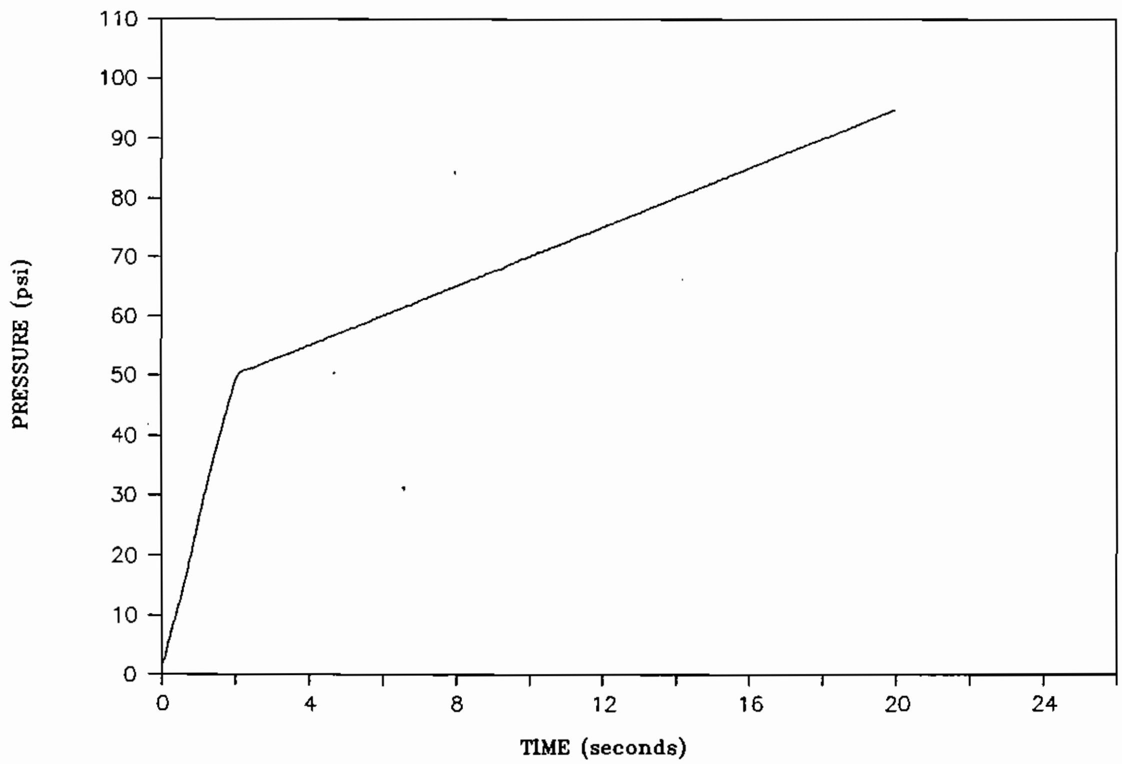

Figure 3.2 Pressure Rise for Burst Pressure Test.

Three discs of each design were instrumented to indicate strain during burst testing. Both lead designs were equipped with a Linear Variable Differential Transformer (LVDT), which indicated the displacement of the center of the disc. The average strain could be calculated from the displacement. Both composites were instrumented with strain gauge rosettes. Three single gauges were used in a similar arrangement on the stainless steel discs. Complete descriptions and locations are provided in Section 4, "Instrumentation and Materials".

Pressure, temperature, and strain data were recorded at 100 samples per second throughout each test. The average burst pressure, as well as maximum, minimum, and standard deviation for each disc type, was calculated after all tests were complete.

3.2 Effect of Temperature on Burst Pressure

There were two parts to the temperature test. The first part dealt with the effects of low temperatures on the burst pressure of each disc type, where tests were performed at a temperature between 29 and 35°F. The second part dealt with high temperatures, where tests were performed at a temperature between 137 and 143°F.

The test procedure was identical to 3.1 with the exception of temperature. Ten discs of each design were tested at the high temperature and another ten were tested at the low temperature. Strain was monitored for two discs out of each group of ten.

3.3 Effect of Creep

The purpose of the creep test was to examine the behavior of frangible discs when exposed to a constant pressure for an extended period of time. The duration of each test was fourteen days. A special fixture, shown in Figure 3.3, was used for the test. Four discs, one of each design, excluding lead with breather hole, were tested simultaneously. It was determined that the breather hole would prevent the lead disc from experiencing creep. Therefore, the test fixture was not designed to provide the high flow rate required to produce a 75 psi pressure drop across the breather hole, and the lead disc with breather hole was not tested for creep. The pressure increased from 0 to 50 psi within two seconds and from 50 to 75 psi at a rate of one psi per second. The pressure remained between 73 and 77 psi for the duration of the test. The ambient temperature was maintained at approximately 75 degrees Fahrenheit.

Strain or deflection was monitored for each disc. Measurements were digitized and recorded every 15 minutes. Time histories of strain were plotted to indicate creep. Only one disc per design was tested with the exception of lead. The creep test was repeated for the lead disc without breather hole at 75, 50, and 25 psi.

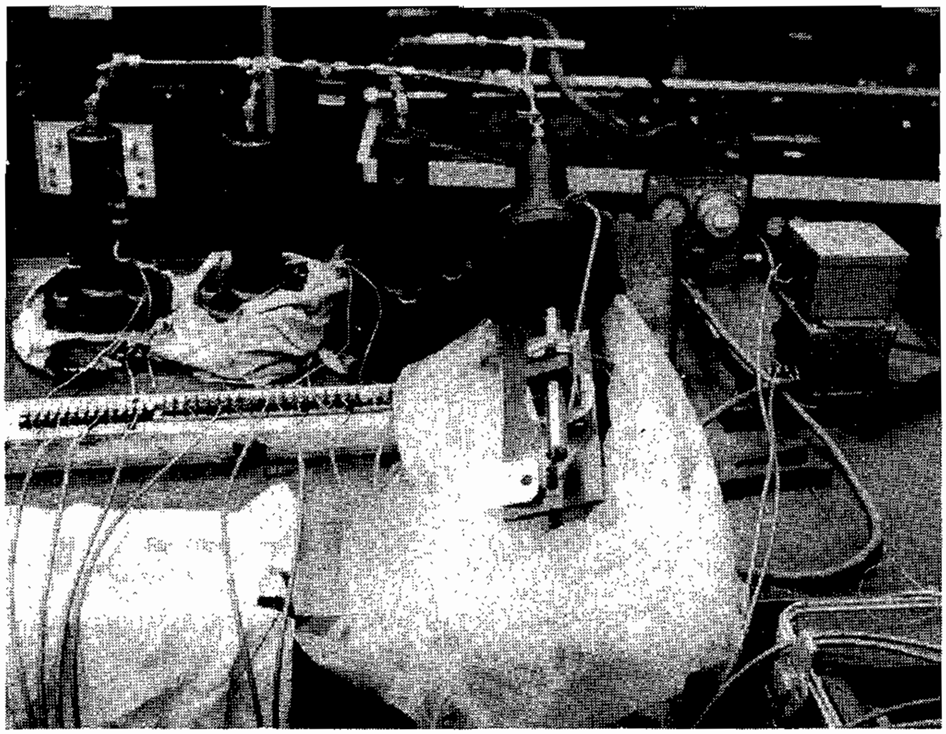

Figure 3.3 Creep Test Fixture.

If the disc did not rupture during the test, it was tested for burst pressure according to Section 3.1 procedure.

3.4 Effect of Pressure Surge

The purpose of the surge test was to examine the behavior of frangible discs when exposed to pressure surges. The test was divided into two segments, with each segment using a different maximum pressure. Pressures of 75 psi and 100 psi were required for tests A and B, respectively. The 75 psi surge was used to examine the possibility that the disc could show weakening strain rate characteristics. The disc would eventually break if that were the case. The 100 psi surge was used as a comparison to the behavior of a disc in the standard burst test. One disc of each design was tested, with the exception of lead with breather hole. The test consisted of 20 pressure surge cycles per segment; during each cycle, the test pressure increased from zero to the maximum pressure in 0.005 seconds.

If the disc ruptured during the test, the surge cycle when burst occurred was recorded on the log sheet. If the disc did not rupture during the test, it was tested for burst pressure according to Section 3.1 procedure. The temperature throughout the test was held between 70 and 75 degrees Fahrenheit.

Strain was monitored for each disc. Pressure and strain related data were digitized and recorded at 1000 samples per second.

The same test setup as the regular burst test was used. The rates were adjusted on the MTS function generator to accommodate the different pressure increase rate.

3.5 Effect of Corrosive Environment

The purpose of the corrosive test was to examine the performance of frangible discs when exposed to a corrosive environment for an extended period of time. Dilute sulfuric acid vapor, a common corrosive environment, was the test medium. The discs were suspended over a 35% sulfuric acid solution in a plastic tank. The tank, pictured in Figure 3.4, required a plenum to hold the discs above the vapor. The liquid in the bottom of the tank gradually vaporized, thus supplying the corrosive environment.

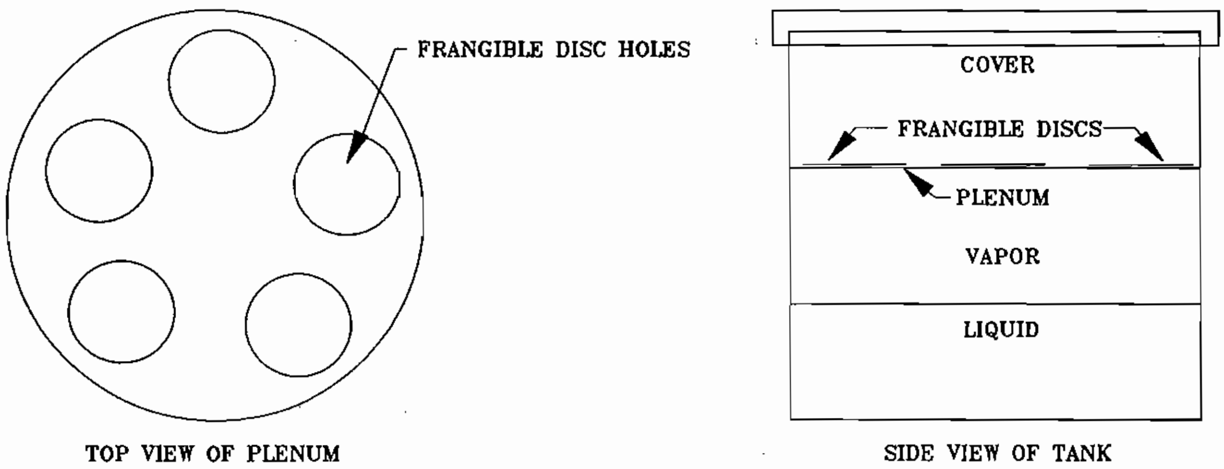

Figure 3.4 Corrosive Environment Test Tank.

One disc of each design was suspended in the tank for fourteen days. After that period, each disc was examined for any physical deterioration which may have taken place. Special interest was taken to observe any damage to the gasket area surrounding the disc.

Upon completion of the visual inspection, the discs were pressure tested in accordance with Section 3.1 procedure, without monitoring strain.

4.0 INSTRUMENTATION AND MATERIALS

4.1 Frangible Disc Description

All frangible discs were rated at a nominal burst pressure of 100 psi and designed for a 2" vent pipe.

4.1.1 Lead Discs

Two types of lead discs, pictured in Figure 4.1, were tested. They were the solid lead disc and the lead disc with a breather hole.

Figure 4.1 Lead Disc With and Without Breather Hole.

The disc diameter was 3.1875", the thickness ranged between .040 and .045 inches. The only difference between the two lead discs was the 0.125" breather hole.

4.1.2 Composite Discs

Two types of composite discs were tested. The only similarity was the outside diameter and nominal burst pressure.

Composite disc #1, pictured in Figure 4.2, was also 3.1875" in diameter. The inner circle of 2.0625" diameter was much thinner than the outer ring. The thickness of the inner circle was approximately 0.085". The outer ring was approximately 0.25" thick. The disc was injection molded and comprised of a poly-phenalin sulfide plastic material.

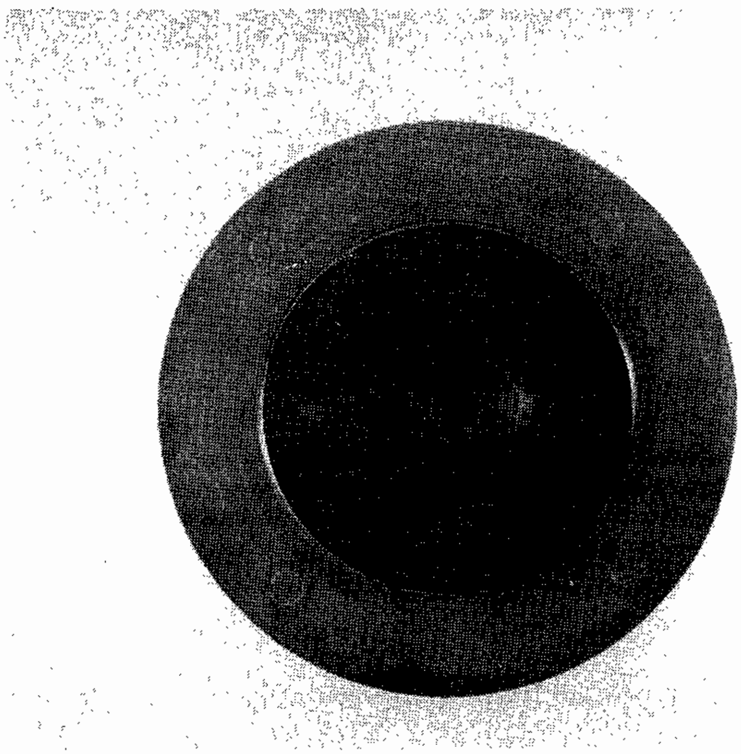

Figure 4.2 Composite Disc #1.

Composite disc #1 came with a gasket to seal the disc to the pressure side of the fixture. The disc was symmetric, allowing it to be used in either direction.

Composite disc #2, shown in Figure 4.3, was a layered design utilizing four different materials.

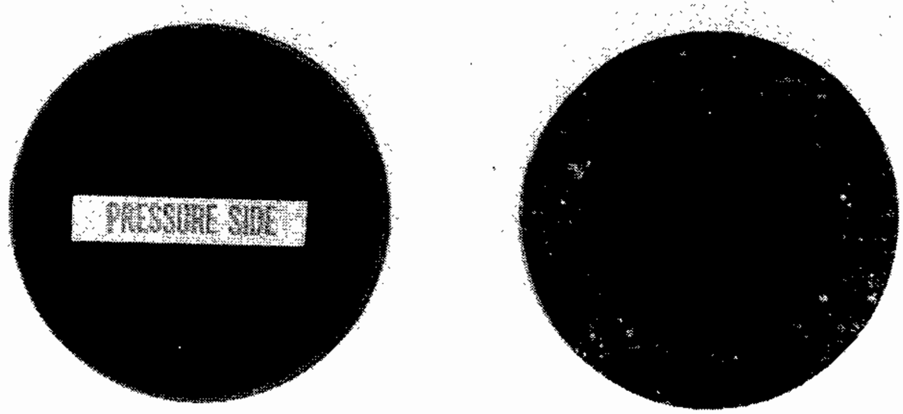

Figure 4.3 Both Sides of Composite Disc #2.

The pressure side began with a neoprene layer. Moving outward, the next layer was a thin sheet of Teflon. The disc itself was graphite. It had a 2.125" relieved area similar to composite disc #1. This relief was only on the atmosphere side; composite disc #1 had the relief on both sides. The last layer was a fiber gasket ring glued to the atmosphere side of the disc. The overall thickness of the disc was 0.3125". The relieved area, which was graphite, was 0.100" thick. Figure 4.4 shows the layers of composite disc #2.

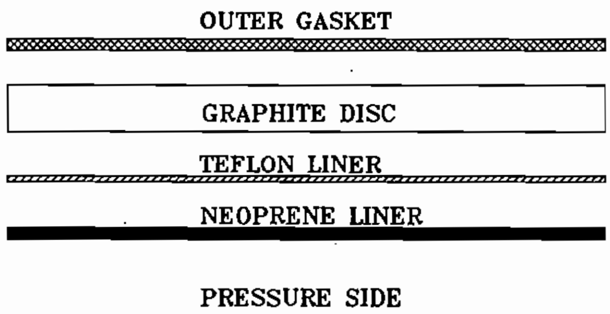

Figure 4.4 Layers Comprising Composite Disc #2.

Due to the unique design, composite disc #2 could only be installed one way. The pressure side was marked with a sticker.

4.1.3 Stainless Steel

The stainless steel disc, shown in Figure 4.5, was also of layered design. The pressure side was stainless steel. A star pattern was cut in the steel to allow the pressure to be exerted on the Teflon liner, while acting as a vacuum support for the Teflon in the middle of the disc. The atmosphere side was also stainless steel. Six slits and holes were cut in the steel to provide weak spots for failure.

This disc was only designed to operate in one direction. The top was clearly marked. The outside diameter was 3.125", and the ring around the designed failure area was 2.0625" in diameter. The holes were 0.125" in diameter.

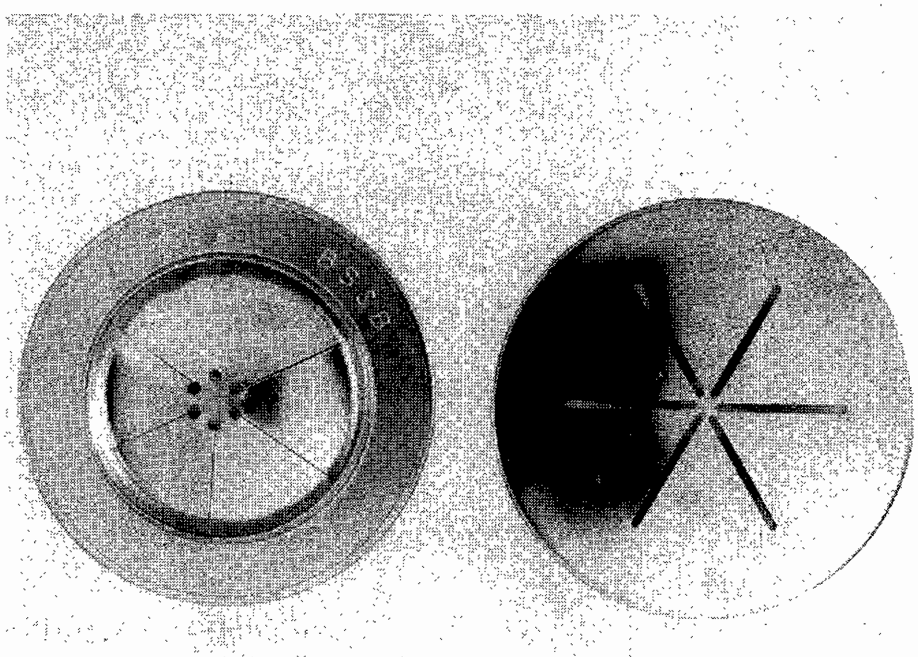

Figure 4.5 Both Sides of Stainless Steel Disc.

4.2 Standard Test Setup

A Mechanical Test System (MTS) servo-hydraulic test machine was used in the test setup for the burst pressure tests. Figure 4.6 shows a schematic of the overall test setup.

The MTS Control Unit, shown in Figure 4.7, drove the MTS actuator. The actuator was in series with a hydraulic cylinder. The pressure side of the hydraulic cylinder was used to provide the burst pressure for the frangible discs.

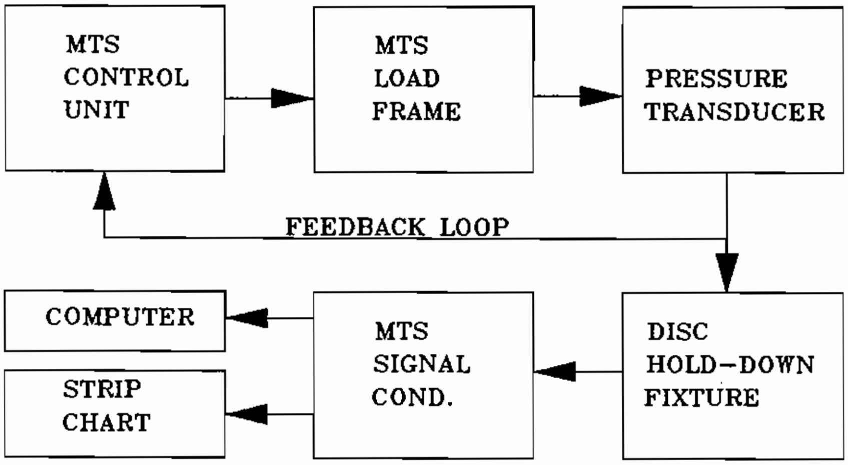

Figure 4.6 Test Setup Schematic.

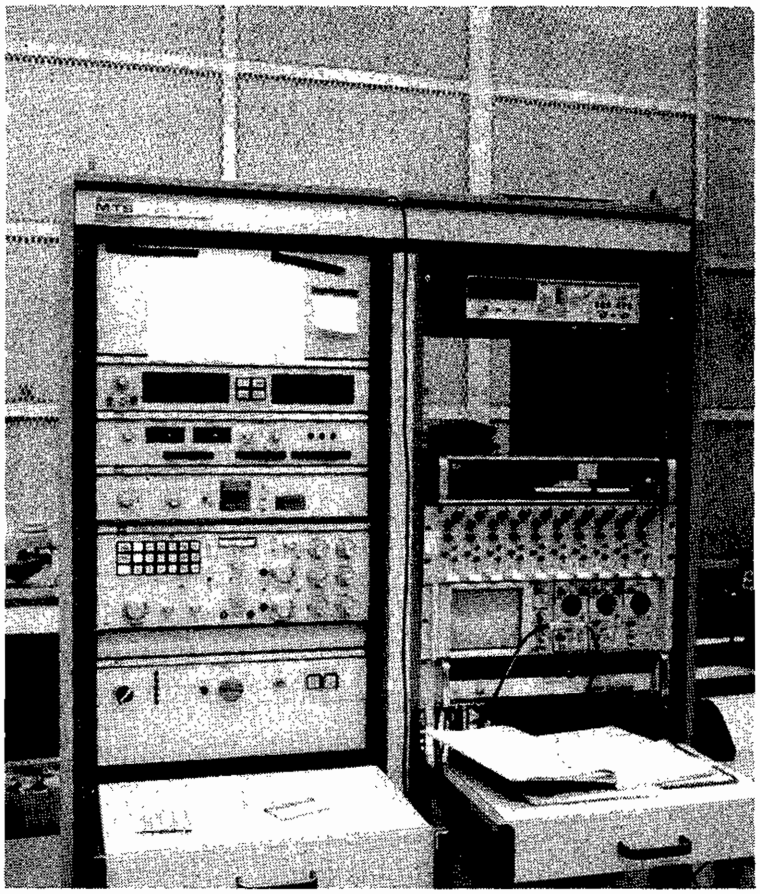

Figure 4.7 MTS Control System.

The two cylinder arrangement is shown in Figure 4.8. The pressure side of the hydraulic cylinder was connected to the frangible disc fixture, as shown in Figure 4.9.

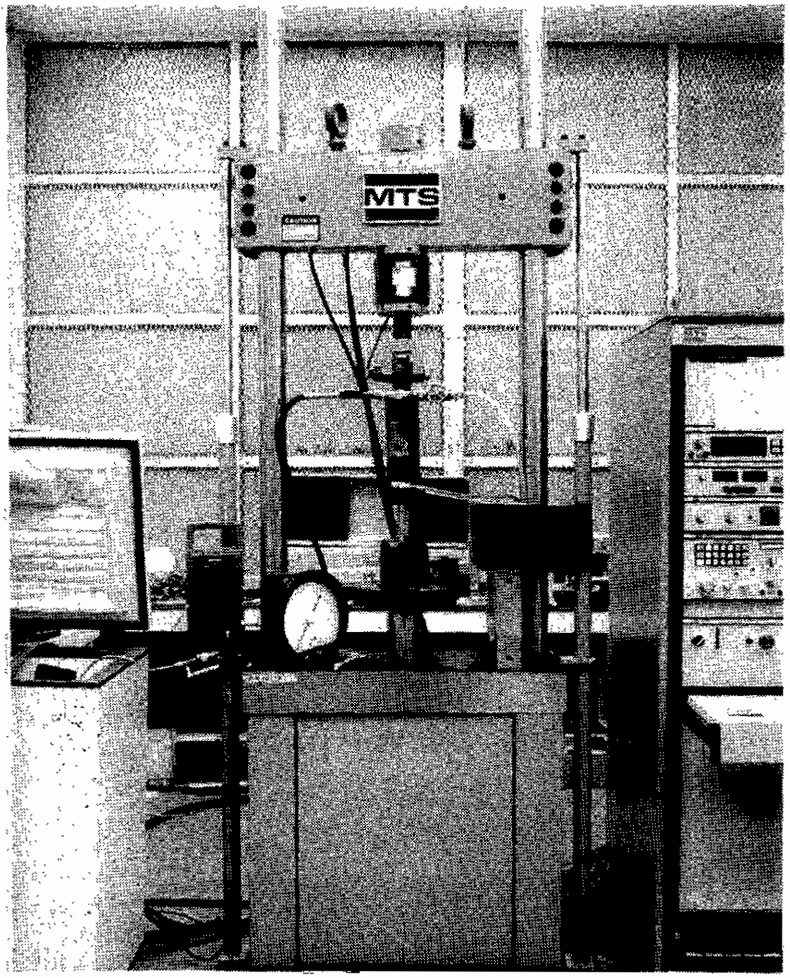

Figure 4.8 Hydraulic Cylinder Used as Pump.

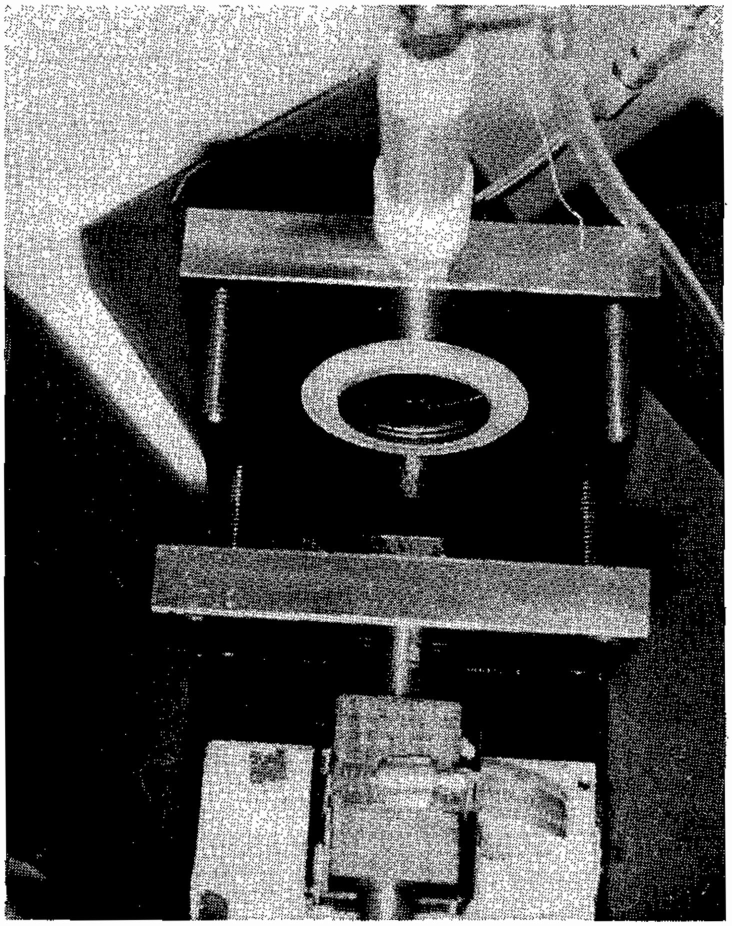

Figure 4.9 Frangible Disc Fixture.

The frangible disc fixture had the same dimensions as the vent pipe arrangement in a tank car. A pressure transducer was installed in the supply line for monitoring the pressure rise as well as providing feedback for the MTS controller.

The fixture was placed inside a small chest-type freezer. The freezer box was utilized as an environmental control chamber. The freezer itself was used to provide cooling for the low temperature tests. A heater was used to apply heat inside the chamber for the high temperature tests. Figure 4.10 shows the complete test setup for the frangible disc burst pressure tests.

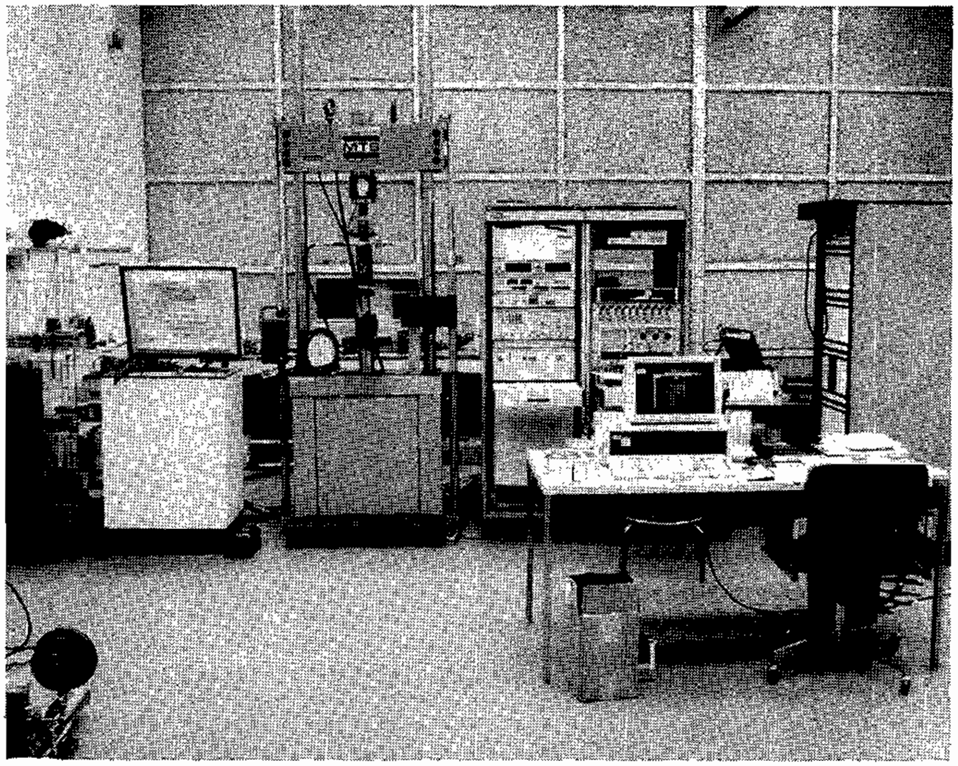

Figure 4.10 Complete Test Setup.

From left to right were the freezer unit, MTS actuator arrangement, MTS controller, and MTS signal conditioning. The Compaq 286 personal computer, used for data acquisition and storage, was placed on a table away from the control unit.

4.3 Creep Test Setup

The creep test setup, pictured in Figure 4.11, utilized the shop's compressed air supply as the source of pressure for the frangible discs.

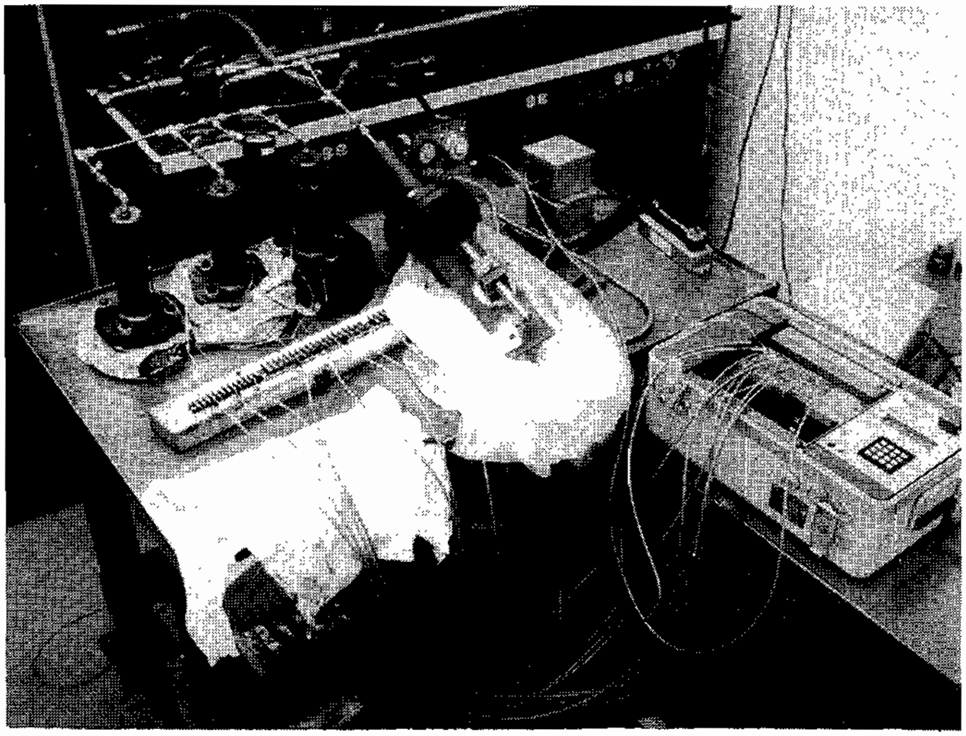

Figure 4.11 Creep Test Setup.

The air pressure was controlled with a regulator and admitted into four oil chambers with a common manifold. Frangible discs were fitted into the flanged portion of the oil chambers. Each leg of the manifold had an isolating valve which was used to keep the whole system from losing pressure in the event of a single disc failure.

A terminal strip was used to connect the wires from the three strain gauge arrangements and the LVDT to the Campbell data logger.

4.4 Data Acquisition

The primary data acquisition unit was the Compaq 286 personal computer, shown in Figure 4.12.

Figure 4.12 Personal Computer Data Acquisition Unit.

The computer was used for data collection during all burst pressure tests. A 16-channel analog to digital converter board was installed in an expansion slot inside the personal computer. Lotus Measure data acquisition software was used. The data was acquired and stored as a Lotus spreadsheet. Analysis was then performed in Lotus.

An Astro Med Dash 8 strip chart recorder was used as a real-time backup data acquisition system. All channels were recorded on the computer and strip chart.

Unlike burst pressure tests, a Campbell Data Logger was used for data acquisition during the creep test. Data was sampled every 15 minutes and written to audio cassette tape.

4.5 Instrumentation

4.5.1 Pressure Transducer

A Standard Control, model #211-75-170-01, 0-150 psi pressure transducer was installed near the disc manifold for burst pressure tests. Feedback to the MTS controller was derived from that transducer as well as data acquisition and storage. The transducer was calibrated precisely before it was put into use.

4.5.2 Thermocouple

The disc manifold was instrumented with a K-type thermocouple. The thermocouple was calibrated with an ice bath (32 degrees Fahrenheit) and a boiling water bath (208 degrees Fahrenheit).

4.5.3 Linear Variable Differential Transformer

An LVDT was used to measure the displacement of the center of the lead discs. The range of the LVDT was $\pm$ 1.5 inches.

4.5.4 Strain Gauges

Micro Measurements type EA-06-250YA-120 strain gauge rosettes were mounted in the center of the composite discs.

Three Omega type 0.6/120LY11 single gauges were mounted on three of the six stainless steel segments between the holes shown in Figure 4.13.

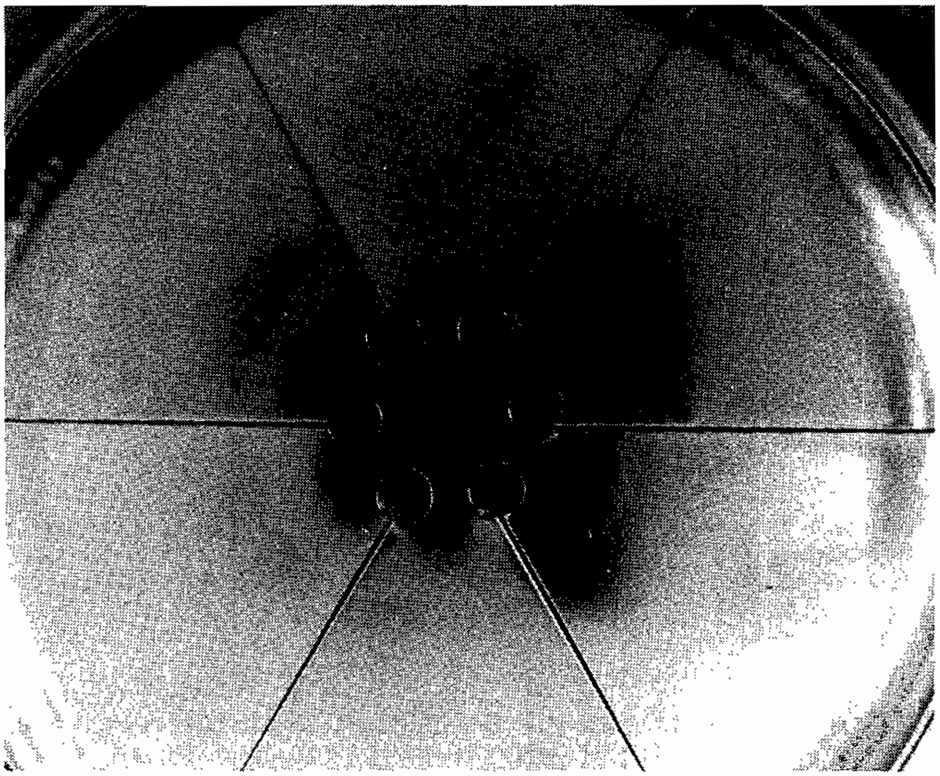

Figure 4.13 Stainless Steel Strain Gauge Location.

4.6 Test Fixture and Instrumentation Calibration

The entire system, including the pressure transducer, signal conditioning, filtering, and A/D board, was calibrated with the dead weight calibration setup shown in Figure 4.14.

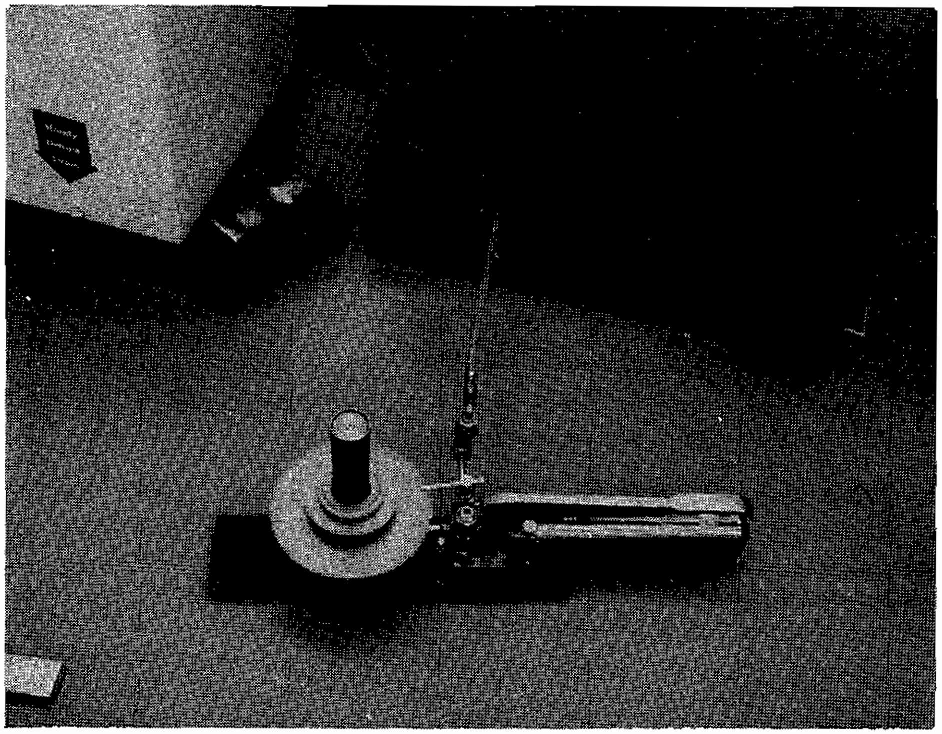

Figure 4.14 Dead Weight Pressure Transducer Calibration Fixture.

The accuracy of the dead weight tester was ±0.25%. The accuracy of the pressure transducer was not available, but the system was calibrated to ±1 psi. No independent calibration of the signal conditioning was necessary. The RI filters were calibrated with the system. A Heiss gauge was used as a visual pressure check. It was also calibrated with the system. Its accuracy was specified at ±.1%.

The accuracy of the LVDT was not available. However, it was calibrated against a Mitutoyo dial gage with an accuracy of $\pm$0.001".

The strain gauges were calibrated with Micro Measurements 59.88 Rcal resistors. The accuracy of those resistors was specified at $\pm$0.01%

5.0 RESULTS

Results were divided into six major sections; failure description, burst test, temperature test, creep test, corrosive test, and surge test. Table 5.1 summarizes the major results of the frangible disc test. A more detailed discussion of the results of each test is presented in the following subsections. Appendix A contains a complete listing of all frangible disc data.

TABLE 5.1 FRANGIBLE DISC RESULTS SUMMARY

				Average Burst Pressure (psi)					
Disc Type	Avg. Burst Pres. (psi)	Std. Dev.	% Discs With B.P. 85-100 psi	At 32 Deg F	At 140 Deg F	Creep	Corr	Surge 75 psi 100 psi	Yield Pres. (psi)
Lead	101.0	2.0	40 %	121.8	75.8	25.0 *	102.8	105.0 101.5	< 5
Lead With Hole	126.4	18.0	8 %	133.0	91.8				< 5
Stain-less Steel	96.7	2.9	88 %	101.4	92.6	98.4	95.9	96.2 77.9	***
Comp 1	107.0	6.4	16 %	111.9	101.3	118.1	111.4	99.9 118.7	Burst ****
Comp 2	101.9	5.0	40 %	107.8	101.9	110.8	99.4	119.6 64.0 **	Burst ****

* Burst during test
** Failed without bursting on 20th cycle
*** See Section 5.1.3
**** Strain rate remained constant to burst pressure

The average burst pressure of each disc type was an important result. Equally important, though, was the standard deviation. Results with a high standard deviation indicated a large distribution of burst pressures and unpredictable behavior. The percent of discs which burst between 85 and 100 psi was important because that was the pressure range allowed in the AAR Specification.

The average burst pressure seemed to increase at lower temperatures and decrease at higher temperatures for all discs. The lead disc was the only one that was sensitive to creep. None of the discs seemed adversely affected by the corrosive atmosphere of sulfuric acid vapor. The lead discs yielded in a plastic nature at low pressures. Permanent deformation occurred at low pressures. It was hard to determine the yield pressure for the stainless steel discs. A discussion of stainless steel disc behavior is presented in Section 5.1. Both composite discs were elastic up to burst pressure. No permanent deformation took place at pressures below the burst pressure.

5.1 Disc Failure Description

In all cases except lead disc with breather hole, each disc type maintained a consistent failure pattern.

5.1.1 Lead Disc Without Breather Hole

The lead disc without breather hole was very predictable. As pressure was applied, the disc bowed in a semicircular manner. At burst pressure, the disc ruptured along the inside edge of the hold down fixture, as shown in Figure 5.1.

The length or circumference of the cut was dependent upon installation. The more uniformly the fixture was bolted together, the longer the cut. Notice the bulged section in the center of the disc.

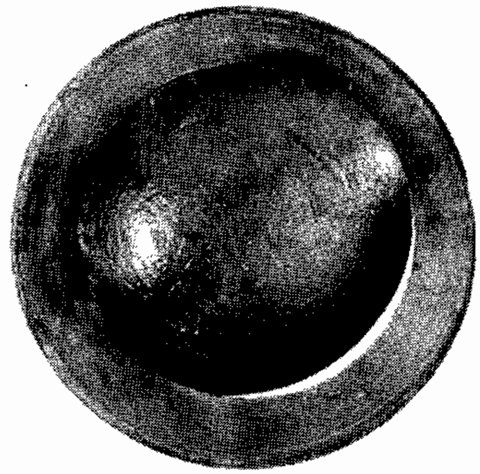

Figure 5.1 Ruptured Lead Disc.

5.1.2 Lead Disc With Breather Hole

The lead disc with breather hole was not consistent in its failure mode and its response to pressure. Permanent deformation took place immediately, similar to the response of the lead disc without a hole. However, the failure mode of both disc types were not always the same. In all instances, the breather hole expanded. In some cases, the hole ripped open, causing failure. In other cases, the disc failed like its counterpart without the breather hole. In some cases, there was a combination of both the hole and the rim failing at the same time, as shown in Figure 5.2.

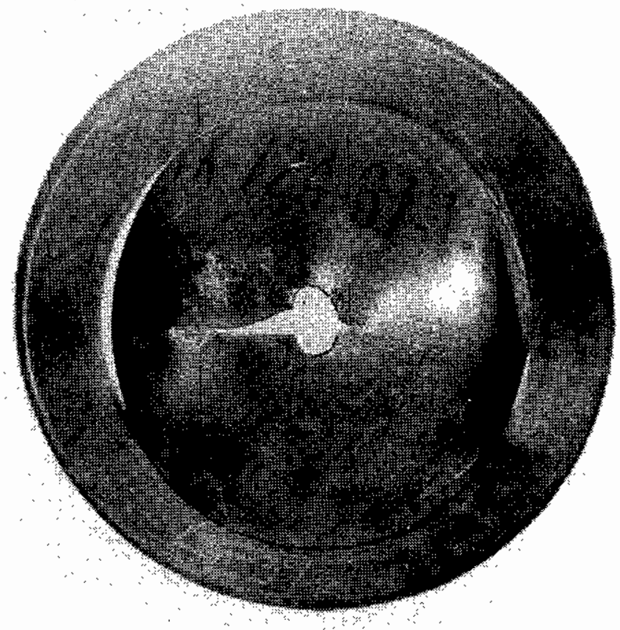

Figure 5.2 Failed Lead Disc with Breather Hole.

5.1.3 Stainless Steel

The stainless steel disc failure was by far the most complicated in comparison to the other types. While the steel was the material which failed, the Teflon liner held the oil back until it ripped after losing the support of the steel. Figure 5.3 shows a schematic of the three layers and a top view of the stainless steel layer that eventually failed.

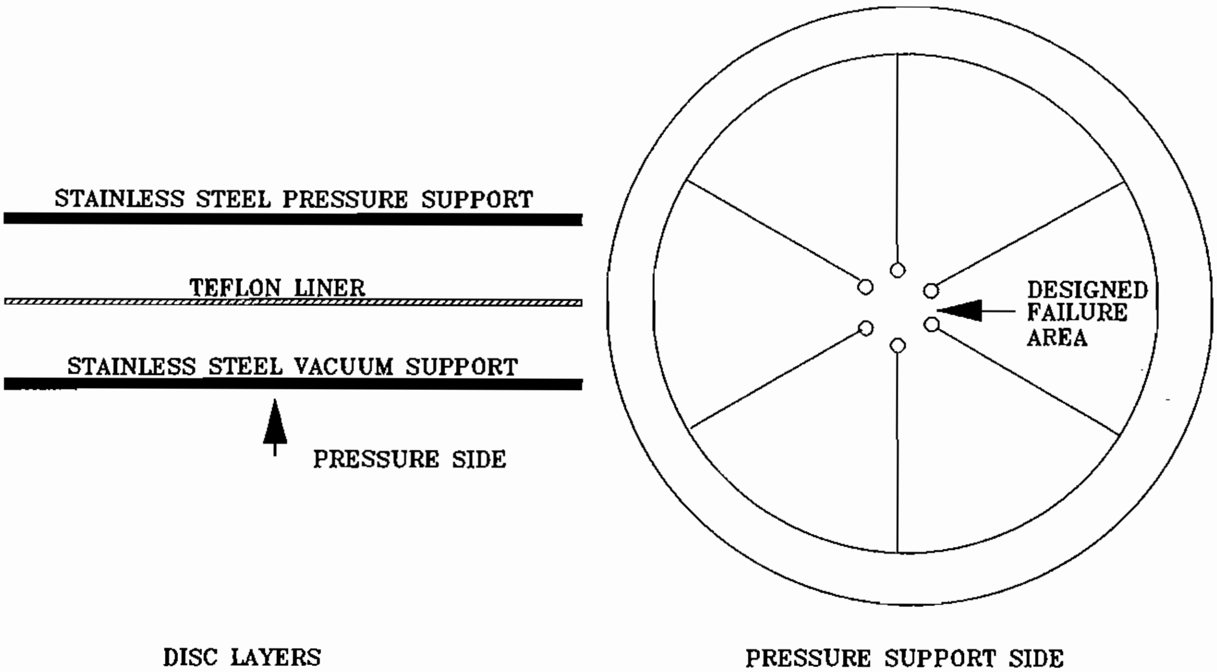

Figure 5.3 Stainless Steel Disc Schematic.

As the pressure increased to 10 psi, the Teflon layer bulged out to meet the pre-bulged stainless steel layer. The stainless steel layer was manufactured with the bulge. As the Teflon liner pushed against the stainless steel, the center star portion tended to bulge slightly more than the outside portion. This tended to bend the small segments in a concave direction. The segments were instrumented with strain gauges, which indicated a compressive surface strain, as shown in Figure 5.4. At 25 to 30 psi, the stainless steel segments were concave. At approximately 50 psi, the segments were found to begin straightening out again. At 60 to 70 psi, the segments were at their original position, indicated by the zero strain, after which they started to bulge out, which was indicated by the positive strain. The gauge became unbonded at 5,000 micro strain, which corresponded to approximately 80 psi. The disc failed at 94 psi. Three to five segments failed after elongating considerably, and the star-shaped center piece bent over, as shown in Figure 5.5.

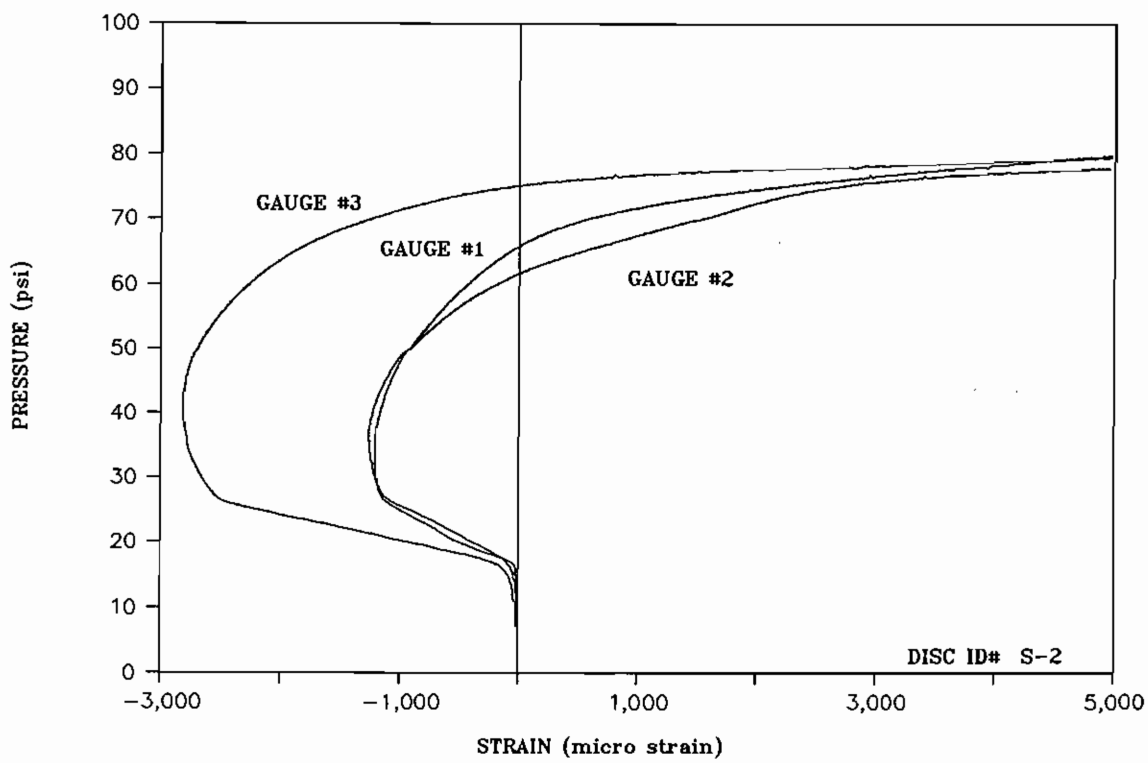

Figure 5.4 Stainless Steel Disc Strain.

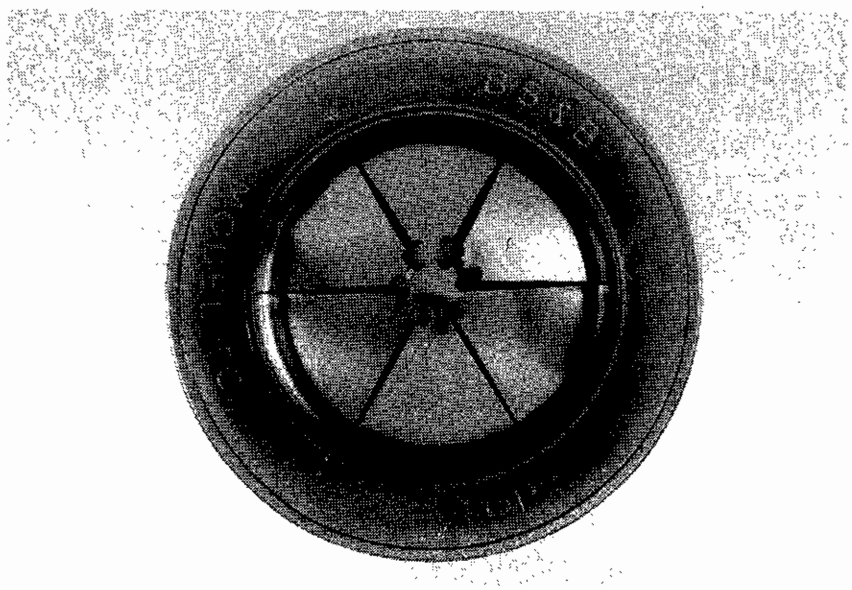

Figure 5.5 Failed Stainless Steel Disc.

The Teflon liner punched through the failed stainless steel shell and burst. To determine when the stainless steel was permanently deformed, a disc was subjected to low pressure cycles, which gradually increased in maximum pressure. It was found that, as shown in Figure 5.6, after the slope of the strain curve went vertical, the stainless steel segment didn't return to its initial shape.

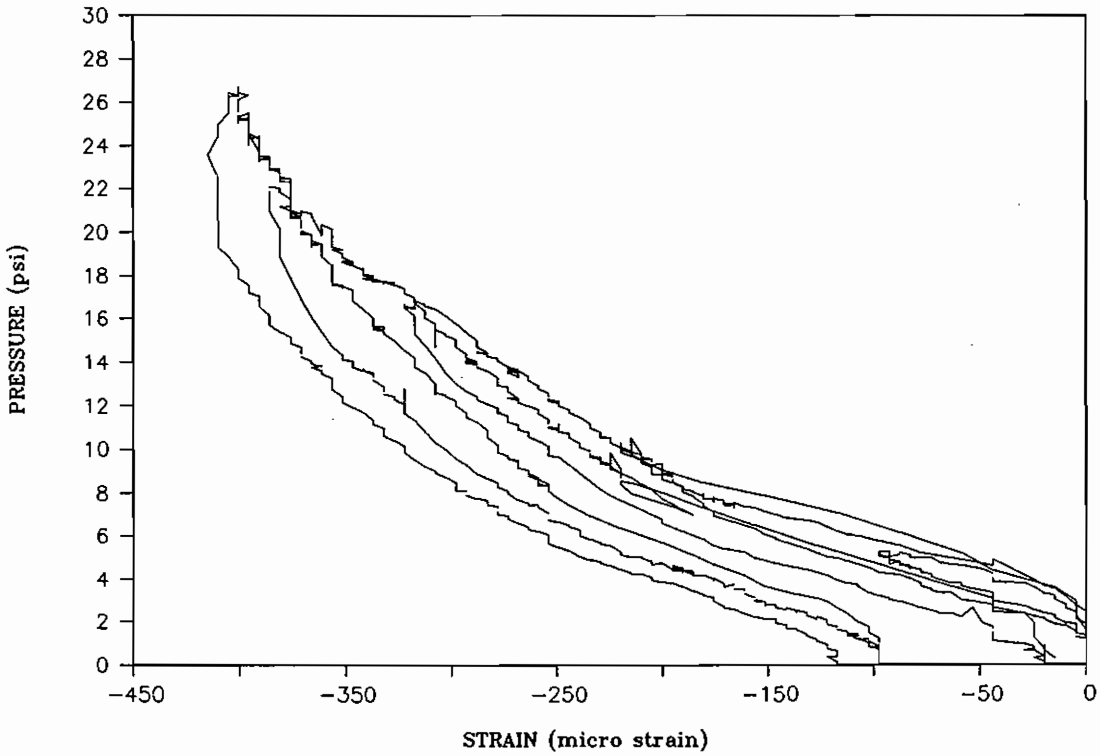

Figure 5.6 Stainless Steel Yield Pressure Test.

5.1.4 Composite Disc #1

Composite disc #1 remained elastic until burst, as shown in Figure 5.7.

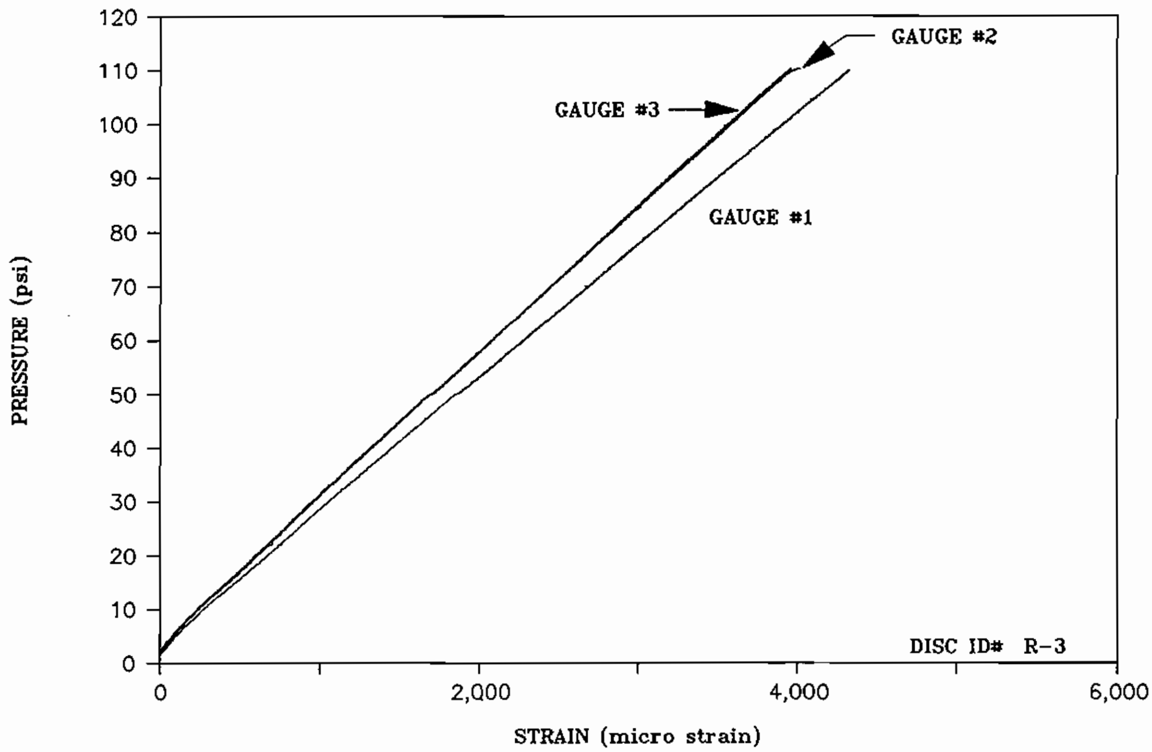

Figure 5.7 Pressure Versus Strain for Composite Disc #1.

The disc usually failed at approximately 4000 micro strain, which corresponded to a pressure between 100 and 120 psi. Calculations, shown in Appendix A, were made for a flat plate in the same environment. The results reflected the strain shown above rather closely. Appendix C contains pressure versus strain plots for all gauged discs. After failure, any gauges which were not damaged read near zero strain. Every disc failure occurred at the same place. There was a small discolored spot, which seemed to be a result of the injection molding process. That spot, pictured in Figure 5.8, served as the crack initiation site.

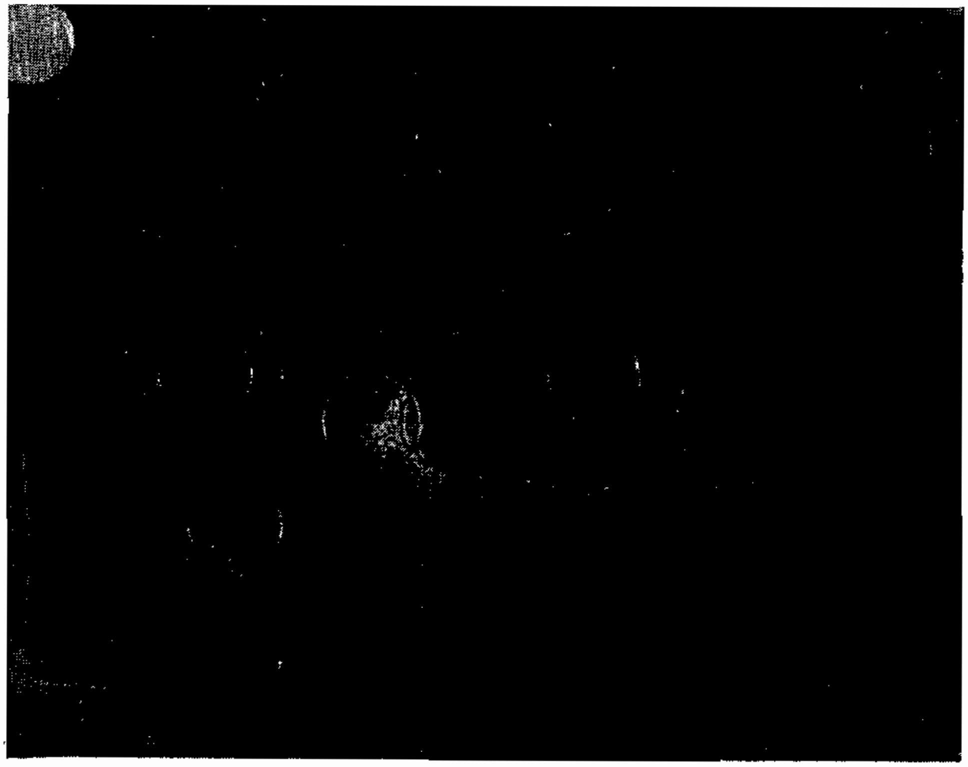

Figure 5.8 Composite Disc Crack Initiation Site.

According to the manufacturer of the plastic material, the "weld lines" produced during injection molding have a yield stress of approximately 1/3 of the regular material. The weld line was created when two flow fronts of injection molded plastic came together. Only polymer bonding took place. There were no fibers to add strength. According to the manufacturer, the whole center of the disc should have blown out. The difference between the manufacturer's test procedure and this test procedure was the working fluid. The manufacturer used air as opposed to the working fluid being oil in this test.

A small test was performed with air to examine the possibility that the working fluid affected the failure characteristics of the disc. The results indicated that the failure characteristics were altered by the working fluid. Three discs were tested with air. Two burst pressures, read from a gauge, were approximately 105 and 115 psi. The average burst pressure with oil was 107 psi, which indicated that the burst pressure wasn't affected by the working fluid. The center portion, however, completely blew out, in contrast to the cracking behavior of the disc burst with oil, as shown in Figure 5.9

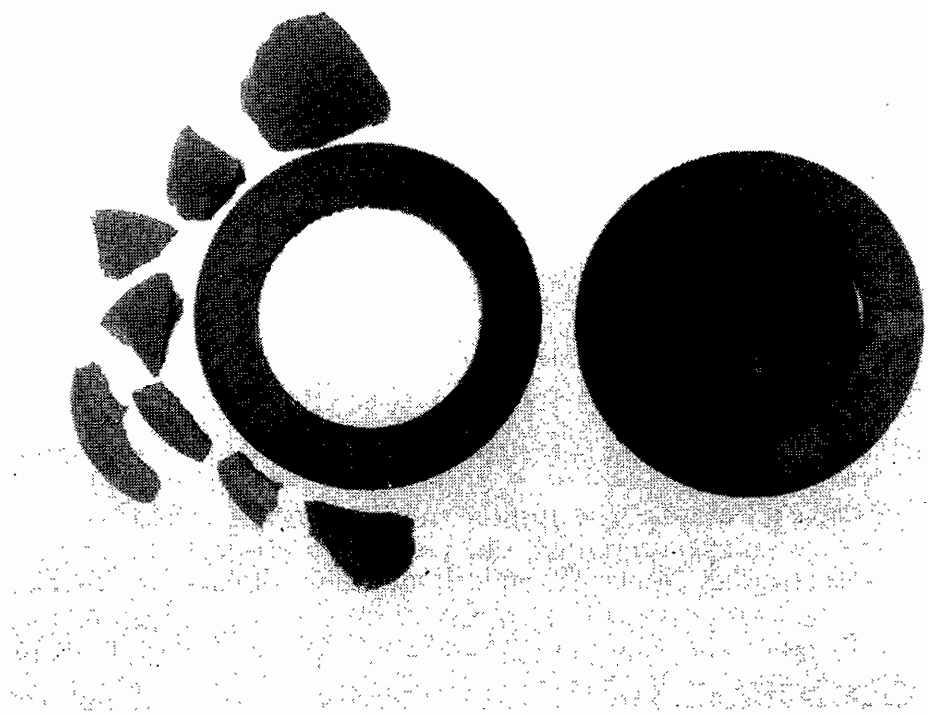

Figure 5.9 Composite Disc #1 Broken with Air (left) and Oil (right).

The difference was attributed to the compressive nature of air. Upon closer examination, it was found that the weld spot was still the crack initiation site.

5.1.5 Composite Disc #2

Composite disc #2 behaved similarly to composite disc #1 in its elastic behavior. The pressure versus strain plot, pictured in Figure 5.10, is nearly linear up to burst pressure.

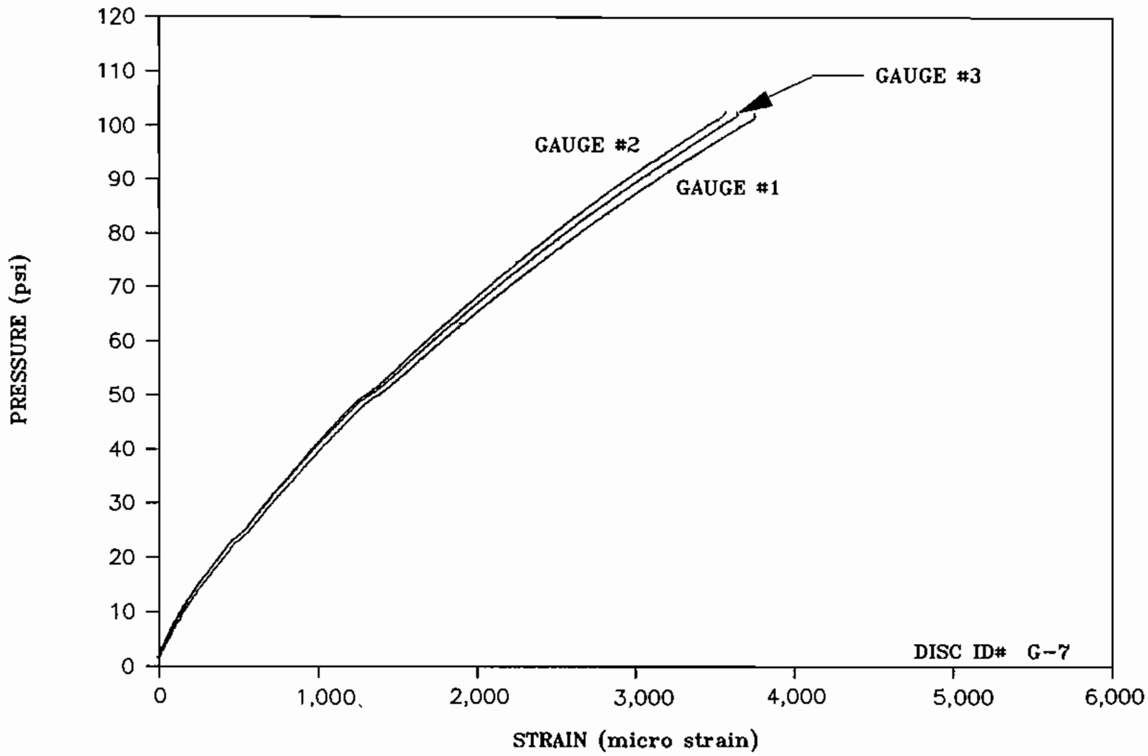

Figure 5.10 Pressure Versus Strain for Composite Disc #2.

The graphite fractured consistently at approximately 4000 micro-strain. When the disc failed, the center circle, which was thinner than the edges, blew out and fractured into numerous small pieces, as shown in Figure 5.11.

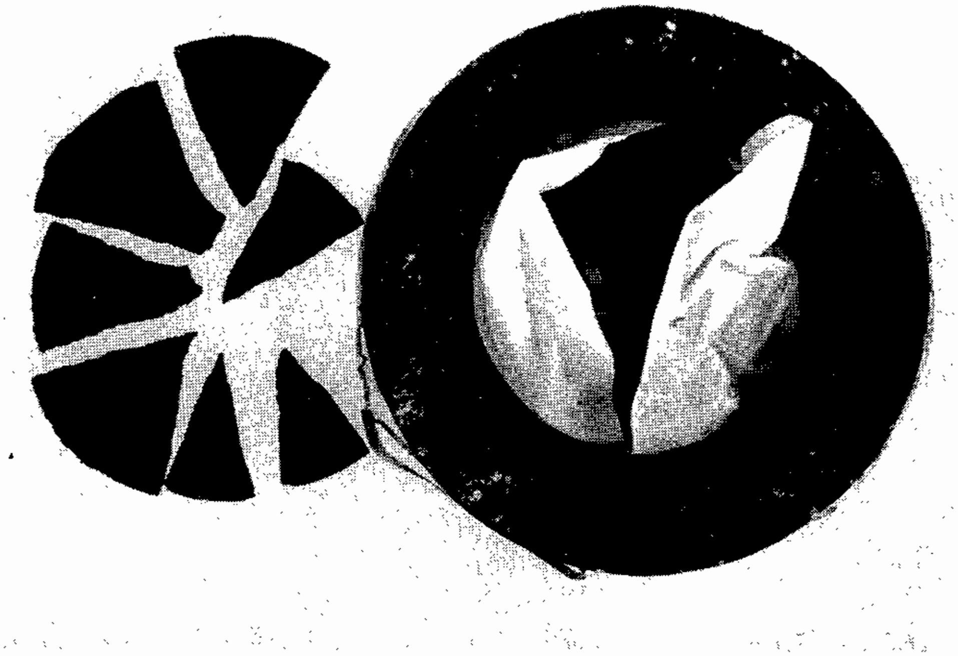

Figure 5.11 Fractured Graphite Disc.

The Teflon liner then burst within seconds. The neoprene liner bulged out and burst seconds after the Teflon. The maximum pressure occurred before the graphite fractured. The pressure decreased as the two liners bulged and burst, as shown in Figure 5.12.

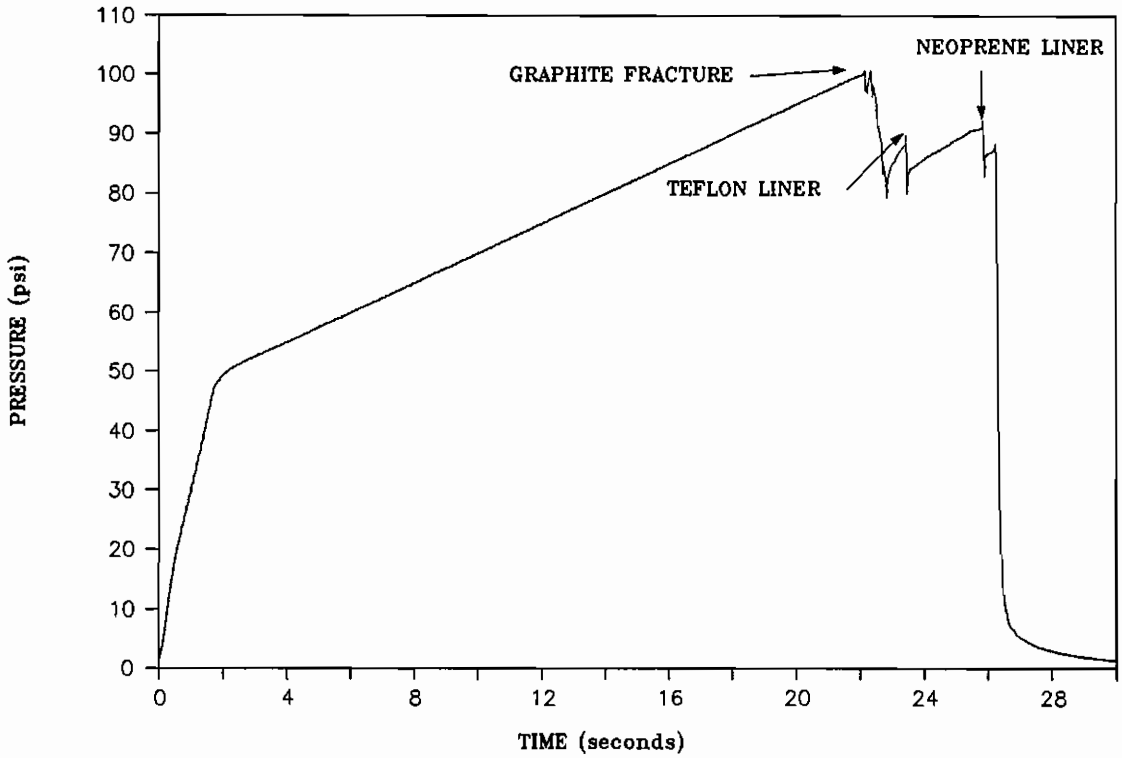

Figure 5.12 Pressure Versus Time for Graphite Disc Burst Test.

According to the manufacturer, the neoprene liner was designed to partially close the vent after burst. This would eliminate unnecessary spillage.

5.2 Burst Pressure Test

There were two important characteristics examined for each disc type. The first was the average burst pressure. The second was the range of burst pressures present in a batch of discs. A good indication of that distribution was the standard deviation of burst pressures. Both average burst pressure and range of burst pressure varied greatly between disc types, as seen in Figures 5.13 and 5.14.

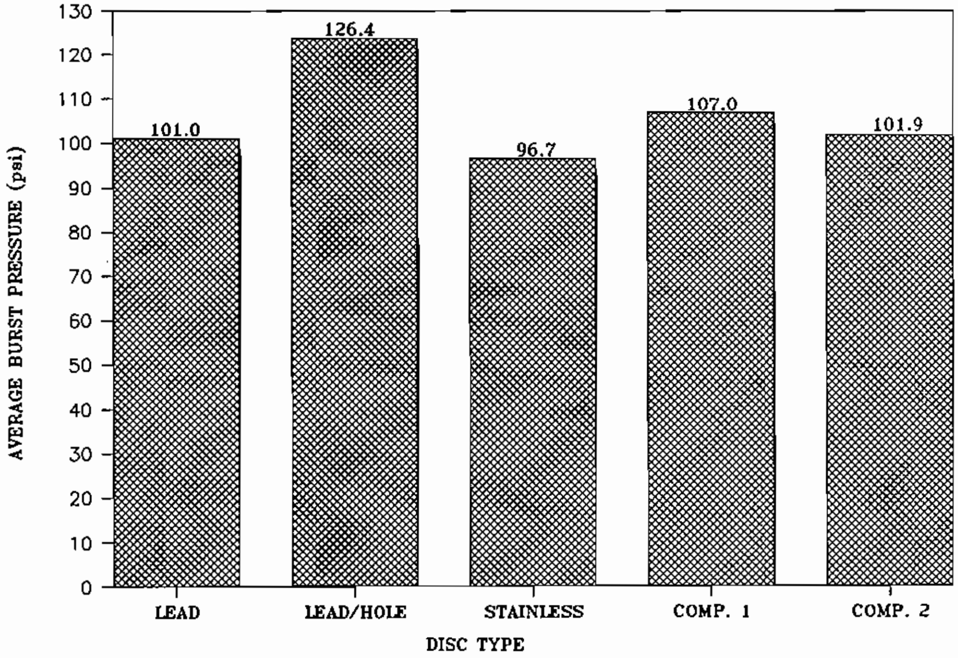

Figure 5.13 Average Burst Pressure for Five Disc Types.

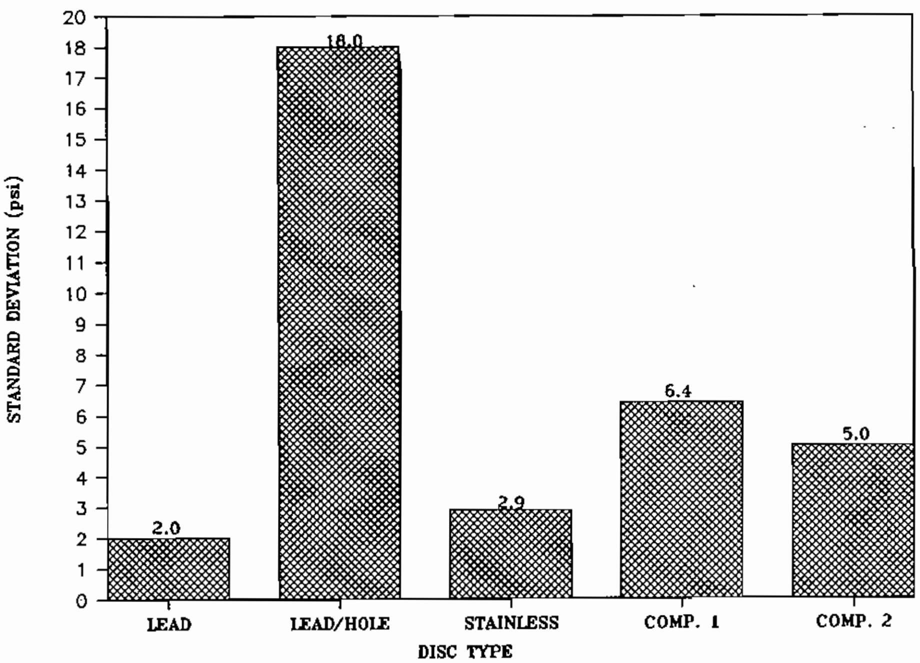

Figure 5.14 Standard Deviation for Five Disc Types.

The lead disc had an average burst pressure of 101.0 psi. It had the lowest standard deviation, 2.0. The average, 101 psi, was slightly higher than the 85 to 100 psi tolerance for the AAR Specification. Only 40% of the discs burst between 85 and 100 psi.

The lead disc with breather hole behaved in a totally different manner. Its average burst pressure was 126.4 psi with a standard deviation of 18.0. Only 8% of the discs burst at pressures between 85 and 100 psi.

The stainless steel disc produced the only average burst pressure under 100 psi. It was 96.7 psi. The standard deviation was 2.9, and 88% of those discs burst within the AAR specified tolerance.

Composite disc #1 produced an average burst pressure of 107.0 psi. The standard deviation was 6.4. This reflects the number of discs which burst within the AAR tolerance, only 16%.

Composite disc #2 produced a lower burst pressure than disc #1 at 101.9 psi. It had a similar range of burst pressures indicated by its 5.0 standard deviation. Forty percent of composite discs #2 burst between 85 and 100 psi. A tabulation of burst pressures and disc thickness is presented in Appendix C.

5.3 Effect of Temperature on Burst Pressure

5.3.1 Low Temperature Test

When the disc and environmental temperature was reduced to 32 degrees Fahrenheit, all disc types produced higher burst pressures, as shown in Figure 5.15.

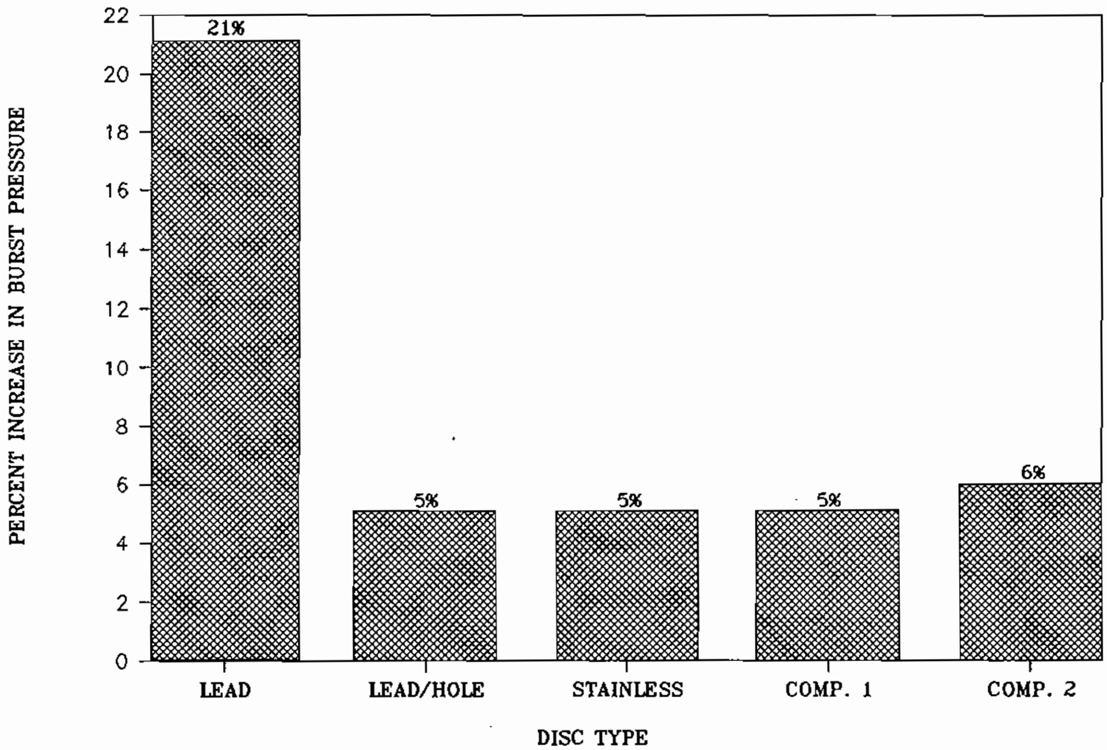

Figure 5.15 Percent increase in burst pressure at 32°F.

The average burst pressure for the lead disc at 32°F was 121.8 psi. That was 21% higher than the average burst pressure at room temperature.

The average burst pressure for the lead disc with breather hole increased 5% to 133 psi at the colder temperature.

The average burst pressure for the stainless steel disc also increased 5% to 101.4 psi. Composite disc #1 also showed an increase in burst pressure of 5% to 111.9 psi, while composite disc #2 produced a 6% increase in burst pressure to 107.8 psi.

5.3.2 High Temperature Test

All disc types except composite disc #2, as shown in Figure 5.16, produced lower average burst pressures when subjected to a temperature of 140°F.

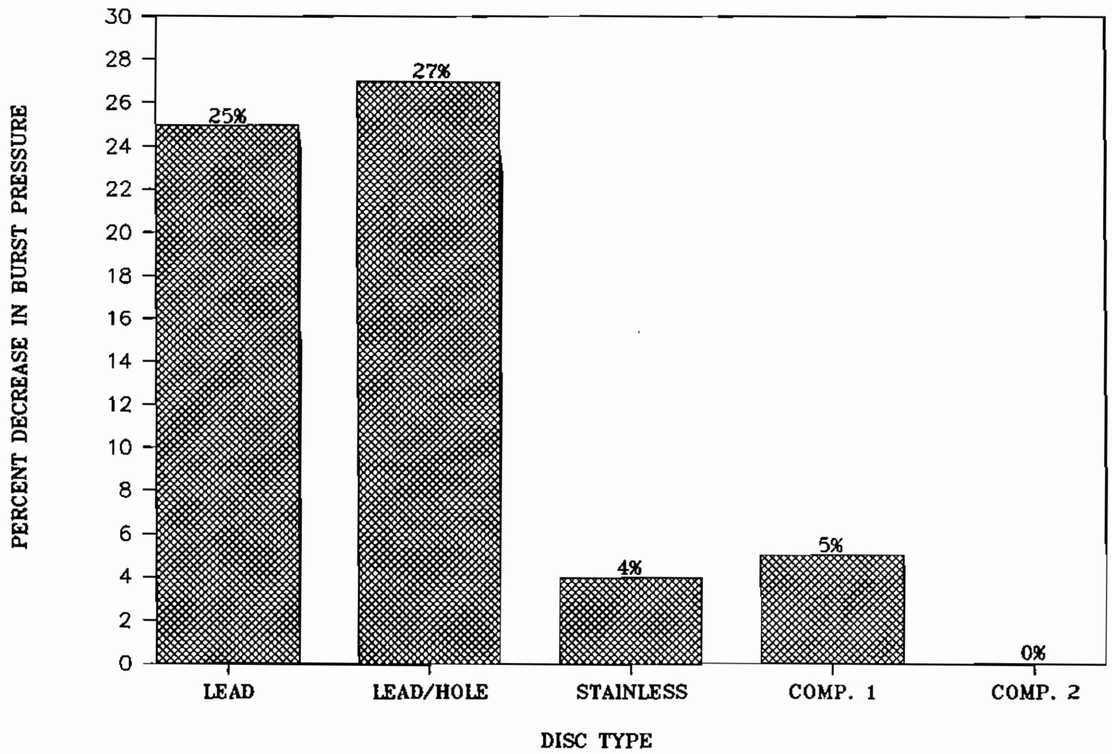

Figure 5.16 Percent Decrease in Average Burst Pressure at 140°F.

The lead discs were affected most by high temperatures. The lead disc showed a 25% reduction in burst pressure to 75.8 psi. The lead disc with breather hole experienced a 27% reduction in burst pressure to 91.9 psi.

A 4% reduction in burst pressure was found with the stainless steel disc. Its average burst pressure at 140°F was 92.6 psi. Composite disc #1 showed a 5% reduction in burst pressure to 101.3 psi. Composite disc #2 showed no change in burst pressure.

5.4 Effect of Creep

Only one disc type seemed to be adversely affected by prolonged exposure to pressures below 100 psi. During the first creep test at 75 psi, the lead disc developed a small hole which allowed it to fail without being detected. After the other discs were removed from the creep fixture 14 days later and tested for burst pressure, more creep tests were performed on the lead discs.

Two lead discs burst less than one minute after being subjected to 75 psi. The next lead disc was subjected to 50 psi. It burst after 10 minutes of exposure. The last lead disc was exposed to 25 psi. It burst after one week.

The stainless steel and composite discs (one each) were strain gauged and exposed to 75 psi for two weeks. None of them seemed to be weakened. After removal, each disc was burst according to AAR Specification A5.03. The stainless steel disc burst at 98.4 psi. Composite disc #1 burst at 118.1 psi and composite disc #2 burst at 110.8 psi.

5.5 Effect of Pressure Surge

One disc of each type, except the lead with breather hole, was exposed to twenty 10 to 75 psi pressure surge cycles. One disc of each type was also exposed to twenty 10 to 90 psi pressure surge cycles, as shown in Figure 5.17. The maximum pressure varied from 90 to 100 psi, depending on the disc.

5.5.1 Lead Disc

The lead disc showed completely plastic behavior throughout the surge test, as shown in Figure 5.18.

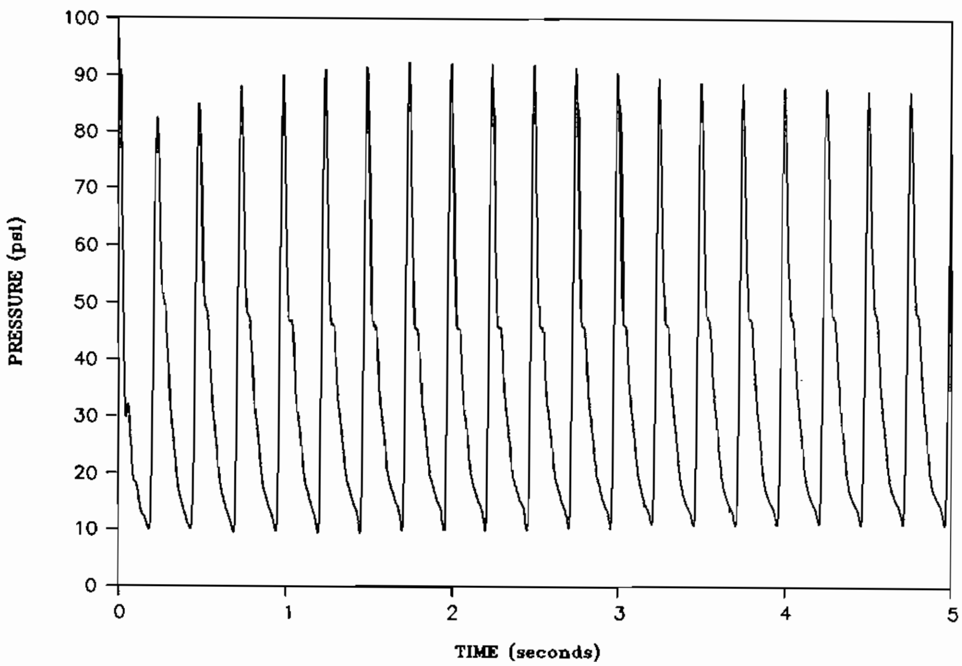

Figure 5.17 Twenty Pressure Surge Cycles.

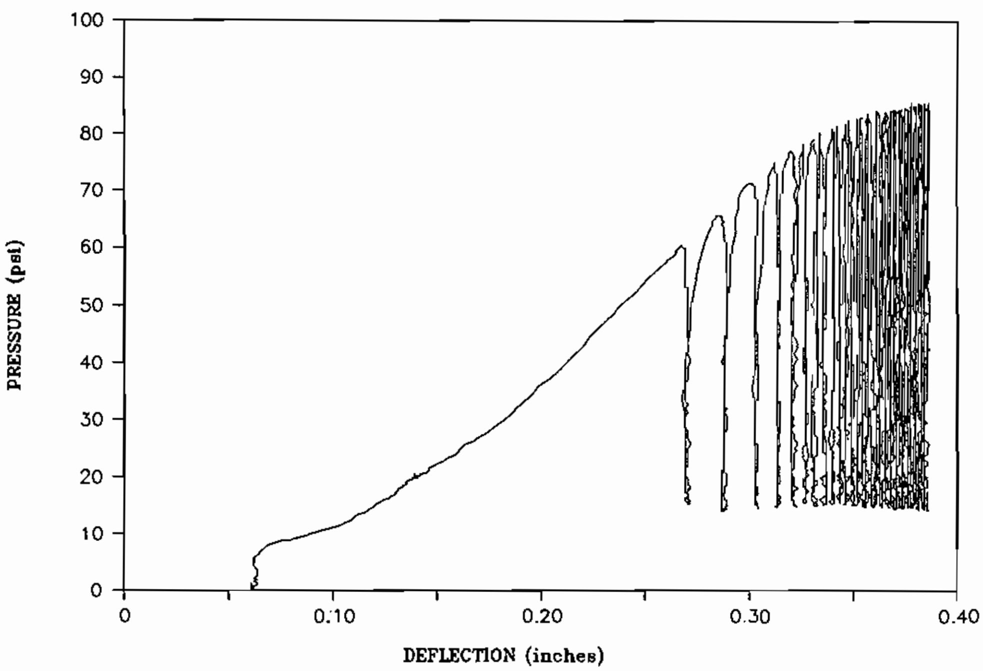

Figure 5.18 Lead Disc Under 90 psi Pressure Surge Cycles.

Most of the deflection took place during the first surge. The pressure gradually increased with each surge. This was due to the test system's inability to respond to the large amount of deformation during the pressure surge. The deflection gradually approached the maximum strain condition, which corresponded to an average of 0.468 inches deflection. Disc #LS62 was surged for more than 20 cycles. The disc failed on cycle #117. The deflection at that point was .554 inches. The other two lead discs, LS60 and LS61, were surged for 20 cycles; one at the lower pressure and one at the higher pressure, respectively. Neither burst.

After surge testing, both discs were subjected to burst tests according to the standard procedure. LS60 burst at a pressure of 105.0 psi, while LS61 burst at 101.5 psi.

5.5.2 Stainless Steel

In both cases, high and low pressure surge, the strain gauges debonded on the first cycle. Both exhibited the same behavior as all other gauged stainless steel discs. The strain began in a negative direction, then went positive before coming unbonded at approximately 5000 micro strain. Disc #S60 was subjected to 20 surge cycles at a maximum pressure of 80 psi. Since it didn't burst, it was subjected to the standard burst test. The burst pressure was 96.2 psi.

Disc #S61 was subjected to 95 psi surge cycles. The disc failed after the sixth surge cycle, as shown in Figure 5.19. Only the last half of the first cycle is shown.

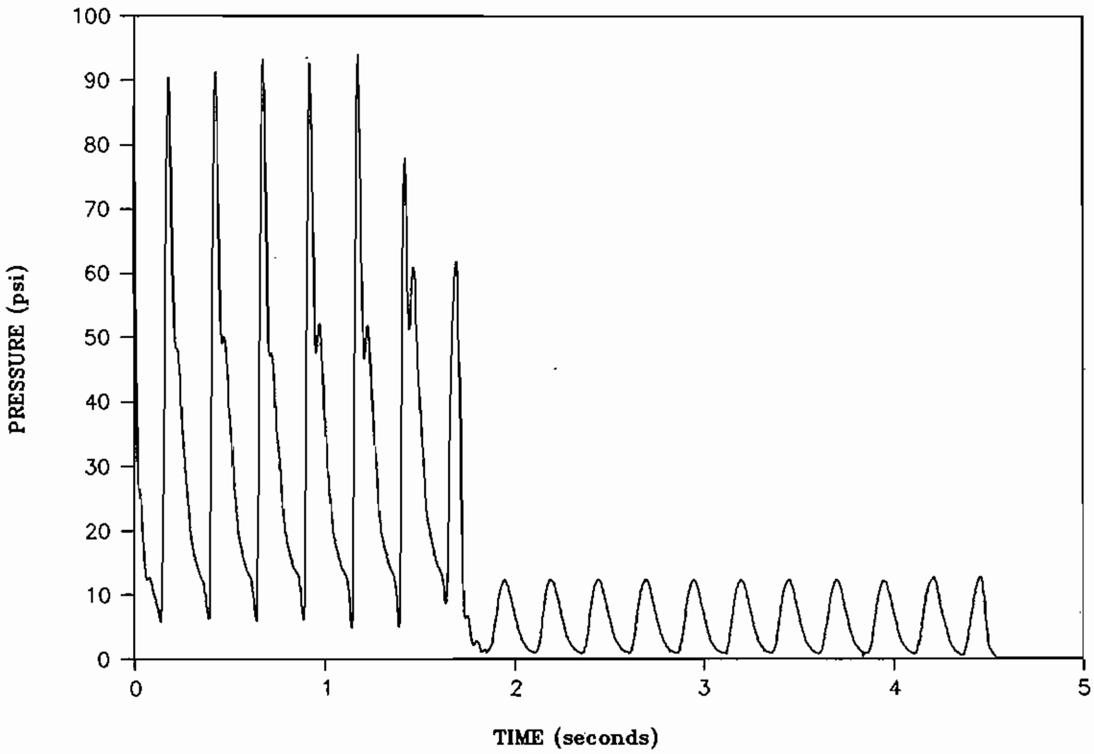

Figure 5.19 Pressure Surge Cycles for Stainless Steel Disc #S61.

There were still two pressure surges after the sixth cycle at which the disc began to fail. Its burst pressure was therefore 95 psi.

5.5.3 Composite Disc #1

Composite Disc #1, #R10, was subjected to twenty 70 psi pressure surge cycles. A pattern of hysteresis, as pictured in Figure 5.20, was observed.

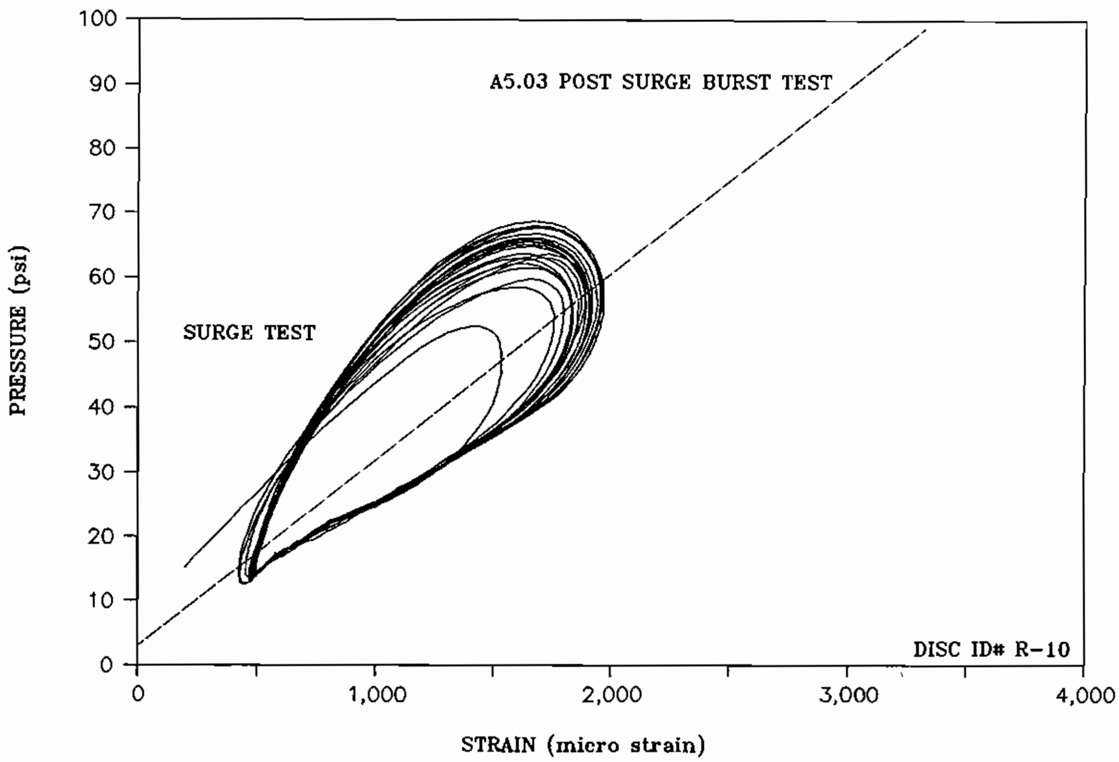

Figure 5.20 Composite Disc #1 in 75 psi Pressure Surge Cycles.

During each pressure surge, the strain increased at a much lower rate than expected. As the pressure decreased, the strain returned along the same slope as in the standard A5.03 tests. The disc was then tested in accordance with the standard A5.03, and burst at a pressure of 99.9 psi.

Due to the strange shape of the pressure vs. strain curve, more tests were performed to determine the source of the apparent hysteresis.

Pressure transducers were compared, the pressure transducer location was changed, and different signal conditioning was tried. A slight roll-off in the original strain gauge signal conditioning was found to be a contributing factor to the apparent hysteresis. A surge test was performed on a composite disc #1 with a single strain gauge. The gauge was located in the same position as it was in a rosette. The hysteresis loop changed shape, as shown in Figure 5.21.

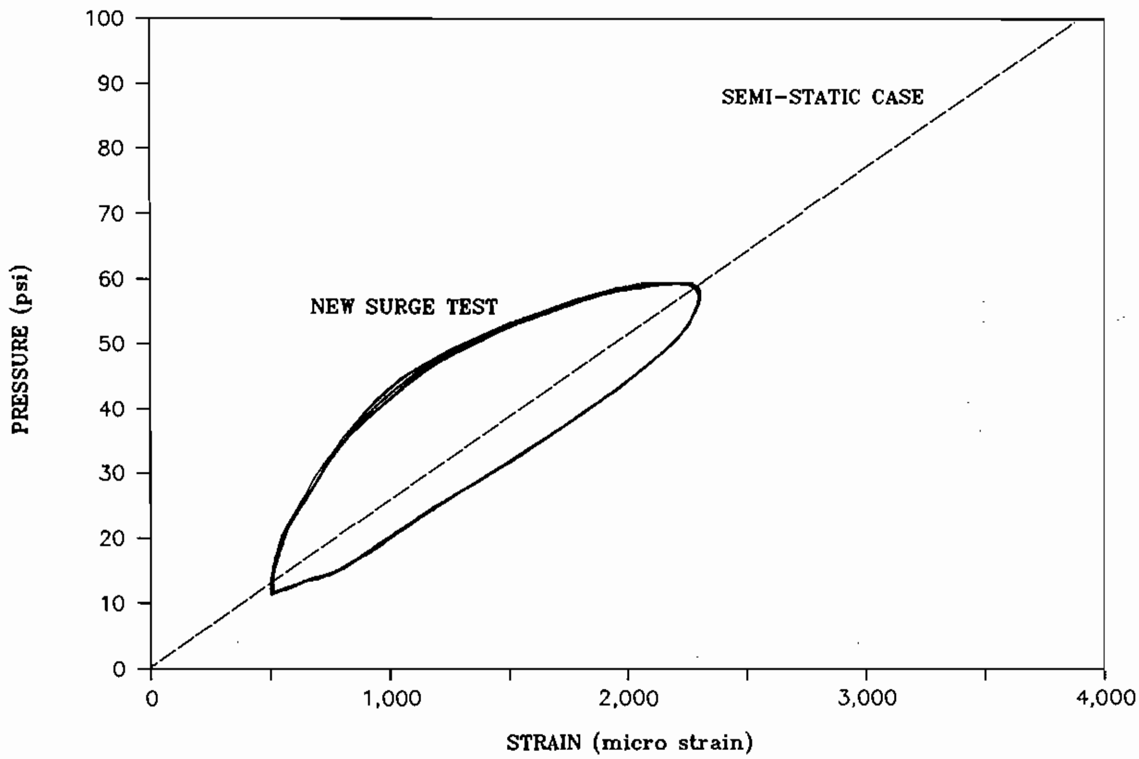

Figure 5.21 Actual Hysteresis in Composite Disc #1.

The dynamic strain followed the semi-static case, indicated by the dashed line. The semi-static values were obtained by measuring the strain while applying pressure at approximately 1 psi per second. Though the hysteresis loop didn't look exactly like those shown in textbooks, the pressure and strain time histories, shown in Figure 5.22, were very similar to those found in <u>Influence of Damping in Vibration Isolation</u>.

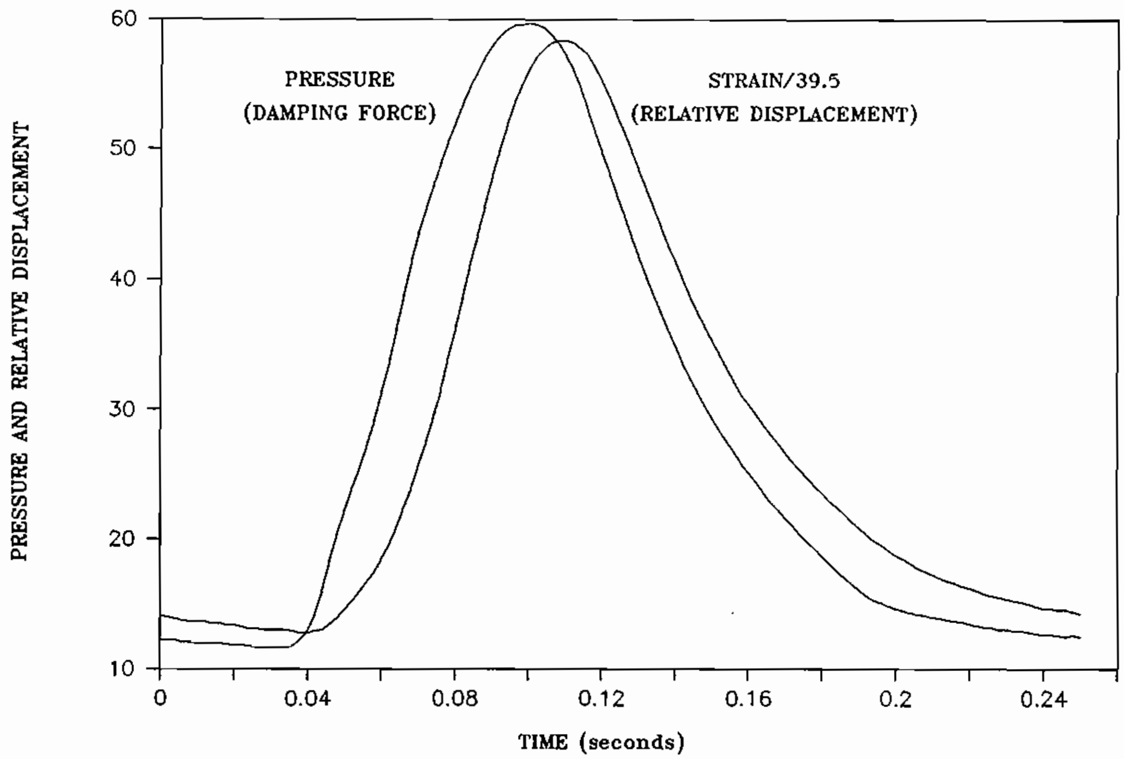

Figure 5.22 Composite Disc #1 Damping Force Time History.

The pressure could be likened to damping force and the strain to relative displacement. The strain was divided by a constant, which was found by dividing the semi-static strain by its respective pressure. The relationship shown would be indicative of internal damping in the material, usually called structural or hysteretic damping.[1]

The relative displacement lagged the damping force by some phase angle. That phase angle was a function of the material property and the frequency of stress application.[2]

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[1] INFLUENCE OF DAMPING IN VIBRATION ISOLATION, Jerome E. Ruzicka and Thomas F. Derby, United States Department of Defense, 1971, pages 6-10.

[2] ANALYTICAL METHODS IN VIBRATIONS, Leonard Meirovitch, Collier-Macmillan Ltd., 1967, pages 400-403.

Composite disc #R9 was subjected to 20 surge cycles at a maximum pressure of 90 psi. Similar hysteretic behavior was observed. The maximum strain was 2500 micro strain. The maximum strain may have been higher, approximately 3000, with the high frequency response signal conditioning. A burst pressure of 118.7 psi was obtained during the standard burst test which followed.

5.5.4 Composite Disc #2

The composite disc #2 showed a strain hysteresis similar to composite disc #1. Disc #G8, shown in Figure 5.23, was subjected to 20 surge cycles at 85 psi.

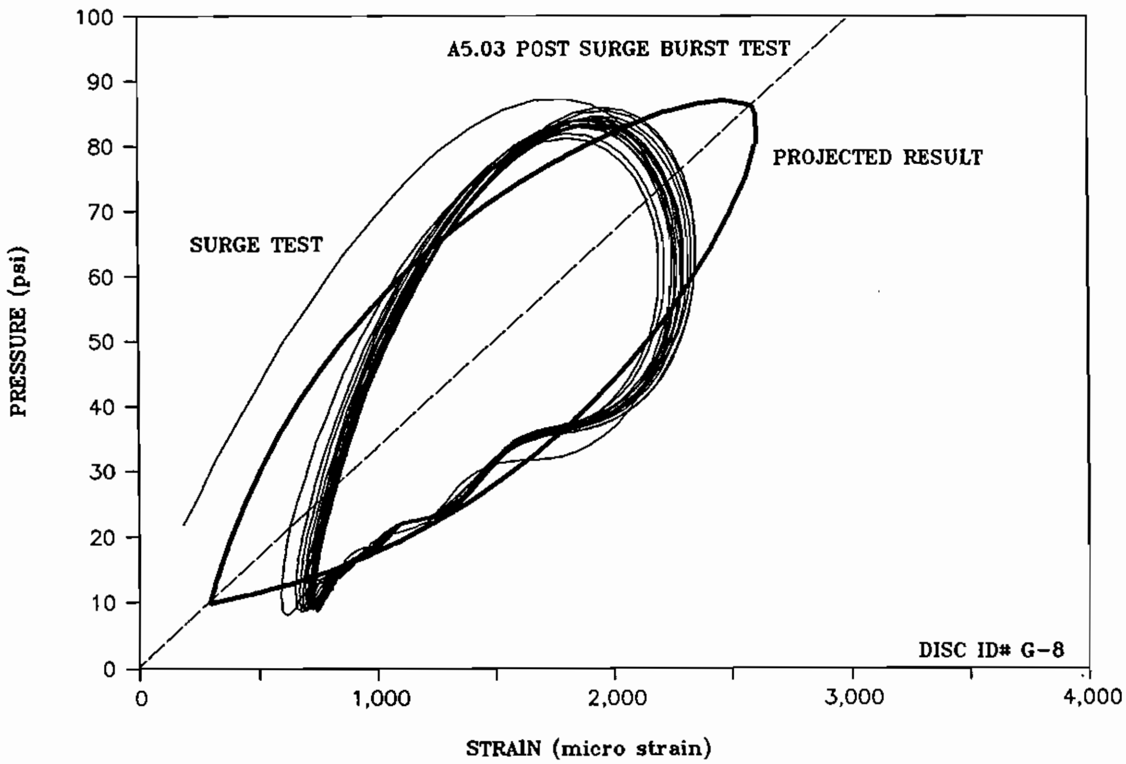

Figure 5.23 Composite Disc #2, #G8 at 85 psi Pressure Surge Cycles.

The response of composite disc #G8 was almost identical to composite disc #R10. The maximum strain was approximately 2300 micro strain. The projected strain may have been 2500 micro strain. Since the disc didn't fail, it was burst tested. A burst pressure of 119.6 psi was achieved.

Composite Disc #G10 was subjected to 20 surge cycles, shown in Figure 5.24.

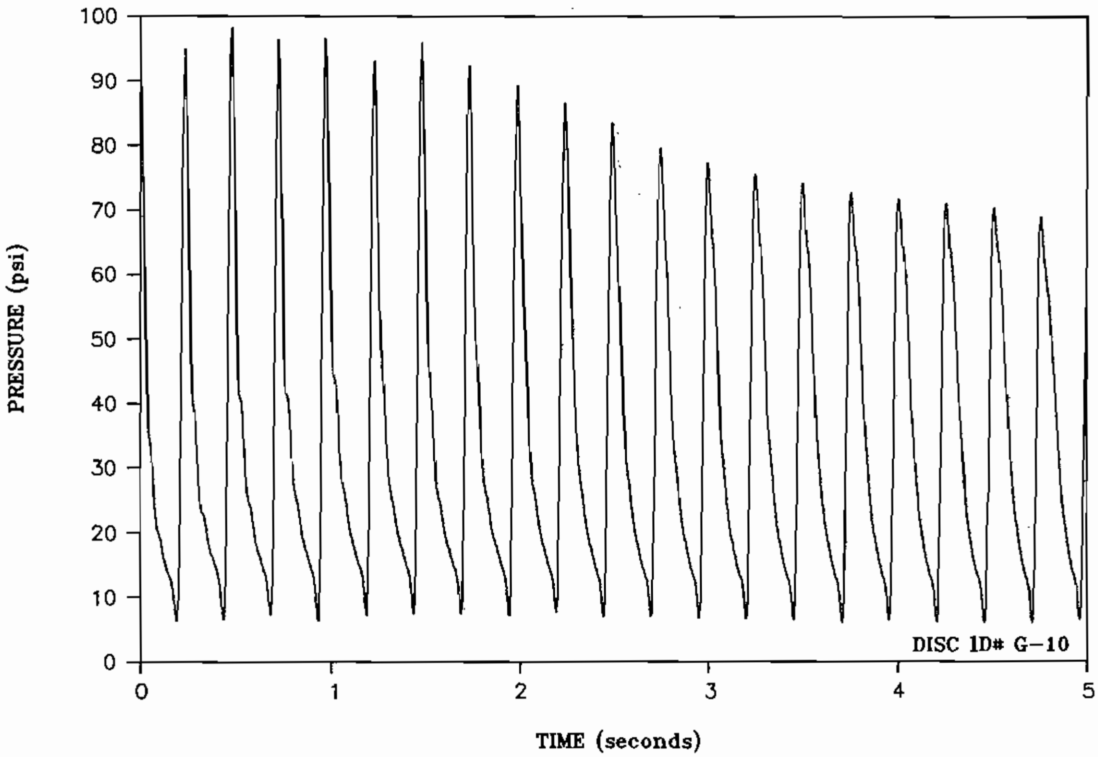

Figure 5.24 Surge Cycles Applied to Composite Disc #G10.

At first, it seemed as though the control system may have produced the decline in pressure. The truth was revealed upon examination of the strain gauge data. The graphite began to crack on or before the seventh cycle, as shown in Figure 5.25.

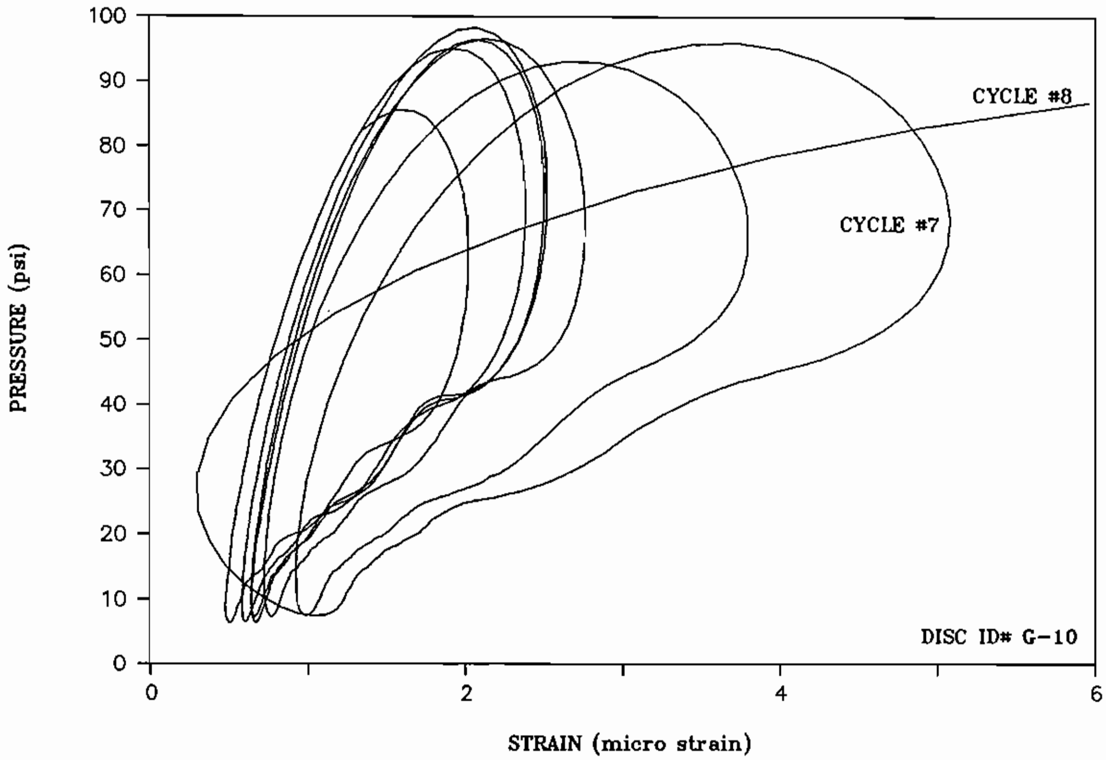

Figure 5.25 Pressure Versus Strain in Disc #G10 Surge Test.

Cycle #7 showed a maximum strain of 4500 micro strain. Cycle #8 showed damage to the gauge as the circuit was opened and the channel became saturated. It was surprising that the disc survived all 20 cycles. The Teflon and neoprene liners remained intact, allowing the disc to flex, to increase its volume, and decrease the maximum pressure in the surge. The 20th cycle peaked at 64 psi, as shown in Figure 5.24.

The disc was burst tested since it didn't burst during surge testing. The burst pressure was 64 psi, as shown in Figure 5.26.

The disc failed during surge testing, but didn't burst. This was undoubtedly a product of such high frequency surge cycles.

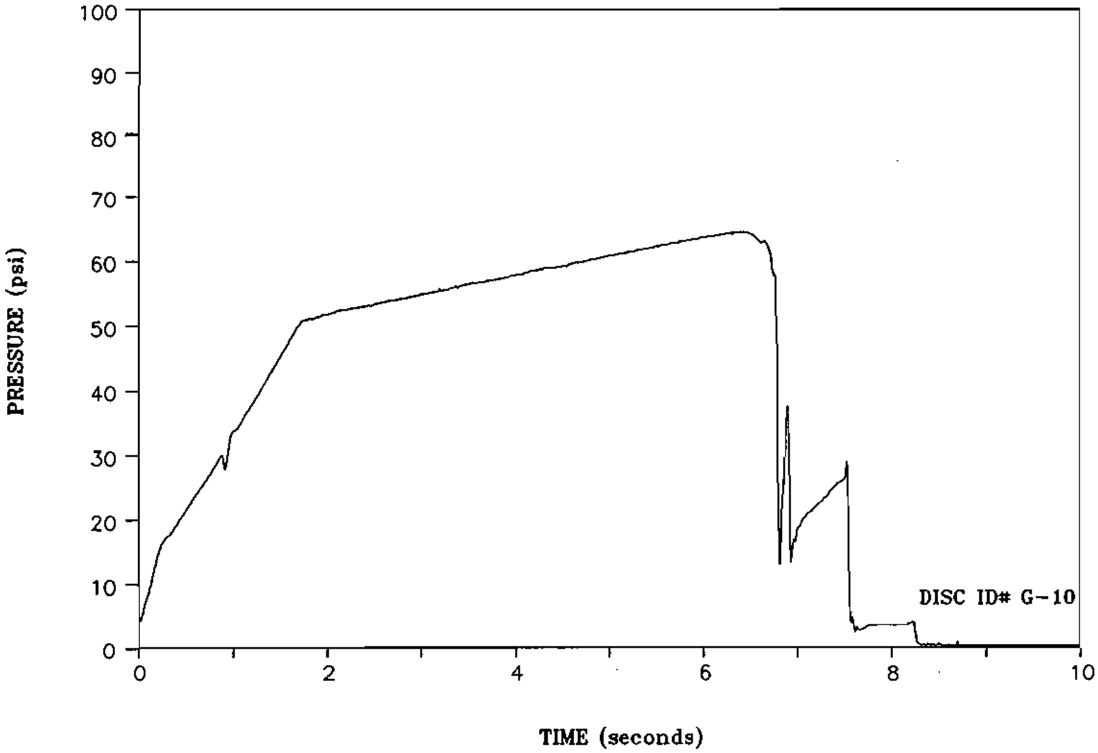

Figure 5.26 Pressure vs Time for Disc #G10 During Post Surge Burst Test.

6.0 CONCLUSIONS

1. The burst pressure test, as specified in paragraph A5.03 in the AAR Tank Car Specifications Manual, is only appropriate for discs with a small variation in their range of burst pressures.

2. Composite discs showed a larger variation in burst pressure ranges than the stainless steel design.

3. Composite discs are less likely to be affected by improper installation. One type had no specified pressure side; it was designed to work either way. The stainless steel design is greatly affected by improper installation. The burst pressure greatly decreases if the disc is installed backwards to the designated pressure side.

4. Composite discs showed little or no permanent damage when subjected to pressures less than their burst pressure; however, stainless steel discs showed permanent deformation at pressures less than their burst pressure.

5. Composite discs are likely to exhibit damping when exposed to cyclic pressure surges.

6. Lead discs are greatly affected by prolonged exposure to pressures lower than burst pressure. (Note: AAR no longer allows lead discs in interchange service).

7. All disc burst pressures were affected by temperature. Lead discs showed the greatest variance in burst pressure with changes in temperature. The tendency to creep would also increase with higher temperatures.

7.0 RECOMMENDATIONS

1. New frangible disc **designs** should be qualified through various tests before they are approved for use. They should pass at least five tests:

    a) Burst Pressure - A specified percentage of discs, from a test batch, must burst between 85 and 100 psi. This would give a statistical base to rely on when evaluating future batches with the single disc burst test, as specified in A5.03. As shown in Section 5.2, for the batch of frangible discs tested, there was a large variation in burst pressures.

    b) Range - Burst pressures within one test batch must not vary more than a specified amount. Every disc must burst between some lower and upper limit. For example, it would be undesirable to have a 100 psi disc with a 150 psi burst pressure, even if it were the only one in the batch which was extremely high.

    c) Creep - Discs should be able to withstand a specified pressure for at least two weeks. It was clear that some discs were unable to withstand pressure for extended periods of time. It would seem desirable to have a disc which would be less susceptible to creep.

    d) Surge - The disc may burst in a surge situation if the pressure increase is above the operating pressure of the disc. This unintentional burst could result in the undesired release of hazardous material. It would be desirable to control the sudden pressure increase due to a surge through the use of a surge chamber, baffles, or other arrangements.

e) Temperature - Acceptable burst pressures should be measured with disc temperatures at the extremes of the operating temperatures. It was shown in Section 5.3 that disc burst pressure can be greatly affected by temperature. Since tank cars operate in a large range of atmospheric conditions and temperatures, it would be desirable to have frangible discs which aren't likely to be affected by temperature variations.

2. Tests should be done to determine what pressure profiles are found in a tank car during impacts and other surge producing situations.

3. Various vent pipe designs should be evaluated for their effectiveness in pressure surge situations.

APPENDIX A

FRANGIBLE DISC STRESS MODEL

A simple model was developed to estimate the stress and strain near the center of a frangible disc. A series of formulas for a circular flat plate with uniform loading and fixed edges were used.[1]

The stress at the center was calculated:

$$\sigma_{max} = \frac{-3W(m+1)}{8\pi m t^2}$$

Where: W = total applied load
m = reciprocal of Poissons ratio
t = plate thickness

The maximum deflection was calculated:

$$Y_{max} = -\frac{3W(m^2-1)r^2}{16\pi E m^2 t^3}$$

Where: r = disc or plate radius
E = modulus of elasticity

The radial stress at the location of the strain gage was calculated:

$$\sigma_R = \frac{3W}{8\pi m t^2}\left[(3m+1)\frac{q^2}{r^2} - (m+1)\right]$$

Where: q = radial location of strain gage.

The strain was then calculated using the uniaxial equation:

$$\epsilon = \frac{\sigma}{E}$$

The results for both composite discs were very similar to the actual data. The stainless steel model did not accurately reflect the complex geometry of that disc. Therefore, the results of the model were not similar to the actual test data.

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1 Kent's Mechanical Engineering Handbook, Twelfth Edition, John Wiley and Sons, Inc., c 1950, page 832.

PLASTIC MODEL

W = total applied load
w = pressure (psi)
t = plate thickness (in) 0.08
E = modulus of elasticity 2000000
m = reciprocal of Poissons ratio 3.333333
r = radius of disc 1.05
q = strain gauge location 0.2

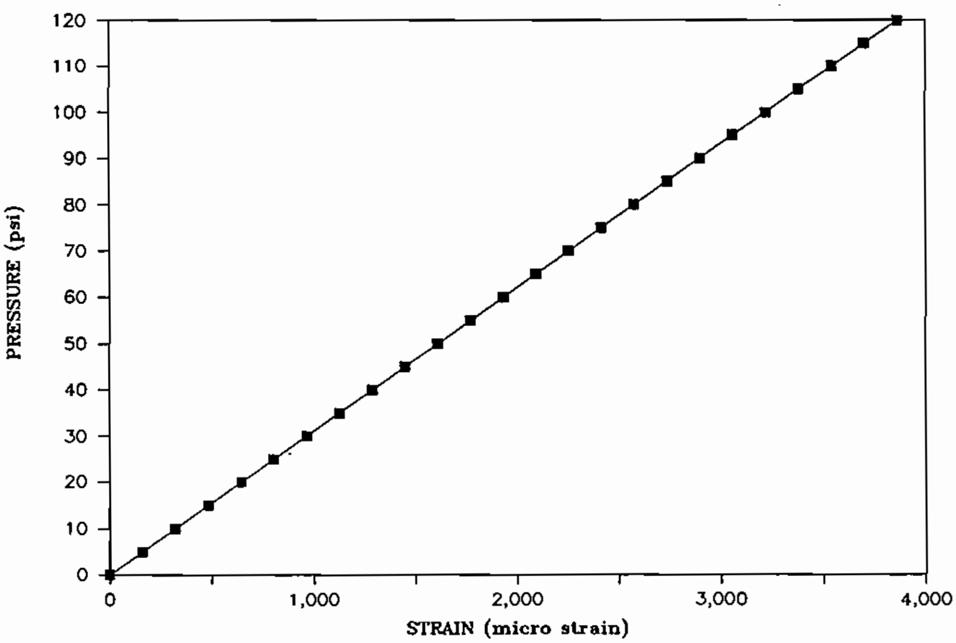
PRESSURE (psi)	W (lbs)	MAXIMUM STRESS (psi)	DEFLECTION (inches)	RADIAL STRESS (psi)	GAUGE STRAIN	MICRO-STRAIN
0	0	0	0.000	0	0.00000	0
5	17.32	420	0.001	377	0.00019	189
10	34.64	840	0.002	755	0.00038	377
15	51.95	1260	0.003	1132	0.00057	566
20	69.27	1680	0.004	1509	0.00075	755
25	86.59	2099	0.005	1886	0.00094	943
30	103.91	2519	0.006	2264	0.00113	1132
35	121.23	2939	0.007	2641	0.00132	1320
40	138.54	3359	0.008	3018	0.00151	1509
45	155.86	3779	0.009	3395	0.00170	1698
50	173.18	4199	0.010	3773	0.00189	1886
55	190.50	4619	0.011	4150	0.00207	2075
60	207.82	5039	0.012	4527	0.00226	2264
65	225.13	5459	0.013	4904	0.00245	2452
70	242.45	5879	0.014	5282	0.00264	2641
75	259.77	6298	0.015	5659	0.00283	2829
80	277.09	6718	0.016	6036	0.00302	3018
85	294.41	7138	0.017	6413	0.00321	3207
90	311.72	7558	0.018	6791	0.00340	3395
95	329.04	7978	0.019	7168	0.00358	3584
100	346.36	8398	0.020	7545	0.00377	3773
105	363.68	8818	0.021	7922	0.00396	3961
110	381.00	9238	0.022	8300	0.00415	4150
115	398.31	9658	0.023	8677	0.00434	4339
120	415.63	10078	0.024	9054	0.00453	4527

GRAPHITE MODEL

W =	total applied load	
w =	pressure (psi)	
t =	plate thickness (in)	0.1
E =	modulus of elasticity	1500000
m =	reciprocal of Poissons ratio	3.333333
r =	radius of disc	1.05
q =	strain gauge location	0.2

PRESSURE (psi)	W (lbs)	MAXIMUM STRESS (psi)	DEFLECTION (inches)	RADIAL STRESS (psi)	GAUGE STRAIN	MICRO-STRAIN
0	0	0	0.000	0	0.00000	0
5	17.32	269	0.001	241	0.00016	161
10	34.64	537	0.001	483	0.00032	322
15	51.95	806	0.002	724	0.00048	483
20	69.27	1075	0.003	966	0.00064	644
25	86.59	1344	0.003	1207	0.00080	805
30	103.91	1612	0.004	1449	0.00097	966
35	121.23	1881	0.005	1690	0.00113	1127
40	138.54	2150	0.006	1932	0.00129	1288
45	155.86	2419	0.006	2173	0.00145	1449
50	173.18	2687	0.007	2414	0.00161	1610
55	190.50	2956	0.008	2656	0.00177	1771
60	207.82	3225	0.008	2897	0.00193	1932
65	225.13	3494	0.009	3139	0.00209	2093
70	242.45	3762	0.010	3380	0.00225	2254
75	259.77	4031	0.010	3622	0.00241	2414
80	277.09	4300	0.011	3863	0.00258	2575
85	294.41	4568	0.012	4105	0.00274	2736
90	311.72	4837	0.012	4346	0.00290	2897
95	329.04	5106	0.013	4588	0.00306	3058
100	346.36	5375	0.014	4829	0.00322	3219
105	363.68	5643	0.015	5070	0.00338	3380
110	381.00	5912	0.015	5312	0.00354	3541
115	398.31	6181	0.016	5553	0.00370	3702
120	415.63	6450	0.017	5795	0.00386	3863

PRESSURE VERSUS CALCULATED STRAIN FOR GRAPHITE DISC

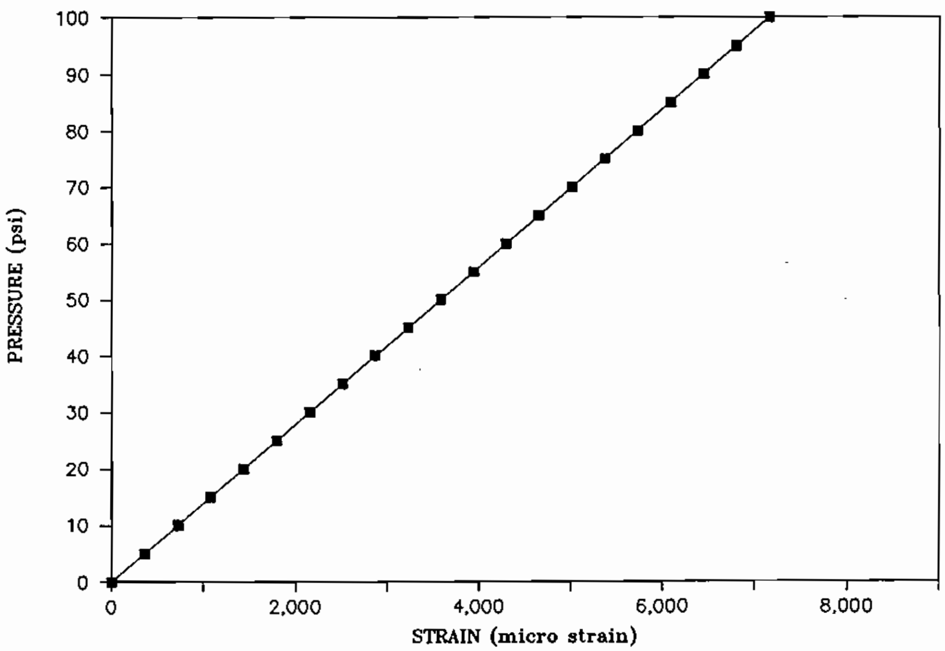


STAINLESS STEEL MODEL

W = total applied load
w = pressure (psi)
t = plate thickness (in) 0.015
E = modulus of elasticity 30000000
m = reciprocal of Poissons ratio 3.333333
r = radius of disc 1.05
q = strain gauge location 0.2

PRESSURE (psi)	W (lbs)	MAXIMUM STRESS (psi)	DEFLECTION (inches)	RADIAL STRESS (psi)	GAUGE STRAIN	MICRO-STRAIN
0	0	0	0.000	0	0.00000	0
5	17.32	11944	0.010	10731	0.00036	358
10	34.64	23888	0.020	21462	0.00072	715
15	51.95	35831	0.031	32193	0.00107	1073
20	69.27	47775	0.041	42924	0.00143	1431
25	86.59	59719	0.051	53655	0.00179	1789
30	103.91	71663	0.061	64386	0.00215	2146
35	121.23	83606	0.072	75117	0.00250	2504
40	138.54	95550	0.082	85848	0.00286	2862
45	155.86	107494	0.092	96579	0.00322	3219
50	173.18	119438	0.102	107310	0.00358	3577
55	190.50	131381	0.113	118041	0.00393	3935
60	207.82	143325	0.123	128772	0.00429	4292
65	225.13	155269	0.133	139503	0.00465	4650
70	242.45	167213	0.143	150234	0.00501	5008
75	259.77	179156	0.154	160965	0.00537	5366
80	277.09	191100	0.164	171696	0.00572	5723
85	294.41	203044	0.174	182427	0.00608	6081
90	311.72	214988	0.184	193158	0.00644	6439
95	329.04	226931	0.195	203889	0.00680	6796
100	346.36	238875	0.205	214620	0.00715	7154
105	363.68	250819	0.215	225351	0.00751	7512
110	381.00	262763	0.225	236082	0.00787	7869
115	398.31	274706	0.236	246813	0.00823	8227
120	415.63	286650	0.246	257544	0.00858	8585

PRESSURE VERSUS CALCULATED STRAIN FOR STAINLESS STEEL DISC



APPENDIX B

FRANGIBLE DISC DATA

TABLE B-1
LEAD DISC AT 70 DEGREES F

DISC ID#	DISC THICKNESS IN INCHES BEFORE EDGE	BEFORE CENTER	AFTER EDGE	AFTER CENTER	BURST PRES. (psi)	MAX DEFL. (in)	NOTES
LS-1	0.040	0.041	0.038	0.034	105.1	0.471	
LS-2	0.040	0.041	0.040	0.034	102.5	0.493	
LS-3	0.036	0.040	0.037	0.033	100.0	0.468	
LS-4	0.036	0.040	0.036	0.032	100.1	0.487	ALL DISCS
LS-5	0.038	0.040	0.036	0.034	102.4	0.509	WERE AT
LS-6	0.040	0.040	0.039	0.035	99.2	0.460	70
LS-7	0.037	0.039	0.038	0.038	103.7	0.471	DEGREES
LS-8	0.037	0.040	0.037	0.031	100.2	0.454	FAHRENHEIT
LS-9	0.038	0.040	0.036	0.033	101.0	0.492	
LS-10	0.037	0.040	0.036	0.032	101.8	0.456	
LS-11	0.036	0.040	0.037	0.031	99.2	0.454	
LS-12	0.039	0.040	0.037	0.032	98.9	0.428	
LS-13	0.038	0.040	0.035	0.030	105.2		
LS-14	0.038	0.040	0.038	0.034	100.6	0.451	
LS-15	0.036	0.040	0.036	0.034	100.8	0.423	
LS-16	0.040	0.040	0.037	0.033	100.3	0.460	
LS-17	0.036	0.041	0.037	0.035	99.9	0.461	
LS-18	0.040	0.040	0.038	0.033	101.0	0.445	
LS-19	0.038	0.040	0.037	0.034	99.9	0.471	
LS-20	0.040	0.042	0.038	0.034	105.2	0.527	
LS-21	0.039	0.040	0.038	0.034	98.0	0.495	
LS-22	0.039	0.041	0.038	0.034	99.9	0.442	
LS-23	0.040	0.041	0.039	0.035	102.3	0.475	
LS-24	0.036	0.039	0.037	0.034	98.9	0.457	
LS-25	0.035	0.039	0.037	0.033	99.3	0.480	
MIN	0.035	0.039	0.035	0.030	98.0	0.423	
MAX	0.040	0.042	0.040	0.038	105.2	0.527	
AVE	0.038	0.040	0.037	0.033	101.0	0.468	
STD	0.002	0.001	0.001	0.002	2.0	0.024	

TABLE B-2
LEAD DISC AT 32 AND 140 DEGREES F

DISC ID#	DISC THICKNESS IN INCHES BEFORE EDGE	BEFORE CENTER	AFTER EDGE	AFTER CENTER	BURST PRES. (psi)	MAX DEFL. (in)	NOTES
LS-26	0.037	0.040	0.037	0.033	122.4		
LS-27	0.036	0.040	0.038	0.033	122.1	0.492	
LS-28	0.037	0.041	0.037	0.032	122.2	0.521	
LS-29	0.038	0.039	0.037	0.035	123.1	0.499	
LS-30	0.039	0.040	0.038	0.034	121.1	0.523	ALL DISCS
LS-31	0.037	0.039	0.038	0.034	121.1	0.497	WERE AT
LS-32	0.039	0.040	0.038	0.033	127.7	0.503	32
LS-33	0.037	0.040	0.038	0.034	116.5	0.481	DEGREES
LS-34	0.038	0.040	0.037	0.034	115.9	0.487	FAHRENHEIT
LS-35	0.037	0.041	0.037	0.034	125.8	0.523	
MIN	0.036	0.039	0.037	0.032	115.9	0.481	
MAX	0.039	0.041	0.038	0.035	127.7	0.523	
AVE	0.038	0.040	0.038	0.034	121.8	0.503	
STD	0.001	0.001	0.000	0.001	3.4	0.015	
LS-40	0.040	0.042	0.039	0.042	70.9		
LS-41	0.040	0.041	0.038	0.039	76.2		
LS-42	0.040	0.040	0.039	0.042	76.1		
LS-43	0.043	0.043	0.041	0.042	91.6		ALL DISCS
LS-44	0.041	0.041	0.039	0.041	81.2		WERE AT
LS-45	0.043	0.041	0.038	0.041	71.4	0.257	140
LS-46	0.042	0.041	0.039	0.040	70.8	0.283	DEGREES
LS-47	0.041	0.040	0.042	0.038	72.8	0.276	FAHRENHEIT
LS-48	0.043	0.041	0.043	0.038	73.1	0.273	
LS-50	0.042	0.040	0.041	0.038	74.3	0.271	
MIN	0.040	0.040	0.038	0.038	70.8	0.257	
MAX	0.043	0.043	0.043	0.042	91.6	0.283	
AVE	0.042	0.041	0.040	0.040	75.8	0.272	
STD	0.001	0.001	0.002	0.002	6.0	0.009	

TABLE B-3
LEAD WITH BREATHER HOLE AT 70 DEGREES F *

DISC ID#	DISC THICKNESS IN INCHES BEFORE EDGE	BEFORE CENTER	AFTER EDGE	AFTER CENTER	HOLE SIZE IN INCHES BEFORE	AFTER	BURST PRES. (psi)	MAX DEFL. (in)	NOTES
LH-1							146.8	---	70 F
LH-2							149.9	---	
LH-3	0.040	0.041	0.040	0.040	0.120	0.230	142.4	---	
LH-4	0.041	0.041	0.040	0.040	0.120	0.230	145.2	1.500	
LH-5	0.041	0.041	0.040	0.040	0.123	0.250	143.8	0.760	
LH-6	0.041	0.041	0.040	0.040	0.125	0.260	142.8	0.900	
LH-7	0.041	0.041	0.040	0.041	0.124	0.300	140.0	0.730	
LH-8	0.042	0.041	0.040	0.040	0.124	0.300	138.0	---	
LH-9	0.041	0.042	0.041	0.042	0.124	0.205	131.2	---	
LH-10	0.041	0.042	0.039	0.040	0.125	0.277	141.7	0.560	
LH-11	0.041	0.041	0.040	0.041	0.125	0.241	138.7	0.600	
LH-12	0.042	0.041	0.040	0.041	0.124	0.233	139.2	---	
LH-13	0.041	0.041	0.040	0.040	0.124	0.230	139.9	0.800	
LH-14	0.040	0.041	0.040	0.041	0.127	SPLIT	105.8	0.730	
LH-15	0.040	0.040	0.038	0.040	0.124	SPLIT	105.9	0.510	
LH-16	0.040	0.040	0.039	0.041	0.126	SPLIT	111.6	---	
LH-17	0.040	0.040	0.039	0.041	0.125	0.220	125.5	0.530	
LH-18	0.040	0.040	0.039	0.040	0.125	SPLIT	103.4	0.650	
LH-19	0.040	0.041	0.039	0.040	0.125	SPLIT	114.3	0.540	
LH-20	0.040	0.040	0.038	0.040	0.126	SPLIT	101.4	0.580	
LH-21	0.042	0.041	0.039	0.040	0.125	0.032	140.8	0.740	
LH-22	0.041	0.041	0.040	0.040	0.124	0.166	107.8	0.630	
LH-23	0.040	0.040	0.040	0.039	0.126	SPLIT	97.1	0.420	
LH-24	0.039	0.040	0.038	0.040	0.124	SPLIT	95.1	0.490	
LH-25	0.040	0.040	0.040	0.040	0.125	SPLIT	110.6	---	
MIN	0.039	0.040	0.038	0.039	0.120	0.000	95.1	0.000	
MAX	0.042	0.042	0.041	0.042	0.127	0.300	149.9	1.500	
AVE	0.041	0.041	0.040	0.040	0.124	0.138	126.4	0.467	
STD	0.001	0.001	0.001	0.001	0.002	0.121	18.1	0.375	

--- :THE LVDT HAD BLOWN OFF BEFORE THE DISC BURST.

* THESE PRESSURE RESULTS ARE FOR A DYNAMIC CONDITION DUE TO THE ORIGINAL HOLE IN THE DISC AND THE LOCATION OF THE PRESSURE SENSOR IN THE LINE GOING TOWARD THE CHAMBER.

TABLE B-4
LEAD WITH BREATHER HOLE AT 32 F AND 140 F *

DISC ID#	DISC THICKNESS IN INCHES BEFORE EDGE	BEFORE CENTER	AFTER EDGE	AFTER CENTER	HOLE SIZE IN INCHES BEFORE	AFTER	BURST PRES. (psi)	MAX DEFL. (in)	NOTES
LH-30	0.038	0.038	0.037	0.037	0.125	0.205	121.7	---	32 F
LH-31	0.040	0.040	0.039	0.039	0.124	SPLIT	122.3	0.550	
LH-32	0.040	0.040	0.039	0.038	0.125	SPLIT	143.8	---	
LH-33	0.041	0.041	0.039	0.039	0.124	SPLIT	144.3	---	
LH-34	0.041	0.041	0.039	0.038	0.124	SPLIT	138.0	---	
LH-35	0.041	0.041	0.040	0.041	0.125	SPLIT	145.8	0.440	
LH-36	0.041	0.040	0.040	0.040	0.126	0.190	126.7	0.640	
LH-37	0.041	0.041	0.039	0.038	0.126	SPLIT	128.0	---	
LH-38	0.040	0.040	0.039	0.040	0.124	SPLIT	126.7	---	
LH-39	0.040	0.040	0.039	0.040	0.124	SPLIT	132.3	---	
MIN	0.038	0.038	0.037	0.037	0.124	0.000	121.7	0.000	
MAX	0.041	0.041	0.040	0.041	0.126	0.205	145.8	0.640	
AVE	0.040	0.040	0.039	0.039	0.125	0.040	133.0	0.163	
STD	0.001	0.001	0.001	0.001	0.001	0.079	8.8	0.253	
LH-40	0.038	0.038	0.035	0.038	0.125	0.270	93.9	---	140 F
LH-41	0.037	0.038	0.037	0.037	0.125	0.260	88.9	0.470	
LH-42	0.041	0.040	0.037	0.037	0.125	0.270	95.4	0.660	
LH-43	0.038	0.038	0.360	0.037	0.126	0.273	90.4	---	
LH-44	0.037	0.037	0.036	0.036	0.124	0.266	92.1	---	
LH-45	0.038	0.038	0.038	0.038	0.125	0.270	87.3	0.470	
LH-46	0.040	0.040	0.039	0.040	0.124	0.272	93.7	0.630	
LH-47	0.040	0.040	0.039	0.040	0.126	0.263	87.2	0.500	
LH-48	0.040	0.040	0.039	0.040	0.125	0.269	92.4	---	
LH-49	0.040	0.040	0.038	0.038	0.124	0.267	97.6	---	
MIN	0.037	0.037	0.035	0.036	0.124	0.260	87.2	0.000	
MAX	0.041	0.040	0.360	0.040	0.126	0.273	97.6	0.660	
AVE	0.039	0.039	0.070	0.038	0.125	0.268	91.9	0.273	
STD	0.001	0.001	0.097	0.001	0.001	0.004	3.3	0.279	

--- :THE LVDT HAD BLOWN OFF BEFORE THE DISC BURST.

* THESE PRESSURE RESULTS ARE FOR A DYNAMIC CONDITION DUE TO THE ORIGINAL HOLE IN THE DISC AND THE LOCATION OF THE PRESSURE SENSOR IN THE LINE GOING TOWARD THE CHAMBER.

TABLE B-5
STAINLESS STEEL DISC AT 70 DEGREES F

DISC ID#	DISC THICKNESS (inches) MAIN BODY	BROKEN LEG	BURST PRES. (psi)	NOTES
S-2			94.0	WITH STRAIN GAUGE
S-3			95.4	WITH STRAIN GAUGE
S-4			100.1	WITH STRAIN GAUGE
S-11			96.4	
S-12			97.2	
S-13			101.2	
S-14			95.9	
S-15			99.8	
S-16			96.5	
S-17			93.2	ALL DISCS WERE AT
S-18			100.6	70 DEGREES
S-19			95.1	FAHRENHEIT
S-20			91.3	
S-21			98.1	
S-22			95.4	
S-23			95.2	
S-24	0.0103	0.0100	97.9	
S-25			93.2	
S-26			93.2	
S-27			91.8	
S-28			99.5	
S-29			99.2	
S-30			97.2	
S-31	0.0098	0.0100	102.5	
S-32			96.8	
MIN			91.3	
MAX			102.5	
AVE			96.7	
STD			2.9	

TABLE B-6
STAINLESS STEEL DISC AT 32 AND 140 DEGREES F

DISC ID#	DISC THICKNESS (inches) MAIN BODY	BROKEN LEG	BURST PRES. (psi)	NOTES
S-5			101.7	WITH STRAIN GAUGE
S-6			99.0	WITH STRAIN GAUGE
S-33			100.5	
S-34			100.6	
S-35			105.6	ALL DISCS WERE AT
S-36			101.1	32 DEGREES
S-37			106.1	FAHRENHEIT
S-38			103.2	
S-39	0.0122	0.0104	94.9	
S-40	0.0106	0.0099	100.9	
MIN			94.9	
MAX			106.1	
AVE			101.4	
STD			3.0	
S-50			58.7	BACKWARDS
S-51			94.6	
S-52			92.7	ALL DISC WERE AT
S-53			92.0	140 DEGREES
S-54			87.5	FAHRENHEIT
S-55	0.0109	0.0095	94.8	
S-56	0.0114	0.0093	94.5	
S-57			87.2	
S-58			94.5	WITH STRAIN GAUGE
S-59			95.9	WITH STRAIN GAUGE
MIN			87.2	
MAX			95.9	
AVE			92.6	
STD			3.0	

TABLE B-7
COMPOSITE #1 DISC AT 70 DEGREES F

DISC ID#	DISC THICKNESS (inches) BEFORE	AFTER	BURST PRES. (psi)	NOTES
R-1		0.082	109.1	WITH STRAIN GAUGE
R-2		0.085	103.4	WITH STRAIN GAUGE
R-3		0.087	111.1	WITH STRAIN GAUGE
R-11	0.085	0.089	97.8	
R-12	0.085	0.087	99.7	
R-13	0.085	0.086	107.9	
R-14	0.085	0.090	100.7	
R-15	0.085	0.087	107.2	ALL DISC WERE AT
R-16	0.085	0.090	102.8	70 DEGREES
R-17	0.085	0.086	101.8	FAHRENHEIT
R-18	0.085	0.090	97.4	
R-19	0.085	0.088	108.2	
R-20	0.085	0.088	114.8	
R-21	0.084	0.088	111.3	
R-22	0.085	0.087	113.0	
R-23	0.084	0.089	115.0	
R-24	0.085	0.090	122.4	
R-25	0.083	0.088	114.1	
R-26	0.085	0.089	109.8	
R-27	0.084	0.089	102.4	
R-28	0.084	0.088	112.5	
R-29	0.083	0.088	101.5	
R-30	0.084	0.089	110.4	
R-31	0.082	0.090	96.3	
R-32	0.083	0.090	105.5	
MIN	0.082	0.082	96.3	
MAX	0.085	0.090	122.4	
AVE	0.084	0.088	107.0	**
STD	0.001	0.002	6.4	

** DIFFERENCE IN APPARENT DISC THICKNESS WAS DUE TO THE INABILITY TO ACCURATELY MEASURE THE THICKNESS OF THE DISC IN A DEFORMED STATE.

TABLE B-8
COMPOSITE #1 DISC AT 32 AND 140 DEGREES F

DISC ID#	DISC THICKNESS (inches) BEFORE	AFTER	BURST PRES. (psi)	NOTES
R-4		0.083	102.5	WITH STRAIN GAUGE
R-5		0.091	114.9	WITH STRAIN GAUGE
R-33	0.083	0.087	115.6	
R-34	0.086	0.089	121.4	
R-35	0.083	0.089	119.8	ALL DISCS WERE AT
R-36	0.085	0.088	109.0	32 DEGREES
R-37	0.085	0.089	106.4	FAHRENHEIT
R-38	0.085	0.088	104.5	
R-39	0.084	0.089	109.4	
R-40	0.083	0.088	115.1	
MIN	0.083	0.083	102.5	
MAX	0.086	0.091	121.4	
AVE	0.084	0.088	111.9	**
STD	0.001	0.002	6.1	
R-6	0.085	0.087	102.7	WITH STRAIN GAUGE
R-7		0.089	102.8	WITH STRAIN GAUGE
R-41	0.083	0.087	94.6	
R-42	0.083	0.087	98.5	
R-43	0.085	0.089	97.6	ALL DISCS WERE AT
R-44	0.087	0.089	106.2	140 DEGREES
R-45	0.082	0.087	105.8	FAHRENHEIT
R-46	0.083	0.087	112.5	
R-47	0.084	0.087	96.8	
R-48	0.085	0.087	95.2	
MIN	0.082	0.087	94.6	
MAX	0.087	0.089	112.5	
AVE	0.084	0.088	101.3	**
STD	0.001	0.001	5.5	

** DIFFERENCE IN APPARENT DISC THICKNESS WAS DUE TO THE INABILITY TO ACCURATELY MEASURE THE THICKNESS OF THE DISC IN A DEFORMED STATE.

TABLE B-9
COMPOSITE #2 DISC AT 70 DEGREES F

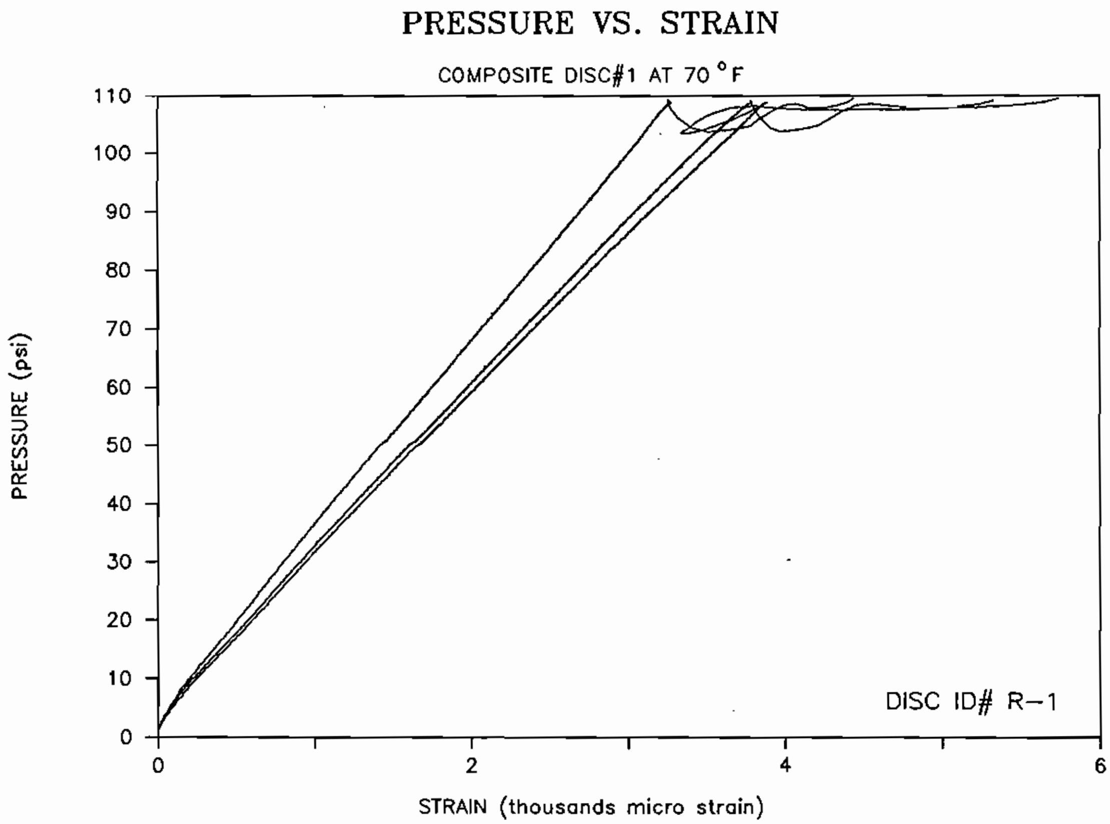
DISC ID#	DISC THICKNESS (inches) BEFORE	AFTER	BURST PRES. (psi)	NOTES
G-1	0.1090		99.9	LOST DATA IN TEST
G-2	0.1090	0.1080	104.7	WITH STRAIN GAUGE
G-3	0.1090	0.1090	99.0	WITH STRAIN GAUGE
G-11	0.1090	0.1070	98.4	
G-12	0.1090	0.1060	89.1	
G-13	0.1090	0.1090	104.8	
G-14	0.1090	0.1070	97.3	ALL DISCS AT 70
G-15	0.1090	0.1090	108.8	DEGREES FAHRENHEIT
G-16	0.1090	0.1070	107.6	
G-17	0.1090	0.1080	109.8	
G-18	0.1090	0.1090	100.8	
G-19	0.1090	0.1060	108.2	
G-20	0.1090	0.1090	102.1	
G-21	0.1090	0.1090	108.8	
G-22	0.1090	0.1070	94.7	
G-23	0.1090	0.1080	102.4	
G-24	0.1090	0.1090	100.0	
G-25	0.1090	0.1070	104.0	
G-26	0.1090	0.1090	96.3	
G-27	0.1090	0.1090	98.8	
G-28	0.1090	0.1070	104.2	
G-29	0.1090	0.1070	101.6	
G-30	0.1090	0.1050	96.8	
G-31	0.1090	0.1090	106.6	
G-32	0.1090	0.1090	103.6	
MIN		0.1050	89.1	
MAX		0.1090	109.8	
AVE	0.1090	0.1079	101.9	**
SD		0.0012	5.0	

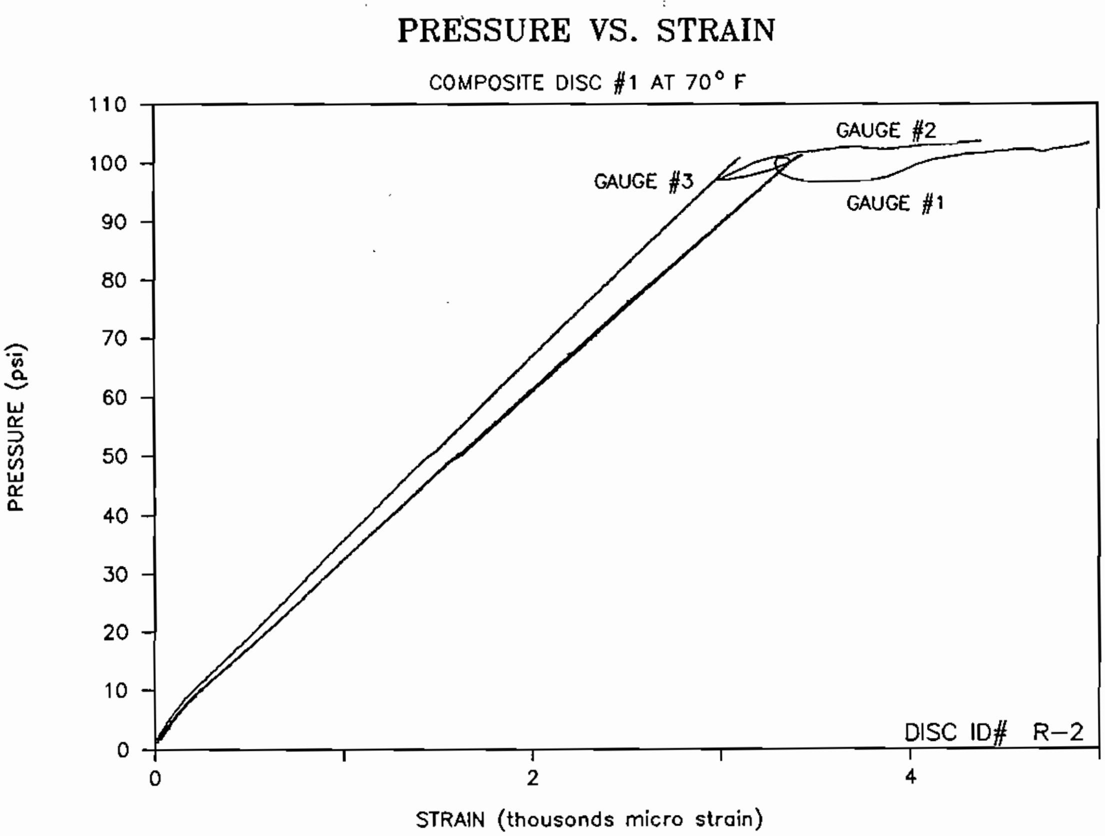
** ONE DISC WAS TAKEN APART TO ALLOW THE MEASUREMENT OF THE THICKNESS OF THE GRAPHITE LAYER. THAT VALUE WAS USED AS THE APPROXIMATE THICKNESS OF EACH DISC.

TABLE B-10
COMPOSITE #2 DISC AT 32 AND 140 DEGREES F

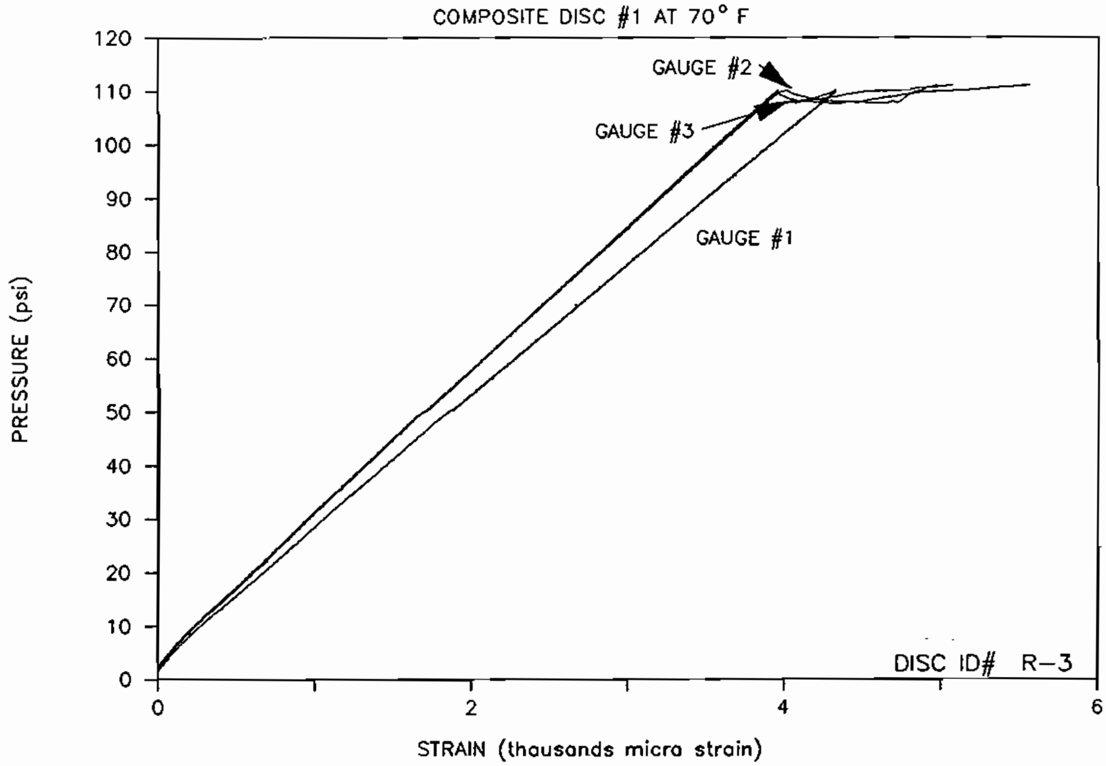
DISC ID#	DISC THICKNESS (inches) BEFORE	AFTER	BURST PRES. (psi)	NOTES
G-4	0.1090	0.1080	111.6	WITH STRAIN GAUGE
G-5	0.1090	0.1110	113.9	WITH STRAIN GAUGE
G-33	0.1090	0.1080	117.5	
G-34	0.1090	0.1090	108.0	
G-35	0.1090	0.1090	98.6	
G-36	0.1090	0.1090	100.1	ALL DISCS AT 32
G-37	0.1090	0.1090	108.1	DEGREES FAHRENHEIT
G-38	0.1090	0.1090	111.4	
G-39	0.1090	0.1090	104.3	
G-40	0.1090	0.1080	104.9	
MIN		0.1080	98.6	
MAX		0.1110	117.5	
AVE	0.1090	0.1089	107.8	**
SD		0.0008	5.7	
G-6	0.1090	0.1070	106.1	WITH STRAIN GAUGE
G-7	0.1090	0.1070	102.4	WITH STRAIN GAUGE
G-50	0.1090	0.1090	117.8	
G-51	0.1090	0.1090	91.9	
G-52	0.1090	0.1090	106.6	
G-53	0.1090	0.1090	106.6	ALL DISCS AT 140
G-54	0.1090	0.1100	96.9	DEGREES FAHRENHEIT
G-55	0.1090	0.1100	92.0	
G-56	0.1090	0.1090	96.1	
G-57	0.1090	0.1090	103.0	
MIN		0.1070	91.9	
MAX		0.1100	117.8	
AVE	0.1090	0.1088	101.9	**
SD		0.0010	7.6	

** ONE DISC WAS TAKEN APART TO ALLOW THE MEASUREMENT OF THE THICKNESS OF THE GRAPHITE LAYER. THAT VALUE WAS USED AS THE APPROXIMATE THICKNESS OF EACH DISC.

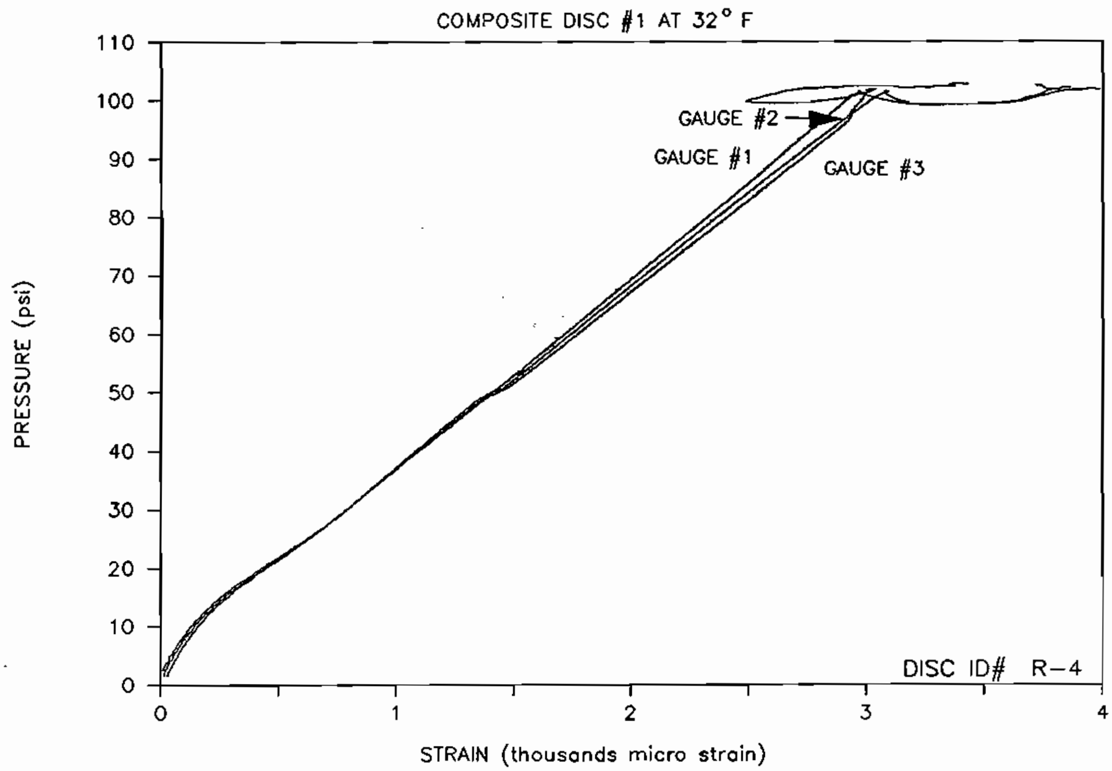

PRESSURE VS. STRAIN
COMPOSITE DISC#1 AT 70 °F
PRESSURE (psi)
STRAIN (thousands micro strain)
DISC ID# R-1
0
10
20
30
40
50
60
70
80
90
100
110
2
4
6


PRESSURE VS. STRAIN
COMPOSITE DISC #1 AT 70° F
PRESSURE (psi)
STRAIN (thousonds micro strain)
GAUGE #2
GAUGE #3
GAUGE #1
DISC ID# R-2
0
10
20
30
40
50
60
70
80
90
100
110
2
4

PRESSURE VS. STRAIN



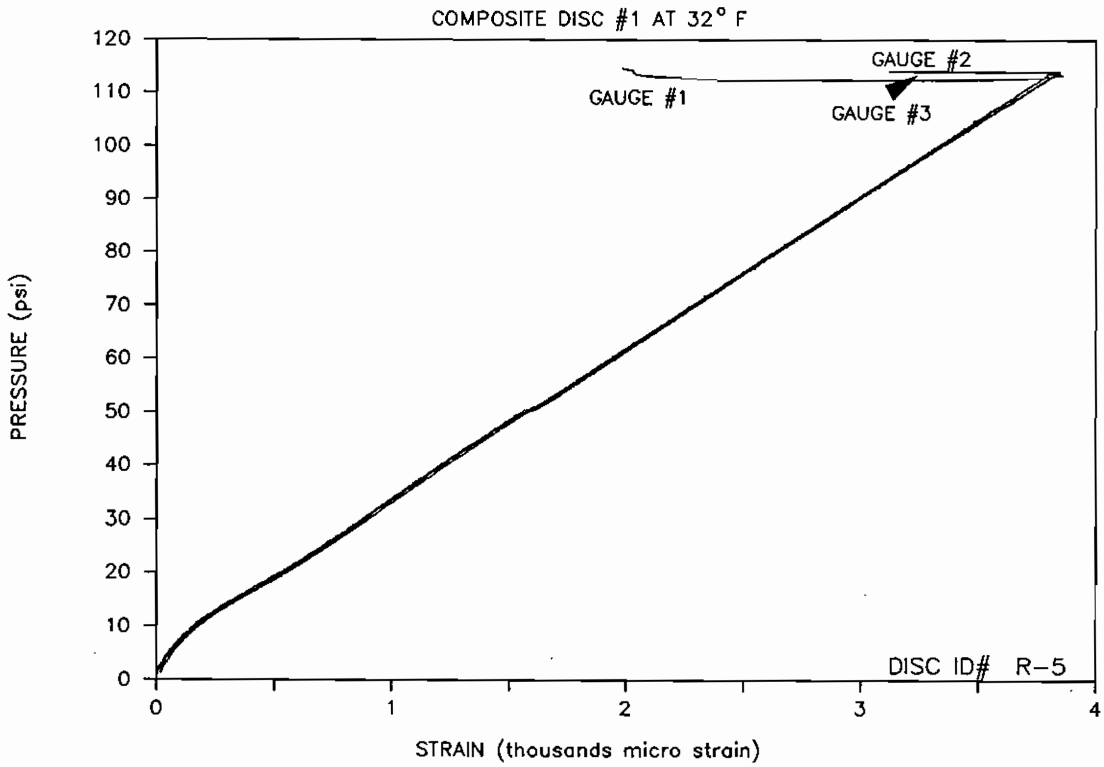
PRESSURE VS. STRAIN



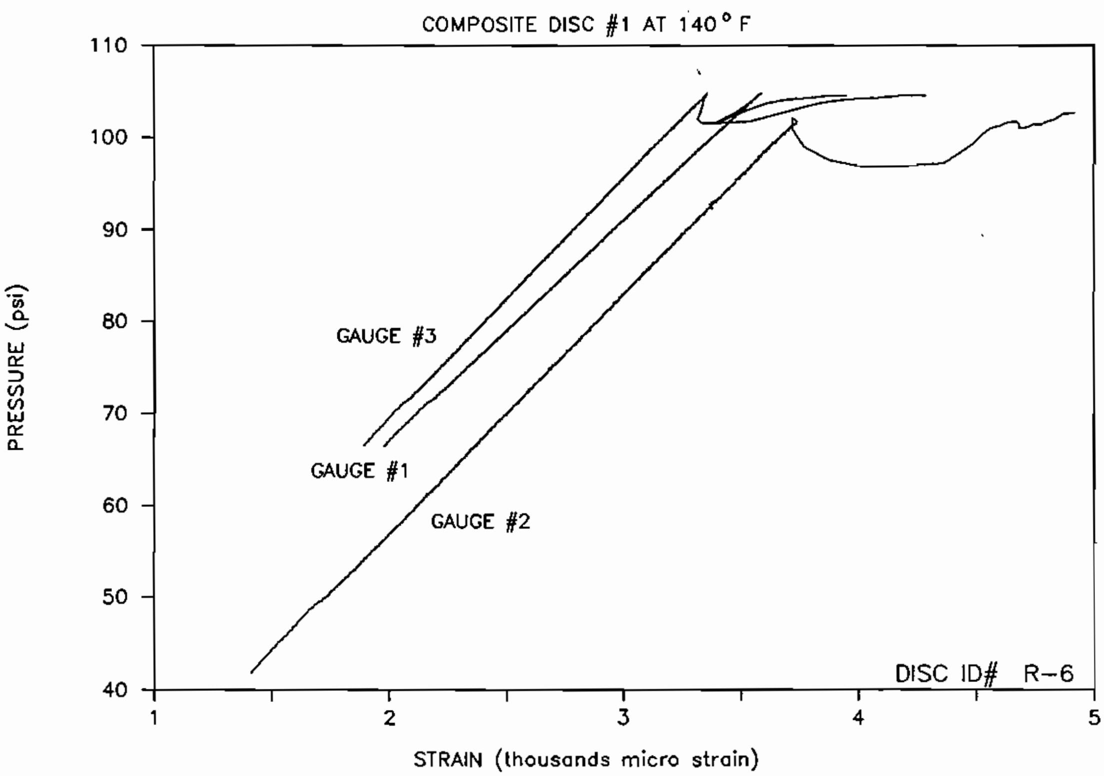
APPENDIX C

FRANGIBLE DISC STRAIN PLOTS

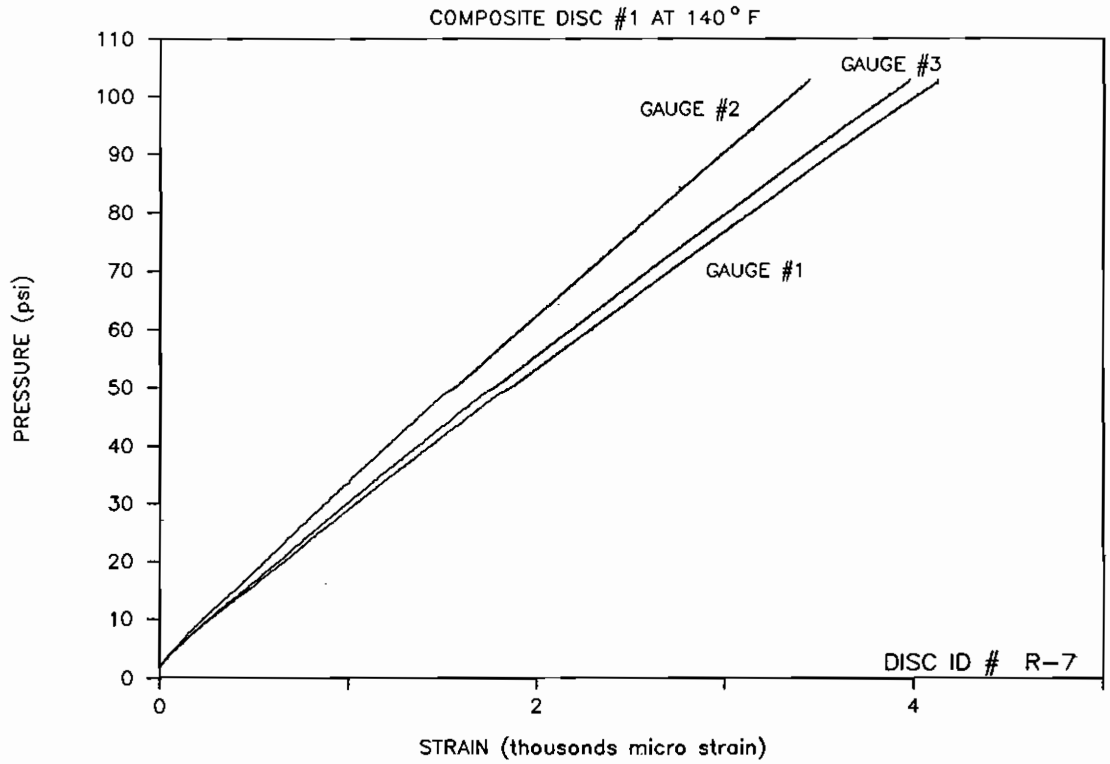
PRESSURE VS. STRAIN



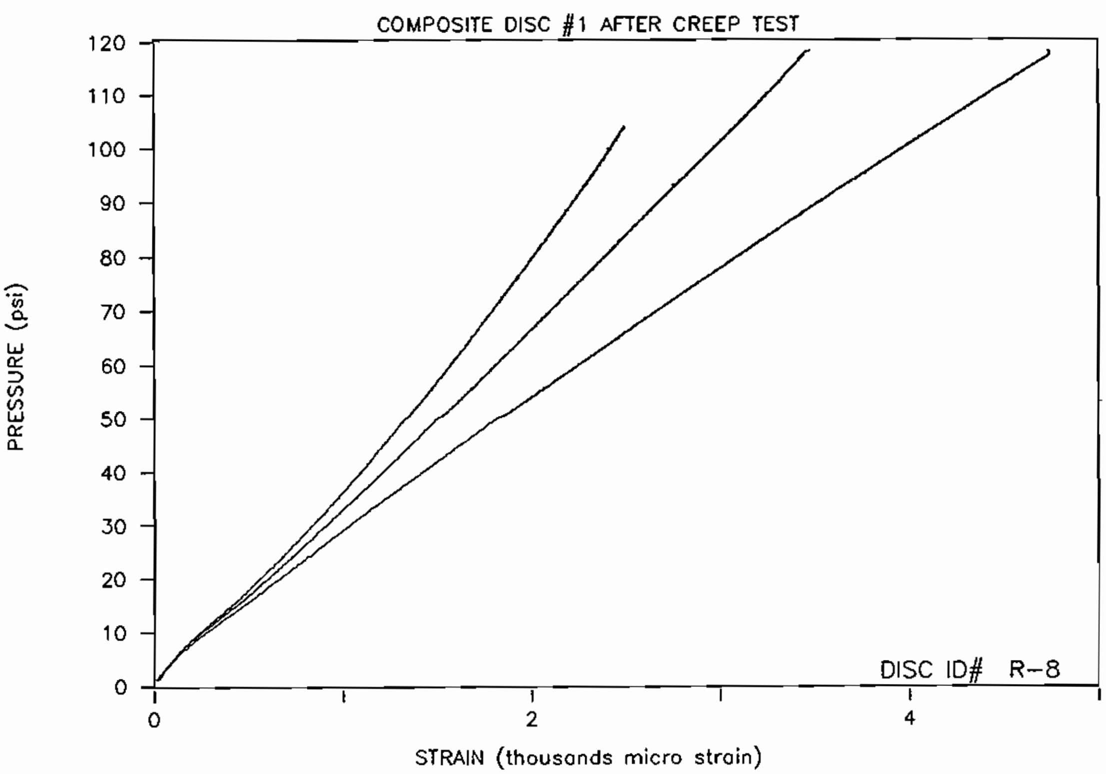
PRESSURE VS. STRAIN



PRESSURE VS. STRAIN

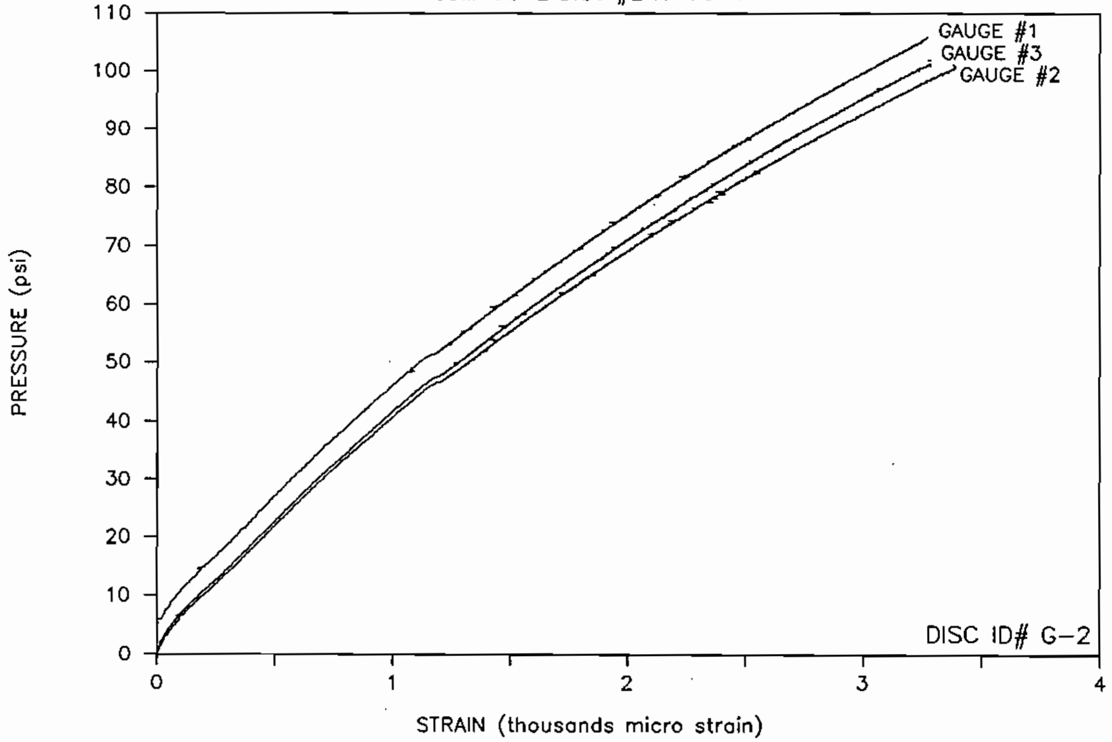


PRESSURE VS. STRAIN



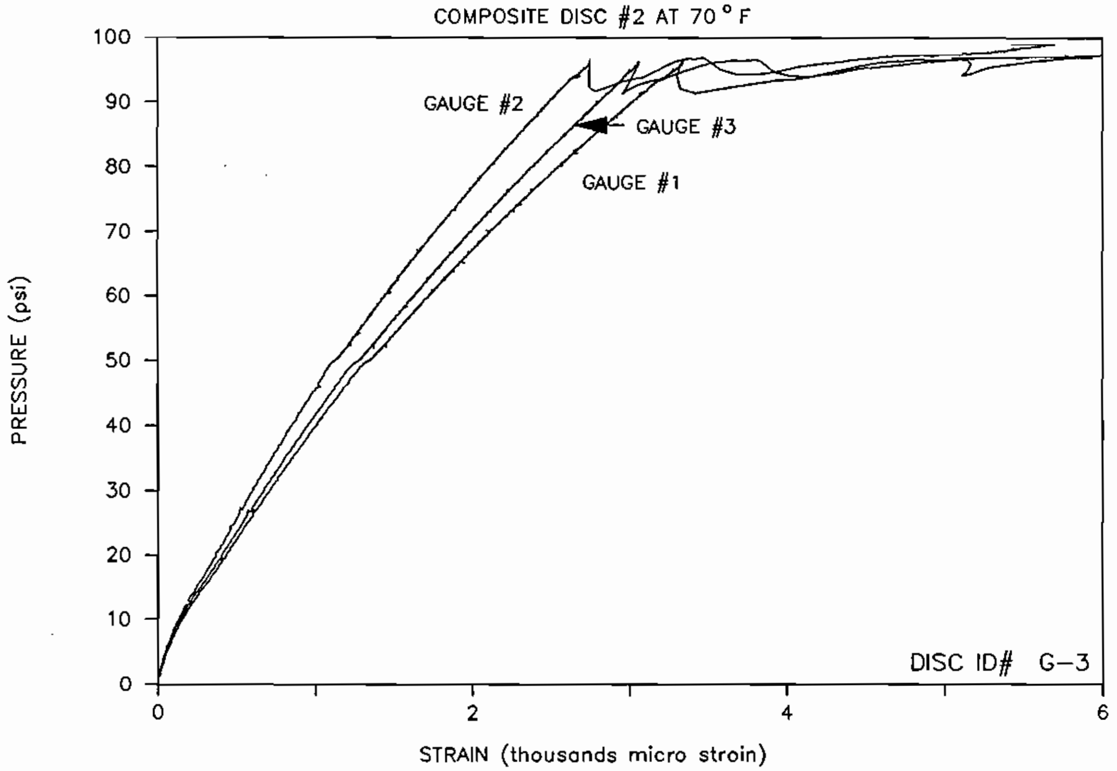
PRESSURE VS. STRAIN

COMPOSITE DISC #2 AT 70 °F



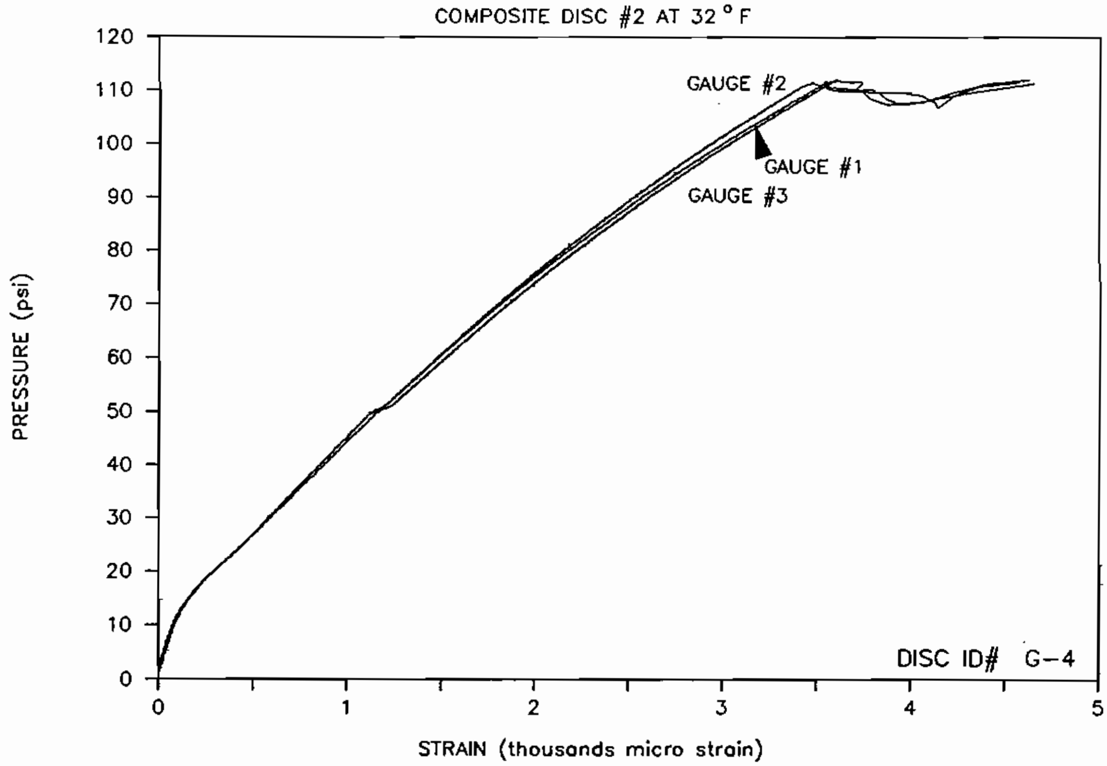
PRESSURE VS. STRAIN

COMPOSITE DISC #2 AT 70 °F



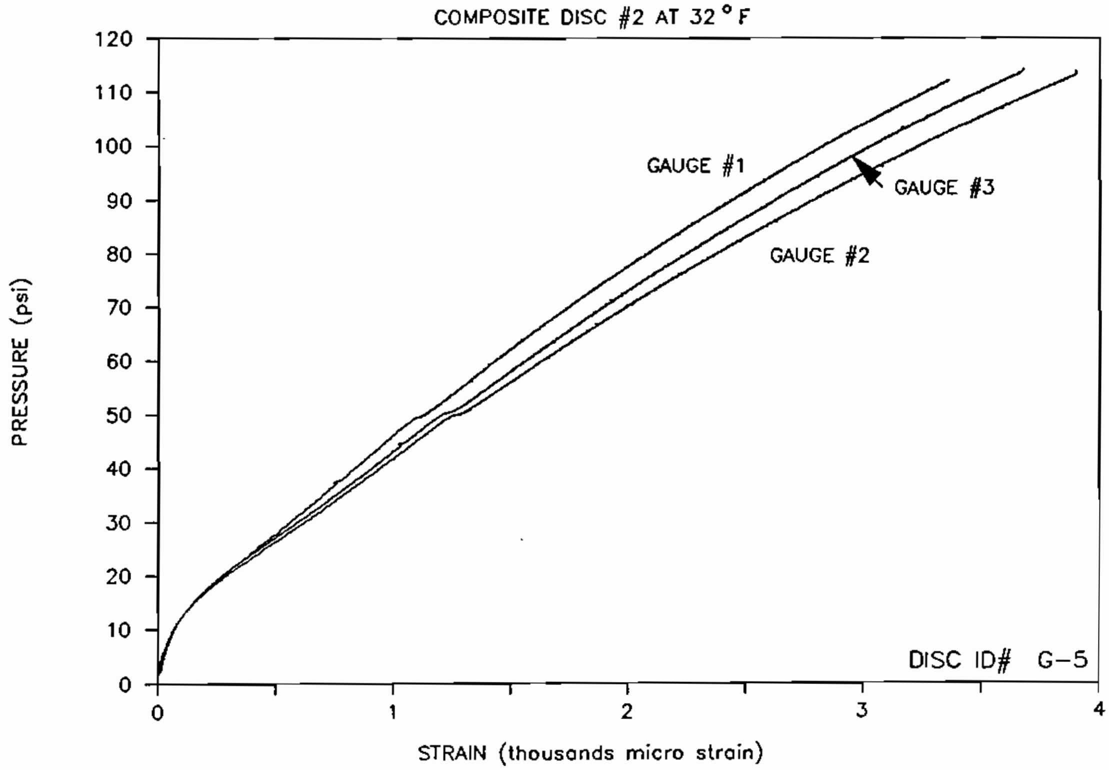
PRESSURE VS. STRAIN

COMPOSITE DISC #2 AT 32 °F



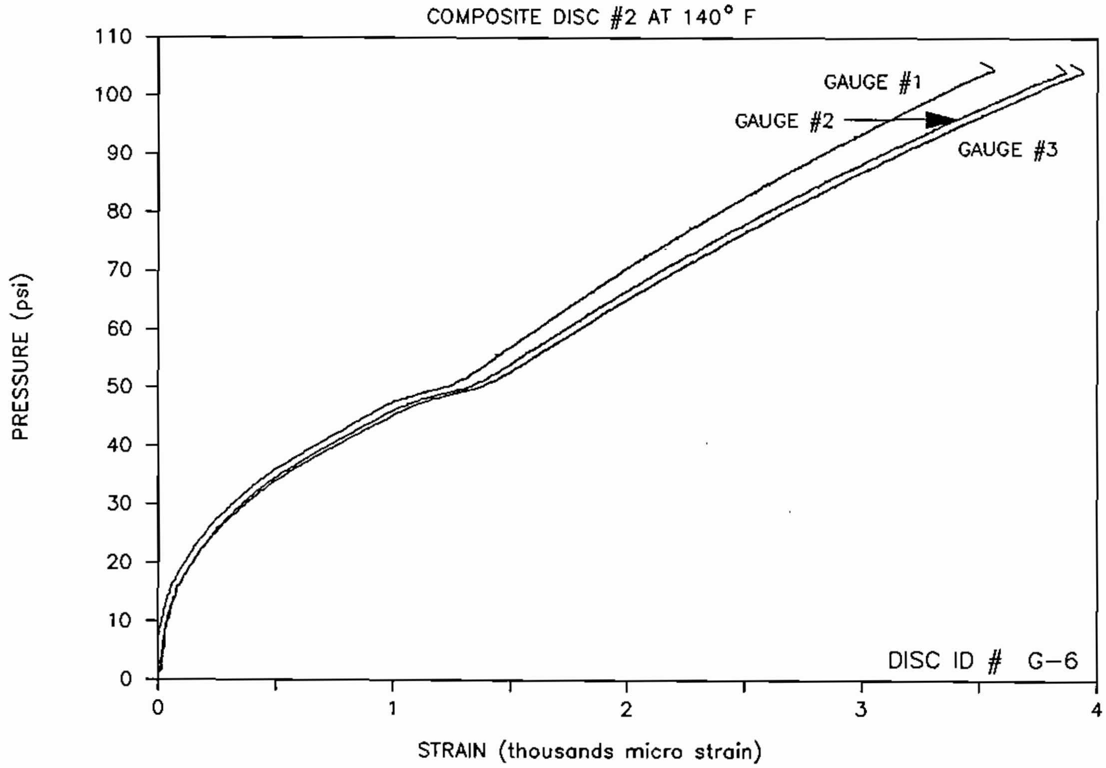
PRESSURE VS. STRAIN

COMPOSITE DISC #2 AT 32 °F



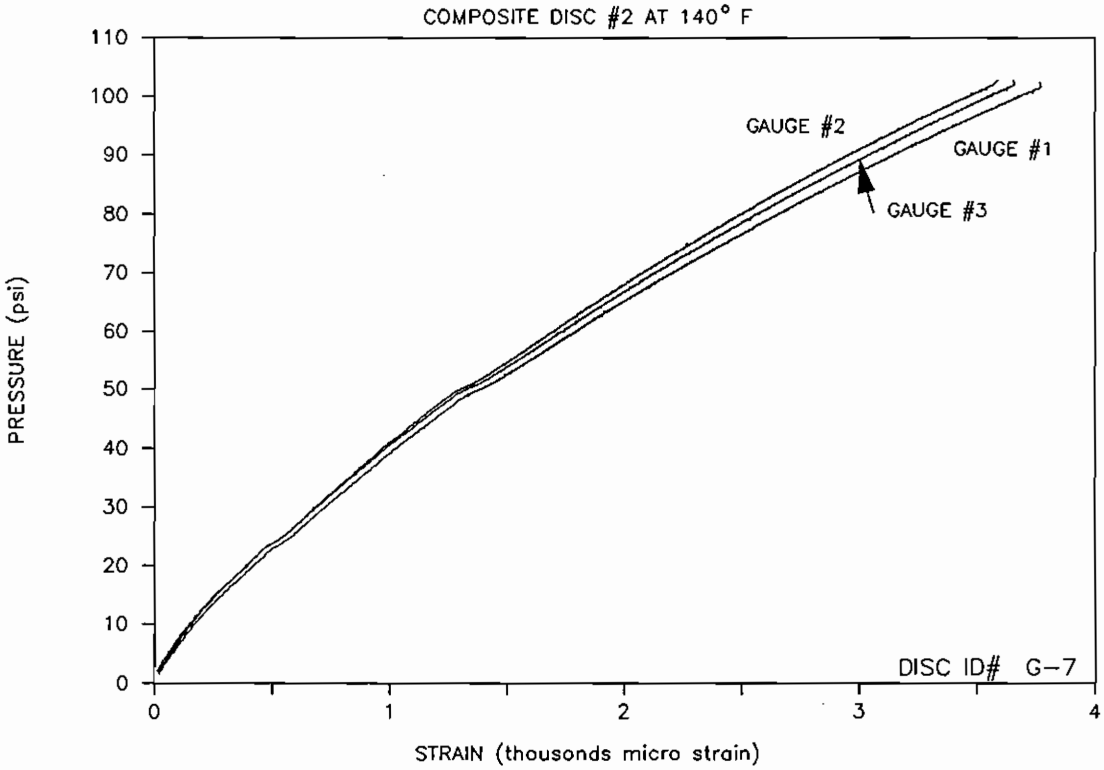
PRESSURE VS. STRAIN

COMPOSITE DISC #2 AT 140° F

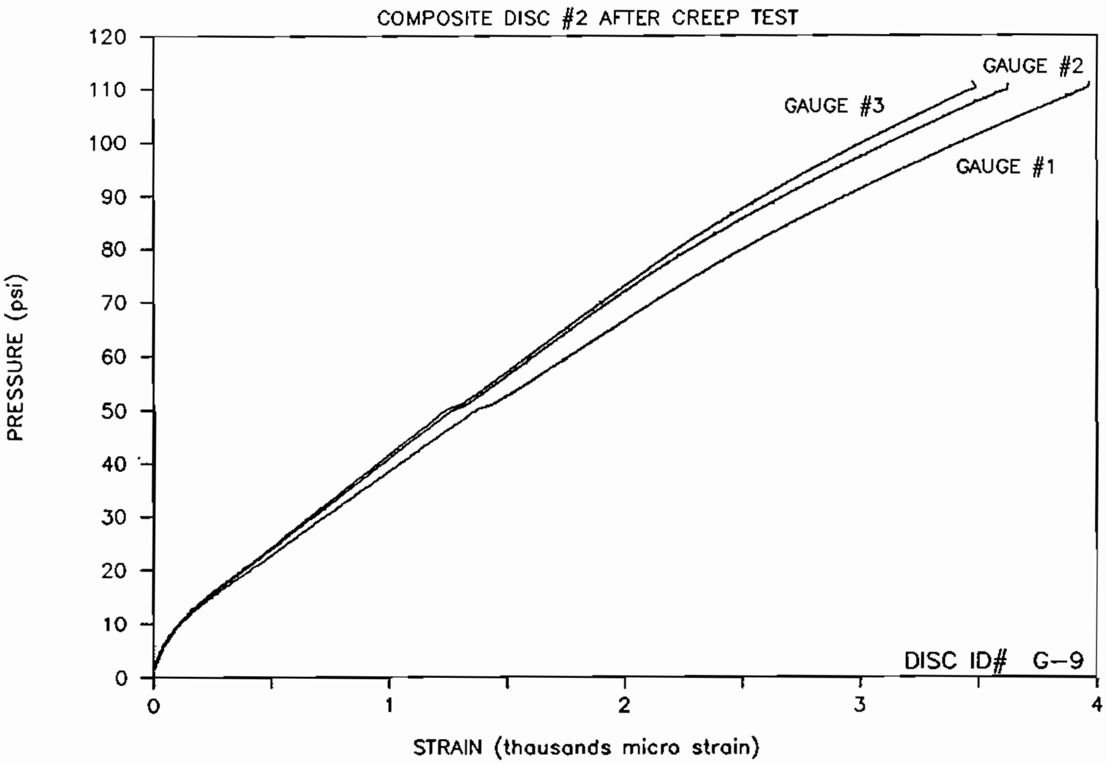


PRESSURE VS. STRAIN

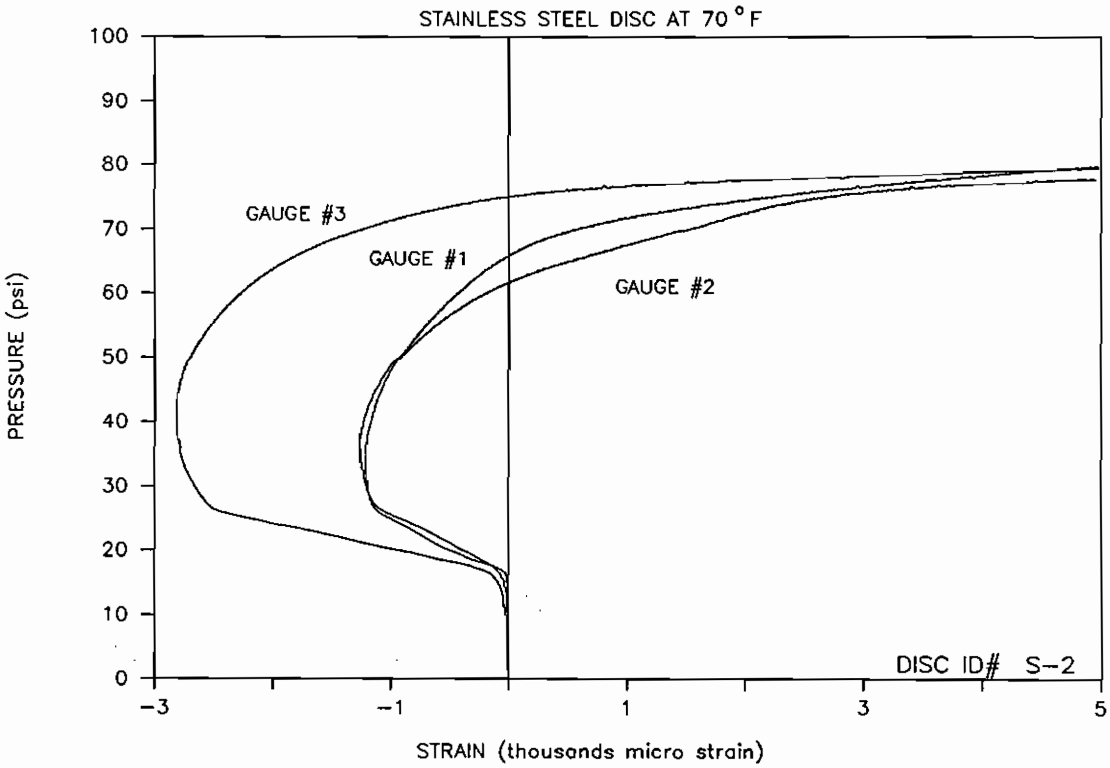
COMPOSITE DISC #2 AT 140° F



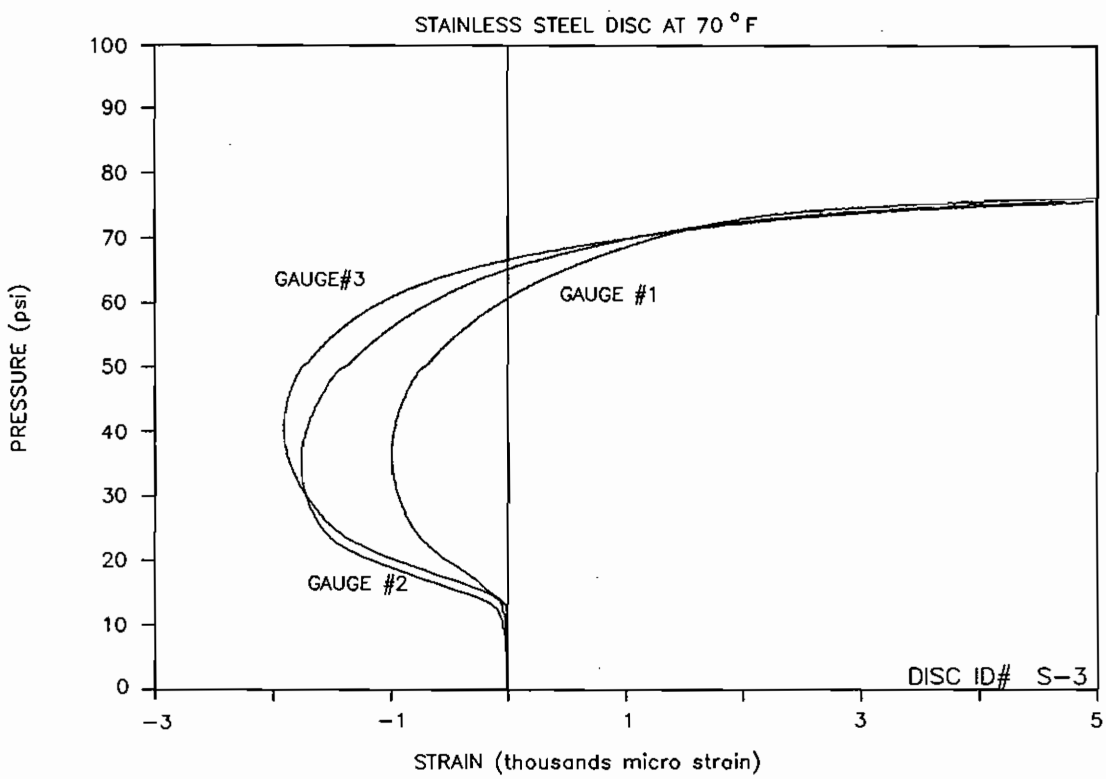
PRESSURE VS. STRAIN



PRESSURE VS. STRAIN

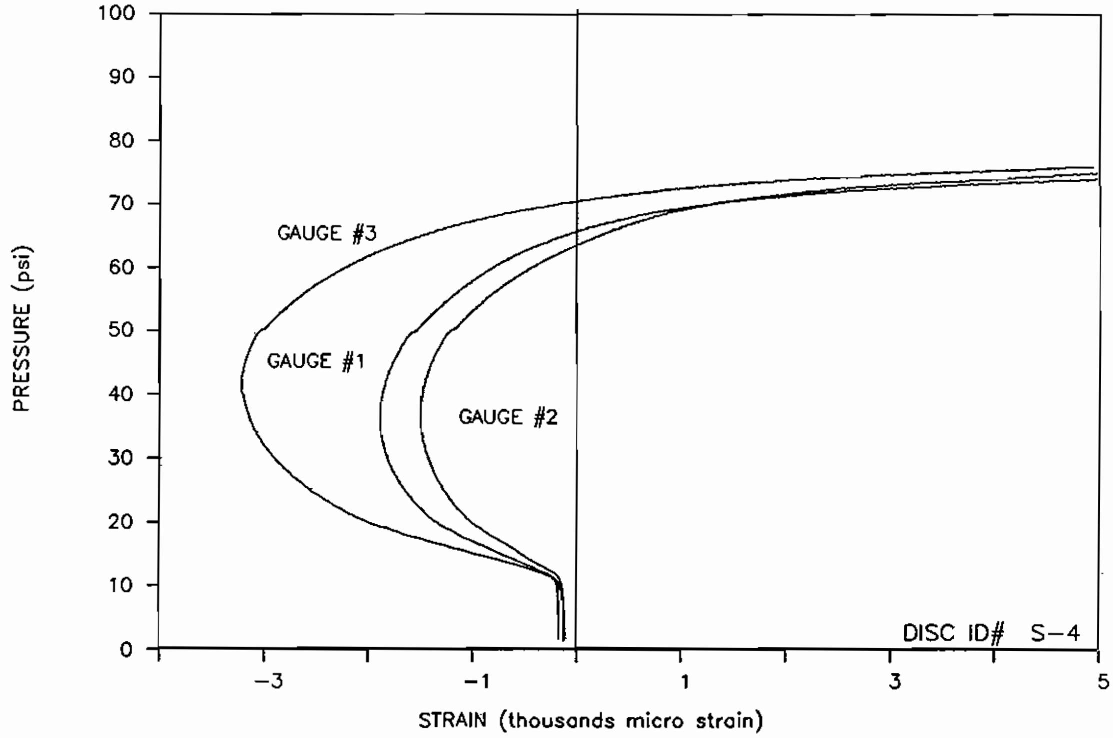


PRESSURE VS. STRAIN



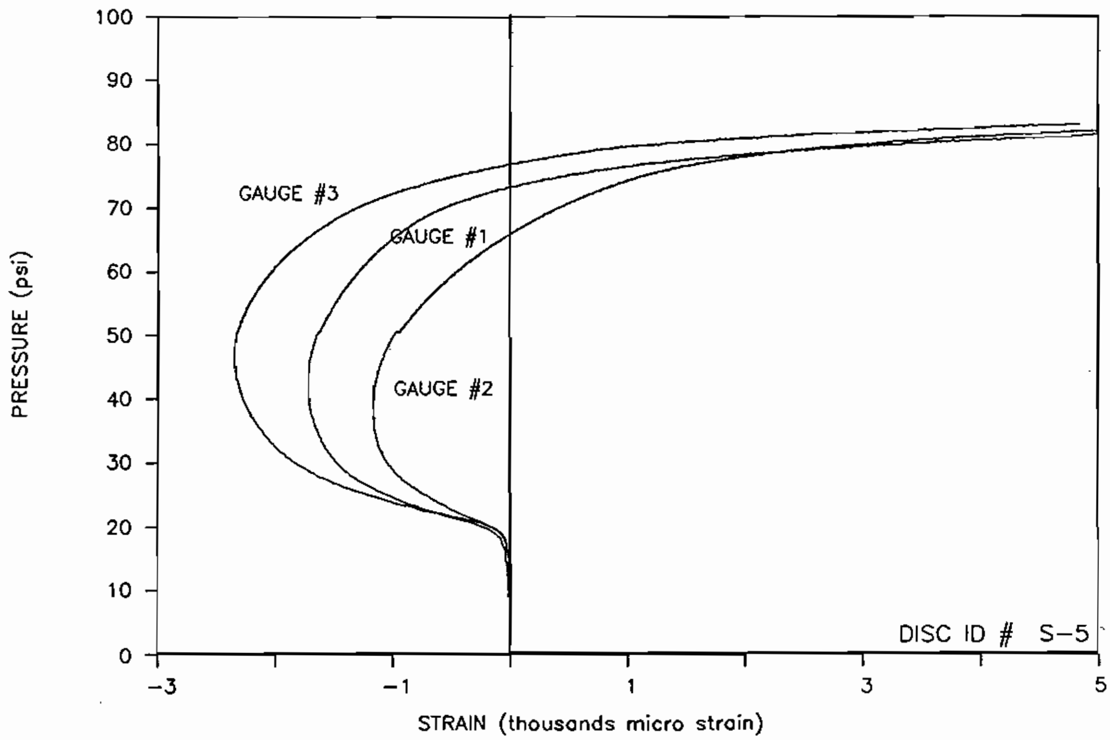
PRESSURE VS. STRAIN

STAINLESS STEEL DISC AT 70° F

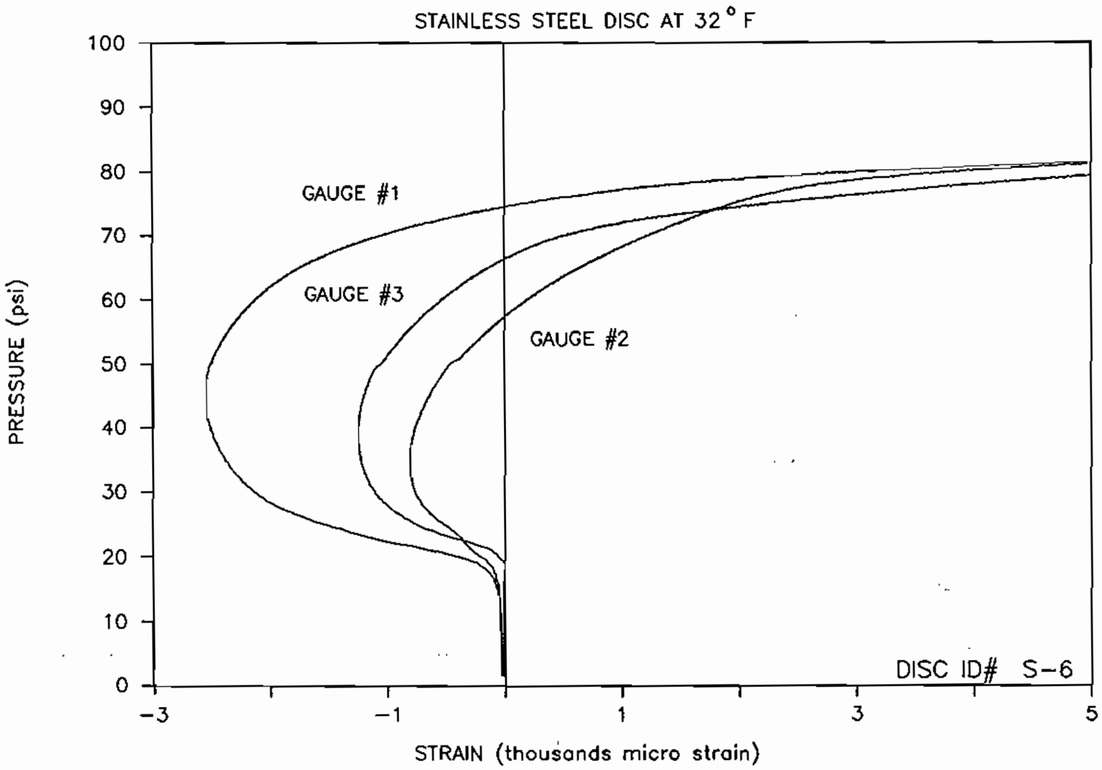


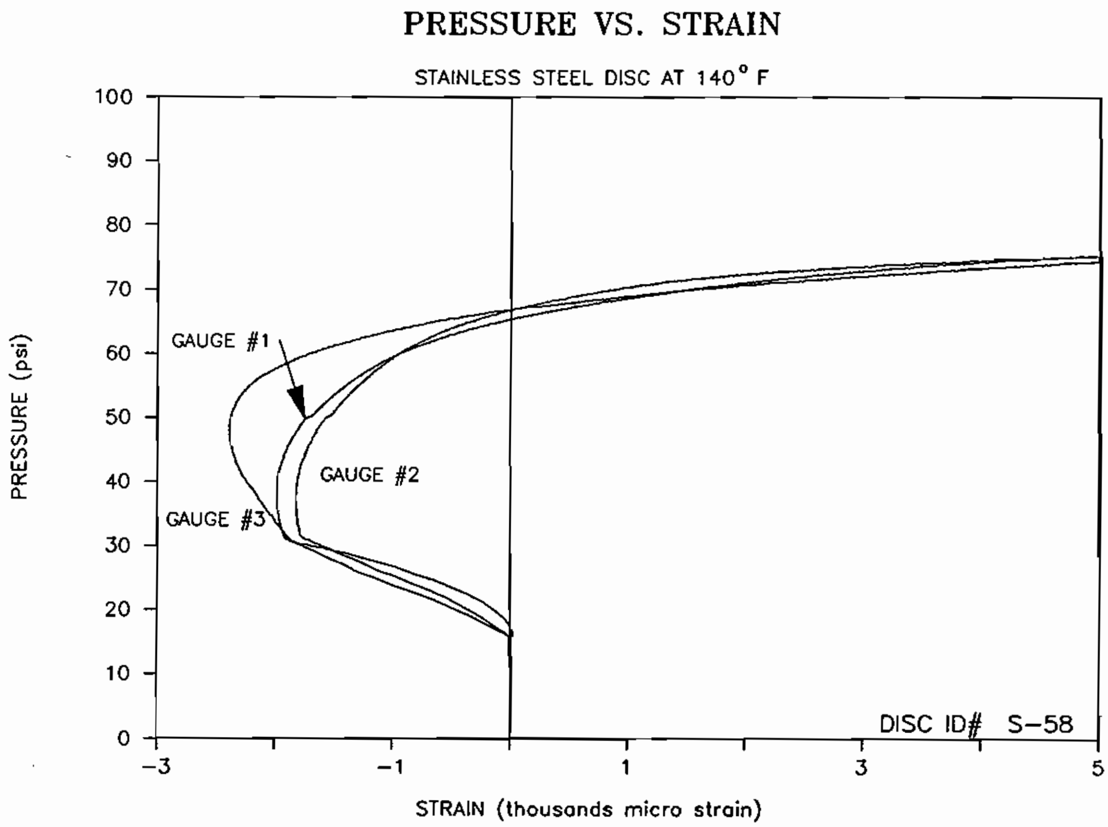
PRESSURE VS. STRAIN

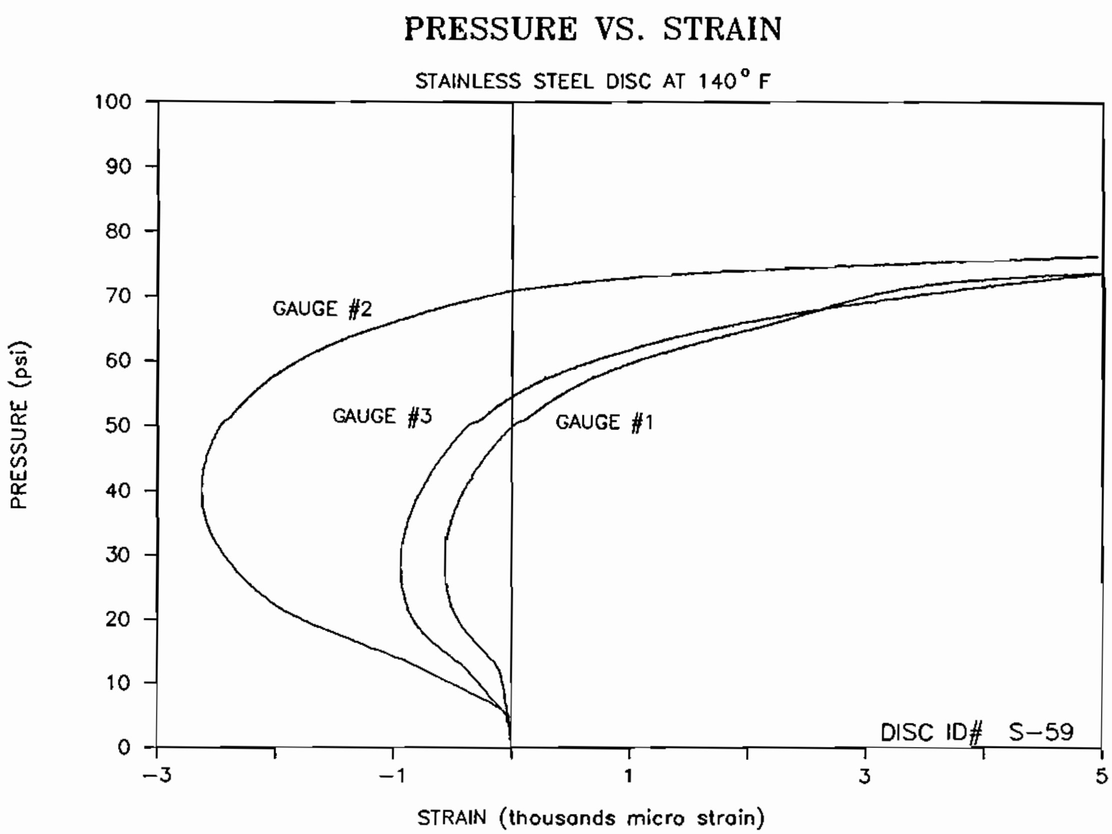
STAINLESS STEEL DISC AT 32° F



PRESSURE VS. STRAIN




PRESSURE VS. STRAIN
STAINLESS STEEL DISC AT 140° F
PRESSURE (psi)
STRAIN (thousands micro strain)
GAUGE #1
GAUGE #2
GAUGE #3
DISC ID# S-58
100
90
80
70
60
50
40
30
20
10
0
−3
−1
1
3
5


PRESSURE VS. STRAIN
STAINLESS STEEL DISC AT 140° F
PRESSURE (psi)
STRAIN (thousands micro strain)
GAUGE #2
GAUGE #3
GAUGE #1
DISC ID# S-59
100
90
80
70
60
50
40
30
20
10
0
−3
−1
1
3
5