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Evaluation of the Leakage Behavior of Inflatable Seals Subject to Severe Accident Conditions

Prepared by M. B. Parks

Sandia National Laboratories

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Sandia National Laboratories, under the sponsorship of the United States Nuclear Regulatory Commission, is currently developing test validated methods to predict the pressure capacity of light water reactor containment buildings when subjected to postulated severe accident conditions. These conditions are well beyond the design basis. Scale model tests of steel and reinforced concrete containments have been conducted as well as tests of typical containment penetrations. As a part of this effort, a series of tests was recently conducted to determine the leakage behavior of inflatable seals. These seals are used to prevent leakage around personnel and escape lock doors of some containments. The results of the inflatable seals tests are the subject of this report.

Inflatable seals were tested at both room temperature and at elevated temperatures representative of postulated severe accident conditions. Both aged (radiation and thermal) and unaged seals were included in the test program. The internal seal pressure at the beginning of each test was varied to cover the range of seal pressures actually used in containments. For each seal pressure level, the external (containment) pressure was increased until significant leakage past the seals was observed. Parameters that were monitored and recorded during the tests were the internal seal pressure, chamber pressure, leakage past the seals, and temperature of the test chamber and fixture to which the seals were attached. A general procedure, which covers a broad range of seal pressures and temperatures, has been developed to predict the containment pressure at which significant leakage past inflatable seals can be expected.

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ACKNOWLEDGEMENTS

Several individuals and organizations, both external to and within Sandia, made significant contributions to the inflatable seals test program. Of particular note, TRENTEC, Inc., the supplier of inflatable seals to nuclear containments, and several individuals from the various nuclear power plants that use inflatable seals, provided indispensable background information on the design and application of inflatable seals in nuclear containments.

I wish to thank Walt von Riesemann for his continual support, patience, and valuable suggestions during the course of the inflatable seals test program.

The efforts of Jim Westmoreland and Bob Eyers, the primary technicians responsible for test preparation and assistance during the tests, are much appreciated. Also, I would like to thank Dwight Lambert for his assistance in preparation of the data acquisition system used to monitor and record the test results.

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Also, the assistance provided by the NRC, and particularly Herman Graves, throughout the inflatable seals test program is gratefully acknowledged.

EXECUTIVE SUMMARY

Under the sponsorship of the United States Nuclear Regulatory Commission, Sandia National Laboratories is conducting a research program to develop methods to predict the pressure capacity at elevated temperatures of light water reactor nuclear containment vessels subject to beyond design basis loadings--the so-called severe accident. A series of scale model tests of steel and reinforced concrete containments has been performed. Also, tests have been conducted to determine the leakage behavior of typical electrical penetrations, a personnel airlock, and typical compression seals and gaskets.

As a continuation of this effort, this report discusses a series of tests to determine the leakage behavior of inflatable seals. Inflatable seals are used to prevent leakage around the perimeter of personnel and escape lock doors. They are fastened to the outer edge of the doors and, when pressurized with air, seal the gap between the door and bulkhead. When deflated, there is a gap of approximately 3/8 of an inch between the sealing surfaces of the seals and the bulkhead. Inflatable seals are either currently installed or planned for use in thirteen commercial nuclear power plant containment structures in the United States. All of the installations are in either PWR or BWR Mark-III type containments.

The test program included the two primary seal designs currently in use in nuclear containments. (The two different types of seals are designated as either the "old" design or the "new" design for discussion purposes in the report.) For each seal design, a pair of unaged and a pair of aged seals were subjected to a series of leakage tests; thus, a total of four series of inflatable seals tests were conducted. During each test series, leakage tests were performed first at room temperature and then finally at elevated temperature.

An "inflation" valve, which is placed in the air supply line for each seal just outside the valve stem, is used to inflate and deflate the seals. During the tests, two different positions of this valve were modeled. For the first, the seals were isolated from their pressure source by a closed valve located near the seals' valve stem after inflation. In this way, increasing containment pressure produces a corresponding increase in seal pressure. For the other valve condition, it was assumed that an open air line connects each seal and accumulator tank during normal operation such that increasing containment pressure has little effect on the seal pressure. In order to model this valve condition, the seal pressure was held constant as the chamber pressure was increased. The second valve condition is more representative of the air supply system in commercial nuclear containments.

A general method has been developed to provide reasonably accurate, yet conservative, estimates of the containment pressure at which significant leakage (>10,000 standard cubic feet per day) can be expected for a given normal operating seal pressure. The method is primarily empirical

and thus, application of the method outside the range of the tested parameters should be performed with caution.

Results of the inflatable seals test program are highlighted below:

- Regardless of the tested seal design, seal pressure, valve condition, applied aging, or test temperature, significant leakage did not occur until the chamber pressure exceeded the initial seal pressure. (Initial seal pressure is defined as the seal pressure at the beginning of each test at room temperature with no applied chamber pressure.)

- For a given initial seal pressure at room temperature, leakage generally began at higher chamber pressures for the new design seals than for the old design. However, there was no distinguishable difference between the two designs at elevated temperature.

- Radiation and thermal aging actually improved the leakage behavior at room temperature; however, at elevated temperature there was no observable difference between the performance of the aged and unaged seals.

- Increasing seal temperature caused a corresponding increase in seal pressure. The amount of increase was adequately predicted using the ideal gas law assuming constant volume. The increase in seal pressure due to temperature usually increased the chamber pressure at which significant leakage began. In all cases, significant leakage did not begin until the chamber pressure exceeded the seal pressure that was predicted by the ideal gas law for the test temperature. If the actual seal temperature is unknown, a lower bound estimate of the containment pressure necessary to cause significant leakage may be obtained by assuming room temperature conditions.

- For temperatures up to 350°F, there were no indications of degradation of the seal material. However, between 350°F and 400°F (the maximum test temperature), signs of a breakdown in the composite seal material began to occur. For this reason, use of inflatable seals in environments in excess of 350°F should be done with caution.

- If inflatable seals are isolated from their pressure source by a closed valve near the seals' valve stem, the internal seal pressure will increase as a result of increasing containment pressure. However, if an open pathway exists between the seal and accumulator tank, no appreciable change in seal pressure will occur due to containment pressure. For either case, methods are presented in Section 6 to predict the containment pressure at which significant leakage will begin.

- For the room temperature tests, the seals always resealed upon reduction in chamber pressure. The resealing pressure was about the same as the chamber pressure at which significant leakage began. At elevated temperatures, significant leakage normally began as a result of a rupture of the seal tube; thus, it was impossible for the seals to reseal upon reduction in chamber pressure.

1. INTRODUCTION

Sandia National Laboratories is currently developing test validated methods to predict the pressure capacity, at elevated temperatures, of light water reactor (LWR) nuclear containment vessels subject to loads well beyond their design basis--the so-called severe accident. Scale model tests of containments with the major penetrations represented have been carried to functional failure by internal pressurization [1]. Also, combined pressure and elevated temperature tests of typical compression seals and gaskets, a full-size personnel airlock, and typical electrical penetration assemblies (EPAs) have been conducted in order to better understand the leakage behavior of containment penetrations [2-5]. Because inflatable seals are also a part of the pressure boundary of some containments, it is important to understand their leakage behavior as well.

1.1 Background Information[1]

Inflatable seals are used to prevent leakage around the perimeter of personnel and escape lock doors. They are fastened to the outer edge of the doors and, when pressurized with air, seal the gap between the door and the bulkhead. When deflated, a gap of about 3/8 of an inch exists between the sealing surfaces of the seals and the bulkhead. The sealing surface on the bulkhead is constructed of a stainless steel cladding with a surface finish of 50 to 60 RMS. A light layer of a silicone-based lubricant is sometimes applied to the sealing surface to enhance the sealing ability and also to reduce the risk of the seals sticking to the bulkhead surface when the door is opened. Figures 1.1 and 1.2 show a typical application of inflatable seals in a personnel airlock. The airlock doors are rectangular with "rounded" corners and vary in size from about 8'-0" X 5'-0" to 6'-6" X 3'-6". Typically the corner radius is about 12 inches.

The pressure inside the seals is furnished by the instrument air supply system. A simplified schematic of a typical air supply system for each seal is provided in Figure 1.3. As shown, an air pressure accumulator tank is placed in the air supply line for each seal. If the instrument air supply is lost, a check valve ensures that the accumulator tank and the seal maintains the system pressure. The accumulator tank is large enough to pressurize the seals to the approximate normal operating pressure. Thus, the airlock doors may be opened and then closed and resealed a few times in the event of a loss of the instrument air supply system.

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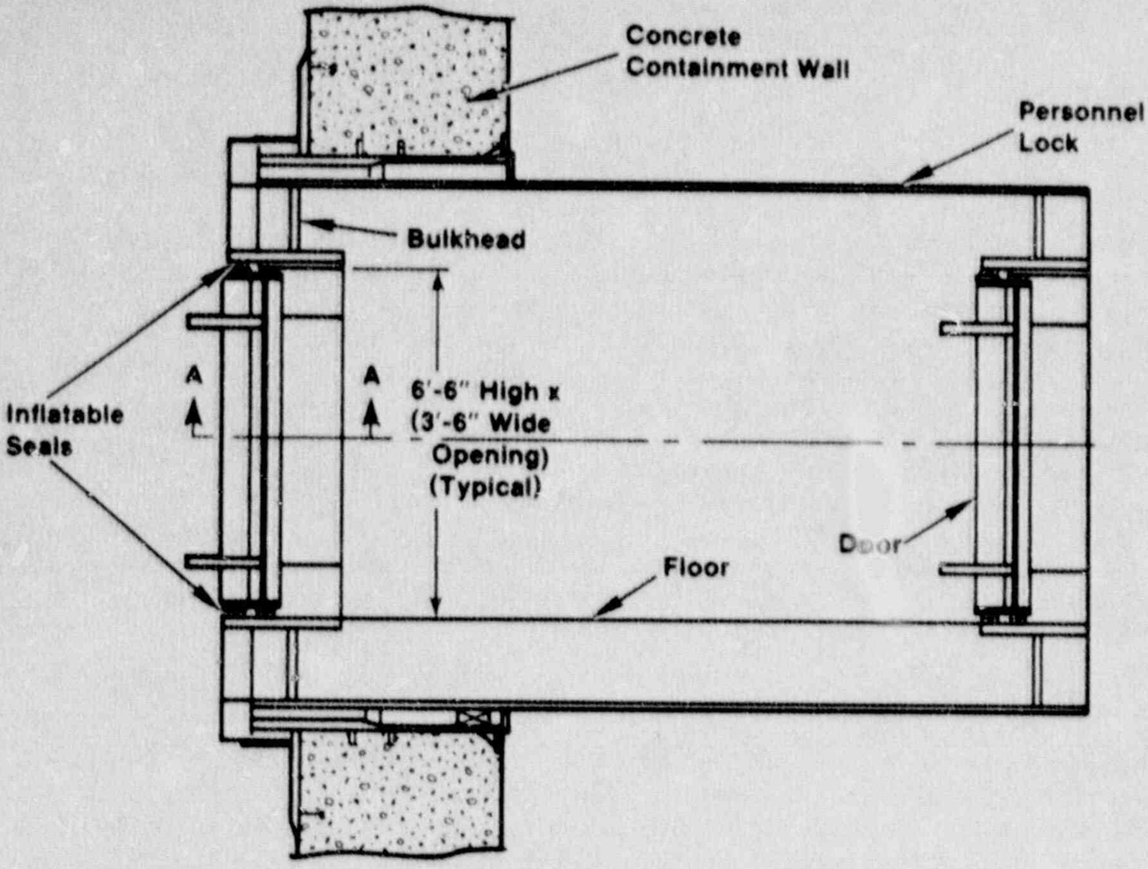
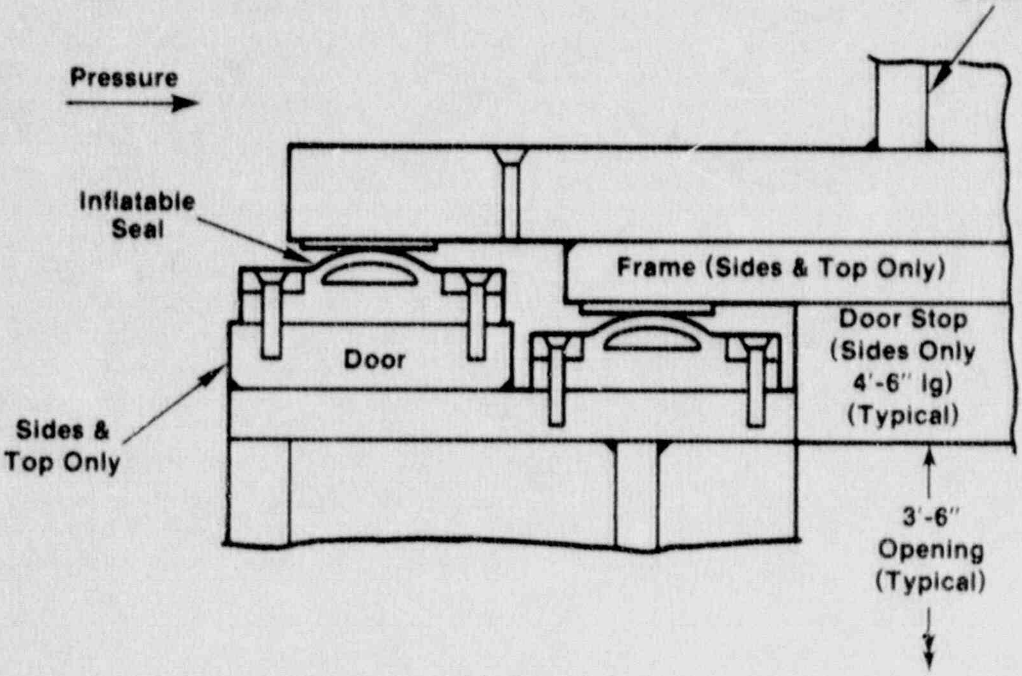
[1] Much of the information presented in Section 1.1 was obtained through conversations with the supplier of inflatable seals and personnel at operating nuclear power plants that use inflatable seals on the airlock doors.

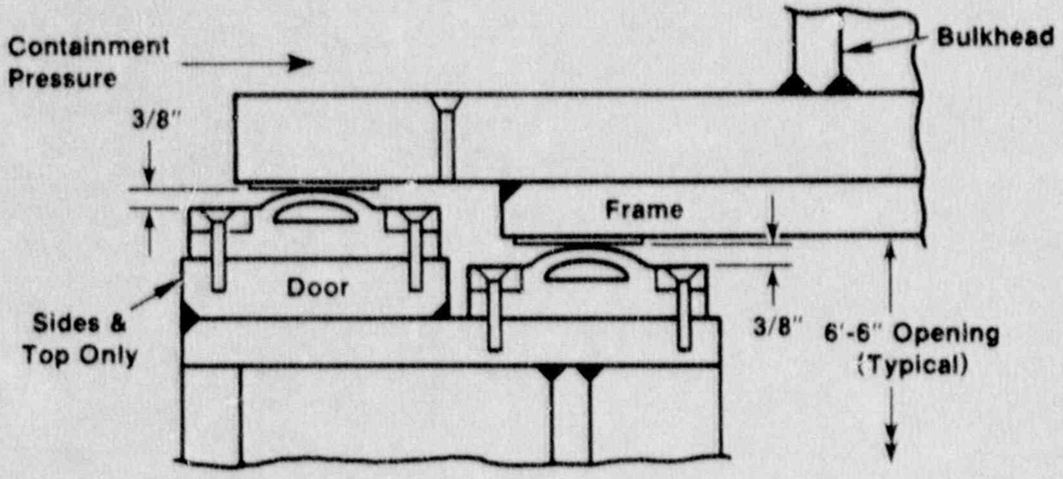


(a) Elevation View

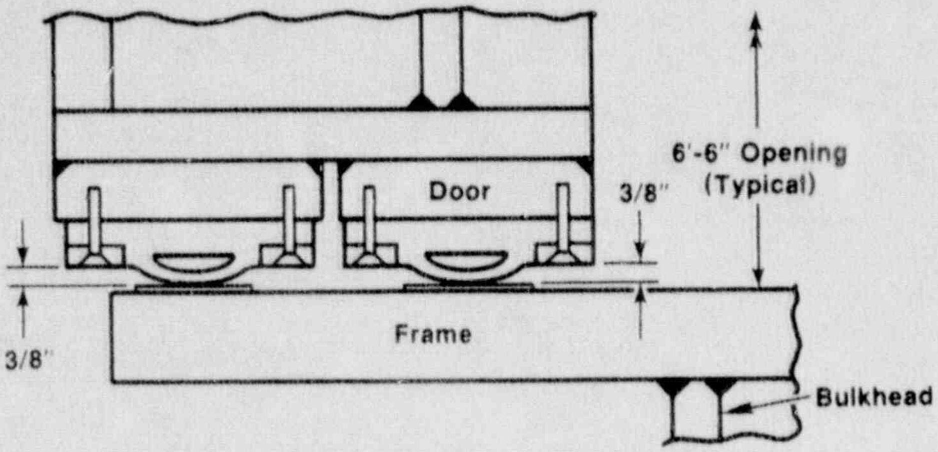


(b) Section A-A

Figure 1.1 Typical Application of Inflatable Seals
in Personnel Airlock Doors
(Note that seals are shown fully inflated.)



(a) Top of a Personnel Airlock Door



(b) Bottom of a Personnel Airlock Door

Figure 1.2. Additional Views of Inflatable Seals
(Note that seals are shown fully inflated.)

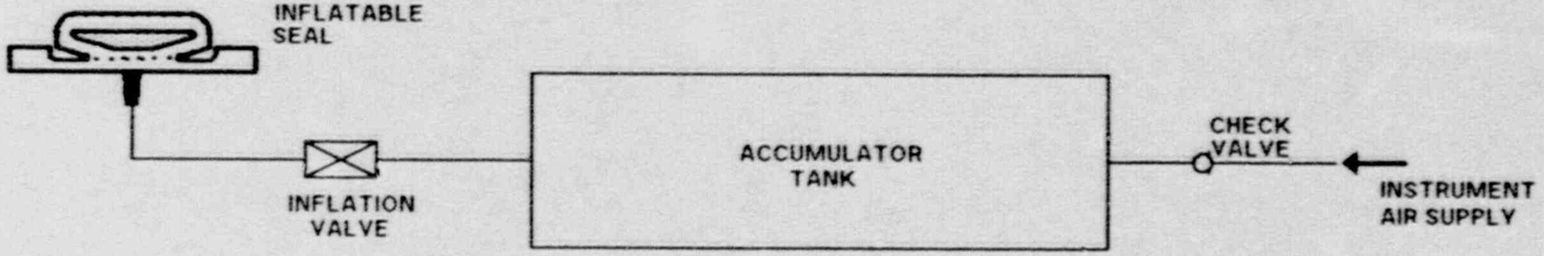


Figure 1.3. Simplified Schematic of Pressure Supply System for Each Inflatable Seal

There is also a two-position inflation valve between each accumulator tank and inflatable seal. The sole purpose of this valve is to inflate and deflate the seals. Once the door is closed, the valve is opened allowing pressure from the instrument air supply system to inflate the seals. The valve remains in this position during normal operating conditions; thus, if the instrument air supply is not regulated, the internal seal pressure varies with the instrument air supply pressure. Before opening the door, the valve is placed in the closed position which shuts off the instrument air supply to the seals and at the same time deflates the seal by releasing its air pressure to the atmosphere. The above description of the air supply system and in particular the function of the inflation valve is believed to be representative of all containments that employ inflatable seals around personnel and escape lock doors.[2]

The internal seal pressure is monitored, but cannot be adjusted, from the control room of nuclear power plants. A warning device is activated inside the control room if the seal pressure falls below a preset level. For the purposes of the inflatable seals tests described in this report, the air supply system is assumed to be working properly.

The maximum in-service life of inflatable seals is five years. In-service leakage testing of the seals includes a between seals test, a "barrel" test of the airlock sleeve, and a test of the seal itself. The between seals test must typically be performed within 72 hours of each use of the door. Because most airlock doors are used on a daily basis, the test is normally conducted every three days. During the test, the loss of coolant accident (LOCA) containment pressure is applied between the seals with the normal operating pressure within the seals. The allowable leakage varies from plant to plant in the range of 10 to 400 standard cubic feet per day (scfd). (Standard conditions are defined at 14.7 psig and 70°F.) The barrel test consists of pressurizing the area between the airlock doors again to the LOCA pressure with the seals at their normal operating pressure. The allowable leakage varies from as little as 10 scfd to as much as 1900 scfd. This test is routinely conducted every six months. Finally, the inflatable seals themselves are checked for leakage of their internal pressure by first inflating the seals to their normal operating pressure and then either observing the pressure drop over a fixed period of time or by simply applying a soap solution to the outer surface of the seal tube. The allowable

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2. During the planning and execution of the inflatable seals tests, it was believed that, based on information obtained from an expert in this field, the seals were isolated from their pressure source by a closed valve after inflation. This valve was believed to be located between the accumulator tank and seal. It was not until after completion of all tests that an accurate description of the air supply system was obtained. Fortunately, tests were conducted that modeled both the case in which the seals are isolated from their pressure source and the case in which they are not. Further discussion on the effects of isolating the seals from their pressure source is presented in Sections 4 and 5 of the report.

pressure drop over a 24 hour period is typically 1.5 to 2.5 psi. The seal leakage test is performed at intervals of from 6 to 18 months, depending on the containment.

Inflatable seals are either currently installed or planned for use in thirteen commercial nuclear power plant containment structures in the United States. All of the installations are in either PWR or BWR Mark-III type containments [6]. According to instructions from the supplier, the seal pressure must be at least 30 psi greater than the containment design pressure in order to ensure that leakage does not exceed design allowables. A survey of the plants that are currently using inflatable seals revealed that the normal operating seal pressure varied from plant to plant with a minimum seal pressure of 50 psig and a maximum of 110 psig. In all cases, the seal pressure is at least 30 psi greater than the containment design pressure.

1.2 Types of Inflatable Seals

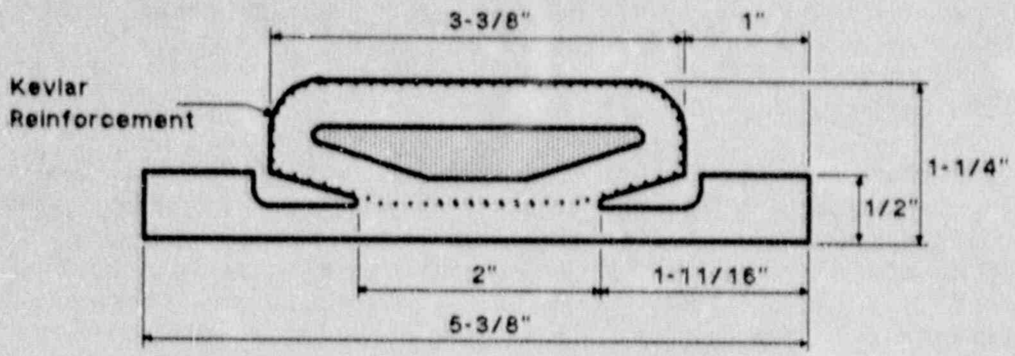
During a review of the applications of inflatable seals, it was determined that three different types of inflatable seals are currently available for use in nuclear containments: an "old" design (Figure 1.4(a)), a modification of the old design (Figure 1.4(b)), and a "new" design (Figure 1.4(c)). For some containments, the old design was found to have undesirable amounts of leakage when compared to design allowable leak rates. Leakage seems to occur along laps in the Kevlar reinforcement, which produce small but visible leak paths across the seal tube. Even though this type of seal design is no longer supplied to the nuclear industry, it is possible that it may still be in use in some containments.

In order to improve the seal performance, two techniques have been employed. In each case a 1/8-inch thick layer of EPDM E401, 40 durometer material has been added to the sealing surface in order to cover any irregularities in the Kevlar reinforcement. (Durometer is a relative measure of the "hardness" of the seal material.)

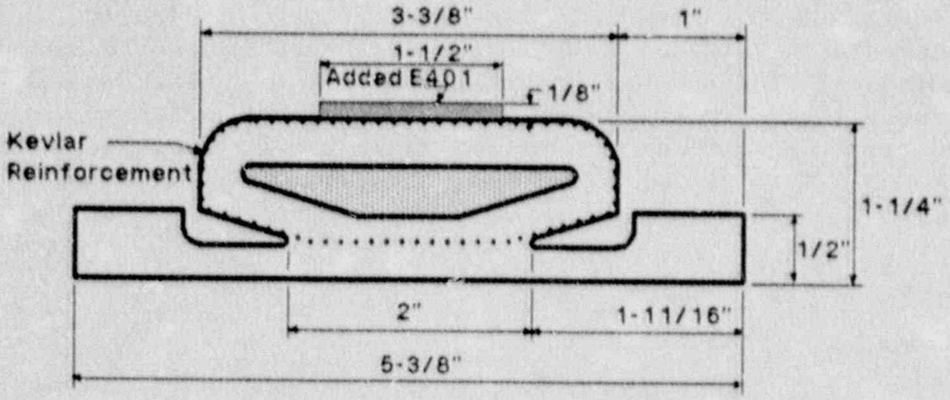
1) For the seals already fabricated using the old design, a 1-1/2-inch wide by 1/8-inch thick layer of EPDM E401, 40 durometer material has been vulcanized to the sealing surface. The modified cross section is shown in Figure 1.4(b).

2) A new design has been developed in which the added E401 material is incorporated as an integral part of the seal as illustrated in Figure 1.4(c). This type of seal is currently supplied for use in nuclear containments.

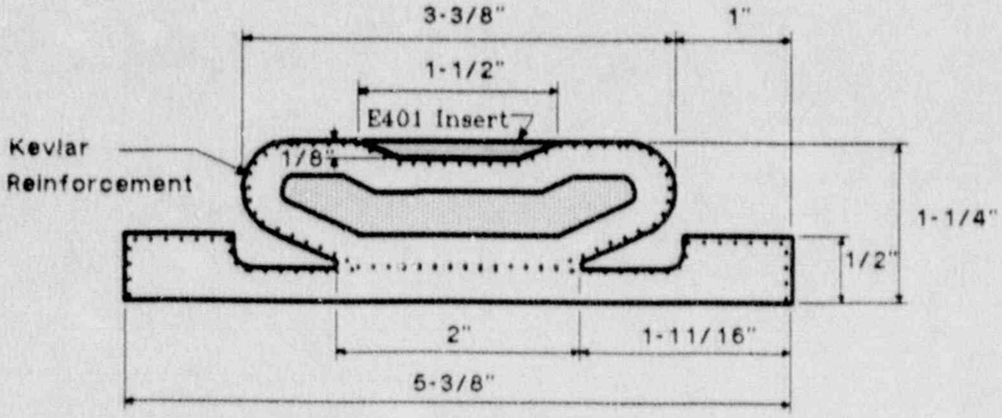
Because the new inflatable seal design is believed to provide a superior seal and because it is now furnished exclusively for nuclear containments, it was included in the Sandia test program. The old design was also included because it may still be in use in some containments. Inflatable seals with the added layer of E401 material (Figure 1.4(b)) were not tested since they were only supplied for a



(a) "Old" Design Seals



(b) Modified Old Design Seals



(c) "New" Design Seals

Figure 1.4. Cross-Sections of Inflatable Seals Used in LWR Containments

short period of time and because their leakage behavior should be at least as good as the old design.

1.3 Previous Work

There has been limited previous research activities that are applicable to the subject inflatable seals. Some testing of these seals to LOCA conditions for qualification purposes has been performed. However, because of the relatively low pressure levels for LOCA conditions, this test data is of limited value for determining the leakage behavior of inflatable seals subject to severe accident combinations of external pressure and temperature.

Several investigations of the leakage behavior of elastomeric compression seals have been conducted for extreme pressure and temperature conditions (up to 143 psig and 700°F) [2,3]. Compression seals achieve leaktightness in a much different manner than inflatable seals and thus, this information is also of limited value. However, because much of the compression seal testing was of EPDM material--the same material as used in inflatable seals--some information on the seal material can be extracted from these studies. For example, Brinson and Graves [2] noted that compression seals constructed of EPDM E603 material rapidly degraded when the seal temperature reached 650°F.

2. DESCRIPTION OF TESTS

2.1 Test Objectives

A detailed list of objectives was prepared during the planning stages of the inflatable seals tests. These objectives are listed below. The methods employed to accomplish these objectives are described in the remainder of Section 2 and in Section 3. As will be discussed in Sections 4 and 5 for the test results, all of the pretest objectives were met as a result of the inflatable seals test program.

1) Determine the minimum differential pressure, ΔP, between the chamber (containment) pressure and the initial seal pressure to prohibit a) any noticeable leakage; and b) significant leakage, approximately 10,000 std. ft^3/day (scfd) (6.94 scfm). (Leakage of 10,000 scfd is equivalent to 1% mass/day at standard conditions from a $1x10^6$ ft^3 containment volume.)

2) Compare the leakage behavior of the old (Figure 1.4(a)) and new (Figure 1.4(c)) seal designs.

3) Determine the relationship between amount of leakage and ΔP.

4) Determine the relationship between resealing chamber pressure and seal pressure (i.e., note chamber pressure at which leakage stops).

5) Determine the effect of aging on ΔP. (By comparing leakage behavior of aged and unaged seals for both designs).

6) Determine the effect of temperature on ΔP.

7) Determine the effect of temperature on the pressure inside the seals.

8) Determine the ability of inflatable seals to reseal themselves at high temperatures after significant leakage has occurred and the containment pressure is decreasing.

9) Note any degrading of seals caused by high temperature. (Seal degrading is not expected based on previous seal and gasket testing for EPDM materials at temperatures <400°F. However, material properties may "soften" considerably at high temperatures).

2.2 Test Matrix

As outlined in Table 2.1, a total of four different series of inflatable seals tests have been performed. The first two tests were of the old seal design whereas the last two tests were of the new design. For each type of seal, an unaged (Test series 1 and 3) and an aged (Test series 2 and 4) pair of seals were tested. For each test series, the seals were tested first at room temperature and then at elevated temperatures at or above 300°F.

Table 2.1
Test Sequence

Test Series No.	Seal Design	Condition	Loading
1	Old	Unaged	Air, Room Temp. & 400°F
2	Old	Aged	Air, Room Temp. & 300°F
3	New	Unaged	Air, Room Temp. & 300°F, 350°F
4	New	Aged	Air, Room Temp. & 300°F

2.3 Selection of Test Temperatures

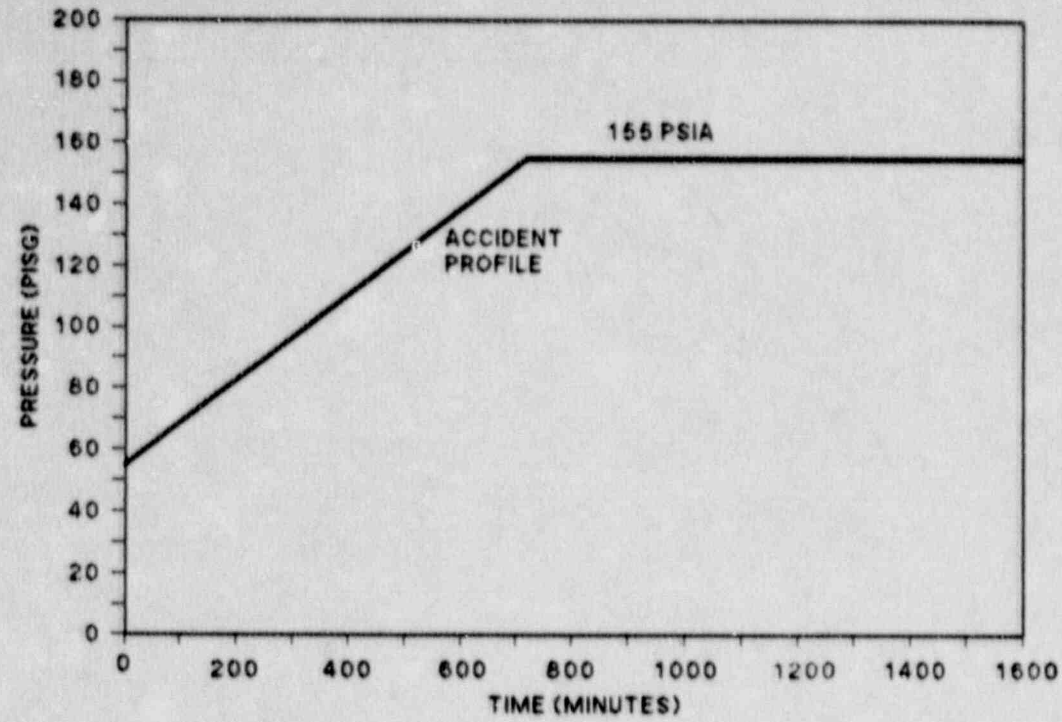
The test temperatures are based on estimates of the airlock seal temperature which would be caused by postulated severe accident conditions within the containment. As mentioned earlier, inflatable seals are only used in PWR and BWR Mk-III type containments. The maximum postulated severe accident pressure and temperature of the containment "atmosphere" for these types of reactors are:

PWR	155 psia, 361°F
BWR, Mark-III	75 psia, 400°F

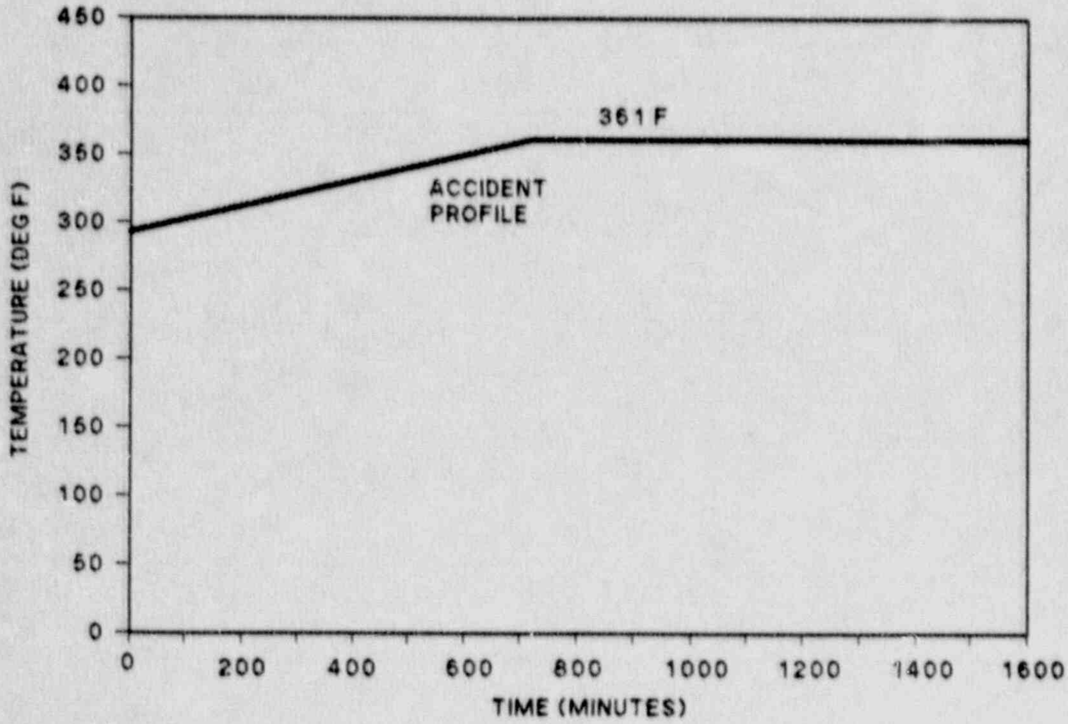
Pressure and temperature profiles for PWR and BWR Mark-III containments are shown in Figures 2.1 and 2.2 respectively. The severe accident profiles were determined under the Severe Accident Sequence Analysis (SASA) program [6]. It is important to note that the maximum pressure in these profiles was equal to the assumed containment failure pressure.

Before the test program began, 400°F was chosen as the test temperature for all of the elevated temperature tests. This temperature was selected as a conservative upper bound on the seal temperature that might be produced during a severe accident. However, because the seals ruptured as a result of the combined effects of elevated temperature and pressure during test series 1, it was decided to begin the remaining elevated temperatures at a more realistic temperature of 300°F. If the seals "survived" (i.e., they did not rupture during the test) the 300°F leakage test, another leakage test was performed at 350°F and then another at 400°F and so on until the seals ruptured.

An initial test temperature of 300°F was chosen because it is highly unlikely that the temperature of the seals, which are located around the personnel airlock doors at the boundary of the containment, would ever exceed 300°F even for a containment "atmosphere" temperature of 400°F.

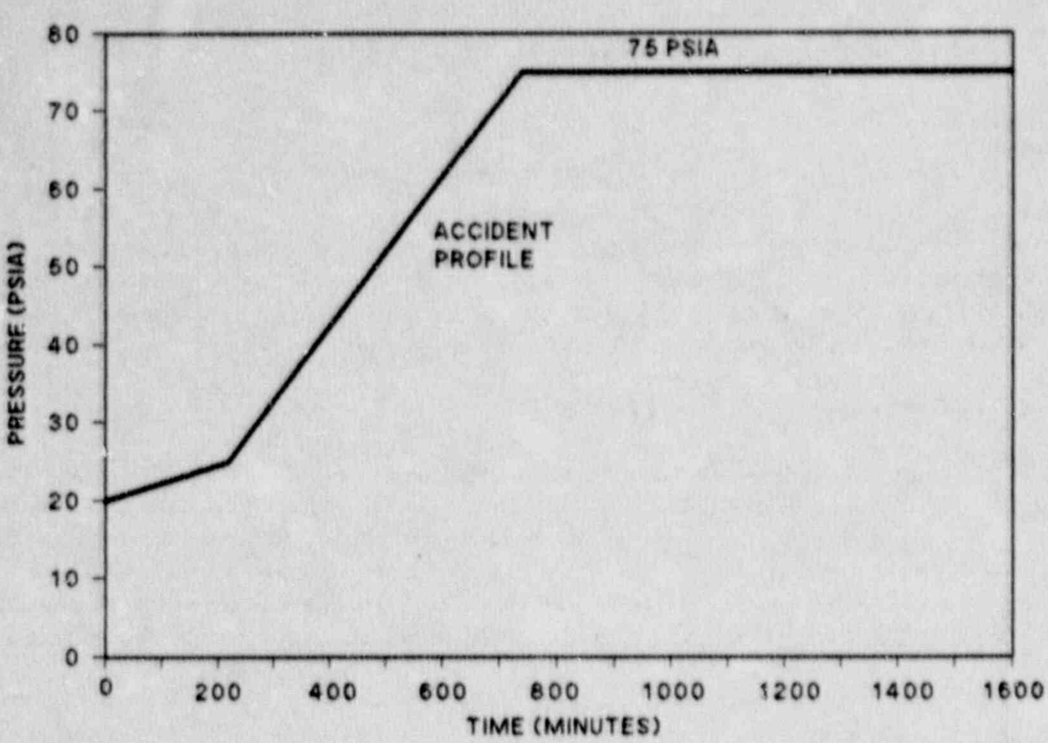


(a) Pressure Vs. Time

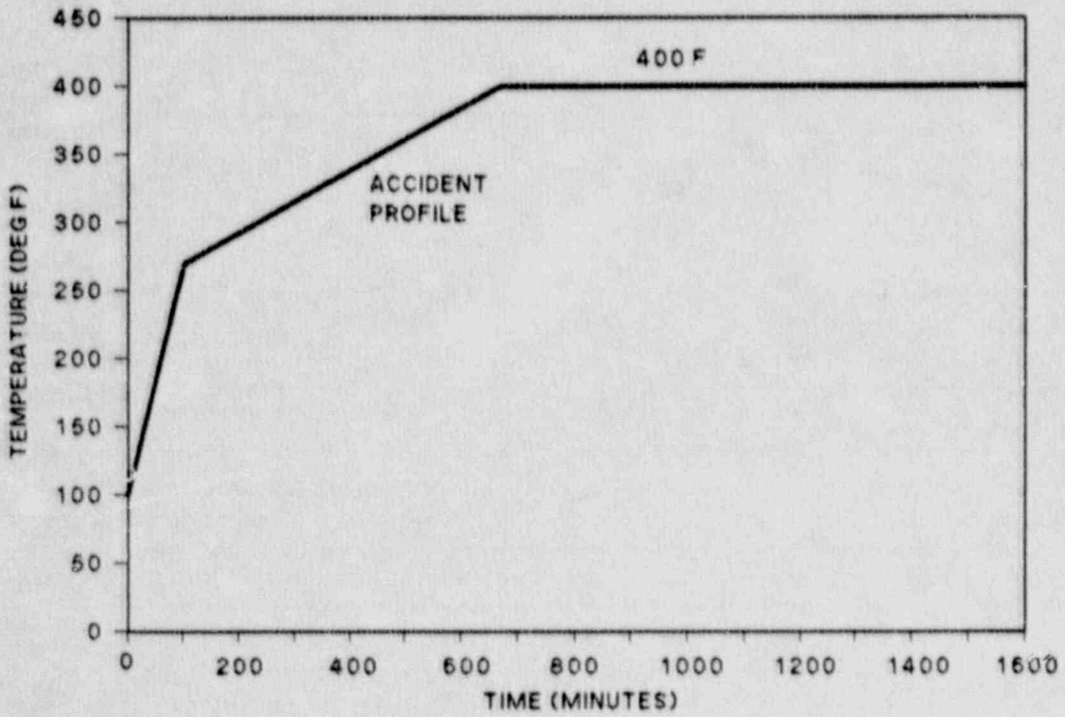


(b) Temperature Vs. Time

Figure 2.1. Postulated Severe Accident Pressure and Temperature Conditions for PWRs (Containment Atmosphere)



(a) Pressure Vs. Time



(b) Temperature Vs. Time

Figure 2.2. Postulated Severe Accident Pressure and Temperature Conditions for BWR Mk-IIIs (Wetwell Atmosphere)

2.4 Selection of Test Seal Pressures

The internal seal pressures that were selected for testing are representative of the actual seal pressures currently in use in LWR nuclear containments. As mentioned in Section 1.1, the normal operating seal pressures used in commercial nuclear containments varies from 50 to 110 psig. Because the number of test specimens were limited and because of the relatively large expense to set up each test, every effort was made to obtain the most information possible regarding the leakage behavior of inflatable seals from each pair of tested seals.

2.4.1 Room Temperature Tests (70-90°F)

Separate leakage tests were conducted at room temperature for several seal pressure levels. For the unaged seals, the room temperature tests began at 50 psig in the seals. The seal pressure was increased in 10 psi increments and a leakage test conducted at each seal pressure level. (For example, leakage tests were conducted for initial seal pressure levels of 50, 60, 70, 80, 90 and 100 psig during the room temperature portion of test series 1.) For those tests that were conducted with the seals isolated from their pressure source by a closed valve near the seals' valve stem, the seal pressure actually increased as the chamber pressure approached the initial seal pressure. In order to minimize any damage that might occur during the room temperature tests, the maximum tested seal pressure level was limited to that which would result in an actual seal pressure at "failure" (≥10,000 scfd leakage past both seals) of approximately 135 psig--the standard proof test pressure applied by the manufacturer before shipping the seals to containments. For the aged seals, only the 60 psig initial seal pressure level was tested again in order to minimize any damage that might occur during room temperature tests.

2.4.2 Elevated Temperature Tests

For test series 1, the equivalent initial seal pressure level at room temperature was only 45 psig, whereas 90 psig was used for test series 2, 3, and 4. Before conducting the first elevated temperature test, it was unknown if relatively high external pressures and 400°F would cause significant damage to the seals. It was hoped that elevated temperature tests at $\leq$ 400°F would be nondestructive and thus, allow multiple testing at several different seal pressure levels just as done for the room temperature tests. However, because the seals ruptured during test series 1--even at an initial seal pressure of 45 psig--it was decided to use a higher, more representative, initial seal pressure level for test series 2, 3, and 4.

2.5 Aging of Seals

The "aged" inflatable seals were subjected first to radiation aging and then later to thermal aging. The seals, while inflated with air at 50 psig, received a total gamma radiation dose of 200 megarads (Mrads) applied at a rate that did not exceed 1 Mrad/hr. Approximately two weeks were required for the radiation aging process. After completion of radiation aging, the seals were thermally aged for 1 week (168 hr) at 250°F while deflated. The aging process described above is intended to produce similar properties in the seal material as would be expected after being subjected to a loss of coolant accident at the end of a 10 year life. The normal operating temperature during the 10 year life was assumed to be 120°F. As mentioned in Section 1.1, the maximum in-service life of inflatable seals is 5 years; thus, the applied aging is conservative.

The following is an explanation of why the seals were deflated for thermal aging but inflated during radiation aging. Thermal aging is intended to accelerate the normal aging process that would naturally occur over a given period of time at the operating temperature. If the seals had been inflated during thermal aging, the combined effect of the relatively high aging temperature (250°F) and the stresses induced in the seals from the internal pressure would have produced more severe conditions in the seals than would likely ever occur during their normal operating life. These conditions might have caused permanent deformation of the seal tube that would not have occurred at normal operating temperature and pressure.

Because the applied radiation dose is intended to primarily represent the radiation due to a LOCA (150 Mrads for LOCA and 50 Mrads for normal operating life), it is most logical to apply the radiation with the seals inflated as they would be during an accident.

3. TEST SETUP

3.1 General

The inflatable seals tests were conducted inside an existing environmental test chamber at Sandia National Laboratories in Albuquerque, New Mexico. The test chamber was originally constructed for use in the severe accident testing of electrical penetration assemblies [5] which was also an NRC-sponsored research program.

An overall view of the inflatable seals test setup is provided in Figure 3.1. During the tests, the inflatable seals test fixture, with inflatable seals installed, was placed inside the large test chamber shown near the center of Figure 3.1. Figures 3.2 and 3.3 show the approximate location of the test fixture within the test chamber. Attachment of the leak detection lines to the test fixture is shown in Figure 3.4. Figure 3.5 shows a cross-section of the test fixture along with a simplified schematic of the entire piping system used during the tests. The seal on the pressure input side of the fixture is denoted as the "inner" seal and the seal opposite the pressure input is the "outer" seal. (This notation corresponds to an actual airlock in which the innermost seal is exposed directly to the containment pressure). The fixture surface that the seals contact when inflated was sanded so that the "worst-case" surface finish was in the range of 50 to 60 RMS.

Separate pressurized air tanks were used to supply air pressure for each seal. A manual valve was placed in each 1/2-inch diameter air supply line so that, after pressurizing the seals to the desired level, the valve could be closed and the seals effectively isolated from their pressure source. The valve was located approximately 36 inches from the valve stem of each seal. A bleed valve was also placed in the air pressure supply line for each seal. The bleed valve was used to deflate the seals after testing and also to bleed off any seal pressure buildup due to external pressure for the constant seal pressure tests. Air pressure for the test chamber, which entered the chamber from the top, was supplied by an air compressor with maximum capabilities of 200 psig at approximately 30 scfm. Two superheaters were placed in the air compressor supply lines to supply the necessary test temperature.

Heating of the test chamber was obtained from two sources. Eleven internal resistance-type heater elements were equally spaced around the circumference, approximately 2 inches from the inner diameter of the test fixture as shown in Figure 3.4. Also, a flow of heated, dry air or steam through the test chamber was used to bring the test chamber up to the desired test temperature. Once at the test temperature, a flow of heated, dry air was used to maintain the chamber temperature.

Leakage past the seals flowed out the leak detection ports on the test fixture, through the leak detection lines, through a heat exchanger that cooled the air to less than 100°F, and into a flowmeter gallery (Figure 3.5). Because the leak detection lines were vented to atmosphere and because leakage first passed through a heat exchanger, the measured

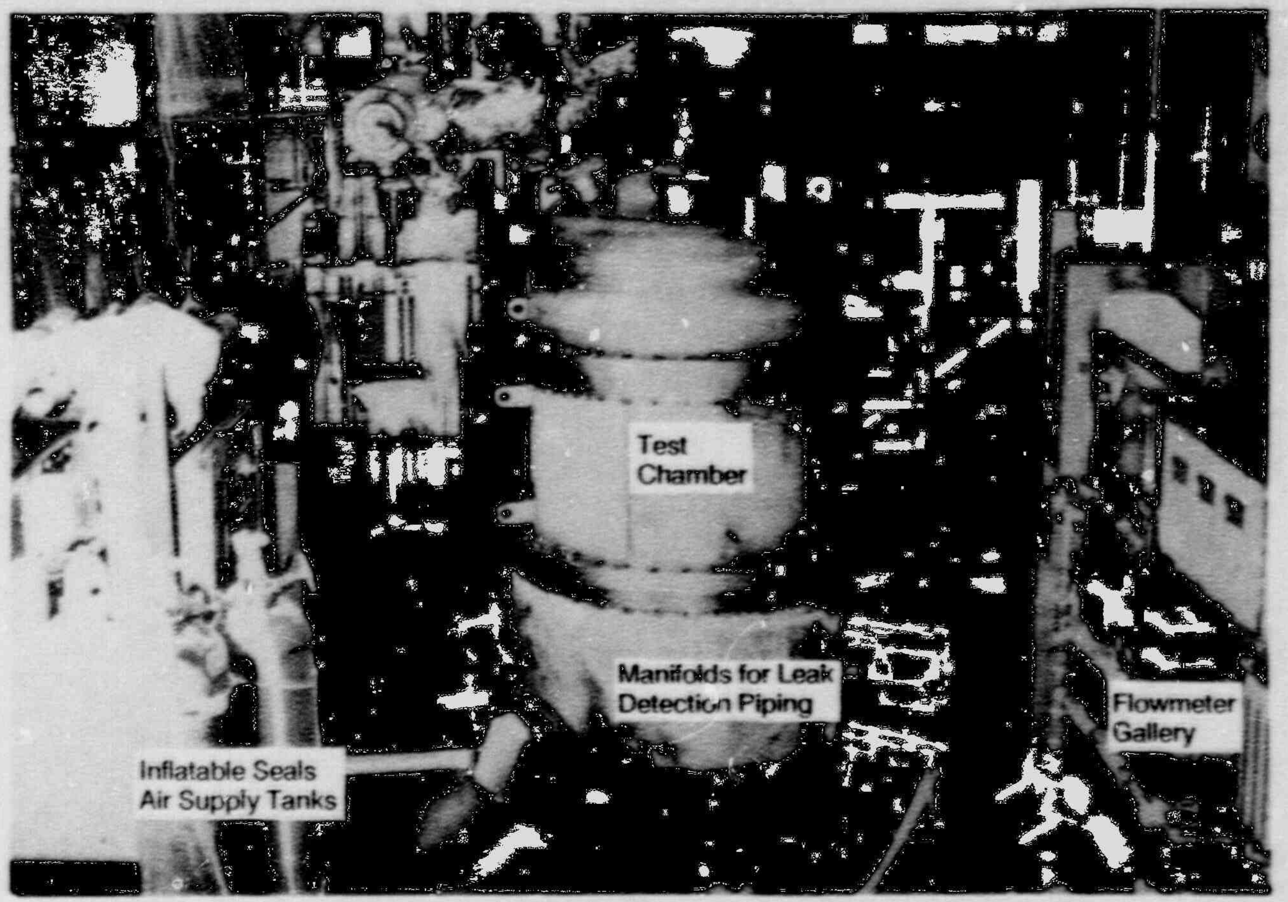


Figure 3.1. Overall View of Inflatable Seals Test Setup

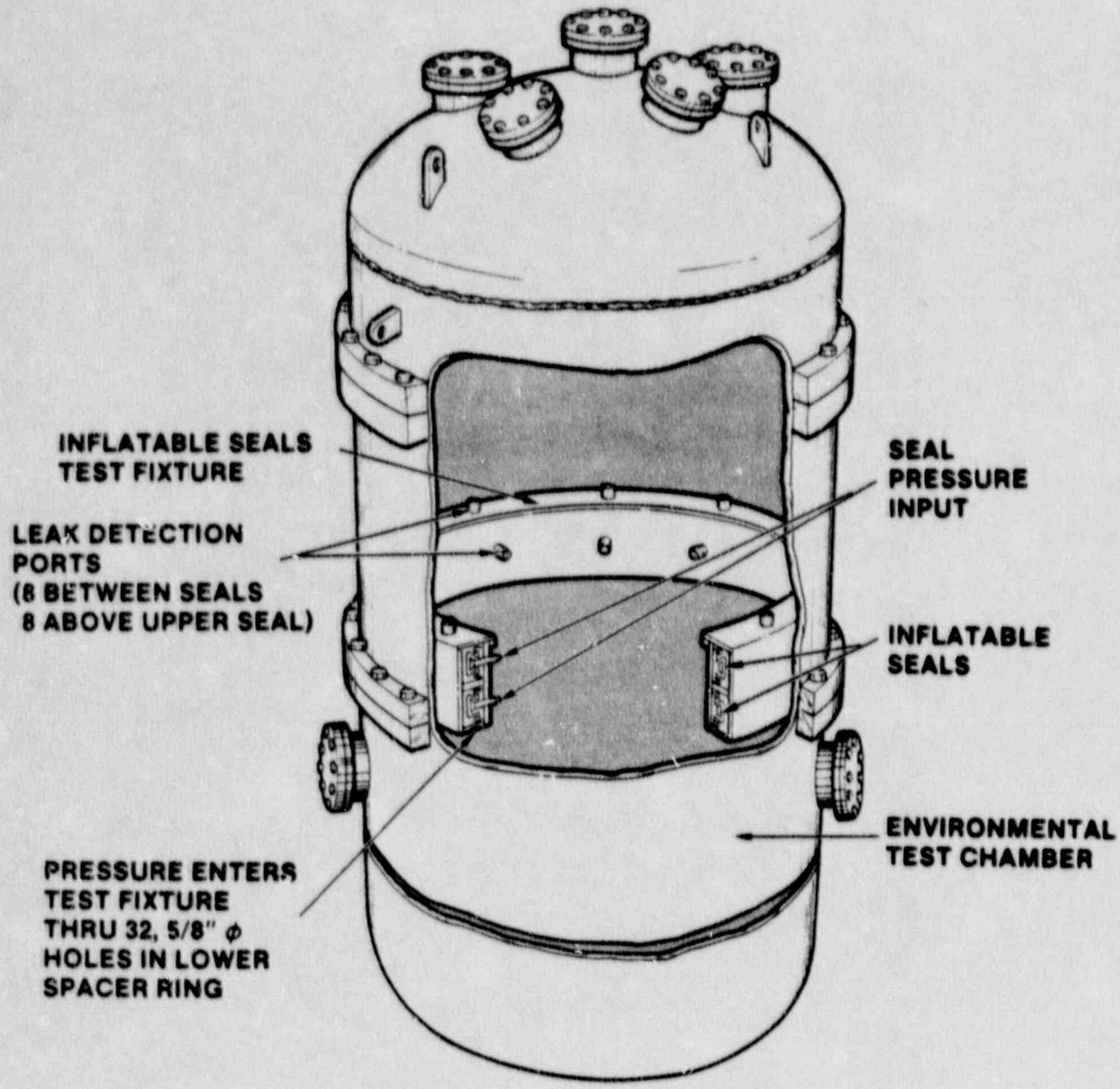


Figure 3.2. Cutaway View of Inflatable Seals Test Fixture Inside Environmental Test Chamber

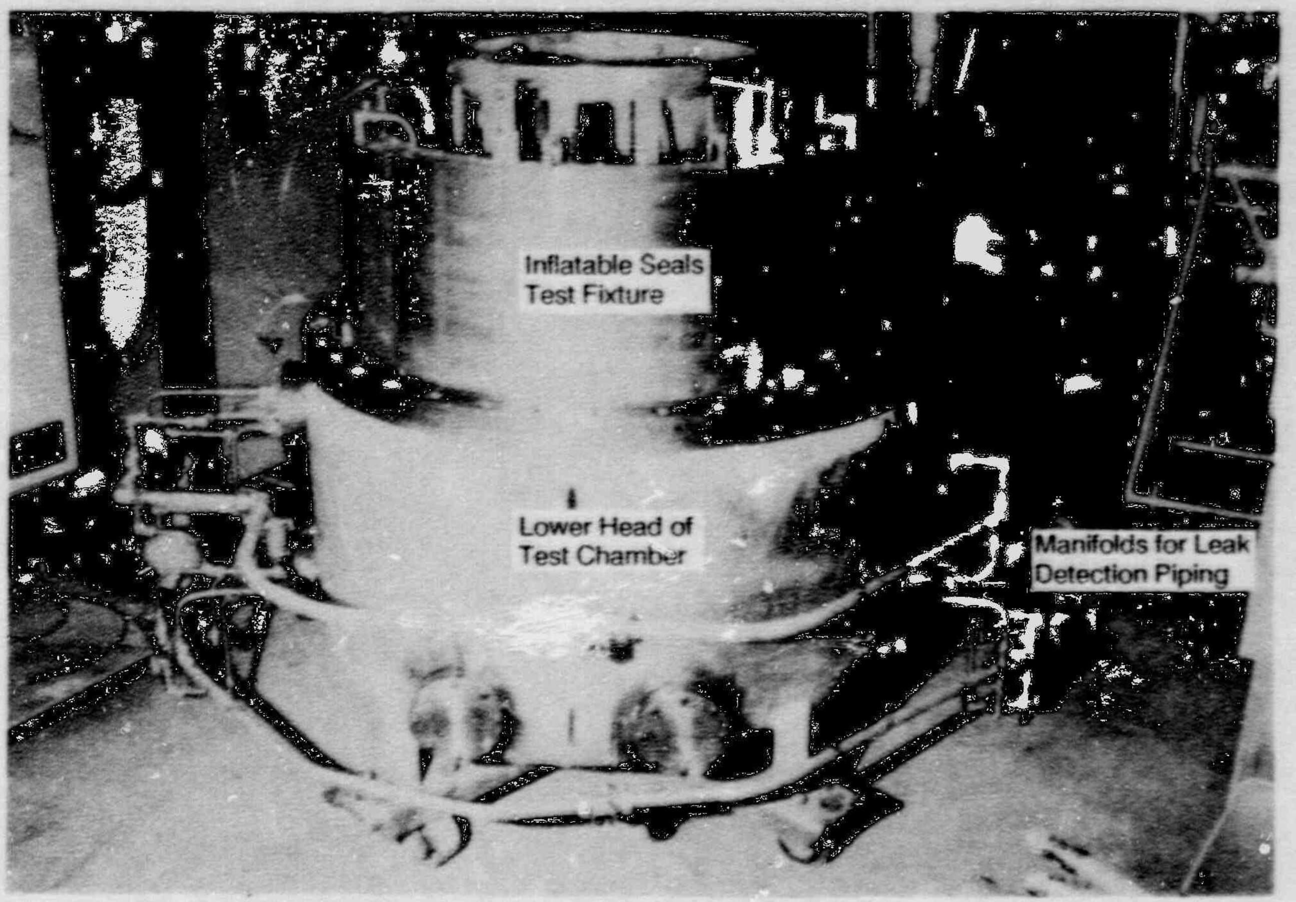


Figure 3.3. Inflatable Seals Test Fixture Within Test Chamber

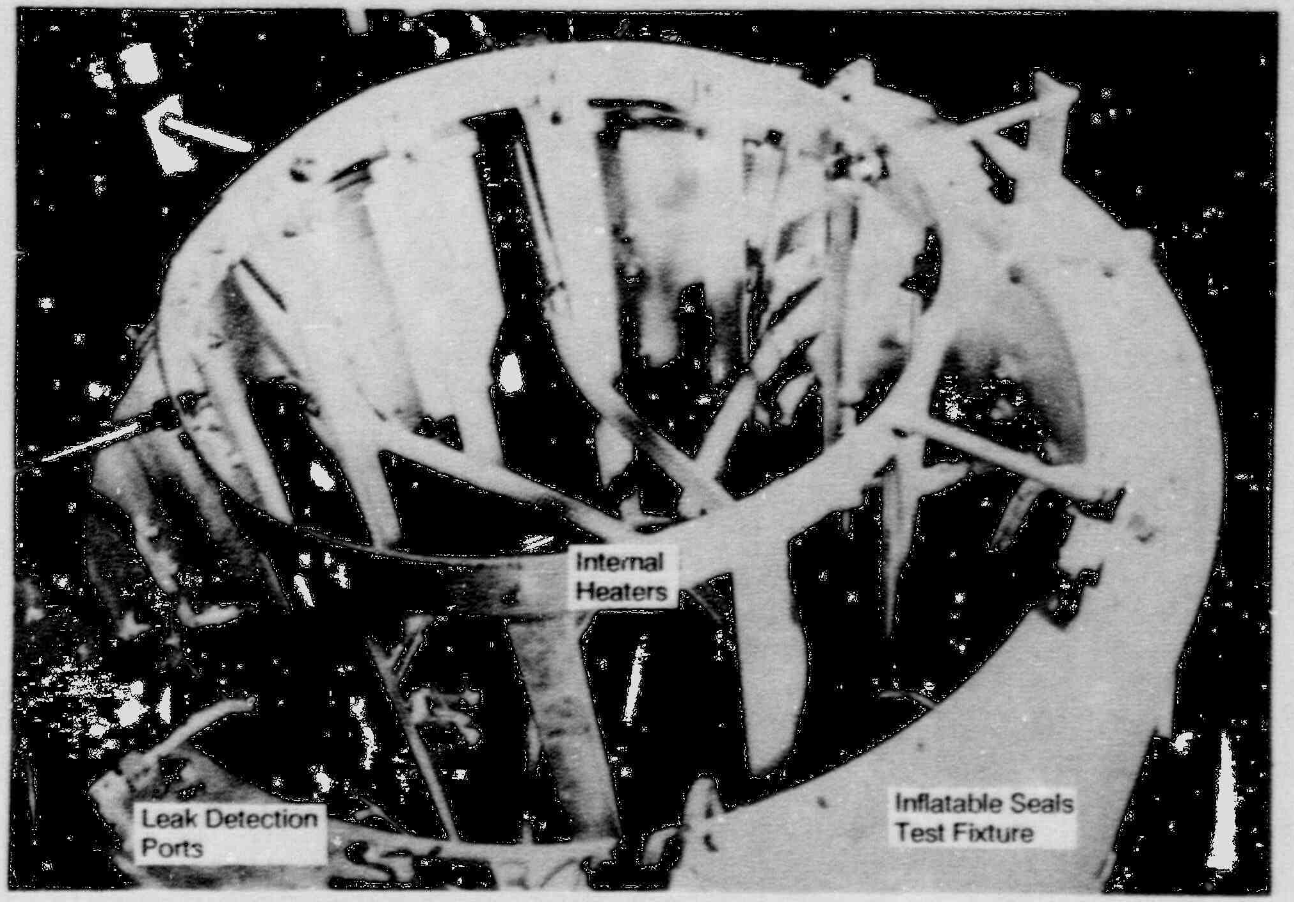


Figure 3.4. Leak Detection Piping for Inflatable Seals Test Fixture

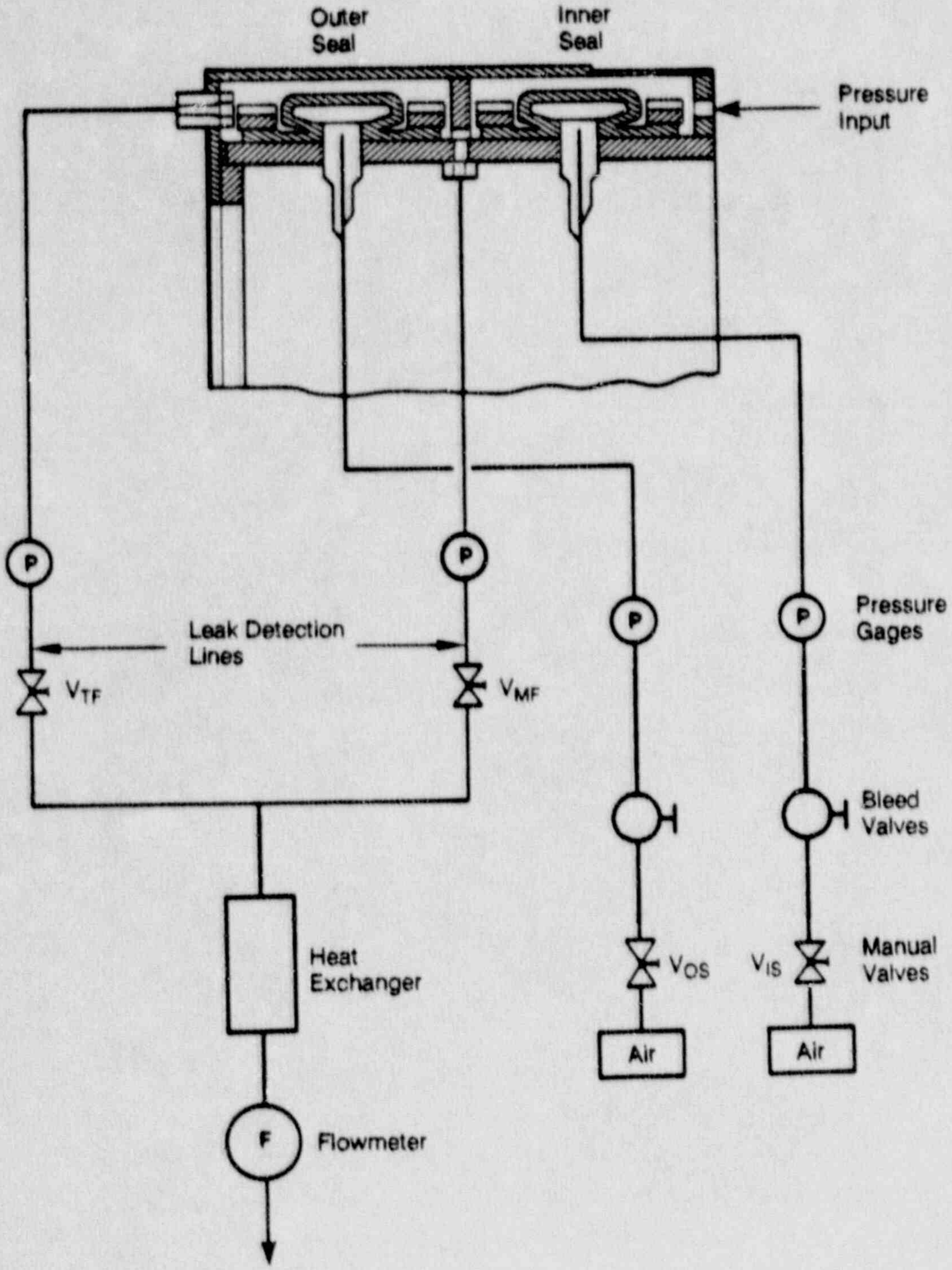


Figure 3.5. Simplified Schematic of Test Setup (Note that seals are shown deflated.)

leakage by the flowmeters was essentially at atmospheric pressure and ambient temperature.

3.2 Test Fixture and Test Chamber

As shown in Figures 3.2 through 3.4, the overall shape of the inflatable seals test fixture is that of a short length of cylinder with an outer diameter of approximately 35-3/4 inches and a length of about 13 inches.

The inner cylinder of the test fixture to which the inflatable seals are attached is approximately 32 inches in diameter. Thus, the circumferential length of the tested seals is approximately 100 inches as compared to a total length of about 240 inches for a 6'-6" X 3'-6" personnel airlock door. (As earlier mentioned, some airlock doors are as large as 8'-0" X 5'-0" for a total perimeter of about 312 inches.) Because the amount of leakage should be approximately proportional to the length of seal, a reasonable estimate of leakage around actual airlock doors would be 2.4 to 3.1 times the measured leakage for the test fixture for a given containment pressure and temperature. A complete set of design drawings for the test fixture is provided in Appendix C.

Pressure enters the fixture through circular openings on the inner end as shown in Figure 3.5. By appropriate arrangement of valves V_{MF} and V_{TF}, leakage past the inner seal may be measured through ports located between the seals; or, leakage past both seals may be measured through ports in the outer end of the test fixture. For all tests included in this report, valve V_{MF} was closed and V_{TF} was open; thus, all reported leakage was measured past both seals.

The test fixture was placed inside an environmental test chamber at Sandia National Laboratories (Sandia). The test chamber has an inner diameter of approximately 36 inches with an overall length of 84 inches; thus, the test fixture was completely surrounded by the chamber environment.

It should be noted that inflatable seals are normally employed to prevent leakage around rectangular doors with "rounded" corners. The corner radius of the doors is usually about 12 inches [7,8]. "Leakage is expected to first start at the corners of the door and as the pressure differential (between the seal and containment) decreases toward zero the leakage is expected to occur around the entire periphery of the door [Source: Letter from Milt Shackelford (Argonne National Laboratories) to C. Subramanian (Sandia National Laboratories) dated May 15, 1984.]." Reasons for initiation of leakage at the corners are: 1) imperfections in manufacturing the doors and door frames seem to be greatest in the corners which result in a nonuniform gap between the door and the sealing surface, and 2) the sealing surface of the inflatable seals is drawn inward as a result of being stretched around the corners which makes the effective gap between the seals and the doors larger than in the straight portions of the door.

The inflatable seals test fixture is not rectangular but round. The ring to which the seals are attached has a radius of approximately 16 inches. Because the entire perimeter of the inflatable seals is curved (as opposed to only the corners in personnel lock doors), a conservative estimate of the leakage behavior of inflatable seals in an actual airlock door should be obtained. A round inflatable seals test fixture was fabricated for the following reasons. In the early planning stages, radiation aging of the inflatable seals was to be performed in a Sandia facility in which the material to be irradiated must be rotated at a constant distance around a fixed radiation source. Thus, primarily for radiation purposes, the inflatable seals test fixture was designed and built in a circular shape instead of rectangular. However, after fabrication of the test fixture, it was determined that the above radiation facility is incapable of delivering the desired radiation dose in a reasonable amount of time. Consequently, Neely Nuclear Research Center at Georgia Tech, was utilized for the radiation aging. Neely will also accept a rectangular test fixture if it is deemed necessary to test such a fixture in the future.

Another reason for designing a round fixture was to be able to test the largest possible length of seals. Because the largest available test chamber was a cylindrical pressure vessel, obviously a round test fixture provided the optimum geometry.

3.3 Assembly of Test Equipment

Special care was taken in assembling the test fixture and attached leak detection piping in order to assure that quality leakage data was obtained. The bolts that connect the flanges of the inflatable seals to the test fixture were tightened until the seal flanges were compressed from a thickness of about 1/2 to 3/8 of an inch. Also, the bolts that connect the inner and outer cylinders (referred to as the door seal test fixture in fixture drawings--Appendix A) at the outer end of the test fixture were torqued to a minimum of 150 in.-lb. A new gasket was used at this connection for each test. The bolts at the inner end of the test fixture were only tightened until snug.

Figure 3.6 illustrates a typical cross-section through the valve stem area of a personnel airlock door. As shown, an O-ring is typically placed in a recessed groove around the valve stem between the seal and the door. The end of the valve stem is threaded so that a nut may be used to tighten the valve stem against the door and thus, minimize the potential for leakage around the valve stem opening.

The detail of the test fixture at the valve stem opening is slightly different. The differences are that there is no recessed O-ring groove around the valve stem and that the test fixture is not as thick as airlock doors. In order to compensate for these differences and thus assure that there was no extraneous leakage entering through the valve stem opening during the tests, the measures shown in Figure 3.7 were employed. Between the inner cylinder of the test fixture and the valve

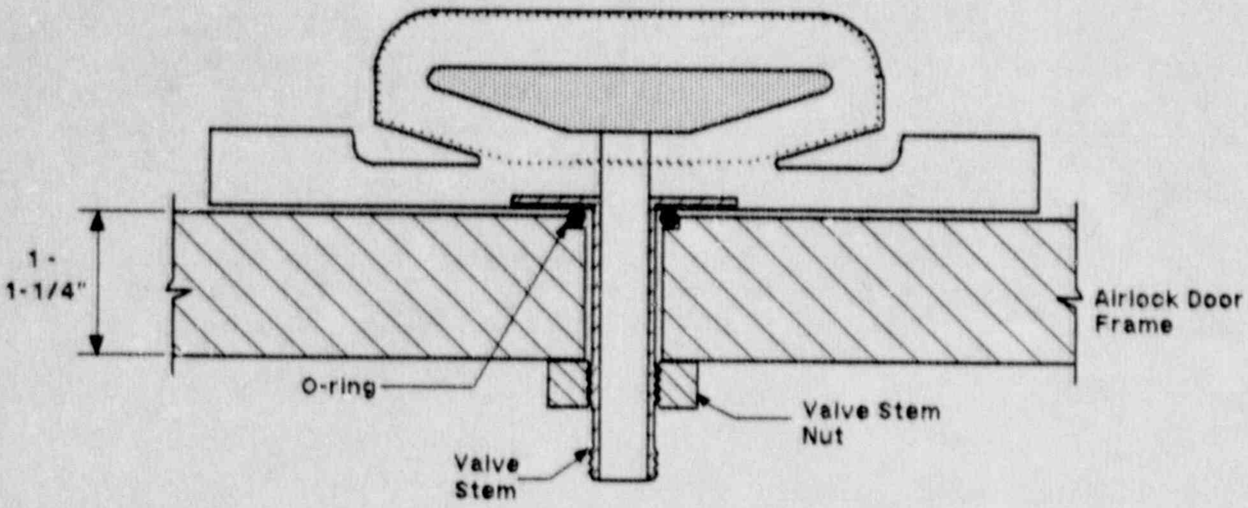


Figure 3.6. Typical Section Through the Valve Stem of an Airlock Door

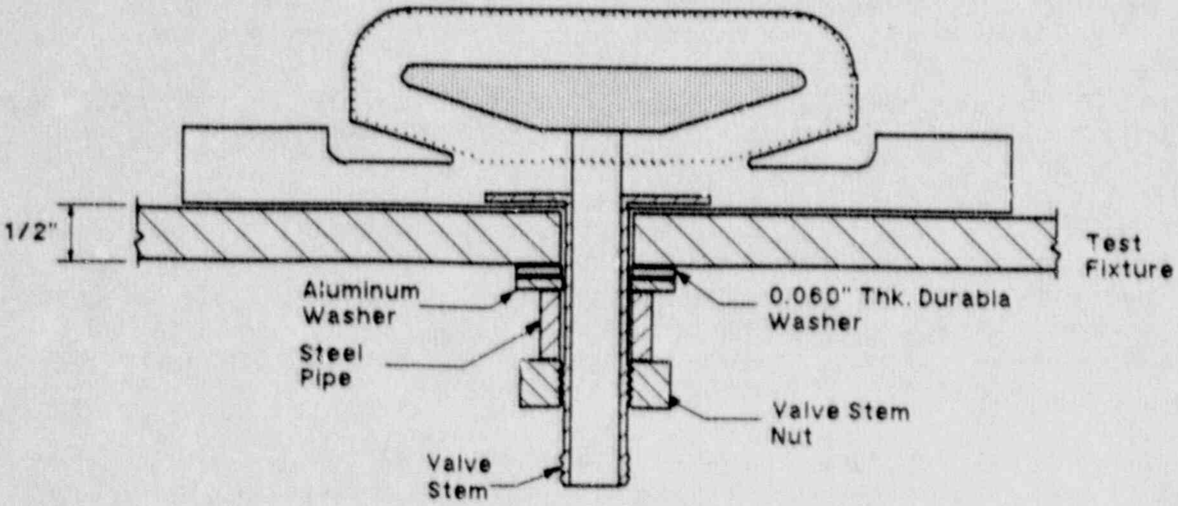


Figure 3.7. Section Through the Valve Stem on the Inflatable Seals Test Fixture

stem nut, a thin (approx. 0.060-inch thick) Durabla gasket, an aluminum washer, and a short length of pipe were placed. By tightening the valve stem nut to about 20 ft-lbs an adequate seal was obtained around the valve stem opening before testing.

Swage-Lock connections, 1/2-inch in diameter, were used to connect the leak detection lines to the test fixture on one end and to the inside of the penetration cover plates of the test chamber on the other end. Outside the test chamber, the leak detection lines were connected through a common manifold into a single 3/4-inch diameter line (Figure 3.3). Of course, a separate manifold "system" was used for the between seals leak detection lines and for the leak detection lines that carried leakage past both seals. The 3/4-inch diameter leak detection lines were connected just before entering the heat exchanger as illustrated in Figure 3.5. As mentioned earlier, between seals leakage and leakage past both seals could be measured during the tests by appropriate arrangement of valves V_{MF} and V_{TF}. A flexible hose, approximately 1-inch in diameter, was used to carry leakage from the heat exchanger to the flowmeter gallery. After passing through the flowmeter gallery, leakage was vented to atmosphere.

3.4 Leak Checks of the Test Apparatus

Before the first test and before attaching the leak detection lines to the test fixture, the test fixture ends of the leak detection lines were capped and the entire leak detection piping system, from the capped ends to the connection to the flowmeter gallery, was pressurized at 150 psig. A soap solution was applied along the length of all piping and particularly at all connections to check for leakage. All noticeable leaks were repaired. Because these connections were not disturbed for the remainder of the test program, this was the only complete check of these particular connections for leakage.

After connecting the leak detection lines to the fixture, a leakage check of the test fixture itself was performed before each test. First, the inner and outer seals were pressurized to 90 psig with clean, dry air. Next, the internal cavity between the seals and between the outer seal and the outer end of the test fixture was pressurized with either helium gas to 50 psig or with air to 60 psig. Because of the difficulty involved in detecting the origin of leakage with helium, it was used before test series 1 only. The test fixture leakage tests for the remaining test series were performed using air with a soap solution used to detect leakage. Any detectable leakage was repaired and rechecked before testing.

After the test fixture and associated piping had been checked for leakage, the three sections of the test chamber were assembled around the test fixture by torquing the flange bolts of the test chamber to approximately 300 ft-lbs.

3.5 Instrumentation

The primary parameters that were monitored during the tests were pressure, temperature, and leakage. A brief description of the instrumentation employed to measure these parameters is provided below.

3.5.1 Pressure

Pressure was monitored at five different locations during the tests: chamber pressure, internal pressure in each seal, pressure between the seals, and pressure within the test fixture on the outer side of the outer seal. Calibrated Duratran pressure gages were used to record the pressure at these locations. In addition, a calibrated Heise pressure gage was employed to provide a visual check of the chamber pressure; however, the readings from this gage were not recorded by the data acquisition system.

3.5.2 Temperature

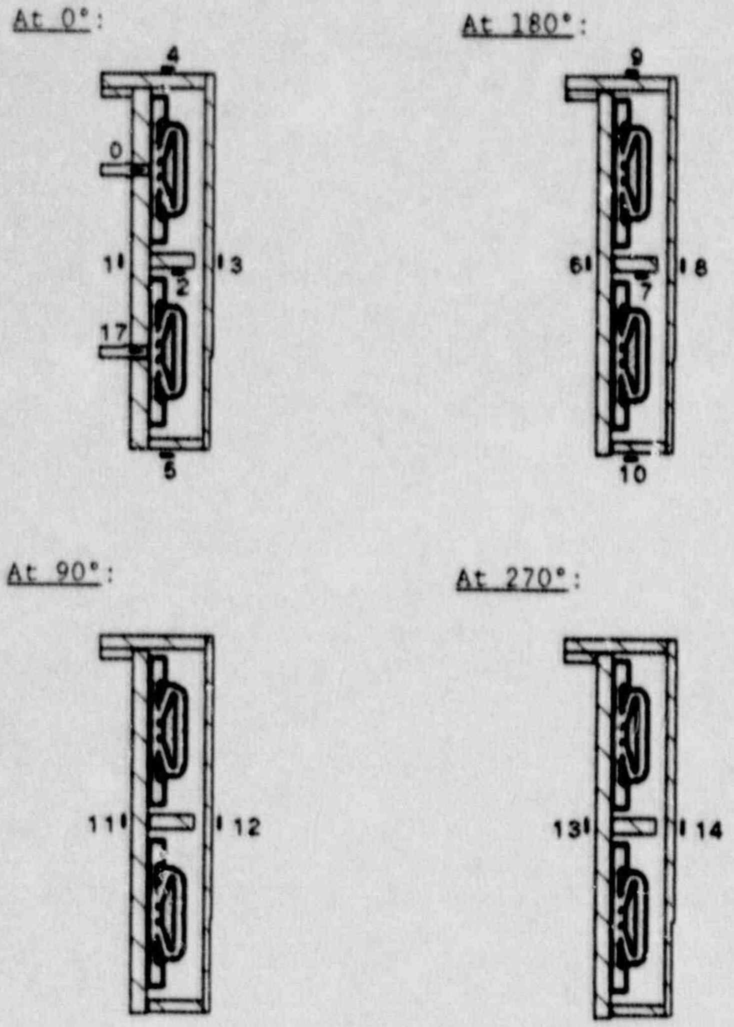
Several type K thermocouples (TCs) were employed to both monitor and record the temperature level and distribution in the test fixture and chamber. Both extrinsic and intrinsic TCs were used. (Extrinsic TCs record air temperature, whereas intrinsic TCs are attached directly to the metal and thus, measure the metal temperature.) A total of 19 TCs were employed for test series 1 with 20 TCs used for test series 2, 3, and 4. Figure 3.8 describes the TC locations on the test fixture for test series 2, 3, and 4. (For test series 1, no TCs were placed inside the valve stems of the seals; however, an additional intrinsic TC was used to measure the metal temperature of the test chamber.)

It should be noted that a TC was placed inside the valve stem of the seals for test series 2, 3, and 4 only. For test series 1, the temperature of the stiffener between the seals is used as the seal temperature for the purposes of presentation of the results.

3.5.3 Leakage

A "gallery" of Hastings linear mass flowmeters, as shown in Figure 3.1, was used to measure leakage past the inflatable seals. The accurate flow ranges of the flowmeters varied from 0 to 1.00 standard liters per minute (slpm) (1 slpm = 50.85 scfd) for the smallest flowmeter to about 5,000 to 30,000 scfd for the largest. Only one flowmeter was open at a time with the remainder valved off from the leakage. As leakage increased, the arrangement of the valves was changed such that the appropriate size flowmeter was selected. The output of each flowmeter was recorded at each pressure level. Data from the closed flowmeters was removed from the test results after completion of the tests.

A maximum flowmeter capacity of 30,000 scfd was sufficient for the following reasons. First, all but one of the elevated temperature tests ended as a result of a rupture in the seals--not because the flowmeters



Description of Other TC's:

15 - At 90°, extrinsic, 2" above test fixture
16 - At 90°, extrinsic, 2" below test fixture
18 - extrinsic, incoming air temperature
19 - extrinsic, temperature of air into flowmeters

Figure 3.8 Thermocouple Locations for Test Series 2, 3, and 4 were incapable of measuring larger leakage. After an inflatable seal ruptures, there is an approximate 3/8-inch gap between the seal tube and the sealing surface of the test fixture. Because this gap extends around the entire 100-inch circumference of the test fixture, the total leak area is approximately 40 in^2. At 150 psig and 300°F, for example, an estimated leakage of $70x10^6$ scfd would be expected for this leak area. It was well beyond the scope of the test program to develop facilities to supply and measure leakage of this magnitude.

The room temperature tests were not meant to be destructive. They were designed so that leakage tests could be conducted at several different seal pressure levels for each pair of tested seals. In order to minimize the threat of damaging the seals during room temperature testing, the tests were discontinued when leakage first exceeded 10,000 scfd. Thus, a flowmeter capacity of 30,000 scfd was more than adequate for the room temperature tests.

There is one final point that should be mentioned. For all the inflatable seals tests (room temperature and elevated temperature), once leakage began it increased rapidly for small increases in chamber pressure. Because there is little reserve "strength" in the inflatable seals design once leakage begins, it is believed that, even if the seal tube remained intact, leakage would grow to several million scfd at only a few psi above the chamber pressure at which leakage on the order of 10,000 scfd began.

3.6 Data Acquisition System

An IBM PC-XT was interfaced with the Sandia data loggers to both monitor the output of the instrumentation during testing and to record all test measurements at each pressure level. The test data was recorded on the hard disk of the computer and later transferred to floppy diskettes and then to a mainframe computer for data reduction.

4. TEST PROCEDURE AND RESULTS

This section presents a general description of the test procedures and results for both the room temperature and elevated temperature inflatable seals tests. Results of the various tests are compared in Section 5. In Section 6, approximate methods are presented to predict the chamber (containment) pressure, for a given initial seal pressure, at which significant leakage will begin. Appendix A provides a complete discussion of each test series both at room temperature and at elevated temperature. A detailed step-by-step listing of the procedure followed before and during each test is provided in Appendix B.

As briefly mentioned in Section 1.1, during the test program it was believed that, after the seals on a typical airlock door are inflated, they are isolated from their pressure source by closing the inflation valve. This information was obtained from an expert in the use of inflatable seals in nuclear containment penetrations. Because the inflation valve is located between the seal and accumulator tank (Figure 1.3), a relatively small, fixed volume of air would be "trapped" inside the seals upon closing the valve. Thus, increasing the external "side" pressure on the seals, as would occur as a result of pressurizing the containment, would produce a corresponding increase in the internal seal pressure. The increasing seal pressure would delay the onset of significant leakage until a larger external pressure than would occur without the seal pressure increase. In order to duplicate the above conditions, the majority of the inflatable seals tests were conducted with the seals isolated from their pressure source by closing valves V_{IS} and V_{OS} (Figure 3.5) after inflation.

After completion of all planned tests, it was determined that the above description of the function of the inflation valve (Figure 1.3) is incorrect. The inflation valve is only used to inflate and deflate the seals.[3] During normal operation, it is actually open allowing a pathway for airflow between the seal and accumulator tank. Because the accumulator tank volume is much larger than that of the seal, increasing chamber pressure has little effect on the seal pressure. If the chamber pressure appreciably exceeds the seal pressure, the air within the seals will be forced into the accumulator tank--effectively deflating the seals. Once deflated, a gap of approximately 3/8 of an inch will exist between the seal tube and the sealing surface of the bulkhead around the entire perimeter of the door.

Fortunately, tests were conducted at room temperature which modeled both the case in which the seals are isolated from their pressure source (Section 4.1.1) and the case in which the seal pressure is essentially constant (Section 4.1.2) as would occur if the inflation valve is open.

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[3] This information was obtained as a result of a field trip to a nuclear power plant that happens to use inflatable seals around the personnel airlock doors.

For future reference, the two valve conditions will be referred to as "seals isolated from pressure source" (inflation valve closed) and "constant seal pressure" (inflation valve open). All elevated temperature tests were conducted with the seals isolated from their pressure source. Unless noted otherwise, significant leakage is defined as leakage past both seals in excess of 10,000 scfd. Also, "initial seal pressure" refers to the internal seal pressure at the start of each test with no applied chamber pressure and at room temperature. Seal temperature during the room temperature tests varied from around 70 to 90°F.

All testing was performed at essentially constant temperature. For each seal pressure level, chamber pressure was slowly increased from 0 psig until leakage past both seals reached 10,000 scfd for the room temperature tests or exceeded the capacity of the flowmeters--approximately 30,000 scfd--for the elevated temperature tests. The rate of pressurization varied from about 2 psi/min. for low chamber pressures and no leakage to as little as 0.1 psi/min. once appreciable leakage began.

4.1 Room Temperature Tests (70-90°F)

Each series of tests for a given pair of inflatable seals began with room temperature tests. During the room temperature tests, leakage past both seals was limited to a maximum of 10,000 scfd so that minimal damage would occur and thus, the same pair of seals could be tested for several seal pressure levels at room temperature and later for elevated temperature conditions. A leakage of 10,000 scfd is equivalent to 1% mass/day leakage at standard conditions from a $1*10^6$ ft^3 containment and is on the order of 100 times greater than the design allowable leak rates discussed in Section 1.1.

4.1.1 Seals Isolated From Pressure Source

Separate tests were performed at room temperature in which the initial seal pressure of the unaged seals (Test series 1 and 3) was varied from 50 to as much as 100 psig in increments of 10 psi. Table 4.1 lists the initial seal pressure levels that were included in each test series. After adjusting the seal pressure to the desired level at zero chamber pressure, valves V_{IS} and V_{OS} (Figure 3.5) were closed--effectively isolating the seals from their source of internal pressure. (Note that, because the seals were isolated from their pressure source by closed valves, the pressure within the seals increased from their initial level as the pressure in the test chamber increased.) Because the seals for test series 2 and 4 were aged, there was some concern that any testing at room temperature might damage the seals before the elevated temperature tests. In order to minimize any potential damage, only the 60 psig seal pressure level was tested at room temperature for test series 2 and 4.

To ensure that no damage occurred during any of the room temperature tests, the minimum seal pressure level was retested after completion of all other room temperature tests and the results compared to the first

Table 4.1 Comparison of Chamber Pressure and Outer Seal Pressure at Failure - Room Temperature Tests

Test* Series Number	Initial* Seal Pressure, P_i (psig)	Maximum* Inner Seal Pressure, P_{is} (psig)	Maximum* Outer Seal Pressure, P_{os} (psig)	Chamber* Pressure At Failure, P_f (psig)	$\Delta P = P_f - P_{os}$ (psig)	$\Delta P/P_{os}$ (6)/(4) (%)
	(2)	(3)	(4)	(5)	(6)	(7)
1	50 (1st Test)	58.7	54.0	51.1	-2.9	-5.4
	60	72.6	66.6	65.4	-1.2	-1.8
	70	85.6	78.8	79.0	+0.2	+0.3
	80	101.2	92.9	94.8	+1.9	+2.1
	90	115.9	106.9	109.9	+3.0	+2.8
	100	135.0	124.6	129.6	+5.0	+4.0
	50 (2nd Test)	59.2	54.2	51.7	-2.5	-4.6
2	60 (1st Test)	78.9	74.7	79.0	+4.3	+5.8
	60 (2nd Test)	76.2	72.2	76.3	+4.1	+5.7
3 Round 1:	50 (1st Test)	94.9	92.0	93.0	+1.0	+1.1
	60	100.7	96.3	98.5	+2.2	+2.3
	60C**	60.0	60.0	60.8	+0.8	+1.3
	70	106.6	101.3	104.3	+3.0	+3.0
	80	127.2	121.2	125.1	+3.9	+3.2
	90	144.8	138.3	142.8	+4.5	+2.7
	90C**	90.0	90.1	92.6	+2.5	+2.8
	50 (2nd Test)	69.9	66.9	67.0	+0.1	+0.2
3 Round 2:	50 (1st Test)	61.8	60.3	58.2	-2.1	-3.5
	60	80.0	77.4	76.9	-0.5	-0.7
	70	100.1	96.3	97.4	+1.1	+1.1
	80	127.3	----	129.1	----	----
	50 (2nd Test)	62.4	60.5	58.9	-1.4	-2.3
4	60 (1st Test)	99.4	93.4	100.5	+7.1	+7.6
	60 (2nd Test)	99.9	94.0	101.0	+7.1	+7.6

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*Seal and Chamber pressures, respectively, at which leakage exceeded 10,000 scfd past both seals.

Initial seal pressure = nominal pressure in both seals at ambient temperature (70-90°F) before increasing pressure in test chamber.

Refer to Table 2.1, page 12, for description of each test series.

**Seal pressure maintained constant throughout test.

test at that pressure level. No significant change in leakage behavior was observed for test series 1, 2, and 4. However, for test series 3 the leakage behavior for the second 50 psig seal pressure test was much different from the first (see Table 4.1). Thus, a second "round" of room temperature tests were conducted for test series 3 in which the 50 through 80 psig seal pressure levels were repeated. No further change in leakage behavior was observed after the second round. Also, to minimize the possibility of damage during the room temperature test, the pressure within the seals was not allowed to significantly exceed the standard proof test pressure of 135 psig that is applied by the seal manufacturer. (A maximum seal pressure of 144.8 psig occurred during round 1 of test series 3 for a chamber pressure of 142.8 psig. For this test, the initial seal pressure at the beginning of the test was 90 psig).

For each seal pressure level, the chamber pressure was increased from 0 psig until leakage past both seals reached approximately 10,000 scfd. The measured chamber pressure at which leakage of 10,000 scfd occurred for each seal pressure level is provided in column (5) of Table 4.1. For test series 1, Figure 4.1 shows the recorded leakage past both seals as a function of chamber pressure for each seal pressure level. Figure 4.2 presents the measured leakage data for test series 2 and 4. Similar test data for test series 3 is provided in Figures 4.3 (round 1) and 4.4 (round 2).

4.1.2 Constant Seal Pressure

During round 1 of test series 3, two leakage tests were conducted in which the seal pressure was held constant throughout the test. In this way, the condition could be modeled where the inflation valve (Figure 1.3) is open. For the first of these tests, the seal pressure was set at 60 psig in both seals. As the chamber pressure was increased, the resulting increase in seal pressure was bled off--keeping a constant 60 psig pressure in both seals throughout the test. A similar test was also performed at 90 psig pressure in each seal. The results of these "constant seal pressure" tests are denoted by a "C" suffix on the initial seal pressure listed in Table 4.1. Figure 4.5 illustrates the measured leakage behavior for both the 60 and 90 psig seal pressure levels. Section 5.5.3 provides a comparison of the leakage behavior of the constant seal pressure tests to similar tests in which the seals were isolated from their pressure source.

4.2 Elevated Temperature Tests

As mentioned above, all of the elevated temperature tests were conducted with the seals isolated from their pressure source. Thus, increasing chamber pressure and temperature both produced corresponding increases in the internal seal pressure.

Once the inflatable seals test fixture reached the desired temperature, the elevated temperature tests were conducted in basically the same manner as the room temperature tests. The main exception being that, because the elevated temperature tests were generally destructive in nature, only one seal pressure level could normally be tested for a given pair of seals. The test temperatures and initial seal pressure level for each test series are summarized in Table 4.2. For test series 1, the temperature of the stiffener between the seals was maintained at 400±10°F whereas the air temperature within the seals was held within ±10°F of the desired test temperature for test series 2 through 4 (Figure 3.8). In most cases, the temperature over the entire test fixture did not vary from the desired temperature by more than 10°F during the leakage tests.

While still at room temperature and at 0 psig chamber pressure, the seal pressure was set to the level shown in column (2) of Table 4.2 and valves V_{IS} and V_{OS} were closed. A combination of internal heaters and a flow of heated, dry air or steam was used to heat the test chamber and inflatable seals test fixture to the desired test temperature. Heated, dry air was used to reach the desired test temperature for test series 1 and 2; however, because of the relatively long time period required to reach the test temperature (12 hours for test series 1 (400°F) and 8-1/2 hours for test series 2 (300°F)), superheated steam was used for test series 3 and 4. The use of steam instead of hot, dry air reduced the time required to reach 300°F to about 2-1/2 hours. Note that, since the inflatable seals fixture was surrounded or "soaked" in the test environment and because each test was conducted at essentially constant temperature, there was little temperature variation across the test fixture.

Once at the test temperature, the chamber temperature was maintained using heated, dry air. The chamber pressure was increased from 0 psig until leakage past both seals exceeded 30,000 scfd--the capacity of the flowmeters. After reaching 30,000 scfd, the chamber pressure was slowly reduced and the resealing of the seals at elevated temperature was recorded. For every test, leakage grew suddenly at failure from less than 5,000 scfd to greater than 30,000 scfd with no appreciable increase in chamber pressure (<2 psi). The internal seal pressure, at elevated temperature, was normally within 5 psig of the chamber pressure when failure occurred. Figure 4.6 illustrates the recorded leakage behavior at 400°F for test series 1. The measured leakage past both seals at 300°F for test series 2, 3, and 4, is shown in Figure 4.7 as a function of chamber pressure. Figure 4.8 presents the measured leakage data at 350°F for Test Series 3. Because the seals remained intact after the test at 350°F for test series 3, an attempt was made to perform yet another leakage test at 400°F. However, as discussed in Section 5.6, the outer seal ruptured just after the fixture temperature reached 400°F with virtually no applied chamber pressure.

Table 4.2 Comparison of Chamber Pressure and Outer Seal Pressure At Failure - Elevated Temperature Tests

Test Series Number	Initial* Seal Pressure (psig) (2)	Nominal Test Temp. (°F) (3)	Maximum** Inner Seal Pressure, P_{is} (psig) (4)	Maximum** Outer Seal Pressure, P_{os} (psig) (5)	Chamber** Pressure At Failure, P_f (psig) (6)	$\Delta P = P_f - P_{os}$ (psig) (7)	$\Delta P/P_{os}$ (7)/(5) (%) (8)
1	50	400	132.3	132.1	132.0	-0.1	-0.1
2	90	300	178.7	180.7	180.0	-0.7	-0.4
3	90	300	181.3	183.2	180.9	-2.3	-1.3
	90	350	150.7	153.8	146.1	-7.7	-5.0
4	90	300	138.1	133.9	137.5	+3.6	+2.7

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*Initial seal pressure = nominal pressure in both seals at ambient temperature (70-90°F) before increasing pressure and temperature in the test chamber.

**Seal and chamber pressures, respectively, at which leakage exceeded 30,000 scfd past both seals.

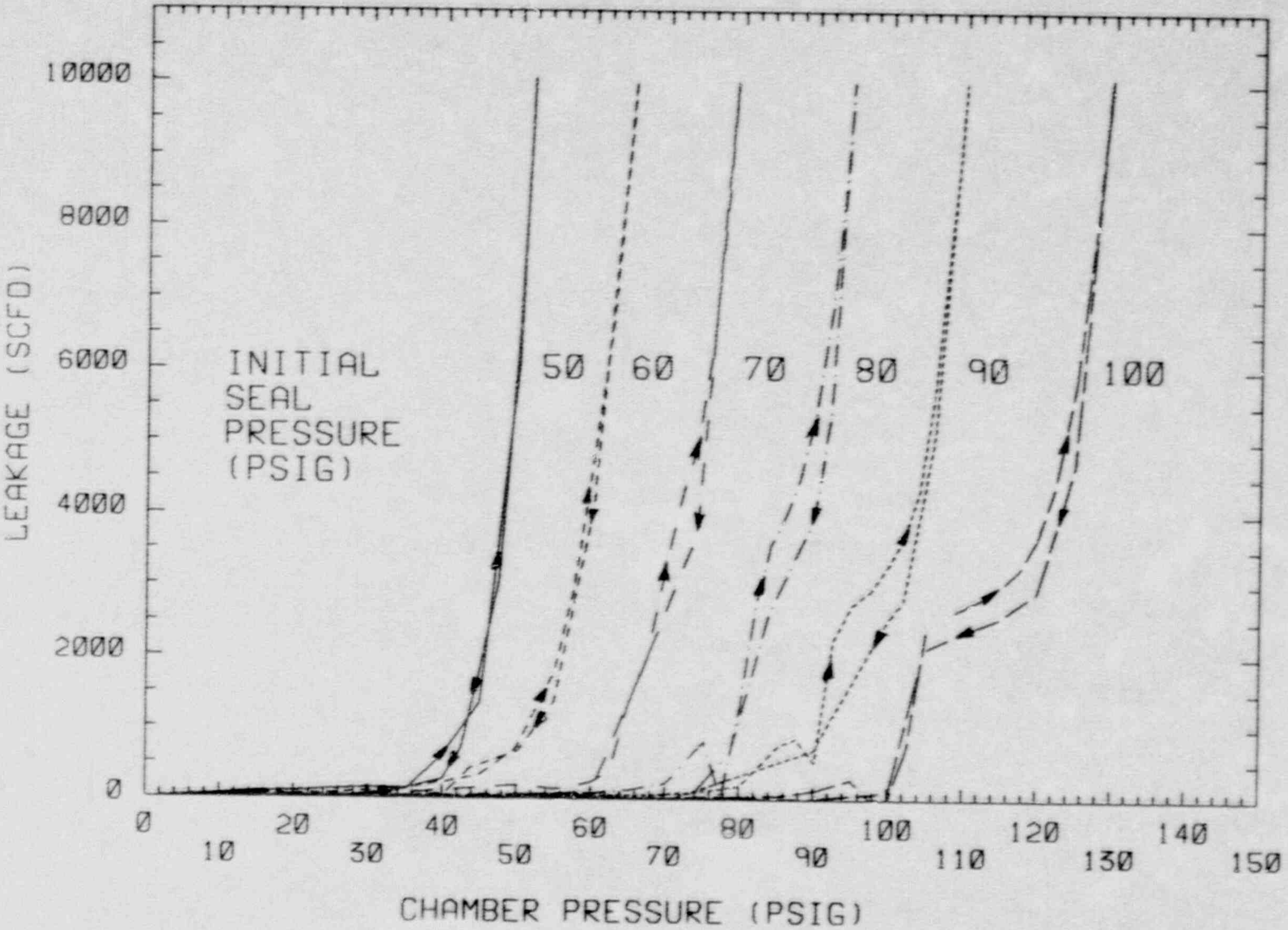

Figure 4.1. Leakage Vs. Chamber Pressure for Various Seal Pressure Levels
Test Series 1 - Seals Isolated From Pressure Source

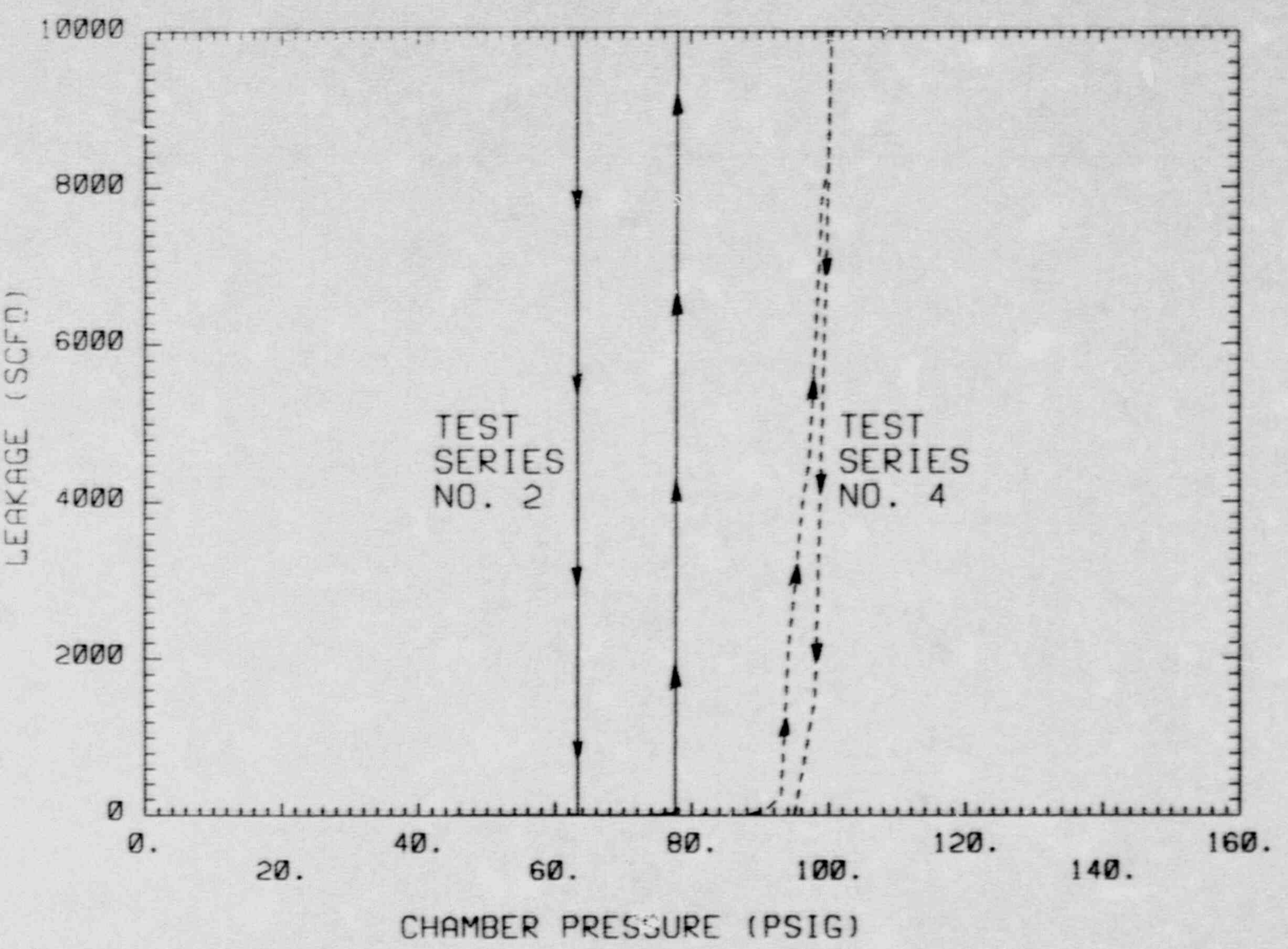

Figure 4.2. Leakage Vs. Chamber Pressure for Test Series 2 and 4
Seals Isolated From Pressure Source
60 Psig Initial Seal Pressure

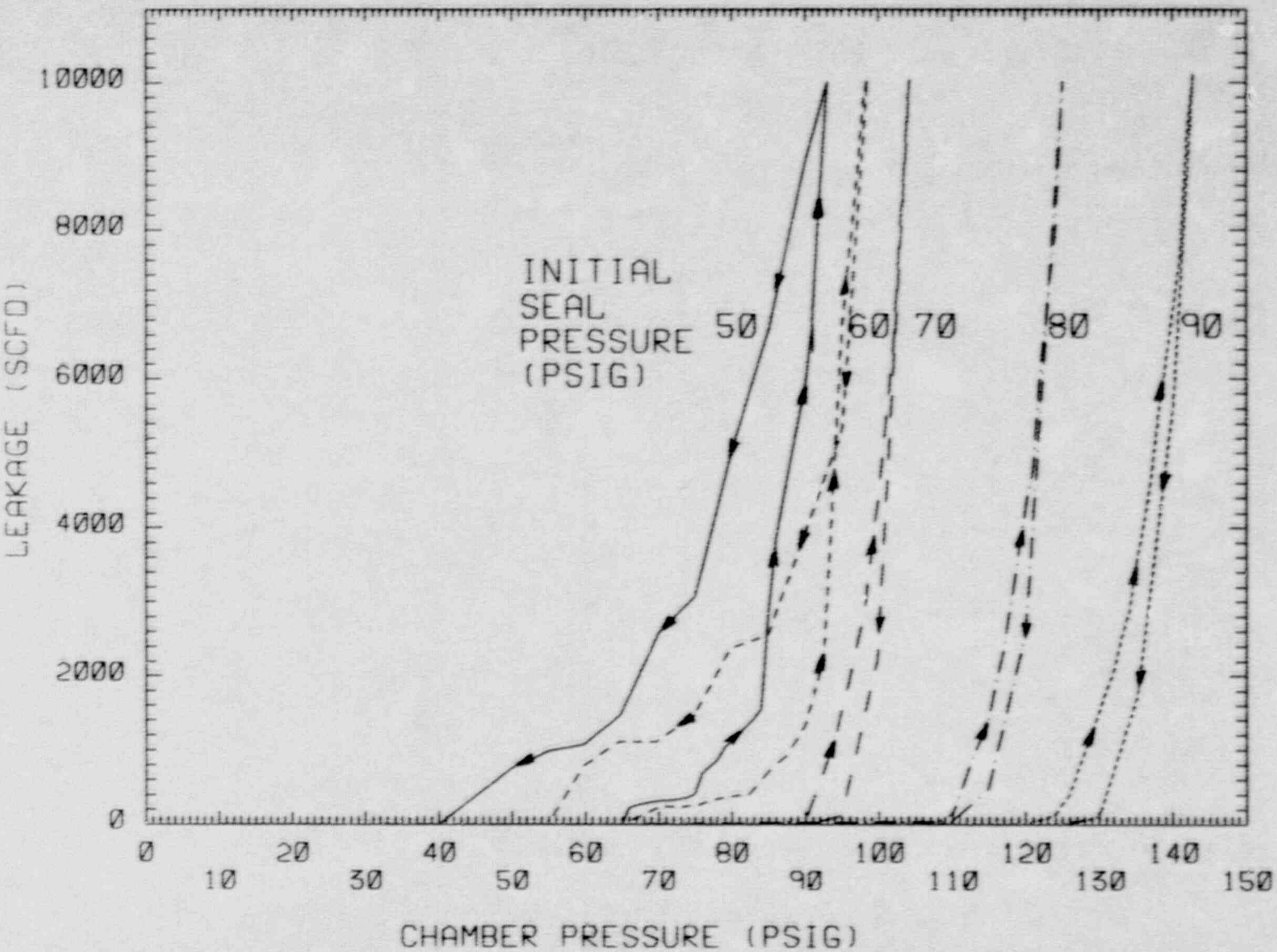

Figure 4.3. Leakage Vs. Chamber Pressure for Various Seal Pressure Levels
Test Series 3 - Round 1 - Seals Isolated From Pressure Source

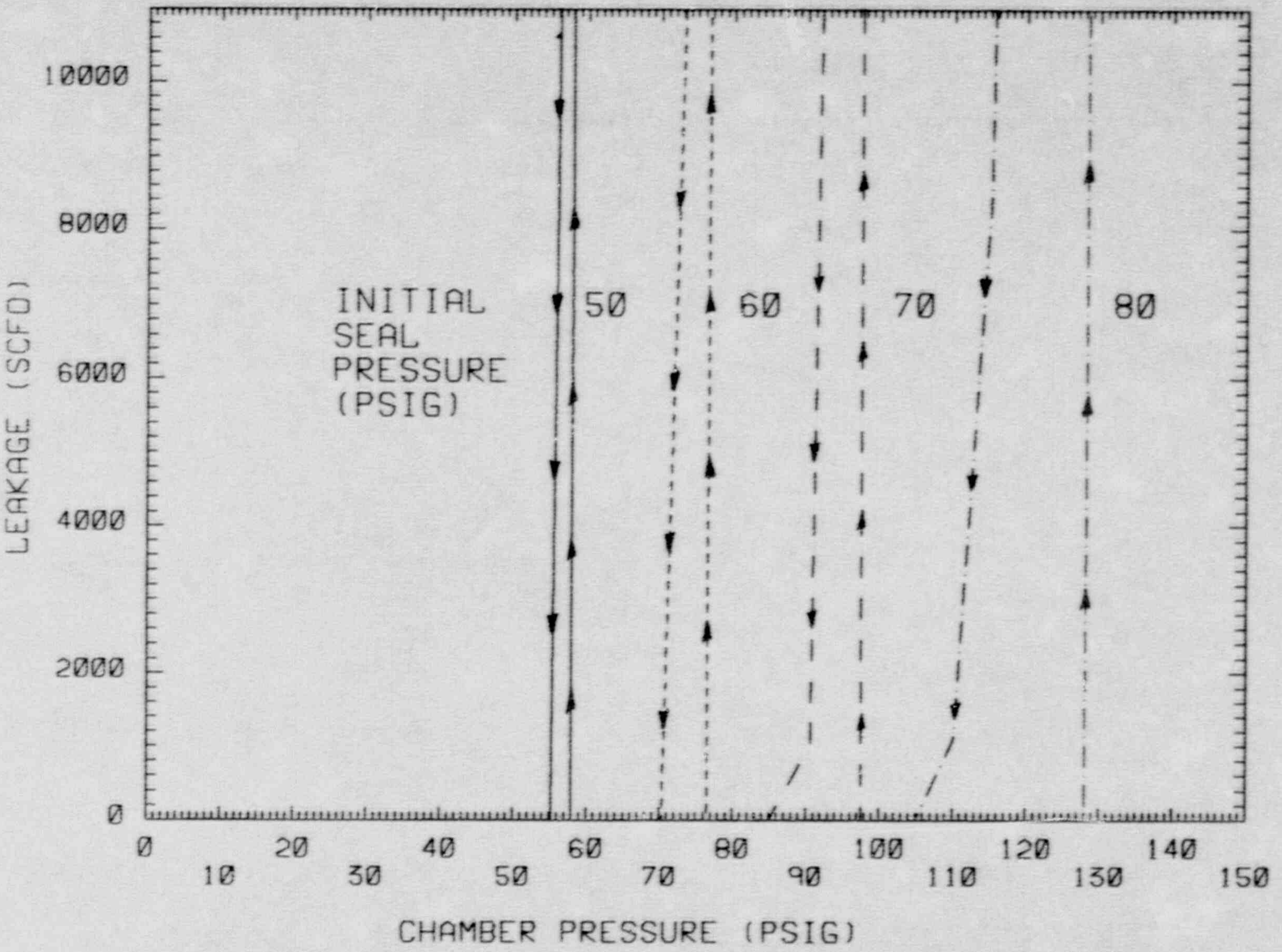

Figure 4.4 Leakage Vs. Chamber Pressure for Various Seal Pressure Levels
Test Series 3 - Round 2 - Seals Isolated From Pressure Source

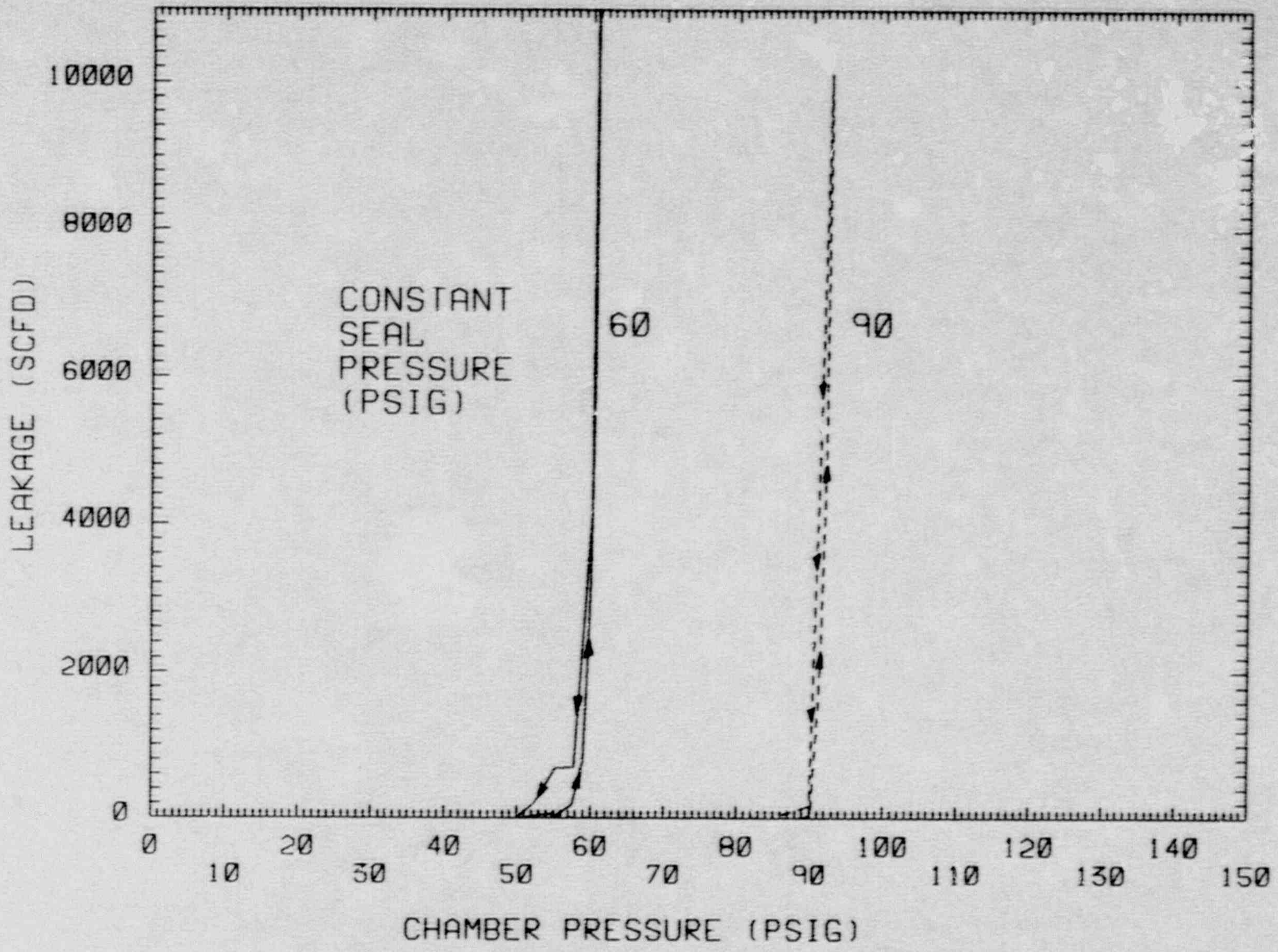

Figure 4.5 Leakage Vs. Chamber Pressure for Various Seal Pressure Levels
Test Series 3 - Round 1 - Constant Seal Pressure

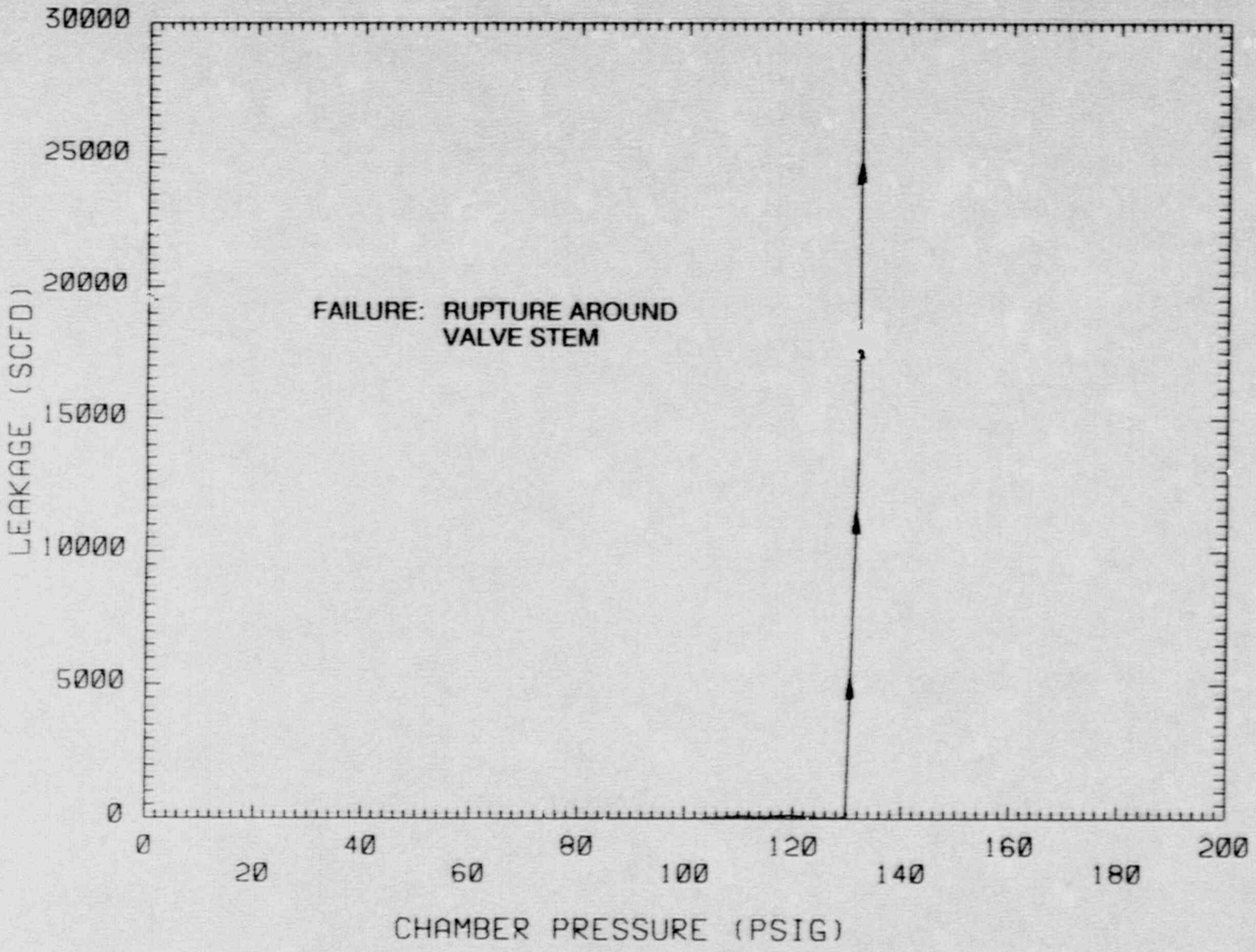

Figure 4.6. Measured Leakage Past Both Seals Vs. Chamber Pressure at 400°F Test Series 1

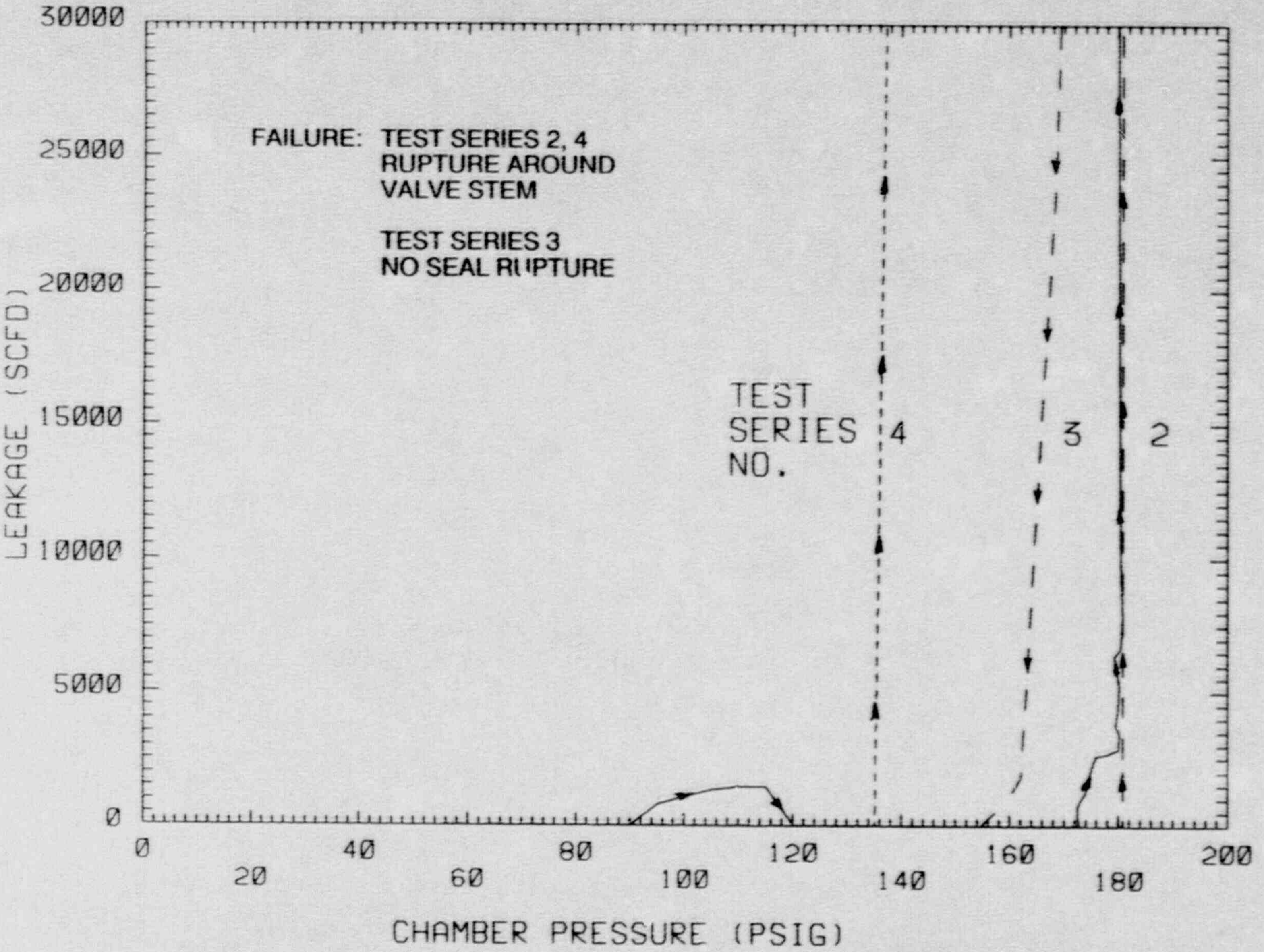

Figure 4.7 Measured Leakage Past Both Seals Vs. Chamber Pressure at 300°F
Test Series 2, 3, 4

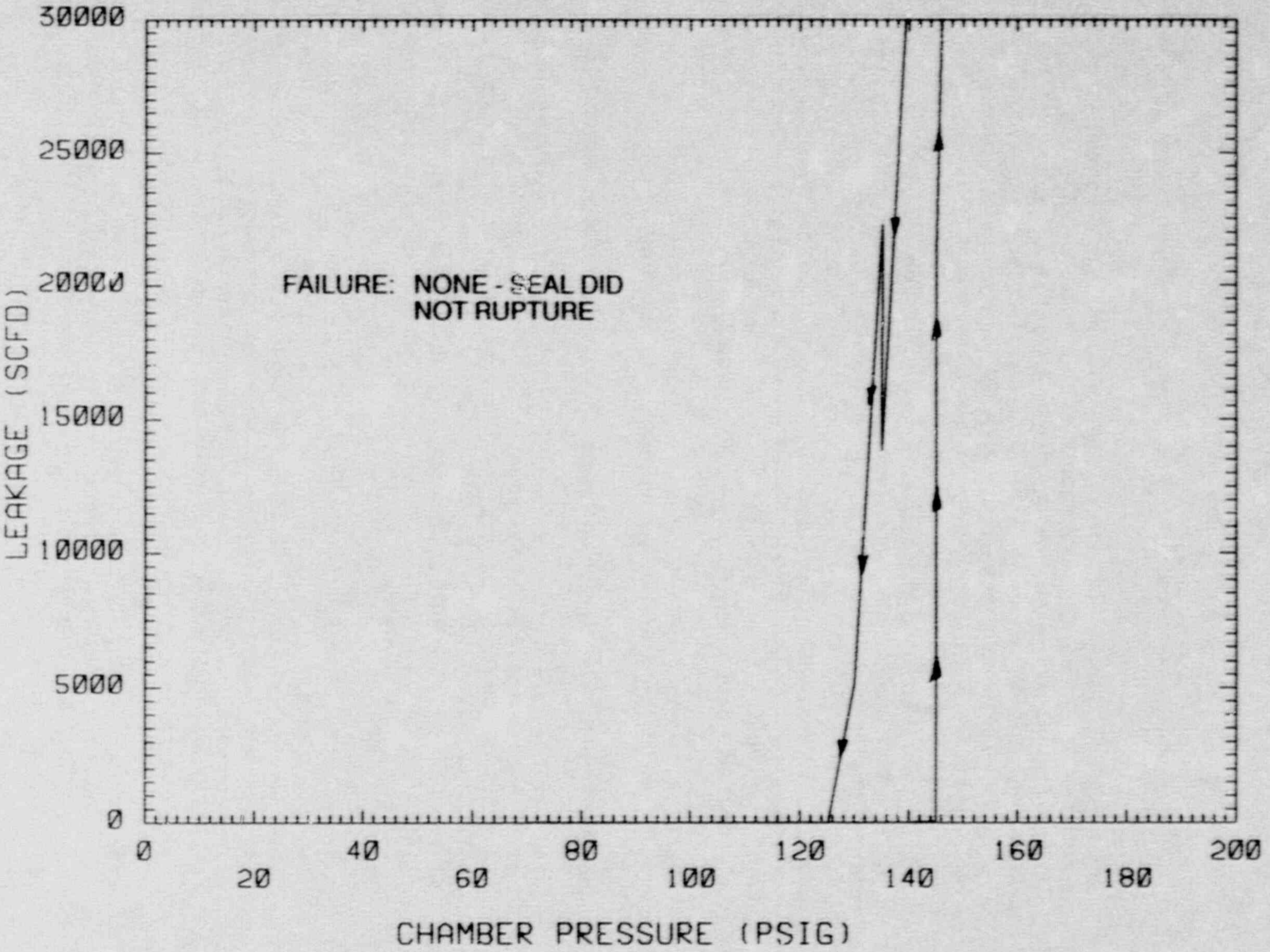

Figure 4.8 Measured Leakage Past Both Seals Vs. Chamber Pressure at 350°F
Test Series 3

5. ANALYSIS OF TEST RESULTS

5.1 Required Differential Between Chamber and Seal Pressures to Prevent Significant Leakage

Column (6) of Table 4.1 presents the measured difference, ΔP, between the chamber pressure, P_f, and the outer seal pressure, P_{os}, at the onset of significant leakage for the room temperature tests. Similar information for the elevated temperature tests is given in column (7) of Table 4.2. As shown, ΔP varies from -7.7 to +7.1 psi. When expressed as a percentage of P_{os}, $\Delta P/P_{os}$ varies from -5.4 to +7.6%. The test results show that, in most cases, significant leakage did not begin until the chamber pressure exceeded the seal pressure. In all cases, significant leakage did not occur until after the chamber pressure exceeded the <u>initial</u> seal pressure.

Thus, it appears that, even with the inflation valve (Figure 1.3) open, significant leakage should not begin until containment pressure reaches the normal operating seal pressure. If the seals are isolated from their pressure source by a closed valve near the valve stem, the chamber pressure required to cause significant leakage may be well above the initial seal pressure. Further discussion on the effect of chamber pressure on the seal pressure is provided in Section 5.5.2.

5.2 Comparison of Leakage Behavior for New and Old Seal Designs

As shown in Table 4.1 and Figures 4.1 through 4.4, the leakage behavior at room temperature of the new design seals was generally better than that of the old design. Figure 5.1 provides a direct comparison of the measured leakage behavior of the old and new seal designs at room temperature for an initial seal pressure of 60 psig. As shown, significant leakage began at considerably higher chamber pressures for the new design than for the old design.

Table 4.2 and Figures 4 through 4.8 summarize the results of the elevated temperature tests. Because of the sparsity of data and because of the scatter within the available test data, it is difficult to conclude which design is best at elevated temperature. Regardless of test temperature and initial seal pressure, significant leakage (≥10,000 scfd) did not occur for either seal design until the chamber pressure exceeded the initial seal pressure.

Based on the test results, it seems that, at room temperature, the new design seals exhibit considerably better leakage behavior than the old design. At elevated temperature, neither seal design is clearly superior to the other.

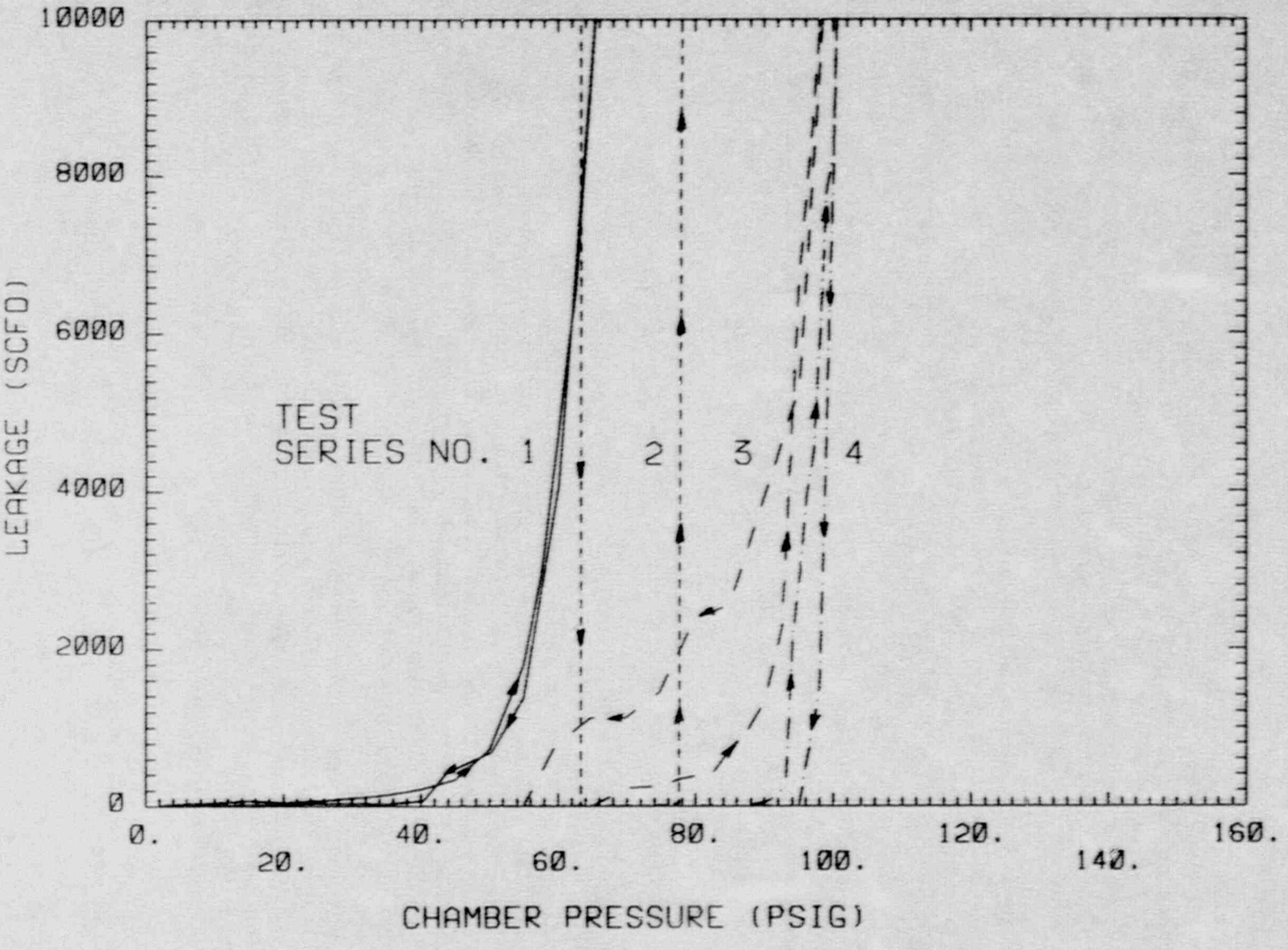

Figure 5.1 Comparison of Leakage at Room Temperature - Test Series 1, 2, 3, and 4 Seals Isolated From Pressure Source - 60 Psig Initial Seal Pressure

5.3 Comparison of Leakage Behavior for Aged and Unaged Inflatable Seals

As shown in Table 4.1, significant leakage (≥10,000 scfd) past both seals at room temperature, for a given seal pressure, began at higher chamber pressures for the aged seals than the unaged seals. The sealing surface of the aged seals was more tacky than the unaged seals which seemed to improve the leakage behavior of the aged seals. Figure 5.1 also compares the leakage behavior of the aged and unaged seals at room temperature for an initial seal pressure of 60 psig.

Table 4.2 provides a comparison of the leakage behavior of aged and unaged seals at elevated temperature. Again, because of the lack of extensive test data and considerable variation within the available test data, the effects of aging on leakage behavior at elevated temperature are difficult to quantify.

Considering the extreme amounts of radiation and thermal aging applied to the aged seals and the fact that there was not a noticeable degradation in the leakage behavior of the aged seals, it appears that radiation and thermal induced aging has no appreciable detrimental effect on the leakage behavior of inflatable seals.

5.4 Comparison of Leakage Behavior at Ambient and Elevated Temperatures

By comparing Tables 4.1 and 4.2 it can be seen that, for a given initial seal pressure, a larger chamber pressure was usually necessary to cause significant leakage at elevated temperature than at room temperature. The improved leakage behavior at elevated temperature is explained as follows. Because the seals were isolated from their pressure sources by closed valves during the elevated temperature tests, the volume of air inside the seals was essentially fixed. Thus, as the air temperature inside the seals increases the seal pressure also increases which enhances the seals capability to remain leaktight.

However, it should be noted that, at elevated temperature, significant leakage normally began as a result of a rupture in the seal tube; thus, it was impossible for the seals to reseal once the chamber pressure was reduced.[4] Figure 5.2 provides a comparison of the measured leakage behavior during Test Series 3 at room temperature, 300°F, and 350°F for an initial seal pressure of 90 psig.

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[4] Test series 3 was the only exception. For this test, the seals did not rupture during the 300°F test and thus, they were able to reseal upon reduction of chamber pressure. Because they were still intact, the chamber temperature was increased further to 350°F and another leakage test was performed. Although the seals also remained intact after this test, they ruptured, with virtually no chamber pressure applied, shortly after the temperature was increased to 400°F.

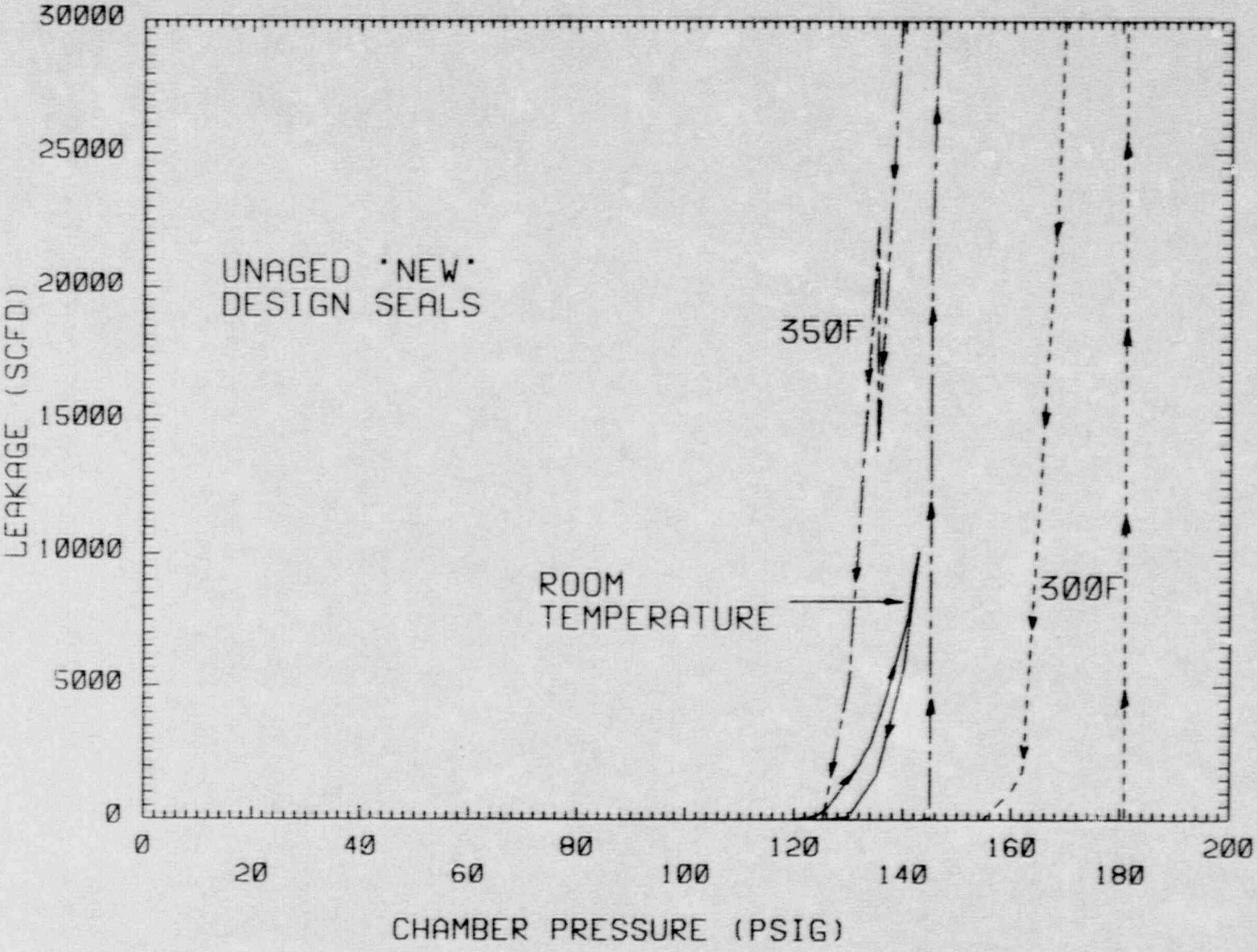

Figure 5.2 Comparison of Leakage Behavior at Room Temperature, 300°F, and 350°F
Test Series 3 - 90 Psig Initial Seal Pressure - Seals Isolated From Pressure

As shown through the above comparisons, the chamber pressure at which significant leakage began was generally higher at elevated temperature than at room temperature. However, as stated above, the risk of a seal rupture upon onset of leakage appears to be much greater at elevated temperature. The effect of elevated temperature on seal pressure is discussed in Section 5.5.1. Section 5.6 provides a complete description of the observed seal failure modes.

5.5 Effect of Elevated Temperature and External Pressure on Seal Pressure

Again, note that, if inflatable seals are isolated from their pressure source by closed valves, a fixed volume of air exists within the seal tube. As shown in Figure 1.4, the seal tube is constructed of EPDM material reinforced with Kevlar. The resulting composite material is relatively flexible in bending but fairly "stiff" against elongation. Thus, the seal tube acts as an approximate fixed volume as the air temperature increases which causes a corresponding increase in the internal seal pressure. Because the bending stiffness of the composite seal material is relatively small, increasing the external pressure applied to the seals produces an increase in the internal seal pressure.

If the inflation valve is open, the seal pressure may still increase due to increasing containment temperatures given the following assumptions: 1) the check valve (Figure 1.3) is closed as a result of a loss of the instrument air supply system, and 2) the air temperature inside the accumulator tank and seal increases as a result of heating the containment atmosphere. (The accumulator tanks are attached to the inner side of each airlock door such that they are subjected to approximately the same temperature conditions as the inflatable seals.)

5.5.1 Effect of Elevated Temperature on Seal Pressure

Table 5.1 provides a listing of the actual seal temperature and pressure before heating the test chamber [columns (3) and (4)] and also after the desired test chamber temperature was obtained [columns (5) and (6)]. Assuming that the seal tube acts as a rigid, fixed volume, the increase in seal pressure due to increasing temperature can be estimated using the ideal gas law. The estimated seal pressure based on the ideal gas law is given in column (7) of Table 5.1 for each seal. Column (8) provides a comparison of the predicted-to-measured seal pressures. As shown, the ideal gas law provides a good estimate of the seal pressure increase due to temperature. Figure 5.3 shows the measured seal pressure vs. seal temperature for test series 1. Note that for test series 1 the seal pressure increased linearly with increasing seal temperature up until about 300°F. Between 300°F and 400°F the increase in seal pressure for a given increase in temperature became considerably less indicating that the seal volume may have actually been increasing in this temperature range due to stretching of the seal tube.

Table 5.1 Comparison of Predicted-to-Actual Seal Pressure Increase Caused by Increasing Seal Temperature

Test Series Number	Location of Seal	Initial Seal Temp. (°F) (3)	Initial Seal Pressure (psig) (4)	Elevated Seal Temp. (°F) (5)	Seal Pressure at Temp. (psig) (6)	Predicted* Seal Pressure (psig) (7)	(7)/(6) (8)
1	Inner	70.4	90.2	389.9	128.2	151.9	1.18
	Outer	70.4	60.0	389.9	104.3	103.5	0.99
2	Inner	78.3	89.9	285.8	127.6	129.3	1.01
	Outer	77.8	90.2	307.0	129.7	133.8	1.03
3	Inner	80.6	90.0	299.2	134.9	131.3	0.97
	Outer	80.4	90.0	299.6	134.2	131.5	0.98
4	Inner	88.3	89.7	297.7	126.6	128.6	1.02
	Outer	88.6	89.8	305.3	126.6	130.1	1.03
						Average	1.03
						Std. Dev.	0.066

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* The ideal gas law was used, assuming constant volume, to compute the predicted seal pressure at the measured seal temperature shown in column (5). Atmospheric pressure at Sandia is assumed to be [illegible].2 psia for these calculations.

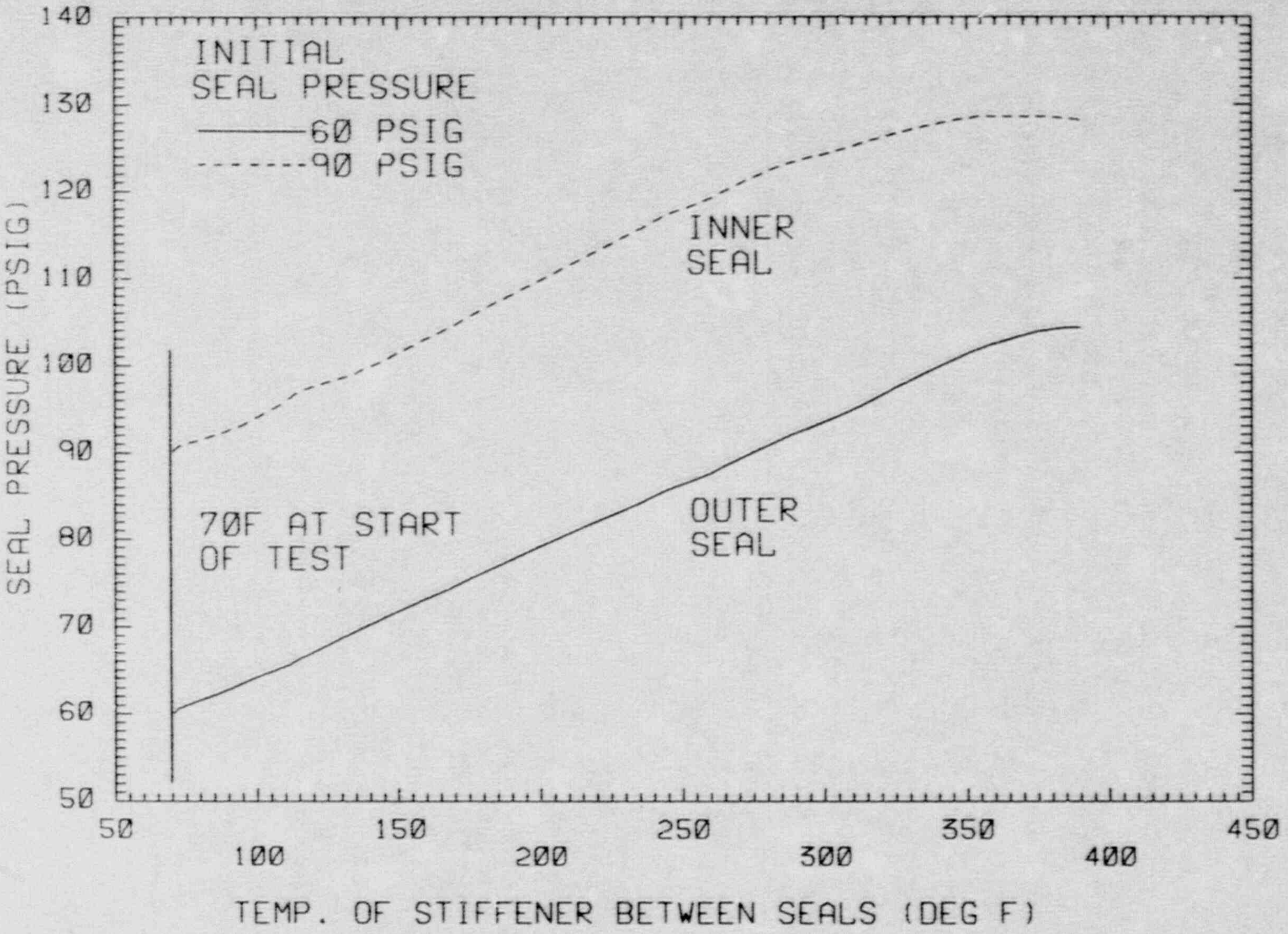

Figure 5.3 Measured Seal Pressure and Temperature During Heatup Test Series 1

5.5.2 Effect of External Pressure on Seal Pressure

For the tests that were performed with the seals isolated from their pressure source by a closed valve, the internal seal pressure increased as a result of increasing external pressure. The internal seal pressure is plotted vs. chamber pressure in Figure 5.4 for an initial seal pressure of 90 psig for test series 3 at room temperature.

As a result of the increasing seal pressure due to chamber pressure, the chamber pressure required to produce significant leakage past both seals, P_f, also increased to levels beyond the initial seal pressure, P_i. Column (6) of Table 5.2 presents the observed ratios of P_f/P_i for all room temperature tests. As shown, in most cases, there is a noticeable increasing trend in the value of P_f/P_i as P_i increases.[5]

For the old design seals in test series 1, P_f was approximately equal to P_i for $P_i = 50$ psig. However, as P_i increased, P_f/P_i also increased. For $P_i = 100$ psig, the measured value of P_f was 129.6 psig. Because the ratio of P_f/P_i increased approximately linearly from $P_i = 50$ psig to $P_i = 100$ psig, the following expression was developed to predict the chamber pressure at failure, P_c:

$$P_c = P_i(0.006P_i+0.70) \qquad (5.1)$$

Similarly, for the new design seals, a prediction equation has been developed which assumes $P_f/P_i = 1.20$ for $P_i = 50$ psig and $P_f/P_i = 1.70$ for $P_i = 100$ psig. This equation may be written as:

$$P_c = P_i(0.010P_i+0.70) \qquad (5.2)$$

For the tests that were conducted while maintaining a constant seal pressure (denoted as 60C and 90C for Test Series 3 - Round 1), the chamber pressure at failure, P_f, was approximately equal to the initial seal pressure, P_i. Thus, if the air supply system is such that the seal pressure is not significantly affected by increasing containment pressure, P_f may be simply estimated as:

$$P_c = P_i \qquad (5.3)$$

The above equations are incorporated into the overall prediction method outlined in Section 6.

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[5] Round 1 of Test Series 3 was the only exception. For some unexplained reason, the failure pressure for the 50, 60, and 70 psig initial seal pressure levels was inordinately high. As shown in Table 5.2, the failure pressures for the second round of tests for the same pair of seals were more consistent with the results of the other test series.

Table 5.2 Comparison of Chamber Pressure at Failure to Initial Seal Pressure - Room Temperature Tests

Test Series Number	Initial Seal Pressure, P_i (psig) (2)	Maximum* Inner Seal Pressure, P_{is} (psig) (3)	Maximum* Outer Seal Pressure, P_{os} (psig) (4)	Chamber* Pressure At Failure, P_f (psig) (5)	P_f/P_i (5)/(2) (%) (6)
1	50 (1st Test)	58.7	54.0	51.1	1.02
	60	72.6	66.6	65.4	1.09
	70	85.6	78.8	79.0	1.13
	80	101.2	92.9	94.8	1.19
	90	115.9	106.9	109.9	1.22
	100	135.0	124.6	129.6	1.30
	50 (2nd Test)	59.2	54.2	51.7	1.03
2	60 (1st Test)	78.9	74.7	79.0	1.32
	60 (2nd Test)	76.2	72.2	76.3	1.27
3 Round 1:	50 (1st Test)	94.9	92.0	93.0	1.86
	60	100.7	96.3	98.5	1.64
	60C**	60.0	60.0	60.8	1.01
	70	106.6	101.3	104.3	1.49
	80	127.2	121.2	125.1	1.56
	90	144.8	138.3	142.8	1.59
	90C**	90.0	90.1	92.6	1.03
	50 (2nd Test)	69.9	66.9	67.0	1.34
3 Round 2:	50 (1st Test)	61.8	60.3	58.2	1.16
	60	80.0	77.4	76.9	1.28
	70	100.1	96.3	97.4	1.39
	80	127.3	----	129.1	1.61
	50 (2nd Test)	62.4	60.5	58.9	1.18
4	60 (1st Test)	99.4	93.4	100.5	1.68
	60 (2nd Test)	99.9	94.0	101.0	1.68

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*Seal and Chamber pressures, respectively, at which leakage exceeded 10,000 scfd past both seals.

Initial seal pressure, P_i = nominal seal pressure in both seals at ambient Temperature before increasing pressure and temperature in test chamber.

**Seal pressure maintained constant throughout test.

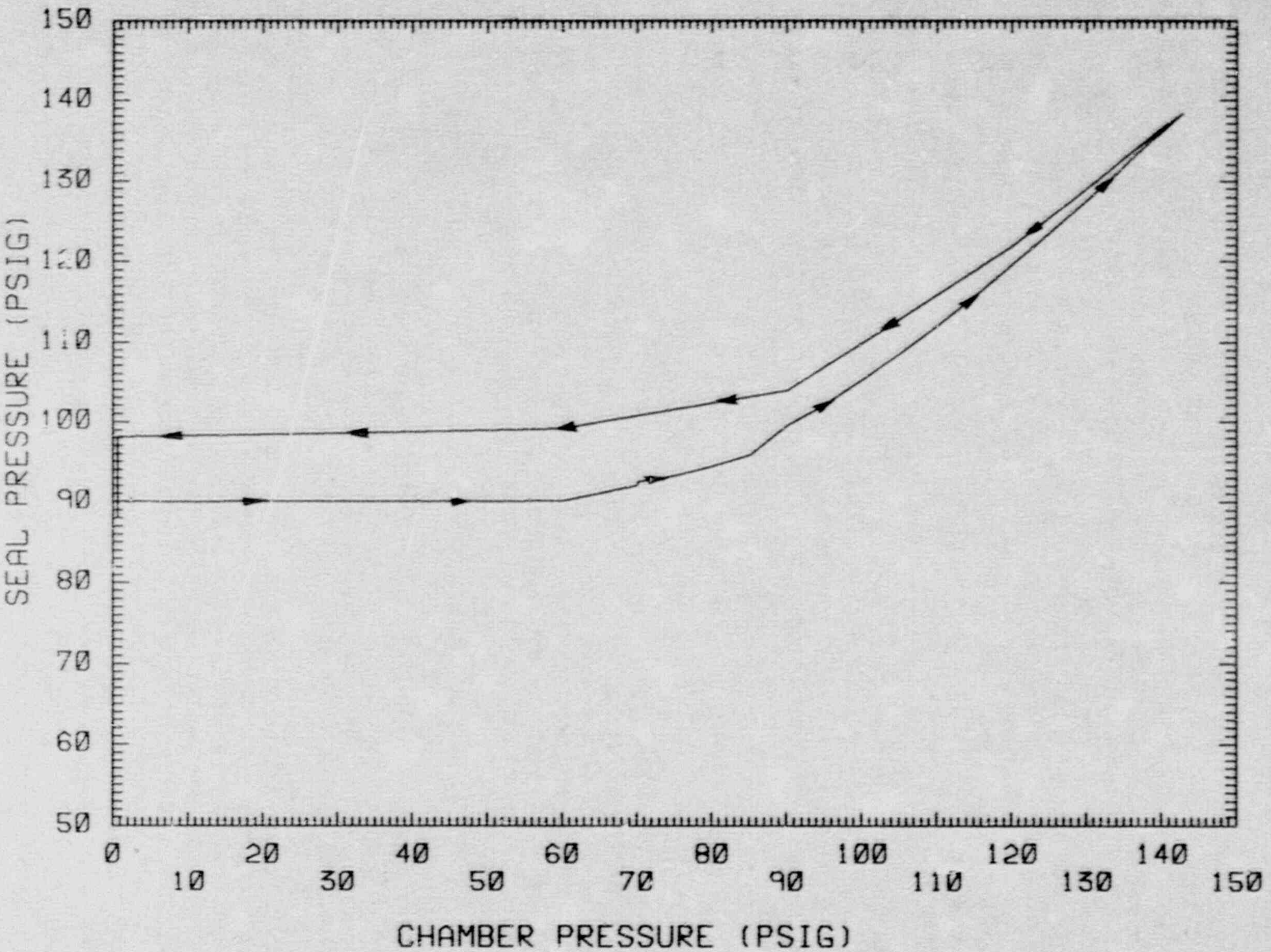

Figure 5.4 Internal Pressure in Outer Seal vs. Chamber Pressure - Test Series 3
90 Psig Initial Seal Pressure - Seals Isolated From Pressure Source

5.5.3 Effect of Isolating Seals From Their Pressure Source

As mentioned in Section 5.5.2, the chamber pressure at which significant leakage began, for a given initial seal pressure, was considerably higher for the seals that were isolated from their pressure source than for those seals that were held at a constant internal pressure. The effect of isolating inflatable seals from their pressure source on the chamber pressure required to cause leakage can be clearly seen in Figure 5.5 for the 60 psig initial seal pressure tests during test series 3. Similar data is shown in Figure 5.6 for an initial seal pressure of 90 psig. As shown, because the seal pressure increased for the seals that were isolated from their pressure source, leakage began at higher chamber pressures than for those tests in which the seal pressure was maintained constant.

It is also interesting to note the difference in the growth of leakage as the chamber pressure is increased. As shown in Figures 5.5 and 5.6, once leakage began for the constant seal pressure tests, leakage increased much more rapidly for a given increase in chamber pressure than for the seals that were isolated from their pressure source.

5.6 Failure Modes of Inflatable Seals

As previously mentioned, the onset of significant leakage occurred as a result of ruptures in the seals for the elevated temperature portions of test series 1, 2, and 4. As explained in the footnote in Section 5.4, the seals in test series 3 remained intact after leakage tests at 300°F and 350°F, but then ruptured at 400°F with virtually no chamber pressure applied. All testing at room temperature ended when leakage past both seals exceeded 10,000 scfd with no apparent damage to the seals.

The typical failure mode at elevated temperature occurred as a longitudinal tear of the seal tube in the vicinity of the valve stem as shown in Figure 5.7. The cause of these tears seems to be a combination of the internal pressure within the seals, the relatively large "side" pressure on the seal tube, and the high degree of restraint of the seal tube near the valve stem.[6]

Just before failure, the pressure between the seals was typically the same (within 0.5 psi) as the chamber pressure. Obviously the pressure on the outer side of the outer seal was atmospheric (0 psig). Thus, the outer seal was always subjected to the largest differential pressure which caused the outer seal to rupture before the inner seal. Posttest inspection revealed that, after failure, a pathway existed from the valve stem opening in the test fixture, through the outer seal, and into the test fixture (Figure 5.8). Thus, after the outer seal failed,

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[6] As discussed in Section 3.3, in order to prevent leakage around the valve stem opening, the seal is drawn in into close contact with the door in this region by tightening a nut on the valve stem. The method used to model the actual restraining conditions on the valve stems in airlock doors is shown in Figure 3.7.

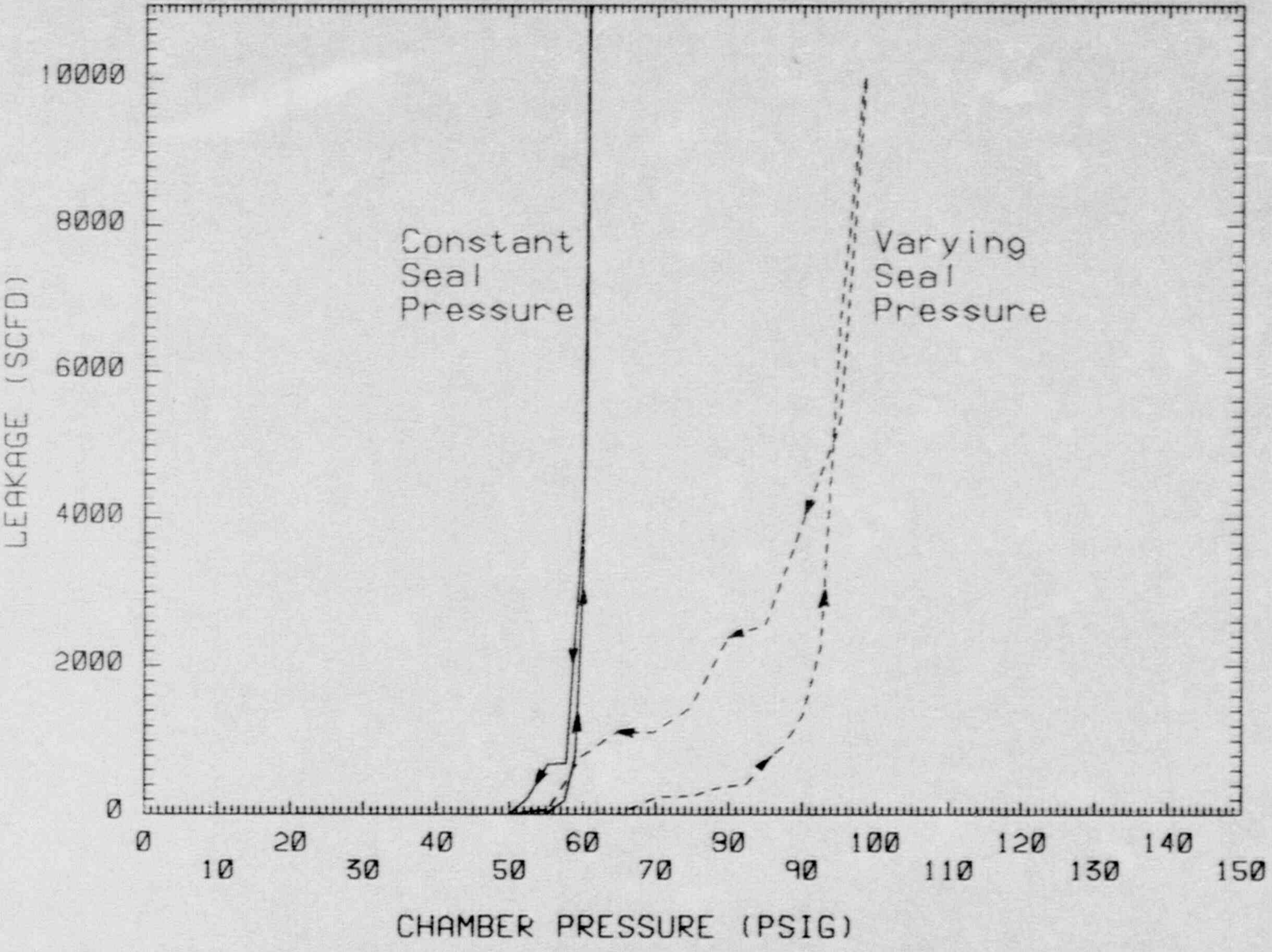

Figure 5.5 Comparison of Leakage Behavior for Seals Isolated From Pressure Source and for Constant Seal Pressure - Test Series 3 - 60 Psig Initial Seal Pressure

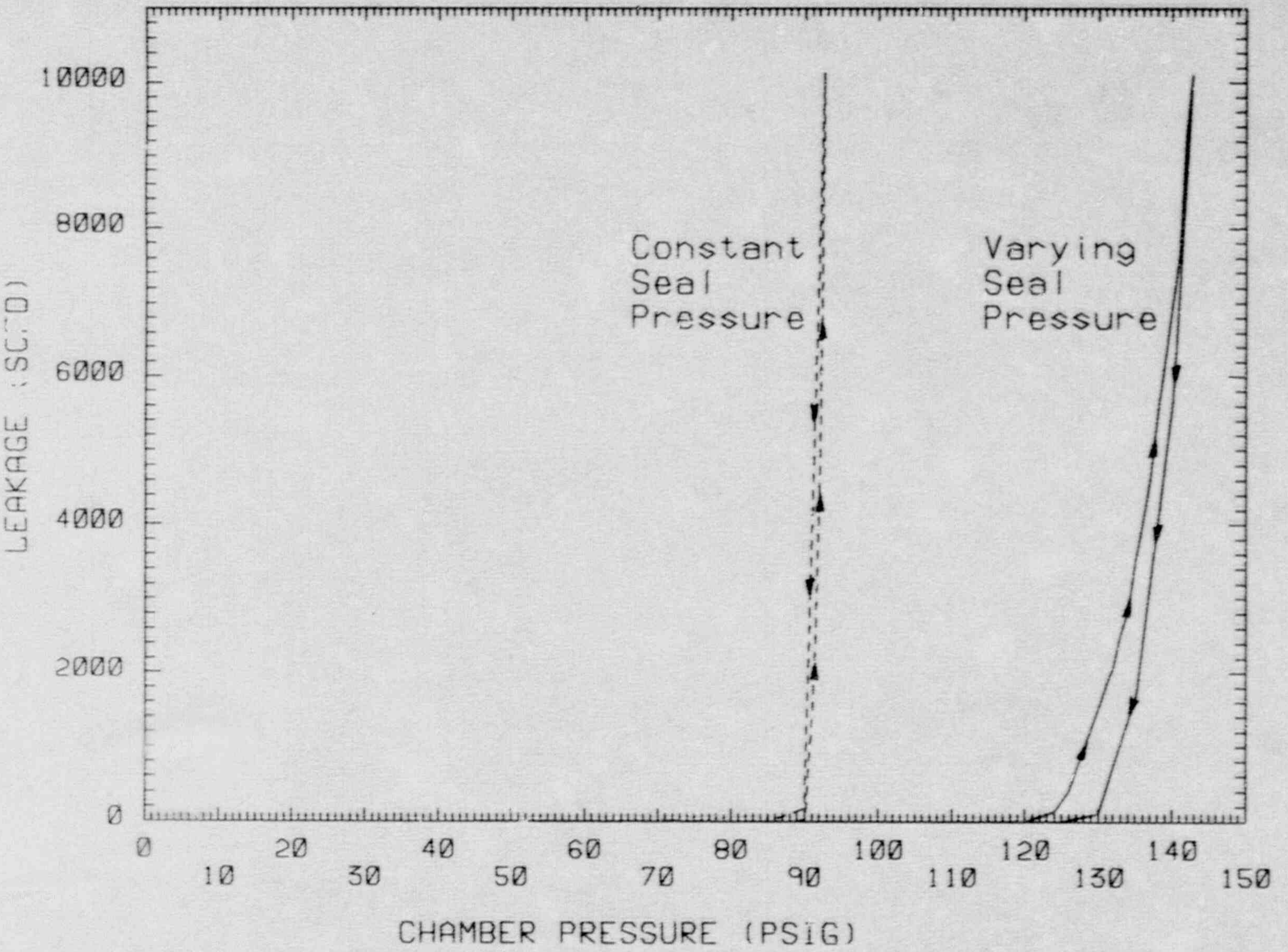

Figure 5.6 Comparison of Leakage Behavior for Seals Isolated From Pressure Source and for Constant Seal Pressure - Test Series 3 - 90 Psig Initial Seal Pressure

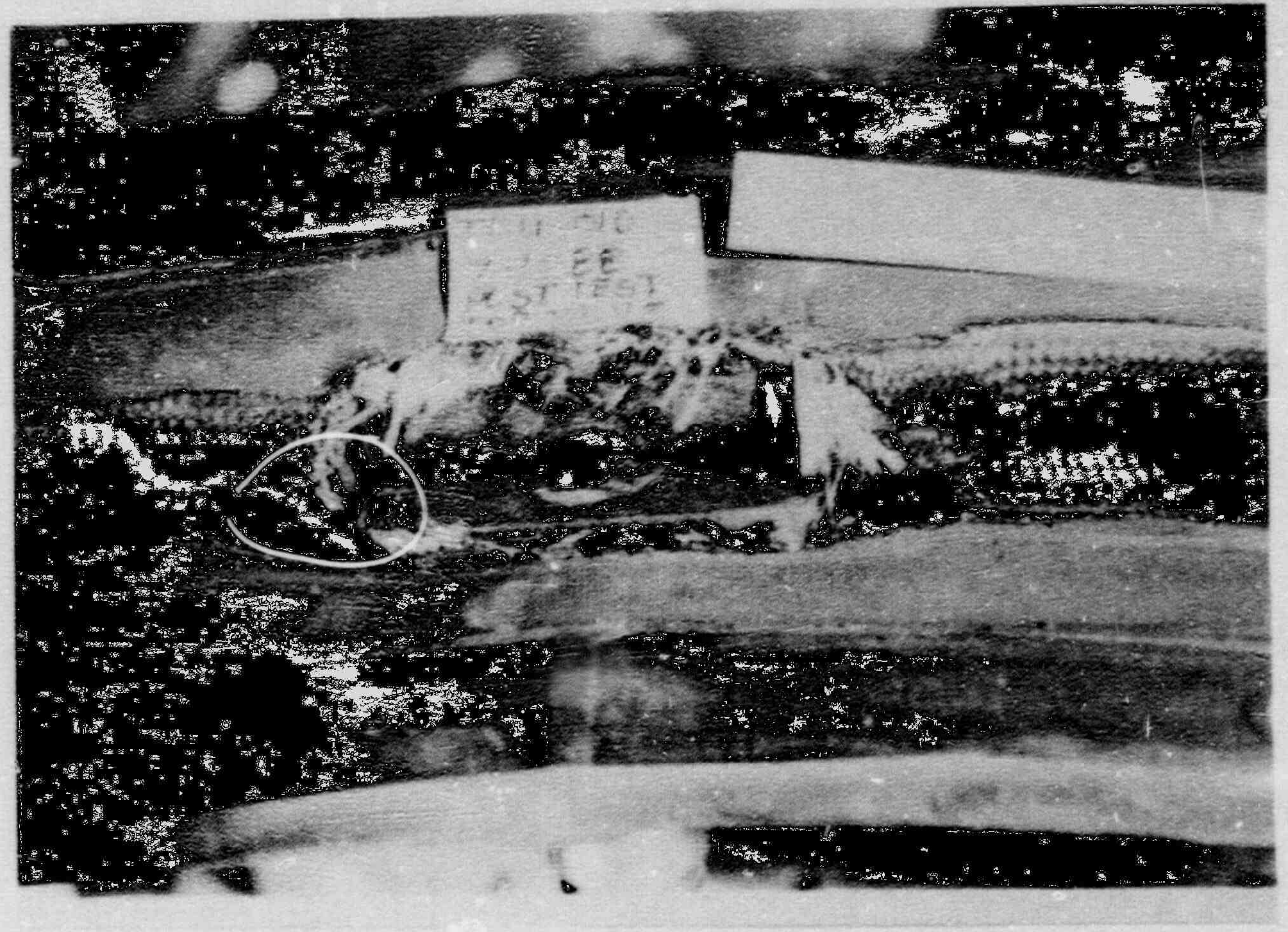

Figure 5.7 Typical Failure of Outer Seal Caused By a Rupture of the Seal Tube Near the Valve Stem

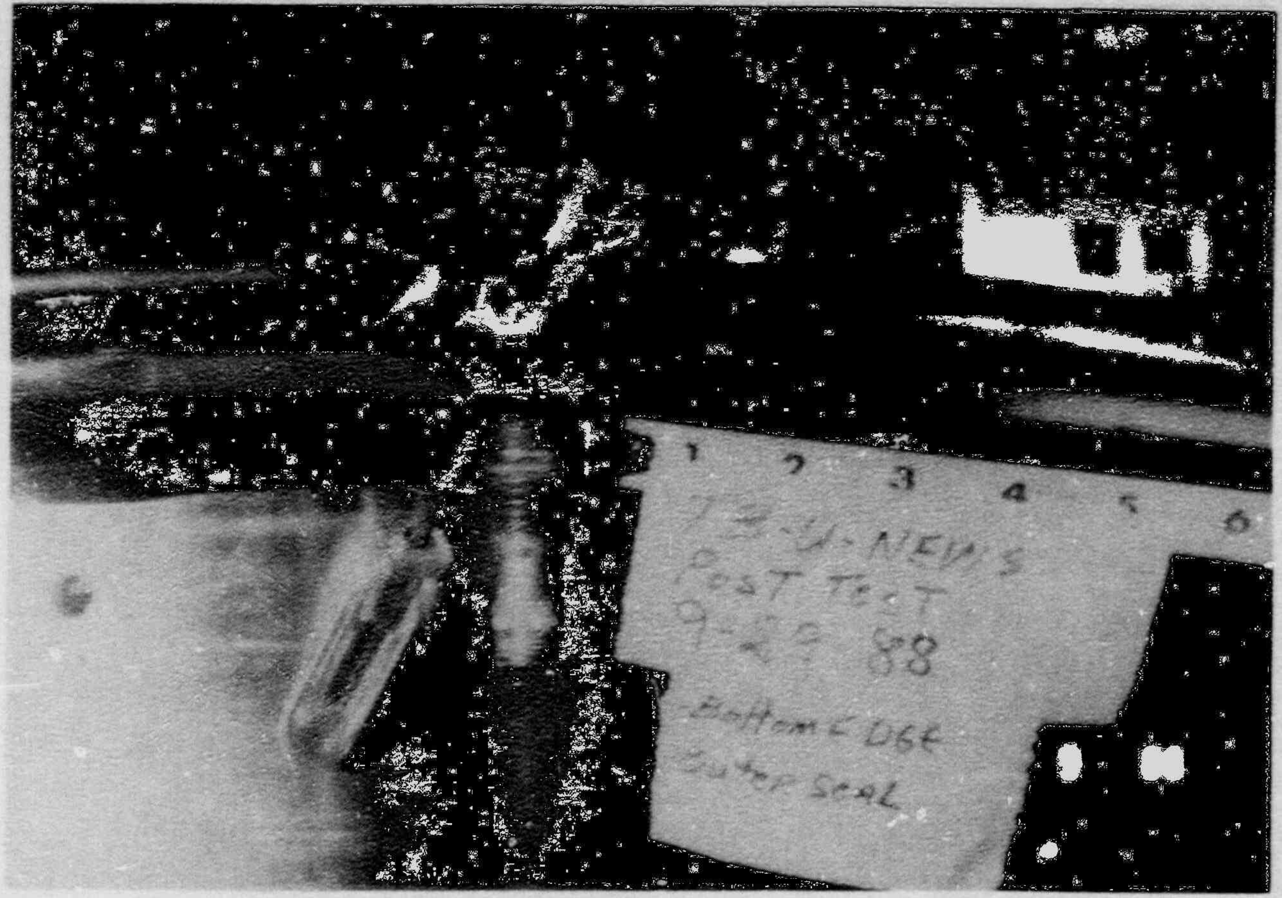

Figure 5.8 Typical Pathway for Leakage Around Valve Stem After Seal Rupture

leakage could enter the test fixture through the valve stem opening--effectively bypassing the inner seal. Because the magnitude of this extraneous leakage was such that the failure pressure level could not be maintained or increased further, the tests were typically ended at this point. However, if the chamber pressure could have been held at the failure level or increased slightly, failure of the inner seal would have likely occurred in the same mode as the outer seal at approximately the same chamber pressure.

The relatively large lateral force caused by the chamber pressure on the outer seal also produced a longitudinal tear, in some cases, between the outer seal tube and its inner flange. Typical tears of this nature are shown in Figures 5.9 and 5.10. Also, inspection of the new design seals revealed that the added layer of EPDM (Figure 1.4(c)) had delaminated from the seal tube along the outer edge in some cases as shown in Figure 5.11. Although the seal damage illustrated in Figures 5.9 through 5.11 show definite signs of distress, this type of damage is not believed to have been the direct cause of rupture of the seals. In most cases, the primary cause of seal rupture was a tear in the seal tube near the valve stem.

Posttest inspection of the seals also revealed that there was no apparent degradation in the EPDM material for test temperatures up to 350°F. However, for test series 1, which was tested at 400°F, the outer layer of EPDM seemed to have degraded slightly as evidenced by its nonuniform thickness and shiny appearance. Also, an oily residue was observed coming out of the flowmeter gallery after failure of the seals. No such residue was noticed during the other tests at up to 350°F. Further evidence that seal decomposition began around 400°F was that EPDM material was found bonded to the sealing surface of the test fixture for test series 1 only. Also, as discussed in Section 5.5.1, the volume of the seal tube appeared to be increasing as the temperature was increased from ≈ 350°F to 400°F during heatup for test series 1.[7] Based on these observations, it appears that appreciable deterioration of the seals begins between 350°F and 400°F. Therefore, caution should be exercised when using the seals in environments that might experience temperatures in excess of 350°F.

5.7 Resealing Capability of Inflatable Seals

As shown in Figures 4.1 through 4.5, after significant leakage was measured past both seals, the seals resealed upon reduction in the chamber pressure at room temperature. However, because the seals ruptured at elevated temperature in test series 1, 2, and 4, they obviously could not reseal as the chamber pressure was reduced. As previously described, all of the elevated temperature tests were conducted with the seals isolated from their pressure source. Thus, the internal seal pressure increased as a result of increasing chamber pressure and temperature.

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[7] An increase in the seal volume seems to indicate that the Kevlar reinforcement was actually slipping with respect to the adjacent EPDM material.

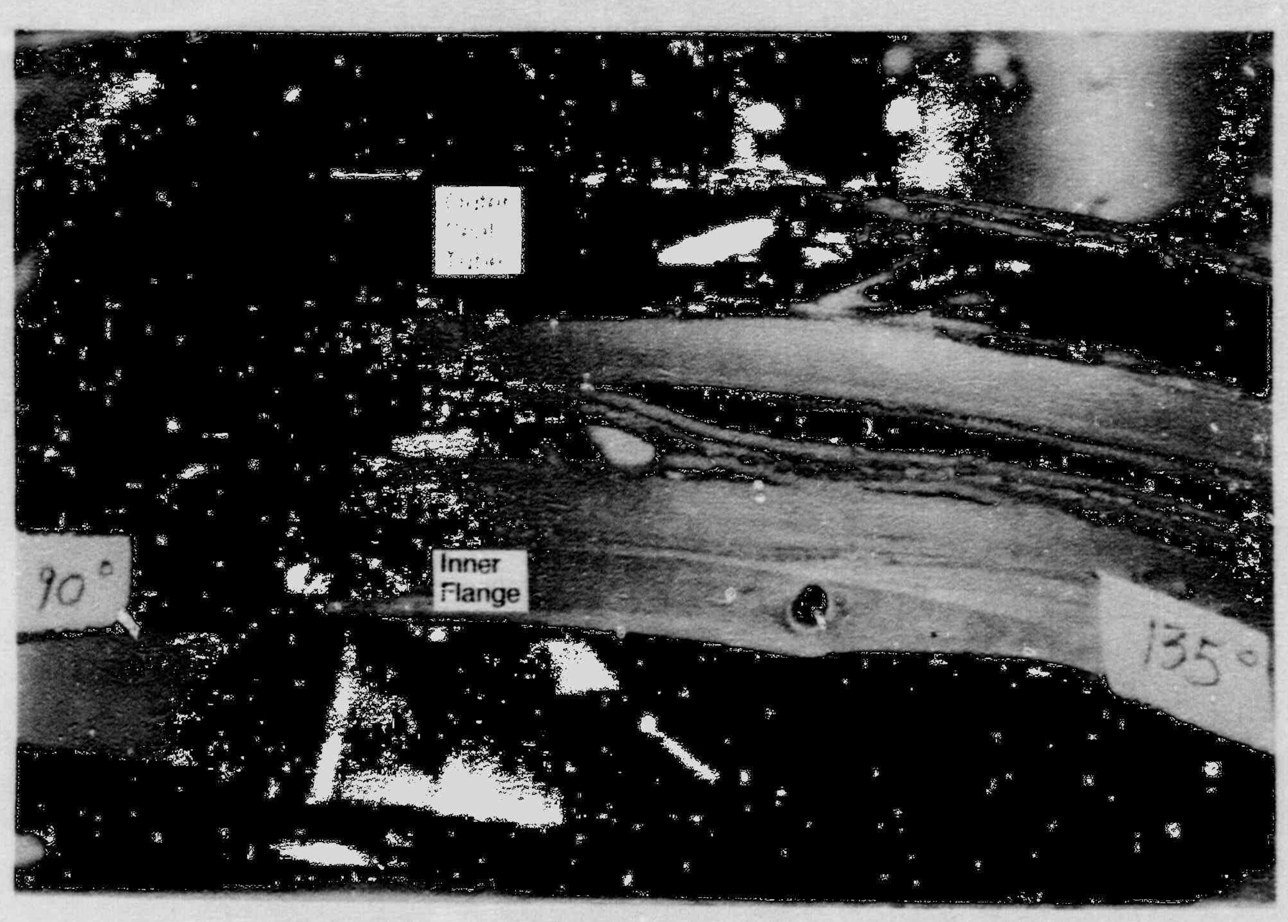

Figure 5.9 Typical Tear Between Outer Seal Tube and Its Inner Flange Test Series 1

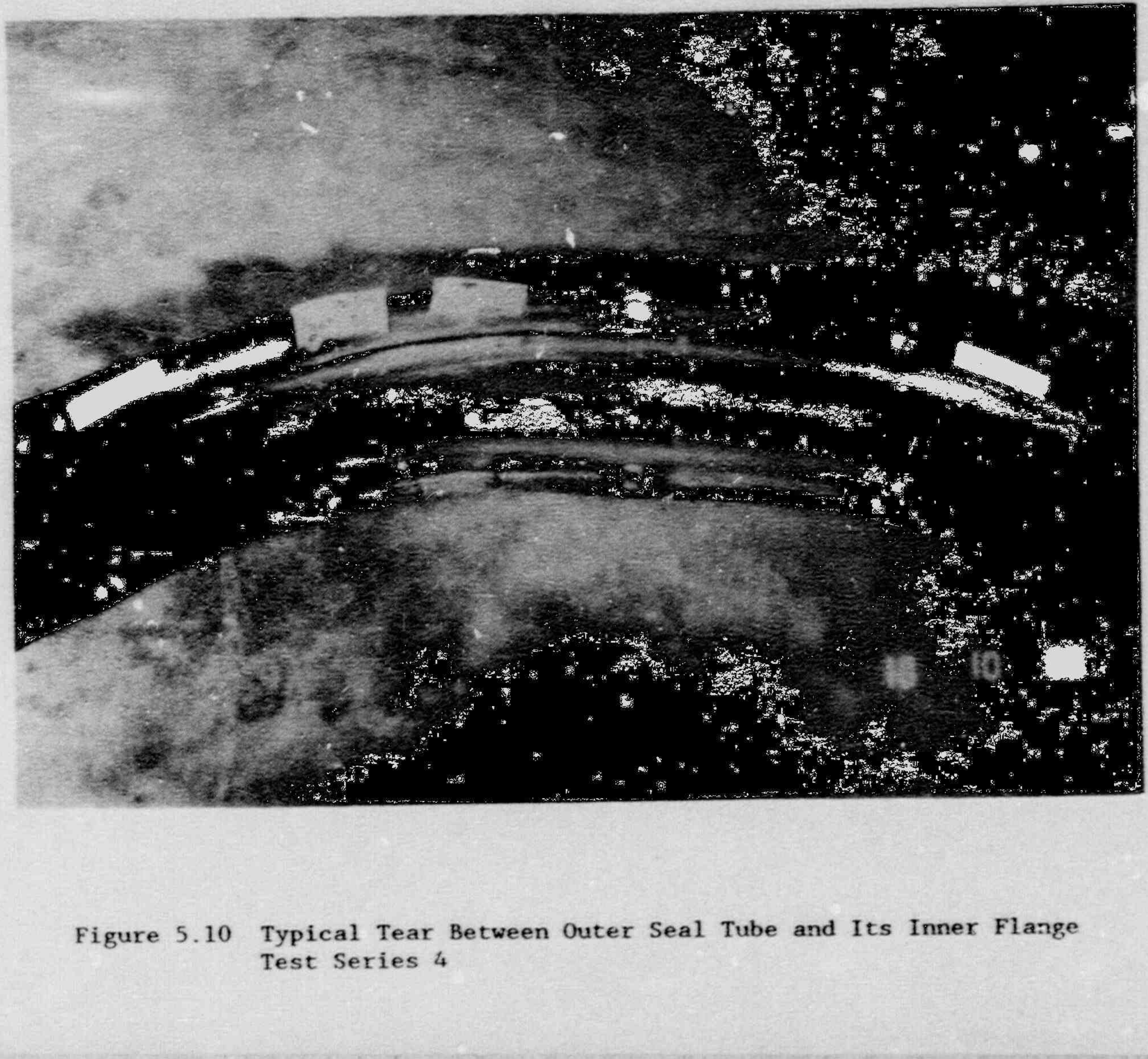

Figure 5.10 Typical Tear Between Outer Seal Tube and Its Inner Flange
Test Series 4

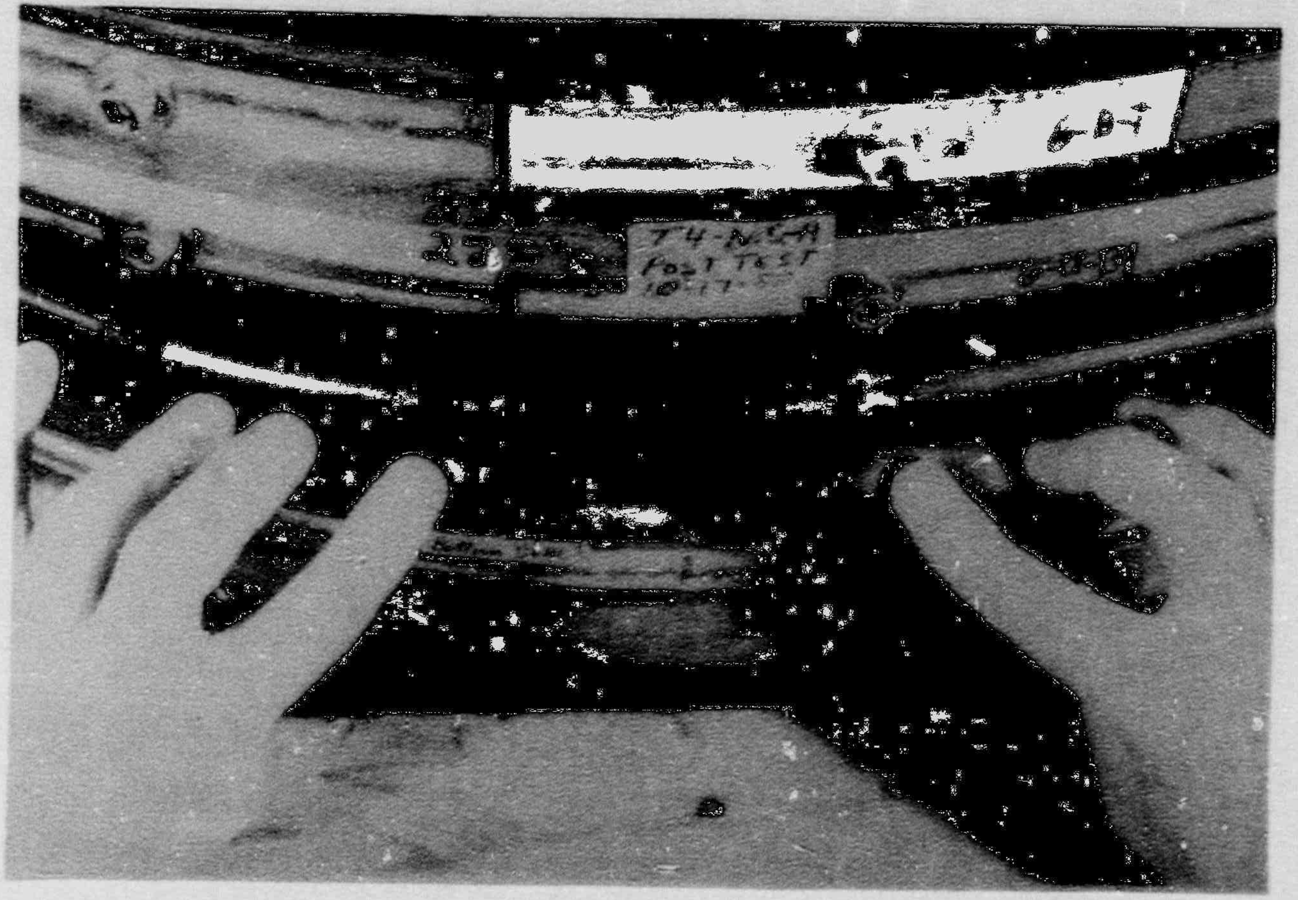

Figure 5.11 Delamination of Added Layer of EPDM Material Along Outer Edge of Inner Seal - Test Series 4

If the seal pressure was only affected by temperature and not by external pressure as would occur if the inflation valve (Figure 1.3) is open, it seems likely that, for temperatures up to 350°F, the seals would not have ruptured. For temperatures significantly in excess of 350°F, it is difficult to form a conclusion on the likely seal failure mode.

6. LEAKAGE PREDICTION METHODS FOR INFLATABLE SEALS

6.1 Presentation of Prediction Equations

The prediction equations presented below have been developed for the following range of test parameters.

$$50 \le P_i \le 100 \text{ psig}$$
$$70 \le T_{elev} \le 400°\text{F}$$

Use of the equations beyond these parameters should be performed with caution.

The containment pressure at which significant leakage is expected, P_c, may be estimated with the following equation:

$$P_c = \lambda P_s \le P_{max} \qquad (6.1)$$

where:

$$P_{max} = 156.67 - 0.067T_{elev} \le 150 \text{ psig} \qquad (6.2)$$

= maximum containment pressure without danger of rupturing the inflatable seals; For $T_{elev} \le 100°F$, $P_{max} = 150$ psig. For $T_{elev} = 400°F$, $P_{max} = 130$ psig.

T_{elev} = estimated average temperature of seals during accident conditions, °F

P_i = seal pressure under normal operating conditions, psig

For ambient conditions:

$P_s = P_i$ = seal pressure under normal operating conditions (i.e., no pressure within containment), psig

For elevated temperatures:

P_s = seal pressure at elevated temperature with no pressure within containment, psig

At elevated temperatures, P_s may be estimated using the ideal gas law and assuming constant volume of the inflatable seals:

P_s = $(TR_{elev}/TR_{amb})(P_{ia}$ @ ambient conditions$) - P_a$, psig

P_{ia} = absolute seal pressure under normal operating conditions, psia

P_a = atmospheric pressure, psig

TR_{elev} = estimated average temperature of seals during accident conditions, °R

TR_{amb} = seal temperature during normal operating conditions, °R

For constant seal pressure, regardless of seal design:[8]

$$\lambda = 1.0 \qquad (6.3)$$

For <u>old seal design</u> and assuming that seals are isolated from their internal pressure source:[9]

$$\lambda = 0.006P_s + 0.70 \qquad (50 \le P_s \le 100) \qquad (6.4)$$

For <u>new seal design</u> and assuming that seals are isolated from their internal pressure source:

$$\lambda = 0.010P_s + 0.70 \qquad (50 \le P_s \le 90) \qquad (6.5)$$

6.2 Comparison of Predicted-to-Actual Chamber Pressures at Failure

The predicted chamber pressures at failure, P_c, using the above equations, are compared to the observed failure pressures at room temperature in Table 6.1. As shown in column (5) of Table 6.1, the above equations provide a good estimate of the required chamber pressure to produce significant leakage past both seals at room temperature.

Table 6.2 provides a comparison of the predicted chamber pressures at failure using the above methods to the inflatable seals tests that were conducted at elevated temperature. As shown in column (7) of Table 6.2, in most cases, the recommended method provides conservative estimates of the chamber pressure required to cause significant leakage. Because of the limited amount of test data at elevated temperature and the scatter within the available data, the expression for P_{max} intentionally provides lower

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[8] Assumes that an open pathway exists between the seal tube and the accumulator tank.

[9] Assumes that a closed valve isolates the seal from the accumulator tank.

bound estimates for the predicted chamber pressure at failure at elevated temperatures.

Figure 6.1 provides a comparison of the predicted-to-actual failure pressure ratios for the tested range of initial seal pressures for both the room temperature and elevated temperature tests.

Table 6.1 Comparison of Predicted-to-Actual Failure* Pressures - Room Temperature Tests

Test Series Number	Initial Seal Pressure, P_i (psig) (2)	Chamber* Pressure At Failure, P_f (psig) (3)	Predicted Failure* Pressure, P_c (psig) (4)	P_c/P_f (4)/(3) (%) (5)
1	50 (1st Test)	51.1	50.0	0.98
	60	65.4	63.6	0.97
	70	79.0	78.4	0.99
	80	94.7	94.4	1.00
	90	109.9	111.6	1.02
	100	129.6	130.0	1.00
	50 (2nd Test)	51.7	50.0	0.97
2	60 (1st Test)	79.0	63.6	0.81
	60 (2nd Test)	76.3	63.6	0.83
3 Round 1:	50 (1st Test)	93.0	60.0	0.65
	60	98.5	78.0	0.79
	60C**	60.8	60.0	0.99
	70	104.3	98.0	0.94
	80	125.1	120.0	0.96
	90	140.1	144.0	1.03
	90C**	92.6	90.0	0.97
	50 (2nd Test)	67.0	60.0	0.90
3 Round 2:	50 (1st Test)	58.2	60.0	1.03
	60	76.9	78.0	1.01
	70	97.4	98.0	1.01
	80	129.1	120.0	0.93
	50 (2nd Test)	58.9	60.0	1.02
4	60 (1st Test)	100.5	78.0	0.78
	60 (2nd Test)	101.1	78.0	0.77
			Average	0.93
			Std. Dev.	0.103

---

*Failure pressure is defined as the chamber pressure in psig at which leakage past both seals exceeded 10,000 scfd for a given seal pressure.

**Seal pressure maintained constant throughout test.

Table 6.2 Comparison of Predicted-to-Actual Failure* Pressures - Elevated Temperature Tests

Test Series Number	Initial Seal Pressure, P_i (psig)	Ambient Temp. (°F) (3)	Nominal Test Temp., T_{elev} (°F) (4)	Actual* Failure Pressure, P_f (psig) (5)	Predicted** Failure Pressure, P_c (psig) (6)	P_c/P_f (6)/(5) (7)
1	45	70.4	400	132.0	95.5	0.72
2	90	77.8	300	180.0	136.6	0.76
3	90	80.4	300	180.9	136.6	0.76
			350	146.1	133.2	0.91
4	90	88.6	300	137.5	136.6	0.99
					Average	0.83
					Std. Dev.	0.116

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* Actual failure pressure represents the measured chamber pressure at which leakage past both seals first exceeded 30,000 scfd.

**Predicted failure pressure, P_c, computed from equations in Section 6.1.

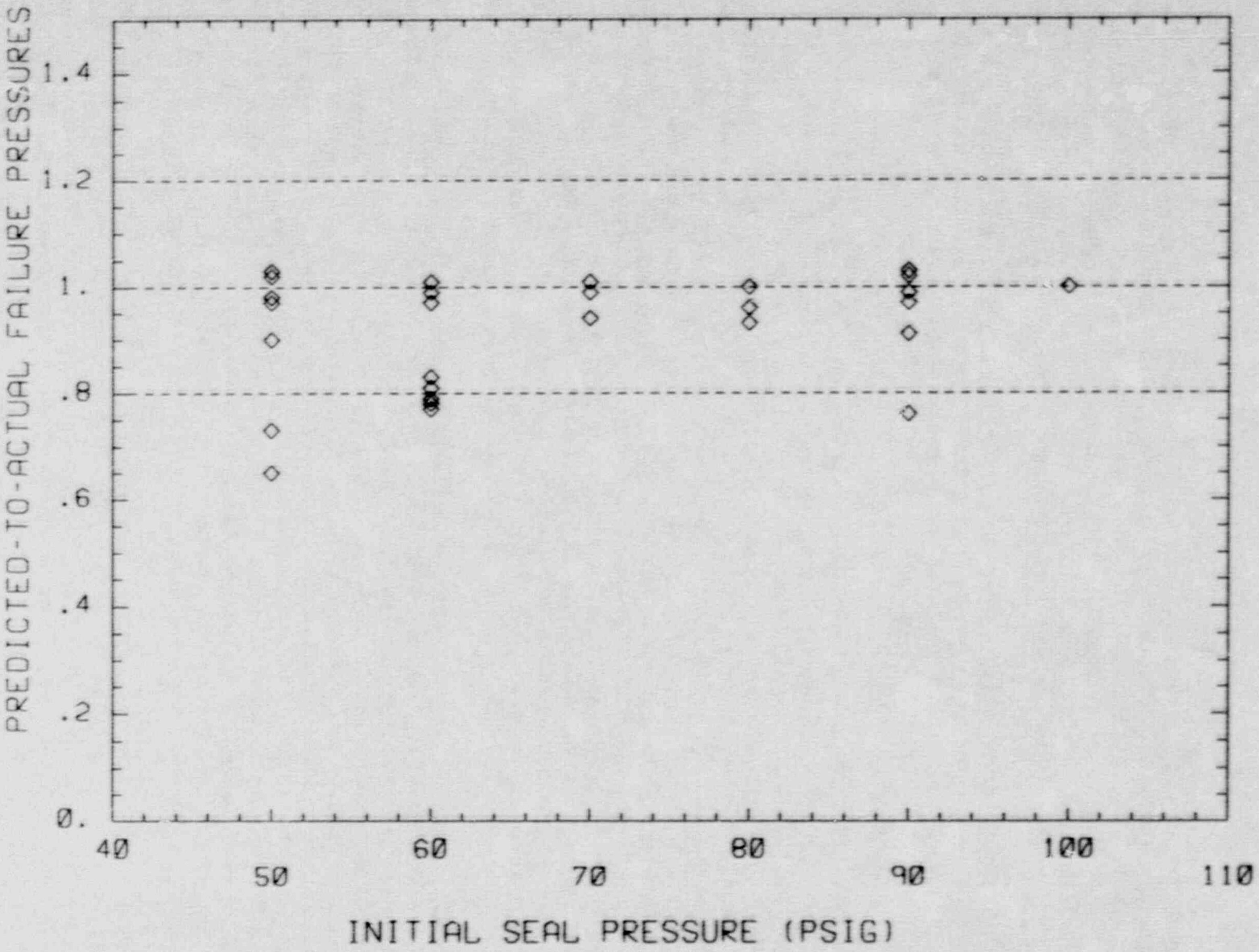

Figure 6.1 Comparison of Predicted-to-Actual Failure Pressures for the Tested Range of Initial Seal Pressures

7. SUMMARY

The results of several tests to determine the leakage behavior of inflatable seals at room temperature and elevated temperatures have been presented and discussed. The room temperature tests covered a wide range of seal pressures representative of the normal operating seal pressures in nuclear containments. Because they were generally destructive in nature, only one seal pressure was normally tested at elevated temperature.

The test program included the two primary seal designs currently in use in nuclear containments. For each seal design, a pair of unaged and a pair of aged seals were tested first at room temperature and then finally at elevated temperature. The aged seals were subjected to both radiation and thermal aging.

During the tests, two different valve conditions were modeled. In the first, it was assumed that the inflation valve (Figure 1.3) is closed after the seals are inflated. Because the inflation valve is between the seal and accumulator tank, the volume of air within the seals is essentially isolated from the pressure source. As a result, increasing external pressure causes a corresponding increase in seal pressure. The other valve condition assumed that the inflation valve remains open after the seals are inflated. If the inflation valve is open during normal operation, there is an open pathway for airflow between each seal and accumulator tank. Because of the large effective volume acting with the seals, increasing external pressure has little effect on seal pressure. The second valve condition is believed to be most representative of current practice in nuclear containments. For either valve condition, increasing containment temperature will likely cause an increase in seal pressure.

Based on the results of all the inflatable seals tests, a general method has been developed to provide reasonable estimates of the containment pressure at which significant leakage can be expected for a given normal operating seal pressure. As described in Section 6, this method may be used to predict the leakage behavior of inflatable seals subject to either of the above valve conditions. Because the prediction method is empirical, use of the prediction equations beyond the tested range of parameters should be performed with caution. Also, it should be kept in mind that only four pairs of inflatable seals have been tested. Although it is thought to be small, the variability in leakage behavior that would naturally occur due to manufacturing variations is difficult to quantify.

It should be remembered that, although the tested seals were identical in cross-section to those used in nuclear containments, the length of the tested seals was somewhat less than the total length of inflatable seals on personnel airlock doors. The tested seals were approximately 100 inches in length whereas those used on airlock doors vary in length from about 240 to 310 inches. Thus, for a given containment pressure and seal pressure, the actual amount of leakage past inflatable seals in nuclear containments will likely be greater than measured for the tested seals.

The results of the inflatable seals tests may be summarized as follows:

- Regardless of seal design, seal pressure, valve condition, applied aging, or test temperature, significant leakage (>10,000 scfd) past both seals did not occur until the chamber pressure reached or exceeded the initial seal pressure at the start of each test. (Initial seal pressure is defined as the seal pressure at the beginning of each test at room temperature with no applied chamber pressure.)

- For a given initial seal pressure at room temperature, leakage generally began at higher chamber pressures for the new design seals than for the old design. However, there was no distinguishable difference between the two designs at elevated temperature.

- Radiation and thermal aging actually improved the leakage behavior at room temperature; however, at elevated temperature there was no observable difference between the performance of the aged and unaged seals.

- Increasing seal temperature produces a corresponding increase in seal pressure. The amount of increase can be adequately predicted using the ideal gas law assuming constant volume. The increase in seal pressure due to temperature also tends to increase the chamber pressure at which significant leakage begins. In all cases, significant leakage did not begin until the chamber pressure exceeded the seal pressure that was predicted by the ideal gas law for the test temperature. If the actual seal temperature is unknown, a lower bound estimate of the containment pressure necessary to cause significant leakage may be obtained by assuming room temperature conditions.

- For temperatures up to 350°F, there were no indications of degradation of the seal material. However, between 350°F and 400°F (the maximum test temperature), signs of a breakdown in the composite seal material began to occur. For this reason, use of inflatable seals in environments in excess of 350°F should be done with caution.

- If inflatable seals are isolated from their pressure source by a closed valve near the seals' valve stem, the internal seal pressure will increase as a result of increasing containment pressure. However, if an open pathway exists between the seal and accumulator tank, no appreciable change in seal pressure will occur due to containment pressure. For either case, methods are presented in Section 6 to predict the containment pressure at which significant leakage will begin.

- For the room temperature tests, the seals always resealed upon reduction in chamber pressure. The resealing pressure was about the same as the pressure at which significant leakage began. At elevated temperatures, significant leakage normally began as a result of a rupture of the seal tube; thus, it was impossible for the seals to reseal upon reduction in chamber pressure.

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APPENDIX A

DETAILED TEST DESCRIPTIONS

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A.1 DETAILED DESCRIPTION OF TEST SERIES 1

Inflatable seals test series number 1 was completed on June 28, 1988. The room temperature portion of the test was performed from June 21 through June 24 and the elevated temperature (400°F) portion was performed on June 28. As shown in Table 2.1, the tested pair of seals were of the "old" seal design and were unaged. All of the leakage tests were conducted with the seals isolated from their pressure source.

A.1.1 Room Temperature Tests

Separate tests were performed at room temperature in which the seal pressure, at the beginning of each test, was varied from 50 to 100 psig in increments of 10 psi. Because the seals were isolated from their pressure sources, the actual seal pressure increased during each test as a result of the increasing chamber pressure. For each seal pressure level, the chamber pressure was increased from 0 psig until leakage past both seals reached approximately 10,000 scfd. Table 4.1 presents the chamber pressure corresponding to approximately 10,000 scfd leakage for each seal pressure. The relative increase in seal pressure, which was caused by the chamber pressure, may be observed by comparing columns (2) and (4) of Table 4.1.

The measured leakage past both seals, as a function of the chamber pressure, may be compared in Figure 4.1 for each seal pressure level. In order to determine the resealing capability of the seals, leakage was also recorded at several levels as the chamber pressure was decreased to 0 psig. The direction of "loading" is indicated by arrows on each of the curves in Figure 4.1. As shown, in most cases, less leakage was measured for a given chamber pressure on the unloading side of the curves. As expected, the chamber pressure at which significant leakage began increased as the seal pressure level was increased. (For example, less leakage occurred, for a given chamber pressure, at 60 psig in the seals than at 50 psig and so forth.) In order to verify that the seals were not damaged during these tests, the 50 psig seal pressure test was repeated after completing all of the originally scheduled room temperature tests. As can be seen in Table 4.1, there was little difference between the two 50 psig seal pressure tests.

A.1.2 Elevated Temperature Tests

An initial test was performed in order to observe the effect of temperature on the internal seal pressure. During this test, the seal pressure was monitored as the test chamber was heated, using hot dry air, to the desired test temperature of 400°F. The pressure within the test chamber was less than 15 psig at all times. The initial seal pressure at room temperature was set at 60 psig in the outer seal and 90 psig in the inner seal. After adjusting the seal pressure to these levels, the seals were isolated from their pressure sources by closing valves V_{IS} and V_{OS} (Figure 3.5). As shown in Figure 5.3, a considerable increase in seal pressure was measured as the fixture temperature increased. The seal temperature was taken from an intrinsic thermocouple (TC) which was attached to the stiffener between the seals; thus, the actual seal temperature may have varied slightly from the temperature recorded from this TC. It is interesting to note that, as discussed in Section 5.5.1, the rate of increase in seal pressure decreased as the fixture temperature approached 400°F.

For the actual leakage test at 400°F, the seal pressure was initially set at 80 psig (at 400°F). (According to the ideal gas law [assuming a fixed volume], a seal pressure of 80 psig at 400°F corresponds to approximately 45 psig seal pressure at 70°F.) The temperature of the stiffener between the seals was maintained at 400±5°F throughout the test. The chamber pressure was increased from 0 psig. Almost no leakage (<150 scfd) was measured until failure of the seals. At approximately 132 psig chamber pressure, leakage past both seals increased suddenly from about 100 scfd to >30,000 scfd (at this point, leakage was greater than the capacity of the flowmeters). Pressure in the outer and inner seals was 132.1 and 132.3 psig, respectively, at failure. Posttest inspection revealed that the outer seal ruptured during the test in the vicinity of the valve stem.

By comparing the chamber pressures at failure at room temperature and at 400°F in Figures 4.1 and 4.6, it can be seen that the leakage behavior for an initial seal pressure of 50 psig is much better at 400°F. The improved performance may be attributed to the increased seal pressure caused by increasing temperature and the "softening" effect of high temperature on the seal material. However, it should be noted that the same factors of increased seal pressure and material softening due to temperature also increase the likelihood of a rupture of the seal.

A.2 DETAILED DESCRIPTION OF TEST SERIES 2

The second series of inflatable seals tests were completed on August 3, 1988. The room temperature portion of the test was conducted on August 1 and the elevated temperature (300°F) portion was performed on August 3. As shown in Table 2.1, the tested pair of seals were of the "old" seal design. The seals were both radiation and thermal aged as described in Section 2.5. All of the leakage tests were conducted with the seals isolated from their pressure source.

A.2.1 Room Temperature Tests

Because the seals were aged for test series number 2, there was some concern before the test that any testing at room temperature might damage the seals before the elevated temperature tests. In order to minimize any potential damage, only the 60 psig seal pressure level was tested at room temperature. Because 60 psig is a relatively low internal pressure for the seals, the resulting stresses in the seal tube are small and thus, the potential for damage was kept to a minimum.

For the first 60 psig seal pressure test, almost no leakage (<50 scfd) was measured past the seals as the chamber pressure was increased from 0 psig until just before failure. At approximately 79 psig chamber pressure, leakage past both seals increased rapidly from about 50 scfd to >30,000 scfd. The outer and inner seal pressures at failure were 74.7 and 78.9 psig, respectively. As shown in Figure 4.2, leakage continued to be >10,000 scfd until the chamber pressure was reduced to approximately 63 psig. At 63 psig chamber pressure, leakage suddenly decreased from >10,000 scfd to about 7 scfd. As the chamber pressure was decreased further to 0 psig, leakage past both seals remained <10 scfd at all times.

In order to determine if the seals were damaged during the above test, a second test with 60 psig seal pressure was performed. During this test, failure again occurred quickly at 76.3 psig chamber pressure at which time leakage grew from around 10 scfd to >30,000 scfd. The outer and inner seal pressures at failure were approximately 72.2 and 76.2 psig, respectively. Leakage stopped abruptly when the chamber pressure was reduced to 68 psig. Because the leakage behavior of the seals was quite similar for both tests, it seems that no damage occurred during the room temperature tests.

A.2.2 Elevated Temperature Tests

As for test series number 1, an initial test was performed in order to observe the effect of temperature on the internal seal pressure. During this test, the seal pressure was monitored as the test chamber was heated, using a flow of hot, dry air, from ambient temperature to the desired test temperature of 300°F. The pressure within the test chamber was less than 15 psig at all times. The initial seal pressure at room temperature was set at 90 psig in both seals. In addition to the fixture thermocouples (TCs) for test series number 1, a TC was placed inside the "valve stem" of each seal (Figure 3.8). As shown in Table 5.1, the pressure within the seals increased from 90 psig to approximately 130 psig as the chamber was heated to 300°F. Approximately 8-1/2 hours were required to reach 300°F in the test fixture.

At the beginning of the leakage test at 300°F, the outer seal pressure was 129.1 psig and the inner seal pressure was 127.5 psig. The temperature of the stiffener between the seals was maintained at 300±5°F throughout the test. The chamber pressure was increased from 0 psig. As shown in Figure 4.7, appreciable leakage past both seals began around 90 psig chamber pressure then stopped at about 120 psig. At no time in this pressure region did the leakage exceed 1500 scfd. No additional leakage of significance occurred until approximately 172 psig chamber pressure. Leakage increased steadily from 172 psig to 180 psig chamber pressure. At 180 psig chamber pressure, leakage past both seals grew from approximately 2500 scfd to >30,000 scfd over a period of about an hour. The outer and inner seal pressures at failure were 180.7 and 178.7 psig, respectively. Posttest inspection revealed that the outer seal tube had again (as in test series no. 1) ruptured near the valve stem. Also, the outer seal tube ripped away from its inner flange around most of the circumference.

A.3 DETAILED DESCRIPTION OF TEST SERIES 3

The third series of inflatable seals tests were completed on September 27, 1988. The room temperature portion of the test was conducted from August 30 to September 19 and the elevated temperature portion of the test was performed on September 27. As shown in Table 2.1, the tested pair of seals were of the "new" seal design and were unaged.

A.3.1 Room Temperature Tests

Two different sets or "rounds" of leakage tests were conducted at room temperature during test series 3. Originally, only one round of room temperature tests were planned. However, because the leakage behavior of the seals was significantly altered during the first round, a second round of room temperature tests were performed. During round 1, room temperature tests were conducted with the seals isolated from their pressure source by a closed valve and also with the seal pressure held constant. A detailed description of the tests that were conducted in each round is provided below.

A.3.1.1 Round 1 (Seals Isolated From Pressure Source)

During round 1, separate tests were performed at room temperature in which the seal pressure, at the beginning of each test, was varied in 10 psi increments from 50 to 90 psig. After completion of the 90 psig seal pressure test, it seemed likely that, for a 100 psig seal pressure test, the internal seal pressure associated with "failure" would be well in excess of the standard "proof" test pressure of 135 psig; thus, in order to minimize the risk of damaging the seals, no test was performed for an initial seal pressure of 100 psig.

For each seal pressure level, the chamber pressure was increased from 0 psig until leakage past both seals reached approximately 10,000 scfd. Table 4.1 presents the chamber pressure corresponding to approximately 10,000 scfd leakage past both seals for each seal pressure level. The relative increase in seal pressure, which was caused by the chamber pressure, may be observed by comparing columns (2) and (4) of Table 4.1. Figure 4.3 graphically illustrates the recorded leakage behavior for each of the first round room temperature tests in which the seals were isolated from their pressure source. After all of the originally scheduled seal pressures were tested in round 1, the 50 psig seal pressure test was repeated in order to ensure that the seals were not damaged during the first round of tests. For the second 50 psig seal pressure test of round 1, the leakage limit of 10,000 scfd was obtained at a chamber pressure of only 67.0 psig--much lower than the first 50 psig seal pressure test. It was believed that, during the round 1 tests, leakage had possibly developed around the valve stem on the outer seal. The test chamber and fixture were disassembled and the valve stems were tightened against the test fixture.

A.3.1.2 Round 1 (Constant Seal Pressure)

Two additional leakage tests were conducted during round 1 in which the seal pressure was maintained constant throughout the test. In this way, the leakage behavior of inflatable seals that are connected to the accumulator tank (Figure 1.3) by an open air line could be modeled. For the first of these tests, the seal pressure was set at 60 psig in both seals. However, as the chamber pressure was increased, the resulting increase in seal pressure was bled off--keeping a constant 60 psig pressure in both seals throughout the test. As shown in Figure 4.5, significant leakage did not begin until the chamber pressure reached the seal pressure of 60 psig. At 60.8 psig chamber pressure, leakage past both seals reached approximately 12,000 scfd. Leakage effectively stopped (<2 scfd) when the chamber pressure was reduced to about 50 psig. A similar test was performed at 90 psig pressure in each seal. As illustrated in Figure 4.5, again, there was no significant leakage past both seals until the chamber pressure reached the seal pressure of 90 psig. At 92.6 psig chamber pressure, leakage reached approximately 10,000 scfd. Leakage effectively stopped (<3 scfd) when the chamber pressure was reduced to about 85 psig. By comparing the results of these two tests to their counterparts in which the seal pressure was allowed to increase (Figure 4.3), it can be seen that much less leakage occurs if the seals are isolated from their pressure source in such a way that the internal seal pressure increases with increasing chamber pressure. The results of these "constant seal pressure" tests are denoted by a "C" suffix under Round 1 in Table 4.1.

A.3.1.3 Round 2

After reassembling the test equipment, a second Round of room temperature tests was conducted, which included seal pressures of 50 through 80 psig. All testing during this round was performed with the seals isolated from their pressure source. As shown in Table 4.1, the chamber pressure at which leakage reached 10,000 scfd was considerably less for the 50 and 60 seal pressure levels than that of round 1. However for the higher 70 and 80 seal pressure levels, there was little difference between the first and second round of room temperature tests. The 90 psig seal pressure test was not repeated in round 2 for fear of damaging the seals before the elevated temperature tests. In order to check for any deterioration in the leakage behavior of the seals that might have occurred during the second round of tests, the 50 psig seal pressure test was repeated. As shown in Table 4.1, there was no significant difference between the two 50 psig seal pressure tests of round 2; thus, it seems that no further change in leakage behavior occurred during round 2. Figure 4.4 shows the measured leakage behavior for each of the second round tests.

In the final analysis, it seems that, even if leakage around the outer valve stem did exist before tightening the valve stems, it certainly was not the major cause of the decrease in chamber pressure at which leakage occurred for the 50 and 60 psig seal pressure levels. Perhaps the main cause of this poorer leakage behavior after round 1 was simply due to an inelastic "stretching" of the seal tube during the higher seal pressure tests in round 1.

By comparing Figures 4.3 and 4.4, one can see that, once leakage began, it increased at a much faster rate for the second round of test than for the first. For each seal pressure level in the second round of tests, leakage grew suddenly at failure from <100 scfd to >30,000 scfd.

A.3.2 Elevated Temperature Tests

Leakage tests were performed, or at least attempted, at 300°F, 350°F, and 400°F during the elevated temperature portion of test series 3. All of the leakage tests at elevated temperature were conducted with the seals isolated from their pressure source. A detailed description of the testing that was conducted at each of these temperatures is given below.

A.3.2.1 300°F

An initial test was performed in order to observe the effect of temperature on the internal seal pressure. During this test, the pressure in each seal was monitored as the test chamber was heated from ambient temperature to the initial test temperature of 300°F. Superheated steam, instead of hot, dry air, was used to bring the test chamber up to temperature. Steam was chosen because of its superior heat transfer qualities which allows the test chamber to reach the test temperature much more quickly. (Approximately 8-1/2 hours were required to reach 300°F in test series 2 in which heated, dry air was used as opposed to only about 3 hours for test series 3 which used superheated steam.) At no time during the heating of the test chamber did the chamber pressure exceed 20 psig. After reaching 300°F, the steam system was isolated from the test chamber and heated, dry air was allowed to flow through the chamber for the last two hours before beginning the leakage test. As in previous tests, heated, dry air was used to supply the chamber pressure during the leakage tests.

The initial seal pressure at room temperature was set at 90 psig in both seals. A thermocouple was placed inside the valve stem of each seal in order to measure the air temperature inside the seals. As shown in Table 5.1, the pressure within the seals increased from 90 psig to approximately 135 psig as the chamber was heated to 300°F.

At the beginning of the leakage test at 300°F, the outer seal pressure was 134.1 psig and the inner seal pressure was 134.8 psig. The air temperature within the seals was maintained at 300±10°F throughout the test. The chamber pressure was increased from 0 psig. As shown in Figure 4.7, appreciable leakage past both seals did not begin until the chamber pressure reached approximately 180 psig. At that point, leakage grew from <50 scfd to >30,000 scfd. The outer and inner seal pressures at failure were 183.2 and 181.3 psig, respectively. Leakage effectively stopped (<50 scfd) when the chamber pressure was decreased to about 155 psig. Further decrease in the chamber pressure to 0 psig revealed that both seals were still inflated. (Previously, for the elevated temperature portion of test series 1 and 2, the outer seal ruptured at failure and thus, would no longer hold its internal pressure.) At 0 psig chamber pressure and 300°F, the inner seal pressure was 123.1 psig and the outer seal pressure was 115.4 psig. The loss of internal seal pressure was apparently caused by inelastic "stretching" of the seal tube as a result of the 300°F temperature and the external "side" pressure on the seals during the test. This stretching of the seal tube increases its volume and thus decreases its internal pressure.

A.3.2.2 350°F

Because the seals were still intact at the end of the 300°F test, it was decided to increase the temperature inside the test chamber to 350°F and perform another leakage test. Steam was again used to increase the chamber temperature and hot, dry air was used during the actual leakage test at 350°F. No significant leakage past both seals (< 50 scfd) was measured until the chamber pressure reached approximately 145 psig. At about 145 psig chamber pressure, leakage grew suddenly from around 50 scfd to >30,000 scfd. The outer and inner seal pressures at failure were 153.8 and 150.7 psig, respectively. Leakage effectively stopped (<10 scfd) when the chamber pressure was reduced to about 125 psig. After reducing the chamber pressure to 0 psig, the outer and inner seal pressures were 112.5 and 127.8 psig, respectively. Figure 4.8 shows the measured leakage as a function of the chamber pressure for the 350°F test. Undoubtedly, there was some damage to the seals during the previous 300°F test due to the effects of both the elevated temperature and the external "side" pressure on the seals; however, the leakage test at 350°F should at least be useful as a lower bound on the chamber pressure necessary to cause failure at 350°F.

A.3.2.3 400°F

Because the seals were still holding internal pressure when the chamber pressure was reduced to 0 psig, an attempt was made to perform yet another leakage test at 400°F. However, during the transition from 350°F to 400°F, the outer seal ruptured and would no longer hold internal pressure. The air temperature within the seals had just reached 400°F and the chamber pressure was approximately 30 psig at the time of the rupture. The outer and inner seal pressures, just before rupture of the outer seal, were 113.8 and 129.2 psig, respectively.

Posttest inspection of the outer seal revealed that a small tear (approximately 1 inch long) occurred in the Kevlar reinforcing on the inner side of the seal tube near the valve stem. The seal material was also torn along the inner edge of the outer valve stem. Both of these tears went through the thickness of the seal material which allowed air to flow into the test fixture along the outer valve stem--effectively bypassing the inner seal. The inner seal was still capable of holding internal pressure at the end of the test and showed little signs of distress.

A.4 DETAILED DESCRIPTION OF TEST SERIES 4

The fourth series of inflatable seals tests were completed on October 14, 1988. The room temperature portion of the test was conducted on October 11 and the elevated temperature (300°F) portion was performed on October 14. As shown in Table 2.1, the tested pair of seals were of the "new" seal design. The seals were both radiation and thermal aged as described in Section 2.5. All of the leakage tests were conducted with the seals isolated from their pressure source.

A.4.1 Room Temperature Tests

Because the seals were aged for test series number 4, there was some concern before the test that any testing at room temperature might damage the seals before the elevated temperature tests. In order to minimize any potential damage, only the 60 psig seal pressure level was tested at room temperature. Because 60 psig is a relatively low internal pressure for the seals, the resulting stresses in the seal tube are small and thus, the potential for damage was kept to a minimum.

For the first 60 psig seal pressure test, almost no leakage (<50 scfd) was measured past the seals as the chamber pressure was increased from 0 psig until about 90 psig. As shown in Figure 4.2, leakage grew from around 50 to approximately 10,000 scfd as the chamber pressure was increased from 90 to 100.5 psig. The outer and inner seal pressures for 10,000 scfd leakage past both seals were approximately 93.4 and 99.4 psig, respectively. Leakage effectively stopped (<10 scfd) when the chamber pressure was reduced to 95 psig. As the chamber pressure was decreased further to 0 psig, leakage past both seals remained <10 scfd at all times.

In order to determine if the seals were damaged during the above test, a second test with 60 psig seal pressure was performed. The leakage behavior for this test was practically identical to the first test. Leakage past both seals remained less than 50 scfd as the chamber pressure was increased from 0 to 95 psig. As the chamber pressure was further increased from about 95 to 101 psig, leakage past both seals grew from approximately 25 to 10,000 scfd. The outer and inner seal pressures for 10,000 scfd leakage were 94.0 and 99.9 psig, respectively. As in the first test, leakage stopped abruptly when the chamber pressure was reduced to 95 psig. Because the leakage behavior of the seals was quite similar for both tests, it is assumed that no damage occurred during the room temperature tests.

A.4.2 Elevated Temperature Tests

As for each of the previous test series, an initial test was performed in order to observe the effect of temperature on the internal seal pressure. During this test, the seal pressure was monitored as the test chamber was heated using superheated steam from ambient temperature to the desired test temperature of 300°F. The pressure within the test chamber was less than 20 psig at all times during heatup. The initial seal pressure at room temperature was set at 90 psig in both seals. In order to monitor the temperature of the seals, a thermocouple (TC) was placed inside the valve stem of each seal. These TCs measure the air temperature inside the seal tube. As shown in Table 5.1, the pressure within the seals increased from 90 psig to approximately 126 psig as the chamber was heated to 300°F. Approximately 2-1/2 hours were required to reach 300°F in the test fixture.

At the beginning of the leakage test at 300°F, the outer seal pressure was 126.3 psig and the inner seal pressure was 126.6 psig. The temperature of the stiffener between the seals was maintained at 300±5°F throughout the test using a flow of heated, dry air. As shown in Figure 4.7, appreciable leakage past both seals began around 138 psig chamber pressure. At 138 psig chamber pressure, leakage past both seals grew suddenly from <50 scfd to >30,000 scfd. The outer and inner seal pressures at failure were 133.9 and 138.1 psig, respectively. The pressure in the outer seal began falling sharply just before failure indicating that the seal had ruptured. However, the inner seal was still intact. After holding the chamber pressure at 138 psig for about 5 minutes, the inner seal pressure suddenly increased from around 140 to 163 psig. Apparently, the "side" pressure on the inner seal pushed the seal tube between its flange and the test fixture resulting in a decrease in the volume of the seal tube and thus, an increase in the seal pressure. After this sudden increase in the inner seal pressure, leakage dropped from >30,000 to about 1600 scfd. Leakage past both seals became relatively stable at 1600 to 1800 scfd for a chamber pressure of 138 psig. Further increase in the chamber pressure led to another large burst of leakage at 146 psig. At this point, the inner seal ruptured and leakage once again exceeded 30,000 scfd. The inner seal pressure had fallen to 142 psig just before the second surge of leakage. Because both seals had burst, it was impossible for the seals to reseal as the chamber pressure was reduced.

APPENDIX B

TEST CHECKLISTS

APPENDIX B TABLE OF CONTENTS

Section B.1 provides a listing of the steps followed before each test. The general procedure for the room temperature and elevated temperature tests is given in Section B.2. Section B.3 provides sample data sheets used during the tests.

B.1 TEST PREREQUISITES

The following items must be performed and checked by the responsible person before performance of each test.

<u>Init/Date</u>

1) Install seals using a light layer of silicone lubricant between seals and test fixture. Coat the bolts that connect the seals to the fixture with "Never-Seez". Torque these bolts until the seal material is compressed to a thickness of 3/8 of an inch. ________

2) Clean seals using isopropyl alcohol. ________

3) Apply light layer of silicone lubricant to sealing surface of test fixture. ________

4) Record seal identification numbers on first page of data sheets. ________

5) Install thermocouples <u>inside</u> fixture. ________

6) Assemble test fixture. Install new gasket between inner and outer shell at outer end of fixture. Torque connecting bolts to 150 in-lbs. Tighten bolts at inner end of fixture until snug. (For unaged seals, skip 7) and 8).) ________

7) Send to Ga. Tech for radiation aging. Radiation aging to be performed with seals inflated at 50 psig. Dosage to be 200 Mrads at 1 Mrad/hr--gamma radiation. Receive documentation from Ga. Tech. ________

8) Thermal age with seals deflated at 250°F for 168 hrs (1 week). Receive and file documentation of time-temperature data for total aging period. ________

9) Check connection of all leak detection and seal pressure lines to the test chamber before attaching these lines to the test fixture. Pressurize the lines to 150 psig with air--use leak detect solution to check for leakage. Also, check all connections and valves outside of test chamber - between test chamber and flowmeter gallery. Repair leaks as required. ________

10) Place test fixture in the lower section of test chamber. ________

11) Connect leak detection lines and seal pressure lines to test fixture. ________

12) Pressurize both seals with air to 90 psig. Using helium, increase pressure to 50 psig (or use air at 60 psig) both between the seals and above upper seal inside the test fixture. This may be accomplished by pressurizing back through the leakage detection lines with valves V_{MF} and V_{TF} open. Check for leakage at connection of leak detection lines to test fixture and at penetration of valve stem of test fixture. Repair leaks as required. ________

13) With seals still pressurized at 90 psig,
   a. check for leakage at connection of pressure supply line to valve stem. ________
   b. isolate seals from pressure supply by closing valves V_{IS} and V_{OS}. Record pressure drop over a 24 hour period. ________

14) Connect remaining thermocouples to test fixture. ________

15) Install heaters within inner diameter of test fixture. ________

16) Install new gaskets between each section of the test chamber. Place remainder of test chamber over test fixture. Torque bolts that connect sections of test chamber to 300 ft-lbs. ________

17) Connect pressure detection piping to pressure transducers. ________

18) Connect pressure transducers to datalogger--verify proper placement of each pressure transducer in datalogger. Record manufacturer, serial number, and application of each pressure gage in log book for each test. ________

19) Connect leak detection piping to flowmeter gallery. ________

20) Connect flowmeter gallery to data acquisition system - verify proper placement of each flowmeter in datalogger. Record manufacturer, serial number, and application of each flowmeter in logbook. ________

21) Connect thermocouples to datalogger--verify proper placement of each TC in datalogger. ________

B.2 GENERAL TEST PROCEDURES

B.2.1 Room Temperature Tests

Documentation that the procedures listed below were followed during each test were provided by completion of the data sheets.

Step 1 Pressurize inflatable seals using clean, dry air to desired initial seal pressure level.

Step 2 Isolate each seal from its pressure source by closing valves V_{IS} and V_{OS}. Record date and time at which test for each seal pressure begins.

Step 3 Increase chamber pressure in small (0.5 to 10 psi) increments[1] until leakage past both seals reaches 10,000 scfd. (8.5 digital output on flowmeter #3) Note that to measure leakage past both seals valve V_{TF} must be open and V_{MF} closed. Record all data at each pressure level.

Step 4 Decrease chamber pressure until leakage past both seals stops. Record all data at each pressure level.

Step 5 Release chamber pressure. Increase seal pressure to next level (normally, previous seal pressure plus 10 psi) and continue from step 2 above. Note that seal pressure should not exceed 135 psig for these tests.

---

[1] For the constant seal pressure tests, the increase in seal pressure caused by increasing chamber pressure was bled off at each chamber pressure level.

B.2.2 Elevated Temperature Tests

Steps 1 through 4 are intended to determine the effect of temperature on the internal pressure in the seals.

Step 1 Inflate seals to desired initial pressure level. Use clean, dry air to inflate the seals. ________

Step 2 Isolate both seals from pressure source by closing valves V_{IS} and V_{OS}. ________

Step 3 Turn on heaters for test fixture--set at 700°F for heater element and 300 to 400°F for fixture TC. Turn on heated flow of air or superheated steam into test chamber. ________

Step 4 Record fixture and air temperature and each seal pressure at 15 or 30 minute intervals until desired fixture temperature is obtained. ________

Documentation that the procedures listed below were followed during each test is provided by completing the data sheets.

Step 5 Record date and time at which test began.

Step 6 With valves V_{TF} open and V_{MF} closed and chamber and fixture at desired test temperature, slowly increase chamber pressure until onset of leakage. Note that chamber pressure must not exceed 180 psig. Record all data - pressure - temperature - flows.

Step 7 Increase chamber pressure in small (0.5 to 10 psi) increments until leakage past both seals reaches 30,000 scfd. Note that to measure leakage past both seals valve V_{TF} must be open and V_{MF} closed. Record all data at each pressure level.

Step 8 Decrease chamber pressure in small increments until leakage past both seals stops. Record all data at each pressure level.

Step 9 Upon completion of the test, the test fixture shall be thoroughly inspected for any signs of possible leakage into the fixture, which would invalidate the recorded leakage during the test. If leakage is suspected, the fixture shall be checked as described in Section 3.4.

Step 10 Verify that seal I.D. number is still legible after testing. If not, relabel the seals.

B.3 DATA SHEETS

DATA ACQUISITION SYSTEM
CHECKLIST

Test Number ________ Date __________

Initial

Step 1 Turn on power supply for pressure gages - adjust to 28 volts. ________

Step 2 Turn on datalogger. Check channel output to ensure all TC's, pressure gages, and flowmeters are being being continuously scanned. ________

Step 3 Turn on PC and load VTERM. ________

Step 4 Input file name in VTERM for current test. ________

Step 5 Press cntl prtsc to write datalogger output to hard disk. ________

Step 6 Before beginning test, start a "dummy" scan and check to see that data is being recorded on hard disk. ________

INFLATABLE SEALS
DATA SHEETS

Test Number ________

Date: Start Test ____________ Completion ______________

Tested By: ____

Description of Test: ____
____

Seal I.D. Numbers: Top ___________ Bottom ___________

Seal Design: ________

Test Temperature: ______ °F

Aging: ____

Notes:

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INFLATABLE SEALS - DATA SHEETS

Test No. ____________________ Date ____________________

Reading	Time	Chamber Pressure (psig)	Top Seal (psig)	Bottom Seal (psig)	Fixture Temp. (°F)	Leak Valves (o-open, x-closed)			Flowmeter (reading or x-closed)				Notes
						V_{MF}	V_{TF}		No.1	No.2	No.3	No.4	
								BB*					
								BB					
								BB					
								BB					
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								BB					

*Bouncing Ball Flowmeter

APPENDIX C

TEST FIXTURE DRAWINGS

APPENDIX C TABLE OF CONTENTS

DESIGN AGENCY PART [redacted] NO.	ISSUE	SUPER ZONE	DESCRIPTION PREPARED BY	DATE	CHKR	APVD
S76836-000	A		MITCHELL 2855/LEWIN 6446			

NOTES

▷1 ASSEMBLE ITEMS 1,2,7,22,23 & 24 AND COMPRESS ITEM 7. MATCH DRILL AND THREAD ITEM 3 .250-20 UNC-2B, 1.25 MIN. DEPTH FROM ITEM 2. ASSEMBLE ITEM 2 AND ITEM 3 USING ITEM 26, MATCH DRILL AND THREAD .250-20 UNC-2B. ITEM 27 TO BE FLUSH TO .020 BELOW SURFACE OF ITEM 1 IN ASSEMBLY

▷2 ASSEMBLE SEALS AND SEAL RINGS WITH SEGMENTS NUMBERED AND MARKED AS SHOWN. MATCH LOCATE AS SHOWN, 2 PLACES PER SEGMENT. CLEARANCE HOLES THRU SEGMENTS AND SEAL FLANGE FOR ITEM 25. THREAD ITEM 2 .375-16 UNC-2B FOR A MINIMUM OF .50 THREAD ENGAGEMENT. SPOTFACE REQUIRED ON SEGMENT AS SHOWN.

▷3 METAL STAMP EACH SEGMENT (A1-A8, B1-B8, ... H1-H8) AS SHOWN AND DOCUMENT LOCATION AND FIXTURE TO ASSURE REASSEMBLY TO ORIGINAL POSITION. SEALS MUST BE IDENTIFIED & DOCUMENTED (#1 THRU #12) AS TO WHICH FIXTURE AND LOCATION AT WHICH THEY WERE MATCHED DRILLED. ITEMS WHICH MAKE FIXTURES #1 AND #2 TO BE IDENTIFIED.

4. LEAK CHECK PROCEDURE:

ASSEMBLE [illegible]TURE WITH SEALS IN PLACE
INFLATE S[illegible]S WITH AIR TO 70 PSIG
CLOSE OFF [illegible] UNUSED PORTS IN FIXTURE
PRESSURIZE INTERNAL CAVITIES WITH 50 PSIG WATER AT AMBIENT TEMPERATURE.
CHECK ALL WELDS AND GASKET SEAL. NO LEAKS PERMITTED. SANDIA REPS WILL WITNESS THIS TEST. AIR USED TO INFLATE SEALS SHALL BE CLEAN, DRY, AND OIL FREE.

5. ALL WELDS WHICH ARE SUBJECT TO LEAK CHECK ARE TO BE ASME CERTIFIED. ALL MATERIAL USED IN THIS FIXTURE TO BE 304 STAINLESS STEEL AND ASME CERTIFIED. (NO STAMP REQUIRED.)

6. REMOVE ALL SHARP EDGES AND BURRS.

▷7 "RECORD" FINISH REQUIRED IN THIS AREA. (SPIRAL MACHINED GROOVE.)

▷8 METAL STAMP INDEX MARK AS SHOWN (270°).

▷9 ROLLED DIMENSION. MACHINE IF NECESSARY.

QTY REQD	PART/CONTROL NUMBER	DESCRIPTION/MATERIAL		NOTES	SHEET ZONE	ITEM
32		SCREW, FL HD. SO HD. S.S.	.250-20 UNC x .75			27
32		SCREW, CAP, S.S.	.250-20 UNC x 1.00			26
64		SCREW, CAP, S.S.	.375-16 UNC x 2.00			25
36		NUT, HEX, S.S.	.250-20 UNC-2B			24
36		WASHER, LOCK, S.S.	.250 I.D.			23
36		BOLT, HEX HD. S.S.	.250-20 UNC x 1.25			22
A		COUPLING, HALF, S.S. SCH. 40	⌀ .875 x .75			18
B		COUPLING, FULL, S.S. SCH. 40	⌀ .875 x 1.50			17
ARS		[illegible] STAINLESS STEEL	⌀ .750			15
ARS		[illegible] STAINLESS STEEL	.500 THK			14
ARS		[illegible] STAINLESS STEEL				13
ARS		[illegible] STAINLESS STEEL	.250 THK			12
ARS		[illegible] STAINLESS STEEL	.375 THK			11
ARS		[illegible] STAINLESS STEEL				10
[illegible]		INFLATABLE FLEXIBLE SEAL	ENERFAB			8
[illegible]		GASKET, DURABLA	.062 THK			7
32		RING SEGMENT				4
1		LOWER SPACER RING				3
1		INNER CYLINDER				2
1		DOOR SEAL TEST FIXTURE				1

QUANTITY ABBREVIATIONS
NR - NO QUANTITY FOR DOCUMENTS
PM - PROCESS MATERIAL
EM - EXPENDABLE MATERIAL
AR - AS REQUIRED
ARS - AS REQUIRED PER ASSEMBLY
ALT - ALTERNATE

S76836-000

SHEET	1	2	3	4	5
ISSUE	A	A	A	A	A

PART CLASSIFICATION: UNCLASSIFIED

DRAWING CLASSIFICATION: UNCLASSIFIED

ORIGIN: SC-ABS-V11.305

STATUS: SC-REL-08-29-8[illegible]

TITLE (U) TITLE CLASSIFICATION

TEST FIXTURE

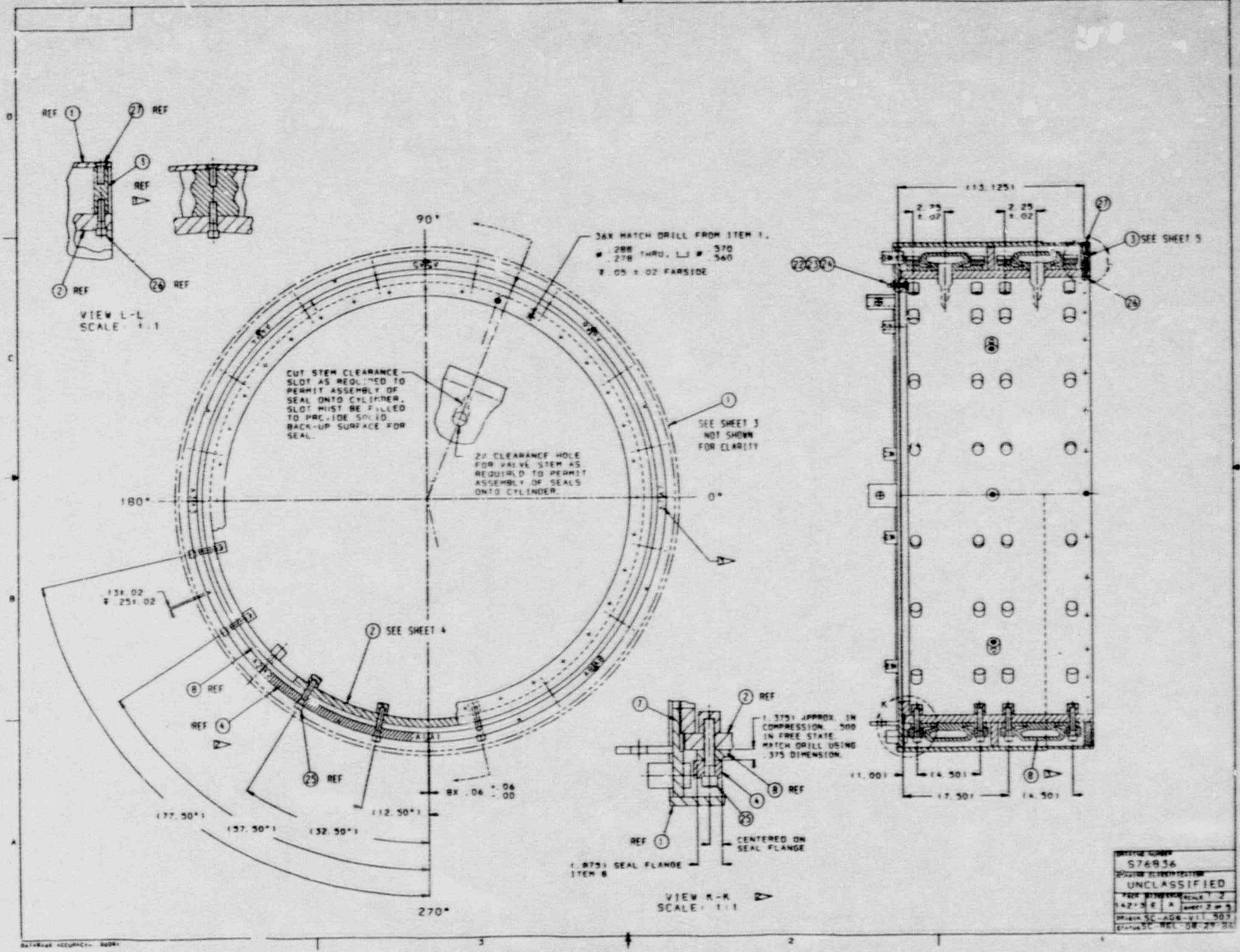
FSCM: 14213

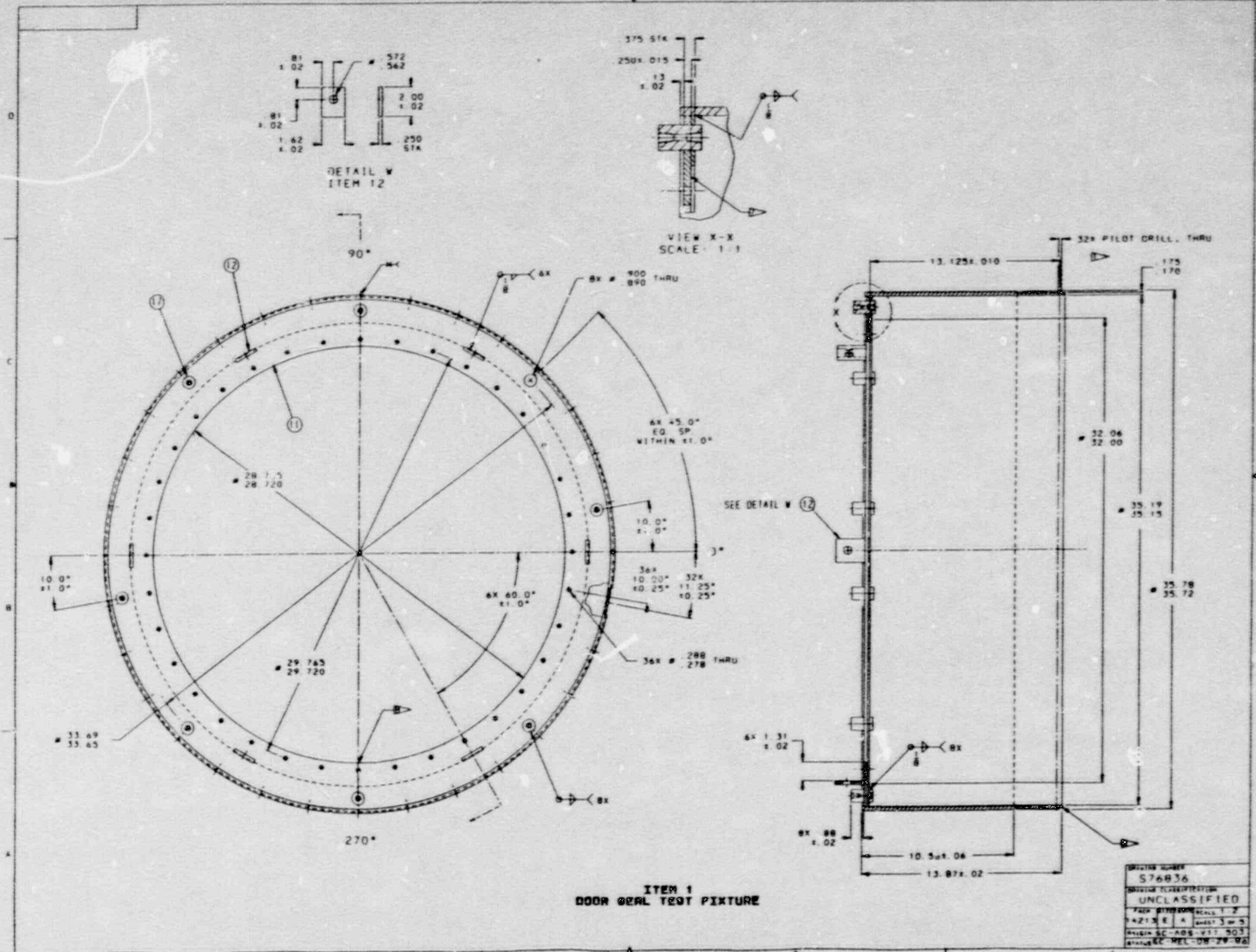
DRAWING NUMBER: S76836

DWG SIZE: E

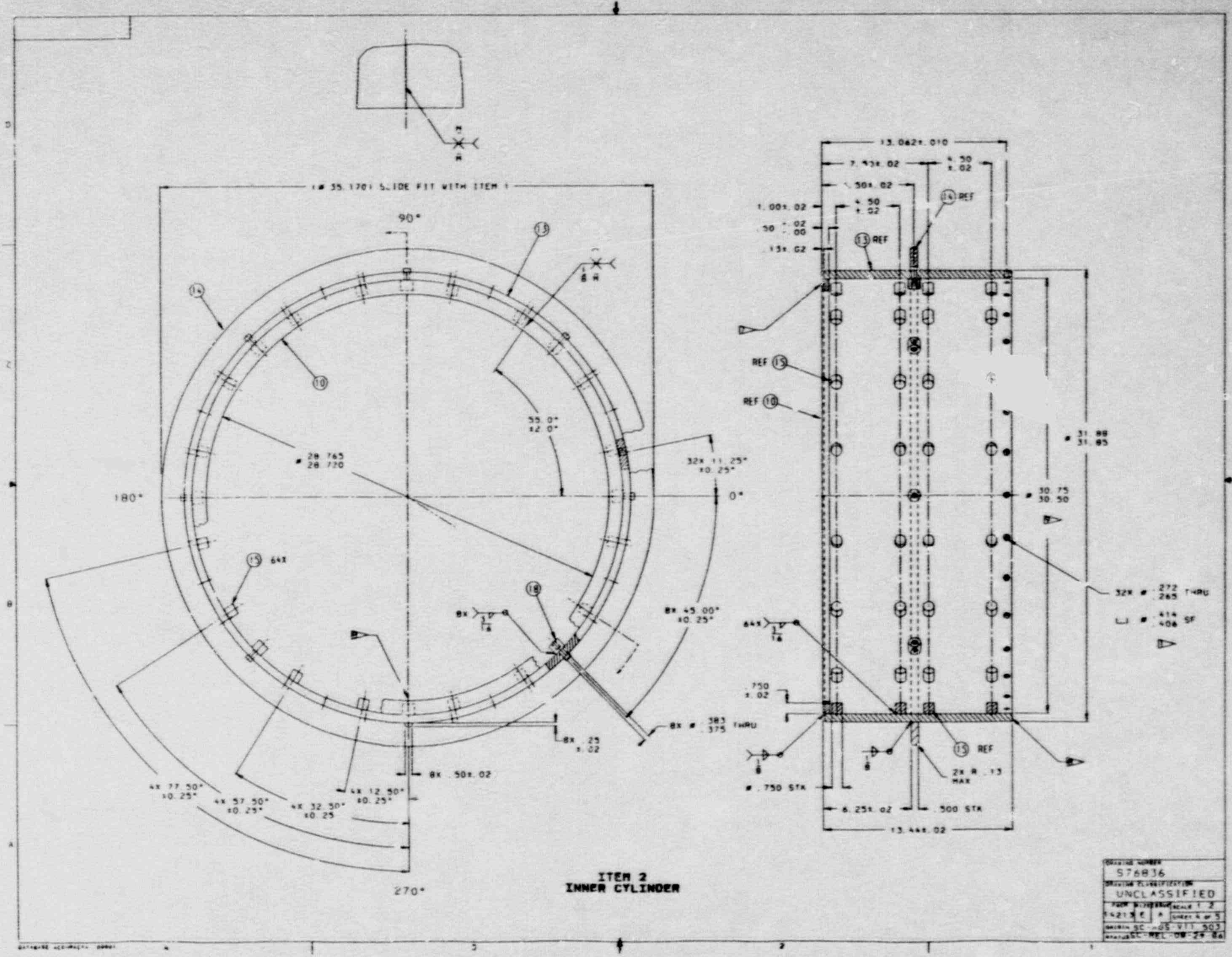
SCALE: 1:2

SHEET 1 OF 5

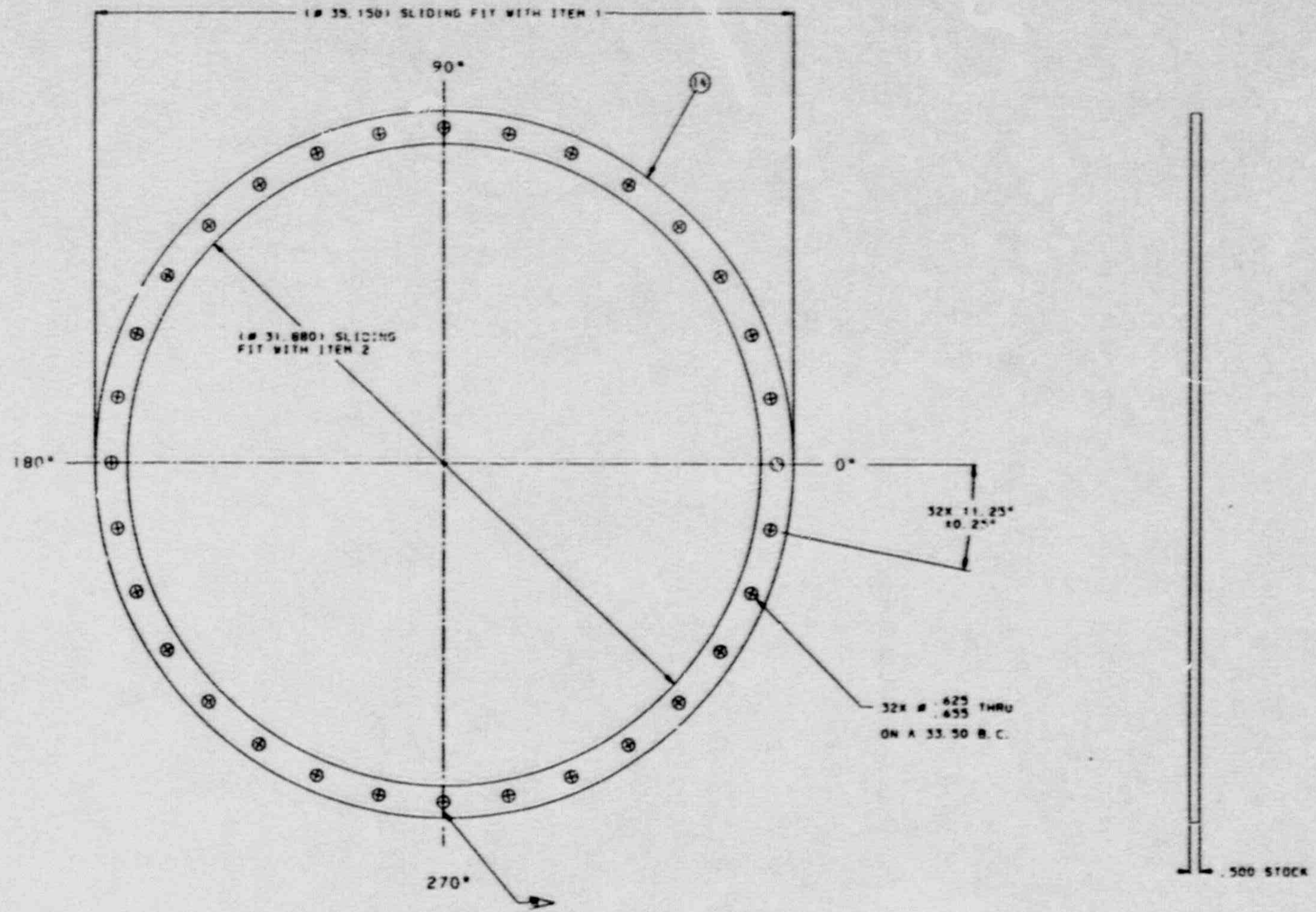

REF ①
㉗ REF
③
REF
② REF
㉔ REF
VIEW L-L
SCALE: 1:1
90°
180°
0°
270°
36X MATCH DRILL FROM ITEM 1.
⌀ .288 / .278 THRU, ⌴ ⌀ .370 / .360
↧ .05 ± .02 FARSIDE
CUT STEM CLEARANCE SLOT AS REQUIRED TO PERMIT ASSEMBLY OF SEAL ONTO CYLINDER. SLOT MUST BE FILLED TO PROVIDE SOLID BACK-UP SURFACE FOR SEAL.
2X CLEARANCE HOLE FOR VALVE STEM AS REQUIRED TO PERMIT ASSEMBLY OF SEALS ONTO CYLINDER.
① SEE SHEET 3 NOT SHOWN FOR CLARITY
② SEE SHEET 4
.13 ± .02
⌀ .25 ± .02
⑧ REF
REF ④
㉕ REF
8X .06 +.06 / -.00
(12.50°)
(32.50°)
(57.50°)
(77.50°)
⑦
② REF
(.375) APPROX. IN COMPRESSION. .500 IN FREE STATE. MATCH DRILL USING .375 DIMENSION.
⑧ REF
④
㉕
REF ①
CENTERED ON SEAL FLANGE
(.875) SEAL FLANGE ITEM 8
VIEW K-K
SCALE: 1:1
(13.125)
2.25 ± .02
2.25 ± .02
㉗
③ SEE SHEET 5
㉒㉓㉔
㉔
K
(1.00)
(4.50)
(7.50)
(4.50)
⑧
S76936
UNCLASSIFIED
SCALE 1:2
142*3
E
A
SHEET 2 OF 5
SC-AGN-VII-503
SC-REL-08-29-86
D
C
B
A
3
2
1



ITEM 1
DOOR SEAL TEST FIXTURE



ITEM 2
INNER CYLINDER



ITEM 3
LOWER SPACER RING

DRAWING NUMBER
S76836
DRAWING CLASSIFICATION
UNCLASSIFIED
14213 E A
SCALE 1:2
SHEET 5 OF 5
SC-AG6-V11 503

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11. ABSTRACT *(200 words or less)*

This report describes tests to determine the leakage behavior of inflatable seals. Inflatable seals are used to prevent leakage around personnel & escape lock doors of some containments. They are either currently installed or planned for use in thirteen commercial nuclear power plant containment structures in the U.S. All of the installations are in PWR or BWR Mark-III containments. This work is a part of an overall effort at Sandia National Laboratories to develop proven techniques for evaluating the performance of LWR containment buildings for beyond design basis loadings.

Inflatable seals were tested at both room temperature and at elevated temperatures representative of postulated severe accident conditions. Both aged (radiation & thermal) and unaged seals were included in the test program. The internal seal pressure at the beginning of each test was varied to cover the range of seal pressures actually used in containments. For each seal pressure level, the external (containment) pressure was increased until significant leakage past the seals was observed. Parameters that were monitored and recorded during the tests were the internal seal pressure, chamber pressure, leakage past the seals, and temperature of the test chamber and fixture to which the seals were attached. A general procedure, which covers a broad range of seal pressures and temperatures, has been developed to predict the containment pressure at which significant leakage past inflatable seals can be expected.

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