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Experimental Results from Containment Piping Bellows Subjected to Severe Accident Conditions

Results from Bellows Tested in Corroded Conditions

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Abstract

Bellows are an integral part of the containment pressure boundary in nuclear power plants. They are used at piping penetrations to allow relative movement between piping and the containment wall, while minimizing the load imposed on the piping and wall. Piping bellows are primarily used in steel containments; however, they have received limited use in some concrete (reinforced and prestressed) containments. In a severe accident they may be subjected to pressure and temperature conditions that exceed the design values, along with a combination of axial and lateral deflections. A test program to determine the leak-tight capacity of containment penetration bellows is being conducted at Sandia National Laboratories under the sponsorship of the U.S. Nuclear Regulatory Commission. Several different bellows geometries, representative of actual containment bellows, have been subjected to extreme deflections along with pressure and temperature loads. The bellows geometries and loading conditions are described along with the testing apparatus and procedures. A total of nineteen bellows have been tested. Thirteen bellows were tested in "like-new" condition (results reported in Volume I), and six were tested in a corroded condition. The tests showed that bellows in "like-new" condition are capable of withstanding relatively large deformations, up to, or near, the point of full compression or elongation, before developing leakage, while those in a corroded condition did not perform as well, depending on the amount of corrosion. The corroded bellows test program and results are presented in this report.

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Executive Summary

The bellows tests described in this report are part of a larger set of experiments that are being conducted at Sandia National Laboratories under the sponsorship of the U.S. Nuclear Regulatory Commission. The purpose of the "larger" set of experiments is to provide data for developing and/or verifying analytical methods for predicting the behavior of nuclear power plant containments subjected to pressure and temperature loadings that exceed the design basis -- the so-called "severe" accidents. Further explanation of the overall containment research programs can be found in Volume I of this report. Because bellows are an integral part of the containment pressure boundary, their performance must be evaluated as part of an overall assessment of the pressure and temperature conditions at which a given containment would develop leakage. The purpose of this experimental program is to investigate the leak-tight capacity of bellows subjected to severe accident conditions.

Volume I describes thirteen tests in which "like-new" bellows specimens were subjected to levels and combinations of internal pressure, temperature, axial compression or elongation, and lateral deformation consistent with conditions that could be expected in severe accidents. This second volume presents six additional tests in which bellows were subjected to corrosion followed by elevated pressure, temperature, and deformation conditions in order to assess the effects of corrosion on the ability of bellows to remain leak tight in a severe accident.

Corrosion has been observed in some two ply bellows used at containment piping penetrations. Leakage through these bellows was detected during 10CFR Part 50, Appendix J Type A testing; however, it was not observed during Local Leak Rate Testing (LLRT). Both plies were found to contain very small cracks, not visible to the naked eye. NRC Information Notice (IN) 92-20, "Inadequate Local Leak Rate Testing," was issued on March 3, 1992. These events revealed that the Type B LLRT performed between the two plies could not be relied upon to accurately measure leakage rate. The reason being that the two plies of the bellows may be in contact with each other, restricting the flow of the test medium to the crack locations. Investigations [1] showed that any two-ply bellows may be susceptible to this problem.

Some of the "like-new" bellows, and all but one of the corroded bellows specimens were tested at an elevated temperature (425°F) because the bellows material (304 stainless steel) degrades with temperature to the point that it has lost approximately 35% of its ductility by the time it reaches 400°F. Most of the loss in ductility occurs between room temperature and 400°F. Therefore, testing at temperatures significantly above 400°F was not believed to be worth the added complexity and cost. Conditions such as physical damage, misalignment, and weld repair were not considered during testing.

Containment bellows convolutions are "cold-formed" from type 304 stainless steel at room temperature. For almost all containment bellows, no postforming annealing is performed so that considerable strain hardening and residual stresses are present in the bellows convolutions. None of the bellows tested in this program were annealed. When subjected to a corrosive environment, highly stressed stainless steel bellows are susceptible to transgranular stress corrosion cracking (TGSSC). A number of occurrences have been reported in operating nuclear power plants. For this reason, it was decided to extend the scope of the bellows test program, which originally was to investigate only "like-new" uncorroded bellows, to include an investigation of bellows subjected to varying degrees of corrosion. To perform the corrosion study, six bellows specimens, originally intended to be tested in "like-new" condition, were subjected to accelerated corrosion environments followed by combinations of elevated pressure, temperature, and axial and lateral deformations. The specimen geometries and load combinations were similar to the "like-new" experiments described in Volume I; thus, insights on the degrading effects of corrosion on leak-tight capabilities of bellows can be obtained by comparing the "like-new" and corrosion test results.

The goal of the accelerated corrosion was to produce bellows corrosion that would be evident in visual inspection, but would not cause the bellows to leak. In this way, the bellows would still pass the required periodic leak tests. Testing of corroded bellows and comparison of results from similar tests of "like-new" bellows would reveal if the capacity of bellows subjected to minor corrosion is reduced. Another intent was to corrode some bellows specimens to the point that leakage would be evident in the periodic leak tests. The goal of these tests was to study the growth of leak paths when extreme loading conditions are applied to such bellows.

In order to accelerate the corrosion process and yield results that would be comparable to observed TGSSC, bellows convolutions were wetted with a concentrated solution of magnesium chloride ($MgCl_2$).

Because of the limited number of corroded specimens and the problems experienced in producing and quantifying the precise amount of desired corrosion, it is impossible to draw any comprehensive conclusions regarding the leak-tight capabilities of bellows with varying degrees of corrosion.

However, some noteworthy insights were gained through these experiments, as described below:

(1) If only one of the two plies of a two-ply bellows is subjected to corrosive environments, it seems that the bellows is fully capable of resisting extreme loadings, up to, or very near, full compression with accompanying pressure, temperature, and lateral deformation loadings, without developing leakage, regardless of the amount of damage in the corroded ply. (Full compression is defined as the point at which all the convolutions and the end spools are in metal-to-metal contact.)

Five of the six corrosion bellows specimens were two-ply bellows. The corrosive environment was applied to the outer ply in each case, with the inner ply protected from the corrosive solution by the outer ply. A small amount of corrosive solution may have reached the inner ply in three of the specimens since some leakage of the outer ply was measured after the specimens were removed from the solution. However, because the solution was not pressurized and because of the relatively small cracks in the outer ply, the actual amount of solution that came into contact with the inner ply is believed to be very small and certainly not enough to appreciably damage the inner ply. The inner ply remained leak tight for each of the two-ply specimens, even after being subjected to more than one cycle of loading in some cases. Therefore, if a given two-ply containment bellows experiences corrosion on only one of its plies, it seems likely that the leak-tight capability of the bellows will not be significantly reduced for severe accident types of loadings.

(2) Three corroded bellows were leak tight before being subjected to extreme loadings, and they were able to withstand severe load combinations before developing leakage. However, no conclusions can be drawn because of the limited number of appropriate test cases. The importance of this matter is to be able to determine if potentially corroded bellows, which still pass leak test requirements, can withstand severe load combinations.

Two of these specimens were leak tight at full compression with accompanying pressure, temperature, and lateral deformation loadings. The third specimen began leaking at about 50% of full compression; however, the source of the leakage was not related to corrosion. Instead, the leak was caused by failure of the weld around the tube used to apply pressure between the plies.

Each of these specimens showed visible signs of corrosion before loading, yet they were leak tight. However, it is not known how close any of these specimens were to a leakage condition before the loading conditions were applied.

(3) If bellows are not leak tight as a result of corrosion before the loads are applied, then the rate of leakage increase caused by increased loadings seems to depend heavily on the pretest condition of the bellows (i.e., how bad the corrosion is before external loads are applied).

Leakage was measured from three of the bellows specimens after the corrosion process was completed, but before any loadings were applied. Two of the specimens exhibited very small leaks from corrosion-induced cracks barely visible without magnification. For these tests, leakage grew steadily, yet relatively slowly, as the applied loadings were increased. For both specimens, the amount of leakage stabilized in the range of 50 to 75% of full compression and did not increase any more as the loading was increased to the point of full compression. This behavior was caused, at least in part, by increasing metal-to-metal contact between adjacent convolutions as the bellows were further compressed, thereby restricting available leak paths from the convolutions. The key point here is that these two bellows did not "fall apart" when subjected to extreme loadings, even though the pretest corrosion damage was significant enough to produce leakage.

Leakage of the magnitude that occurred during the bellows tests would not cause a failure of the Type A test, but this amount of leakage could not be considered insignificant. In nearly all Boiling Water Reactors (BWRs), there is a Technical Specification requirement limiting the leakage of main steam isolation valves to approximately 0.2 standard cubic feet per minute (scfm). In the bellows tests, the measured leakage of bellows specimen C-6-2 (Test I-5-SCT) at 50% of full compression was 0.25 scfm. Bellows specimen A12-2-2 (Test I-8-SCT) had a measured leak of 1.0 scfm at 50% of full compression.

The third bellows that leaked prior to loading was severely damaged by the corrosive process. This was the first specimen subjected to the accelerated corrosion process and, because of unanticipated problems, the bellows experienced severe damage before the corrosion process was stopped. For this specimen, a few relatively large cracks, with a width similar to the thickness of the bellows ply thickness of 0.020 inch, were present, along with many smaller cracks. The specimen would have appeared damaged in even a casual visual inspection and would have had no hope of passing a leak test. For this third specimen, the small cracks joined together to form much larger cracks at only 10% of full compression. As the applied compression increased, the cracks grew even larger and the outer ply began peeling away from the bellows, opening large leak areas. However, the inner ply, which was not subjected to corrosion prior to testing, remained leak tight up to full compression in spite of the level of damage in the outer ply.

Acknowledgments

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[1] Ktech Corporation.

1 Introduction

The bellows tests are part of the Containment Integrity Programs [2], which are being conducted at Sandia National Laboratories under the sponsorship of the Nuclear Regulatory Commission (NRC). The final goal of the Containment Integrity Programs is to generate a suite of validated methods that can be used to predict containment behavior when subjected to severe accident conditions. In pursuit of this goal, a series of scale model containment buildings have been tested to failure. The models were subjected to static internal overpressurization at ambient temperatures, with the response being monitored by a large number of sensors. The measured response was then compared with analytical results that were compiled both before and after the test, in order to verify the analytical methods.

Because of the limited number and scale of the containment models, separate programs have been conducted to further investigate the severe accident behavior of containment penetrations. Electrical penetration assemblies, compression seals and gaskets, inflatable seals, personnel airlocks, and equipment hatches have been tested. The ongoing bellows experiments are a part of the containment penetration test series.

1.1 Background

The bellows test program was initiated as a result of concerns that bellows could be a possible source of containment leakage during a severe accident. The goal of this research program was to investigate the pressure, temperature, and deformation conditions that would be likely to cause a tear in the bellows, and produce a leak path through the containment boundary.

Bellows are used at the piping penetrations of containments to minimize the loadings imposed on the containment shell caused by differential movement between the pipe and the containment wall. Since these bellows are an integral part of the containment pressure boundary, they are subjected to the same conditions as the containment building. During a severe accident, those conditions would involve combinations of axial and lateral displacements, internal or external pressure, and elevated temperatures.

A review of past bellows research programs, containment bellows applications, and finite element analysis of bellows is provided in [3]. Several bellows manufacturers and designers were also interviewed as part of the extensive background review into past research efforts. Analytical methods were unable to model the bellows at the large deformations required for bellows failure, therefore, an experimental program was initiated to develop empirical methods to estimate bellows capacity.

Bellows are used primarily in steel containments, and are of two main types [4]. One type, used in both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) containments, is process piping bellows, which vary in size from 6 to 60 inches in diameter. The other type is vent line bellows that are used in BWR Mk-I containments. They range in size from 65 to 125 inches in diameter. Process piping bellows are normally constructed of two plies of SA240, type 304, stainless steel which are separated by a thin wire mesh (~0.010-inch wire diameter). The redundant outer ply provides a means to check for leakage of the bellows by pressurizing the space between plies and noting any drop in pressure. In contrast with process piping bellows, the majority of vent line bellows are one-ply; approximately 10% are two-ply. Figures 1, 2A and 2B illustrate the relative location and construction details of some typical containment bellows.

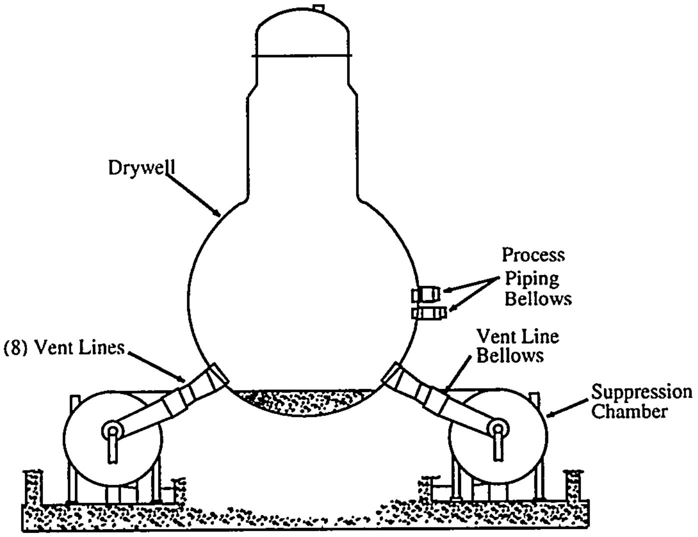

Figure 1. BWR Mark-I Containment

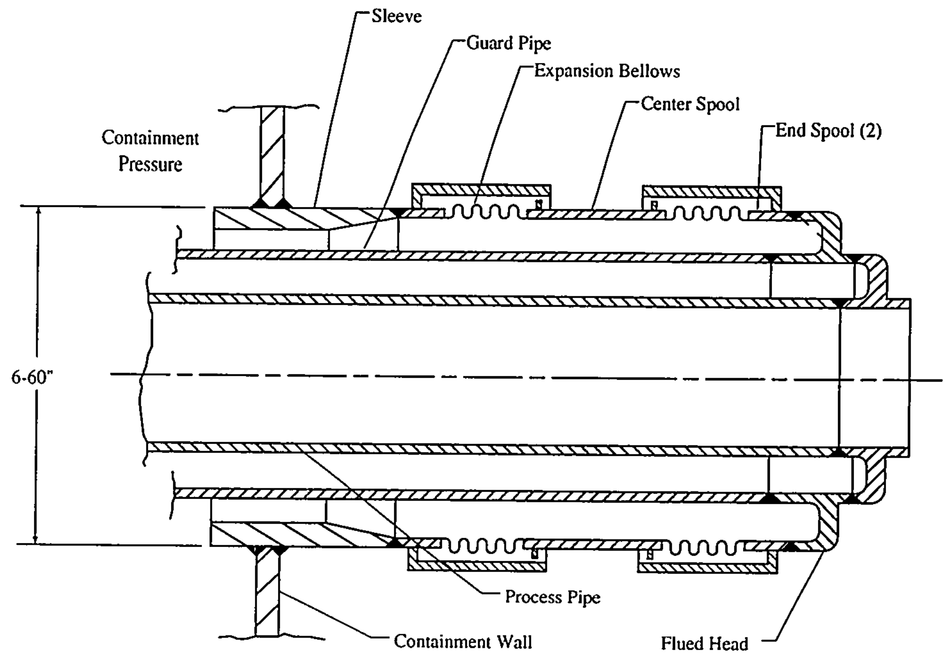

Figure 2A: Typical Process Piping Bellows Configuration

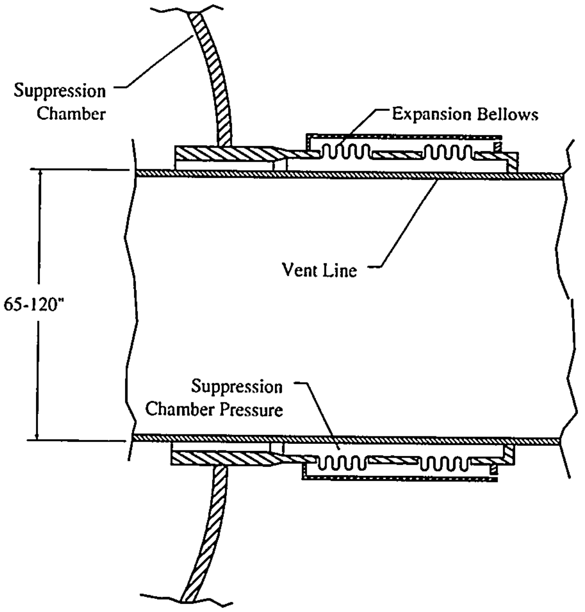

Figure 2B: Typical Vent Line Bellows Configuration

Bellows are designed to accommodate differential movements that occur between the containment shell and the pipe to which they are attached. The design basis for these movements are obtained by summing the maximum deformations associated with normal operation, safe shutdown earthquake (SSE), and loss of coolant accident (LOCA). The design standards are provided by the Expansion Joint Manufacturers Association (EJMA) [5]. Normally, bellows are conservatively designed to withstand about 5000 cycles of design-basis loading, although they typically experience only a few minimal cycles due to startup and shutdown of the reactor.

In the event of a severe accident, the bellows could be subjected to pressure, temperature, and deflections well beyond the design basis. As illustrated in Figure 3, the axial displacement of the bellows would be relatively small until the containment vessel yields in the axial direction. After yielding, the axial displacement per unit change in pressure would increase at a much faster rate. In most cases, the bellows are connected to the outside of the containment shell (as shown in Figures 2A and 2B) such that radial growth of the containment due to internal pressure would impose axial compression on the bellows. In a few cases, the bellows would be elongated due to the bellows being installed on the inside of containment. The bellows would also be deflected transversely, due to the upward movement of the containment caused by pressure acting on the dome, and by thermal expansion of the containment. It is likely that the bellows would fail if the convolutions become fully compressed. Failure would occur as the end spools (see Figures 2A and 2B) cut through the thin bellows material or as a result of failure of the connection of the end spools to the piping, since these connections were not designed for transferring the movement (loading) of the containment shell directly to the piping. The primary question to be answered is: are containment bellows capable of reaching the point of full compression without leaking?

After a background review did not reveal any data on the performance of bellows subjected to severe accident conditions [3], a test series was formulated to examine the behavior of various configurations of bellows geometries under severe accident loadings. The specimen geometries were selected after a lengthy search to determine the types most frequently used by the nuclear power industry, and to derive a representative cross-section of those types. Twenty specimens were constructed in an effort to include variations in numbers of convolutions, depth of convolutions, ratio of convolution depth to ply thickness, and universal versus single-element bellows.

Thirteen bellows specimens were tested in "like-new" condition. The results of those tests are reported in Volume 1 of this report [6]. Because the results of the thirteen tests indicated that "like-new" bellows would remain leak-tight up to, or near, the point of full axial compression, while subjected to extreme conditions of internal pressure, elevated temperature, and lateral deformation, the decision was made to test the remaining seven bellows specimens in a degraded condition.

There are various conditions that may result in a reduction of bellows capacity, such as corrosion, physical damage, misalignment, and weld repair. Because of the insignificant number and magnitude of loading cycles during normal operating conditions, fatigue is not believed to be an important issue in determining containment bellows capacity in undamaged, properly aligned bellows. Evidence that fatigue is a factor in limiting the capacity of a bellows that has been subjected to physical damage or misalignment has been reported [7]. However, physical damage, misalignment, weld repair, and resultant fatigue issues are outside the scope of this study, and therefore were not investigated.

Because bellows are generally not annealed after cold forming operations, stresses introduced during forming are present. This causes bellows to be susceptible to stress corrosion cracking. Transgranular stress corrosion cracking (TGSSC) of containment bellows has been reported at some power plants. The TGSSC was not detected during the general visual examination required by 10 CFR Part 50, Appendix J, nor was it detected during the Appendix J Type B testing. The corrosion was detected with performance of the Appendix J Type A test when the leakage was observed to be abnormally high. Both plies of the bellows were found to have cracks, which resulted in replacement of the bellows [8].

After researching available data, the decision was made to corrode the remaining seven bellows specimens in a manner that would be representative of reported occurrences of TGSCC. Testing of those corroded bellows is the subject of this report.

The material properties of type 304 stainless steel, which is used in containment bellows construction, degrades with increasing temperature. The loss of elongation (or "ductility") is reportedly reduced by about 35% from ambient to 400°F. Figure 4 was generated using material data taken from several sources [9, 10, 11, 12].

Since ductility is the most important material property in determining bellows tearing, and the largest change occurred between room temperature and 400°F, all but one of the corroded specimens were tested at temperatures of 425 ±25°F.

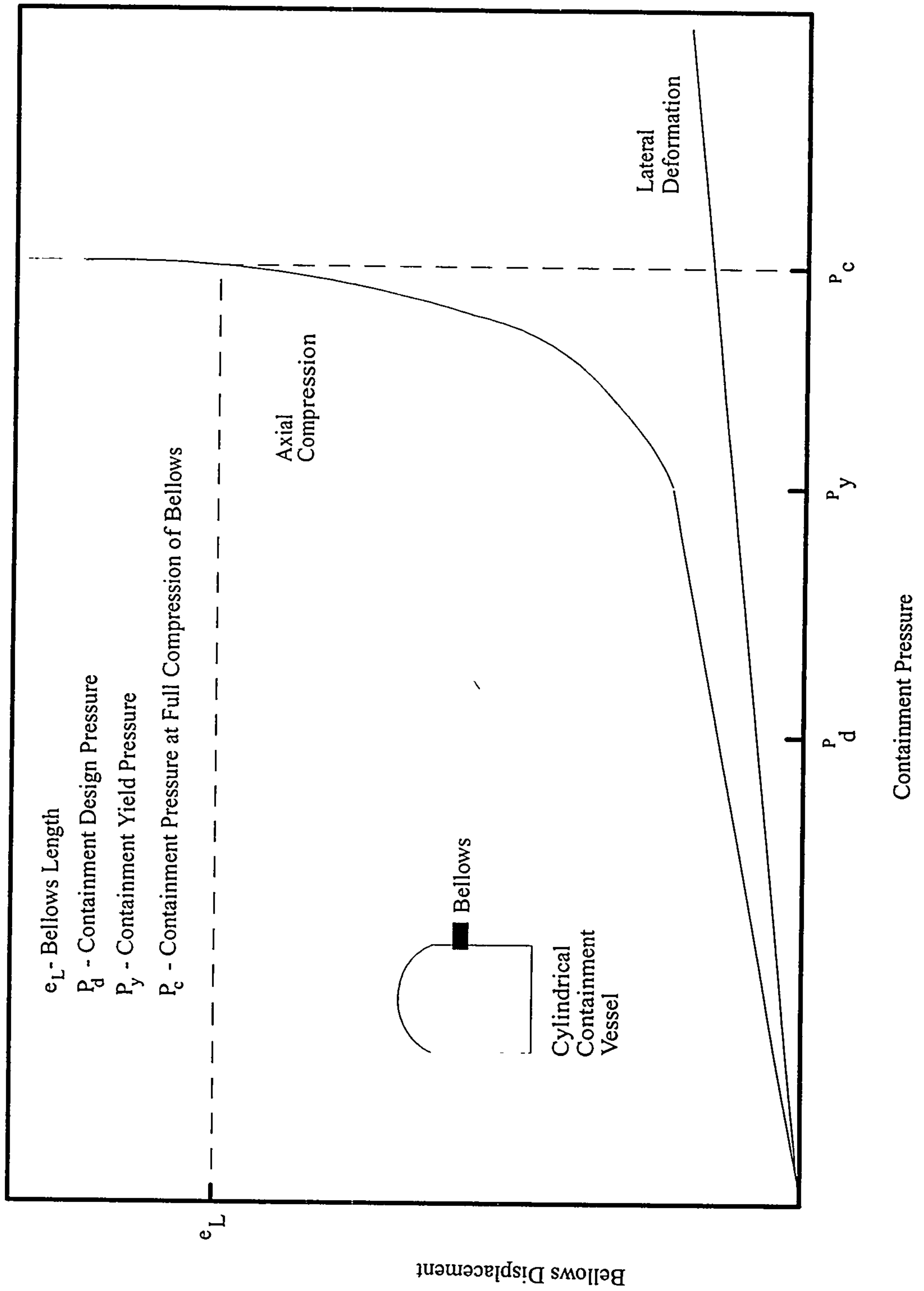

Figure 3. Typical Bellows Loadings Vs. Containment Response

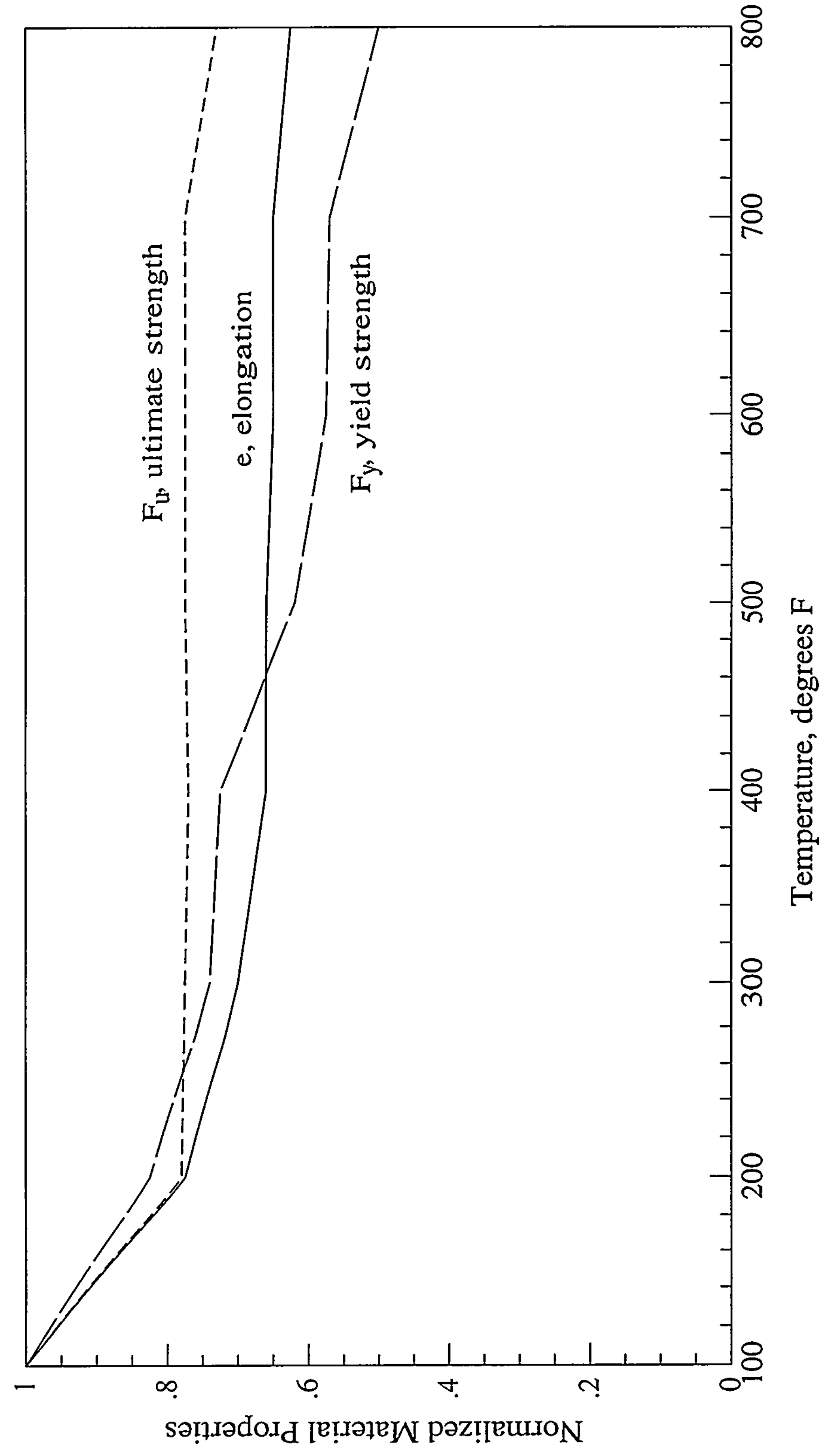

Figure 4. Effect of Elevated Temperature on F_u, F_y, and e of Type 304 Stainless Steel

2 Test Specimens

2.1 Specimen Construction

All of the bellows specimens were fabricated by a supplier of nuclear grade bellows, and were fabricated to nuclear specifications.

The specimens that were tested in a corroded condition were originally part of the twenty specimens that were to be tested in "like-new" condition. After thirteen tests had shown that bellows in "like-new" condition were very resilient and able to withstand extreme displacement and remain leak tight, the remainder of the bellows were set aside for a series of corroded specimen tests. The geometry of the tested bellows specimens is provided in Table 1. Figures 5 and 6 show the bellows convolution parameters listed in Table 1. All of the bellows specimens were constructed of type 304 stainless steel. The sheet material from which the bellows were formed was annealed. The bellows were not annealed after fabrication, so high residual stresses were present. This makes them vulnerable to stress corrosion cracking when exposed to corrosives such as chlorides.

2.2 Corrosion Process Development

Contact was made with utilities that had experienced corrosion of bellows in an attempt to retrieve whatever information was available. This effort met with limited response, but some very useful information on the type and extent of corrosion that had been observed on some power plant bellows was obtained. After assimilating the information, Sandia's Mechanical and Corrosion Metallurgy Department was contacted. Discussions and reviews of the information with them revealed that the most damaging aspect of the corrosion was transgranular stress corrosion cracking (TGSCC) caused by chlorides. A recommendation was made to use a saturated solution of magnesium chloride ($MgCl_2$) heated to a temperature of 207 °F to initiate TGSCC.

The temperature of 207 °F was chosen to reduce the complexity of the setup described in the American Society for Testing and Materials (ASTM) standard for a corrosive solution of $MgCl_2$ [13]. That standard specifies a closed-loop vapor recovery system with the temperature of the corrosive solution maintained at the boiling point of the concentrated solution (311 °F). Because the physical size of the bellows specimens would have required a complex and expensive corrosion setup to follow the ASTM standard, a method that would achieve the desired results at a cost of increased time was chosen. Basically, the lower temperature would allow the corrosive process to be set up without a vapor recovery system, and allow the use of a corrosion-resistant container made from less costly material.

Subsequent tests conducted by Sandia's Mechanical and Corrosion Metallurgy Department showed that it was possible to produce TGSCC in a small section cut from a formed bellows constructed of 304 stainless steel within a reasonable amount of time. The specimens were removed from a similar section of bellows containing the same residual stresses as the bellows that were to be tested. Specimens developed cracks in approximately 55 hours. It was noted that the cracks seemed to start at the cut edges of the samples. Further tests were made with specimens having the cut edges coated with room temperature vulcanizing rubber (RTV). The time to cause cracks to initiate away from the edges increased to approximately 70 hours.

After an acceptable method of initiating TGSCC had been developed, attempts were made to generate cracks that did not penetrate the thickness of the bellows material. The impetus behind this desire was to produce a bellows that had enough corrosion to possibly degrade its performance during a severe accident, but not enough to be detectable by means of a containment leak rate test.

Several longitudinal strips were cut from extra bellows specimens and subjected to corrosion, but the random nature of the corrosive process seemed to preclude being able to predict with any certainty when the cracks would develop. Once the cracks had developed, they propagated rapidly, and if the specimen was not inspected frequently, the corrosion rapidly reached the point of being excessive for testing purposes.

An attempt was made to employ an acoustic sensor to detect the initiation of cracking. Some success was realized, but the process did not prove to be reliable.

After expending considerable time and effort to develop a reliable method of developing TGSCC and meeting with limited success, it was decided to scale up the process to a full bellows specimen. The bellows chosen (specimen A-12-2-1) was one of the only identical pair of specimens available.

Table 1 Bellows test specimen data*

Specimen I.D.	Number Required	Inner Diameter d_i (in.)	Number of Convolutions N	Number of Plies, n	Ply Thickness t (in.)	Convolution Depth w (in.)	Convolution Pitch q (in.)	End Tangent l_t (in.)	Center Spool L_c (in.)
Phase I:									
A-8-2	1	12.00	8	2	0.020	0.50	0.50	1.00	Single†
A-12-2	2	12.00	12	2	0.020	0.50	0.50	1.00	Single
C-6-2	1	12.00	6	2	0.020	0.50	0.50	1.00	4.00
D-6-2	1	12.00	6	2	0.020	1.25	0.50	1.00	4.00
Subtotal	5								
Phase II:									
VL-1	1	19.25	12	1	0.020	0.50	0.50	1.00	3.00
Subtotal	1								
Total	6								

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*Specimen I.D. numbers in Phase I tests denote the bellows construction. The first letter (A, C or D) indicates convolution depth (A and C=0.5 in. and D=1.25 in.). The first number indicates the number of convolutions (6, 8 or 12), and the second number indicates one or two plies .

†Specimens with A designation are single bellows. C, D, and VL (vent line) are universal (see Figure 6) bellows.

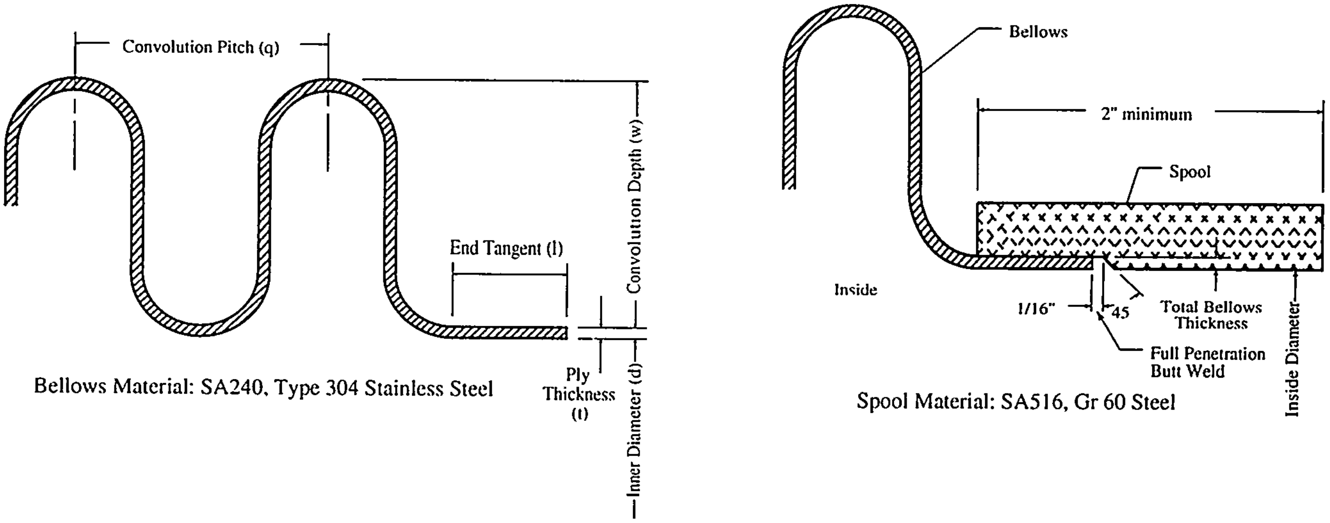
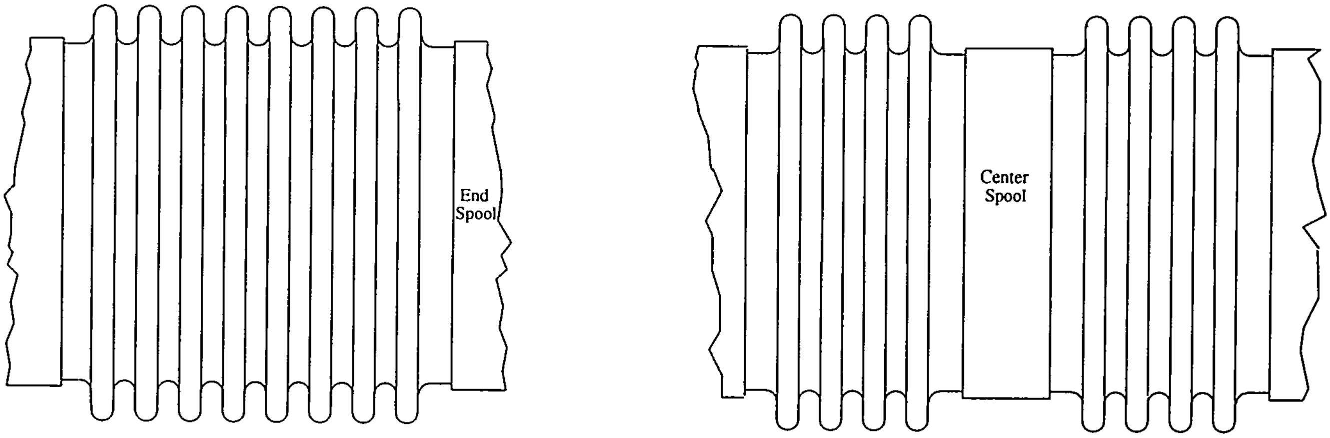


Figure 5. Bellows Construction Details.



Single Element Bellows

Universal Bellows

Figure 6. Bellows Configurations.

A large container made of polyethylene plastic was selected to contain the corrosive solution. Immersible electric heaters were placed around the specimen to maintain a temperature of 207 °F. An acoustic sensor was attached to the specimen to attempt to detect the onset of cracking.

The specimen was periodically removed and checked for cracks visually. After the time greatly exceeded that shown to give results in the small lab tests, more small samples were tested. Test were conducted using the same type of hydrated $MgCl_2$ that was being used in the corrosive solution that the full bellows was immersed in. The results were basically the same as those observed earlier.

A theory was proposed by Sandia's Mechanical and Corrosion Metallurgy Department as to the possible cause of the problem. It was surmised that a voltage was being developed as a result of the galvanic action between the dissimilar metals (stainless steel and mild steel) that comprise the bellows specimen, and the magnesium chloride solution. That condition was not experienced in the laboratory, since the only material in the test solution was a section of a stainless steel bellows.

Subsequent measurements confirmed that a voltage was being generated, and was of the right magnitude and polarity to cause the stainless steel to be protected from the corrosive solution.

The course of action chosen to remedy the situation was to coat the mild steel portion of the bellows specimen (end spools and mounting flanges) with an insulating epoxy that would withstand the elevated temperature and corrosiveness of the $MgCl_2$ bath.

Measurements made on the specimen and corrosive bath after the bellows had been coated indicated that the coating was performing well, but the bellows had not developed any cracks after exposure to the corrosive bath for approximately 9 days. The corrosive bath was refreshed with new solution and a similar solution was used in the lab to run more tests to try to determine the difference between the small sample and the bellows.

An equipment failure during an unattended period led to melting a hole in the polyethylene container and loss of the corrosive fluid surrounding the bellows. On inspection of the bellows it was found to be severely cracked. It was surmised that the temperature had increased to some high level because of the loss of the fluid, and the bellows had been exposed to a corrosive steam atmosphere.

The bellows was tested as described in Section 5 (Test I-7-SC) and corrosion attempts continued on the next test specimen.

Based on the assumption that cracks had developed as a result of the bellows being exposed to high temperature corrosive steam, the next bellows test specimen was placed on blocks above the liquid level. It was surmised that this would also cause an increase in oxygen levels which might accelerate the stress corrosion process. Higher temperatures (approximately 216°F) were also used in an attempt to accelerate the corrosive process. A small specimen cut from a section of the bellows convolutions cracked in approximately 24 hours in this environment. However, the specimen did not crack.

Since attempts to corrode the bellows met with very little success because of the galvanic action of the dissimilar metals, a method was sought to prevent the galvanic action from occurring. The method that had been used to this point was to try to insulate the mild steel from the corrosive solution by coating it with some material that would insulate it electrically and be capable of withstanding attack by the corrosive at elevated temperatures. It is believed that small imperfections in the epoxy coating allowed the galvanic action to continue at a somewhat reduced rate.

The new method that was tried was to place the bellows in a horizontal configuration with a saturated solution of $MgCl_2$ applied through a "drip" system at the top of the convolutions. In this way, the carbon steel end spools were not exposed to the corrosive solution and thus galvanic action between the carbon steel end spools and stainless steel bellows was prevented. A temperature-resistant blanket was wrapped around the convolutions to keep the stainless steel of the convolutions wet with the corrosive solution (Figure 7). The solution was heated in the catch-basin located beneath the bellows. A pump was used to recirculate the solution to the distribution manifold above the specimen. Infrared heat lamps were trained on the bellows at four locations to supplement the heat input to the solution. Specimen A12-2-2 was the first bellows subjected to this corrosive process.

After exposure for one day (approximately 7 hours), the specimen exhibited several rust-colored areas and small pits, but no cracks. The following day the specimen received approximately 5 hours of exposure. When it was inspected, there was more evidence of discoloration of the surface and some pitting. After another exposure of approximately 7 hours, there was an increase in rust-colored areas and possibly some very small cracks. After another 4 hours of exposure, it was decided that there was sufficient corrosion for testing purposes, and the bellows was tested as described in Section 5 (Test I-8-SCT). The remainder of the bellows specimens were corroded in this manner.

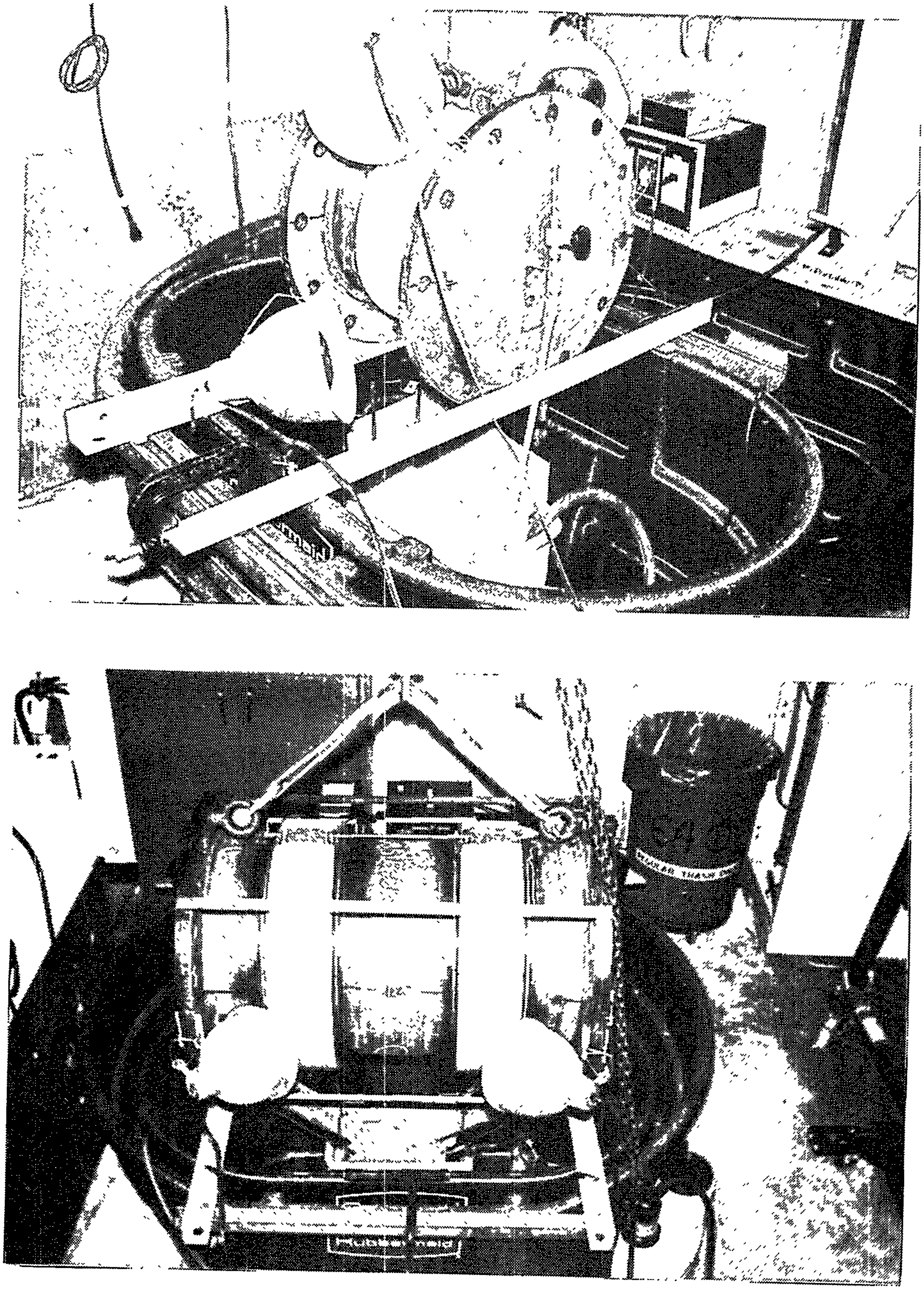


Figure 7. Corrosion Setup.

3 Description of Tests

The test series subjected corroded bellows to severe accident loadings. During the tests, internal pressure, temperature, axial compression, and lateral deformation were applied. The bellows were loaded axially in compression because the amount of axial deformation is more limited in compression than extension owing to the occurrence of full compression. Full compression is defined as the point where all the convolutions and the end spools are in metal-to-metal contact. Also, most bellows are located so that they would be compressed during a severe accident.

Bellows specimens were divided into two broad categories. Phase I specimens were designed to incorporate a variety of design features found in actual containment bellows, while Phase II specimens were meant to be representative of specific bellows geometries.

For the corrosion test series, there were five Phase I specimens and one Phase II specimen (Table 1). In the original test plan, Phase I specimens were intended to determine which of nine different geometries are more likely to leak when subjected to severe accident conditions, and to determine the capacity of bellows in general.

As shown in Table 1, five of the six bellows corrosion specimens were of two-ply construction; however, only the outer ply was subjected to corrosion. Because the inner ply of two-ply specimens is only accessible through small, tapped holes in the bellows end plates, the decision was made to not attempt corrosion of the inner ply. Therefore leakage of the bellows specimens due to corrosion was determined by leakage through only the outer ply.

No attempt was made to adhere to a "Type B" leakage test as is required for containment penetrations. A Type B leakage test is conducted at a pressure greater than the design basis accident (DBA) for the containment that the penetration is installed in. There is also a requirement that the pressure be maintained for a duration of not less than 15 minutes for the pressure decay method of leak detection and measurement.

Leakage of the bellows test specimens was measured to give a relative indication of corrosion damage to the bellows leak integrity.

The test designation, shown and described in Table 2, was followed through the first load cycle. In most cases, if leakage did not occur during the first load cycle, the bellows was subjected to additional loadings until a leak finally developed. The types of additional loadings varied, depending on the tests; the exact loadings applied to each specimen are described in Section 5.

Phase II specimens are representative of specific bellows geometries. The one Phase II specimen that was tested was representative of an approximately 1:4 - scale vent line bellows in a BWR Mark - I.

The maximum test pressure is based on a rough estimate of the pressure capacity of the type of containment in which the bellows would be employed. The maximum lateral deformation represents a "normal" clearance between the pipe and the containment penetration opening. The amount of possible lateral deformation imposed on the bellows is limited to this clearance.

All except one of the tests were conducted at 425 ±25°F to determine the effect of lower ductility at temperature on the ability of bellows to remain leak tight during a severe accident. Elevated temperature testing was required because the bellows material (304 stainless steel) degrades with temperature to the point that it has lost approximately 35% of its ductility at 400°F. Because most of the loss of ductility occurs between room temperature and 400°F, testing at higher temperatures was not investigated. The first specimen that was tested in a corroded condition was tested at room temperature to permit closer inspection of crack development.

All testing may be considered pseudo-static, with each test requiring a few hours to complete.

Prior to corroding the bellows specimens, initial elastic stiffness measurements were recorded for each specimen. The specimen was extended a small amount while the load required for that extension was monitored . The stiffness is the force divided by the distance. That number is reported in the test results (Section 5) for each specimen.

The test procedure for the vent line specimen (VL-1) followed the procedure designated as SCT (see Table 2) with the exception of the lateral deformation, which was limited to 1 inch. This limitation was imposed as a conservative value for the approximately 1:4-scale of this specimen.

Table 2 Description of tests

Test No.	Specimen I.D.	Test Designation*	Maximum Test Pressure (psig)
1	A-8-2	SCT	150
5	C-6-2	SCT	150
6	D-6-2	SCT	75
7	A-12-2	SC	150
8	A-12-2	SCT	150
20	VL-1	†	150

*SC: Simultaneously apply internal pressure, axial compression, and lateral deformation. Internal pressure, axial compression, and lateral deformation shall be increased linearly such that the internal pressure reaches the maximum test pressure level in Table 2 when the total applied lateral deformation is 2 inches when the bellows are fully compressed. If the bellows are still intact after being fully compressed, reverse the applied test conditions by removing axial and lateral deformation as well as internal pressure at the same rate at which each was originally applied. Continue unloading until either a crack develops or until all originally applied displacement and pressure have been removed.

SCT: Same as SC designation, except the temperature is 425 ±25°F throughout the specimen for the entire test.

† This Phase II specimen was subjected to the SCT test designation with the exception of lateral displacement, which was limited to 1 inch.

4 Test Apparatus and Instrumentation

All of the bellows specimens were tested in a hydraulically actuated load frame as described in Section 4.0 of Volume I. All instrumentation and data recording procedures described in Volume I were followed during testing of the corroded bellows. Strain gages were not used on the corroded specimens because of the concern that, once the specimens were in the corroded condition, the additional handling required to install the gages might damage the bellows. Also, strain gages were not used for the bellows tested at elevated temperature owing to the high cost of purchasing and installing gages that could withstand such temperatures.

5 Test Results

Six tests were conducted on bellows that had been previously subjected to corrosion. These tests subjected bellows to extreme axial and lateral deformations as described in Section 3 of this report. As expected, the bellows generally did not perform as well as those tested in "like-new" condition.

All of the corrosion test specimens were subjected to elevated temperature (425°F) except the first specimen, which was severely corroded, resulting in large leakage paths before the test. Because the specimen could not be monitored for leaks, the decision was made to conduct the test at ambient temperature. This meant that the specimen would be more accessible to observation of crack development, since there would be no insulation on the specimen.

Table 3 lists the tests, along with failure conditions for each. The test identification number is coded to indicate the test phase (I or II), the test number (1 through 20; only 19 of the 20 originally planned tests were conducted because one specimen was damaged prior to testing, and could not be used), and the test type (e.g. CL, SE, etc. as described for Table 2). The specimen I. D. is defined in Table 1.

All the test data plots are contained in Appendix A.

The axial deformation required to cause full compression is shown for each specimen in Table 3. Four of the six specimens leaked before reaching full compression. The percent of full compression at the time of first leakage is provided in Table 3 for these specimens. A fifth specimen began leaking on the final axial deformation step to full compression. Leakage was defined as a leak through the outer ply of two-ply specimens because that was the surface exposed to the corrosive.

A detailed description of each test is provided below. An evaluation of test results is presented in Section 6.

Test I-7-SC

The first corrosion bellows specimen was identified as A-12-2-1. The specimen had been subjected to a corrosive solution for many hours with no effects because of initial problems described in Section 2.2. When cracks did occur, they were in excess of the desired conditions. Efforts had been directed at developing specimens with visible corrosion but no measurable leakage.

Upon inspecting the specimen, it was found to contain numerous small cracks and a few larger ones (see Figure 8). Attempts to pressurize the interply volume revealed several major leaks. Because the specimen leaked excessively, it was decided to conduct the test at ambient temperature with extensive photographic coverage of crack development. Since the inner ply was intact, the inner volume was incrementally pressurized in conjunction with displacement steps as described in Table 2 for the SC test designation.

During the test, very little change occurred in the large cracks, which were all located in the convolution nearest the end spool on one end. However, the small cracks developed into larger cracks very early during displacement steps. At approximately 10% of full compression, the cracks had begun to grow larger (Figures 9 and 10), and by approximately 25% of full compression, several of the very small cracks had joined together and opened up into much larger cracks (Figure 11). The inner ply, which had not been subjected to the corrosive bath, remained leak tight through full metal-to-metal compression (Figure 12) and return to original displacement conditions. The inner ply leaked after being partially compressed (approximately 40%) a second time.

Test I-6-SCT

After being exposed to $MgCl_2$ for approximately 355 hours in two different configurations, bellows test specimen D-6-2 did not develop stress corrosion cracking. However, several pits that appeared to be deep enough to possibly cause a leak were observed after the specimen had been immersed in the corrosive solution for approximately 275 hours and placed in a corrosive steam environment of $MgCl_2$ for a period of approximately 80 hours. Figure 13 shows a typical pit. Upon discovery of the pits, the bellows was tested for leaks and found to be leak tight. Because the pits appeared to be deep enough that any further exposure to the corrosive solution might cause a leak, the specimen was tested with no detectable cracks.

The specimen was tested at an elevated temperature of 425°F. The bellows began to leak through the outer ply at approximately 50% of the calculated axial displacement for full compression (end spools in metal-to-metal contact). Axial compression and lateral displacement steps were continued until the bellows was fully compressed and displaced laterally 2 inches (Figure 14). At that time, the inner ply remained leak tight. There was no visible cracking of the outer ply, but the leak appeared to be located in an area where one of the large pits had been observed. After the specimen cooled sufficiently to be removed from the testing machine, it was examined more closely. Because the deformed convolutions were obstructing the area of interest, the specimen was dissected to allow access to the area in question. After the specimen was cut apart, it was apparent that the leak was due to a failed weld at the base of the tube that is used to pressurize the space between the two plies (Figure 15), and not the corrosion pit that had been suspected. It appeared that the weld failure was not related to the effects of corrosion.

Table 3 Bellows failure conditions

Test I.D.	Specimen I.D.	Nominal Test Pressure (psig)	Nominal Test Temperature (°F)	Leaktight at Full Compression of First Loading (yes or no)	Axial Deformation at Full Compression (in.)	Percent Compressed at First Leakage	Initial Elastic Stiffness (lb/in.)
I-1-SCT	A-8-2	150	405	no	3-3/4	100	4070
I-5-SCT	C-6-2	150	430	no	5	10^1	2750
I-6-SCT	D-6-2	75	410	no	5-5/8	50	230
I-7-SC	A-12-2-1	150	Ambient	no	5	*	‡
I-8-SCT	A-12-2-2	150	420	no	5-1/2	20^*	5210
II-20	VL-1	150	410	yes	11-1/4	†	4140

* These specimens were not leak tight at the start of the test, as described in Section 5.
The number represents percent compressed at first change in leak rate.

† This specimen did not develop a leak..

‡ Not measured.

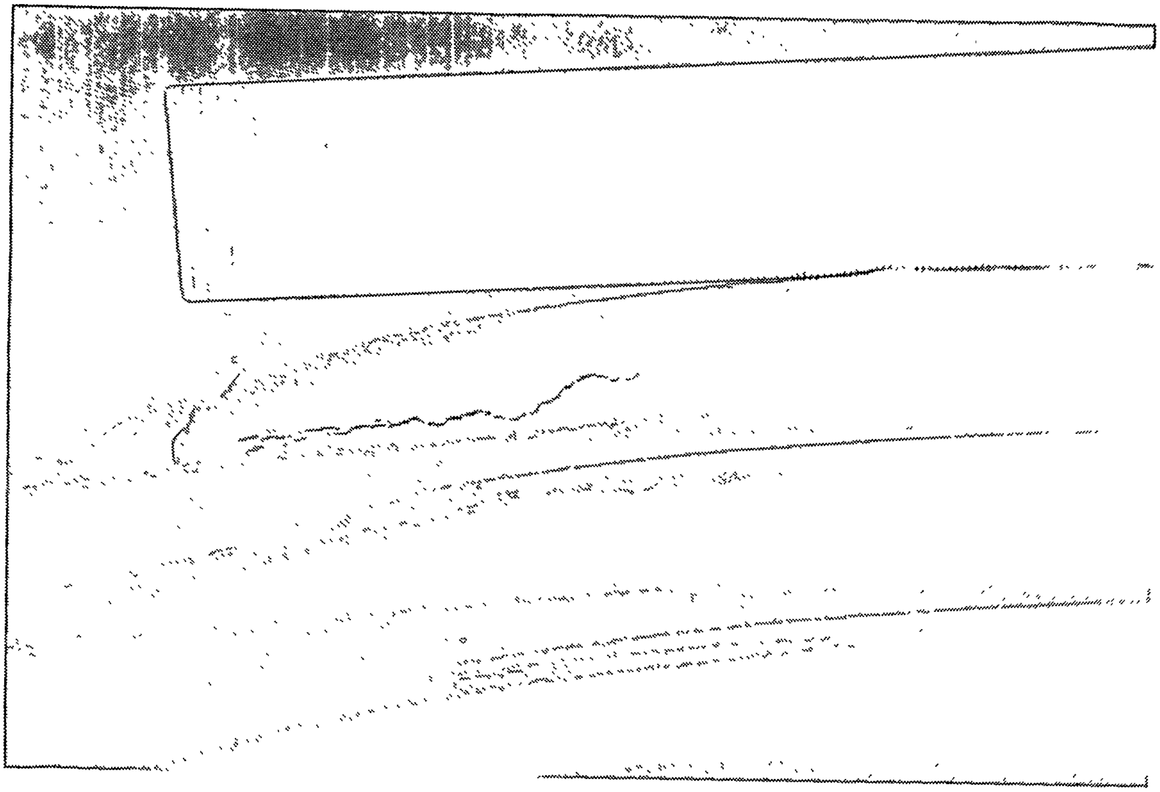


Figure 8. Test I-7-SC. Specimen A-12-2-1 Showing Pretest Cracks.

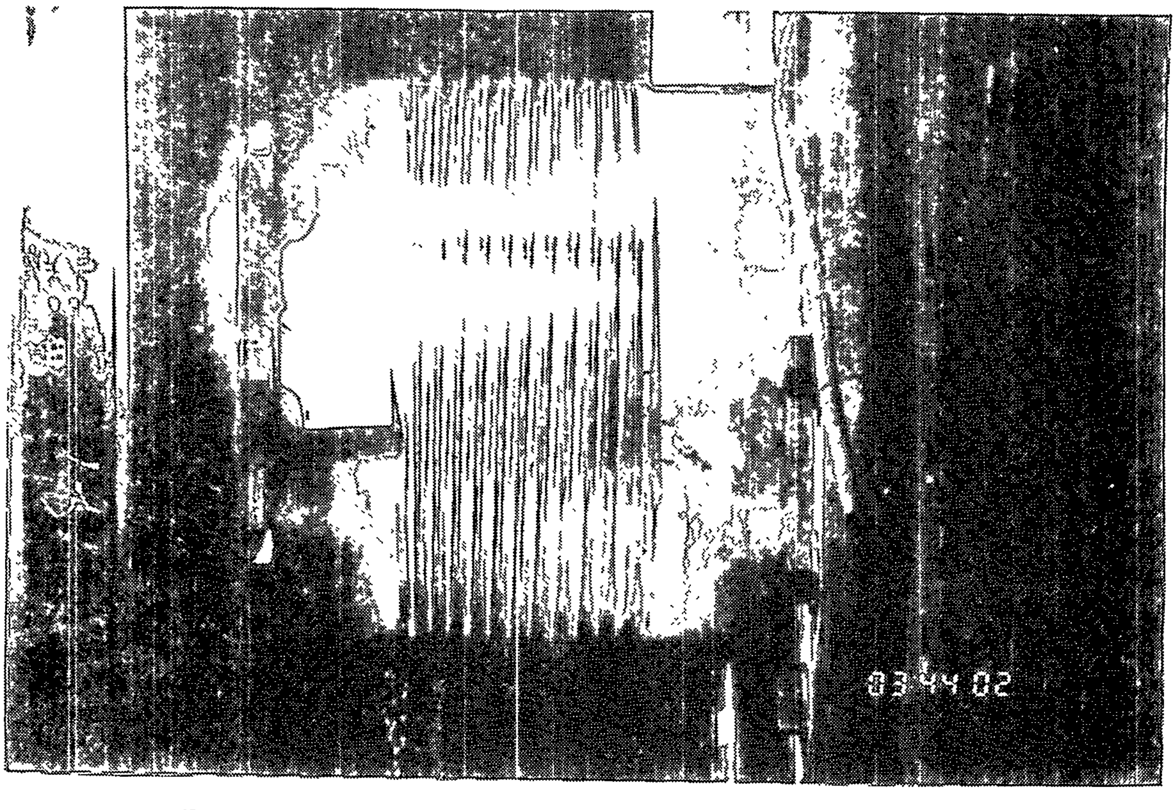


Figure 9. Test I-7-SC. Specimen A-12-2-1 Compressed 10%.

Figure 10. Test I-7-SC. Specimen A-12-2-1 Showing Cracks at 10% Compression.

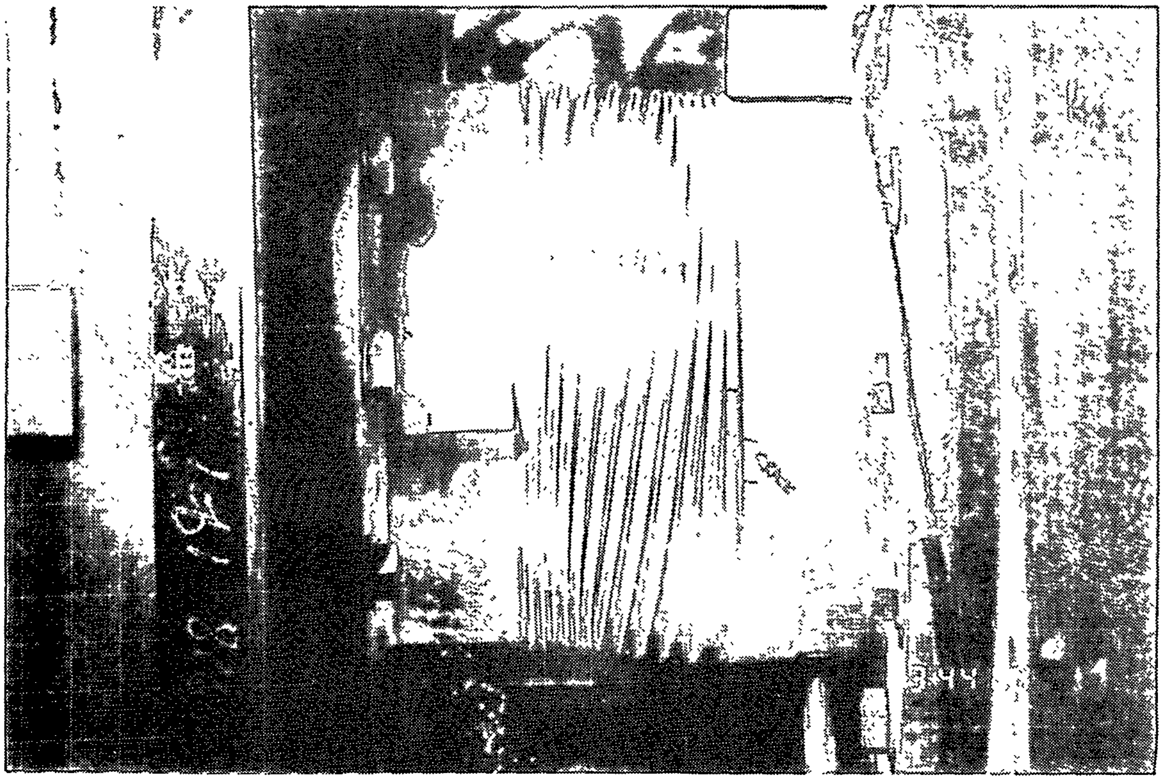


Figure 11. Test I-7-SC. Specimen A-12-2-1 Compressed 25%.

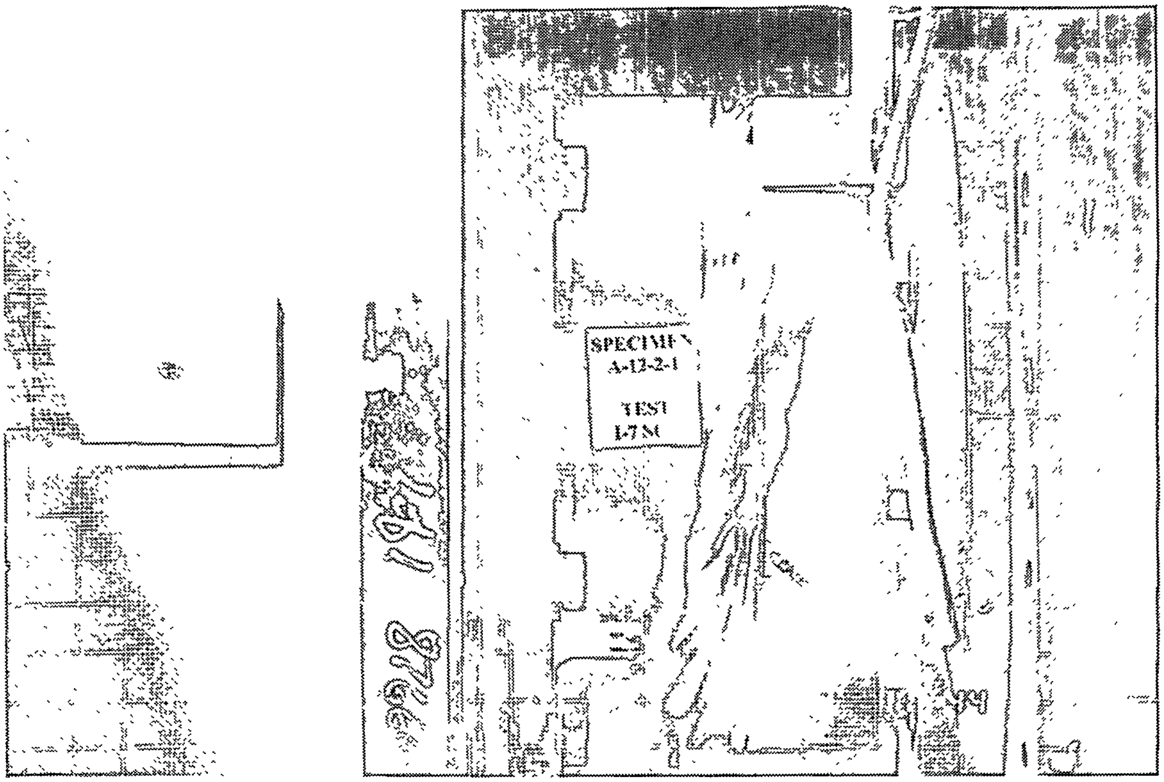


Figure 12. Test I-7-SC. Specimen A-12-2-1 Fully Compressed.

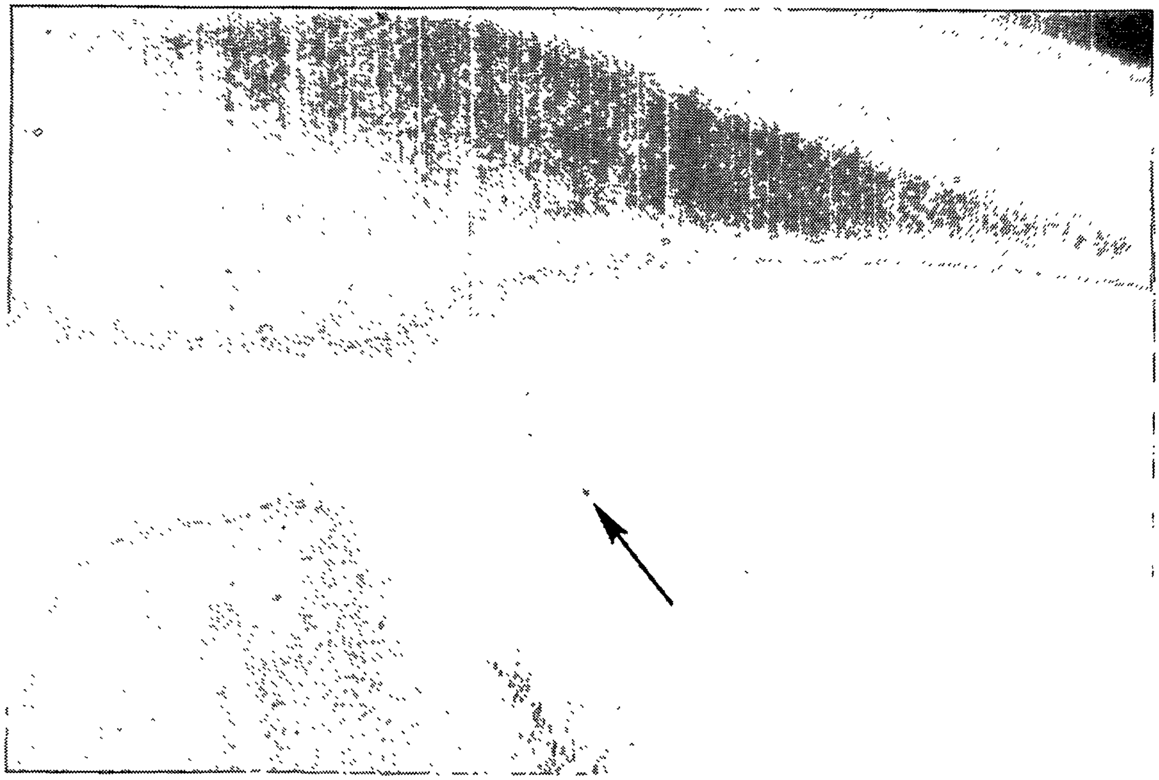


Figure 13. Test I-6-SCT. Specimen D-6-2 Showing Typical Pit.

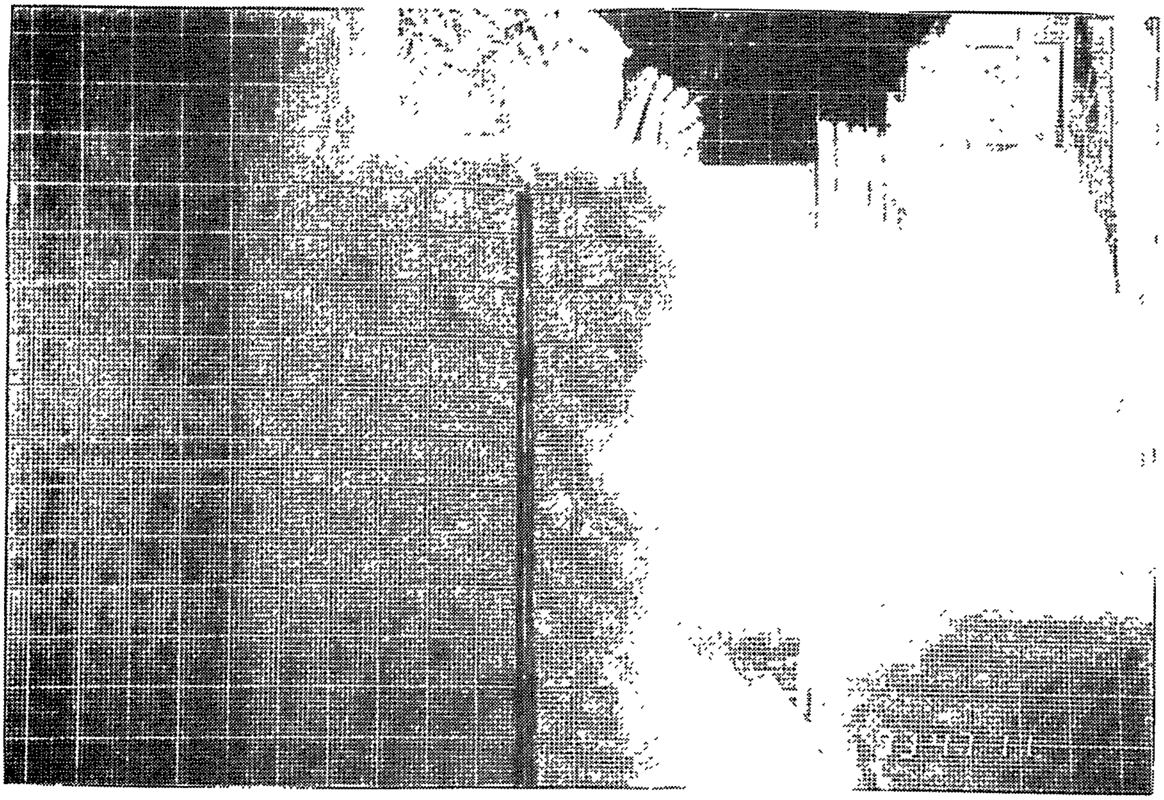


Figure 14. Test I-6-SCT. Specimen D-6-2 Fully Compressed.

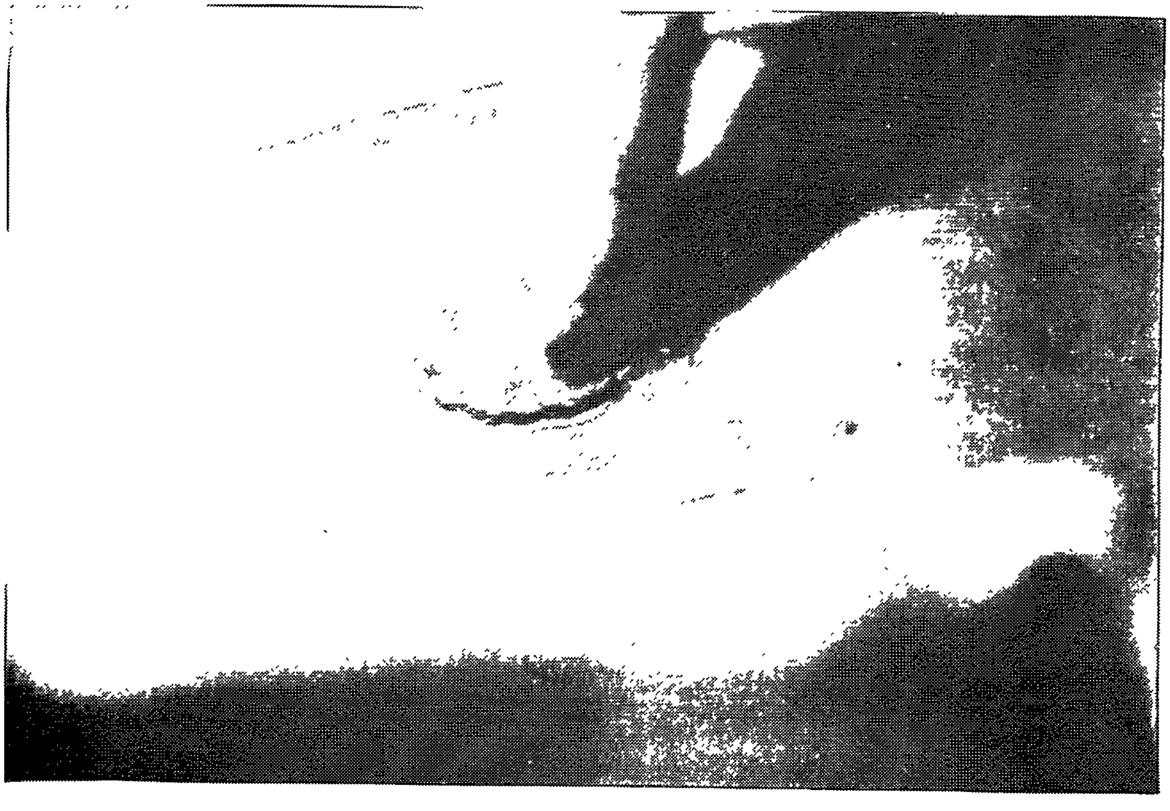


Figure 15. Test I-6-SCT. Specimen D-6-2 Showing Weld Failure of Tube.

Test I-8-SCT

Bellows specimen A12-2-2 exhibited several areas of well-defined cracks that were easily visible to the naked eye after being subjected to the corrosive "drip" system described earlier in Section 2 for a period of approximately 27 hours. When pressurized to approximately 20 psig, three small leaks were detected with a soap solution. The leakage was measured at 0.004 scfm (standard cubic feet per minute).

After the bellows was heated to the test temperature of 425°F, the leak was measured at only 0.003 scfm, which was probably due to thermal expansion and the restraint of the testing` machine. The leak increased to 0.01 scfm when the bellows was displaced axially and laterally to 1.132 inches and 0.4 inch, respectively, which was approximately 20% of the calculated maximum axial displacement for full compression (Figure 16). The leak continued to increase with each displacement step until it reached a maximum of 1.0 scfm at axial and lateral displacements of approximately 2-3/4 inches and 1 inch, respectively, which is approximately 50% of full compression. The leak stabilized at that level and did not increase as the specimen was fully compressed, and displaced laterally 2 inches (Figure 17). As the bellows was returned to the starting displacements, the leak increased again to a maximum of 1.8 scfm (Figure 18). The reason the leak did not continue to increase with axial compression was apparently caused by closing of the small cracks and/or restriction of the leakage path between plies as the bellows was compressed. An example of cracks observed during post-test inspection can be seen in Figure 19.

Test I-5-SCT

Bellows specimen C-6-2 was exposed to $MgCl_2$ for a shorter period of time than the previous specimen in hopes of stopping the corrosive action before a leak developed. The specimen was exposed to the corrosive solution for approximately 13 hours. However, the saturated blanket contacting the specimen was left in place overnight, adding approximately 16 hours of cool-down and cold contact with the corrosive solution.

On pressurizing the bellows to 20 psig, leakage was indicated at several small cracks (Figures 20 and 21) by means of a soap solution. Areas of darker appearing corrosion were plainly visible to the naked eye, but cracks could not be seen without the aid of magnification. The leaks were measured in each section of this universal bellows, with one section showing a leak of 0.00007 scfm and the other 0.0002 scfm[1].

Axial displacement to achieve full compression of the specimen was calculated to be approximately 5 inches. After the specimen was displaced to approximately 10% of full compression, the leakage increased to 0.001 scfm. From that point leakage increased with each compression step. At approximately 25% of full compression the leak had increased to 0.005 scfm (Figure 22), and at approximately 50% of full compression, the leak was measured at 0.25 scfm (Figure 23). The leak continued to increase until the bellows reached approximately 75% of full compression, where the leakage was measured at 1.34 scfm. From that point until the bellows was fully compressed (Figure 24) and expanded back to approximately 75% of full compression, the leak remained constant or decreased. The leak continued to increase from that point until the specimen was returned to the starting displacements where the maximum leakage was measured at approximately 2.12 scfm (Figure 25).

Test I-1-SCT

Bellows specimen A-8-2-4 was tested after being subjected to the corrosive solution by means of the "drip system" for approximately 7-1/2 hours. The major corrosion areas were on the sidewalls of the convolutions at the top and bottom relative to the horizontal placement of the bellows during the corrosion process (Figure26). The corroded areas were smaller than other specimens previously tested. Even though the corroded areas were very small and relatively few in number, there were minute cracks, visible with the aid of magnification, emanating from several of the corroded areas (Figure 27). There was no detectable leakage from the bellows prior to testing.

During testing, the specimen did not leak until full axial compression was achieved (Figure 28). The leak at that point was measured at 0.0004 scfm. The leak increased as the specimen was returned to the original axial and lateral dimensions (Figure 29). Maximum leakage was measured at 0.023 scfm. Post-test inspection of the bellows revealed that there were four leaks. Three of the leaks were located at small cracks in the roots of the convolutions (Figure 30), while the fourth was a much larger leak located near the tube that is used to monitor leakage from the volume between the plies. Further investigation of this larger leak revealed that it was a tear in the bellows material caused by the deformed convolution being forced into the sharp corner of the end spool at the cutout for the interply leak monitoring tube (Figure 31).

Test II-20

The last bellows test specimen, a 1:4-scale single-ply vent line specimen identified as VL-1, was leak tested before being subjected to corrosion because it had been stored outdoors and exhibited a slight amount of surface corrosion.

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[1] Leak measurements were made using three flowmeters with increasing range. The smallest flowmeter had a range of 0 to 1 SLPM (standard liter per minute).

The specimen was verified to be leak tight and was subsequently exposed to the corrosive solution for approximately 7 hours. When the specimen was inspected after the first 3 hours of corrosion, several small rust-colored spots were noted.

The specimen was inspected in 2-hour intervals after that because the specimen is a single-ply bellows, and the need to maintain leak tightness was essential to provide internal pressure loading. Each inspection revealed more and larger corroded areas. The corrosion process was terminated at the end of the day because it was felt than any added corrosion would jeopardize the ability of the bellows to remain leak tight until the start of the test. A few locations exhibited what appeared to be very small cracks, visible with the aid of magnification, starting at corroded locations (Figure32).

The bellows specimen did not develop a leak during the test. The specimen endured two complete cycles of full compression (Figure 33), with accompanying pressure and lateral deformation loadings, and return to original displacements without developing a leak. The test was terminated at the end of the second cycle even though there was no leak. The deep convolutions were very minimally distorted since the lateral displacement was limited to 1 inch. Post-test inspection of the test specimen revealed that some of the cracks had widened during the test (Figure 34), but the bellows remained leak tight.

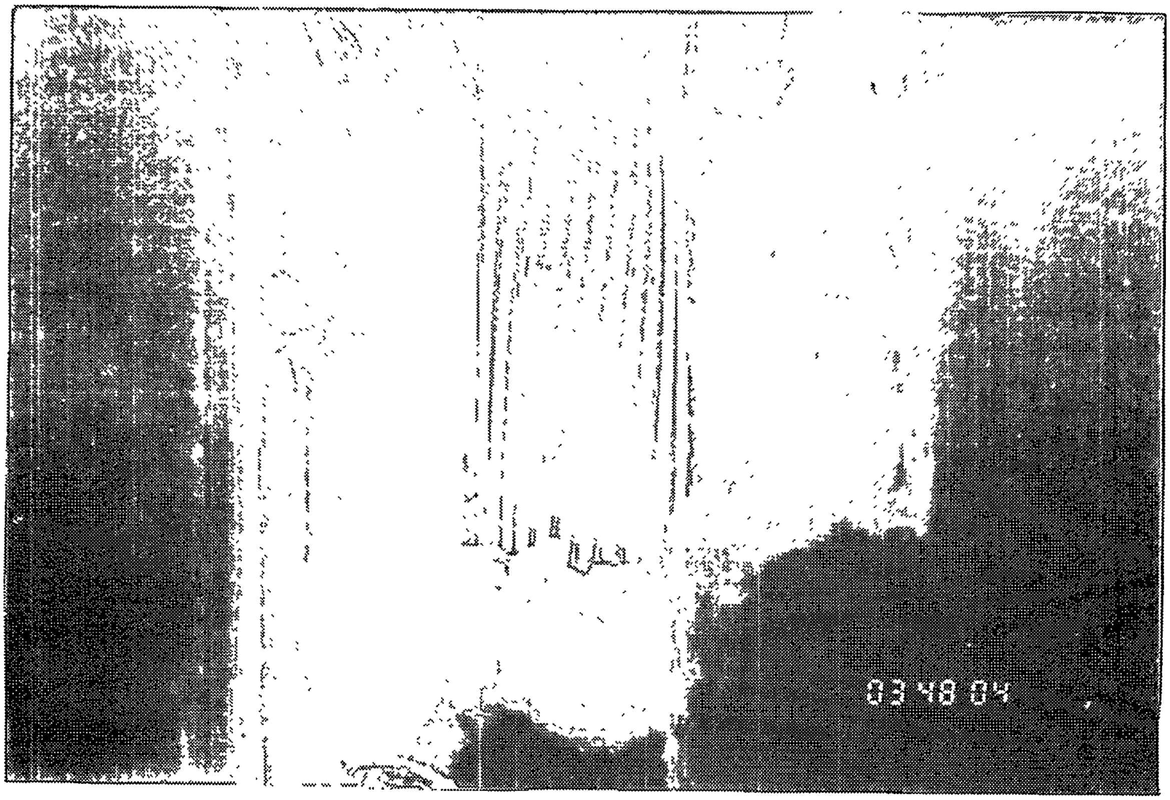

Figure 16. Test I-8-SCT. Specimen A-12-2-2 Compressed 20%.

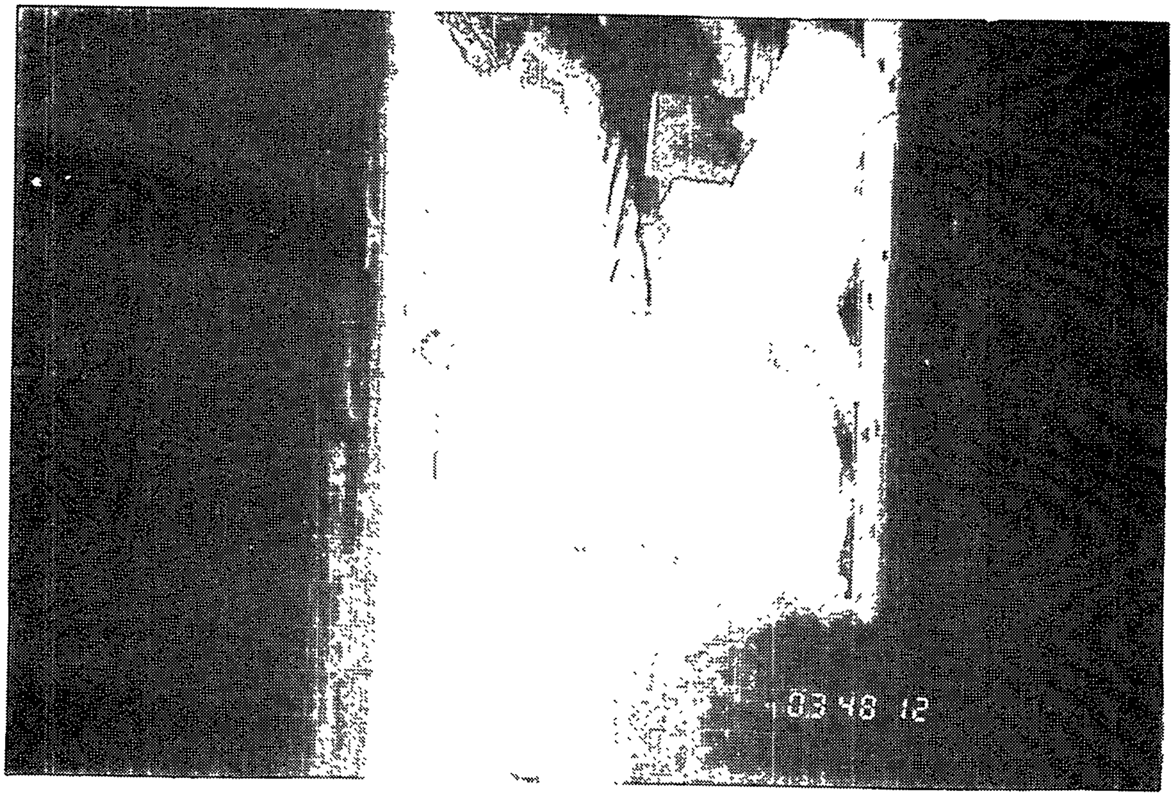

Figure 17. Test I-8-SCT. Specimen A-12-2-2 Fully Compressed.

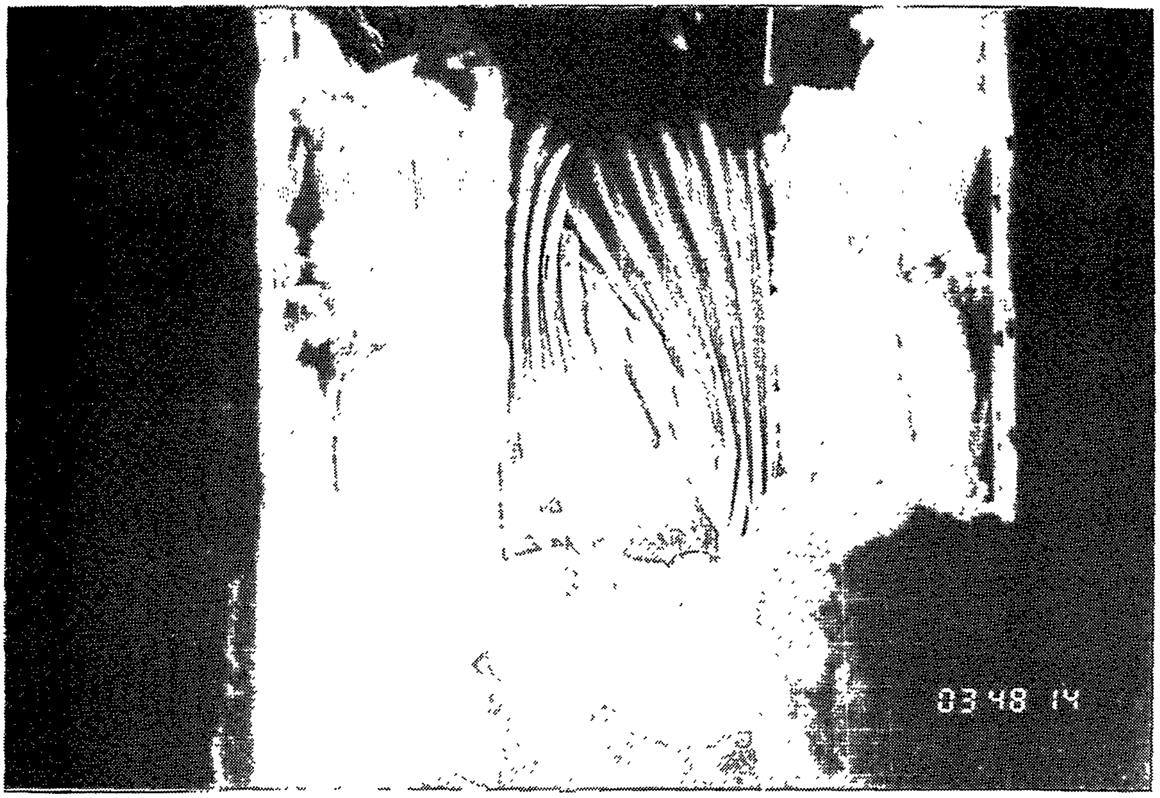

Figure 18. Test I-8-SCT. Specimen Returned to Zero Displacement.

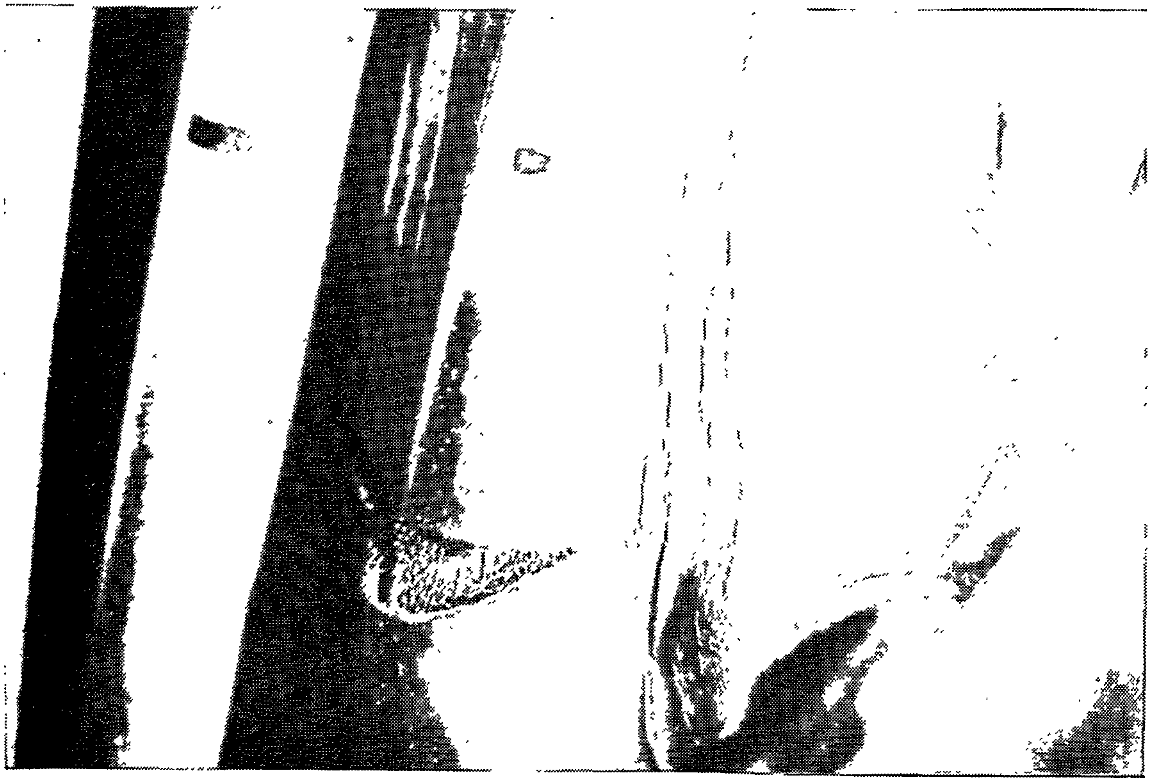

Figure 19. Test I-8-SCT. Specimen A-12-2-2 Showing Post-Test Cracks.

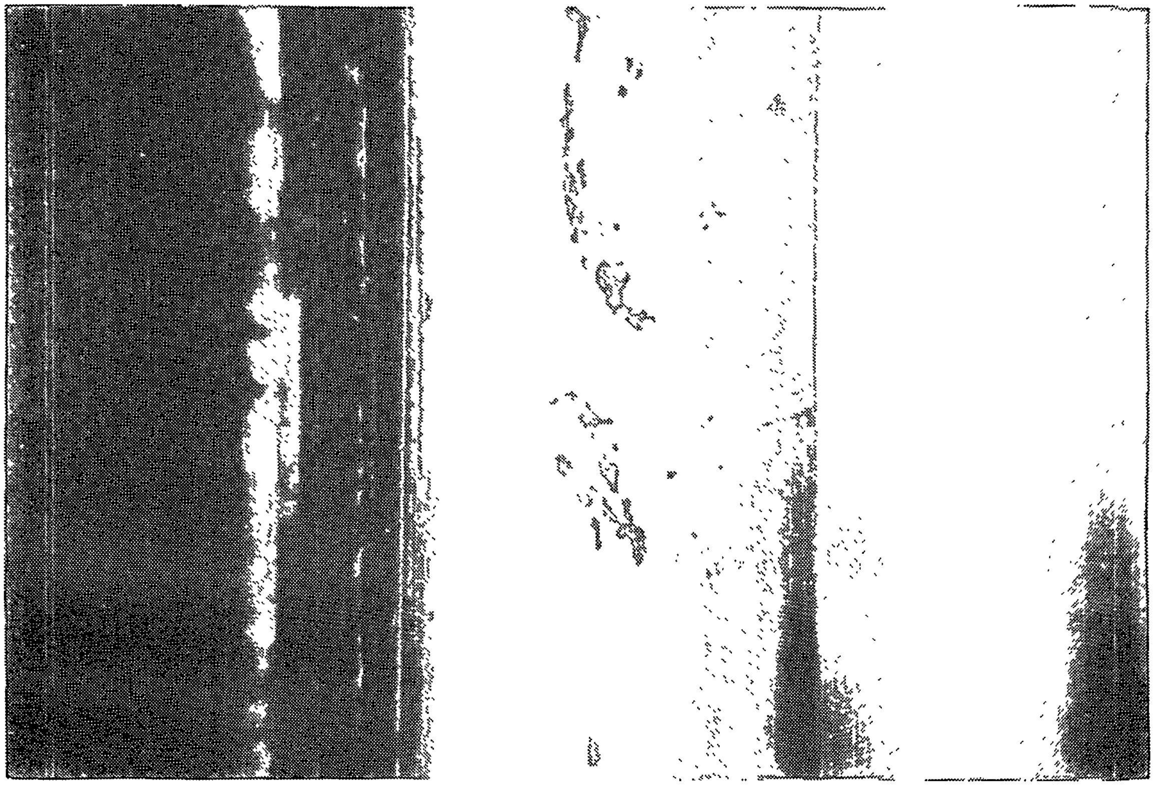

Figure 20. Test I-5-SCT. Specimen C-6-2 Showing Pretest Cracks.

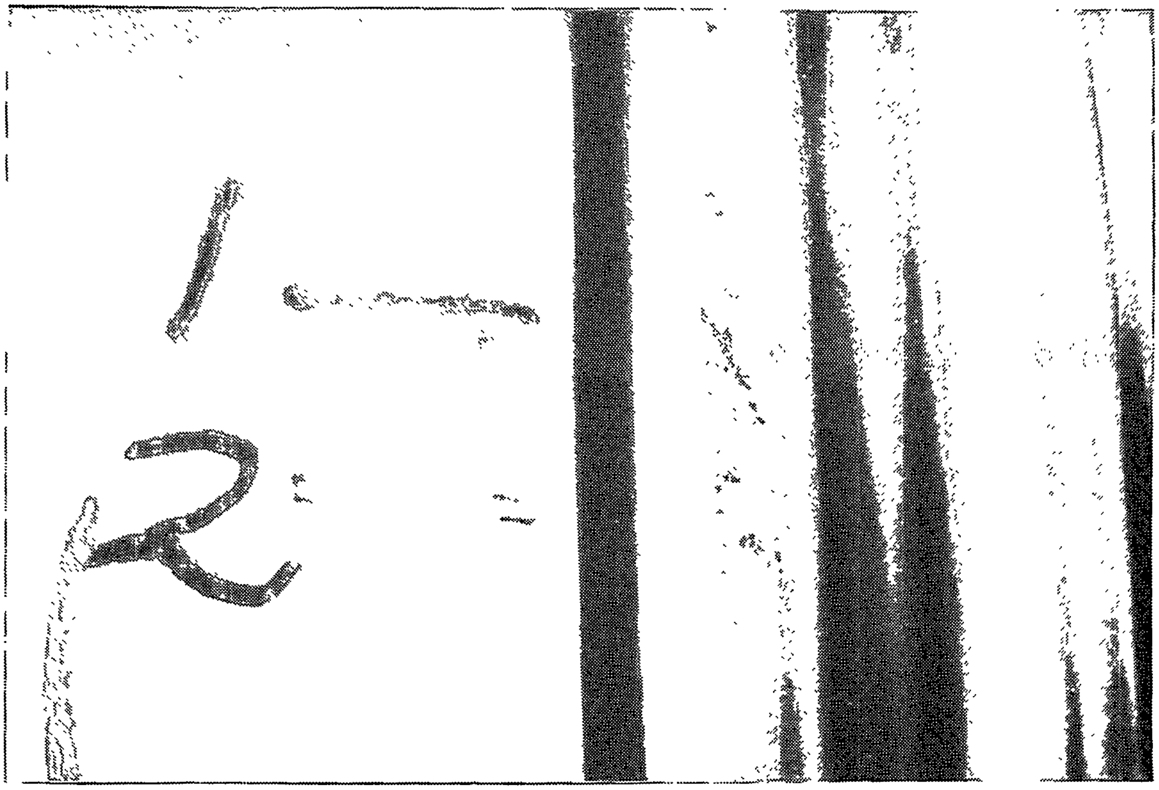

Figure 21. Test I-5-SCT. Specimen C-6-2 Showing Pretest Cracks.

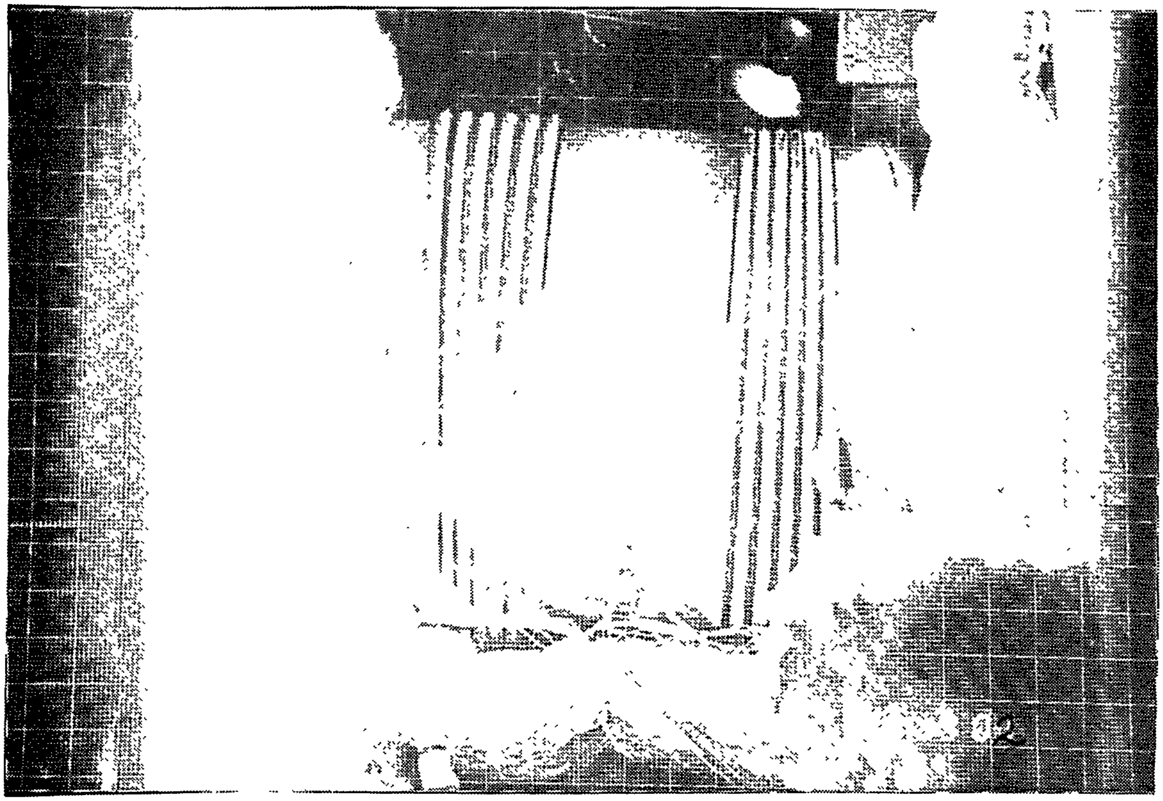

Figure 22. Test I-5-SCT. Specimen C-6-2 Compressed 20%.

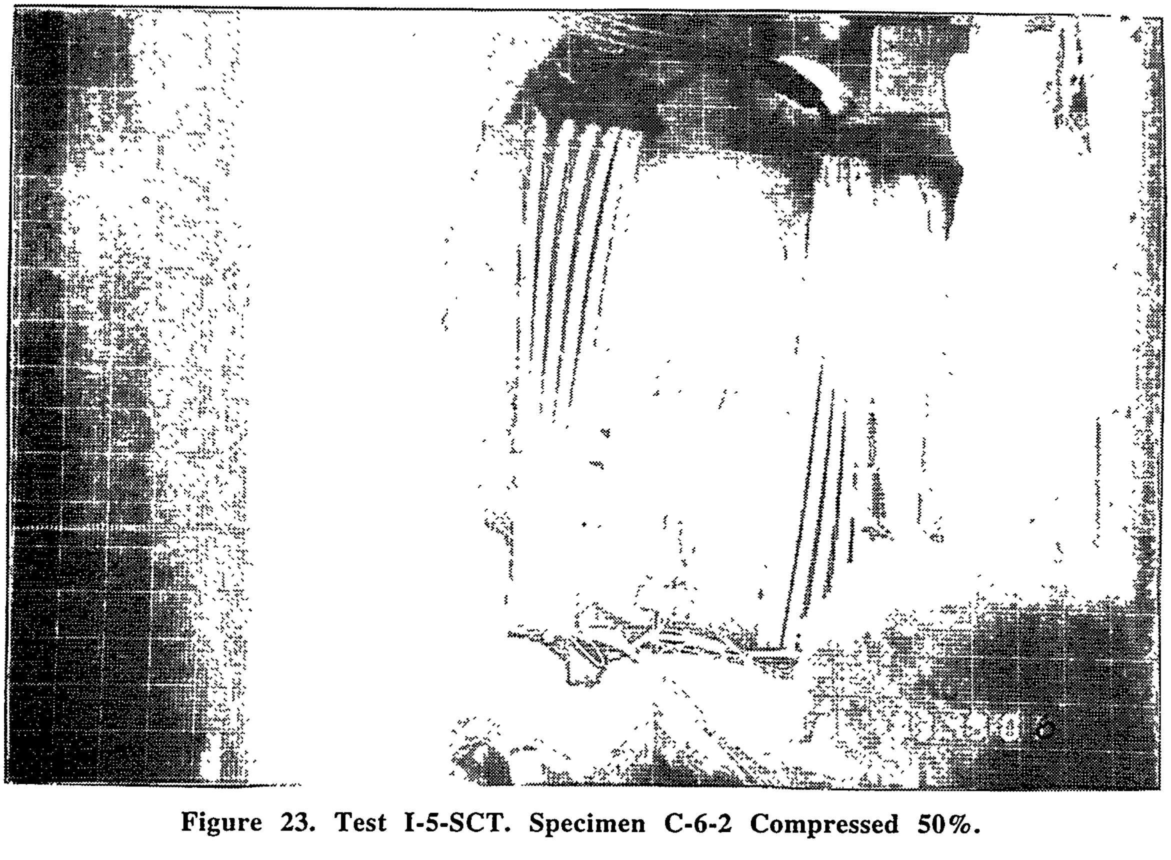

Figure 23. Test I-5-SCT. Specimen C-6-2 Compressed 50%.

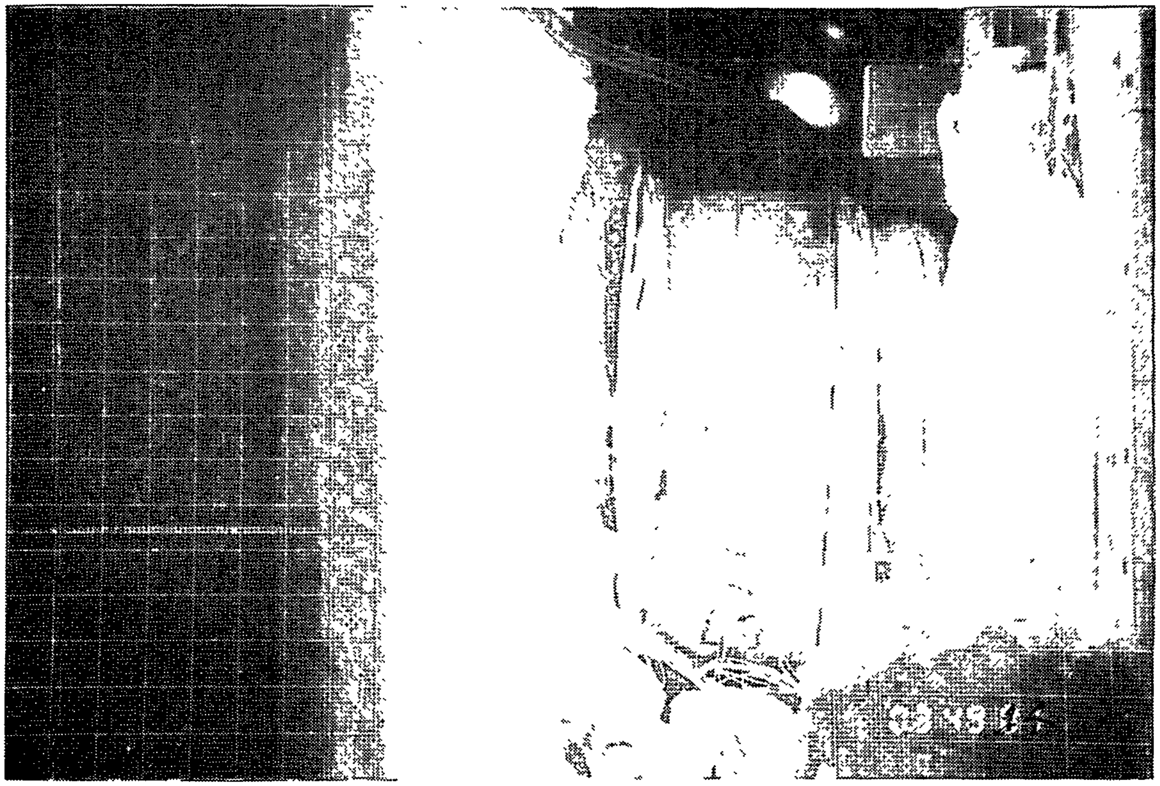

Figure 24. Test I-5-SCT. Specimen C-6-2 Fully Compressed.

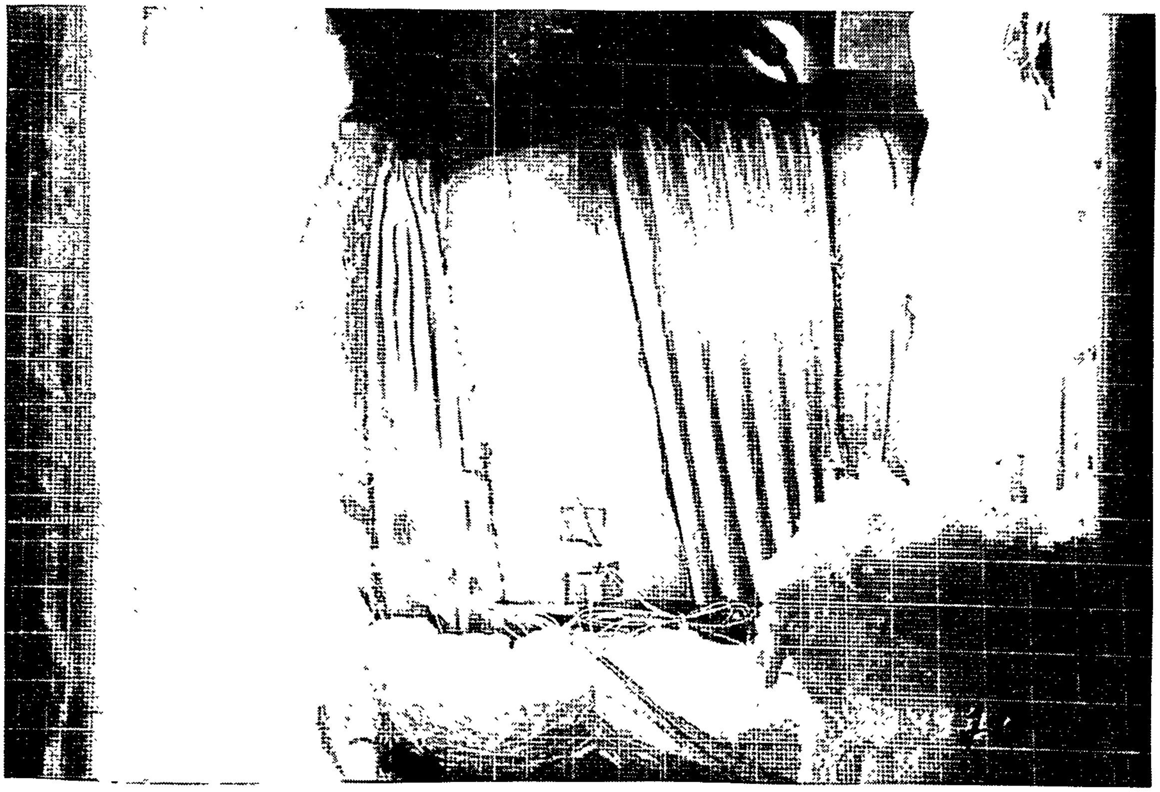

Figure 25. Test I-5-SCT. Specimen C-6-2 Returned to Zero Displacement.

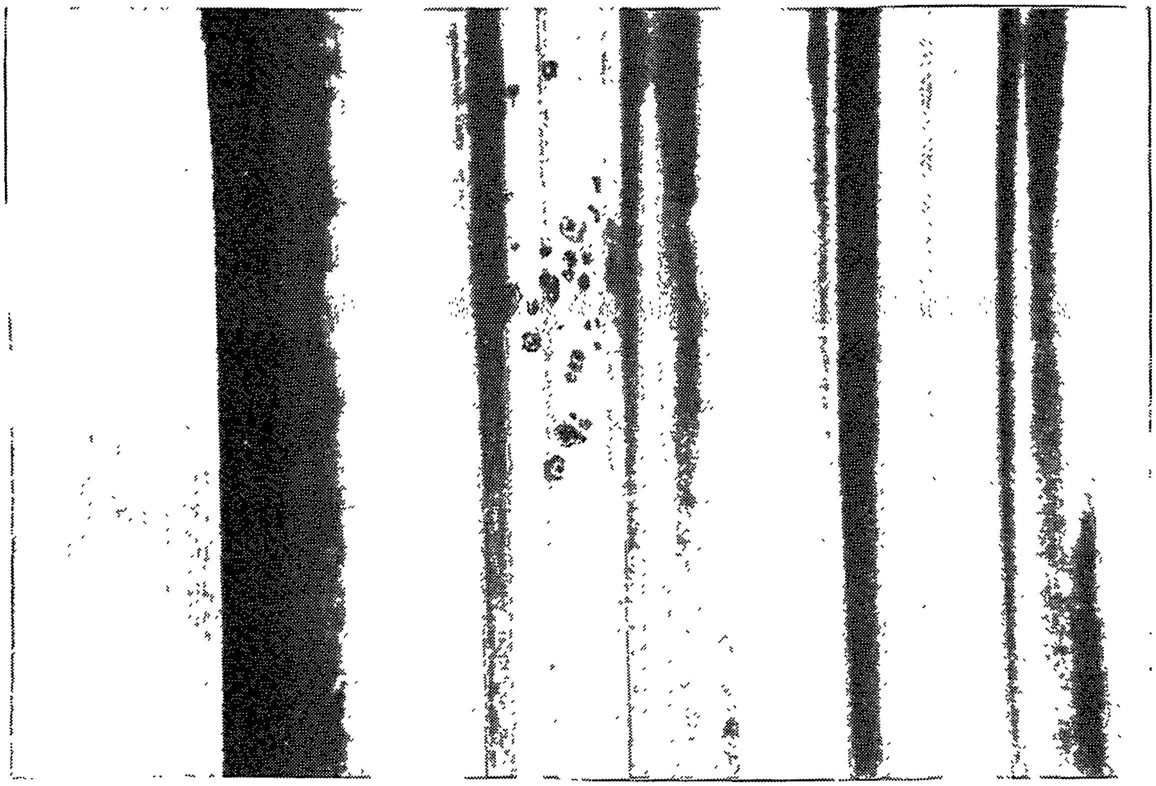

Figure 26. Test I-1-SCT. Specimen A-8-2-4 Showing Pretest Corrosion.

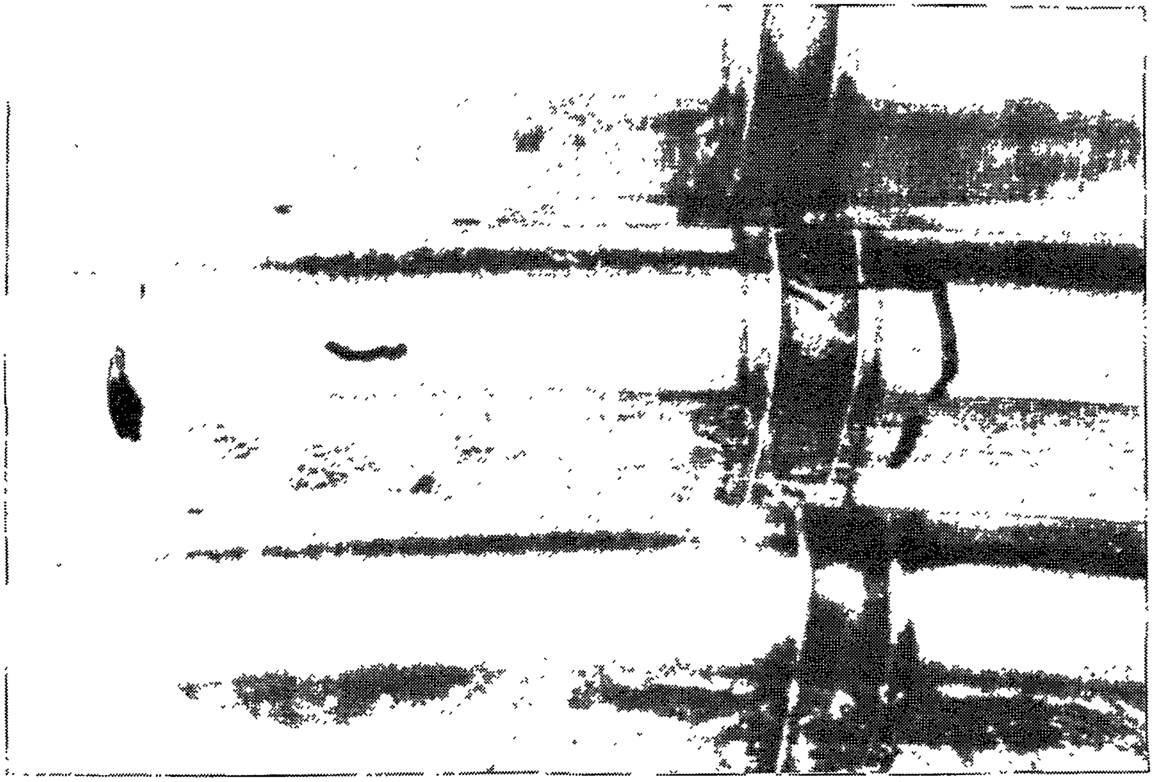

Figure 27. Test I-1-SCT. Specimen A-8-2-4 Showing Pre-Test Cracks.

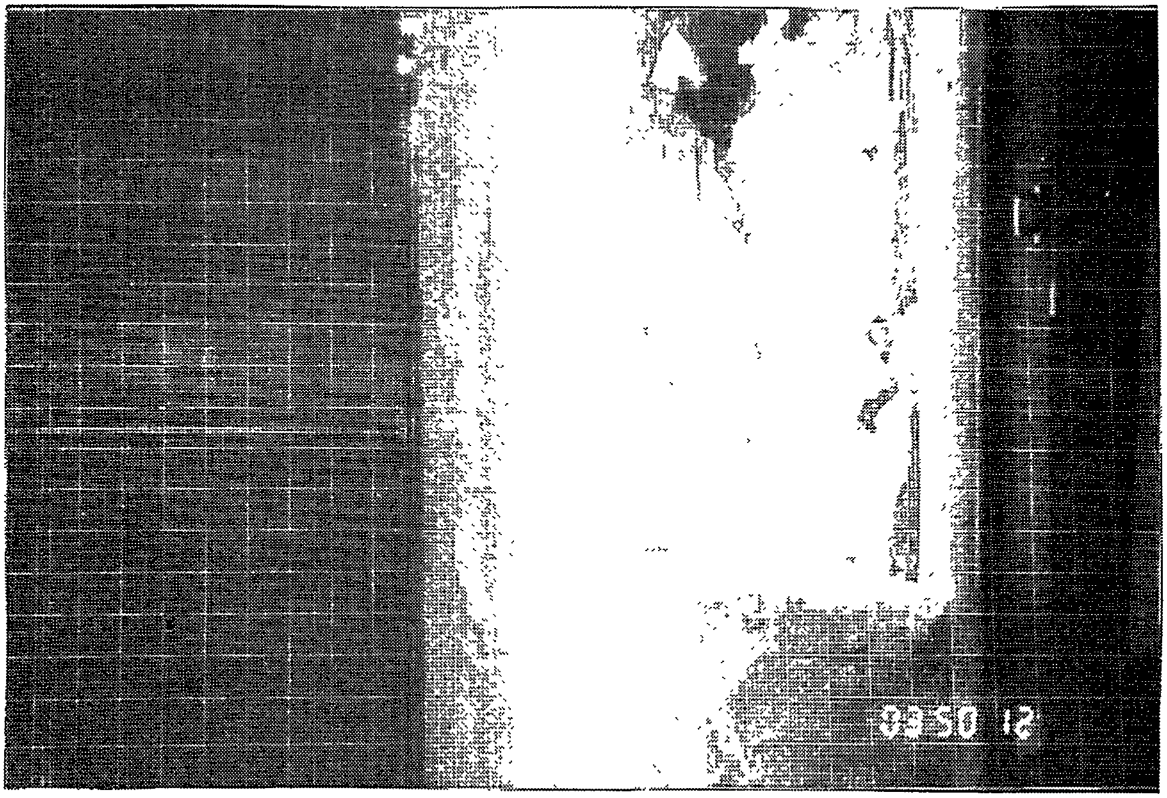

Figure 28. Test I-1-SCT. Specimen A-8-2-4 Fully Compressed.

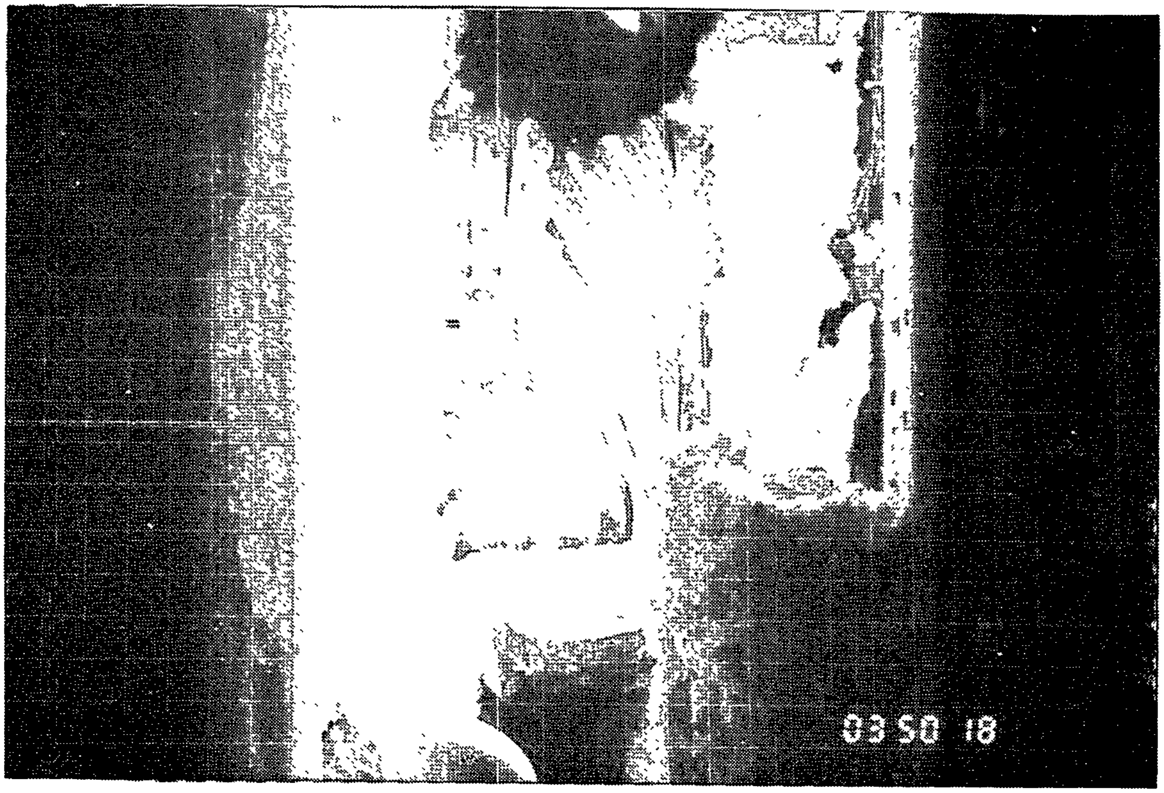

Figure 29. Test I-1-SCT Specimen A-8-2-4 Returned to Zero Displacement.

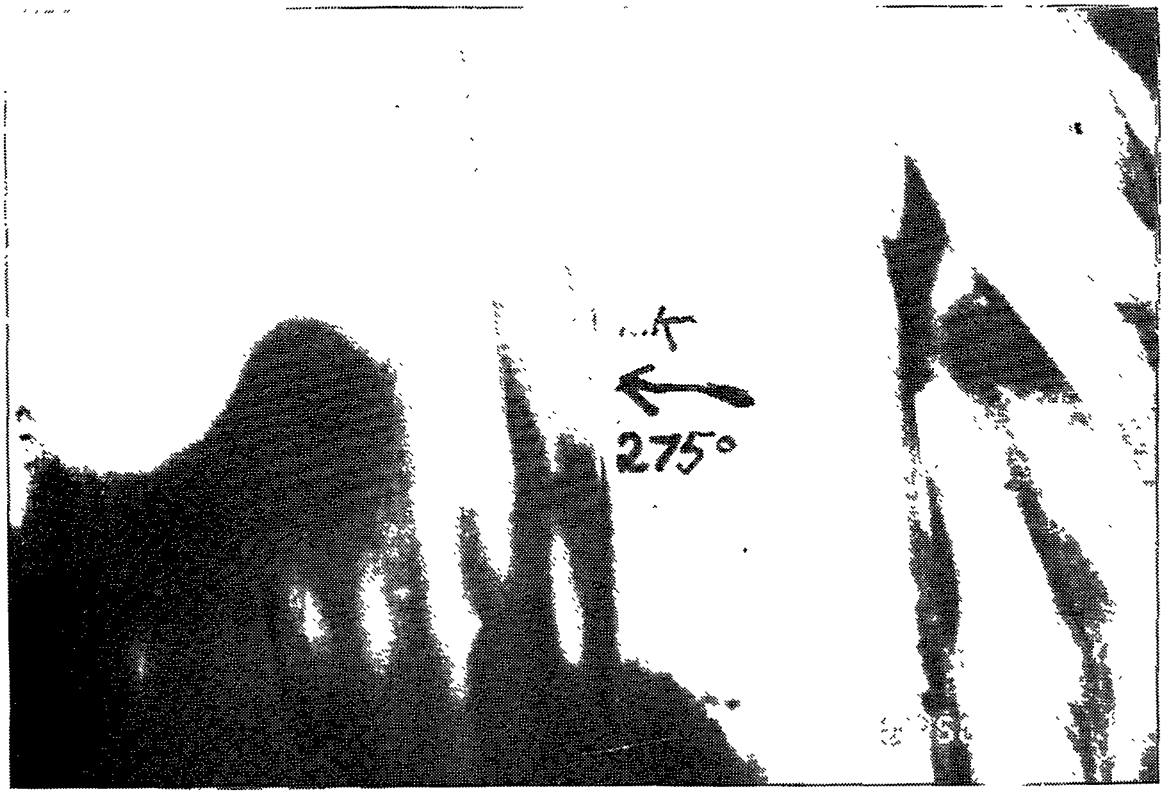

Figure 30. Test I-1-SCT. Specimen A-8-2-4 Showing Post-Test Cracks.

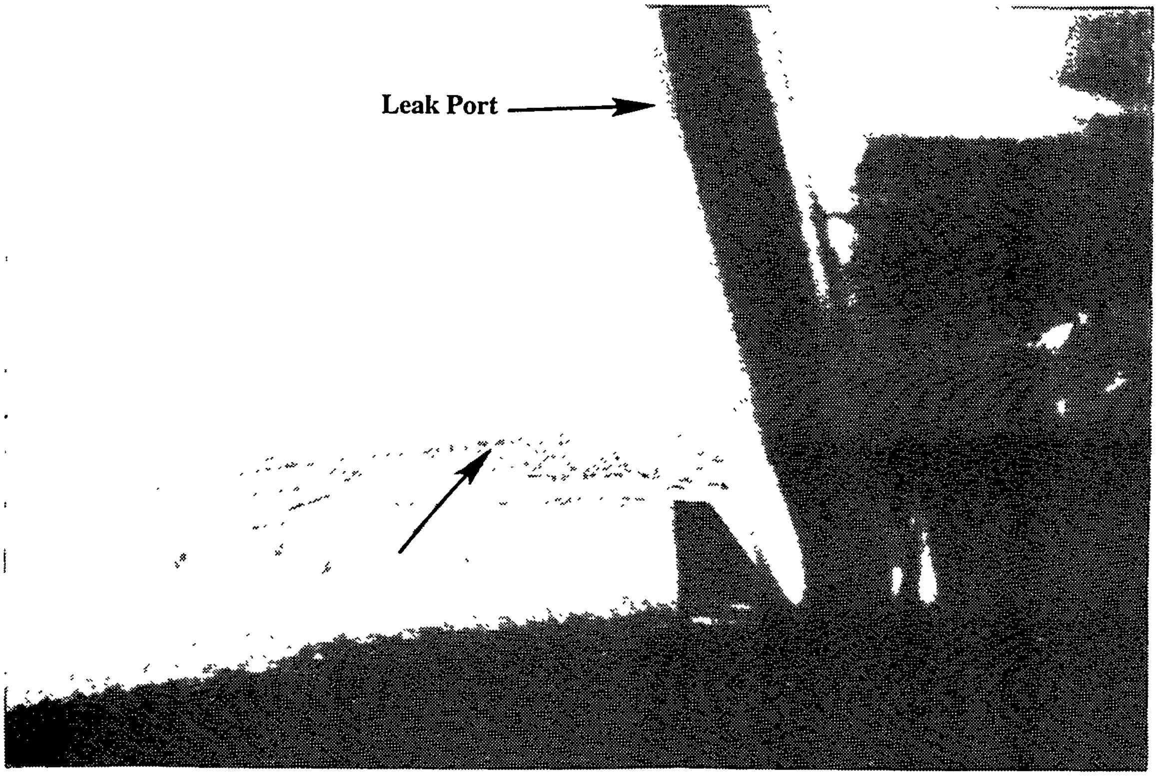

Figure 31. Test I-1-SCT. Specimen A-8-2-4 Showing Tear at Cutout.

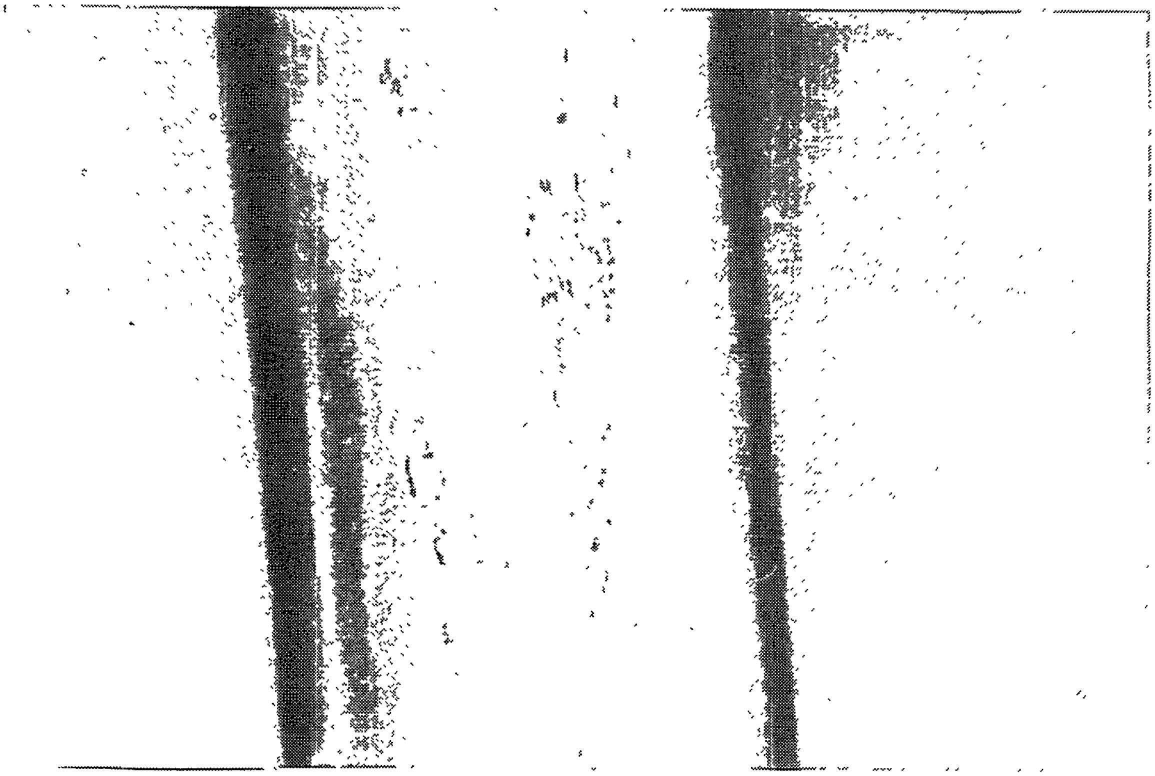

Figure 32. Test II-20. Specimen VL-1 Showing Pretest Corrosion.

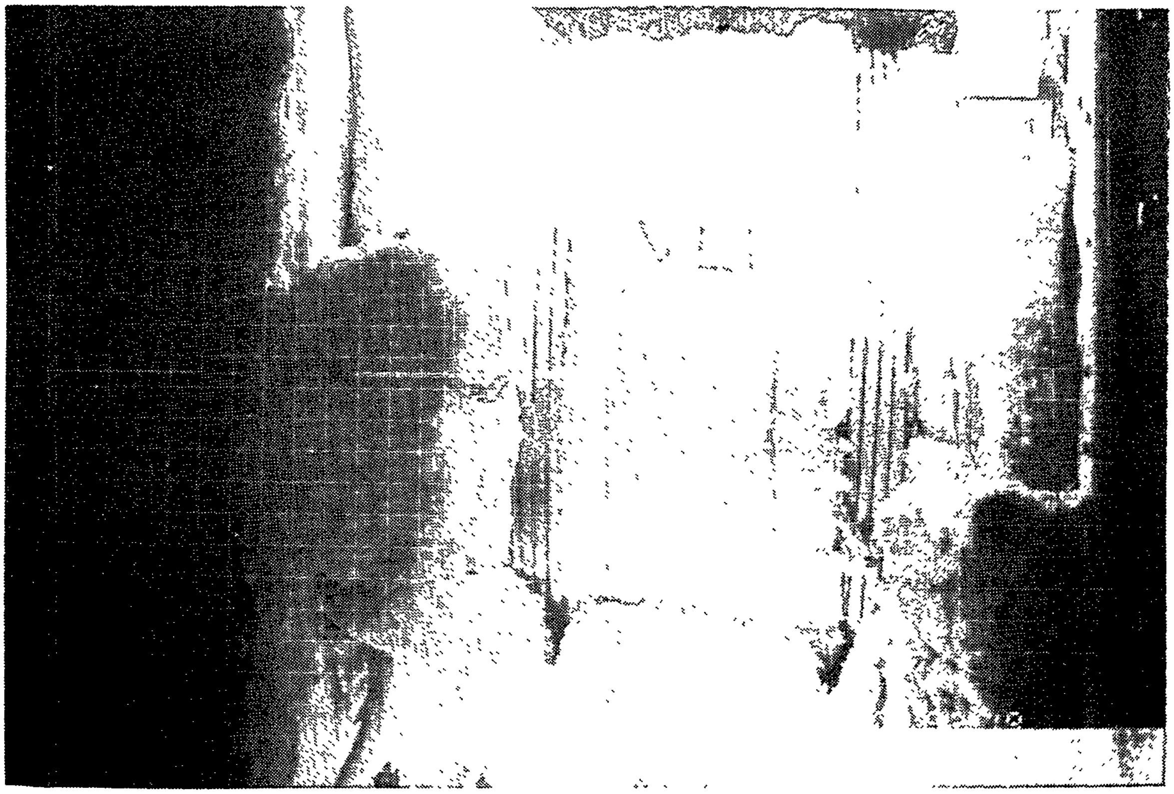

Figure 33. Test II-20. Specimen VL-1 Fully Compressed.

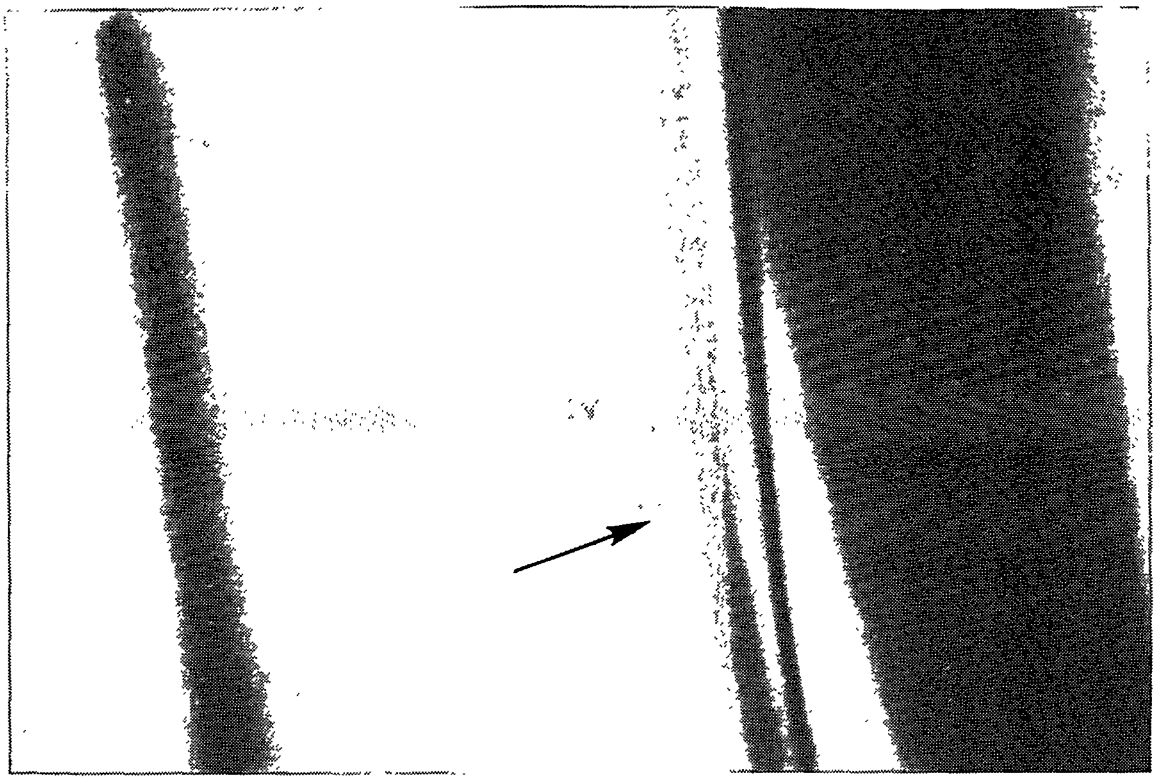

Figure 34. Test II-20. Specimen VL-1 Showing Posttest Cracks.

6 Evaluation of Test Results

6.1 Corrosion Characterization

Because of the limited number of bellows specimens and difficulties encountered in developing "representative" corrosion in the specimens, there was a large variability in the amount of corrosion at the time of testing. Also, the corrosion that was present was difficult to quantify. The methods used to infer the amount of corrosion were visual observation, and leakage testing. Corrosion present on some of the bellows was readily apparent to the naked eye, and cracks could be plainly discerned. On others, a small amount of corrosion could be seen with the naked eye, but magnification was necessary to determine the presence of cracks.

Since the areas of most severe corrosion did not occur in the same location or even on the same part of the bellows convolution in every case, it is difficult to compare one geometry with another. However, owing to the propensity for cracks to occur in the bellows where any corrosion was evident, it can be said that the same general trends noticed in the specimens tested in "like-new" condition holds true. That is, the tendency of some bellows geometries to develop creases in the material, as discussed in Volume I, could render them prone to early leakage if any corrosion were present.

6.2 Test Observations

Because of the variation in corrosion damage, leakage at the time of testing varied from large leak rates to leak tight. The first specimen (A-12-2-1) that was subjected to corrosion exhibited a large leak rate that would have failed a typical containment leak-rate test. Two of the bellows specimens had very small leak rates at the time of testing, and would have passed a containment leak-rate test. Three of the specimens had no leakage prior to testing.

During testing, the cracks in the most severely corroded specimen began to propagate very early during deformation. After approximately 10% of the deformation necessary to achieve full compression (full compression is defined as the point at which all the convolutions and the end spools are in metal-to-metal contact), cracks began to merge and expand. The inner ply, which had not been corroded, remained leak tight at full compression.

The two bellows that were corroded to the point where a small amount of leakage could be measured prior to testing (A-12-2-2 and C-6-2) exhibited no change in leak rate until the bellows reached approximately 25% of full compression. At that point the leak rate began to increase with each incremental deformation movement until the bellows were compressed sufficiently to restrict the leak path (50% to 75% of full compression) owing to contact between the convolutions.

Bellows specimens that were leak tight at the start of the test did not develop leakage attributable to corrosion prior to full compression. Of the three specimens tested, one (D-6-2) did not exhibit any surface corrosion, but several pits were observed. The other two had several areas of "minor" corrosion. One of those specimens (VL-1) appeared to be very close to leaking at the point of full compression because of a crack that developed in a corroded area. The remaining leak-tight specimen (A-8-2-4) exhibited minute cracks in the corroded areas, but did not leak until the last incremental compressive move to full compression.

7 Summary

During the corrosion part of the bellows test program, six bellows tests were conducted. The purpose of the tests was to determine the behavior of containment bellows that were degraded by corrosion prior to being subjected to severe accident conditions.

Difficulties were encountered in developing a method to corrode bellows specimens to the desired condition. The desired condition was a bellows corroded to the point that its degraded condition would likely not be detectable by means of a containment leak rate test, but would likely affect the performance of the bellows in the event of a severe accident.

The amount of corrosion present before testing of the specimens to severe accident conditions varied to the point that some bellows were leak tight prior to testing, some leaked slightly, and one had severe leakage. During testing, the bellows with no leakage did not develop corrosion-induced leakage prior to full compression. Those specimens with a small amount of leakage developed increased leak rates as they were compressed, and the one with an initially large leak rate developed even larger cracks very early in the compressive loading steps.

Because of difficulty in developing a corrosive process that was repeatable, and because of the limited number of test specimens available, the results lead to limited conclusions. Observations did show that performance may be degraded by relatively small amounts of corrosion.

In the case of two-ply specimens, one undamaged ply will afford uncompromised performance. Tests were not performed where both plies were corroded, so no conclusions can be made for that case.

In test specimens, detectable leaks degraded the performance of the bellows. These leaks were small enough that they would not cause a containment to fail a "leak test." The bellows with a large leak that would have caused a containment to fail a leak test showed a significant degradation in performance.

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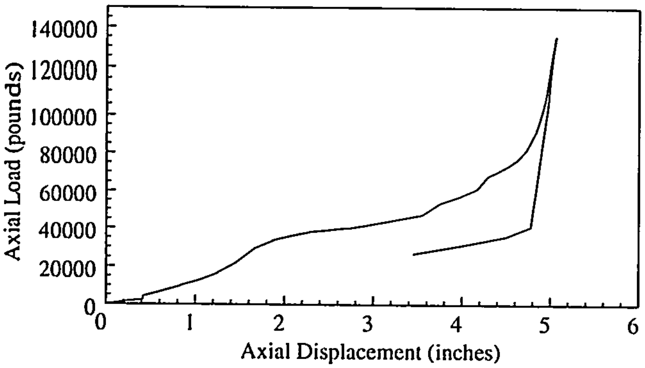
Appendix A

The data from displacement transducers, load cells, pressure transducers, and thermocouples recorded during the tests are presented in this appendix. Descriptions of the individual tests that generated the data plotted here are contained in Section 5.



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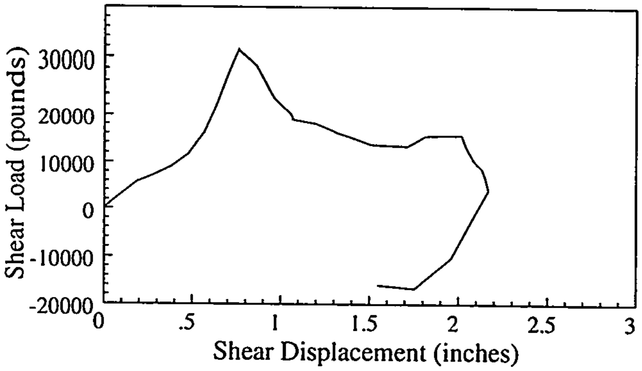

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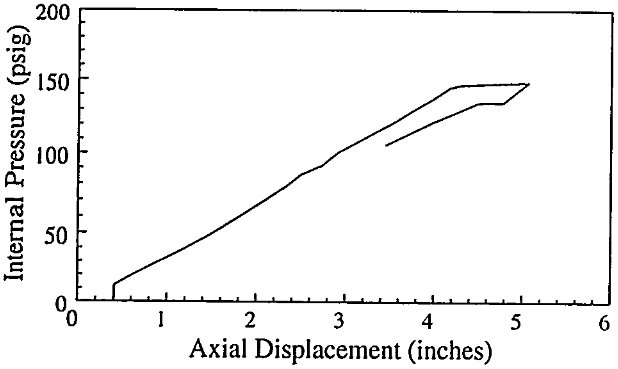

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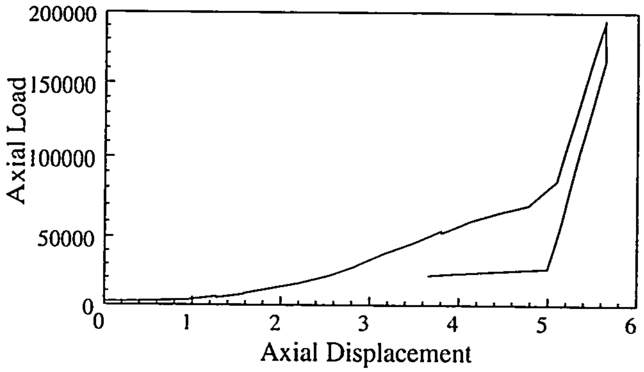

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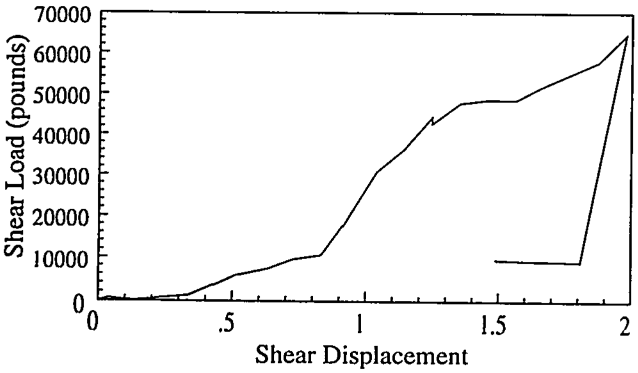

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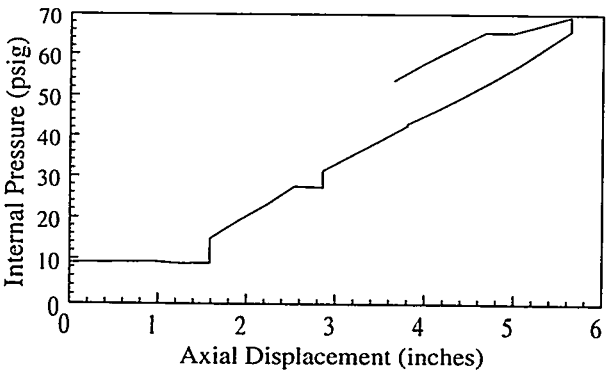

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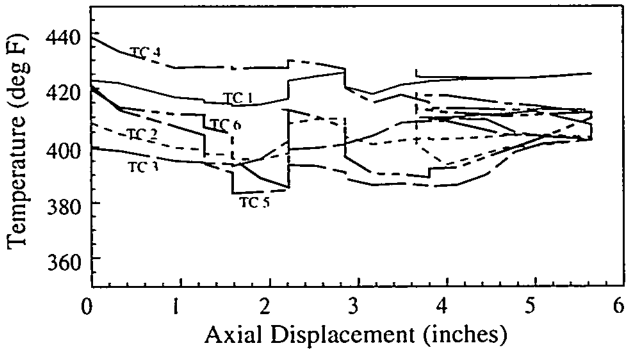

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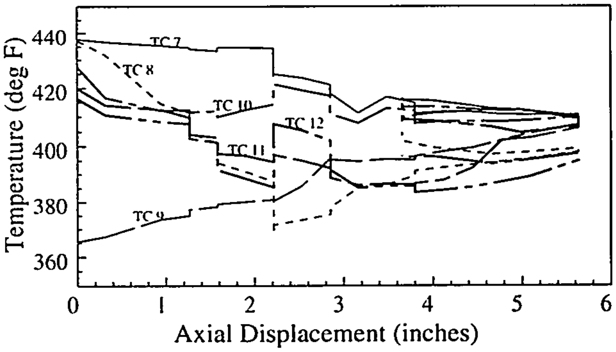

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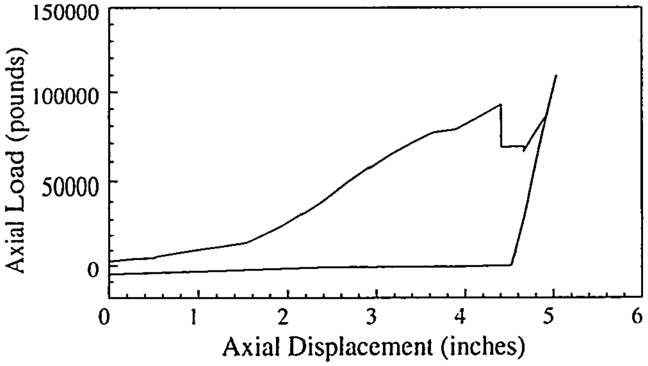

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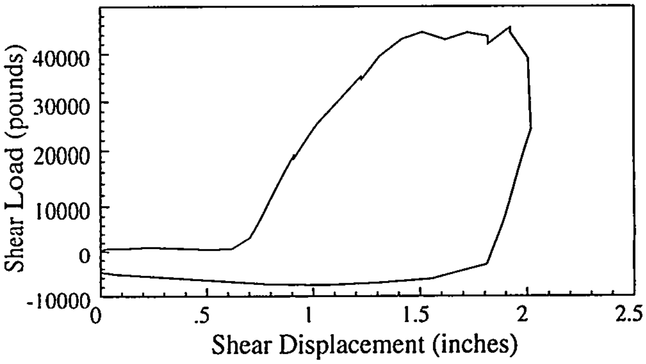

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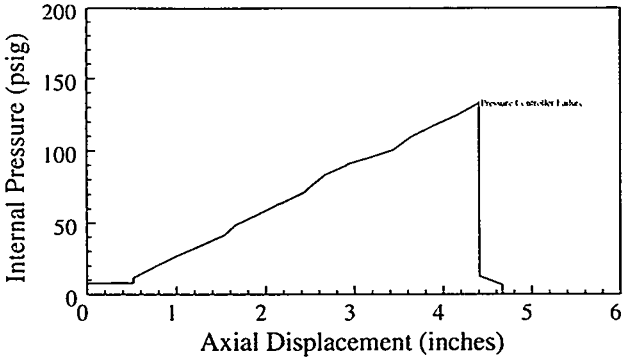

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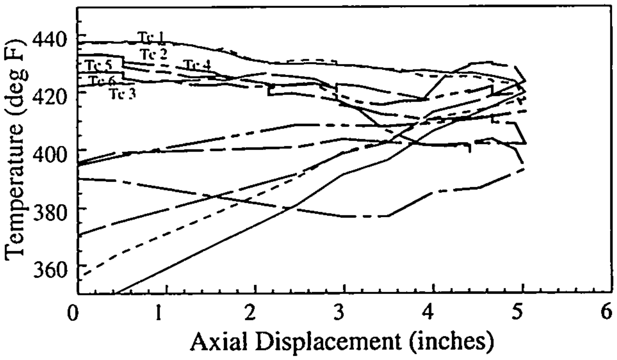

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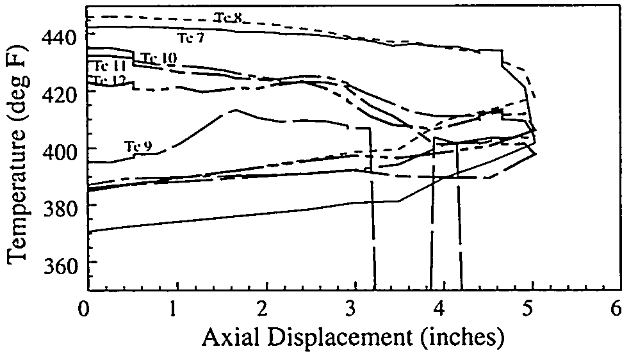

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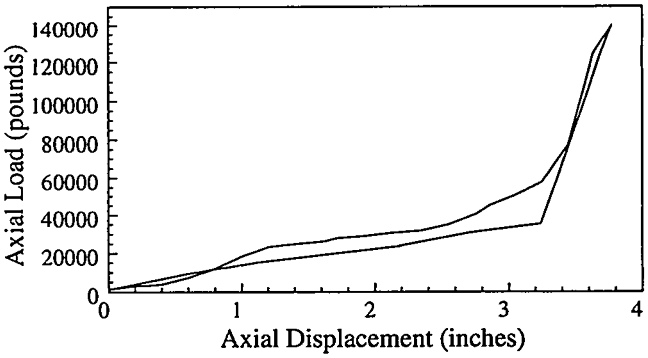

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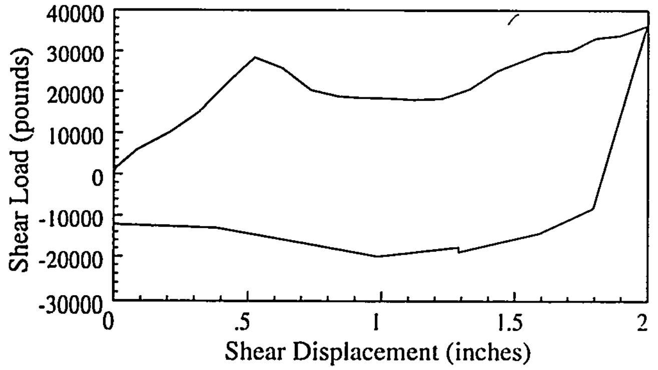

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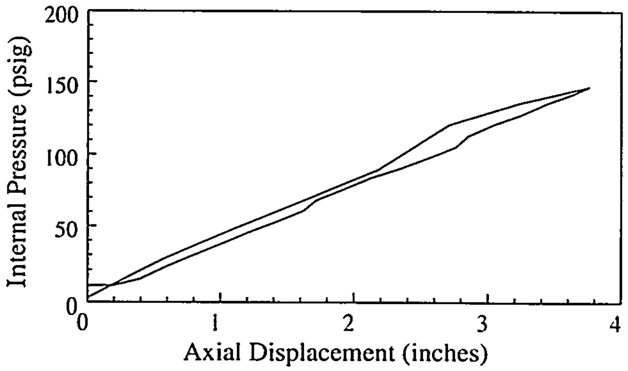

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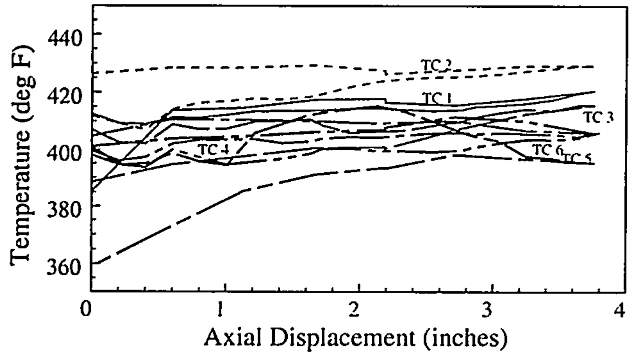

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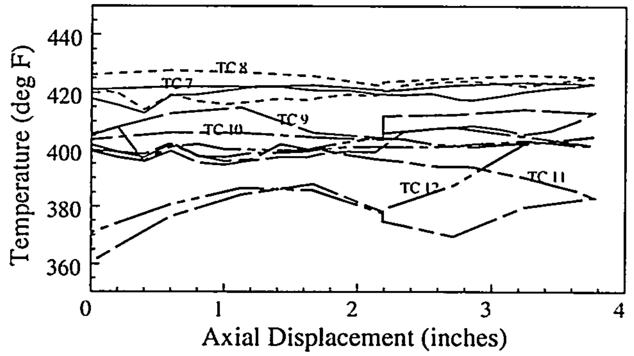

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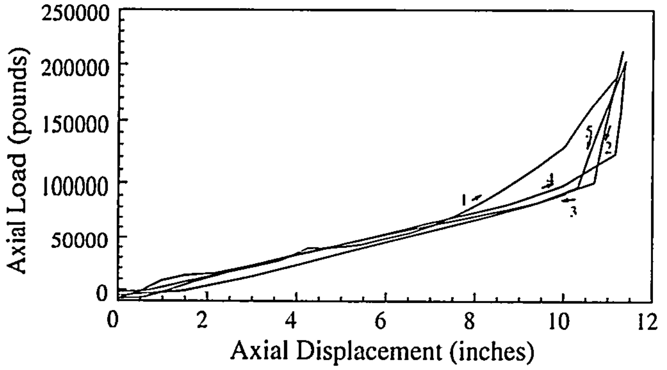

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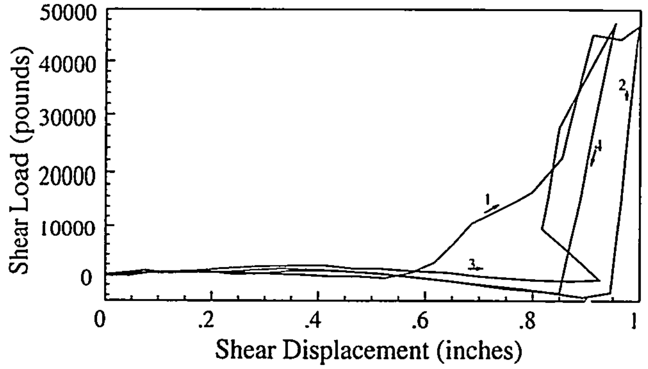

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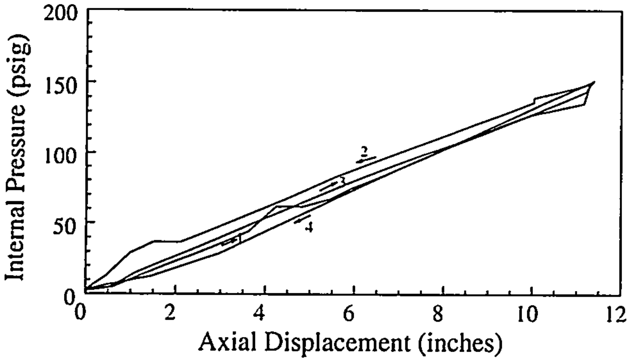

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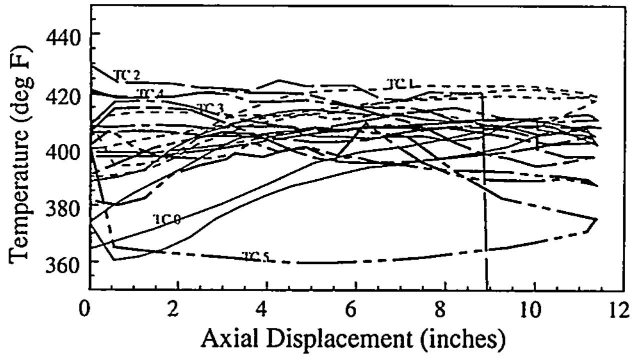

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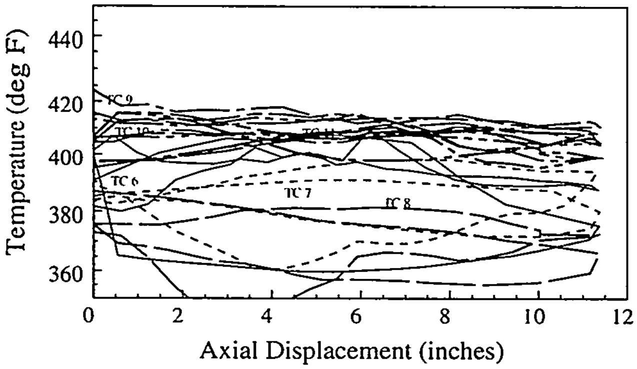

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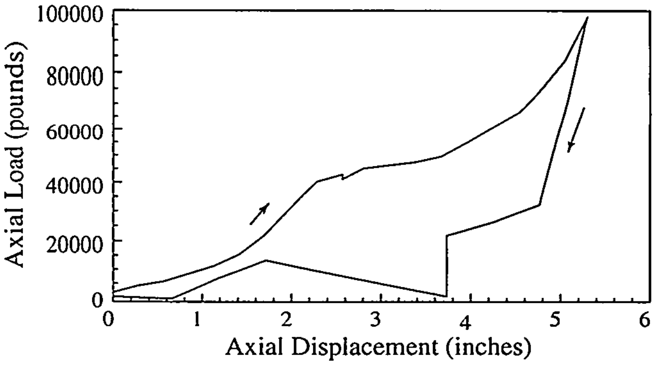

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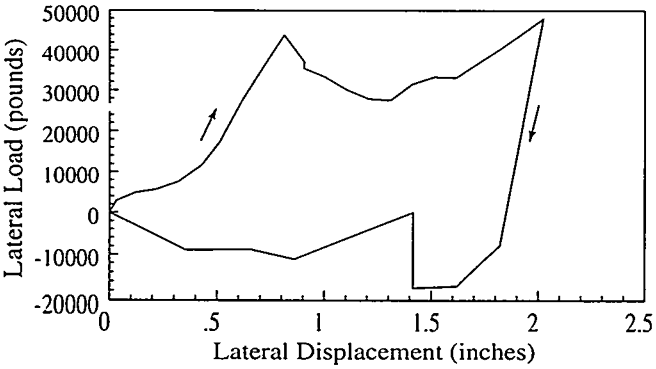

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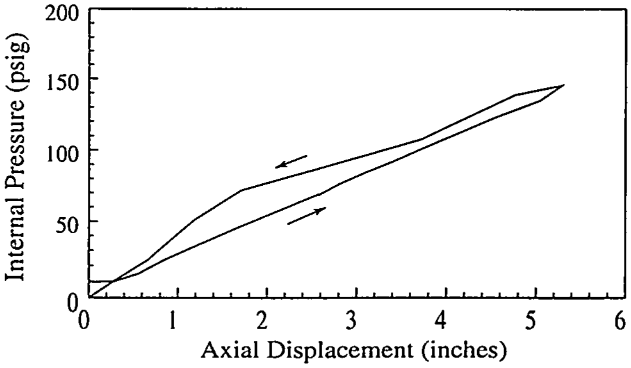

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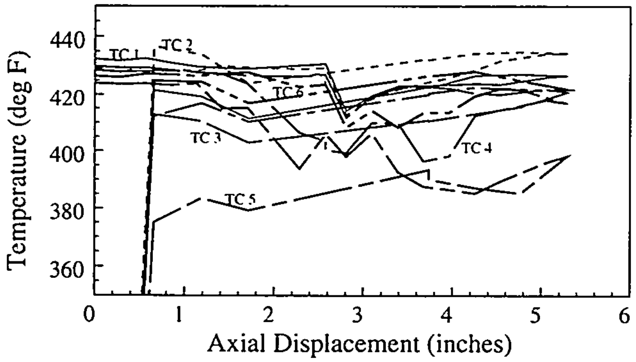

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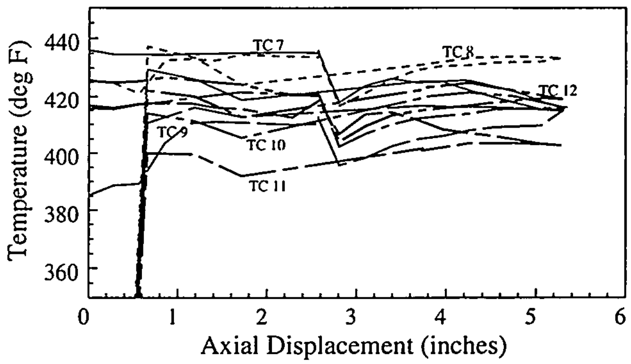

Figure A28. Bellows Test I-8-SCT

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10. SUPPLEMENTARY NOTES

W. Norris, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Bellows are an integral part of the containment pressure boundary in nuclear power plants. They are used at piping penetrations to allow relative movement between piping and the containment wall, while minimizing the load imposed on the piping and wall. Piping bellows are primarily used in steel containments; however, they have received limited use in some concrete (reinforced and prestressed) containments. In a severe accident they may be subjected to pressure and temperature conditions that exceed the design values, along with a combination of axial and lateral deflections. A test program to determine the leak-tight capacity of containment penetration bellows is being conducted at Sandia National Laboratories under the sponsorship of the U.S. Nuclear Regulatory Commission. Several different bellows geometries, representative of actual containment bellows, have been subjected to extreme deflections along with pressure and temperature loads. The bellows geometries and loading conditions are described along with the testing apparatus and procedures. A total of nineteen bellows have been tested. Thirteen bellows were tested in "like-new" condition (results reported in Volume 1), and six were tested in a corroded condition. The tests showed that bellows in "like-new" condition are capable of withstanding relatively large deformations, up to, or near, the point of full compression or elongation, before developing leakage, while those in a corroded condition did not perform as well, depending on the amount of corrosion. The corroded bellows test program and results are presented in this report.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

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containment
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