Experimental Results From Containment Piping Bellows Subjected to Severe Accident Conditions

Results From Bellows Tested in 'Like-New'
Conditions

Manuscript Completed: August 1994
Date Published: September 1994

Prepared by
L. D. Lambert, M. B. Parks

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0744

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC FIN A1375

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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 under the sponsorship of the U.S. Nuclear Regulatory Commission at Sandia National Laboratories. 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 thirteen bellows have been tested, all in the 'like-new' condition. (Additional tests are planned of bellows that have been subjected to corrosion.) The tests showed that bellows are capable of withstanding relatively large deformations, up to, or near, the point of full compression or elongation, before developing leakage. The test data is presented and discussed.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Contents

<u>Section</u>	<u>Page</u>
1.0 Introduction.....	1
1.1 Background	1
2.0 Test Specimens.....	6
3.0 Description of Tests.....	8
4.0 Test Apparatus and Instrumentation	11
5.0 Test Results.....	14
6.0 Evaluation of Test Results	36
7.0 Summary.....	39
8.0 References.....	40
Appendix A.....	A1
Appendix B.....	B1

Figures

<u>Figure</u>	<u>Page</u>
1. BWR Mark-I Containment.....	1
2A. Typical Process Piping Bellows Configuration	2
2B. Typical Vent Line Bellows Configuration.....	2
3. Typical Bellows Loadings Vs. Containment Response	4
4. Effect of Elevated Temperature on F_u , F_y , and e of Type 304 Stainless Steel.....	5
5. Bellows Configurations.....	6
6. Bellows Convolution Detail.....	6
7. Internal Bellows to End (or Center) Spool Connection Detail.....	6
8. Bellows Load Frame	11
9. Video Coverage of Tests.....	12
10. Still Camera Coverage of Tests.....	12
11. Bellows Pressurizing and Heating System.....	12
12. Strain Gage Locations for Test I-11-CL.....	13
13. Strain Gage Locations for Other Ambient Temperature Tests.....	13
14. Thermocouple Locations.....	13
15. Typical Strain Data.....	14
16. Typical Thermocouple Data.....	14
17. Typical Axial Loadcell Data	14
18. Test I-11-CL. Specimen A-8-2-1 at Start of Test.....	16
19. Test I-11-CL. Specimen A-8-2-1 Fully Compressed.....	17
20. Test I-11-CL. Specimen A-8-2-1 at First Leakage.....	17
21. Test I-12-LC. Specimen A-8-2-2 Displaced Laterally 2 Inches.....	19
22. Test I-12-LC. Specimen A-8-2-2 Fully Compressed.....	19
23. Test I-3-SC. Specimen B-8-2-1 at Start of Test.....	20
24. Test I-3-SC. Specimen B-8-2-1 Fully Compressed.....	20
25. Test I-4-SCT. Specimen B-8-2-2 at Start of Test.....	21
26. Bellows Specimen Showing Thermocouple Placement	21
27. Test I-10-SCT. Specimen B-12-2-1 at Start of Test.....	23
28. Test I-10-SCT. Specimen B-12-2-1 at Termination of Test.....	23

Figures (continued)

<u>Figure</u>	<u>Page</u>
29. Test I-9-SC. Specimen B-12-2-2 at Termination of Test	24
30. Test II-19. Specimen VL-2 at Start of Test.....	24
31. Test II-19. Specimen VL-2 at Termination of Test.....	25
32. Test II-17. Specimen PP-2 at Start of Test.....	25
33. Test II-17. Specimen PP-2 at Termination of Test.....	26
34. Test II-17. Specimen PP-2 Close-up of Tear in Outer Ply	26
35. Test I-13-SE. Specimen A-8-1e-1 at Start of Test.....	27
36. Test I-13-SE. Specimen A-8-1e-1 at First Leakage.....	27
37. Test I-14-SE. Specimen A-8-2e-1 Fully Extended.....	29
38. Test I-14-SE. Specimen A-8-2e-1 at First Leakage.....	29
39. Test I-14-SE. Specimen A-8-2e-1 Showing Large Tears.....	30
40. Test I-15-SE. Specimen B-8-1e-1 at Start of Test	30
41. Test I-15-SE. Specimen B-8-1e-1 Fully Extended	31
42. Test I-15-SE. Specimen B-8-1e-1 Partially Returned From Full Extension.....	31
43. Test I-14-SE. Specimen B-8-1e-1 at Termination of Test	32
44. Test I-16-SE. Specimen B-8-2e-1 at Start of Test	32
45. Test I-16-SE. Specimen B-8-2e-1 Fully Extended	33
46. Test I-16-SE. Specimen B-8-2e-1 Close-up of Tear at Sharp Crease	33
47. Test I-4-SCT. Inner View of Tested Bellows With 8 Convolutions.....	34
48. Test I-10-SCT. Inner view of Tested Bellows With 12 Convolutions	34
49. Test I-9-SC. Quarter Section of Tested Specimen	35
50. Test I-9-SC.. Close-up of Quarter Section of Tested Specimen.....	35

Appendix A Figures

A1. Bellows Test I-11-CL	A1
A2. Bellows Test I-11-CL	A1
A3. Bellows Test I-11-CL	A1
A4. Bellows Test I-11-CL	A1
A5. Bellows Test I-12-LC	A1

Appendix A Figures (continued)

<u>Figure</u>	<u>Page</u>
A6. Bellows Test I-12-LC	A1
A7. Bellows Test I-12-LC	A2
A8. Bellows Test I-12-LC	A2
A9. Bellows Test I-12-LC	A2
A10. Bellows Test I-13-SE	A2
A11. Bellows Test I-13-SE	A2
A12. Bellows Test I-13-SE	A2
A13. Bellows Test I-13-SE	A2
A14. Bellows Test I-13-SE	A2
A15. Bellows Test I-14-SE	A3
A16. Bellows Test I-14-SE	A3
A17. Bellows Test I-14-SE	A3
A18. Bellows Test I-14-SE	A3
A19. Bellows Test I-14-SE	A3
A20. Bellows Test I-15-SE	A3
A21. Bellows Test I-15-SE	A3
A22. Bellows Test I-15-SE	A3
A23. Bellows Test I-15-SE	A4
A24. Bellows Test I-15-SE	A4
A25. Bellows Test I-16-SE	A4
A26. Bellows Test I-16-SE	A4
A27. Bellows Test I-16-SE	A4
A28. Bellows Test I-16-SE	A4
A29. Bellows Test I-16-SE	A4
A30. Bellows Test I-3-SC	A4
A31. Bellows Test I-3-SC	A5
A32. Bellows Test I-3-SC	A5
A33. Bellows Test I-3-SC	A5

Appendix A Figures (continued)

<u>Figure</u>	<u>Page</u>
A34. Bellows Test I-3-SC	A5
A35. Bellows Test I-4-SCT	A5
A36. Bellows Test I-4-SCT	A5
A37. Bellows Test I-4-SCT	A5
A38. Bellows Test I-4-SCT	A5
A39. Bellows Test I-4-SCT	A6
A40. Bellows Test I-2-SCT	A6
A41. Bellows Test I-2-SCT	A6
A42. Bellows Test I-2-SCT	A6
A43. Bellows Test I-2-SCT	A6
A44. Bellows Test I-2-SCT	A6
A45. Bellows Test I-10-SCT.....	A6
A46. Bellows Test I-10-SCT.....	A6
A47. Bellows Test I-10-SCT.....	A7
A48. Bellows Test I-10-SCT.....	A7
A49. Bellows Test I-10-SCT.....	A7
A50. Bellows Test I-9-SC	A7
A51. Bellows Test I-9-SC	A7
A52. Bellows Test I-9-SC	A7
A53. Bellows Test I-9-SC	A7
A54. Bellows Test I-9-SC	A7
A55. Bellows Test II-19-SCT.....	A8
A56. Bellows Test II-19-SCT.....	A8
A57. Bellows Test II-19-SCT.....	A8
A58. Bellows Test II-19-SCT.....	A8
A59. Bellows Test II-19-SCT.....	A8
A60. Bellows Test II-17-SCT.....	A8
A61. Bellows Test II-17-SCT.....	A8

Appendix A Figures (continued)

<u>Figure</u>	<u>Page</u>
A62. Bellows Test II-17-SCT.....	A8
A63. Bellows Test II-17-SCT.....	A9
A64. Bellows Test II-17-SCT.....	A9

Appendix B Figures

B1. Elongation Comparison From Heat No. 710288.....	B1
B2. Tensile Test From Lot No. 212060. Longitudinal Orientation. Room Temperature	B1
B3. Tensile Test From Lot No. 212060. Longitudinal Orientation. Room Temperature	B2
B4. Tensile Test From Lot No. 212060. Longitudinal Orientation. Room Temperature	B2
B5. Tensile Test From Lot No. 212060. Transverse Orientation. Room Temperature	B2
B6. Tensile Test From Lot No. 212060. Transverse Orientation. Room Temperature.....	B2
B7. Tensile Test From Lot No. 212060. Transverse Orientation. Room Temperature.....	B2
B8. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.....	B2
B9. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.....	B3
B10. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.....	B3
B11. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.....	B3
B12. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.....	B3
B13. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.....	B3
B14. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.....	B3
B15. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.....	B4
B16. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.....	B4
B17. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.....	B4
B18. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.....	B4
B19. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.....	B4
B20. Tensile Test From Lot No. 710288. Longitudinal Orientation. 425 °F	B4
B21. Tensile Test From Lot No. 710288. Longitudinal Orientation. 425 °F	B5
B22. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F	B5
B23. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F	B5
B24. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F	B5

Appendix B Figures (continued)

<u>Figure</u>	<u>Page</u>
B25. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F	B5
B26. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F	B5
B27. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F	B6
B28. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F	B6
B29. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F	B6
B30. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F	B6
B31. Tensile Test From Lot No. 710342. Longitudinal Orientation. Room Temperature.....	B6
B32. Tensile Test From Lot No. 710342. Longitudinal Orientation. Room Temperature.....	B6
B33. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.....	B7
B34. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.....	B7
B35. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.....	B7
B36. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.....	B7
B37. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.....	B7
B38. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.....	B7
B39. Tensile Test From Lot No. 847672. Transverse Orientation. Room Temperature.....	B8
B40. Tensile Test From Lot No. 847672. Transverse Orientation. Room Temperature.....	B8
B41. Tensile Test From Lot No. 847672. Transverse Orientation. Room Temperature.....	B8
B42. Deep Convolution.....	B9
B43. Shallow Convolution.....	B9
B44. Photomicrograph of Grain Structure in Undeformed Region (magnification 200X).....	B10
B45. Photomicrograph of Grain Structure at Large Deformation (magnification 200X).....	B10
B46. Convolution Thickness	B11

Tables

<u>Table</u>	<u>Page</u>
1. Bellows Test Specimen Data	7
2. Description of Phase I Tests	9
3. Load Combinations for PP-1 and PP-2 Phase II Tests	10
4. Bellows Failure Conditions	15

Appendix B Tables

B1. Material Heats	B1
B2. Hardness Measurements of Deep Convolution (Knoop Scale)	B9
B3. Hardness Measurements of Shallow Convolution (Knoop Scale)	B9

Executive Summary

Several experiments have been conducted at Sandia National Laboratories, under the sponsorship of the U.S. Nuclear Regulatory Commission, to verify analytical methods for predicting the behavior of nuclear power plant containments subjected to 'severe' accidents. By severe accident, it is implied that the accident would cause pressure and temperature conditions inside the containment building that exceed the design values. Some of the past experiments examined the behavior of the containment building as a whole, while others focused on penetrations in the containment building, such as equipment hatches, personnel airlocks, and electrical penetrations. The bellows tests are a continuation of the containment penetration test series.

Because bellows are an integral part of the containment pressure boundary, their performance during severe accident conditions must be evaluated in order to assess the pressure and temperature conditions at which a given containment would develop leakage. The final goal of the containment research programs is to develop a suite of analytical methods, that have been verified by comparison to experimental results, for predicting the leakage behavior of the entire containment pressure boundary in the unlikely event of a severe accident.

Containment piping penetration bellows are primarily used in steel containments, with only limited use in reinforced and prestressed concrete containments. The purpose of containment bellows is to minimize the loading imposed on the containment shell caused by differential movements between the containment shell and the pipe to which the bellows are attached. These movements are typically caused by startup and shutdown of the reactor. The bellows are designed to accommodate the differential movements caused by a loss of coolant accident (LOCA) and/or a safe shutdown earthquake (SSE). These movements are relatively small and because they are 'low cycle' events, pose no threat to the bellows integrity. However, much more significant differential movement can be caused by severe accidents. In the event of a severe accident, the bellows could be subjected to pressure, temperature, and deflections well beyond the design basis. The purpose of this experimental program is to investigate the leak-tight capacity of bellows subjected to severe accident conditions.

Most bellows are connected to the outside of the containment shell, and would be subjected to internal pressure and axial compression, along with lateral deflection, in a severe accident. A few bellows are installed inside containment and would be subjected to external pressure and axial elongation during an accident. The test series subjected a total of thirteen bellows specimens to various levels and combinations of internal pressure, temperature, axial compression or elongation, and lateral deformation. Some of the bellows were tested at 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 at 400°F.

All of the bellows specimens were tested in 'like-new' condition. The test series did not address the potential degrading effects of fatigue and corrosion. Because of the small number of load cycles, fatigue is not believed to be an important issue in determining containment bellows capacity and thus, was not considered in this test series. However, corrosion could have a significant effect on bellows capacity. Additional testing of corroded bellows is planned and will be reported at a later date.

The bellows tests were divided into two Phases. In Phase I, eleven bellows with different geometries were subjected to various worst-case loading conditions. The bellows were representative of certain features of actual containment bellows, although they were not intended to be duplicates of any specific containment bellows. The purpose of these tests was to determine which bellows geometries and load combinations were most likely to produce leakage through the bellows pressure boundary. Phase II specimens were representative of specific bellows applications, with one specimen representing approximately 1:4-scale vent line bellows and the other one being representative of a full-size process piping penetration.

In all cases, the bellows that were subjected to axial compression and lateral deflection remained leak tight up to, or very near, the point of full compression. Full compression is defined as the point where all the convolutions and the end spools are in metal-to-metal contact. Bellows that were tested at elevated temperature failed earlier in the loading cycle than bellows tested at room temperature. Also, bellows with deeper convolutions developed leakage earlier in the loading cycle than bellows with shallower convolutions. However, the deepest convolution bellows at 400°F were more than 85% compressed at the start of leakage. This occurred in spite of the bellows being simultaneously subjected to the worst conceivable combinations of internal pressure, elevated temperature, and lateral deformation.

In the case of axial elongation, most of the specimens were fully elongated to the point where all the convolutions were flattened into a cylinder before developing a leak. The bellows were capable of this extreme elongation even though they were simultaneously subjected to worst-case lateral deformations. However, it should be noted that actual containment bellows that would be elongated during a severe accident would also be subjected to external pressure and elevated temperature. External pressure and elevated temperature were not applied during these tests, because of the complexity and costs that it would have added to the program and because of the limited number of actual bellows that would be subjected to this loading condition. Further evaluation would be necessary to determine the effect of external pressure and elevated temperature, combined with elongation and lateral deformation, on the leak-tight capacity of containment bellows.

The next question may be, how should this information be used to assess the pressure at which containment bellows would develop leakage in a given containment? The results of these tests should not be 'blindly' extrapolated for all containment bellows. One must determine if the bellows in the containment in question fall within the parameters of the bellows that were tested in this program. Of particular concern should be the type of material, the extent of corrosion, number and depth of convolutions, ply thickness and number of plies, type of bellows (universal or single), as well as the relative loading conditions of pressure, temperature, lateral deformation, and possibly others. The intent of this test program was to cover as wide a range of bellows geometries and loadings as possible; however, there may be some actual bellows that are not covered by these tests. Engineering judgment will likely be needed in the final assessment of whether these tests are applicable to a given situation.

If it is deemed that these test results are applicable, the following approach is recommended to estimate when leakage might occur in bellows that would be compressed during a severe accident. First, a nonlinear, axi-symmetric or three dimensional analysis of the containment should be performed to determine the expansion of the containment shell as a function of internal pressure and temperature at the location of penetration bellows. A conservative assumption would be to assume the bellows would leak when the axial compression reaches 75% of the deformation necessary to cause full compression.

For bellows that are elongated due to severe accident conditions, no specific recommendations can be made without further consideration of the effects of external pressure and elevated temperatures.

Acknowledgments

This project was sponsored by the U.S. Nuclear Regulatory Commission (NRC). Special thanks are due to James Costello, Herman Graves, III, and Wallace Norris of the NRC for their guidance throughout the program and for their assistance in providing information on bellows in nuclear power plants.

Barry Spletzer also invested time and effort in managing the project in its infancy, and writing the data acquisition and control software for the bellows load frame. He has been a valuable resource throughout the program.

Thanks are also due to the very competent team of Robert Eyers¹ and John Pantuso who did the specimen preparation and test setup work on this project, and also assisted during the tests.

¹Ktech Corporation.

1.0 Introduction

The bellows tests are part of the Containment Integrity Programs [1], 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 is to investigate the pressure, temperature, and deformation conditions that would likely cause a tear in the bellows, which would 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 [2]. 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 [3]. 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) [4]. 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 Figure 2) 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 Figure 2) 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 the background review did not reveal any data on the performance of bellows subjected to severe accident conditions, a test series was formulated to examine the behavior of various configurations of bellows geometries under severe accident loadings. The test series contained thirteen tests of nine different bellows geometries that are representative of those found in actual containments.

Because of the insignificant number and magnitude of loading cycles during normal operating conditions, it was decided to test the bellows in like-new condition without considering fatigue issues. Corrosion was also not considered in these experiments. Additional testing of bellows in a degraded condition is planned.

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 [5, 6, 7, 8].

In order to verify the material data shown in these sources, tensile tests were performed on samples taken from the same heat lots that were used in the construction of the bellows specimens. These tests showed the same general trends as indicated in the literature (see Figure B1 in Appendix B).

Since ductility is the most important material property in determining bellows tearing, and the largest change occurred between room temperature and 400°F, some of the bellows tests were conducted at temperatures of $425 \pm 25^\circ\text{F}$.

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

2.0 Test Specimens

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

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. An effort to include extremes in numbers of convolutions, depth of convolutions, ratio of convolution depth to ply thickness and universal versus single element bellows (see Figure 5) was made.

Single Element Bellows

Universal Bellows

Figure 5. Bellows Configurations

The geometry of the tested bellows specimens is provided in Table 1. Figures 6 and 7 define 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. In the fabrication of a bellows, a flat stainless steel sheet is first rolled into a cylindrical shape and welded; then the convolutions are cold-formed. Microhardness tests were performed on samples of the bellows material to determine how the forming operations had affected the hardness. The results of these tests are reported in Appendix B, and the results show that there was a significant amount of strain hardening, but not an extreme amount.

Bellows Material: SA240, Type 304 Stainless Steel

Figure 6. Bellows Convolution Detail

Spool Material: SA516, Gr 60 Steel

Figure 7. Internal Bellows to End (or Center) Spool Connection Detail

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	3	12.00	8	2	0.020	0.50	0.50	1.00	Single*
A-8-2-e**	1	12.00	8	2	0.020	0.50	0.50	1.00	Single
A-8-1-e	1	12.00	8	1	0.020	0.50	0.50	1.00	Single
B-8-2	2	12.00	8	2	0.020	1.25	0.75	1.00	Single
B-8-2-e	1	12.00	8	2	0.020	1.25	0.75	1.00	Single
B-8-1-e	1	12.00	8	1	0.020	1.25	0.75	1.00	Single
B-12-2	<u>2</u>	12.00	12	2	0.020	1.25	0.75	1.00	Single
Subtotal	11								
Phase II:									
PP-2	1	19.25	6	2	0.031	1.50	1.00	2.00	9.50
VL-2	<u>1</u>	19.25	4	2	0.020	0.50	0.50	1.00	3.00
Subtotal	<u><u>2</u></u>								
Total	13								

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

*Specimens A and B are single bellows. PP (process piping) and VL (vent line) are universal (see Figure 5) bellows.

**"e" indicates that the end tangent shall be attached to the outer diameter of the end spool for these specimens (total 4). All other details of the connection are the same as shown in Figures 6 and 7. The end tangents of the remaining specimens shall be attached to the inner diameter as shown in Figure 7.

3.0 Description of Tests

The test series subjected representative bellows to severe accident loadings. During the tests, various levels and combinations of internal pressure, temperature, axial compression or elongation, and lateral deformation were applied. Torsional loading was not incorporated into this test series as it would have added considerably to the cost of this project, and it has been researched [9].

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.

There are 11 tests of Phase I specimens and 2 tests of Phase II specimens. Phase I specimens are 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. Table 2 provides a description of the Phase I tests.

Leakage of the bellows specimens was mainly a qualitative indication. In the case of ambient temperature tests, Leakage of the bellows was determined by a flow indication from flowmeters that monitored the pressurizing line to the interior volume of the specimen, and, in cases of two-ply bellows, the pressurizing line to the space between the two plies. In the case of elevated temperature tests, leakage was determined by visually monitoring the bellows for any loss of the heat transfer oil, which was pressurized (see Figure 11).

The test designation, shown and described in Table 2, was followed through the first load cycle. If leakage did not occur during the first load cycle, the bellows were 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, with one of the specimens representing approximately 1:4 - scale vent line bellows (VL-2 specimen) in a BWR Mark - I and the other one being representative of a full size process piping bellows (PP-2 specimen) in a PWR containment.

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.

Some of the tests were conducted at $425 \pm 25^\circ\text{F}$ to determine the effect of lower ductility at temperature on the ability of bellows to remain leaktight during a severe accident.

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

Prior to load testing, initial elastic stiffness measurements were recorded for each specimen. The specimen was extended a small amount while monitoring the load required for that extension. The stiffness is the force divided by the distance. That number is reported in the test results for each specimen.

As shown in Table 1, two tests were performed in Phase II. The first test of Phase II was of specimen PP-2. Table 3 provides a list of the combinations of internal pressure, lateral deformation and axial compression that were applied. This load combination is determined from the expected deformation of a particular containment at a bellows piping penetration, as determined from finite element analysis of that containment. The bellows specimen was held at $425 \pm 25^\circ\text{F}$ at all times during the test. As shown in Table 3, the internal pressure, axial compression, and lateral deformation were increased until the bellows was fully compressed at an internal pressure of approximately 75 psig. Per the test plan, if the bellows is still intact when fully compressed, the applied test conditions are reversed by removing axial and lateral deformation as well as internal pressure at the same rate at which each was originally applied. Additional loadings applied to cause a tear in the bellows are described in Section 5.

The test procedure for the vent line specimen (VL-2) 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 Phase I Tests

<u>Test No.</u>	<u>Specimen I.D.</u>	<u>Test Designation</u>	<u>Maximum Test Pressure (psig)</u>
Compression Tests:			
2	A-8-2	SCT	150
3	B-8-2	SC	75
4	B-8-2	SCT	75
9	B-12-2	SC	75
10	B-12-2	SCT	75
11	A-8-2	CL	ambient
12	A-8-2	LC	ambient
Elongation Tests:			
13	A-8-1-e	SE	ambient
14	A-8-2-e	SE	ambient
15	B-8-1-e	SE	ambient
16	B-8-2-e	SE	ambient
Test Designation	Description		
CL	Axially compress the bellows until all convolution roots are fully compressed. If the bellows are still leak tight, apply lateral deformation until a tear in the bellows occurs. No internal pressure will be applied during this test.		
LC	Apply lateral offset until the bellows become unstable (i.e., very small increase in lateral load produces relatively large lateral deformation). If the bellows are still intact, apply axial compression until all convolutions are fully compressed. If the bellows are still intact after being fully compressed, apply additional lateral deformation until a tear develops in the bellows. No internal pressure will be applied during this test.		
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 has been removed.		
SCT	Same as SC except test temperature is 425 ±25°F throughout the specimen for the entire test.		
SE	Simultaneously apply axial elongation and lateral deformation. Axial elongation and lateral deformation shall be increased linearly such that the total applied lateral deformation is 2 inches* when the bellows are fully elongated. If the bellows are still leak tight after being fully elongated, reverse the applied test conditions by removing elongation and lateral deformation at the same rate at which each was originally applied. Continue this process until either a crack develops or until all originally applied deflection has been removed. No internal pressure will be applied during this test.		

* A lateral displacement of 2 inches is a conservative estimate of the amount of vertical displacement that a containment building would experience during a severe accident. Also, the spacing between the pipe and the opening in the containment is usually less than 2 inches (which limits the amount of lateral displacement of the pipe).

Description of Tests

Table 3
Load Combinations for PP-2
Phase II Test

<u>Internal Pressure (psig)</u>	<u>Lateral Deformation (in.)</u>	<u>Axial Compression (in.)</u>
0.2	0.24	0.13
0.6	0.73	0.39
1.0	1.21	0.64
5.0	1.34	0.73
10	1.48	0.85
20	1.71	1.08
30	1.90	1.26
40	2.06	1.47
45	2.14	1.59
50	2.22	1.77
52	2.25	1.89
54	2.28	2.08
56	2.31	2.35
58	2.33	2.80
60	2.34	3.61
62	2.37	4.45
64	2.39	5.37
66	2.40	6.37
68	2.42	7.43
70	2.44	8.55
72	2.46	9.85
74	2.48	11.25

4.0 Test Apparatus and Instrumentation

All of the bellows specimens have been tested in a hydraulically actuated load frame (Figure 8). The cylinders that load the bellows in the axial and lateral directions have force capabilities of 350,000 pounds and 250,000 pounds, respectively. The hydraulic power unit contains a variable flow pump for each cylinder. The flow rate is adjusted before the start of a test. The load frame operates at a constant displacement rate, with movement based on operator input to a computer that controls hydraulic valves. The same computer also controls the pressurizing and oil circulating systems and records test data.

A second computer receives load, displacement, internal pressure, and temperature data from the first and displays it in a window over a video image of the specimen during the test for recording on video tape (Figure 9). This video is used to document, in a qualitative sense, the bellows deformations that result from applied loadings. It also allows production of 'time lapse' coverage of the tests, where the bellows deformation, from start to finish, can be viewed in a few minutes.

A still camera also captures images of the bellows specimen during the test. A grid is superimposed over the image of the bellows by means of a partially reflective glass plate located in front of the camera, where the image of the grid is reflected (Figure 10). The grid marks are spaced approximately 1/10 inch apart. Reference marks, that are attached to the test frame at fixed spacings, are included in the field of view so that the accuracy of the grid spacing can be checked and calibrated if necessary. The superimposed grid provides a method of quantifying the amount of bellows deformation for a given set of loading conditions. This is a practical method that was used to record the extreme bellows deformation at many loading steps. If the need arises, the deformed bellows shape from these photographs can be compared to finite element analyses to check the ability of such analyses to predict bellows deformation up to the point of leakage. There is no current plan to conduct additional finite element analyses.

Figure 8. Bellows Load Frame

Test Apparatus and Instrumentation

Figure 9. Video Coverage of Tests

Figure 10. Still Camera Coverage of Tests

The test specimen is bolted into the load frame by means of flanges that are welded to the end spools of the bellows. The bellows is positioned so that the axial dimension is equal to the free length of the bellows measured outside of the load frame. The bellows is then displaced in steps as the test progresses. In the case of a test that includes internal pressure, or internal pressure and temperature, as test parameters, the bellows is filled with oil prior to being mounted in the load frame.

The pressurizing system is nitrogen gas over oil which minimizes the stored energy in the test specimen and facilitates the input of heat to the specimen for the elevated temperature tests (Figure 11).

Instrumentation used during testing consists of strain gages (ambient temperature tests only; Figures 12 and 13), displacement transducers, load cells (axial and lateral), thermocouples (Figure 14), pressure transducers, and flowmeters.

Six strain gages were installed on the first test (I-11-CL), whereas nine gages were installed on the balance of the tests conducted at ambient temperature. Strain gages were not used on the elevated temperature tests due to difficulties in measuring large strains at elevated temperature. Strain data was recorded for possible comparison between analytical and experimental data at some later date.

Figure 11. Bellows Pressurizing and Heating System

**Figure 12. Strain Gage Locations
for Test I-11-CL**

**Figure 13. Strain Gage Locations
for Other Ambient Temperature Tests**

Test Apparatus and Instrumentation

Figure 14. Thermocouple Locations

All of the sensors were scanned at each incremental displacement step. The output from the axial load cell was monitored closely as the bellows neared full compression, to determine, by a sharp increase in load, when the bellows was fully compressed metal-to-metal.

5.0 Test Results

Thirteen tests have been conducted. These tests subjected bellows to extreme axial and lateral deformations such as those that could be experienced during a severe accident. The bellows have demonstrated the ability to withstand relatively large deformations before developing a leak. Most of the Phase I test specimens were able to endure one complete cycle of full compression, or full extension, with 2 inches of lateral displacement and remain leak tight.

Several tests in this series have investigated the effect of elevated temperature (425°F) as well as the effect of internal pressure on the loading conditions required to produce bellows leakage. Other tests in the series have examined the performance of test specimens that are representative of some full size process piping bellows such as those found in a PWR and approximately 1:4-scale vent line bellows found in a BWR Mark - I.

Some representative data from strain gages, thermocouples, and load cells is shown in Figures 15 through 17. The balance of the data plots are contained in Appendix A.

Table 4 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 13 of the 20 originally planned tests were conducted) and the test type (e.g. CL, SE, etc. as described for Table 2). The specimen I. D. is defined in Table 2.

Figure 17. Typical Axial Loadcell Data

As shown in Table 4, most specimens were leaktight upon reaching either full axial compression² or elongation³ for the first time. The axial deformation required to cause full compression or elongation is shown for each specimen in Table 4. Four of the thirteen specimens leaked before reaching full compression or elongation. The percent of full compression or elongation at the time of first leakage is provided in Table 4 for these specimens.

A detailed description of each test is provided below. The axial compression tests are described first in Section 5.1, followed by the elongation tests in Section 5.2. Section 5.3 presents information on the posttest condition of some of the specimens that were cut apart after testing. Test results are discussed in Section 6.

5.1 Axial Compression Tests

Test I-11-CL

Test I-11-CL was conducted first since it followed the relatively simple 'CL' loading procedure which does not include pressure or elevated temperature. This test utilized specimen A-8-2-1 which is a two-ply specimen with 8 convolutions of 1/2 inch depth. Initial stiffness averaged 3980 pounds/inch. Figure 18 shows the specimen instrumented and ready for testing. The test consisted of compressing the specimen axially until reaching full compression and then displacing it laterally while maintaining that axial displacement. For this specimen the calculated axial displacement to achieve full

²Full compression is achieved when the applied axial compression equals the bellows undeformed length between the end spools minus twice the number of convolutions times the number of plies times the ply thickness (plus half of the wire mesh diameter for two-ply bellows).

³Full elongation is defined as the length of the bellows between the spools measured along the outside surface of the bellows convolutions. During testing, the bellows were assumed to be fully elongated when the above deformation was reached and the observed axial load increased rapidly with increasing axial elongation.

Figure 15. Typical Strain Data

Figure 16. Typical Thermocouple Data

Table 4
Bellows Failure Conditions

<u>Test</u>	<u>Specimen I. D.</u>	<u>Nominal Test Pressure (psig)</u>	<u>Nominal Test Temperature (° F)</u>	<u>Leaktight at Full Compression or Elongation of First Loading (yes or no)</u>	<u>Axial Deformation at Full Compression or Elongation (in.)</u>	<u>Percent Compressed or Elongated at First Leakage</u>	<u>Initial Elastic Stiffness (lb/in.)</u>
Compression Tests:							
I-11-CL	A-8-2-1	Ambient	Ambient	yes	3-1/4	*	3970
I-12-LC	A-8-2-2	Ambient	Ambient	yes	3-3/8	*	3370
I-3-SC	B-8-2-1	75	Ambient	yes	4-3/4	*	260
I-4-SCT	B-8-2-2	65	415	no	5-3/8	86	340
I-2-SCT	A-8-2-3	150	420	yes	3-3/4	*	3780
I-10-SCT	B-12-2-1	68	410	no	8-1/8	91	350
I-9-SC	B-12-2-2	72	Ambient	no	8-1/2	99	350
II-19	VL-2	150	415	yes	3	*	7650
II-17	PP-2	74	400	yes	10-1/2	*	1770
Elongation Tests:							
I-13-SE	A-8-1-e	Ambient	Ambient	no	6-1/2	88	1870
I-14-SE	A-8-2-e	Ambient	Ambient	yes	-6	*	4360
I-15-SE	B-8-1-e	Ambient	Ambient	yes	-17	*	50
I-16-SE	B-8-2-e	Ambient	Ambient	yes	-18	*	70

* These specimens did not leak during the initial compression or elongation of the bellows. Leakage occurred only after additional loadings were applied as described in discussions of each test in Section 5.

Test Results

compression was about 3-1/4 inches. Full compression is readily observable during the test, as the load increases sharply when all the spaces are closed. Axial displacement increments of .10 inch were made until the total axial displacement was approximately 3.3 inches and the axial load had increased to about 300,000 pounds. Lateral displacement steps were then initiated. The specimen is shown fully compressed in Figure 19. At

that point, the bellows specimen was displaced laterally until a leak developed, which, in this test, occurred at a lateral displacement of approximately 2.6 inches. The displaced specimen is shown in Figure 20. The lateral displacement steps were continued to a maximum displacement of approximately 4.6 inches by which time several large tears were visible. The test was terminated at this point.

Figure 18. Test I-11-CL. Specimen A-8-2-1 at Start of Test

Figure 20. Test I-11-CL.
Specimen A-8-2-1 at First Leakage.

Figure 19. Test I-11-CL.
Specimen A-8-2-1 Fully Compressed.

Test Results

Test I-12-LC

Test I-12-LC was the next test. The specimen was identified as A-8-2-2, and was identical to the specimen that was tested in I-11-CL. Initial stiffness averaged 3370 pounds/inch. The calculated axial displacement for full compression for this specimen was approximately 3-1/2 inches. The loading sequence was reversed from that of the first test. That is, the specimen was first subjected to a lateral displacement followed by axial compression. The total lateral displacement was limited to two inches because that is a conservative calculation of the amount of vertical displacement that the containment building could experience during a severe accident. After being displaced laterally a total distance of 2 inches and remaining leak tight (Figure 21), the bellows was compressed axially for a total displacement of approximately 3-3/8 inches (Figure 22). At that time all convolutions were fully compressed. The bellows remained leak tight at that point. The bellows was subsequently elongated to its original length and displaced transversely back to the centerline. The bellows was still leak tight at that time, and was again fully compressed axially and displaced transversely 2 inches. After this second cycle, the bellows remained leak tight. The lateral displacement was then increased to approximately 2-3/8 inches where a leak developed through both plies. The leak increased rapidly as the lateral displacement was increased to about 2-5/8 inches. The test was terminated at this point. The lateral displacement beyond 2 inches was done to determine the bellows ultimate capacity. A comparison with test I-11-CL shows that even though this specimen had undergone a complete cycle of compression and elongation, the amount of transverse displacement to cause leakage was similar.

Test I-3-SC

This was the first test to include internal pressure. The pressure was increased incrementally so that the maximum pressure and maximum displacement were arrived at concurrently. The specimen was of two-ply construction with deep convolutions (1-1/2 inches). The specimen identification number is B-8-2-1 (Figure 23). Initial stiffness averaged 260 pounds/inch. The measured distance between end spools was approximately 4-7/8 inches, with a calculated dimension of approximately 4-1/2 inches for full compression. The maximum pressure for this test was 75 psig.

A leak developed between plies at axial and lateral displacements of approximately 4-3/4 inches and 2-1/4 inches, respectively (Figure 24). The bellows leaked to the outside after returning to axial and lateral displacements of approximately 4-1/4 inches and 2 inches, respectively. The leak was coming from a sharp crease that had developed on the crest of a convolution. The specimen was depressurized and the test was terminated.

Test I-4-SCT

Test I-4 utilized a bellows specimen of the same construction as test I-3 (specimen B-8-2-2), with the difference being temperature. Initial stiffness averaged 340 pounds/inch. This was the first test in this series to subject a bellows specimen to elevated temperature. Figure 25 shows the specimen installed in the load frame. An insulating blanket was attached to the lower one third of the specimen to aid in achieving a more uniform temperature.

The specimen was heated by directing hot oil through a loop containing an electric circulation heater. Radiant heaters were also used to bring the specimen up to test temperature. The radiant heaters were switched off at the start of the test to minimize the danger of fire in the event of a leak, which could spray hot oil on the heater elements.

Twelve thermocouples were attached to the outer ply of the specimen. They were located around the circumference of the specimen at 90 degree intervals and spaced 3 to a row along the axial centerline (see Figure 26). After each thermocouple indicated a temperature of $425 \pm 25^\circ\text{F}$, the specimen was subjected to incremental displacement and pressure steps. The measured distance between end spools was approximately 5-3/8 inches, yielding a calculated displacement of approximately 5 inches for full axial compression.

The bellows developed a leak at axial and transverse displacements of approximately 4-5/8 inches and 1-7/8 inches, respectively. The bellows was leaking at a sharp crease that had developed on the crest of a convolution. The measured distance between end spools at the termination of the test was approximately 15/16 inch.

Test I-2-SCT

The specimen for this test was identified as A-8-2-3, which has 1/2 inch deep convolutions. Initial stiffness averaged 3780 pounds/inch. This test also employed pressure and temperature as test parameters. The measured distance between end spools was 4 inches. The calculated displacement for full compression was approximately 3-5/8 inches.

The specimen remained leak-tight after full compression and lateral displacement of 2 inches. At this point the displacement direction was reversed so that the specimen was being extended toward its original dimensions. A leak was indicated from between plies to the outside at axial and lateral displacements of approximately 3/4 inch and 3/8 inch, respectively. After the displacement was returned to the starting point, the specimen was again compressed. The indicated leak increased at axial and lateral displacements of approximately 1/2 inch and 3/8 inch, respectively. The specimen was fully compressed a second time without developing a leak from the inner ply. At this point, the axial displacement was retracted

Figure 22. Test I-12-LC.
Specimen A-8-2-2 Fully Compressed.

Figure 21. Test I-12-LC.
Specimen A-8-2-2 Displaced Laterally 2 Inches.

Figure 23. Test I-3-SC. Specimen B-8-2-1 at Start of Test.

Figure 24. Test I-3-SC. Specimen B-8-2-1 Fully Compressed.

Figure 25. Test I-4-SCT. Specimen B-8-2-2 at Start of Test.

Figure 26. Bellows Specimen Showing Thermocouple Placement.

Test Results

approximately 1/8 inch and the pressure was maintained at 150 psig while the lateral displacement was removed in steps. The bellows developed a leak through both plies after returning to lateral zero for the second time.

Test I-10-SCT

Test I-10 utilized a specimen containing a greater number of convolutions than any previously tested. The bellows test specimen, identified as B-12-2-1, contains 12 convolutions (Figure 27). Because of the large number of convolutions and their depth, this specimen is very flexible. Initial stiffness averaged 350 pounds/inch. The measured distance between end spools at the start of the test was approximately 8-5/8 inches. Computed axial displacement for full compression was approximately 8-1/8 inches. The specimen leaked during the move to axial and lateral offsets of 7-3/8 inches, and 1-7/8 inches, respectively. The deep convolutions were observed to fold over the end spools immediately prior to leakage, indicating that the bellows material may have been sheared by the end spools. Figure 28 shows the specimen as it was removed from the load frame.

Test I-9-SC

The same type of specimen that was tested in I-10-SCT was tested at room temperature in this test. The specimen is identified as B-12-2-2. Initial stiffness averaged 350 pounds/inch. Distance between end spools was measured as 9 inches, with approximately 8-1/2 inches of axial displacement calculated to achieve full compression. A large leak developed during the axial and lateral moves to 8-3/8 inches, and 2 inches, respectively. The same folding over of the bellows convolutions that was observed during Test I-10-SCT was again observed during this test (Figure 29).

Test II-19

This was the first test of the larger bellows designated as phase II specimens. The bellows was specimen VL-2 (Figure 30), which is a universal two-ply vent line bellows of approximately 1:4-scale. Initial stiffness averaged 7650 pounds/inch. Axial compression, lateral offset, and internal pressure were increased linearly such that an offset of 1 inch and internal pressure of 150 psig was reached when the bellows were fully compressed. The temperature was held at $425 \pm 25^\circ\text{F}$ throughout the test. The bellows was leak tight after two cycles of full compression. At this point, the bellows was returned to lateral zero while remaining fully compressed axially. The bellows was still leak tight at this point. The bellows developed a leak through the outer ply after being displaced a distance of approximately 2-1/2 inches laterally while remaining fully compressed axially. Both plies leaked after the lateral displacement was incremented to approximately 2-7/8 inches. The internal pressure was maintained at 150 psig during the lateral displacements. The specimen is shown, after removal of the insulation, in Figure 31.

Test II-17

A full-scale process piping bellows was used in this test. The bellows is a universal type of two-ply construction (Figure 32). Initial stiffness averaged 1770 pounds/inch. This bellows was subjected to the test profile listed in Table 3. This loading profile represents the postulated conditions that a bellows could be subjected to during a severe accident. The temperature of the bellows was maintained at $425 \pm 25^\circ\text{F}$ throughout the test. The inner ply began to leak as the specimen approached metal-to-metal contact axially. The specimen was subjected to the loading cycle twice without developing a leak through the outer ply, however. It was then displaced laterally a total distance of approximately 5 inches while remaining fully compressed axially and at the maximum internal pressure of 74 psig. The outer ply was still leak tight at this point, and the lateral displacement was reversed so that the incremental steps were in the direction of zero lateral displacement. As the displacement approached approximately 1-3/4 inches the outer ply began to leak. Figure 33 shows the specimen as it was removed from the load frame. A close view of the tear in the outer ply is shown in Figure 34.

5.2 Elongation Tests

As shown in Table 4, all four elongation tests were conducted at ambient temperature and without considering the effects of external pressure.

Test I-13-SE

Test I-13-SE was a simultaneous extension test, meaning that the displacement is stepped in the axial and lateral directions simultaneously. The specimen tested was A-8-1e-1, which is a single-ply bellows with 8 convolutions of 1/2 inch depth. Initial stiffness averaged 1870 pounds/inch. At the maximum axial displacement the bellows is fully extended to the original cylindrical shape (all convolutions flattened out) at a shear displacement of about 2 inches. This condition could occur when a bellows is located inside containment and the outward expansion of the containment causes the bellows to elongate. Because bellows located inside containment are subjected to external pressure, the bellows end tangents are welded externally to the end spools. The bellows is shown at the beginning of the test in Figure 35. The calculated maximum extension for this specimen was approximately 6-1/2 inches (for comparison, the meridional length of the undeformed bellows along the convolutions was about 3-3/4 inches). The bellows developed a leak at an axial elongation of approximately 5-3/4 inches and a shear displacement of approximately 1-1/4 inches (Figure 36). The specimen was leaking from a small tear next to what appeared to be a weld repair near one end spool. The test continued until the leak had increased rapidly and a tear had progressed approximately halfway around the specimen at an axial displacement of approximately 7 inches.

Figure 27. Test I-10-SCT. Specimen B-12-2-1 at Start of Test.

Figure 28. Test I-10-SCT. Specimen B-12-2-1 at Termination of Test.

Figure 29. Test I-9-SC. Specimen B-12-2-2 at Termination of Test.

Figure 30. Test II-19. Specimen VL-2 at Start of Test.

Figure 31. Test II-19. Specimen VL-2 at Termination of Test.

Figure 32. Test II-17. Specimen PP-2 at Start of Test.

Figure 33. Test II-17. Specimen PP-2 at Termination of Test.

Figure 34. Test II-17. Specimen PP-2. Close-up of Tear in Outer Ply.

Figure 35. Test I-13-SE.
Specimen A-8-1e-1 at Start of Test.

Figure 36. Test I-13-SE.
Specimen A-8-1e-1 at First Leakage.

Test Results

The test was terminated at that point. The specimen was fully extended at the time the long tear developed.

Test I-14-SE

The test procedure for I-14-SE was identical to test I-13-SE, with the difference being the specimen construction. Test I-14-SE utilized a two ply bellows with all other dimensions remaining the same. Initial stiffness averaged 4360 pounds/inch. The calculated displacement for maximum axial elongation was about 5-7/8 inches. The specimen was extended to approximately 6 inches and sheared approximately 2 inches at that maximum extension (Figure 37). At the maximum extension, the bellows did not leak and the displacement steps were reversed to compress the bellows axially while returning to center laterally. At an axial displacement of approximately 1-1/2 inches and a shear displacement of approximately 1/2 inch, a tear developed (Figure 38). At this point the displacement direction was again reversed so that the bellows was being elongated, and that extension was continued to approximately 6 inches axially and 2 inches laterally. Several large tears had developed at that time (Figure 39) and the test was terminated.

Test I-15-SE

Specimen B-8-1e-1 was utilized in Test I-15-SE (Figure 40). This was another simultaneous extension test with the same displacement characteristics as the previous two. However, the specimen in this test had much deeper convolutions than the two preceding. The specimen had 8 convolutions of 1-1/4 inch depth and was of single-ply construction. Initial stiffness averaged 50 pounds/inch. The original length of the specimen between end-tangent welds was approximately 7-3/4 inches. The calculated maximum axial extension was approximately 16-1/2 inches, more than twice its original length.

The test specimen was extended axially a distance of 17 inches and displaced laterally a distance of 2 inches with no leakage (Figure 41). The specimen was then compressed back to an axial displacement of approximately 7 inches at a lateral displacement of about 3/4 inch without developing a leak (Figure 42). At that point, the bellows was again extended to an axial and a lateral displacement of approximately 9-3/4 inches and 1-1/4 inches, respectively, at which point a leak developed. The leak increased as the specimen was extended to approximately 10 3/4 inches and laterally displaced to approximately 1 3/8 inches. Upon further extension to approximately 11 1/4 inches at a lateral displacement of approximately 1-1/2 inches, several more small tears appeared and there was a large increase in leakage. The

test was terminated at a maximum axial and lateral deformation of approximately 18 inches, and approximately 2 inches respectively, when the length of the tears had increased so that the specimen stiffness had decreased markedly (Figure 43).

Test I-16-SE

This test was another simultaneous extension test with a specimen similar to the one tested in I-15-SE. The dimensions and convolution depth were the same, but this specimen (B-8-2e-1) is of two-ply construction. However, initial stiffness averaged only 70 pounds/inch. The calculated maximum extension for this specimen was about 17-1/2 inches. This specimen was sprayed with a white powder coating to enhance the contrast for the fine-grain black-and-white film used during this test. Also, the initial field of view is larger in order to complete the test without changing camera position. Figure 44 shows the specimen at the start of the test. The bellows specimen developed a leak from between the plies to the inner volume at axial and lateral displacements of approximately 16 3/4 inches and 1 7/8 inches, respectively. However, there was no leakage from inside the bellows to the external environment. The specimen was further displaced axially and laterally to approximately 18 inches and 2 inches, respectively, with no change in leakage (Figure 45). After compressing the specimen back to an axial and a lateral displacement of approximately 17 inches and 1.5 inches, respectively, a leak developed in the outside ply of the bellows. That leak was typical of what had been seen previously. That is, it developed at a sharp crease as the bellows was compressed and re-extended (Figure 46). At this time the specimen was extended again to approximately 18 3/4 inches and displaced laterally to approximately 2 1/4 inches at which time the leak had increased, but the tear had not progressed to the point of substantially decreasing the stiffness of the specimen. The test was terminated at this point due to the high loads experienced by the load frame.

5.3 Posttest Specimen Dissection

A few of the bellows were cut in half along the axial centerline in the direction of the applied shear load to allow inspection of the inner ply (Figures 47 and 48). No evidence of failure of the internal weld between bellows and end spools is apparent. Buckling of the bellows wall caused by the shear load is readily visible in the figures. One of the specimen halves was itself cut in half to reveal internal deformation of the end sleeve caused by the shear load (Figures 49 and 50).

Figure 37. Test I-14-SE.
Specimen A-8-2e-1 Fully Extended.

Figure 38. Test I-14-SE.
Specimen A-8-2e-1 at First Leakage.

Figure 39. Test I-14-SE.
Specimen A-8-2e-1 Showing Large Tears.

Figure 40. Test I-15-SE.
Specimen B-8-1e-1 at Start of Test.

Figure 41. Test I-15-SE. Specimen B-8-1e-1 Fully Extended.

Figure 42. Test I-15-SE. Specimen B-8-1e-1. Partially Returned From Full Extension.

Figure 43. Test I-15-SE. Specimen B-8-1e-1 at Termination of Test.

Figure 44. Test I-16-SE. Specimen B-8-2e-1 at Start of Test.

Figure 45. Test I-16-SE. Specimen B-8-2e-1 Fully Extended.

Figure 46. Test I-16-SE. Specimen B-8-2e-1. Close-up of tear at Sharp Crease.

Figure 47. Test I-4-SCT. Inner View of Tested Bellows With 8 Convolutions.

Figure 48. Test I-10-SCT. Inner View of Tested Bellows With 12 Convolutions.

Figure 49. Test I-9-SC. Quarter Section of Tested Specimen.

Figure 50. Test I-9-SC. Close-up of Quarter Section of Tested Specimen.

6.0 Evaluation of Test Results

The purpose of this section is to provide further comments on the collection of test results and provide some thoughts on the use of this data for assessing the leakage behavior of bellows in actual containments. Results of the compression tests are evaluated in Section 6.1 followed by the elongation tests in Section 6.2. Section 6.3 describes the manner in which the data could be applied to actual containment bellows, along with warnings about the limitations of the test data.

6.1 Compression Tests

The test series was designed so that the effect of various parameters on the ability of bellows to remain leaktight during a severe accident could be evaluated. The tests have shown that a wide range of 'like-new' bellows geometries are capable of resisting large axial and lateral deformations, along with internal pressure and elevated temperature, before developing leakage. The bellows were deformed to the point of full compression, or very near full compression, before tears developed that lead to leakage. (It is believed that leakage will begin soon after the bellows are fully compressed as the containment wall moves further out as the containment pressure increases. The leakage will likely be caused by failure of the connection of the end spools to the process pipe, since these connections were not designed for direct load transfer between the containment wall and pipe.)

Some bellows geometries performed slightly better than others. Consistent trends for the parameters of convolution design, test temperature, and bellows design (single vs. universal) can be observed from the test results shown in Table 4. These trends are described below.

6.1.1 Effect of Convolution Depth

Two basic convolution geometries were tested in Phase 1. The A specimens represent the lower end of the range of convolution depth-to-ply thickness ratios that could be found in actual containments, whereas the B specimens are representative of the larger convolution depth-to-ply thickness ratios. As shown in Table 4, for all applied loading conditions, the A specimens remained leaktight up to the point of full axial compression. However, some of the B specimens developed tears and associated leakage before reaching full compression. This result was not expected before the tests. Before testing, it was felt that the lower axial stiffness of the B specimens would be beneficial in allowing them to deform when subjected to extreme loadings without tearing. (The difference in axial stiffness between the A and B specimens can be seen in Table 4.)

Close inspection of the failed bellows specimens reveals that sharper and deeper creases were formed in the deeper convolution specimens, particularly when the bellows neared the point of full compression and as the lateral

deformation was further increased. For this deformed geometry, it was as if the extra material contained in the deeper convolutions was forced to re-locate into sharp creases during the lateral deformation. The shallower convolutions did not seem to 'lock up' in the same manner and thus, they were able to meet the applied end deformation conditions without tearing.

Again, it should be pointed out that, even for the extreme convolution depth-to-ply thickness ratios in the B specimens, the bellows remained leaktight up to, or very near, the point of full compression. Also, the maximum applied lateral deformation of 2 inches is very large for a single convolution bellows. In most, if not all, process piping bellows applications, universal bellows are employed, which are designed to resist lateral deformation and would likely have performed better than the single B specimen bellows. The observed behavior of single bellows specimens is compared to that of a universal bellows in a later section.

6.1.2 Effect of Elevated Temperature

It was known before the tests that Type 304 stainless steel loses ductility with increasing temperature. Based on material property data found in the literature, about 35% of the ductility is lost from room temperature to 400°F (Figure 4). For that reason, some of the bellows were tested at $425 \pm 25^\circ\text{F}$ to determine the effect on the ductility loss on the ability of the bellows to resist extreme deformations without leaking.

The effect of temperature can be readily observed by comparing the behavior of identical specimens at room temperature and at $425 \pm 25^\circ\text{F}$. As shown for the B specimens in Table 4, the bellows at elevated temperature consistently leaked earlier in the load cycle than their counterpart at room temperature. Also, from the detailed description of the A specimen tests in Section 5.1, the elevated temperature specimens also leaked earlier than similar specimens at room temperature, although the specimens remained leaktight up to the point of full compression, even at elevated temperature. Leakage was only observed after additional deformation cycles were applied.

Based on the test results, it is apparent that elevated temperature does have a negative effect on the amount of deformation that bellows can resist before leaking. However, even for the worst case combinations of convolution depth and elevated temperature, along with internal pressure and lateral deformation loadings, the bellows specimens were still capable of reaching at least 85% of full compression before leakage began.

6.1.3 Effect of Bellows Design - Single Vs. Universal

Only two universal bellows were tested. The remainder were single bellows. Perhaps the most informative comparison can be obtained by comparing the PP-2 specimen behavior with that of the B specimens. The primary difference between the PP-2 specimen and the B specimens is the bellows design. The PP-2 specimen is a universal bellows, whereas the B specimens are single bellows.

The PP-2 specimen has a relatively large convolution depth-to-ply thickness ratio, similar to the B specimens. However, the PP-2 specimen was capable of reaching full axial compression, combined with internal pressure, temperature, and lateral deformation, without developing leakage. The specimen also resisted further deformation load cycles, as described in Section 5.1, before finally tearing. After resisting two full cycles of simultaneous compression and lateral deformation, the bellows was still leaktight. A lateral offset of 5 inches was finally applied to the PP-2 bellows, while they were fully compressed, before a leak developed.

Universal bellows are better designed to resist lateral deformation than single bellows of similar size. Rotation of the center spool of universal bellows reduces the amount of rotation and associated strains that the bellows convolutions must resist. Comparison of the behavior of the PP-2 specimens with that of the B specimens demonstrates the greater resistance of universal bellows to the effects of lateral deformation.

6.2 Elongation Tests

All of the elongation tests were of single bellows specimens. The loadings consisted of simultaneously increasing the axial elongation and lateral deformation until the bellows were either fully elongated or a tear developed. However, external pressure and elevated temperature were not applied to these tests. Pressure and temperature were not included for three reasons: (1) the complexity that it would have added to the program, (2) the limited number of actual containment bellows that would be subjected to these types of loadings, and, most importantly, (3) it is believed that bellows can generally be elongated to greater axial lengths than the same bellows could be compressed.

'Typical' bellows can be elongated to two to three times their undeformed length before reaching the point of 'full elongation', where all of the convolutions have been collapsed back into a cylinder. The amount of possible elongation depends on the height of the convolutions. Of course, the undeformed length of a bellows is the maximum dimension that the bellows can be compressed, so bellows are inherently capable of extending further than they can be compressed. This is the basis for the third reason given above as to why pressure and temperature were not included in the elongation tests.

Inspection of the test results in Table 4 reveals that all of the elongation bellows specimens were leaktight up to, or very near, the point of full elongation. For the shallower convolution A specimens, the bellows were elongated to about twice their undeformed length, whereas the deeper convolution B specimens reached more than three times their undeformed length.

Again, the effects of external pressure and elevated temperature were not examined during these tests. These effects must be considered also before assuming that a given containment bellows could be fully elongated without leaking.

6.3 Application of Test Results to Actual Containments

A relatively wide range of bellows parameters and loading conditions have been examined in this test series. However, there may be some bellows in actual containments that are used in different applications, are of different geometrical design, or would be subjected to different load combinations than the bellows specimens in these tests. Also, the effects of corrosion were not considered in these tests. Therefore, the results of these tests can not be 'blindly' extrapolated to cover all containment piping penetration bellows. Careful evaluation of the test results and of the given bellows application must be performed to determine the applicability of these results to any particular bellows. The following guidelines are provided for bellows that would be compressed during a severe accident (compression bellows) and for bellows that would be elongated (elongation bellows).

6.3.1 Compression Bellows

In order to assess the containment pressure and temperature at which a given bellows might leak, the following procedure is recommended. First, perform a nonlinear, axi-symmetric (or three dimensional) finite element analysis of the containment shell when subjected to the internal pressure and elevated temperatures of interest. From this analysis, determine the radial and lateral movement of the containment shell at the location of the bellows. If the bellows geometry and pressure, temperature, and lateral offset is within the range covered by these tests, then a conservative approach would be to assume that the bellows will leak when the axial compression reaches 75% of the deformation necessary to cause full compression. The corresponding containment pressure and temperature required to produce this amount of bellows axial deformation can be determined from the axi-symmetric analyses of the containment shell.

6.3.2 Elongation Bellows

The range of loadings and bellows geometries covered by this test series is not as broad for bellows that would be elongated during an accident as for those that would be compressed.

Evaluation of Test Results

The performance of the test specimens was excellent. However, the effects of external pressure and elevated temperature were not included in the tests. Because of these limitations, no recommendations are made regarding the amount of deformation that these

types of bellows can resist without leaking. Further evaluation of the effects of external pressure and elevated temperature would be required to determine the conditions that would cause leakage of these types of bellows.

7.0 Summary

A series of thirteen bellows tests have been conducted. The purpose of the tests is to determine the behavior of containment bellows in the unlikely event of a severe accident. If a severe accident occurred, the bellows could be subjected to combinations of pressure, temperature, and axial and lateral deformations, that are well beyond the design conditions. The ultimate objective of the tests is to determine the combinations of the above loadings that could lead to bellows failure.

Results of the tests have shown that bellows in 'like-new' condition are capable of remaining leak tight under extreme combinations of displacement, pressure and elevated temperature. Bellows capacity is somewhat degraded by temperature; however, they are still capable of remaining leak tight for extreme conditions.

As expected, the universal type of bellows withstood more extreme lateral displacements due to its design. Another geometric factor that affects performance is the depth of convolutions. The deeper convolutions develop sharp creases with less lateral displacement than those with shallow convolutions. Tears usually developed at one of these creases.

These tests show that a wide range of containment bellows, if in 'good' condition, will 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. After being fully compressed, additional outward movement of the containment will likely cause large leakage as the bellows are either cut by the end spools or the connection of the bellows to the end spools will fail, since it was not designed to withstand this type of loading. A method has been developed to estimate the containment pressure and temperature at which leakage would begin.

For bellows that would be elongated during a severe accident, the tests showed that bellows can be stretched to two to three times their undeformed length without leaking. However, the tests did not consider the effects of elevated temperature or external pressure. These loading should also be considered in an evaluation of these types of bellows.

Since all the bellows in this series were tested in 'like-new' condition, the question of degraded capacity as a result of corrosion has not been answered. Additional tests of bellows that have been subjected to corrosion are planned and will be reported at a later date.

8.0 References

- [1] M. B. Parks, D. S. Horschel, W. A. vonRiesemann, *Summary of NRC-Sponsored Research on Containment Integrity*, Transactions of the Eleventh Conference on Structural Mechanics in Reactor Technology, Tokyo, Japan, 1991, Session SD0, Paper No. 01/3.
- [2] L. Greimann, et al., *Analysis of Bellows Expansion Joints in the Sequoyah Containment*, NUREG/CR-5561, SAND90-7020, Sandia National Laboratories, Albuquerque, New Mexico (December 1991).
- [3] M. H. Shackleford, et al., *Characterization of Nuclear Reactor Containment Penetrations*, NUREG/CR-3855, SAND84-7180, Sandia National Laboratories, Albuquerque, New Mexico (1985).
- [4] *Standards of the Expansion Joint Manufacturers Association, Inc.*, 5th Edition, (1985 addenda), EJMA, Inc., 25 North Broadway, Tarrytown, NY.
- [5] *Nuclear Systems Materials Handbook*, Vol 1 Design Data, TID 26666 Volume 1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1987.
- [6] *Aerospace Structural Metals Handbook*, Vol 2, Code 1303 (304 Stainless Steel), Batelle Columbus Laboratories, March 1973.
- [7] Henry J. Rack, et al., *An assessment of Stress-Strain data Suitable for Finite-Element Elastic-Plastic Analysis of Shipping Containers*, NUREG/CR-0481, SAND77-1872, Sandia National Laboratories, Albuquerque, New Mexico (September 1978).
- [8] *Handbook of Stainless Steels*, Peckner and Bernstein (ed.), McGraw-Hill, New York, N.Y., 1977.
- [9] Reiger, W., *Torsion of Expansion joints - First Information and Test Results for Stability Properties and Behavior Under Stress*, Seventh International Conference on Structural Mechanics in Reactor Technology, Vol. J, 1983, pp. 331-338.

Appendix A

The plotted test data from strain gages, thermocouples, load cells, pressure transducers and flowmeters that were used during the bellows tests are presented in this

appendix. Descriptions of the individual tests that generated the data that are plotted here are contained in Section 5.

Figure A1. Bellows Test I-11-CL

Figure A2. Bellows Test I-11-CL

Figure A3. Bellows Test I-11-CL

Figure A4. Bellows Test I-11-CL

Figure A5. Bellows Test I-12-LC

Figure A6. Bellows Test I-12-LC

Figure A7. Bellows Test I-12-LC

Figure A8. Bellows Test I-12-LC

Figure A9. Bellows Test I-12-LC

Figure A10. Bellows Test I-13-SE

Figure A11. Bellows Test I-13-SE

Figure A12. Bellows Test I-13-SE

Figure A13. Bellows Test I-13-SE

Figure A14. Bellows Test I-13-SE

Figure A15. Bellows Test I-14-SE

Figure A16. Bellows Test I-14-SE

Figure A17. Bellows Test I-14-SE

Figure A18. Bellows Test I-14-SE

Figure A19. Bellows Test I-14-SE

Figure A20. Bellows Test I-15-SE

Figure A21. Bellows Test I-15-SE

Figure A22. Bellows Test I-15-SE

Figure A23. Bellows Test I-15-SE

Figure A24. Bellows Test I-15-SE

Figure A25. Bellows Test I-16-SE

Figure A26. Bellows Test I-16-SE

Figure A27. Bellows Test I-16-SE

Figure A28. Bellows Test I-16-SE

Figure A29. Bellows Test I-16-SE

Figure A30. Bellows Test I-3-SC

Figure A31. Bellows Test I-3-SC

Figure A32. Bellows Test I-3-SC

Figure A33. Bellows Test I-3-SC

Figure A34. Bellows Test I-3-SC

Figure A35. Bellows Test I-4-SCT

Figure A36. Bellows Test I-4-SCT

Figure A37. Bellows Test I-4-SCT

Figure A38. Bellows Test I-4-SCT

Figure A39. Bellows Test I-4-SCT

Figure A40. Bellows Test I-2-SCT

Figure A41. Bellows Test I-2-SCT

Figure A42. Bellows Test I-2-SCT

Figure A43. Bellows Test I-2-SCT

Figure A44. Bellows Test I-2-SCT

Figure A45. Bellows Test I-10-SCT

Figure A46. Bellows Test I-10-SCT

Figure A47. Bellows Test I-10-SCT

Figure A48. Bellows Test I-10-SCT

Figure A49. Bellows Test I-10-SCT

Figure A50. Bellows Test I-9-SC

Figure A51. Bellows Test I-9-SC

Figure A52. Bellows Test I-9-SC

Figure A53. Bellows Test I-9-SC

Figure A54. Bellows Test I-9-SC

Figure A55. Bellows Test II-19

Figure A56. Bellows Test II-19

Figure A57. Bellows Test II-19

Figure A58. Bellows Test II-19

Figure A59. Bellows Test II-19

Figure A60. Bellows Test II-17

Figure A61. Bellows Test II-17

Figure A62. Bellows Test II-17

Figure A63. Bellows Test II-17 **Figure A64. Bellows Test II-17**

Appendix B

This appendix contains the plotted data from tensile tests that were conducted on coupons taken from the material heat lots that were used in the bellows fabrication.

Also included are data obtained from microhardness tests, photomicrographs of the grain structure, and thickness measurements that were conducted on a convoluted section of a sample bellows.

B1.0 Tensile Test Data

Tests were performed on samples of the bellows material to ascertain the condition of the material at the time of testing. Material coupons taken from the heats used in the construction of these bellows specimens were subjected to tensile tests at ambient temperature and elevated temperatures of 425°F and 700°F. Those elevated temperatures were chosen because the first is the range where the bellows material has undergone the largest change in ductility, and the second is the nominal upper bound of elevated temperatures that would be experienced during a severe accident. Typical tensile curves are shown in Figure B1. The loss of ductility at 425°F is apparent in the Figure. Note that the loss of ductility between 425°F and 700°F, is negligible (see Figure 4, Section 1.0).

**Figure B1. Elongation Comparison
From Heat No. 710288**

Table B1 lists the bellows specimens and the material heats used in the construction of each. All specimens are listed here, including the specimens not yet tested, since tensile test data are reported on the heats used in the construction of all the specimens.

**Table B1
Material Heats**

<u>Specimen I.D.</u>	<u>Material Heat No.</u>
A-8-2-X*	710288
A-8-2e	710288
A-8-1e	710288
B-8-2-X	710288
B-8-2e	710288
B-8-1e	847672
B-12-2-X	847672
PP-2	320358
VL-2	710288/710342
C-6-2	710288
D-6-2	710288/847672
PP-1	212060
VL-1	710288
A-12-2-X	710288

* X denotes multiple specimens

**Figure B2. Tensile Test From Lot No. 212060.
Longitudinal Orientation. Room Temperature.**

Appendix B

Figure B3. Tensile Test From Lot No. 212060. Longitudinal Orientation. Room Temperature.

Figure B6. Tensile Test From Lot No. 212060. Transverse orientation. Room Temperature.

Figure B4. Tensile Test From Lot No. 212060. Longitudinal Orientation. Room Temperature.

Figure B7. Tensile Test From Lot No. 212060. Transverse orientation. Room Temperature.

Figure B5. Tensile Test From Lot No. 212060. Transverse orientation. Room Temperature.

Figure B8. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.

Figure B9. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.

Figure B12. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.

Figure B10. Tensile Test From Lot No. 320358. Longitudinal Orientation. Room Temperature.

Figure B13. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.

Figure B11. Tensile Test From Lot No. 320358. Transverse Orientation. Room Temperature.

Figure B14. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.

Appendix B

Figure B15. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.

Figure B18. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.

Figure B16. Tensile Test From Lot No. 710288. Longitudinal Orientation. Room Temperature.

Figure B19. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.

Figure B17. Tensile Test From Lot No. 710288. Transverse Orientation. Room Temperature.

Figure B20. Tensile Test From Lot No. 710288. Longitudinal Orientation. 425 °F.

Figure B21. Tensile Test From Lot No. 710288. Longitudinal Orientation. 425 °F.

Figure B24. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F.

Figure B22. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F.

Figure B25. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F.

Figure B23. Tensile Test From Lot No. 710288. Transverse Orientation. 425 °F.

Figure B26. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F.

Appendix B

Figure B27. Tensile Test From Lot No. 710288. Longitudinal Orientation. 700 °F.

Figure B30. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F.

Figure B28. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F.

Figure B31. Tensile Test From Lot No. 710342. Longitudinal Orientation. Room Temperature.

Figure B29. Tensile Test From Lot No. 710288. Transverse Orientation. 700 °F.

Figure B32. Tensile Test From Lot No. 710342. Longitudinal Orientation. Room Temperature.

Figure B33. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.

Figure B36. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.

Figure B34. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.

Figure B37. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.

Figure B35. Tensile Test From Lot No. 710342. Transverse Orientation. Room Temperature.

Figure B38. Tensile Test From Lot No. 847672. Longitudinal Orientation. Room Temperature.

**Figure B39. Tensile Test From Lot No. 847672.
Transverse Orientation. Room Temperature.**

**Figure B40. Tensile Test From Lot No. 847672.
Transverse Orientation. Room Temperature.**

**Figure B41. Tensile Test From Lot No. 847672.
Transverse Orientation. Room Temperature.**

B2.0 Microhardness Data

In the fabrication of a bellows, a flat stainless sheet is first rolled into a cylindrical shape and welded along the seam. Convolutions are then formed in the cylinder. Microhardness tests were conducted on samples of the bellows material to determine the effect of forming on material hardness.

One section was removed from a convolution that was 1/2 inch deep and another was removed from a convolution that was 1-1/4 inches deep. The samples were mounted and polished so that hardness measurements could be made perpendicular to the thickness of the material. The thickness of the material dictated a Microhardness test, which means that the hardness probe is smaller than standard, and is attached to a machine with precision control. Little difference was noted in hardness measurements that were made along the convolution (Figures B42 and B43). The hardness averaged 255 (224 Brinell Hardness Number [BHN]) along the centerline of the material and 310 (262 BHN) along the outer edge for the deeper convolutions. Hardness averaged 237 (202 BHN) along the centerline of the shallower convolutions. Measurements made a small distance from the convolutions averaged 220 (189 BHN). These numbers, when compared with an average of 150 BHN for annealed 304 stainless, show that there was a significant amount of strain hardening, but not an extreme amount. As an example of strain hardening due to cold work, data for 304 stainless [5] indicate that a 7/8 inch diameter cold drawn stainless bar will have an average hardness of 277 BHN. Testing of the bellows specimens verified that the material retained a great deal of elasticity.

Tables B2 and B3 list the hardness measurements that were made at the locations indicated in Figures B42 and B43.

Figure B42. Deep Convolution

Figure B43. Shallow Convolution

Table B2
Hardness Measurements of Deep Convolution
(Knoop Scale)

<u>Point</u>	<u>Test 1</u>	<u>Test 2</u>	<u>Test 3</u>	<u>Average</u>
1	253	288	258	266
2	255	264	278	266
3	244	266	263	258
4	279	259	270	270
5	287	255	254	266
6	289	267	280	279
7	261	269	249	260
8	292	288	320	300
8A	281	289	272	281
8B	303	331	318	317
8C	352	324	303	326
9	299	292	300	297
9A	305	304	305	305
9B	295	329	305	310
9C	305	309	314	309

Table B3
Hardness Measurements of Shallow
Convolution
(Knoop Scale)

<u>Point</u>	<u>Test 1</u>	<u>Test 2</u>	<u>Test 3</u>	<u>Average</u>
1	214	240	226	227
2	245	239	237	240
3	230	249	242	240
4	244	263	255	254
5	225	268	237	243
6	228	239	218	228
7	263	242	264	257
8	229	246	246	240
9	226	238	231	232

Photomicrographs of the grain structure of the Bellows material bear out the measured hardness, as they show little of the 'twinning' of grain structure that is an indication of the amount of strain hardening present. Figure B44 is a photomicrograph made in the undeformed (with the exception of rolling into a cylinder) region of the deep convolution bellows. The grain structure is fairly uniform. Figure B45 is a photomicrograph of the region of the deep convolution at its greatest deformation, located on Figure B42 by numbers 9 and 9B. Some 'twinning' is visible, indicated by closely spaced parallel lines in the grain structure.

**Figure B44. Photomicrograph of Grain Structure in Undeformed Region
(magnification 200X)**

**Figure B45. Photomicrograph of Grain Structure at Large Deformation
(magnification 200X)**

B3.0 Thickness Measurements

Thickness measurements were made at three locations on the deeper convolution to ascertain the effect of forming on the material thickness. These very limited measurements indicate that only minimal thinning of the material had occurred. Figure B46 illustrates location of measurements, along with measured values.

Figure B46. Convolution Thickness

Distribution:

Wallace E. Norris (10)
U.S. Nuclear Regulatory Commission
RES/DE/SSEB/STS
TWF-MS-L1
Washington, D.C. 20555-0001

Hansraj G. Ashar
U.S. Nuclear Regulatory Commission
NRR/ESGB, OWFN 7H15
Washington, DC 20555-0001

Goutam Bagchi
U.S. Nuclear Regulatory Commission
NRR/ESGB, OWFN 7H15
Washington, DC 20555-0001

James F. Costello
U.S. Nuclear Regulatory Commission
RES/DE/SSEB
TWF-MS-L1
Washington, DC 20555-0001

Herman L. Graves
U.S. Nuclear Regulatory Commission
RES/DE/SSEB/STS
TWF-MS-L1
Washington, DC 20555-0001

Chen, P. Tan
U.S. Nuclear Regulatory Commission
NRR/ESGB, OWFN 7H15
Washington, DC 20555-0001

Keith Wichman
U.S. Nuclear Regulatory Commission
NRR/EMCB OWFN 7D4
Washington, DC 20555-0001

Thomas J. Ahl
Chicago Bridge & Iron
Technical Services Co.
800 Jorie Boulevard
Oak Brook, IL 60521

Bryan A. Erler
Sargent & Lundy Engineers
55 East Monroe Street
Chicago, IL 60603

Nathaniel Foster
Tennessee Valley Authority
1101 Market Street
LP4G-C
Chattanooga, TN 37408

Lyle D. Gerdes
ABB Combustion Engineering
Nuclear Power
Combustion Engineering, Inc.
P. O. Box 500

Windsor, CT 06095-0500

L. Greimann
Iowa State University
Dept. of Civil Engineering
420 Town Engineering Bldg.
Ames, IA 50011

Theodore E. Johnson
1435 Waters Edge Dr.
Augusta, GA 30901

J. M. Kennedy
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

R. F. Kulak
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Richard S. Orr
Westinghouse Electric Corporation
NATD
MS 4-28
P. O. Box 355
Pittsburgh, PA 15230

Y. R. Rashid
ANATECH International Corp.
3344 N. Torrey Pines Court
LaJolla, CA 92037

Phillip Pfeiffer
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Mete A. Sozen
Department of Civil Engineering
University of Illinois
Room 1245 Newmark Laboratory
205 N. Mathews Ave.
Urbana, IL 61801-2397

John D. Stevenson
Stevenson & Associates
9217 Midwest Ave.
Cleveland, OH 44125

H. T. Tang
Electrical Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Harold Townsend
GE Nuclear Energy
ABWR Programs
175 Curtner Avenue
San Jose, CA 95125

Distribution

Joseph J. Ucciferro
UE&C Nuclear Inc.
% Philadelphia Electric
965 Chesterbrook Blvd.
MS 62C-3
Wayne, PA 19087

Richard N. White
School of Civil & Environmental Engineering
Hollister Hall
Cornell University
Ithaca, NY 14853

Expansion Joint Manufacturers Association, Inc.
25 North Broadway
Tarrytown, NY.

M. Livolant
Commissariat a L'Energie Atomique
Centre d'Etudes Nucleaires de Saclay
F-91191 Gif-Sur-Yvette Cedex
France

P. Jamet
Commissariat a L'Energie Atomique
Centre d'Etudes Nucleaires de Saclay
F-91191 Gif-Sur-Yvette Cedex
France

A. Hoefler
Gesellschaft fuer Reaktorsicherheit
Schwertnergasse 1
D-5000 Koln 1
Germany

R. Krieg
Kernforschungszentrum Karlsruhe GmbH
Postfach 3640
D-7500 Karlsruhe
Germany

Dr. K. Kussmaul
Direktor der Staatlichen
Materialprufungsanstalt (MPA)
Universitat Stuttgart
D-70569 Stuttgart 80 (Vaihingen)
Germany

W. Rieger (2)
Technischer Uberwachungs-Verein Stuttgart e.V.
Abteilung Kernenergie und Strahlenschutz
Gottlieb-Daimler-Str. 7
D-7024 Filderstadt 1
Germany

F. Schleifer
Gesellschaft fuer Reaktorsicherheit
Schwertnergasse 1
D-5000 Koln 1
Germany

H. Schulz

NUREG/CR-6154

Gesellschaft fuer Reaktorsicherheit
Schwertnergasse 1
D-5000 Koln 1
Germany

Giuseppe Pino
ENEA-DISP
ACO-CIVME
Via Vitaliano Brancati, 48
Italy

Masashi Goto
Toshiba Corporation
Nuclear Plant Design & Engineering Department
Isogo Nuclear Engineering Center
8, Shinsugita-cho, Isogo-ku, Yokohama
Kanagawa 235, Japan

Katsuyoshi Imoto
Obayashi Corporation
Structural Engineering Department
Technical Research Institute
640, Shimokiyoto 4-chome, Kiyose-shi
Tokyo 204, Japan

Tadashi Kume
Hitachi, Ltd.
Nuclear Equipment 1st Design Section
3-1-1, Saiwai-cho, Hitachi-shi
Ibaraki-ken 317, Japan

Dr. Takashi Kuroda
Shimizu Corporation
Nuclear Power Division
SEAVANS SOUTH
No. 2-3, Shibaura 1-chome, Minato-ku
Tokyo 105-07, Japan

Yasuyuki Murazumi
Taisei Corporation
1-25-1, Nishi Shinjuku, Shinjuku-ku
Tokyo 1 63-06, Japan

Masayuki Soejima
Senior Engineer
Mitsubishi Heavy Industries, Ltd.
Nuclear Containment Vessel Designing Section
1-1-1, Wadasaki-cho Hyogo-ku
Kobe 652, Japan

Dr. Toshikazu Takeda
Obayashi Corporation
Director & General Manager
Technical Research Institute
640, Shimokiyoto 4-chome, Kiyose-shi
Tokyo 204, Japan

Yoichiro Takeuchi
Deputy General Manager
Design Department
Nuclear Power Division
Shimizu Corporation

Mita 43, Mori Bldg. 13F,
No. 13-16, Mita 3-chome, Minato-ku,
Tokyo 108, Japan

Dr. Kenji Takumi (2)
Director and General Manager
Systems Safety Department
Nuclear Power Engineering Corporation
Shuwa-Kamiyacho Building
3-13, 4-chome
Toranomon, Minato-ku
Tokyo 105, Japan

Haruji Tsubota
Kajima Corporation
Building Structural Engineering Department
Kajima Technical Research Institute
19-1 Tobitakyu 2-Chome, Chofu-shi
Tokyo 182, Japan

Bertold W. Pfeifer
Bechtel Power Corporation
23rd Floor, Daewoo Center Building
541 5-ga, Namdaemoon-ro, Chung-ku
Seoul, Korea

D. W. Phillips
Atomic Energy Authority
Safety and Reliability Directorate
Wigshaw Lane, Culcheth
Warrington WA3 4NE
United Kingdom

Peter Watson
HM Nuclear Installations Inspectorate BrC
St. Peter's House
Bootle, Merseyside L20 3LZ
United Kingdom

Internal SNL:

MS/0736 (6400) N. R. Ortiz
MS/0744 (6403) W. A. vonRiesemann
MS/0744 (6403) J. L. Cherry
MS/0744 (6403) R. N. Evers
MS/0744 (6403) M. F. Hessheimer
MS/0744 (6403) L. D. Lambert (10)
MS/0744 (6403) V. K. Luk
MS/0744 (6403) D. W. Pace
MS/0744 (6403) J. G. Pantuso
MS/0744 (6403) M. B. Parks
MS/0744 (6403) M. J. Rightley
MS/0949 (2111) B. L. Spletzer
MS/0899 (7141) S. A. Landenberger (5)
MS/0619 (7151) G. C. Claycomb
MS/9017 (8523) R. C. Christman

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-6154
SAND94-1711
Vol. 1

2. TITLE AND SUBTITLE

Experimental Results From Containment Piping Bellows
Subjected to Severe Accident Conditions

Results From Bellows Tested in 'Like-New' Conditions

3. DATE REPORT PUBLISHED

MONTH | YEAR
September | 1994

4. FIN OR GRANT NUMBER

A1375

5. AUTHOR(S)

L. D. Lambert, M. B. Parks

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address, if contractor, provide name and mailing address.)

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0744

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

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 under the sponsorship of the U.S. Nuclear Regulatory Commission at Sandia National Laboratories. 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 thirteen bellows have been tested, all in the 'like-new' condition. (Additional tests are planned of bellows that have been subjected to corrosion.) The tests showed that bellows are capable of withstanding relatively large deformations, up to, or near, the point of full compression or elongation, before developing leakage. The test data is presented and discussed.

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

bellows
containment
penetrations
piping
loading
concrete

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE