

CONTAINMENT BELLOWS TESTING UNDER EXTREME LOADS

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1. INTRODUCTION

Since the incident at Three Mile Island, an increased emphasis has been placed on understanding the consequences of accidents that produce pressure and temperature conditions within containment that exceed the design basis. Because the containment is the last engineered barrier to the release of radioactive material, an accurate estimate of the containment's ultimate capacity is essential in order to develop accident management strategies.

Sandia National Laboratories (SNL) is conducting several research programs to help develop validated methods for the prediction of the ultimate pressure capacity, at elevated temperatures, of light water reactor (LWR) containment structures. These research programs, which are collectively known as the Containment Integrity Programs, are sponsored by the U. S. Nuclear Regulatory Commission (NRC).

To help understand the ultimate pressure of the entire containment pressure boundary, each component must be evaluated. The containment pressure boundary consists of the containment shell and many access, piping, and electrical penetrations. The focus of the current research program is to study the ultimate behavior of flexible metal bellows that are used at piping penetrations.

Bellows are commonly used at piping penetrations in steel containments; however, they have very few applications in concrete (reinforced or prestressed) containments. The purpose of piping penetration bellows is to provide a soft connection between the containment shell and the pipe to which they are attached while maintaining the containment pressure boundary. In this way, piping loads caused by differential movement between the piping and the containment shell are minimized. An example of a typical process piping bellows is shown in Figure 1.

An extensive review of bellows-related literature (Greimann 1991) has been conducted and several bellows manufacturers and designers have been interviewed. This background review did not reveal any past research efforts in which bellows have been subjected to the extreme loading conditions that might occur during a severe accident. Therefore, SNL is conducting a test program to determine the leaktight capacity of containment bellows when subjected to postulated severe accident conditions. If the test results indicate that containment bellows could be a possible failure mode of the containment pressure boundary, then methods will be developed to predict the deformation, pressure, and temperature conditions that would likely cause a bellows failure. Results from the test program would be used to validate the prediction methods.

The remainder of the paper provides a description of the use and design of bellows in containment piping penetrations, the types of possible bellows loadings during a severe accident, and an overview of the test program, including available test results at the time of writing.

2. BACKGROUND AND MOTIVATION FOR TEST PROGRAM

The information presented in this section has been obtained through extensive interviews with experienced bellows designers and manufacturers. Previous summaries of containment penetrations (Bump 1984, Shackelford 1985) also provided much of the geometric details that will be discussed.

There are two basic types of applications of piping penetration bellows in steel containments: process piping bellows and vent line bellows. Process piping bellows vary in size from 6 to around 60 inches in diameter. They are normally constructed of two plies of SA240, Type 304, stainless steel that are separated by a thin wire mesh (~0.010-inch wire diameter). The primary purpose of the redundant outer ply is to provide a means to check for leakage of the bellows by pressurizing the space between plies and noting any drop in pressure.

Bellows are also used at the penetration of the vent line into the suppression chamber in BWR Mark-I containments. Vent line bellows range in diameter from about 65 to 125 inches. In contrast with process piping bellows, most vent line bellows are one ply; approximately 10% are two-ply. The vent line bellows are also constructed of SA240, Type 304 stainless steel.

Containment bellows are designed to resist differential movements between the containment shell and the pipe to which they are attached. The differential movements result from normal operation, safe shutdown earthquake (SSE), and loss of coolant accident (LOCA). In most cases, the bellows design movements are obtained by summing the maximum deformations associated with each of these conditions as if they occurred simultaneously. The provisions included in the Standards of the Expansion Joint Manufacturers Association (EJMA 1985) are used for the bellows design. Normally, bellows are conservatively designed to resist about 5,000 cycles of the above loading combinations, although they typically experience only a few minimal load cycles due to startup and shutdown of the reactor. Also, each ply is sized to resist the full containment design pressure. Using the EJMA approach, a minimum factor of safety of four against burst due to only internal pressure must be obtained. Thus, especially for the two-ply bellows, a considerable margin should exist between normal containment design conditions and those conditions that would cause a failure of the bellows pressure boundary.

In the event of a severe accident, pressure and temperature conditions within containment may reach levels that are well beyond the design basis. In most cases, radial growth of containment due to internal pressure imposes axial compression on the bellows. (There are a few cases in which radial growth of containment elongates the bellows.) For cylindrical containments, the bellows must also absorb lateral deformation caused by the vertical growth of the containment shell due to increasing temperature and the upward movement caused by the pressure acting on the dome. If the containment pressure is sufficient to cause general yielding in the hoop direction, then the radial growth of the containment increases rapidly for small additional increases in pressure. If the containment pressure is high enough, it is possible that the bellows could become fully compressed by the containment's radial expansion (i.e., each convolution is fully closed so that there is no remaining flexibility of the bellows). Upon reaching full compression, it is extremely likely that a leak path will develop in the containment pressure boundary as a result of either a tear in the bellows as the end spools¹ cut through the thin bellows material or failure of the bellows connection to the end spool. The main unknown is, "Are containment bellows capable of reaching the fully compressed state, when subjected to simultaneous lateral deformation, internal pressure, and elevated temperature, without developing a tear in the bellows material or in the connection of the bellows to the end spool?"

The current series of tests subjects representative bellows to postulated severe accident loadings based on the above discussion. The maximum load combinations are based on conditions that could occur in a severe accident. The goal of the test program is to investigate the pressure, temperature, and deformation conditions that will likely cause a tear in the bellows, which could produce a large leak path through the containment boundary. Because of the insignificant number and magnitude of loading cycles during normal operating conditions, and the routine in-service inspections to check bellows integrity, it was decided that the bellows in this series of experiments would be tested in the like-new condition.

¹ The end spools are the pipe sections to which the bellows are attached.

3. TEST PLAN

Two phases of containment bellows tests are being conducted. In Phase I, a total of 16 relatively small (12-inch) diameter bellows will be subjected to a variety of extreme combinations of internal pressure, axial and lateral deformation, and temperature. The test specimens and test conditions have been selected to represent a wide cross-section of containment bellows. The primary objective of the Phase I tests is to determine which bellows geometries are most likely to develop leakage when subjected to severe accident conditions. The Phase I tests are not intended to represent any particular bellows geometry or a specific accident scenario. Rather they are primarily intended to determine the ultimate capacity of bellows in general when subjected to the types of loadings that might occur during a severe accident.

An outline of all the planned Phase I tests is provided in Table 1. The table identifies each test with a letter code (such as CL or SCT). The test procedure associated with the letter code is given below.

<u>Test Code</u>	<u>Test Description</u>
CL	(Compression-Lateral) - consists of axially compressing the bellows until all convolution roots are fully compressed (i.e. in contact with each other). If the bellows are still leaktight, lateral deformation will be applied until a tear in the bellows occurs. No internal pressure will be applied during this test.
LC	(Lateral-Compression) - lateral offset is applied until the bellows become unstable (i.e., bellows lateral stiffness begins to reduce significantly). If the bellows are still intact, axial compression will be applied until all convolutions are fully compressed. If the bellows are still intact after being fully compressed, additional lateral deformation will be added until a tear develops in the bellows. No internal pressure will be applied during this test.
SC	(Simultaneous-Compressive) - consists of simultaneously applying internal pressure, axial compression and lateral deformation. Internal pressure, axial compression and lateral deformation shall be increased proportionally such that the internal pressure reaches the maximum test pressure level in Table 1 when the total applied lateral deformation is 2 inches and the bellows are fully compressed. If the bellows are still intact after being fully compressed, the test condition will be reversed by removing axial and lateral deformation as well as internal pressure at the same rate at which each was originally applied. Unloading and reloading will continue until a tear develops in the test specimen.
SCT	(Simultaneous-Compressive-Temperature) - the same as SC except that the test temperature is $425 \pm 25^{\circ}\text{F}$ throughout the specimen for the entire test. An elevated temperature condition of 425°F was chosen to correspond to the minimum ductility temperature for Type 304 stainless steel.
SE	(Simultaneous-Extension) - similar to SC above. Here axial elongation and lateral deformation are simultaneously applied. Axial elongation and lateral deformation will be increased proportionately such that the total applied lateral deformation is 2 inches when the bellows are fully elongated. If the bellows are still leaktight 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. This process of loading and unloading will be continued until a tear develops in the bellows specimen. (Only 4 elongation-type test will be conducted, because there are only a small percentage of containment bellows that would be elongated due to severe accident loadings.)

In contrast to the Phase I tests, the Phase II tests are intended to represent specific bellows applications currently in use in nuclear containments. A total of four 19.25-inch diameter bellows will be tested in Phase II. Two Phase II specimens represent full-size process piping (PP) penetration bellows in current use in a pressurized water reactor (PWR) containment. The other two Phase II specimens are approximate 1/4-scale models of typical vent line (VL) bellows used at the penetration of the vent lines into the suppression chamber of BWR Mark-I containments. Both the PP and VL specimens will be subjected to loadings based on the expected severe accident conditions of the actual containments in which they are employed. The Phase II test conditions will include various combinations of internal pressure, axial compression, lateral deformation, and elevated temperature. An elevated temperature condition of $425 \pm 25^\circ\text{F}$ will be applied during testing to correspond to the minimum ductility temperature for Type 304 stainless steel.

For the PP specimens, the displacements and pressures to be applied during testing are derived from analyses of the response of an actual containment under severe accident conditions. The internal pressure, axial compression, and lateral deformation will be increased until the bellows are fully compressed at an internal pressure of approximately 75 psig. If the bellows are still intact when fully compressed, the applied test conditions will be reversed by removing axial and lateral deformation as well as internal pressure at the same rate at which each was originally applied. If there is still no significant leakage after unloading, then the original load combinations will be repeated. This process of loading and unloading will be continued until a leak path develops in the bellows pressure boundary.

The VL specimens will be subjected to axial compression, internal pressure, and lateral deformation simultaneously. These loadings will be increased linearly from ambient conditions such that the internal pressure is 150 psig and the lateral deformation is 1 inch when the bellows are fully compressed axially. If the bellows is still intact when fully compressed, the applied test conditions will be removed and then reapplied until a leak path develops in the bellows pressure boundary.

4. STATUS REPORT ON BELLOWS TEST PROGRAM

Three Phase 1 bellows tests have been completed at the time of writing. They are tests 11, 12, and 13 as shown in Table 1. Each of these bellows specimen contain 8 consecutive convolutions. The depth and width of each convolution is 0.5 inches. These specimens are constructed of 0.020inchthick, SA240, Type 304 stainless steel. Specimens 11 and 12 are constructed of two separate plies, while a single ply is used for specimen 13.

For Test 11, the CL loading procedure was followed. The specimen was first fully compressed in the axial direction and then subjected to increasing lateral deformation. Leakage first began when the lateral deformation reached 2.6 inches. Photographs of the specimen before testing and at the point just after the first tears occurred are shown in Figure 2. As shown, large inelastic deformation was required to cause the tears in the bellows. The initial tears occurred in the roots of convolutions near each end of the specimen. Although not directly visible in the photograph, the relative locations of the tears are shown by the soap bubbles in the photograph. These bubbles were caused by air leaking through a leak detection solution that was used to detect initial tearing of the bellows.

The LC test procedure was followed in Test 12. For this test, the lateral deformation was first increased to about 2 inches followed by increasing levels of axial compression. The specimen remained leaktight up to the point of full compression. The specimen was then elongated back to its original length and then recompressed to the point of full compression, again without significant leakage through the bellows pressure boundary. At this point, the lateral deformation was increased to a total of about 2.2 inches (with the bellows still fully compressed) at which a tear occurred in the bellows.

An elongation test of type SE was conducted for Test 13. In this test, the bellows specimen was elongated and subjected to lateral deformation simultaneously. A tear developed in the bellows specimen at an axial elongation of 5.8 inches and an associated lateral offset of 1.2 inches. At this point, the applied elongation was greater than the original bellows length.

5. SUMMARY

The ongoing bellows test series is providing experimental data that was not available previously. The purpose of the tests is to determine if containment penetration bellows are a possible early failure mode of the containment pressure boundary. If they are, the test results will be used to validate analytical methods for predicting the types of severe accident loadings that would likely cause a bellows failure.

The completed tests, which have been conducted at room temperature, have shown that bellows can absorb large deformations before tearing. However, we expect that less deformation will be required to develop a tear at elevated temperatures. This is because the ductility of stainless steel reaches a minimum at approximately 425°F. Bellows testing at elevated temperatures will begin in the Spring of 1993. The test program is scheduled for completion in late 1993.

6. ACKNOWLEDGMENTS

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Table 1. Phase 1 Test Series

<u>Test No.</u>	<u>Test Code</u>	Maximum Internal Pressure (psig)	<u>Test No.</u>	<u>Test Code</u>	Maximum Internal Pressure (psig)
1	SC	150	9	SC	75
2	SCT	150	10	SCT	75
3	SC	75	11	CL	0
4	SCT	75	12	LC	0
5	SCT	150	13	SE	0
6	SCT	75	14	SE	0
7	SC	150	15	SE	0
8	SCT	150	16	SE	0

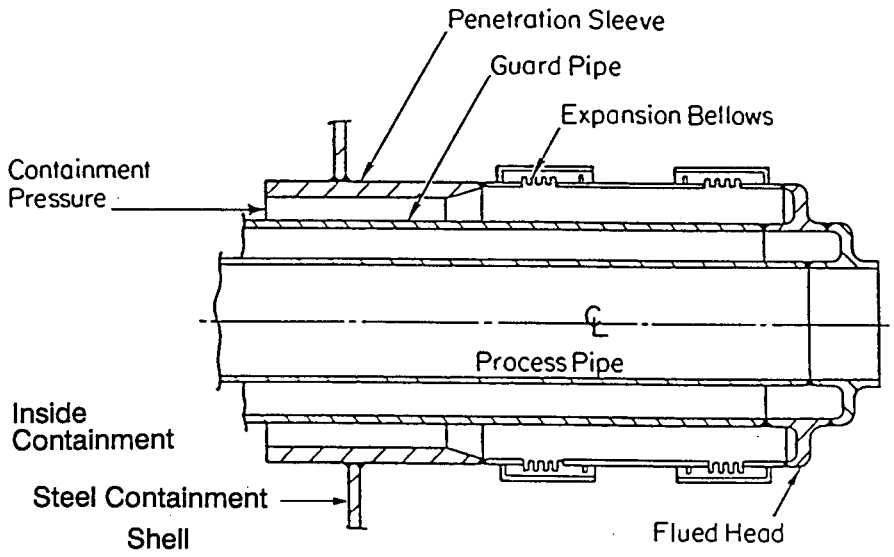
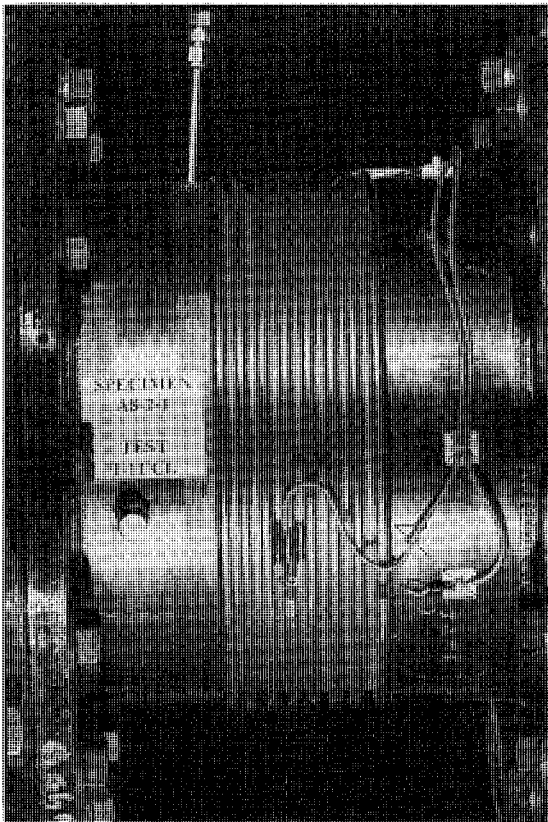
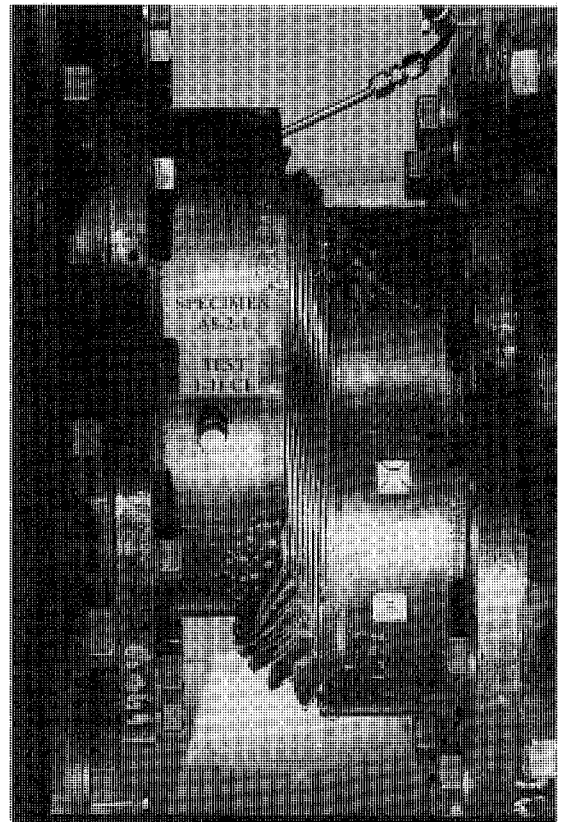


Figure 1. Typical Process Piping Bellows (Greimann 1991)



(a) Before Testing



(b) At Point of First Leakage

Figure 2. Photographs of Test 11