DEVELOPMENT OF BELLOWS FOR SODIUM VALVES IN JAPAN

S. TANIGAWA, K. MUKAI, T. FUKADA, T. TAKAHASHI
Japan

Abstract

Sodium valves for FBR are required to isolate sodium side from the atmosphere completely throughout its lifetime because of preventing sodium leakage with or without radioactivity.

A great number of sodium valves have been used in FBR test facilities at O-arai Enginering Center of PNC and many troubles have been occurred through their operational experience. Most of the cause of the troubles are the bellows failure followed by sodium leakage.

A research and development program on bellows was started to clarify many uncertain factors of its performance and to establish the feasibility of bellows used in sodium. In this program Small Bellows Test Loop was built to perform low cycle fatigue tests on bellows under high temperature conditions.

In this report some examples of the investigation of failed bellows occurred at O-arai Engineering Center of PNC are described. The research and development program on bellows is also explained with the summary of recent test results.

1. Investigation of Failed Sodium Valve Bellows in O-arai Engineering Center

1.1 Introduction

In FBR test facilities at O-arai Engineering Center of PNC, many sodium valves are used with sizes ranging from 3/8 inch to 12 inch, and a number of troubles have been experienced in them. They were caused by sodium leakage from the valve seat, stem stick, failure of seal bellows, etc., but most of sodium leakage from the failed valves are due to the failure of seal bellows.

For these failed valves, we have started collecting their operating history. The purpose of this program is to clarify the cause of bellows failure from the collected data and to utilize the information for the improvement of the bellows design, manufacturing process, and reliability, leading eventually to the standardization of them.

In support of this program, inspection of the sound bellows used in the long serviced sodium valves was also added to that of failed bellows to determine the possible factors in operation which in one case lead the bellows to failure and in another leave it sound.

1.2 Example of Investigation of Failed Bellows

Most frequently used sodium valves in OEC are the bellows sealed globe valves utilized for shut-off and flow control purposes. Among the sodium valves of sizes ranging from 3/8 inch to 12 inch, 95% are bellows sealed valves (see Table 1-1).

In about 30 sodium valves failures so far occurred in OEC, which represents about 3% of the total in service, 21 of them are originated from bellows failure (see Figure 1-1). This fact necessitated to investigate the cause of bellows failure. In Table 1-2 several results of inspection of the bellows where sodium leakage was observed are listed and briefly described.

In these investigations, the direct cause of the failure is generally difficult to define. The most typical conditions of the failure is that, the crack of several millimeter length occurs near the bellows ends (either the crown or the root) and the sodium leaked through the crack reacts with the air inside the bellows, thus corroding the thin bellows plate. It is not known yet as to which side of the bellows, inner or outer surface, the crack initializes and grows. This is one of the topics left to be determined.

1.3 Inspection of Sound Bellows

The material test on the bellows used for stem sealing of 6 inch valve was conducted to compare the material properties of the bellows before and after its use in sodium and to clarify the effect of high temperature sodium on the bellows material. The valve had been in service in the Thermal Shock Test Loop of OEC, PNC. This bellows is not the one from which sodium leaked during operation. Its soundness has been confirmed at least by the visual observation from outside and the air-tight leak test.

The specifications of the bellows are as follows:

Type:	Welded 2-plies bellows
Material:	316L stainless steel
Number of convolutions:	25 convolutions x 4 blocks (100 convolutions in total)
Free length:	About 240 mm
Stroke:	50 mm

Operating conditions are as follows:

Sodium temperature:	max. 560°C
Thermal shock cycle:	400°C ↔ 500°C
Thermal shock frequency:	200 times (ΔT = max. 160°C)

As the results of visual observation from outside, the pitch from the end (E.P.O.) to the 7th convolution of the first block counted from the disc side was enlarged. The enlarged pitch was particularly large between the 1st and 2nd convolutions, showing that a large stress concentration had occurred at this area. This seems to have been caused by a fast open/close operation. The hardness test revealed that the plate in this area was slightly hardened probably due to the bending action of the bellows. No leakage of sodium was observed inside the bellows. Neither trace of bellows contact with guide sleeve nor stem stick were observed. The plate thickness measurement and analysis of contents by XMA showed no remarkable change before and after the service in the loop.

By the scanning electron microscope, it was found that spherical substances were deposited on or attached to the sodium contacting surface while the surface not contacting the sodium liquid was covered with something like an oxide film, so that they looked considerably different from the surface of a virgin bellows.

Table I-1. Small Sodium Valves in O-arai Engineering Center

Size bore inches	Number of operations	Stem seal type	
		bellows	freeze seal
3/8	105	105	
1/2	135	135	
3/4	108	108	
1	223	223	
1 1/2	8	8	
2	111	111	
3	34	34	
4	23	16	7
6	17	9	8
8	5	4	1
10	6		6
12	20	6	14
Total	795	759	36

Table 1-2. Examples of Failed Bellows Data

	Example 1	Example 2
Valve type	Manual L-type stop valve	Manual L-type stop valve
Nominal bore	3/4 inch	3/4 inch
Stem seal	316L stainless steel, 2-plies formed bellows	316L stainless steel, 2-plies formed bellows
Test Loop	General Purpose Test Loop	General Purpose Test Loop
Operating condition	250 ∿ 500°C	250 ∿ 500°C
Operating hours before failure	about 4,200 hrs.	about 6,600 hrs.
Open/close frequency	Up to 25 times	Up to 35 times
Trouble conditions	Sodium leakage from the stem sealing part was found out when the open/close operation of the valve was carried out after sodium was drained from the loop.	After sodium was drained from the loop, the valve was attempted to be opened, but it was too tight to open. It was used about 1,200 hrs. at the closed state.
Results of inspection	a) Visual observation from outside: A crack of 7-10mm length was found at the first root from the bonnet side (see Figure 1∿2). b) Microscopic observation: A remarkable intergranular corrosions was observed near the broken part. The intergranular corrosion occurred and developed from the small gap between plies. No intergranular corrosion was observed except around the broken part.	a) Visual observation from outside: A crack of 7-10mm length was found at the 2nd crown from the disc side (see Figure 1∿3). b) Microscopic observation: Same as in the case of example 1. c) Hardness measurement: Hardness of the crown and the root is slightly higher than other parts.

Table 1-2. Examples of Failed Bellows Data (continued)

	Example 3	Example 4
Valve type	Pneumatic Y-type stop valve	Pneumatic Y-type stop valve (see Figure 1∿5).
Nominal bore	3/4 inch	12 inch
Stem seal	316L stainless steel, 2-plies formed bellows	316L stainless steel, welded single ply bellows
Test Loop	General Purpose Test Loop	50 MW Steam Generator Test Facility
Operating condition	∿ 400°C	Max. 505°C
Operating hours before failure	about 5,600 hrs.	about 4,800 hrs.
Open/close frequency	Up to 210 times	Unknown
Trouble conditions	During the operation of the loop, the valve was attempted to be opened, but it could not be opened by air and further it was too tight to open manually. Then sodium leakage from the stem sealing part was found out.	During the loop was in hot standby, the valve became inoperable at its open position.
Results of inspection	a) Visual observation from outside: The failed positions on the bellows are shown in Figure 1∿4. Black solid matter is attached to the bellows inner surface (the side not contacting sodium). Inner ply was lost by corrosion in cases of the 1st, 2nd and 3rd items (see Figure 1∿4). b) Microscopic observation: Failed parts are the welded portion or its neighboring area. An intergranular corrosion was observed between the double plies. c) Hardness measurement: Bellows was hardened during the service particularly at the crown.	a) Visual observation from outside: Major erosion was observed in 4 parts around bellows, 2 parts out of which had sodium leaks (see Figure 1∿6 and Figure 1∿7). Eroded parts on the bellows and the position of drain hole on the bellows cover generally coincide with each other. From this, it is supposed that the bellows was eroded by sodium passing through the drain hole, and through the resulting pin holes sodium entered inside the bellows. For remodelling, the position of drain hole was shifted so that sodium flow didn't directly strike the bellows (see Figure 1∿8).

Table 1-2. Examples of Failed Bellows Data (continued)

	Example 5	Example 6
Valve type	Pneumatic Y-type stop valve	Pneumatic Y-type stop valve
Nominal bore	6 inch	1 inch
Stem seal	316L stainless steel, 2-plies welded bellows	316L stainless steel, 2-plies welded bellows
Test Loop	Thermal Shock Test Loop	Thermal Shock Test Loop
Operating condition	390 ∿ 540°C, Thermal shock ΔT = 150°C max.	400 ∿ 500°C
Operating hours before failure	about 1,000 hrs.	about 4,500 hrs.
Open/close frequency	Up to 40 times	Up to 1,500 times
Trouble conditions	Smoke caused by leaked sodium was detected after the test.	The valve could not be operated well. Sodium metal granules were found attached to the valve stem sealing part.
Results of inspection	a) Visual observation from outside: The bellows consists of 4 blocks. The failed part was confirmed at the 21st root of the 3rd block from the disk side. b) Microscopic observation: The crack was hardly observed 1st and 2nd block, but, concentrated at the 3rd block. The crocks occurred only at the inside beads. The trouble seems to have been caused by repeated operations to stop the flow of high temperature sodium (flow rate: 6m/sec) at each second, which led to transient rise in sodium level and also uneven expansion/compression of bellows (local high strain). Eventually the cracks seem to have occurred due to thermal fatigue.	a) Visual observation from outside: The inside bead part at the concave part between 2nd and 3rd root from the disc side was circumferentially cracked over a length of 25 mm. b) Conditions of cracking: HAZ of the inside bead had microcracks in average length of 30μ extended from almost all air side plates. The trouble was caused by fatigue failure of material, as striation and dimple were clearly observed. The starting point of fatigue failure had a notch effect on the inside bead parts, and the stress concentrated at the grain boundary.

Table 1-2. Examples of Failed Bellows Data (continued)

	Example 7	
Valve type	Motor operated Y-type stop valve	
Nominal bore	1 inch	
Stem seal	316L stainless steel, 2-plies formed bellows	
Test Loop	Small Bellows Test Loop	
Operating condition	400 ∿ 500°C	
Operating hours before failure	about 20,000 hrs.	
Open/close frequency	Unknown	
Trouble conditions	The valve could not be operated well. Sodium metal granules were found attached to the stem sealing part.	
Results of inspection	a) Visual observation from outside: As shown in Photo 1, the shape of each convolution is remarkably deformed, and becomes like a plate. The failed part is confirmed at the 13th crown from the bonnet side. From this part the deformation advances to the bonnet side and the disc side. The location of this valve in the loop was happened to be undrainable and this loop was heated when this valve contained the frozen sodium. So this bellows which is the weak structure against the outer pressure, seems to have been broken by the difference in the heat expansion of each parts and sodium.	

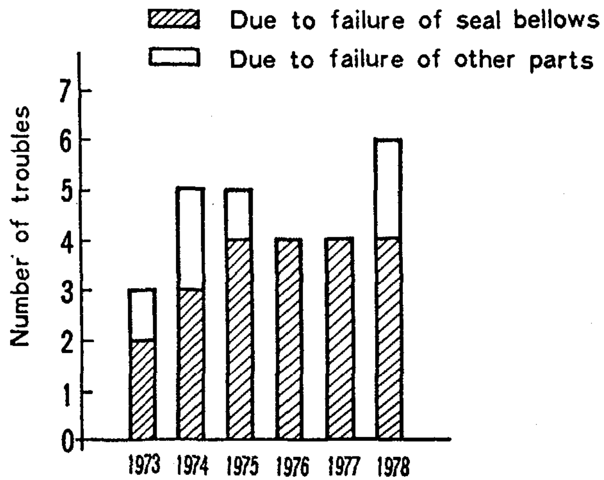

Figure 1-1

Number of Troubles for Sodium Valves

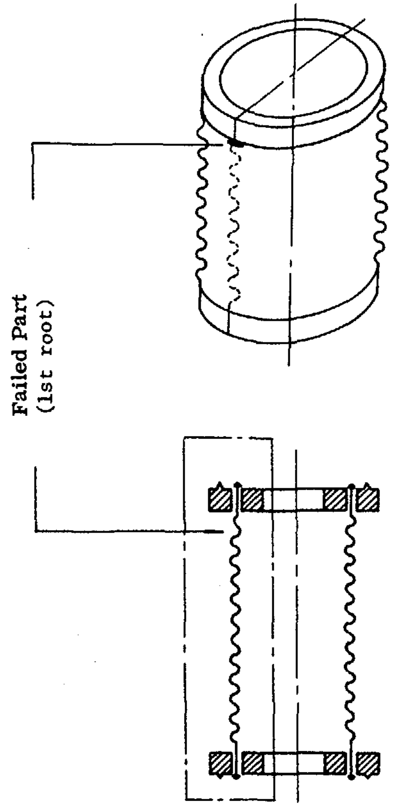

Figure 1-2 Position of Failure on the Bellows of Example 1 Valve

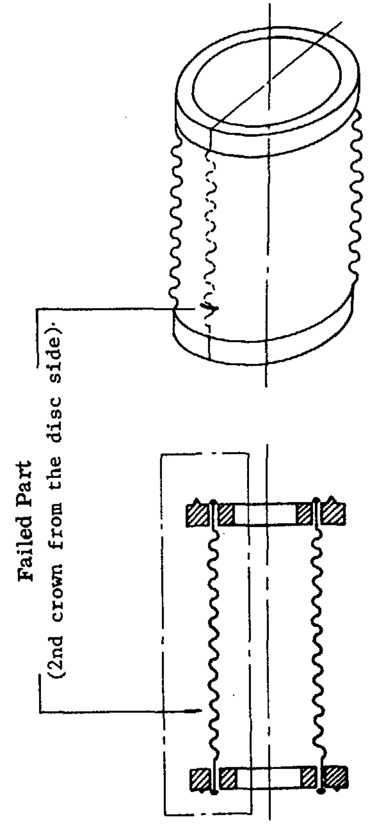

Figure 1-3 Position of Failure on the Bellows of Example 2 Valve

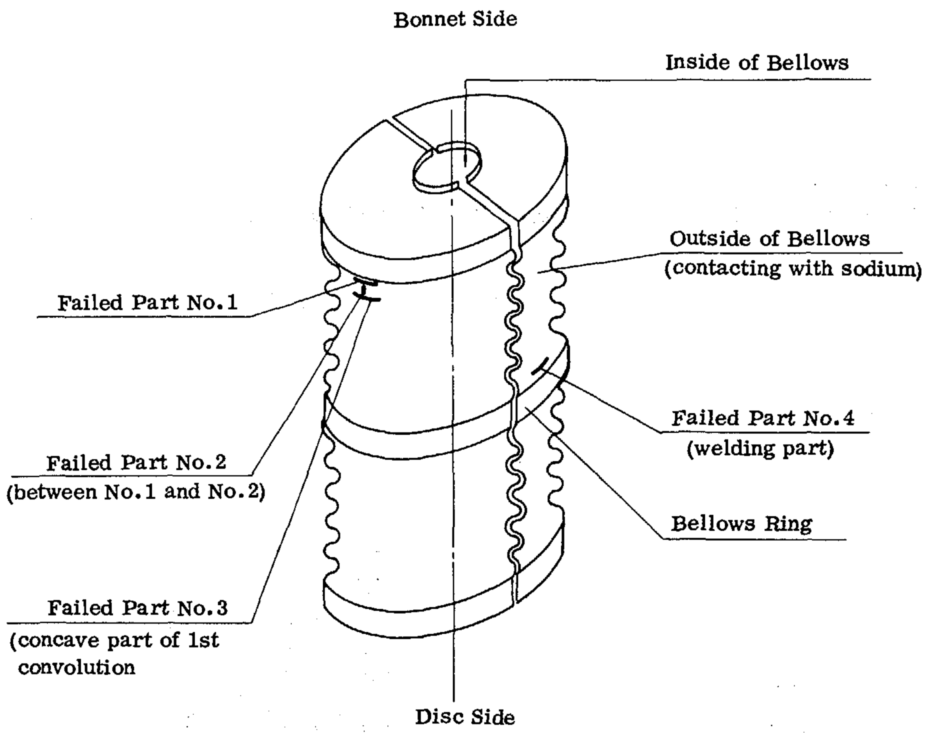

Figure 1-4 Position of Failure on the Bellows of Example 3 Valve

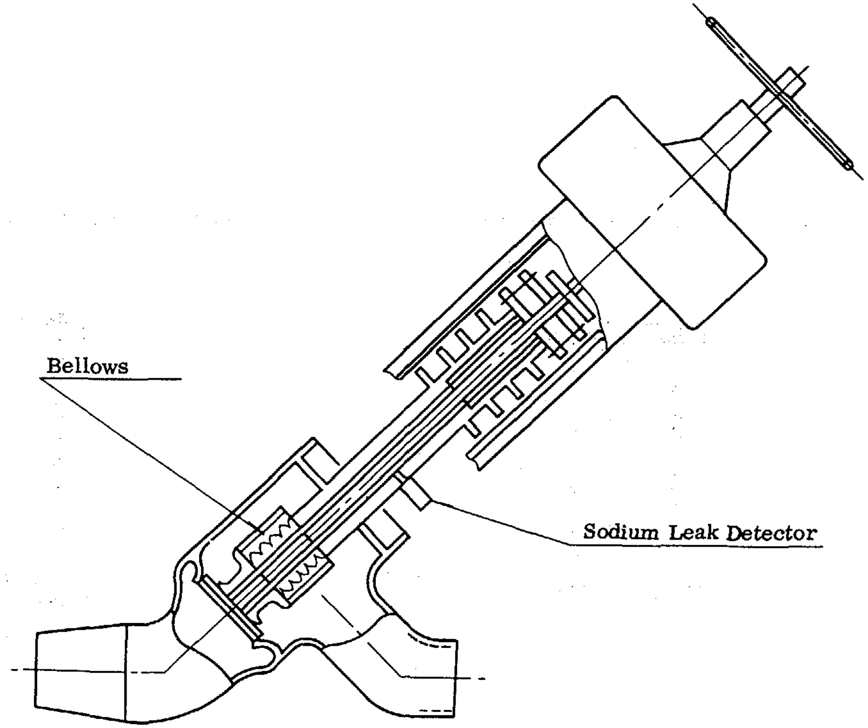

Figure 1-5 Example 4 Valve Assembly

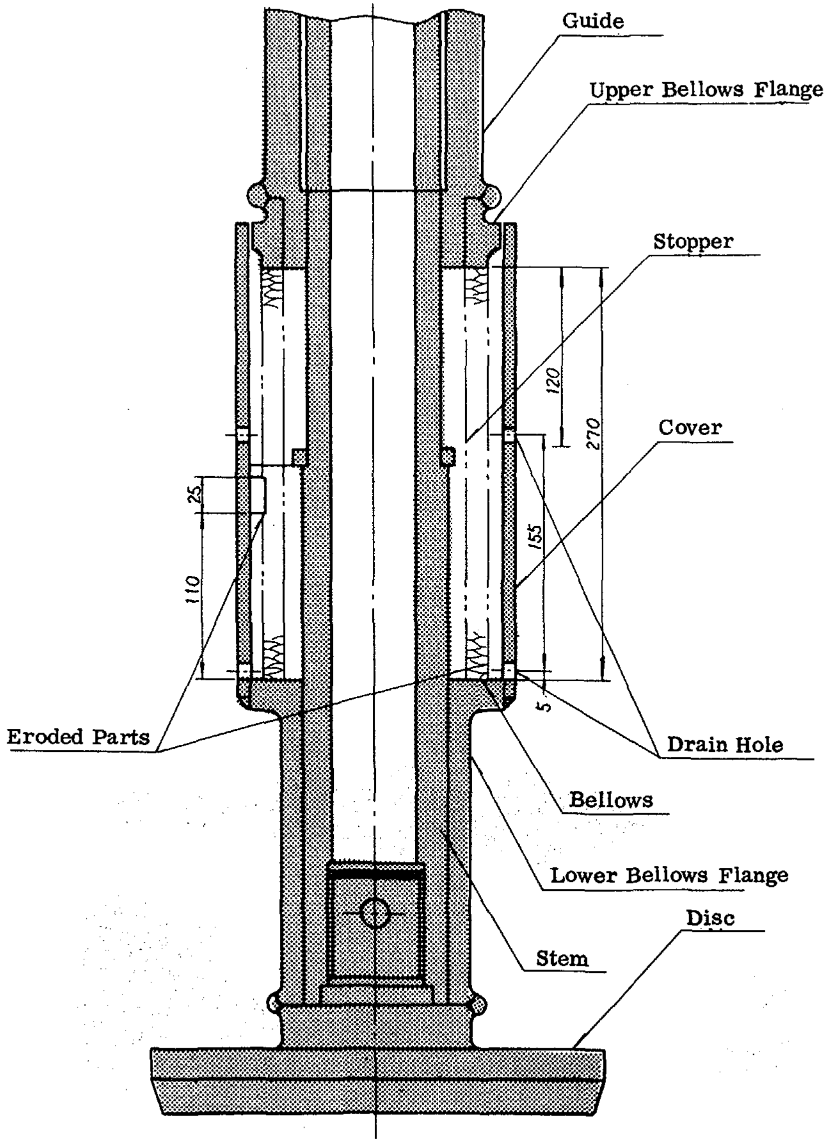

Figure 1-6 Position of Failure on the Bellows of Example 4 Valve

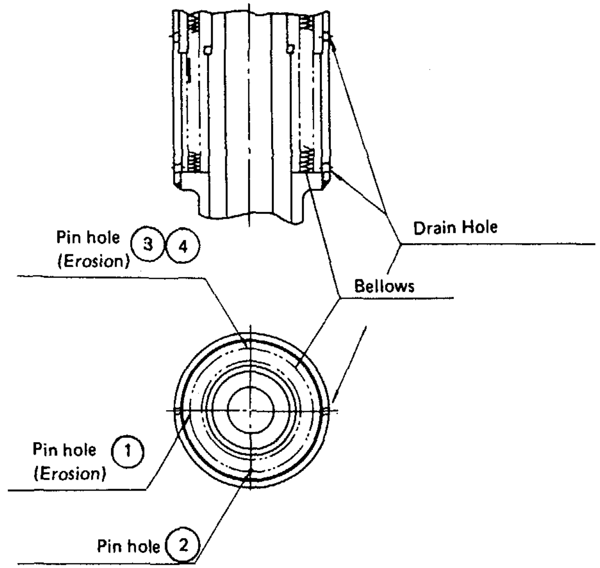

Figure 1-7 Detail of Failure Position of Bellows

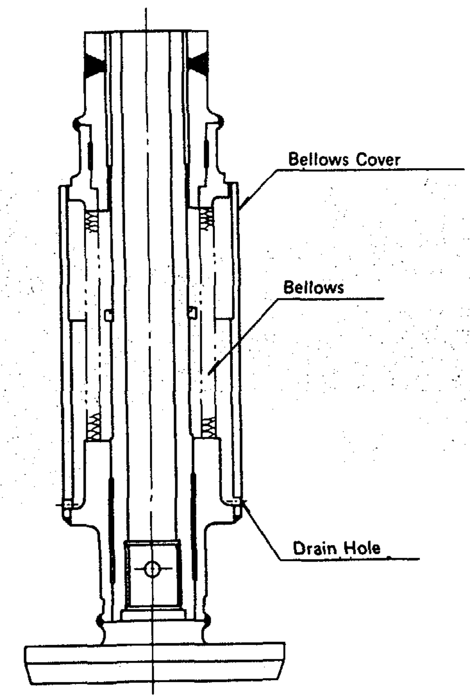

Figure 1-8 Improved Bellows Cover

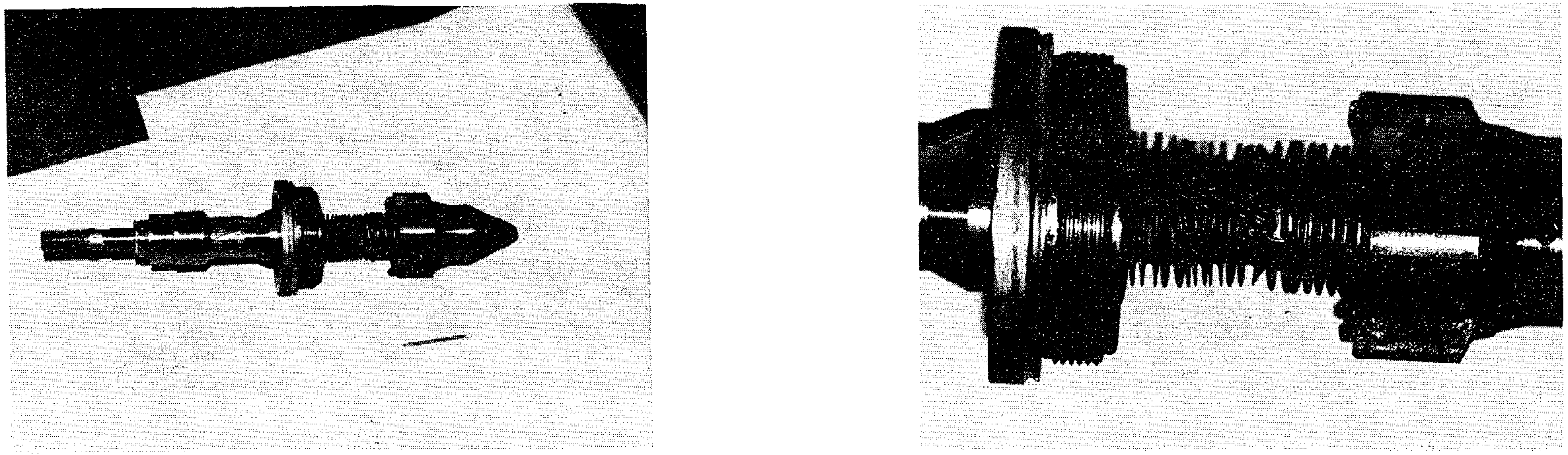

Photo 1-1. Failure Condition of Example 7 Valve.

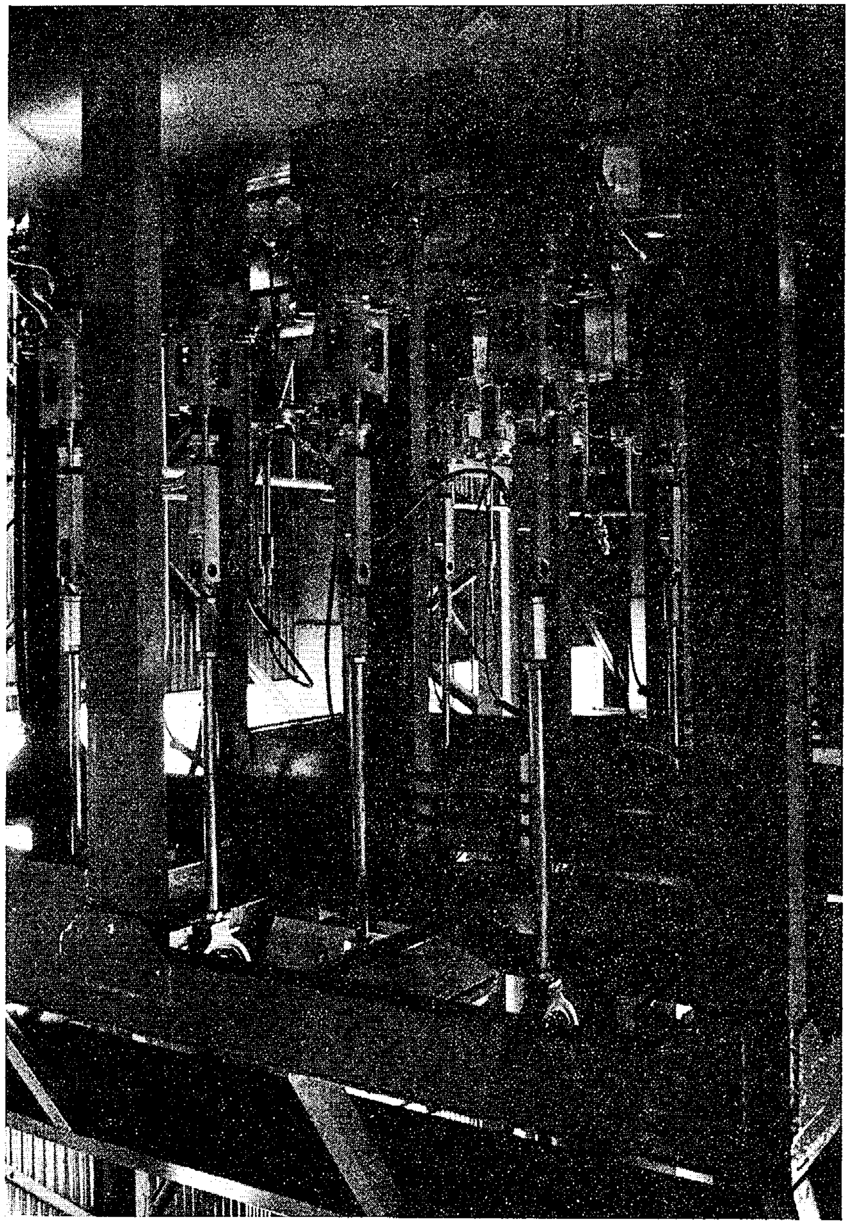

Photo 2-1. Fatigue Test Section of SBTL.

2. High Temperature Low-Cycle Fatigue Tests on Bellows for Small Sodium Valves

2.1 Introduction

Various types of bellows are used for sodium valves, but there still remain many uncertain factors as to their performance and applicability in high temperature service, and only limited data are available for their evaluation. Sodium valves occasionally lose their function due to the failure of bellows, and many of the causes of such failures still remain unclarified.

Besides the inadvertent operations, the following may be accountable for the causes of bellows failure.

(1) Corrosion of bellows plate by sodium,
(2) Fatigue due to cyclic operation,
(3) Thermal fatigue,
(4) Effect of holding at the state of constant deflection in high temperature sodium,
(5) Irregular actuation by deposits or frozen sodium, and
(6) Combined effect of two or more of the above stated items.

The factors related to these items may be taken as follows:

(1) Materials of bellows,
(2) Number of ply and wall thickness,
(3) Deflection rate,
(4) Configuration,
(5) Fabrication technique and quality control, and
(6) Atmospheric conditions.

In order to investigate all these probelms comprehensively, R & D program was formulated to conduct a series of tests on bellows in high temperature sodium environment. For this purpose, a test loop was built and installed in the Sodium Components Test Facility, O-arai Engineering Center, PNC. A series of tests have been conducted since August, 1978. These tests include corrosion behavior tests of unprocessed and processed materials of thin plate for bellows and low-cycle fatigue tests on bellows for small valves.

2.2 Description of Test Loop

Small Bellows Test Loop (SBTL) was installed in the Sodium Components Test Facility, O-arai Engineering

Center, PNC. This loop consists of three test sections (two fatigue test sections and one static test section) and service systems (see Figure 2-6).

1) Fatigue Test Section

Two test sections are provided for the fatigue test of bellows, each of which is capable of performing fatigue test of 6 bellows at a time. The expansion-compression drive section consists of a motor, a reduction gear, a drive shaft and double-eccentric cam (see Photo 2-1). The stroke can be adjusted from zero to 25 mm by the double excentric cam. The outer side of the bellows is exposed to sodium, while the interior of the bellows is filled with argon gas. Any failure of bellows can be detected by three electrode terminals and the method of 2 out of 3 is exercised in order to ensure higher detection reliability.

2) Static Test Section

The static test section designed for the corrosion test of bellows is similar to the fatigue test section except that the drive mechanism is not provided for this section. It has a test vessel and six nozzles for installation of test specimens.

3) Service System

This loop, which is to supply sodium independently to the three test sections, consists of a circulation system, a purity control system, a supply-drain system connected to the mother loop and the gas system.

The circulation system comprises tank, electromagnetic pump, heater, flowmeter, etc.. The purity control system which comprises a cold trap and a plugging indicator is independent from the circulation system. SBTL is remotely and semi-automatically controlled and operated from the central operation room.

2.3 Test Programs

A number of test programs have been completed, and others are still in progress. These test programs cover the following features: 1) corrosion resistance of bellows materials; 2) low-cycle fatigue life of bellows in high temperature sodium; and 3) effect of creep on the fatigue life. The following paragraphs briefly summarize these test programs.

2.3.1 Corrosion Test on Bellows Materials

(a) Purpose

Both the unprocessed and the processed materials of two types of bellows (formed type and welded type) are exposed in order to investigate the corrosion behavior and the combined effect of working process and sodium exposure on the material properties. These test specimens are placed in the three different environment; namely, in the high temperature sodium, in the vicinity of sodium surface, and in the argon cover gas including sodium vapor.

(b) Test Pieces

The unprocessed materials are the pieces of formed bellows cut out from the bellows tube, and those of welded bellows cut out from the bellows plate. The processed materials are the two types of finished bellows, formed and welded. Materials of test pieces are 316 stainless steel, 316L stainless steel, Inconel 718, etc..

(c) Test Conditions

1)	Environment:	in the high temperature sodium, in the vicinity of sodium surface, and in the cover gas (argon).
2)	Sodium temperature:	500°C
3)	Sodium flow rate:	50 l/min.
4)	Sodium purity:	about 3 ppm (oxygen) (about 150°C in plugging temperature)
5)	Cover gas pressure:	100 mmAq.G (argon gas)

(d) Test Period in Sodium

1000, 3000, 6000, 10000 hrs.

(e) Material Examination

Microscopic inspection, chemical analysis, and XMA to examine corrosion behavior, mechanical strength test including tensile test, etc. to examine property deterioration are conducted.

2.3.2 Fatigue Tests (I)

(a) Purpose

Cyclic expansion tests on two types of bellows are carried out in high temperature sodium till the bellows fails by fatigue in order to obtain the correlation between stress or strain amplitude and fatigue life, and also to verify the acceptability of design including bellows materials and configurations. Materials, number of ply and configurations are selected as parameters.

(b) Test Pieces

1)	Bellows size:	to be used for 1 to 4 inch valves
2)	Materials:	various types of materials, especially SUS 316L which is generally used for small sodium valves
3)	Thickness of the ply:	0.15 to 0.30 mm
4)	Number of plies:	1 to 3 plies

(c) Operating Conditions

1)	Sodium temperature:	400 to 500°C
2)	Sodium flow rate:	50 l/min.
3)	Sodium purity:	about 3 ppm (oxygen)
4)	Cover gas pressure:	100 mmAq. G (argon gas)

(d) Load Conditions

1)	Number of cycles:	30 cycles/min. Up to the bellows failure or 10^6 cycles
2)	Total deflection rate:	max. 25 mm
3)	Load direction:	simple axial direction (expansion or compression)
4)	Cyclic loading mode:	sine wave

(e) Analyses and Inspection

Performance and applicability of the bellows are to be evaluated by organic linking of macro/micro-observation of fractured section, fatigue life and stress analyses. The effect of sodium environment is to be compared with the results of fatigue tests in inert gas or atmospheric environment.

(f) Test Procedure

1)	Step 1:	Standard size bellows used for 3 inch valve are examined
2)	Step 2:	Materials, number of ply, configurations, etc. are selected as parameters for fatigue testing bellows.

2.3.3 Fatigue Tests (II)

(a) Purpose

In order to investigate the effects of additional conditions on the fatigue life, fatigue tests (II) are to be conducted according to the following items:

1) Combined effect of corrosion and fatigue by the mechanical cycles of bellows after holding at a free length position for a certain period,

2) Effect of creep on fatigue life,
3) Effect of torsion on fatigue life,
4) Combined effect of thermal and mechanical fatigue,
5) Effect of deposits on the surface of bellows,
6) Evaluation of metallographic change by carburization, etc., and
7) Fatigue life in inert gas including sodium vapor.

2.4 Results of Fatigue Tests (I)

As a first step of fatigue tests, two types of standard bellows for 3-inch sodium valve have been tested by Small Bellows Test Loop since August, 1978. At present fatigue test I-1 and I-2 have been completed and these test results are described below.

Table 2-1 summarizes test conditions, which are the same for both tests except sodium temperature. Sodium temperature was 400°C for test I-1, and 500°C for test I-2.

Formed seemless bellows produced by two Japanese manufacturers A and B and shown in Figure 2-1 and 2-2, were tested in the fatigue test I-1, and the design specifications of these bellows are listed in Table 2-2.

These bellows are formed by oil pressure forming. In this process the thickness of plies is generally constant in the direction of circumference, but in the direction of axis the thickness at the crown is thinner than that at the root. The bellows after forming process is subjected to annealing and heat treating according to the each manufacturers' method; for example, solid-solution heating at 1050°C or low temperature annealing at about 480°C.

Welded bellows produced by two Japanese manufacturers C and D and shown in Figure 2-3 and 2-4, were tested in the fatigue test I-2 and the design specifications of these bellows are listed in Table 2-3. In order to obtain the large deflection and the uniform spring constant, the plate of welded bellows is subjected to press forming into convolutions which is slightly different at each manufacturer. The bellows after forming and welding process is also subjected to annealing and heat treating.

Since there are no standard method available for calculating the strength and fatigue life of bellows, manufacturers use their own design equations which are generally based on the design equations of the M. W. Kellogg Company (Design of Piping Systems).

Table 2-4 summarizes the deflection loading of the fractured bellows for the fatigue test I-1 and I-2. For other bellows the tests were continued until about 1.1 x 10^6 cycles were reached without failure. The No. 4 welded bellows of Manufacturer D fractured at 1.32 x 10^5 cycles; but the another similar bellows with the same deflection loading did not fracture until the cycles to failure reached about 1.1 x 10^6. With several bellows, failures have been experienced due to the poor welding at the welds between the bellows ends and the end plates. Therefore, it is uncertain in this case whether or not the failed bellows truly reached its fatigue life. Presently, this bellows as well as others is undergone materials examination to search for the location and the cause of the failure.

Figure 2-5 shows an example of the comparison of design lifetimes with experimental results of the prescribed fatigue tests in sodium and the fatigue tests at room temperature in air. Table 2-5 and Figure 2-5 summarizes the deflection loading of the bellows used in these tests. It can be seen from the figure that the cycles to failure of bellows in high temperature sodium is about 100 or 200 times of the design value calculated by manufacturers' design equation which was derived from the test data at room temperature in air. Similar results were obtained with formed seamless bellows. It is probable, therefore, that the high purity sodium may extend the fatigue life of bellows for the expansion or compression in the simple axial direction. This observation is supported by the fact that the fatigue life in vacuum is longer than that in air.

As to the standard size bellows for 3-inch sodium valve, the fatigue life of welded bellows is longer than that of formed bellows because the deflection per one convolution of the former is about one half of that of the latter.

In order to investigate the effect of sodium temperature on the fatigue life, the formed seamless bellows with the same size and configuration were subjected to cyclic tests at sodium temperature of 400°C and 500°C. The cycle to failure at 500°C in sodium turned out to be about 10 to 20 % less than that at 400°C.

In conclusion it is necessary to clarify the fatigue life in air for the bellows used in sodium valves because the manufacturers' design equation such as a design curve in Figure 2-5 is derived from the test data of various types of bellows which are mainly used in PWR or BWR. So we have now the test program for the bellows used in sodium valves to obtain the fatigue life data in air both at room temperature and at high temperature, and to establish the design curve in air. While the fatigue tests in sodium is to be continued in order to establish the basic curve and the design equation in sodium according to the prescribed test program.

Table 2-1 Test Conditions for Fatigue Test I-1 and I-2

Sodium temperature	I-1 : 400 °C I-2 : 500 °C
Sodium flow rate	50 ℓ/min
Sodium purity	1.12 ppm (Oxygen)
	Plugging temperature 127 °C
	(by the equation by R.L. Eichelberger)
Cover gas pressure	100 mmAq. G (Argon gas)
Cycle speed	10 cycles / min.
Number of cycles	Up to the bellows failure or 10^6 cycles.
Load direction	Simple axial direction
Cyclic loading mode	Sine wave

Table 2-2 Specification of Bellows for Fatigue Test I-1.

Manufacturer	A	B
Type	Formed seamless	Formed seamless
Number of plies	2 plies	2 plies
Material	316L stainless steel	316L stainless steel
Convolute outer diameter	60 mm	55 mm
Convolute inner diameter	43.5 mm	36 mm
Number of convolutes	12 convolutions (6 convolutions × 2)	11 convolutions
Number of blocks	2 blocks	1 block
※) Free length	87 mm	86 mm
Thickness of the ply	0.23 mm × 2 plies	0.25 mm × 2 plies
Number of test pieces	6 pieces	6 pieces

※) Free length includes attachment length which is 14 mm for manufacturer A and 36 mm for manufacturer B.

Table 2-3 Specification of Bellows for Fatigue Test I-2

Manufacturer	C	D
Type	Welded type	Welded type
Number of plies	One-ply	Two plies
Material	316L stainless steel	316L stainless steel
Convolute outer diameter	45 mm	61.9 mm
Convolute inner diameter	25 mm	36.5 mm
Number of convolutes	26 convolutions	20 convolutions
Number of blocks	1 block	1 block
※)Free length	64 mm	72 mm
Thickness of the ply	0.2 mm × 1 ply	0.152 mm × 2 plies
Number of test pieces	5 pieces	5 pieces

※) Free length includes attachment length which is 17 mm for manufacturer C, and 42 mm for manufacturer D.

※※) Fatigue test I-2 includes each one bellows of fatigue test I-1.

Table 2-4 Failed Bellows in Fatigue Test I-1 and I-2

Test	Manu-facturer	Deflection loading mm / convolute	Design cycles to failure	Test result of cycles to failure
I-1	A	1.32	2.70×10^3	5.95×10^5
	B	1.39	4.92×10^3	4.32×10^5
I-2	A	1.29	2.06×10^3	5.24×10^5
	B	1.42	3.77×10^3	3.22×10^5
	D	1.25	※) about 9×10^3	1.32×10^5

※) As the design equation of this manufacturer is not applicable to this deflection rates, this design cycles to failure are calculated by the equation of other manufacturer.

Table 2-5 Deflection Loading of Test Bellows for Fatigue Test I-2

No.	Manufucturer C (welded bellows)			
	Deflection loading mm / convolute	Design cycles to failure	Test result of cycles to failure	Failure
1	0.69	2.8×10^4	(1.105×10^6)	No
2	0.77	1.9×10^4	(〃)	No
3	0.85	1.4×10^4	(〃)	No
4	0.96	8.9×10^3	(〃)	No
5	0.95	8.9×10^3	(〃)	No

Cycles in ( ) refer to the test pieces which have not failed at this time.

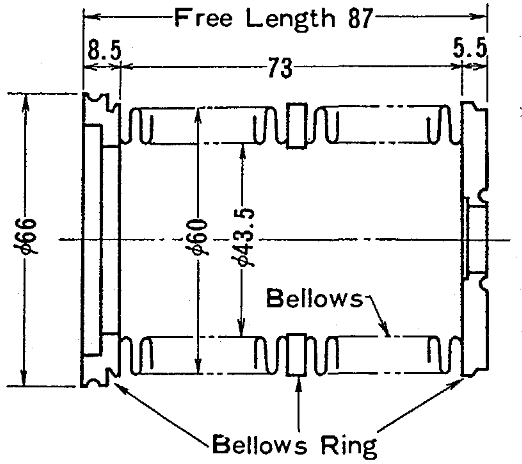

Figure 2-1 Details of Bellows
A for Fatigue Test I-1

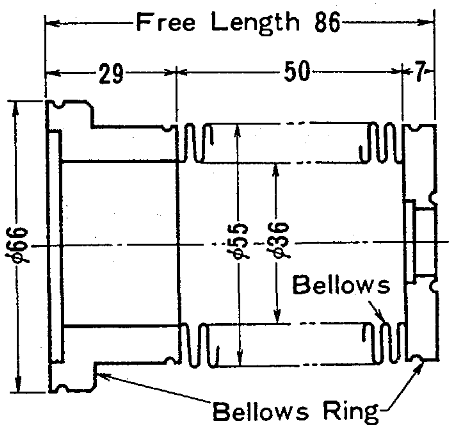

Figure 2-2 Details of Bellows
B for Fatigue Test I-1

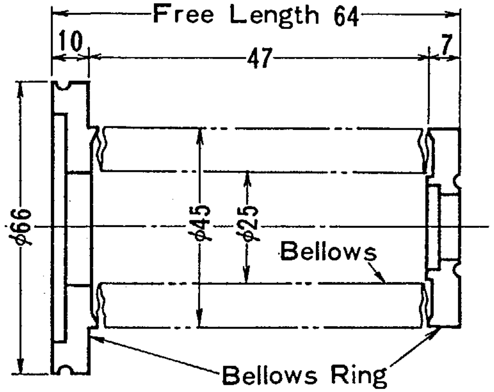

Figure 2-3 Details of Bellows
C for Fatigue Test I-2

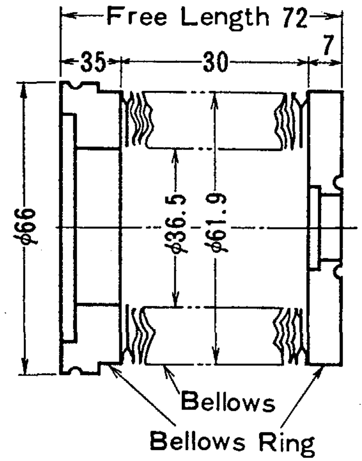

Figure 2-4 Details of Bellows
D for Fatigue Test I-2

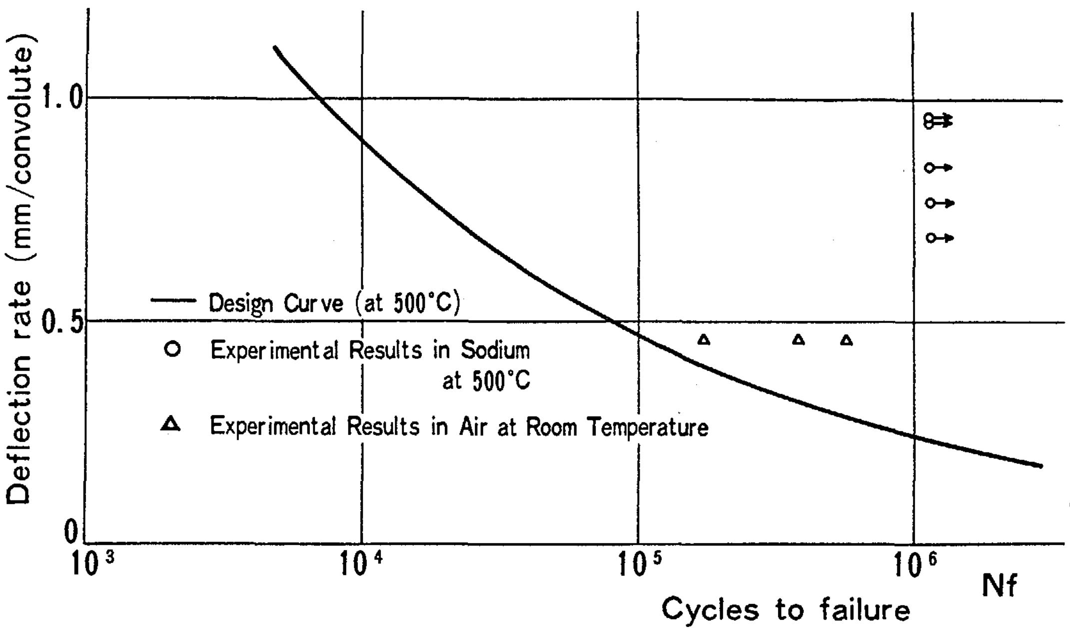

Figure 2-5 Comparison of Design Lifetimes with Experimental Results on Welded Bellows

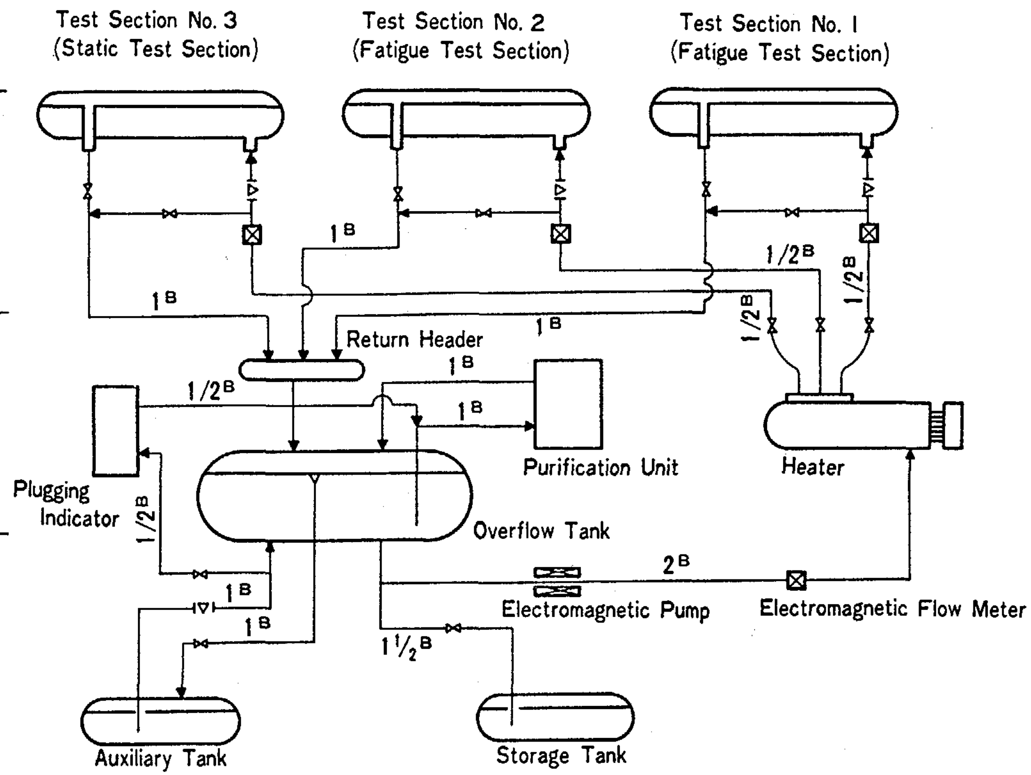

Figure 2-6 Flow Diagram of small Bellows Test Loop

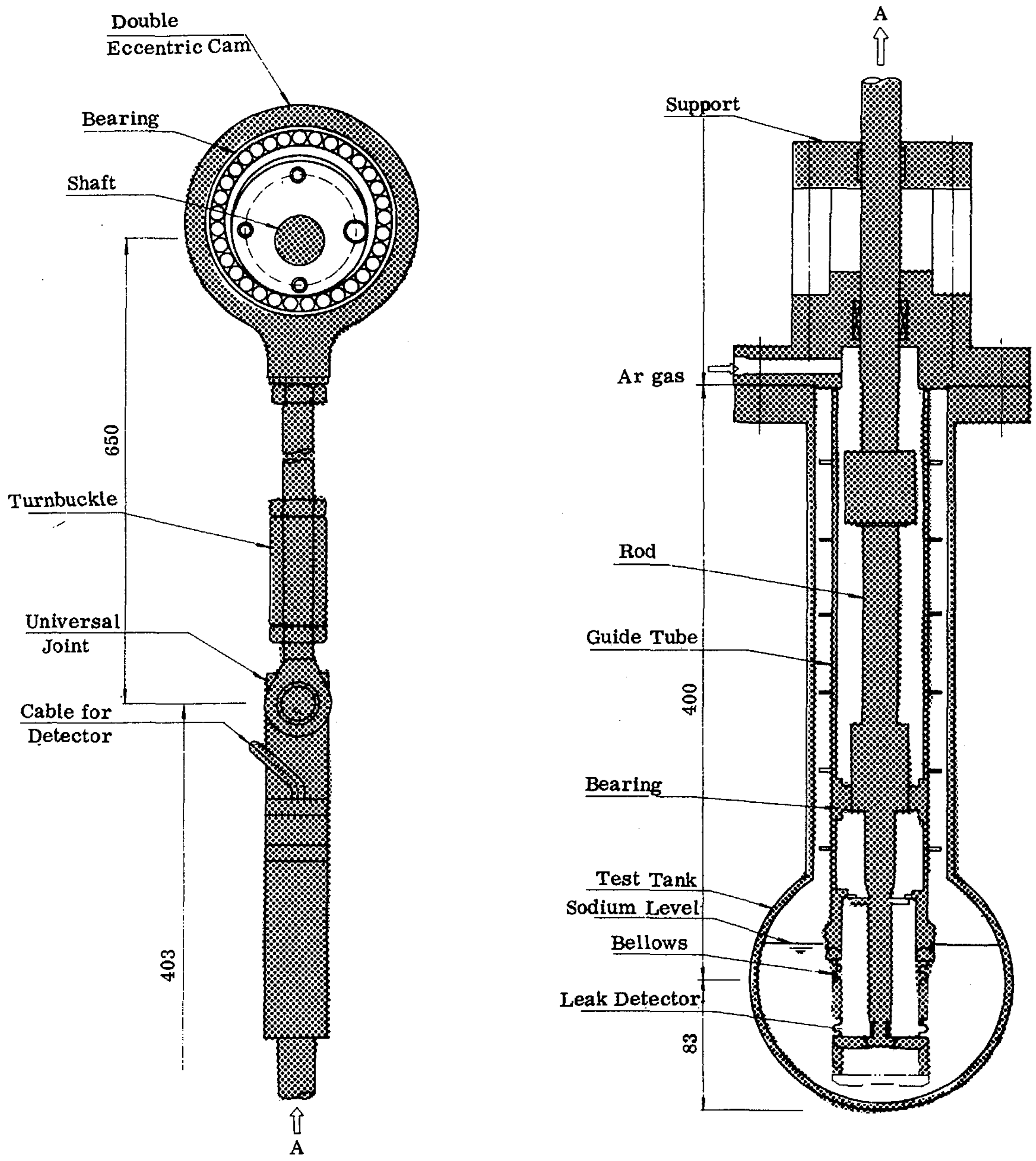

Figure 2-7 Bellows Expansion Joint