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Bellows for Control Rod Drive Mechanism of "MONJU"

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Bellows for Control Rod Drive Mechanism of "MONJU"

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Abstract

The full mock-up operation test of Control Rod Drive Mechanism (CRDM) for "MONJU" have been carried on since 1972 in OEC of PNC.

Welded type bellows were adopted for CRDM as the boundary between sodium and atmosphere.

In design, two different locations were considered for bellows, one in sodium and the other in argon gas with sodium vapor and some experiences on the bellows have been obtained.

Besides the prototype tests of CRDM, several R & D on CRDM bellows, such as environment effect test and endurance test are conducted.

1. Design

1.1 Introduction

The design work for control rod drive mechanism (CRDM) of "MONJU" is entrusted separately to three Japanese manufacturers by PNC. PNC plays the role of finalizing the design of CRDM by the contribution of the R & D work in which PNC strongly participates and also the experience gained from the construction and operation of "JOYO".

In the present "MONJU" design, two types of bellows are considered for the primary seal of the CRDM; namely, the stroke bellows for sealing between upper guide tube and drive shaft and the gripper bellows for sealing between drive shaft and gripper actuator rod. They are all nesting type welded bellows, but have several different design points in their details.

This chapter deals with the design philosophy and two typical design examples of bellows for CRDM of "MONJU".

1.2 Design Philosophy

One of the most interested thing for the design of the bellows is to decide the position where the bellows should be installed. The following three positions for the bellows are proposed:

1) in hot sodium
2) in cold argon gas with sodium vapor
3) in hot argon gas with sodium vapor.

However, there are comparative merit and demerit among them; for instance,

in case of 1)

1 The corrosion rate in liquid sodium is smaller than that in sodium vapor.
2 Argon gas blowing down system is not needed.

in case of 2)

1 Temperature effect on the bellows material is less severe.
2 Argon gas blowing down system is needed to prevent sodium vapor deposition and purge radioactive gas.

As described in Chapter III, in the first generation test of CRDM, bellows were installed in these three different positions and good test results were obtained for all cases.

1.3 Design Examples

"MONJU" has three kinds of CRDM, i.e., fine control rod drive mechanism (FCRDM), coarse control rod drive mechanism (CCRDM) and back-up control rod drive mechanism (BCRDM). Different bellows have been disigned for each CRDM but only two typical design examples will be introduced in this paper. In the first case, both stroke and gripper bellows are installed in hot sodium and in the second case both bellows are installed in cold argon gas region.

1.3.1 Example (1)

(1) Configuration; TBD for plant CRDM

(2) Material

(a)	Bellows core:	SUS316L, Inconnel 718
(b)	Mounting flange & guide structure:	SUS304 etc.

(3) Design Criteria

(a)	Stroke; (for stroke bellows)	1000 mm
	(for gripper bellows)	30 mm
(b)	Internal Diameter:	90 mm
(c)	External Diameter:	120 mm
(d)	Internal pressure (design max):	some 1 kg/cm^2g
(e)	Internal pressure (service):	0.85 kg/cm^2g
(f)	External pressure (design max):	0.56-0.77 kg/cm^2g (some)
(g)	External pressure (Reactor cover gas):	0.55 ± 0.05 kg/cm^2g
(h)	Design temperature:	550°C
(i)	Operating temperature:	some 529°C (max.)
(j)	Drive speed	
	(a) stroke bellows translating speed:	0-300 mm/min.
	(b) gripper bellows:	0-300 mm/min.
(k)	External environment	
	(a) stroke bellows:	Liquid sodium
	(b) gripper bellows:	ditto
(l)	Internal environment	
	(a) stroke bellows:	fresh argon gas
	(b) gripper bellows:	ditto
(m)	Life cycles (service)	
	(a) full stroke translating:	4000/10 years
	(b) scram:	300/10 years
	(c) control rod latch motion:	100/10 years
	(d) short stroking: (translating some 20 mm at a few positions with driving speed 0-300 mm/min.)	50000/10 years
(n)	Number of blocks:	some 13
(o)	Number of convolutions per block:	some 55
(p)	Convolution type:	nesting, coned edges
(q)	End fitting attachment:	machined as profiled bellows convolution

(4) Helium Leak Test

If leak rate is less than $1x10^{-6}$ acc/sec at less than $1x10^{-4}$ Torr atmosphere, acceptable.

1.3.2 Example (2)

(1) Configuration: TBD for plant CRDM

(2) Material

(a)	Bellows core:	SUS316, 347, Inconnel 718
(b)	Mounting flange & guide structure:	SUS304 etc.

(3) Design Criteria

(a)	Stroke: (for stroke bellows)	1000 mm
	(for gripper bellows)	50 mm
(b)	Internal Diameter:	90 mm
(c)	External Diameter:	120 mm
(d)	Internal pressure (design max):	some 2.0 kg/cm^2g
(e)	Internal pressure (service):	0.7-0.95 kg/cm^2g
(f)	External pressure (design max):	3.0 kg/cm^2g (some)
(g)	External pressure (service):	0.55±0.05 kg/cm^2g
(h)	Design temperature:	350°C
(i)	Operating temperature:	some 350°C (max.)
(j)	Drive speed	
	(a) stroke bellows translating speed:	0-300 mm/min.
	(b) gripper bellows:	100 mm/min. (max.)
(k)	External environment	
	(a) stroke bellows:	argon with small amount of sodium vapor
	(b) gripper bellows:	ditto
(l)	Internal environment	
	(a) stroke bellows:	fresh argon gas
	(b) gripper bellows:	ditto
(m)	Life cycles (design)	
	(a) full stroke translating:	13000
	(b) scram:	2500
	(c) control rod latch motion:	250
	(d) short stroking: (translating some 20 mm at a few positions with driving speed 0-300 mm/min.)	200000
(n)	Number of blocks:	some 24
(o)	Number of convolutions per block:	some 35
(p)	Convolution type:	nesting, coned edges
(q)	End fitting attachment:	machined as profiled bellows convolution

(4) Helium Leak Test
If leak rate is less than $1x10^{-6}$ acc/sec, acceptable.

2. R & D work

2.1 Introduction

CRDM of course is one of the reactor components which

require the highest reliability. PNC has proceeded extensive R & D program for the CRDM of "MONJU" since 1972.

As mentioned in the next chapter, 3 units and 4 units of prototypes have been manufactured as first and second generation test models respectively, and in-water as well as in-sodium tests have been performed. Besides these prototype tests, two kinds of R & D on CRDM bellows are conducted, one is environment effect test and the other endurance test.

2.2 R & D work

2.2.1 Environment Effect Test of Bellows

(1) Purpose

Bellows after a long period of immersion in hot sodium and in argon gas with sodium vapor, are investigated for their environment effects such as carbonization and stress corrosion. The test is conducted with the changing of oxygen and carbon rates in sodium.

(2) Test Article

Test article of bellows is a partial model of the prototype bellows. The specifications of the article are as follows:

core outer diameter:	125 mm
core inner diameter	85 mm
thickness:	0.25 mm
material:	SUS-316
number of convolutions:	about 50
number of test articles:	12
	6...for in hot sodium test
	6...for in argon gas test

2.2.2 In-sodium Endurance Test of Bellows

(1) Purpose

The purpose of the program is to demonstrate the integrity of the bellows for use with LMFBR CRDMs in a elevated temperature sodium environment.

(2) Bellows Design for CRDM

Two sets of bellows are provided for the drive line to protect the drive mechanism from liquid sodium and its vapor attacks. Both are immersed in liquid sodium. One bellows forms a seal between the drive shaft and the guide tube, while the other seals the space between the gripper actuator rod and the drive shaft. The bellows are of welded type design. The design parameters are as follow:

	Stroke Bellows	Gripper Bellows
Operating environment:	529°C liquid sodium	same as left
Stroke:	1100 mm	30 mm
Number of full stroke operations:	5000 cycles	3300 cycles
Type of bellows:	welded type	same as left

(3) Test Article for Bellows Life Test
Test article of bellows is a partial model of the prototype bellows. The specifications of the article are as follows:

	Stroke Bellows	Gripper Bellows
Core outer diameter:	approx. 25 mm	approx. 85 mm
Overall installed length of bellow:	max. 750 mm	150 mm
Stroke:	300 mm	30 mm
Number of test articles(Phase I):	(7 block model) x 3 pieces	45 pieces

(4) Test Description (Summary)
The test article will be immersed in liquid sodium and be subjected to repetition operations similar to those of the actual one for a number of cycles up to the design fatigue limit. Testing conditions are as follows:

	Stroke Bellows	Gripper Bellows
Stroke:	300 mm	30 mm
Repetition mode:	sine wave or triangular wave	sine wave
Max. repetition number:	8×10^4 cycles	1×10^4 cycles
Sodium temperature:	529°C	same as left
Internal pressure of bellows:	0-0.3 kg/cm^2g	same as left

Test rig is shown in Figure 2-1.

(5) Testing and Examination after Repetition Test
(a) Non-destructive testing
1) Visual inspection
2) Dimensional examination
3) Spring constant measurement
4) Helium leak testing
(b) Destructive testing
1) Fractographic examination of failed sections
2) Micro structure analysis
3) Hardness testing

(6) Data Analysis
The data will be presented in the form of stress-to-failure against cycle-to-failure curves.

3. Experiences

3.1 Introduction

R & D of CRDM for "MONJU" started since 1972 and 3 units of prototypes were manufactured as the first generation test model. And in-water and in-sodium tests of these models were carried out in 1973 through 1976, the former in manufacturer's works and the latter in O-arai Engineering Center, PNC.

Manufacture of second generation test model started since 1974, and as today prototypes of BCRDM and SCRDM were manufactured and both of them have gone through a series of in-water and in-sodium tests.

As to regulating control rod drive mechanism (RCRDM), 1 unit each of FCRDM and CCRDM is under manufacturing.

This chapter describes the test results and troubles of bellows found during the testing of the first generation and the second generation test models.

3.2 Experiences of the First Generation CRDM Test Models

3.2.1 CRDM Test Model (1)

This test model was designed and manufactured in 1972, and both stroke and gripper bellows of this test model were installed in low temperature argon gas region. About 10,000 cycles of tests were carried out for this model by way of in-water and in-sodium tests. The result of inspection of bellows after the tests showed nothing abnormal except in minor changes observed in the pitch of bellows core. The specification and used conditions of the bellows used in this model is shown in Table 3-1, and their configurations are provided in Figure 3-1.

3.2.2 CRDM Test Model (2)

This test model was designed and manufactured in 1972, and both stroke and gripper bellows of this test model were installed in sodium region. The specification and used conditions of the bellows are shown in Table 3-2. As it can be seen from this table, this model was tested so many both in-water and in-sodium tests. The result of inspection of the bellows after the tests showed nothing abnormal in the stroke bellows but pin-holes caused by alkali corrosion were observed in the gripper bellows with subsequent leak of sodium inside (See Photograph 3-1)

3.2.3 CRDM Test Model (3)

This test model was designed and manufactured in 1972, and the functional tests were performed in-water and in-sodium from 1972 to 1973. The design concept of their bellows, stroke and gripper one is quite the same as that of "JOYO" CRDM, and both bellows were positioned in hot argon gas region with sodium vapor. The stroke bellows was used only for CRDM vertical translation drive and moved slowly. On the other hand, the gripper bellows was operated rapidly at every scramming. During the functional tests both of the bellows were kept sound.

The specification and used conditions of the bellows used in this model is shown in Table 3-3, and their configurations are provided in Figure 3-2.

3.3 Experiences of the Second Generation CRDM Test Models

3.3.1 BCRDM Test Model

While the first generation test models are so designed

that 1 model has both the functioned of RCRDM and SCRDM, the second test models are designed so that each has a single, special function.

As described before, as the second generation test models, BCRDM and SCRDM were already completed and RCRDM is in the manufacturing at present.

This BCRDM test model was designed and manufactured in 1975, and both stroke and gripper bellows of the model were installed in sodium region.

In-water and in sodium tests have been carried out for this model, but the gripper bellows experienced failure after about 900 cycles of scram repetition in-sodium test, while the stroke bellows showed nothing abnormal.

The configurations of the bellows used in this model is shown in Figure 3-3.

3.3.2 SCRDM Test Model

The SCRDM test model was designed and manufactured in 1976, and both stroke and gripper bellows were installed in sodium region. A schematic structure of this test model is shown in Figure 3-4.

After its completion, in-water and in-sodium tests have been performed for this model, but the stroke bellows experienced failure after about 500 cycles of scram repetition in-sodium test, however, the gripper bellows kept sound during these tests.

3.4 Knowledge

As for CRDM for "MONJU", the first and the second generation test models have been manufactured as of today, and in-water and in-sodium tests have been carried out for them, and many useful data for the CRDM bellows have been obtained.

The knowledge that has been obtained from our experiences with the first and the second generation test models is summarized as follows.

(1) There is no instance of failure in double bellows.
(2) It is better to adopt rather thicker bellows wall near the fitting edge in order to reduce bellows failure.
(3) The stopper of guide ring must be not come off, for instance, full circumference type is suitable to use.
(4) The existing bellows can stand 500 $\sim$ 900 cycles of scram operation. (This number of cycles is almost equal to that of scram operation during reactor life.)

Table 3-1 Specification and Used Conditions of Test Model (1) Bellows

	Item		The 1st Generation Test Model No. 1 Bellows	
			Stroke	Gripper
Specification	Natural Length (mm)		910	47
	Installed Length (mm)		1330	65
	Maximum Compressed Length (mm)		780	27
	Axial Deflection (mm)		±550	±20
	I.D. (mm) x O.D. (mm)		98x124	27x40
	Thickness (mm)		0.15	0.1
	Number of Convolutions		36 conv. x 13 blocks = 598	60 conv. x 1 blocks = 60
	Material		SUS347 (Without Heat Treatment)	SUS347 (Without Heat Treatment)
Used Conditions	Environment		Argon with Small Amount of Sodium Vapor [Air (In Water Tests)]	Same as Stroke Bellows.
	Temperature (°C)		Some 200	Some 200
	Pressure (kg/cm^2)	Cover Gas	0.02, 0.26	0.02, 0.26
		Bellows Inner Gas	0.09~0.28, 0.3~0.34	ditto
		Pressure Difference	0.07~0.26, 0.04~0.08	-(0.26~0.07), -(0.08~0.06)
	Hold-on Time	Full Stroke Position (Hr)	Some 5000	Some 1
		Hold-on Position (Hr)	120	Some 5000
	Max. Operation Speed (m/s)	Normal	300 (mm/min.)	Some 1
		Scram	Some 4	-
	Stress (kg/mm^2) (Kellog's Equations)	Due to Pressure	2.8~10.2	0.7~2.7
		Due to Deflection	-18.4~18.4	-17.4~17.4
	Bellows Condition		No trouble	No trouble

Table 3-2 Specification and Used Conditions of Test Model (2) Bellows

Item			CRDM Bellows	
			Stroke	Gripper
Specification	Natural Length (mm)		2650	210
	Installed Length (mm)		2600	210
	Maximum Compressed Length (mm)		1500	170
	Axial Deflection (mm)		-1100	-40
	ID. x OD. (mm x mm)		90 x 120	49.2 x 74.6
	Thickness (mm)		0.2	0.18
	Number of Convolutions		con. blocks con. 50 x 28 = 1400	con. blocks con. 35 x 2 = 70
	Material		SUS316L	SUS316L
Used Conditions	Pressure (kg/cm^2)	Cover Gas	0.02	0.02
		Bellows Inner Gas	0.045 - 0.10	
		Pressure Difference	external 0.275 - 0.12	
	Temperature (°C)		540	
	Hold time	Full Stroke Position (Hr)	5000	1.0
		Hold-on Position (Hr)	15	4600
	Max. Operation Speed (m/s)		3.1	
	Stress (kg/mm^2) (Kellog's equ.)	Due to Pressure	3.87 - 1.69	3.43 - 1.49
		Due to Deflection	0.8 - 17.2	0 - 15.1
Number of Full Stroke Excursions in Air and Water			180	
Number of Full Stroke Excuusions in Sodium			15000	
Number of Full Stroke Scrams in Water			120	
Number of Scrams before failure in Sodium			2000	
Bellows Condition			not falled	pin hole by alkali corrosion

Table 3-3 Specification and Used Conditions of Test Model (3) Bellows

Item			Bellows for CRDM Test Model No. 3	
			Stroke	Gripper
Specification	Natural Length (mm)		1590	145
	Installed Length (mm)		1965	130
	Maximum Compressed Length (mm)		840	70
	Axial Deflection (mm)		+375/-750	-15/-75
	ID. x OD. (mm x mm)		90 x 120	40 x 65
	Thickness (mm)		2 x ^{t}0.178 (double)	0.15
	Number of Convolutions		45 con. x 13 blocks	25 con. x 3 blocks
	Material		SUS316L	SUS316L
Used Conditions	Pressure (kg/cm^2)	Cover Gas	0.02	0.02
		Bellows Inner Gas	0.3 ~ 0.45	0.3 ~ 0.45
		Pressure Difference	internal 0.3 ~ 0.45	internal 0.3 ~ 0.45
	Temperature (°C)		540	540
	Hold time	Full Stroke Position (Hr)	?	?
		Hold-on Position (Hr)	?	?
	Max. Operation Speed (m/s)		0.005 (300 mm/min)	1
	Stress (kg/mm^2) (Kellog's equ.)	Due to Pressure	5.4 ~ 8.0	10.4 ~ 15.6
		Due to Deflection	+31.9 ~ -63.8	-12.1 ~ -60.5
Number of Scrams before failure in Sodium			Shim 2000 , fine 100,000	Scram 550
Bellows Conditions			not failed	not failed

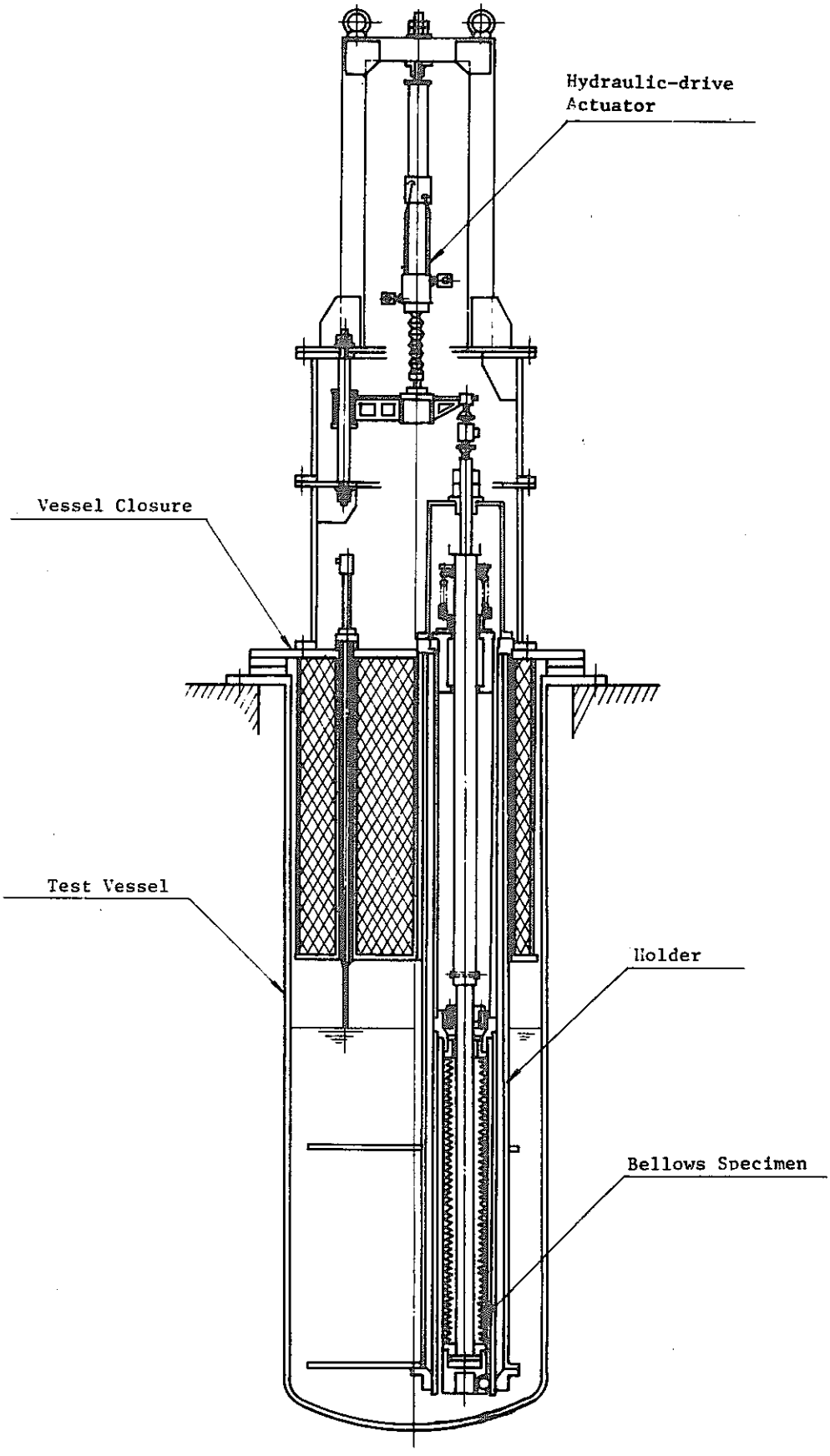
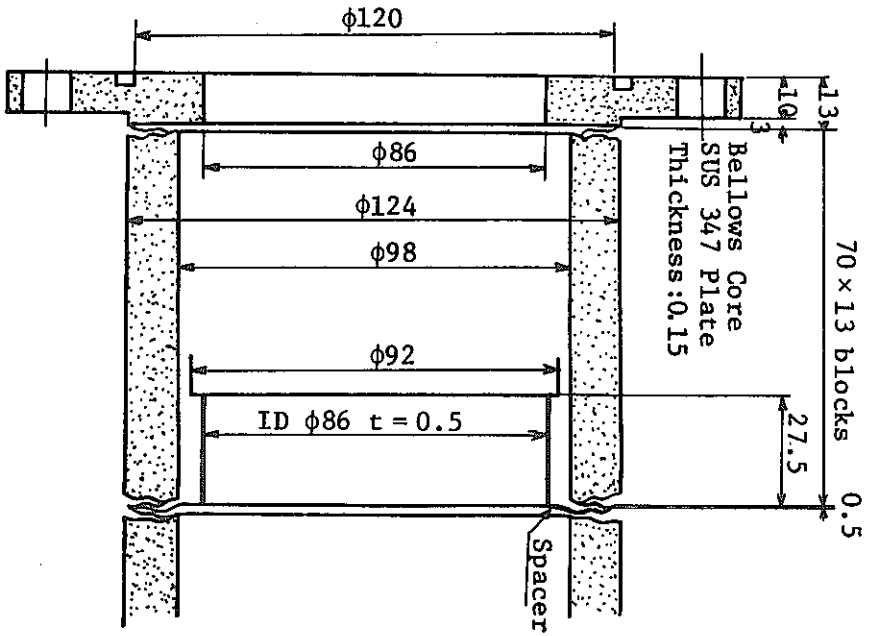
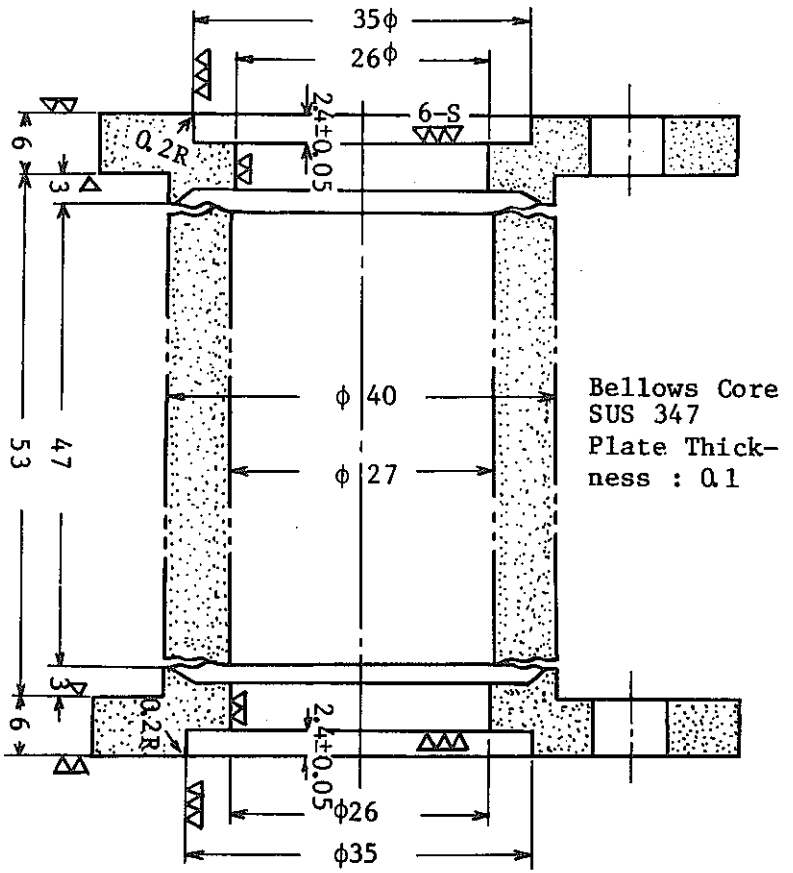


Figure 2-1 Bellows Cyclic Endurance Test Apparatus

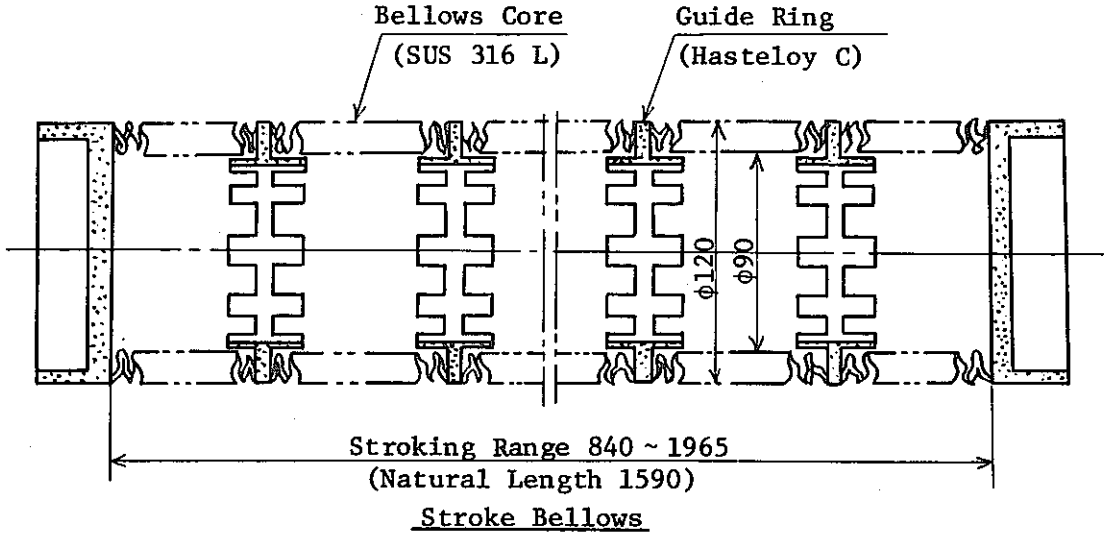


Stroke Bellows



Gripper Bellows

Figure 3-1 Configurations of Bellows for CRDM Test Model (1)



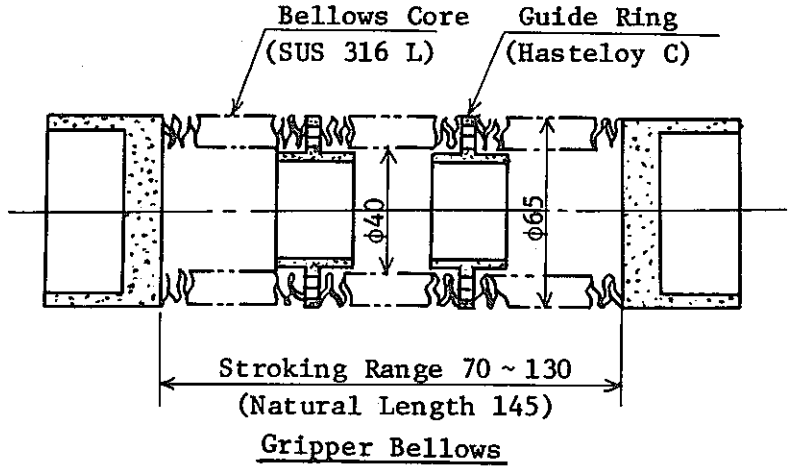


Figure 3-2 Configurations of Bellows for CRDM Test Model (3)

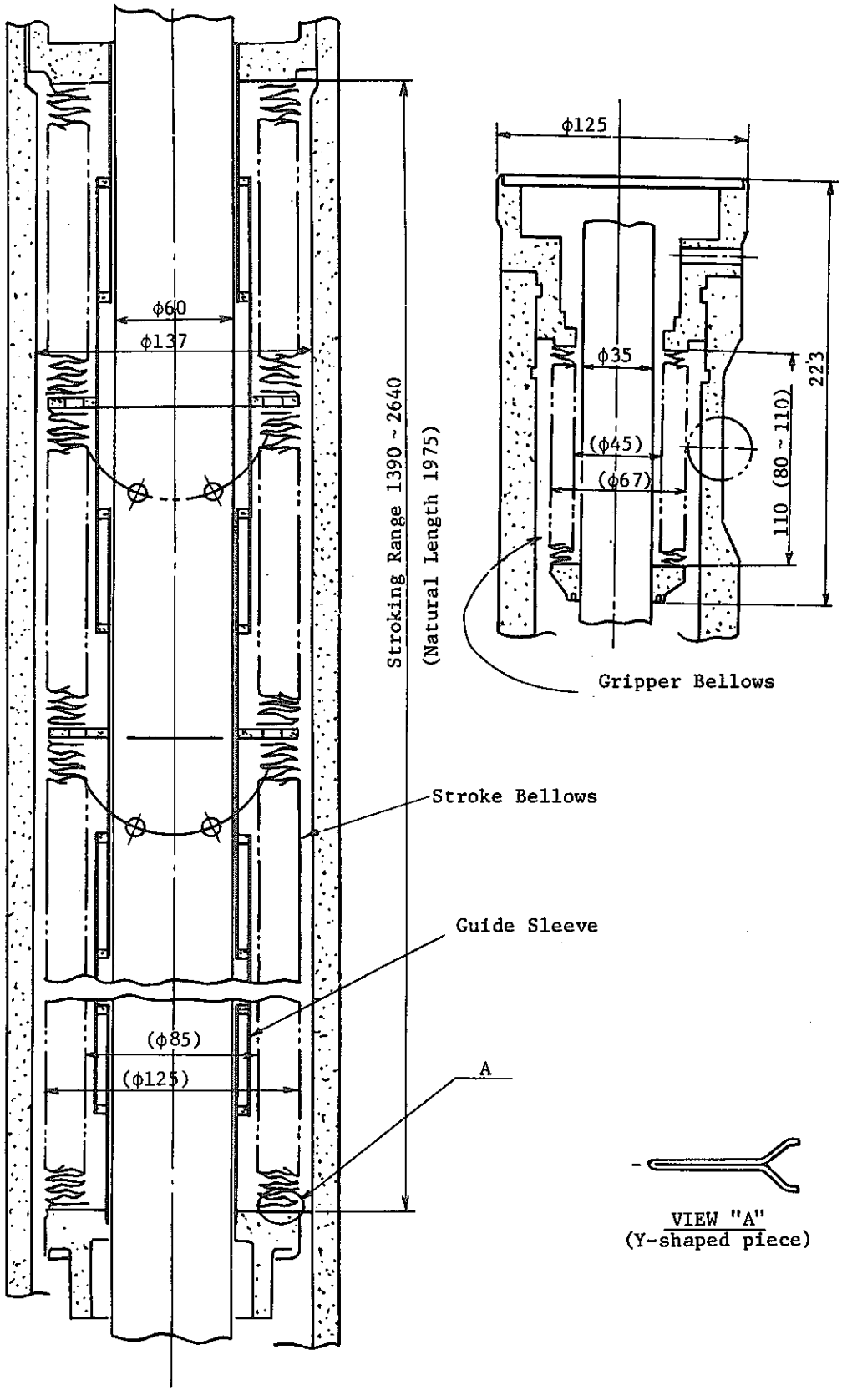


Figure 3-3 Configurations of Bellows for BCRDM Test Model

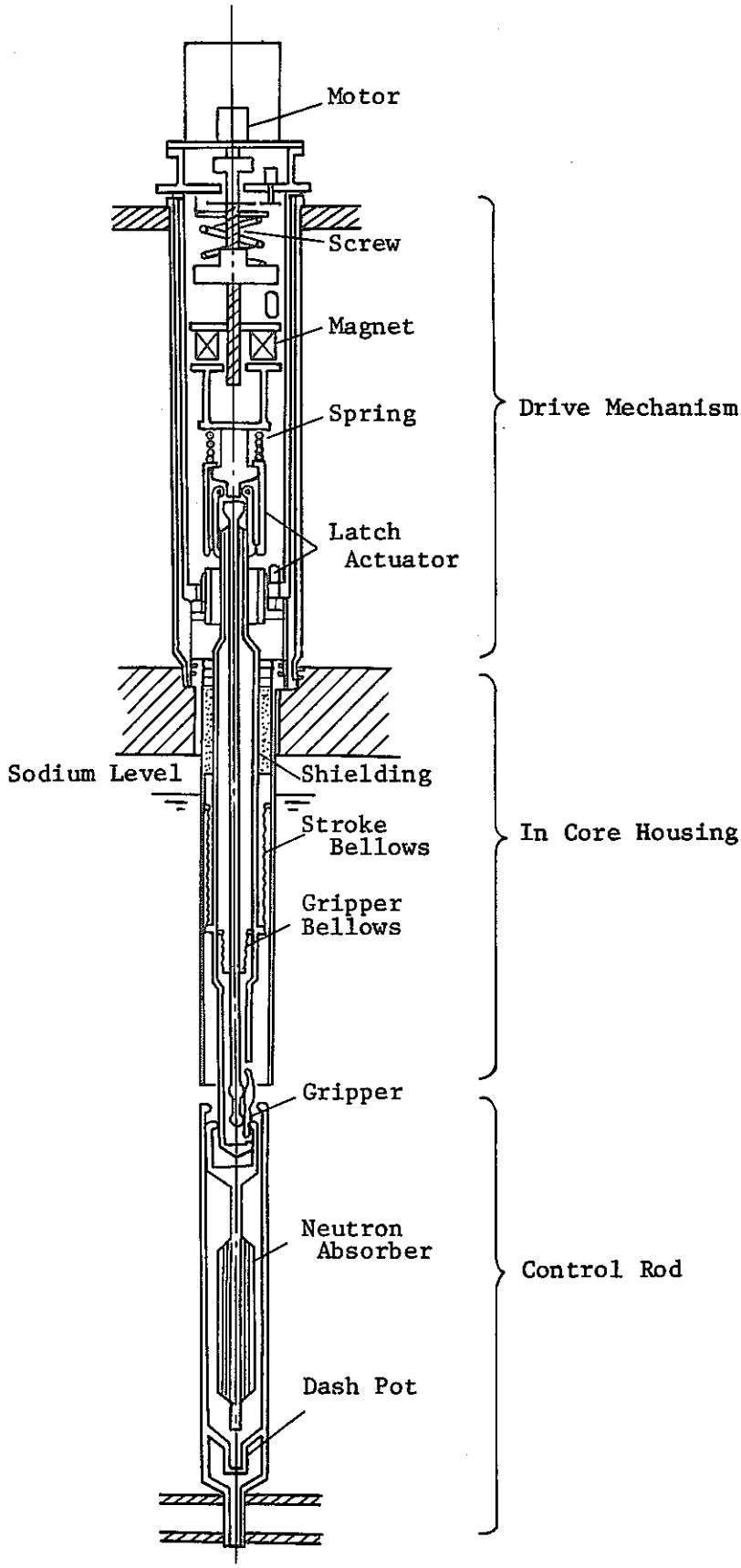
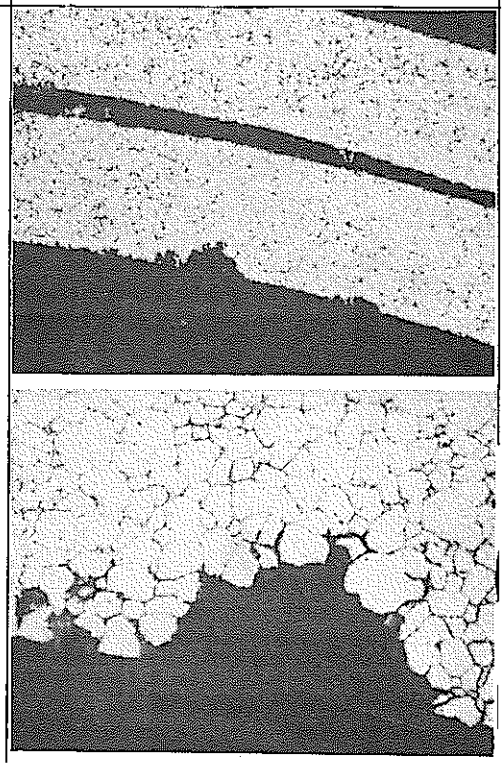


Figure 3-4 SCRDM Test Model

	CRDM
	Gripper Bellows
Failure Mode	Pin Hole
Failure Cause (Presumed)	Alkali Corrosion
Fractograph (SEM)	

Photograph 3-1 Gripper Bellows Failure