MECHANICAL FRETTING ENDURANCE TEST OF CANFLEX FUEL BUNDLE

SEOK-KYU CHANG, HO CHUN SUK

Korea Atomic Energy Research Institute, 150 Dukjin-Dong,
Yusong-Gu, Daejon, Korea(R.O.K), 305-600

ABSTRACT

A 3000 hour mechanical fretting endurance test for the verification of the CANFLEX fuel bundle was performed in the KAERI CANDU Hot Test Loop facility. The test conditions were the same as the real reactor normal operating conditions. After the test, the dimensions and fretting wears of the test bundles and the pressure tube were carefully measured and inspected, which met the acceptance design criteria. Also, the historical trends of fretting wears of bearing pads and spacers were evaluated with the test results.

1. INTRODUCTION

During CANDU reactor operation, turbulent coolant flow and structurally transmitted oscillation cause the vibration of the fuel bundles in the pressure tube of the fuel channel. Such relative motions between bearing pads of the fuel bundle and the pressure tube or between spacers, can create fretting wear on spacers, bearing pads and the inner surface of the pressure tube. These fretting wears are not desirable for reactor safety and must be less than the design limits.

As part of the qualification of the CANFLEX-NU fuel bundle design for use in CANDU reactors, it is required to verify that the fretting wears of new bundles are sufficiently low during lifetime and also pressure tube fretting is acceptable.

Since fretting is an extremely complex process, no analytical correlation is found to appropriately predict the fretting of an out-reactor or out-reactor condition. But, using the results of the experiences of fretting endurance tests performed by KAERI and AECL, it is possible to predict the lifetime fretting wear by extrapolation technique with sufficient conservatism.

A 3000 hour mechanical fretting endurance test, with two intervals at 500 and 1000 hour test runs, was performed. After each run, the dimensions and fretting wears of the test bundles and the pressure tube were carefully measured and inspected.

2. DESCRIPTION OF TEST FACILITY

2.1 CANDU Hot Test Loop

KAERI CANDU Hot Test Loop facility used for the endurance test is equipped with a test rig as a full-scale fuel channel of Wolsong reactor (Figure 1). This facility consists of main circulation line, cooling line and feed water line. The main circulation line has circulation pump, heater, cooler and pressurizing pump. Thus, this facility can simulate the real conditions (pressure, temperature, flow rate) of CANDU reactor power plant and was used for various verification tests of CANFLEX fuel bundle as well as CANDU-37 fuel bundle.(1) The loop is operated and controlled by a dual type Distributed Control System during the test. The experimental data from the test rig as well as typical loop parameters are collected and analyzed by HP3054A data acquisition system.

2.2 Test Rig

The test rig used in this test consists of end fittings, pressure tube, liner tubes and shield plugs and is equivalent to the CANDU 6 design (Figure 2). The method of supporting the end fittings, the arrangement of the feeder pipes, and garter spring supports are similar to a reactor installation. The feeder geometry represents a worst-case feeder i.e., channel L-5 with elbows located close to the inlet end fitting, giving typical poor coolant velocity distribution at the inlet to the liner annulus. This channel geometry was chosen based on experience with flow visualization rig tests.

2.3 Test Bundles

The test bundles were made in accordance with the CANFLEX-NU fuel bundle technical specification(2) by the CANDU fuel fabrication team at KAERI. All the test bundles were loaded by using shim stock, to avoid sliding damage to the bearing pads and pressure tube. The bundles were rotated to pre-determined alignment angles which were taken from the results of the bundle rotational tests,(1) to produce the maximum string pressure drop. This angle was chosen to provide the worst turbulence at the bundle junctions, and hence the worst fretting condition. Table 1 shows the identification of all the bundles and their locations in the test rig. The test bundles were oriented at the same angles for each endurance test run, and the same bundles were in the same axial positions in the pressure tube of the test rig.

3. TEST CONDITIONS

The test conditions specified in the fretting endurance test were:

Temperature	=	266 °C
Pressure (Inlet)	=	11.0 MPa
Mass Flow	=	31.0 kg/s

These conditions were kept during the initial (500 hour) test run. During the intermediate (1000 hour) test run, there was a decrease of the flow rate in the test rig caused by loop crudding. After resolving the crudding problem by cleaning the loop and test bundles, the last two bundles in the test rig were replaced by an equivalent fuel spacer for getting the margin of flow rate. At the final (1500 hour) test run, additional outlet two bundles were replaced by a second fuel spacer for more flow rate margin. All other bundles were loaded in the same positions and orientations during each test run. Figure 3 shows the history of the loop parameters for the entire 3000 hour endurance test. It was shown that the loop pressure and temperature were in very good control (11.0 MPa, 265.7 °C in average) and the channel flow rate was close to the specified value (29.9 kg/s in average). During the test, the coolant quality was checked by loop monitoring system. For the turbidity control, a 10 μm order cartridge filter was used to clean the rig water through the feed and bleed system. Proper chemical treatment was performed for maintaining the appropriate pH level. Dissolved oxygen was controlled using the steam deaerator in the feed and bleed system.

4. TEST RESULTS AND DISCUSSION

4.1 Measurements and Inspections

During the test, the dimensions and fretting wears of three inlet bundles were carefully measured and inspected at each interval of the test runs (500 and 1000 hour test run). Prier to and at the completion of the test, the dimensions and fretting wears of all the bundles (bundle #1 to #8) were fully measured and inspected.

The following measurements and inspections were made on test bundles (bundle #1 to #8).

· Bearing pad heights and surface profiles

- Gap distances at the outer inter-element spacers
- Element lengths including both end plates
- End plate profiles for both ends
- Element bows from end to end

Also, the following inspections were made on the inner surface of the pressure tube.

- Videoscope inspections
- Inspections of the casting for the fret marks at the locations of the bundle bearing pads

4.2 Wear Marks on Bearing Pad

At the completion of the 3000 hour test, all the test bundles were carefully examined to look for fret marks on the bearing pads. Observations of the bearing pad wear were recorded with wear maps, photographs and castings(Figure 4).

On bundle #1 (KF9601), the maximum decreases of the pad heights occurred on elements #13, #14 and #21. The element #13 and #14 are not in the range of contacting area with pressure tube. Therefore, these bearing pad wear marks were mainly due to sliding during loading and unloading. In the case of element #21, the fret wear marks on the middle plane pad were slightly larger at both ends, approximately 5.0 mm x 2.1 mm. The position of element #21 in the pressure tube was between 3 and 4 o'clock which is above the range covered by the casting, unfortunately. Careful inspection of corresponding position of element #21 in the pressure tube was done by using videoscope for getting the information of wear mark depth. The size of the wear marks corresponding to the middle plane of the element #21 in the pressure tube was measured as 4.0 mm x 1.5 mm at both ends. From the evaluation of the mass loss, the decrease of the pad height was calculated as 0.065 mm. This is close to the data from the direct measurement, 0.067 mm, and is quite small when compared to the 37-element data. Also, the depth of the wear marks equivalent to the mid-plane of element #21 in the pressure tube were deduced to be 0.033 mm from the size observed with the videoscope. This amount is also far below the acceptance criterion limit in the pressure tube.

On other test bundles, there were also many decreases of the pad heights. Comparing with the casting of the corresponding position of the pressure tube, there were just small fret marks at several positions which are equivalent to the bearing pads. All the decreases of these pads are not significant and did not affect the pressure tube.

Average fretting wear of all 21 elements on each three positions of eight test bundles are shown on Figure 5, and also the average fretting wear of the maximum wear of each elements on eight bundles are shown on Figure 6.

For the inlet three test bundles, there are a series of bearing pad wear data as including two sets of measurement data on intermediate test run with the measurement data prior to and after completion of the test. Careful data sorting was done for getting the consistent information among the database which contains the relatively large measurement errors comparing small magnitude of fretting wears on the intermediate test run. Figure 7 shows the development of the fretting wear on the inlet three bundles. In this figure, the rate of fretting wears was relatively high up to 1500 hours after the beginning of the test and thereafter the rate was decreased markedly. This is supposed to occur because the bearing pads do not make complete contact with the inner wall of the pressure tube at first. As wear proceeds, however, local asperities are worn off first and there is a large increase in contact area. These effects greatly reduce the apparent fretting rate during the first few thousand hours. Figure 8 describes the polynomial extrapolation of the fretting wear with the average fretting wear development data and its correlation is as follows.

$$Y = 0.0003\, X^{0.5905} \qquad (1)$$

where, X is reactor normal operation time(hour) and Y is fretting rate(mm) of bearing pad. It shows that the average wear magnitude of the bearing pad is around 0.067 mm at the end of the fuel lifetime (9600 hour), which is fairly small.

4.3 Spacer Wear of Outer Elements

Spacer wear amounts of the outer elements are measured using thickness gauge. The maximum and average fretting wear of the outer spacers after the test are 0.160 mm and 0.048 mm, respectively (Figure 9). This maximum fretting wear of outer spacer is far below the acceptance criterion.

Similar to the case of bearing pads, rapid wear development on the spacers of the fuel elements tends to occur at the beginning period of the test. This is due to the imperfection of the contact between adjacent spacer surfaces at the beginning. For the inlet three test bundles, also there are four sets of data including two data sets of intermediate test run which can provide the information of the fretting rate of spacer wear. But there are some inconsistent measurement data of intermediate test run (after 1500 hour from the beginning of the test) comparing the other measurement data sets and these were omitted from evaluation the fretting rate. From the averaged spacer gap data of each 21 elements for three inlet bundles, the consistent data which can represent the historical trends were sorted and averaged. Figure 10 shows the fretting wear development of the three inlet test bundles and from this figure it can be concluded that the high fretting rate occurs during the beginning of the test. Figure 11 shows the polynomial extrapolation of the average spacer fretting wear up to fuel bundle lifetime from the average fretting wear development of three inlet bundles and its correlation is as follows.

$$Y = 0.0048\ X^{0.3004} \quad (2)$$

where, X is reactor normal operation time(hour) and Y is fretting rate(mm) of spacer. The extrapolated spacer fretting wear (0.075 mm) is far below than the acceptance criterion.

4.4 Fretting Wear of Pressure Tube

At the completion of the endurance test, the videoscope inspections were performed carefully and castings were taken from all the positions of bearing pad positions on the inner wall of the pressure tube. There was a noticeable fret mark on the inner wall of 3:30 o'clock position at the location of bundle #1 as discussed in section 4.2 (Figure 4). Several fret marks were seen on the castings at the inlet three bundle positions and no fret marks were found on other castings. The fret marks on the castings were measured by using the laser profilometer and the measurement surface roughness(10 μm) on the inner wall of the pressure tube. These values are within the acceptance criterion for this test.

4.5 Other Measurements

For supplementary assurance of the fuel bundle integrity, the measurements of the element lengths, end plate profiles and element bows of the test bundles were performed for all eight bundles at the end of the test including for three inlet bundles at each test runs. From the data of the element lengths at the completion of the test, many of the elements were lengthened comparing to the beginning of the test. The average length changes of the inlet three bundles along the test runs are in Figure 12 and shows the gradual increase of the element length. This might have been caused by the tendency of the elements which were restricted excessively at the manufacturing stage, and became straight after being exposed to high temperature during the test.

The end plate profiles of the bundles at the end of the test were evaluated in terms of the waviness and showed the changes of the waviness were within the magnitude of 0.38 mm (maximum change). Figure 13 shows the changes of the average waviness of the inlet three bundles at marked and plain end. There is no monotonic dependency of the waviness of the bundle along the test runs.

The maximum bow of each element of the bundles were evaluated from the bow data. As can be seen from the Figure 14, there were no remarkable changes of bows in bundles after the test. Also, the bows on inlet three bundles with intermediate bow data have no remarkable time dependency as shown in Figure 15.

CONCLUSION

The 3000 hour endurance test for the verification of the CANFLEX fuel bundle was performed successfully. It was checked whether the test results of measurement parameters satisfied the design limit criteria. The historical trends of fretting wears of bearing pads, spacers and pressure tube were evaluated with the test results including the laser measurement data of bearing pad and pressure tube castings. And also the geometrical configurations of the bundles were surveyed along the test runs. The following conclusions are made from the analysis of the test results.

(1) The rate of fretting wear on bearing pads was relatively high after the beginning of the test and thereafter the rate decreased markedly. The fretting wears of bearing pads were very low at the completion of the test and satisfied the acceptance criterion.

(2) The rate of spacer wear of outer elements was relatively high after the beginning of the test and thereafter the rate decreased markedly. The spacer wears were very low at the completion of the test and satisfied the acceptance criterion.

(3) A few witness marks were found at inlet region of the pressure tube and depths of fretting wear are as small as the order of the scratched surface roughness of the pressure tube.

(4) The configurational variations of test bundles in terms of the element lengths, end plate profiles and element bows were very small or even had no monotonic trends along the test. The overall integrities of bundles were maintained during the test.

Acknowledgement

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References

(1) C. H. Chung, S. K. Chang, H. C. Suk, P. Alavi and I. E. Oldaker, "Performance of the CANFLEX fuel bundle under mechanical flow testing", Proceedings of the 5th International Conference on CANDU Fuel, Vol.1, pp.10-69, September 21-25 1997, Toronto, CANADA

(2) W. W. R Inch, P. Thompson and H. C. Suk, "CANFLEX from Development Concept to a

Proven Fuel", Presented at the 13th KAIF/KNS Annual Conference, Seoul, Korea, 1998 April 15-16

Table 1 Test bundle identifications on fretting endurance test

Flow → Inlet Outlet

Bundle No.	1	2	3	4	5	6	7	8	9	10	11	12
500 hour Test Run	KF9601	KF9602	KF9604	KF9605	KF9606	KF9603	KF9607	KF9608	KF9609	KF9610	KF9611	KF9612
1000 hour Test Run	KF9601	KF9602	KF9604	KF9605	KF9606	KF9603	KF9607	KF9608	KF9609	KF9610	Spacer1	
1500 hour Test Run	KF9601	KF9602	KF9604	KF9605	KF9606	KF9603	KF9607	KF9608	Spacer2		Spacer1	

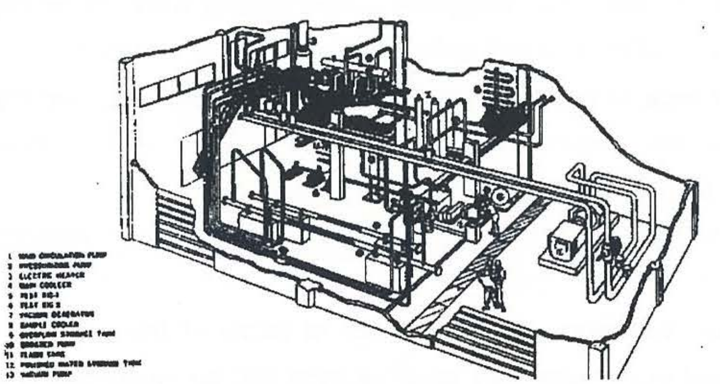

Figure 1 Layout of the CANDU Hot Test Loop facility

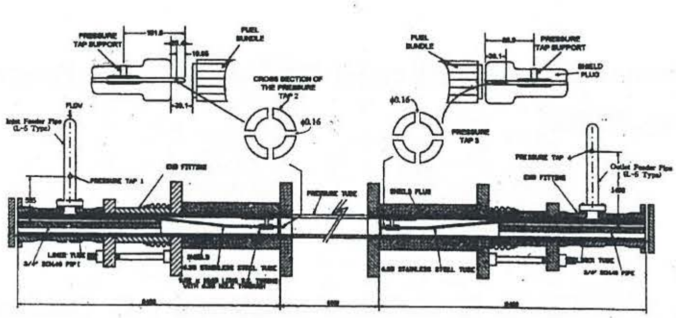

Figure 2 Test rig (CANDU type) for endurance test

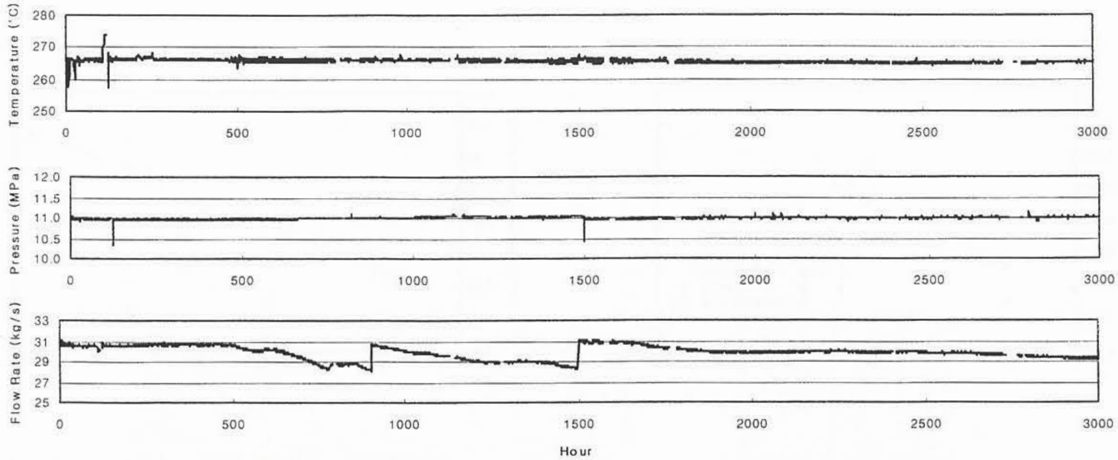

Figure 3 The historical trends of the loop parameters during the test

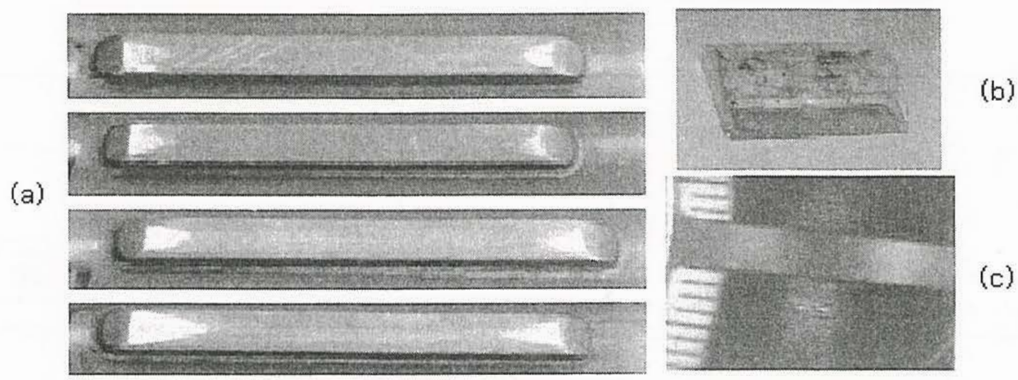

Figure 4 Fretting wears on bearing pads and inner surface of the pressure tube
(a) Wear marks on bearing pads
(b) Fret mark on the inner surface of the pressure tube
(c) Printed fret mark on the casting

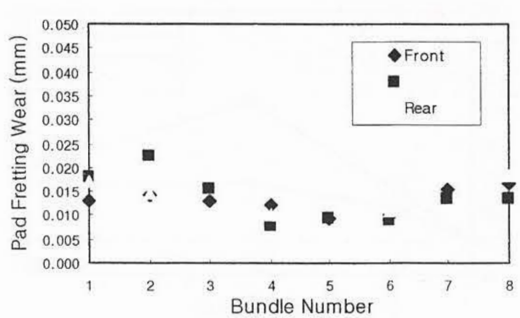

Figure 5 Average fretting wears of bearing pads at three positions of eight bundles

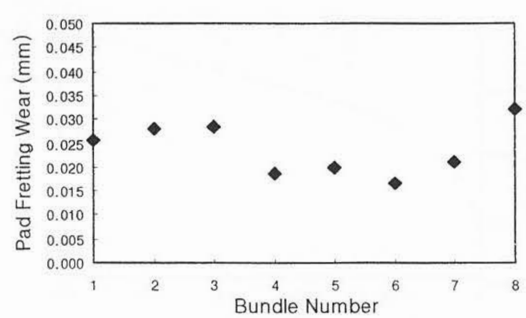

Figure 6 The maximum pad wear of each elements on eight bundles

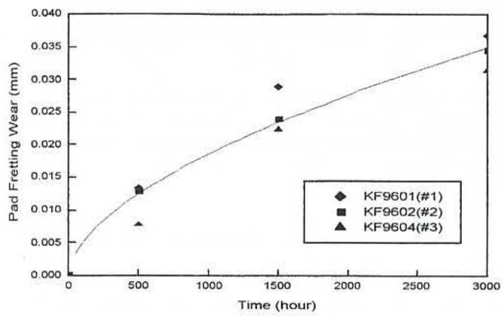

Figure 7 Development of the fretting wears of bearing pads on the inlet three bundles

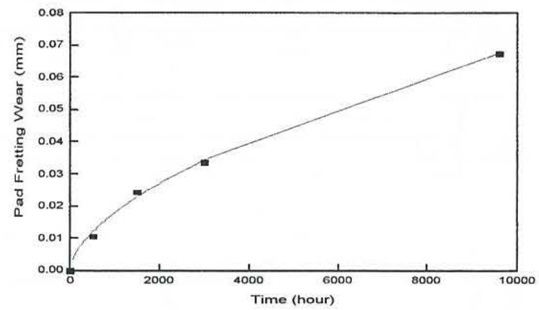

Figure 8 Extrapolation of the average fretting wear development of bearing pads

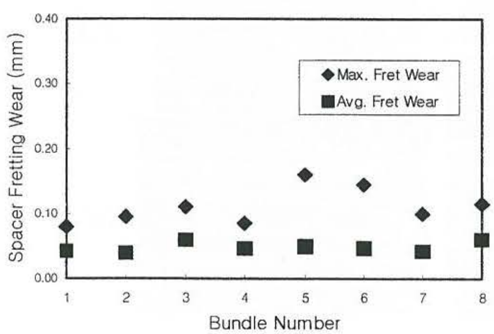

Figure 9 The maximum and average spacer Fretting wears of each bundles

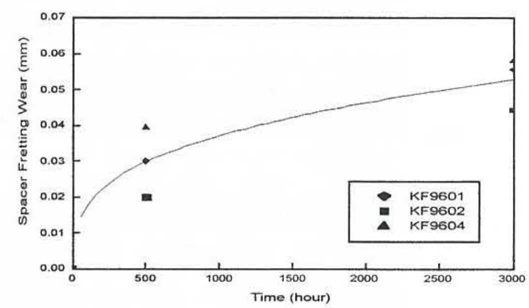

Figure 10 Development of the spacer fretting wears of the inlet three bundles

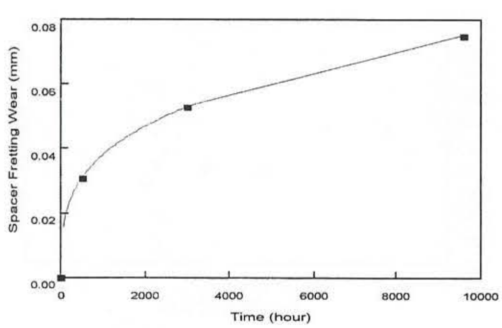

Figure 11 Extrapolation of the average spacer fretting wear development

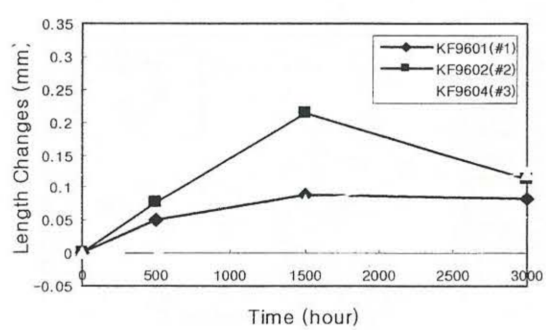

Figure 12 Development of the average element length changes of the inlet three bundles

(a) Marked side

(b) Plain side

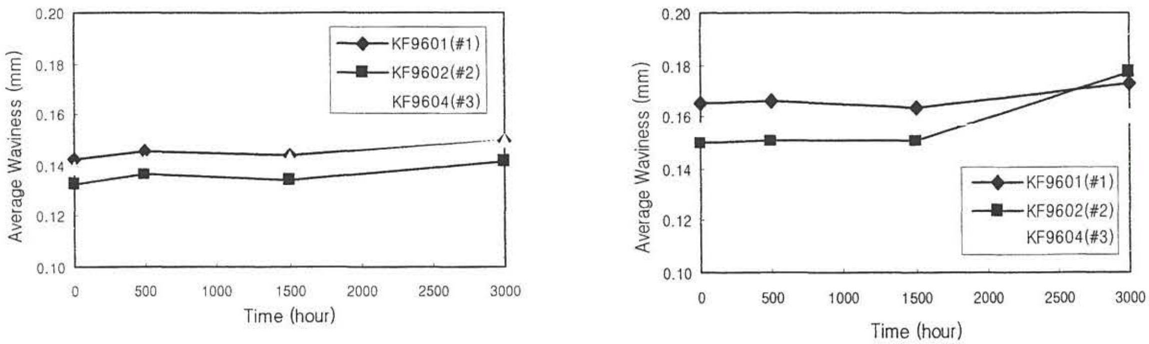

Figure 13 Development of the average waviness of the inlet three bundles

(a) X-direction

(b) Y-direction

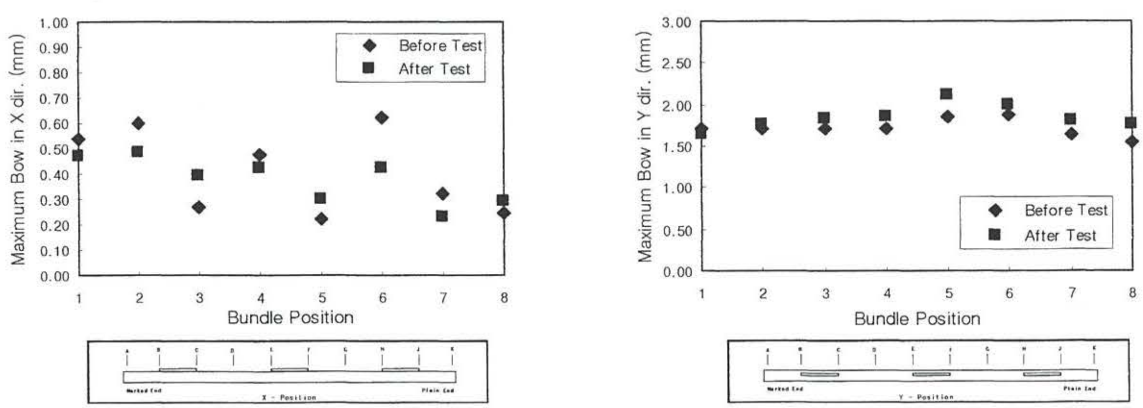

Figure 14 Maximum bows of the eight bundles

(a) X-direction

(b) Y-direction

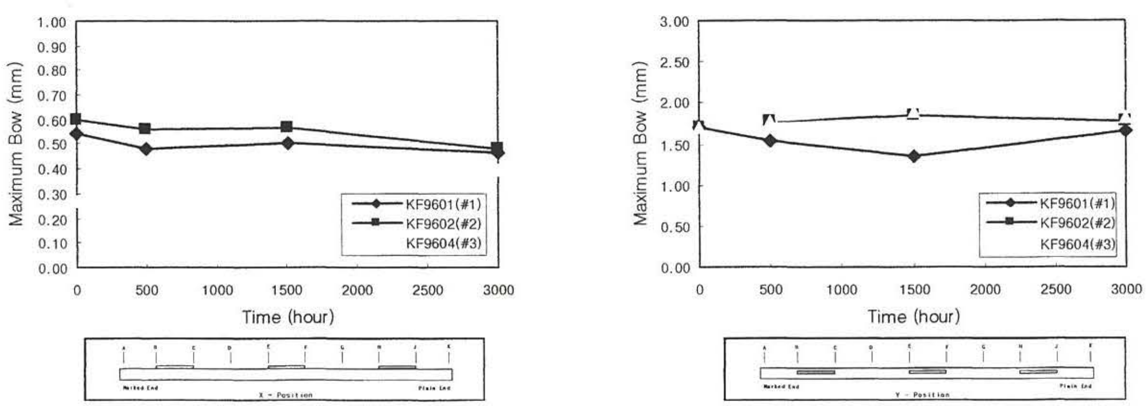

Figure 15 Development of the maximum bows on inlet three bundles