An In-Bay Equipment For The Visual And Dimensional Inspections Of CANDU Fuel Bundles

M. S. Cho[(1)], C.K. Jo[(1)], D.S. Gu[(1)],
K.J. Park[(1)], J. S. Jun[(1)], J. Y. Jung[(1)], H. C. Suk[(1,2)]

[(1)] Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Daejon City, 305-600, Korea (R.O.K.)
[(2)] New address: Canadian Nuclear Safety Commission, P.O. Box 1046, Station B, 280 Slater St., Ottawa, Ontario, Canada, K1P 5S9; sukhc@cnsc-ccsn.gc.ca

ABSTRACT

KAERI developed the equipment for the precise inspections of visuals and dimensions of CANDU existing and advanced fuel bundles in spent fuel storage water-bay as well as in-air by using the remote control systems of a radiation resistance under-water TV camera and eleven LVDTs. The LVDT sensors are calibrated with a standard drum bundle which is equipped with one step motor for the rotation of the calibration disk and one linear actuator. The disk and actuator calibrate the LVDT sensors for the measurements of radial displacements and endplate waviness, respectively. The LVDT axial moving and rotational systems are calibrated with three standard drum bundles. All standard drum bundles used in this work were calibrated with a standard-equipment approved by Korean Standard Bureau. The 7th and 9th order linear polynomial functions are introduced in the calibrations of each LVDT sensor and each system of LVDT axial moving and rotational structures, respectively. The measurement accuracy of the in-bay inspection equipment in a water-pool bay was found to be 0.01 mm (10μm) as a maximum measurement error. As a commissioning test, the in-bay inspection equipment was successfully operated for the visual and dimensional measurements of the 8 37-element bundles irradiated normally in the two phase flow region of a three high power channels and one low power channel of Wolsong PGS Unit 3.

1. INTRODUCTION

Korea Institute of Nuclear Safety (KINS) reviewed the Final Safety Report of Wolsong Power Generating Stations (WPGSs) 2, 3 and 4 [1] in around 1997 and then, as one of the findings, requested the experimental evidence or evaluation of channel and fuel bundle integrities with respect to the wears of the pressure tube inside surface and bearing pad surfaces of fuel bundles placed in the two phase flow region of the fuel channels with the coolant flow rate above 24 kg/sec. The two phase flow may induce dynamic fluid force that causes structural vibration. This vibration may result in failures of components due to the fretting wear and the fatigue. Issuing the possibility of fuel failure by KINS, Korea Atomic Energy Research Institute (KAERI) had performed, as one of 2002-2004 Korea National Nuclear R & D programs, (i) the irradiation of test fuel bundles in WPGS-3 reactor, (ii) visual and dimensional measurements of the fresh and spent fuel bundles, (iii) fuel channel inspection by CIGAR and (iv) the reactor operational data analysis with respect to the fuel irradiation and the degree of fretting wears of the fuel bundle's bearing pads and the pressure tube inside surface, where the visual and dimensional measurements of the spent fuel bundles and CIGAR inspection after the irradiation would be performed in the period of 2005 to 2007 years. Whereas, KAERI developed a precise equipment to conduct the visual and dimensional inspections of CANDU fuel bundles in the bay as well as in air.

This paper describes the in-bay inspection equipment, the calibration of the in-bay inspection system as well as the calibration of Linear Variable Differential Transformers (LVDTs) for the dimensional measurements, the accuracy of the dimensional measurements by the in-bay inspection system, and the commissioning test of the in-bay inspection equipment with the irradiated fuel

2. OUTLINE OF THE IN-BAY INSPECTION EQUIPMENT

The in-bay equipment for the visual and dimensional inspections of CANDU fuel bundles consists of two parts of the in-bay system (see Figure 1) and the control system (see Figure 2).

The control system of the in-bay equipment consists of two functional racks which shall be placed at the out-of-water pool: one is the remote control system for the under-water TV camera (Imaging & Sensing Technology Ltd, UK, Model: R-981) and the other is the remote control and data processing system for the in-bay LVDTs (RDP Electronics Ltd, UK, Model: D5/200AW; stroke of ± 5mm, Non-linearity of 0.25%/F.S., 0~2.4V DC output) dimensional measurement system. All LVDTs of the in-bay inspection equipment can be operated under water conditions by remote control. Figure 3 shows the main program screen of the control system.

The in-bay system of the in-bay equipment consists of two functional devices which can be placed in the water-bay. One of the devices is the radiation resistance under-water TV camera to do the visual examination of bundle and bundle components such fuel sheath, endcaps, endplates and appendages as shown in Figure 1. The TV camera is placed in front of the place of fuel bundle in the in-bay system to be inspected. The four servo motors are able to move the TV camera in the X-Y plane and to rotate in X-Y and Y-Z planes. So the TV camera can catch the visual of bundle surface along the axis and also the visual of the bundle endplate. The other device consists of two components: One is the rotator of the bundle placed on the underpinning and the other is the system of 11 LVDTs for the dimensional measurements of bundle diameter, element axial profile, endplate waviness profile. Where the 8 LVDTs of them measure the waviness profiles of both endplates and the length of bundle by placing 4 LVDTs on each endplate side, where 1 servo motor on each endplate side is able to rotate the 4 LVDTs. By using 1 servo motor, the 2 LVDTs of them measure axial profiles of bundle and elements, which contain the bearing pad wear and element bow. And one of the LVDTs identifies the bundle rotational position.

The LVDT sensors for the dimensional measurements are calibrated a standard drum bundle having one step motor and one linear actuator as shown in Figure 4. The step motor rotates a calibration disk by every 8.65° and so the radius of this calibration disk increases by every 1.0 mm to calibrate the two LVDT sensors for the radial displacement measurements of bundle diameter and element axial profile. The linear actuator moves forward a plunger plate by every 1.0 mm to calibrate the LVDTs for the measurement of endplate waviness. As shown in Figure 5, one aluminium master and two SUS 303 masters as the standard drum bundles were made for the calibrations of endplate waviness and element axial profile measurement systems, respectively, where one of two SUS30 master is called as “CANDU 37-element fuel master” simulated for CANDU-6 37-element fuel bundle design and the other is called as “CANFLEX fuel master” simulated for CANDU-6 CANFLEX Mk IV fuel bundle design. Each side plane of CANDU 37-element or CANFLEX fuel master has two groves of 1 mm and 1.2 mm depths. The CANFLEX 37-element or CANFLEX fuel master has also the circumferential grooves of 1.0 mm, 1.4 mm and 1.0 mm depths at three plane of CANDU 37-element or CANFLEX fuel master as shown in Figure 5. Also the aluminium master calibrates the bundle length. The calibration disk, the linear actuator and the three standard drum bundles were calibrated with the standard equipment approved by Korea Standard Bureau.

As shown in Figure 1, an electrical junction box in the in-bay system is made to connect all signal and electrical cables between the in-bay system and the control racks. The inside junction box is designed to have the air pressure which is always maintained slightly higher pressure than the water pressure to prevent water leak into the inside box. During the operation of the in-bay inspection equipment under water conditions, the water temperature and pressure are also always monitored.

3. CALIBRATIONS OF LVDT SENSORS AND IN-BAY SYSTEM

The calibration of the current in-bay inspection equipment is conducted with respect to the LVDT reading itself and the substructure of the in-bay system as detailed below.

3.1 LVDT Calibration

The calibration of LVDT reading is the calibration of LVDT signal voltages against standard displacements by using the calibration disk and linear actuator as mentioned in the previous Section 2, which is referred to "LVDT Calibration." The signal output voltages of the two LVDT sensors for the measurements of the axial element and bundle profiles are calibrated with the calibration disk for a given axial displacement position. The signal output voltages of the 4 LVDT sensors for the waviness measurements of each endplate are calibrated with the linear actuator for a given rotational angle of the LVDT sensors. As an example, Table 1 shows the LVDT signal output voltages and the displacements of the calibration disk, which can be correlated optimistically with a 7^{th} order linear polynomial function:

$$y_i = \sum_{i=0}^{7} a_i x^i$$

where y_i is the displacement (mm), x_i is the LVDT output signal voltage (V) for a given signal i, a_i as shown in Table 2 is the coefficients for a given signal i. The maximum error of the correlation is 0.004 mm (4μm) as shown in Table 3.

3.2 In-Bay System Calibration

After the LVDT calibrations, it should conduct the structure calibration which is divided into two calibrations, which is referred to "In-bay System Calibration.": One is the displacement calibration of axial moving structure of the two LVDT sensors for the measurement of bundle and element axial profiles against the axial displacement of the standard drum bundles mentioned in the Section 2, and the other is the rotational structure calibration of the four LVDE sensors for the measurements of each endplate waviness profiles against the end plane of the aluminum master.

If the aluminum master is placed on the underpinning of the in-bay system, the rotational profile of LVDT sensors for the measurement of the endplate waviness can be calibrated against the end plane of the aluminum master. The maximum surface roughness of the end plane of the aluminum master is 1 ~ 2μm, which was measured by one branch of Korean Standard Bureau. As an example, Figure 6 shows the rotational profile of one end-plane of the aluminum master. Also this figure shows the maximum displacement error of about 0.015 mm. The system of the LVDT rotational structure can be made as a function of the rotational angle. As the function of the rotation angle, the end plane surface roughness of aluminum master can be optimistically correlated with the LVDT measured surface roughness:

$$y_i = \sum_{i=0}^{9} a_i \, x^i$$

where y_i is the displacement (mm) for a given rotation angle i, x_i is the displacement measured by LVDT for the angle i, a_i is the coefficients for the angle i. Using this 9th order linear polynomial equation, the measurement error of the LVDT rotational system would be reduced up to ±0.005 mm as shown in Figure 7.

The system of the LVDT axial moving structure can be made as a function of the axial displacement of LVDT axial moving structure of the in-by system. Figure 8 shows an axial profile of the CANDU 37-element fuel master placing on the underpinning of the in-bay system, which is axially scanned by one of the two LVDTs for the measurement of bundle or axial profile. The axial profile shown in Figure 8 is calibrated to be the profile as shown in Figure 9 by using also the 9th order linear polynomial equation.

3.3 Measurement Accuracy of the In-Bay Inspection Equipment

The in-bay inspection equipment measures the endplate profiles, the axial displacement profiles, bundle diameters, and bundle lengths of both the CANDU 37-element and

CANFLEX fuel masters in a water bay as shown in Tables 4 to 8, respectively. In these Tables, the values measured by the Korea standard equipment mentioned in the previous Section 2 are contained to evaluate the measurement accuracy of the equipment.

Reviewing Tables 4 and 5 on the accuracy of endplate waviness measurement, the maximum difference between the in-bay inspection equipment measurement and Korea Standard Bureau measurement is found to be 0.0077mm.

Tables 6 and 7 show the accuracy of axial displacement measurements including the axial profiles of element bows and axial profiles of bearing pad heights. They indicate that the maximum difference between the measurements of the in-bay inspection equipment and Korea Standard Bureau is 0.010 mm.

Table 8 shows the accuracy of fuel bundle diameter and length measurements and indicates that the maximum difference between the measurements of the in-bay inspection equipment and Korea Standard Bureau is 0.011 mm.

4. IN-BAY INSPECTION OF IRRADIATED 37-ELEMENT BUNDLES WITH THE IN-BAY INSPECTION EQUIPMENT

As a commissioning test, in October 11, 2004, the in-bay inspection equipment was operated at the spent fuel reception bay of Wolsong Power Generation Station (WPGS) Unit 3 to conduct the visual and dimensional inspections of 8 37-element fuel bundles irradiated in the 11^{th} and 12^{th} channel positions (two phase flow region) of G13, Q15 and O07 high power channels and D06 low power channel. The fuel bundles were manufactured and supplied by Korea Nuclear Fuel Cooperation (KNFC) and normally discharged from the core at the same day of April 22, 2204.

As an example of visual examination results, Figure 10 shows the endplate integrity of B226772 fuel bundle irradiated in WPGS-3 O07 high power channel. Figures 11 and 12 show the axial profiles and the permanent bow of outer elements of B226772 fuel bundle, respectively. Figures 13 and show the endplate waviness and the fuel element lengths over endplates of B226772 fuel bundle, respectively.

These results indicate that the measured heights of bearing pads are in the range of

1.2098 mm to 1.3582 mm, which is comparable with the maximum design height of 1.385 mm. The bowings of the irradiated fuel elements are generally greater than those of the non-irradiated fuel bundle. However, the "S" shape bowing is not appeared in all the irradiated bundles inspected at this time.

5. SUMMARY AND CONCLUSIONS

KAERI developed the equipment for the precise inspection of visuals and dimensions of CANDU fuel bundles in a spent fuel storage water-pool bay or in air. The equipment is assembled with a radiation resistance under-water TV camera for the visual examination of CANDU fuel bundle and bundle components, where the camera can be moved in the X-Y plane and also rotated in X-Y and Y-Z planes. The test bundle can be rotated by using a system of under-water electric motor. The bundle dimensions such as axial profiles of elements, bundle diameter, element length over endplates, and endplate waviness can be measured precisely by using eleven LVDTs.

The LVDT sensors are calibrated with one standard drum bundle which is equipped with one step motor for the rotation of a calibration disk and one linear actuator. The disk and actuator calibrate the LVDT sensors for the measurements of radial dimensions and endplate waviness, respectively. The axial moving and rotational displacements of LVDT systems are also calibrated with three standard drum bundles. All standard drum bundles used in this work were calibrated with a standard-equipment approved by Korean Standard Bureau. The 7^{th} and 9^{th} order linear polynomial functions are introduced in the calibrations of each LVDT sensor and each system of LVDT axial moving and rotational structures, respectively. The measurement accuracy of the in-bay inspection equipment in a water-pool bay was found to be 0.01 mm as a maximum measurement error.

As a commissioning test, the in-bay inspection equipment was successfully operated for the visual and dimensional measurements of the 8 37-element bundles irradiated in the two phase flow region of three high power channels and one low power channel of Wolsong PGS Unit 3.

ACKNOWLEGEMENT

This work has been carried out under the Mid- and Long-Term Nuclear R & D Programs pushed by the Korea Ministry of Science and Technology

REFERENCES

[1] "Final Safety Report of Wolsong Power Generating Stations 2, 3 and 4", Korea Electric Power Cooperation, 1996.

Table 1. LBDT Output Voltage (volts) vs. Korea Standard Bureau(KSB)'s Measured Values (mm)

LVDT Voltage (volt)	1.8807	1.7068	1.5332	1.3601	1.1868	1.0145
KSB's Value (mm)	0.0000	1.0055	2.0095	3.0100	4.0105	5.0120
LVDT Voltage (volt)	0.8416	0.6687	0.0470	0.3294	0.1747	
KSB's Value (mm)	6.0135	7.0160	8.0180	9.0195	10.0210	

Table 2. Coefficients of the 7th Order Linear Polynomial Function $y_i = \sum_{i=0}^{7} a_i x^i$

Coefficients	a_0 =11.36819	a_1 =-8.78401	a_2 =7.78905	a_3 =-10.8611
Coefficients	a_4 =8.71449	a_5 =-4.02281	a_6 =0.99184	a_7 =-0.10106

Table 3. Accuracy of the 7th Order Linear Polynomial Function (LPF) $y_i = \sum_{i=0}^{7} a_i x^i$

KSB Value (mm)	0.0000	1.0055	2.0095	3.0100	4.0105	5.0120
IBIE value (mm)	0.0000	1.0020	2.0080	3.0110	4.0110	5.0090
Δ =KSB-IBIE (mm)	0,0000	0.0035	0.0015	-0.0010	-0.0005	0.0030
KSB Value (mm)	6.0135	7.0160	8.0180	9.0195	10.0210	
IBIE value (mm)	6.0130	7.0190	8.0220	9.0210	10.0230	
Δ =KSB-IBIE (mm)	0.0005	-0.0030	-0.0040	-0.0015	-0.0020	

KSB value = The values measured by the Korea Standard Bureau's Equipment

IBIE value = The values measured by the current In-bay Inspection Equipment (IBIE)

Table 4. Measured Values of Endplate Groove Depths of CANDU 37-Element Fuel Master

Left Hand Side Endplate Grooves		Inner ring	Intermediate ring	Outer ring
1 mm Depth Groove	KSB Measured value (mm)	-0.9921	-0.9904	-0.9839
	IBIE Measured value (mm)	-0.9857	-0.9872	-0.9763
	Δ =KSB-IBIE (mm)	0.0064	0.0032	0.0076
2 mm Depth Groove	KSB Measured value (mm)	-1.9850	-1.9833	-1.9819
	IBIE Measured value (mm)	-1.9897	-1.9858	-1.9783
	Δ =KSB-IBIE (mm)	-0.0047	-0.0025	0.0036

Right Hand Side Endplate Grooves		Inner ring	Intermediate ring	Outer ring
1 mm Depth Groove	KSB Measured value (mm)	-0.9847	-0.9780	-0.9782
	IBIE Measured value (mm)	-0.9866	-0.9828	-0.9813
	Δ =KSB-IBIE (mm)	-0.0019	-0.0048	-0.0031
2 mm Depth Groove	KSB Measured value (mm)	-1.9839	-1.9720	-1.9738
	IBIE Measured value (mm)	-1.9833	-1.9665	-1.9715
	Δ =KSB-IBIE (mm)	0.0006	0.0055	0.0023

Table 5. Measured Values of Endplate Groove Depths of CANFLEX Fuel Master

Left Hand Side Endplate Grooves		Inner ring	Intermediate ring	Outer ring
1 mm Depth Groove	KSB Measured value (mm)	-0.9857	-0.9789	-0.9807
	IBIE Measured value (mm)	-0.9831	-0.9831	-0.9810
	Δ =KSB-IBIE (mm)	-0.0026	0.0042	0.0003
2 mm Depth Groove	KSB Measured value (mm)	-1.9792	-1.9752	-1.9746
	IBIE Measured value (mm)	-1.9830	-1.9794	-1.9823
	Δ =KSB-IBIE (mm)	0.0038	0.0042	0.0077

Right Hand Side Endplate Grooves		Inner ring	Intermediate ring	Outer ring
1 mm Depth Groove	KSB Measured value (mm)	-0.9807	-0.9664	-0.9666
	IBIE Measured value (mm)	-0.9849	-0.9736	-0.9714
	Δ =KSB-IBIE (mm)	0.0042	0.0072	0.0048
2 mm Depth Groove	KSB Measured value (mm)	-1.9801	-1.9662	-1.9649
	IBIE Measured value (mm)	-1.9775	-1.9660	-1.9583
	Δ =KSB-IBIE (mm)	-0.0026	-0.0002	-0.0066

Table 6. Measured Values of Circumferential Groove Depths of CANDU 37-Element Fuel Master

Axial Position (mm)	Angle Position						Remarks
	0º			90º			
	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	
7.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
64.0	-0.9910	-0.9940	0.0030	-0.9977	-0.9880	-0.0097	1mm groove
114.0	-0.0007	-0.0030	0.0023	-0.0003	-0.0080	0.0083	
227.0	-0.0012	-0.0070	0.0058	0.0000	-0.0100	0.0100	
247.65	-1.3950	-1.3980	0.0030	-1.3983	-1.3970	-0.0013	1.4mm groove
347.0	-0.0012	0.0020	-0.0032	0.0002	0.0000	0.0002	
449.0	-0.9970	-0.9910	-0.0060	-0.9987	-0.9920	-0.0067	1mm groove
477.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	

Axial	Angle Position		
	180º	270º	

Position (mm)	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	Remarks
7.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
64.0	-0.9974	-0.9910	-0.0064	-0.9948	-0.9990	0.0042	1mm groove
114.0	-0.0007	0.0020	-0.0027	-0.0012	0.0000	-0.0012	
227.0	-0.0008	0.0030	-0.0038	-0.0015	0.0020	-0.0035	
247.65	-1.3980	-1.4030	0.0050	-1.3980	-1.4040	0.0060	1.4mm groove
347.0	-0.0013	0.0000	-0.0013	-0.0017	0.0010	-0.0027	
449.0	-0.9975	-0.9960	-0.0015	-0.9969	-0.9930	-0.0039	1mm groove
477.65	0.0000	0.0030	-0.0030	0.0000	0.0030	-0.0030	

Table 7. Measured Values of Circumferential Groove Depths of CANFLEX Fuel Master

Axial Position (mm)	Angle Position						Remarks
	0º			90º			
	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	
7.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
64.0	-1.1088	-1.1050	-0.0038	-1.1092	-1.1050	-0.0042	1mm groove
114.0	-0.0020	0.0000	-0.0020	-0.0005	0.0010	0.0005	
227.0	-0.0011	0.0000	-0.0011	-0.0015	0.0030	0.0015	
247.65	-1.3988	-1.3900	-0.0088	-1.3987	-1.3950	-0.0037	1.4mm groove
347.0	-0.0015	0.0000	-0.0015	-0.0010	0.0030	0.0020	
449.0	-1.1135	-1.1080	-0.0056	-1.1102	-1.1130	0.0028	1mm groove
477.65	0.0000	0.0000	0.0000	0.0000	0.0010	0.0010	

Axial Position (mm)	Angle Position						Remarks
	180º			270º			
	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	KSB (mm)	IBIE (mm)	Δ=KSB-IBIE (mm)	
7.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
64.0	-1.1155	-1.1130	-0.0025	-1.1085	-1.1110	0.0025	1mm groove
114.0	-0.0020	0.0020	-0.0040	-0.0035	0.0050	-0.0085	
227.0	-0.0025	0.0000	-0.0025	-0.0045	0.0000	-0.0045	
247.65	-1.4032	-1.4070	0.0038	-1.3970	-1.4070	0.0100	1.4mm groove
347.0	-0.0040	0.0020	-0.0060	-0.0037	0.0010	-0.0047	
449.0	-1.1157	-1.1200	0.0043	-1.1087	-1.1170	0.0083	1mm groove
477.65	0.0000	-0.0010	0.0010	0.0000	0.0010	-0.0010	

Table 8. Measured Values of CANDU 37-Element and CANFLEX Fuel Masters' Diameters and Lengths

	CANDU 37-Element Fuel Master			**CANFLEX Fuel Master**			Remarks
	KSB (mm)	IBIE (mm)	Δ (mm)	KSB (mm)	IBIE (mm)	Δ (mm)	
D1	99.712	99.712	0.000	99.188	99.188	0.000	7.65 mm axial position from the left end
D2	99.722	97.728	-0.006	96.964	96.973	-0.009	54 mm axial position from the left end
D3	99.714	99.705	0.009	99.188	99.190	-0.002	152.65 mm axial position from the left end
D4	96.918	96.911	0.007	96.384	96.391	-0.007	247.65 mm axial position from the left end
D5	99.714	99.716	-0.002	99.189	99.189	0.000	342.65 mm axial position from the left end
D6	97.717	97.726	-0.009	96.956	96.961	-0.005	441.33 mm axial position from the left end

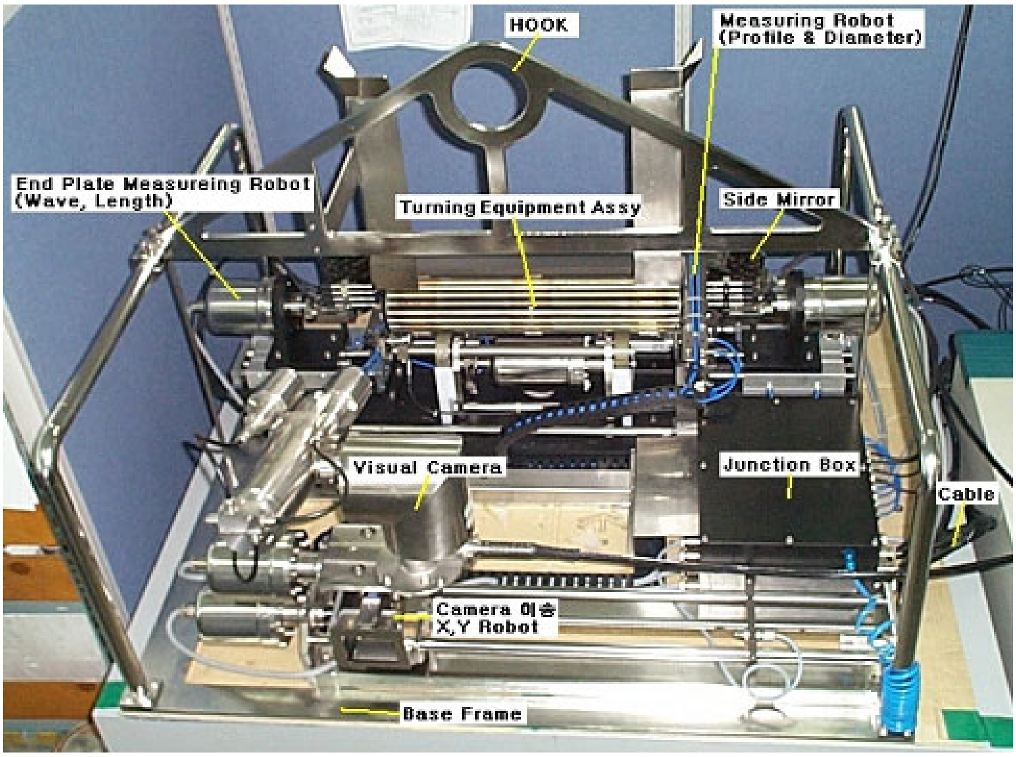
D7	99.713	99.712	0.001	99.199	99.188	0.011	487.65 mm axial position from the left end
L0	495.297	495.287	0.010	-	-	-	Center position
L1	495.284	495.288	-0.004	495.306	495.309	-0.003	43.3 mm radial position (at 180º position)
L2	495.282	495.283	0.000	495.313	495.310	0.003	28.765 mm radial position (at 180º position)
L3	495.383	495.287	-0.004	495.303	495.307	-0.004	14.86 mm radial position (at 180º position)
L4	495.285	495.288	-0.003	495.298	495.300	-0.002	43.3 mm radial position (at 260º position)

Di = Master diameter at the given position i

Li = Master length at the given position i

Δ=KSB –IBIE(mm)

Figure 2. In-Bay System of the In-Bay Inspection Equipment



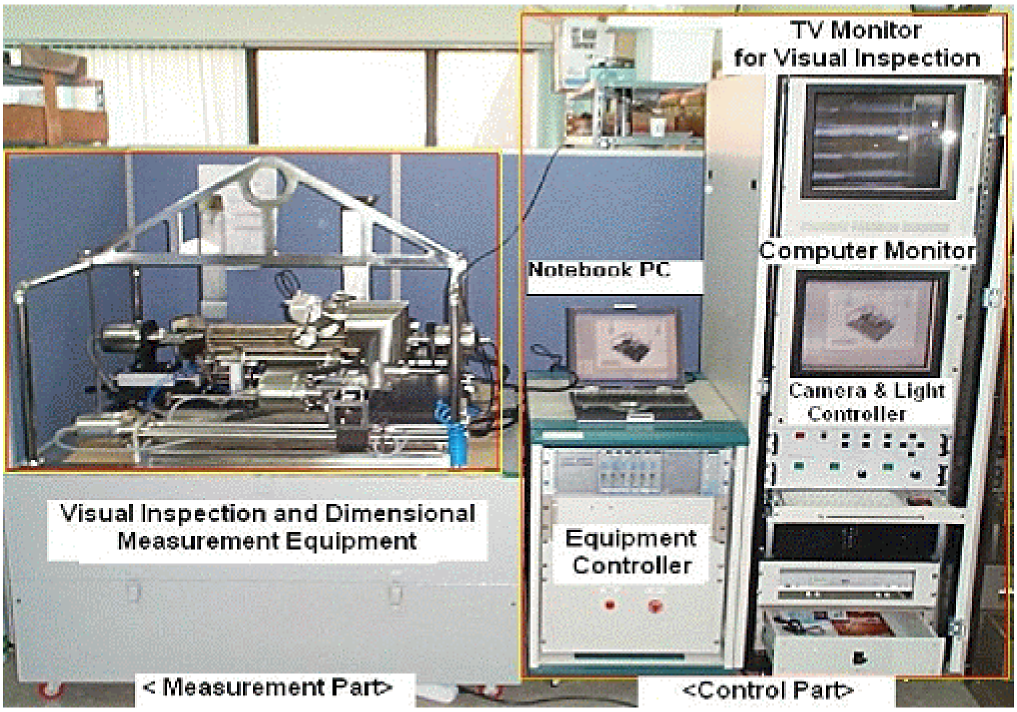


Figure 2. Overall Assembly of the In-Bay Inspection Equipment

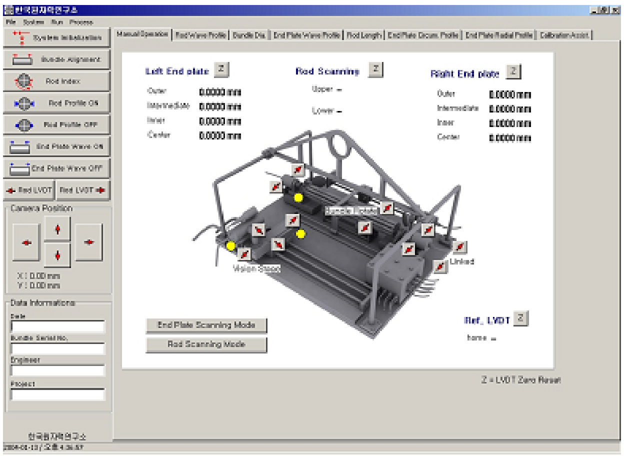


Figure 3. Main Screen of Executive Program for the In-Bay Inspection System

Figure 4. Standard Drum Bundle having One Step Motor and One Linear Actuator for the Calibration of LVDTs

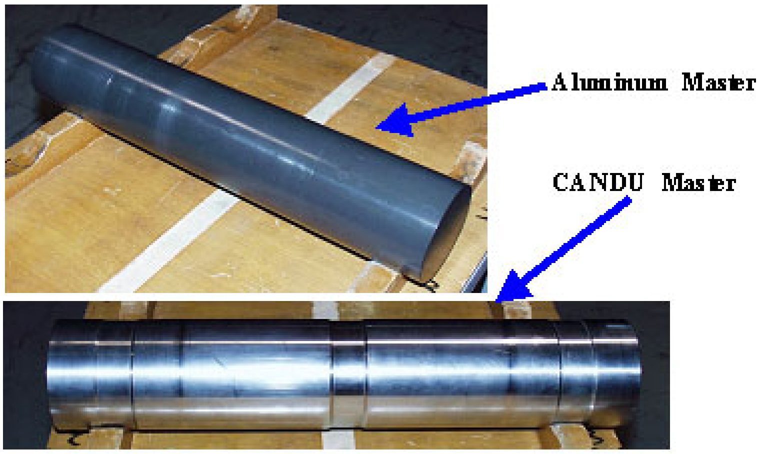


Figure 5. Aluminium Master and CANDU 37-Element Fuel Master

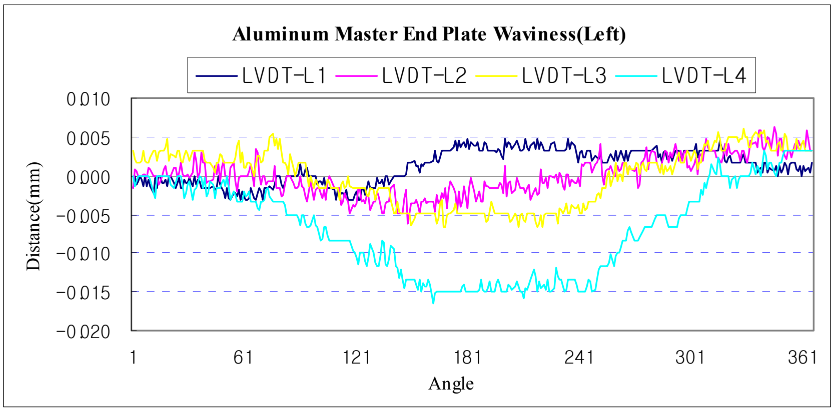


Figure 6. Waviness Profile of Left End Plane of Aluminium Master without the Calibration of the Rotational Structural-System

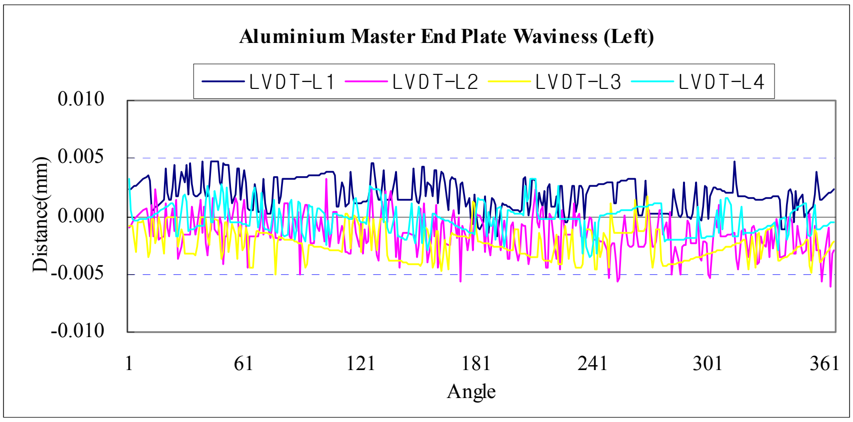


Figure 7. Waviness Profile of Left End Plane of Aluminium Master with the Calibration of the LVDT Rotational Structural-System

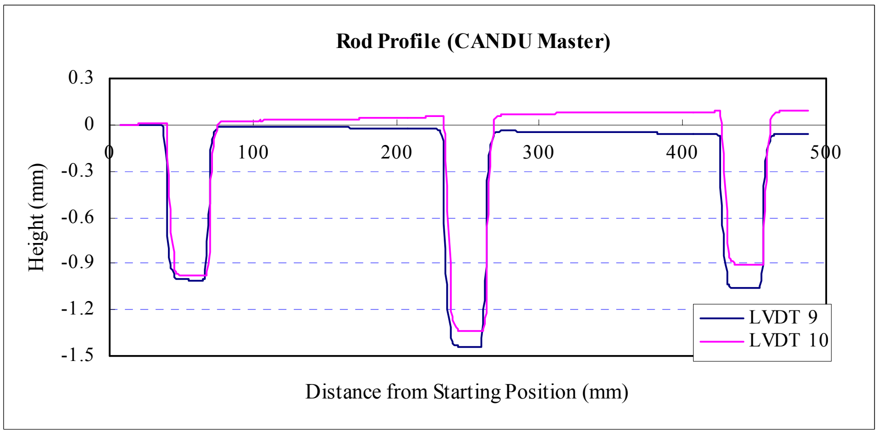


Figure 8. Axial Profile of CANDU 37-Element Fuel Master without the Calibration of the LVDT Axial Moving Structural-System

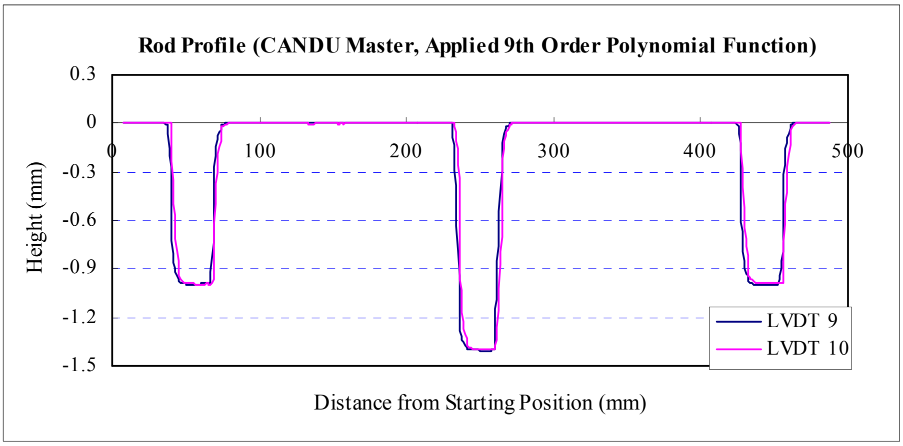


Figure 9. Axial Profile of CANDU 37-Element Fuel Master with the Calibration of the LVDT Axial Moving Structural-System

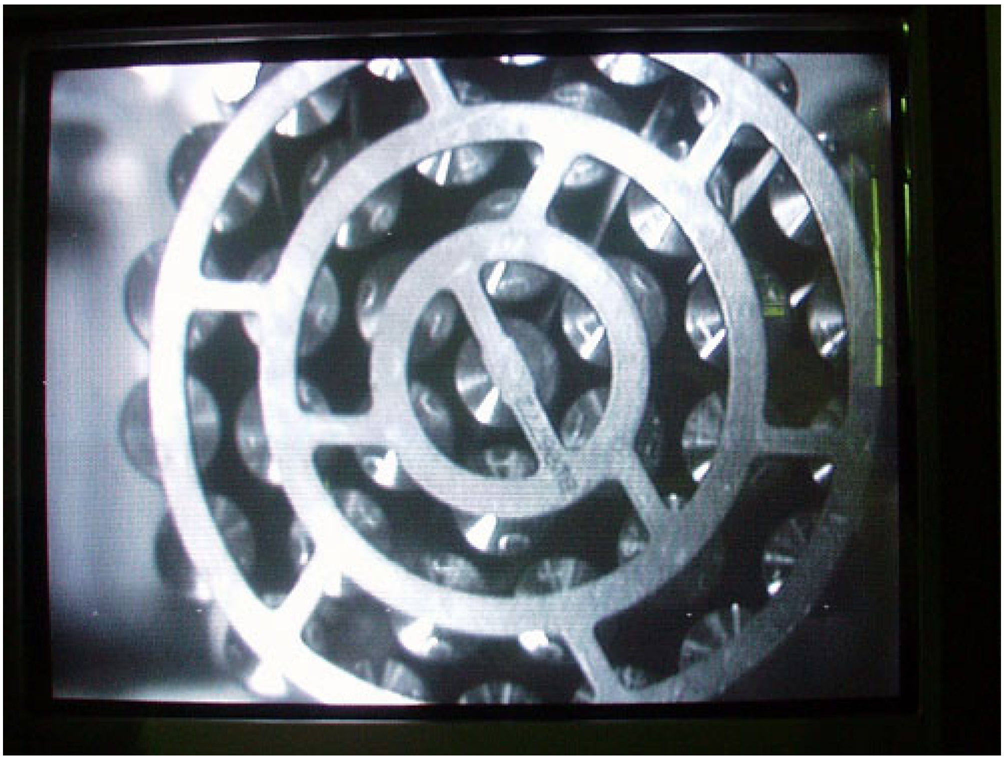
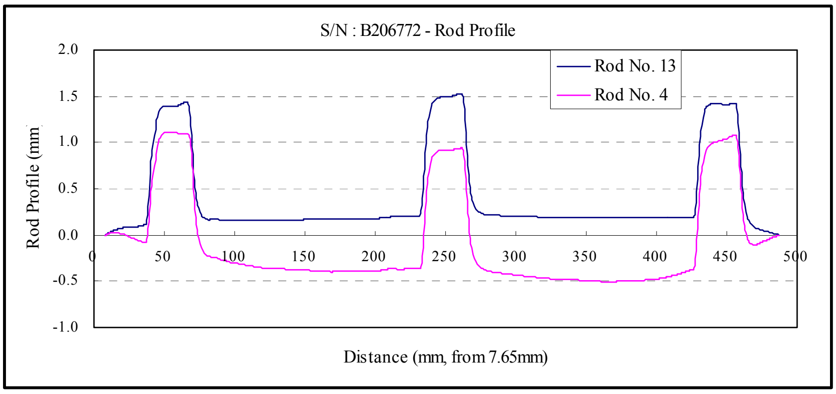


Figure 10. An Endplate Shape of the B206772 Bundle Discharged Normally from the O07 Channel of WPGS-3



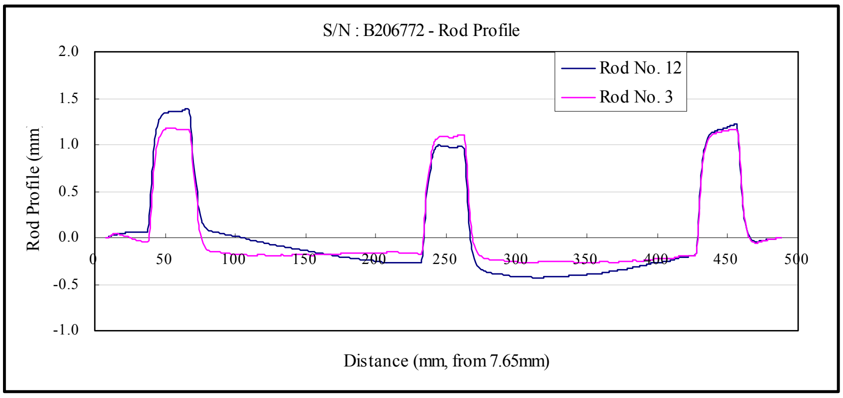


Figure 11. Axial Profile of Outer Element Bowings of the B206772 Bundle Discharge Normally from the O07 Channel of WPGS-3

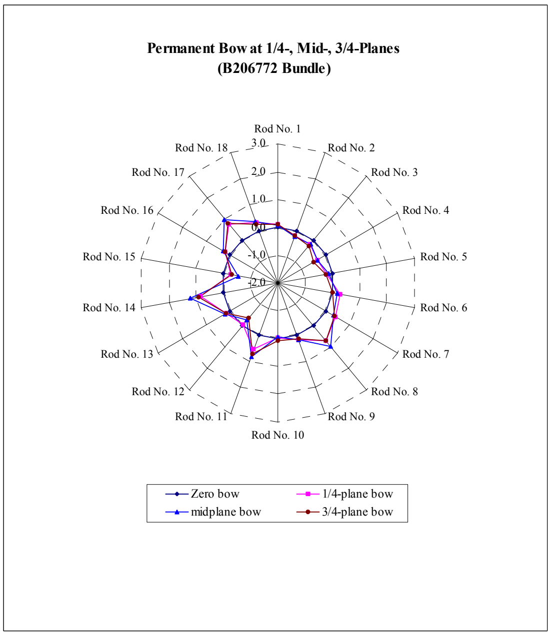
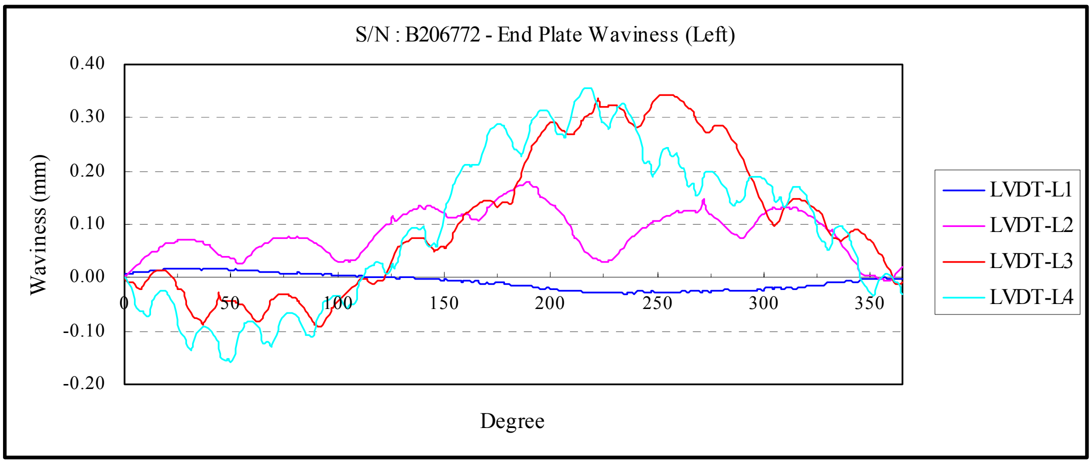


Figure 12. Radial Bundle-Profile of Outer Element Bowings of the B206772 Bundle Discharged Normally from the O07 Channel of WPGS-3



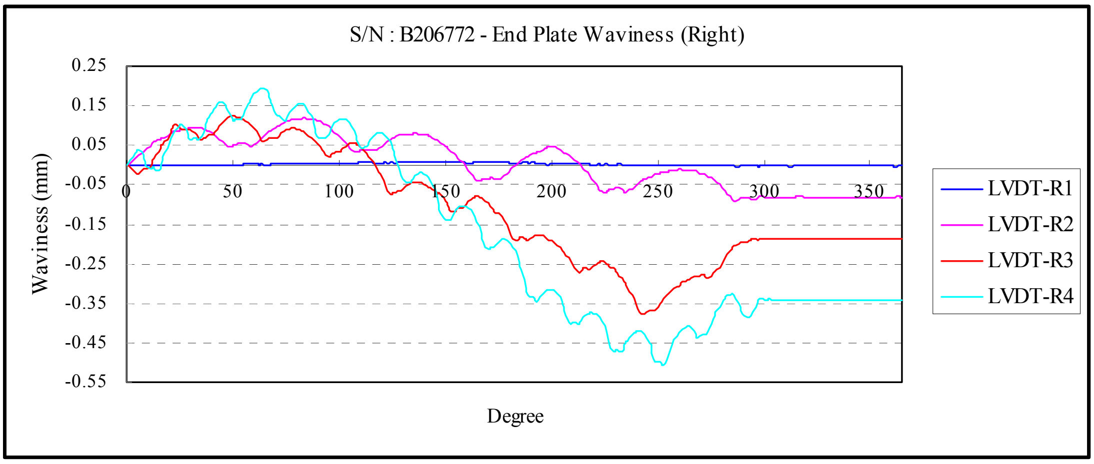


Figure 13. An Endplate Waviness Profile of the B206772 Bundle Discharge Normally from the O07 Channel of WPGS-3

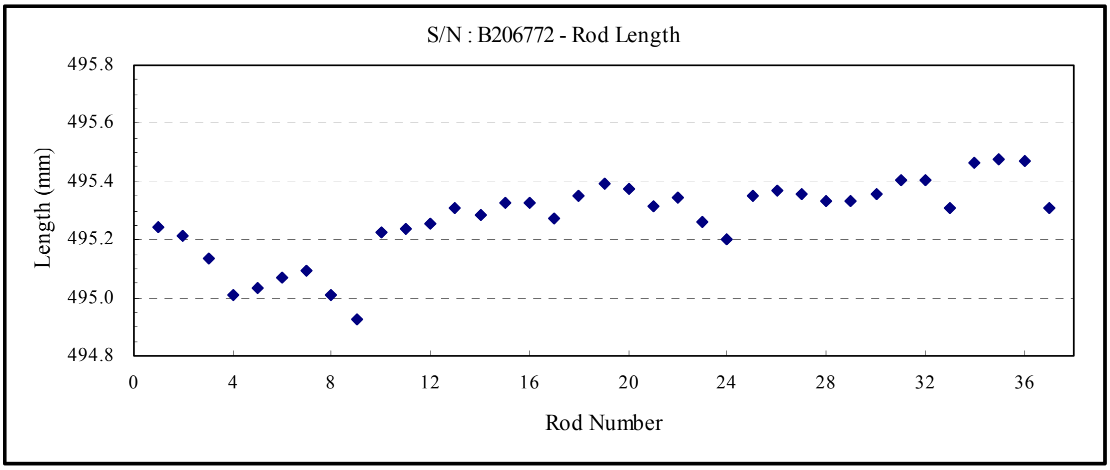


Figure 14. Element lengths over the Endplates of the B206772 Bundle Discharge Normally from the O07 Channel of WPGS-3