Non-destructive examination onthe spent fuel rods

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Abstract: In order to investigate the behavior of PWR fuel rods, eight fuel rods removed from 3 assembliesof Qinshan nuclear power plant(QNPP) were examined at the hot cell facility of China Institute of Atomic Energy (CIAE) in Beijing. The maximum burnup was about 40GWd/tU. This paper presents the results of non-destructive examination. The results included: 1) Status of cladding surface, 2) cladding integrity, 3) distribution of oxide film on the outer surface of claddings, 4) dimensional change on axial and circumferential, 5) distribution of fission products in the fuel column, 6) defects, uniformity and structural integrity of the fuel and cladding. The obtained data can be used to evaluate the fuel performance after irradiation.

Keywords: Post irradiation non-destructive examination, PWR type reactors, fuel rod, Zircaloy-4

1. Introduction

The prosperity of nuclear power development in China is just beginning. There are21 nuclear power units in operation now, 26units are under construction. According to the development programthe total installed nuclear power capacity will be 70–80 GW(e) until 2020[1].

As the second generation of nuclear power plant, QNPP with capacity of 310 MW(e) came into operation in 1991. QNPP is the first nuclear plant which is designed and constructed domestically in mainlandChina.

There are121 fuel assemblies (Fas)inside the core of QNPP which were designed by Shanghai Nuclear Engineering Research and Design Institute and manufactued by China Jianzhong Nuclear Fuel Co., Ltd (CJNF). Each FA composed of 204 fuel rods, 20 guide thimbles and 1 instrument thimble arrayed in a matrix of 15×15 and the enrichment of U-235 is 3.4% since balance cycle. The cladding material is Zr-4.

Outerdiameter of the claddingis 10 millimeter, with thickness of 0.7 millimeter. The 8 grid spacers are Inconel (GH4169) and the top and bottom nozzles are stainless steel (0Cr18Ni10Ti). Two major modifications were performed to the fuel assemblies after 7cycles, bottom nozzle filter and dish chamfers of pellet are added [2].

CIAE was authorized to perform the post irradiation examination tothe 8 fuel rods. Main parameters of the selected eight rods are listed in Table 1. The fuel rod arrangement is shown in Fig.1. Non-destructive examinations (NDE)in the hot laboratoryincludevisual examination, eddy current testing, oxide film thickness measurement, cladding diameter measurement, fuel rod length measurement, gamma scanning, X radiography.After NDE destructive examination will be performed includingfission gasrelease measurement, metallographic and ceramographic examination, axial tension test and hydrogen content analysisof the cladding, SEM analysis, burnup analysis. This paper introduce about the results of NDE.

Table 1 Main parameter of selected eight fuel rods

Fuel Assembly No.	YQ-30BZ			YQ-30C6			YQ-005U	
Position of rod	A-15	K-08	N-04	A-15	K-08	N-04	K-08	N-04
Load date	2000-12-24			2002-7-6			1994-12-28	
Unload date	2006-6-25			2006-6-25			2002-4-14	
Cooling time(Year)	6.0			6.0			10.2	
Enrichment of U-235(%)	3.4			3.4			3.0	
Burrup(MWd/tU)	39922.18			36006.96			33956.02	
Core Cycle	9			9			6	

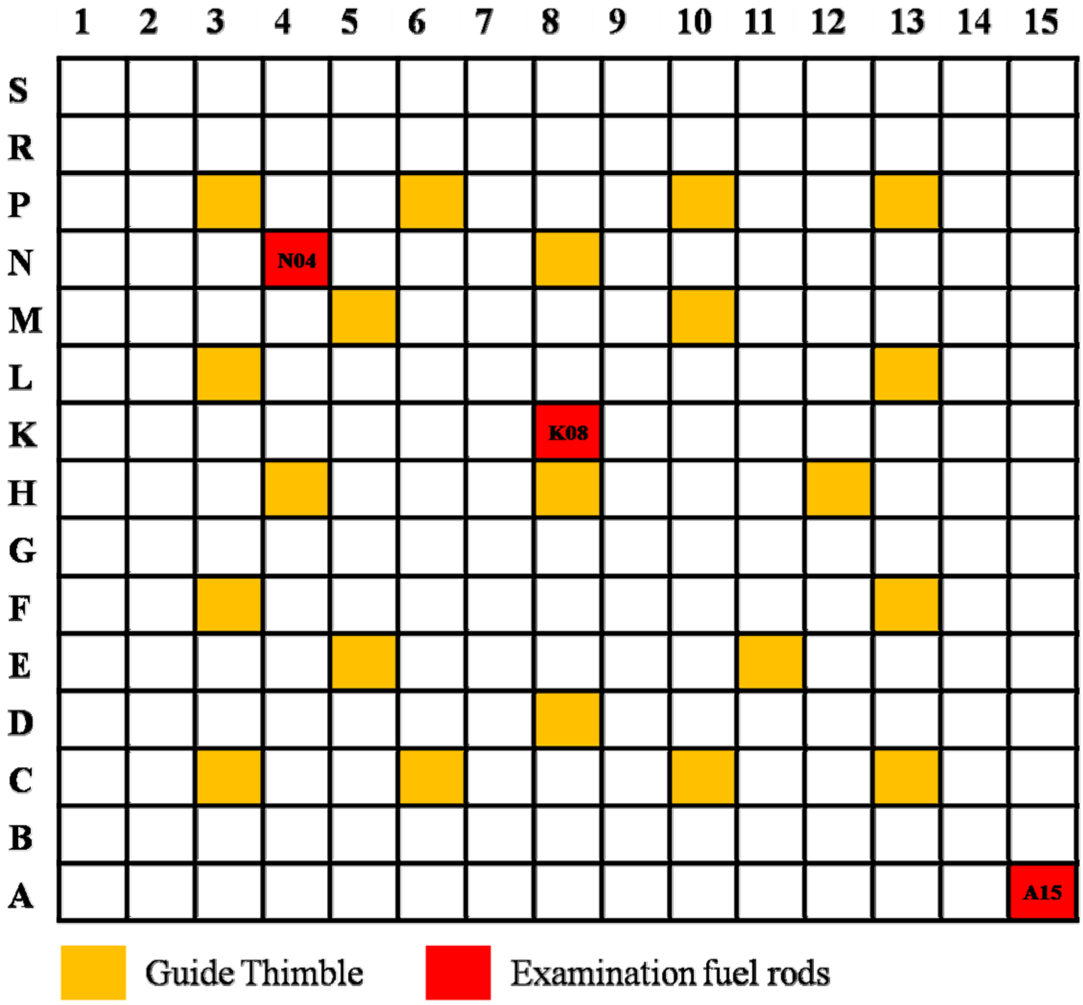

Fig. 1 The examination fuel rods location in assembly

2. Non-destructive examination results

2.1 Visual examination

Eight fuel rods were visually examined throughview windows of hot cell and by means of the in-cell digital camera. The appearance of fuel rods was recorded in photographs and video. All the fuel rods showed similar appearances except the fuel rod YQ-005U-N04.

At the lower part from 1st to 2nd grid, the appearance was lustrous blackat the very start and gradually to the mottled. At the center part from 2nd to 7th grid, the color was changed into gray continuously. The upper part of the fuel rod was transformed into black. The typical appearance of fuel rod is shown in Fig. 2.

Scents of cladding interaction with the spacer grid indents were observed during visual examination to all eight fuel rods. Especially for the fuel rod of YQ-005U-N04, the bottom part had obvious Fretting mark(Fig. 3). No unusual bending and twisting, remarkable corrosion, unusual deformation and defects were observed in visual examination except for YQ-005U-N04.

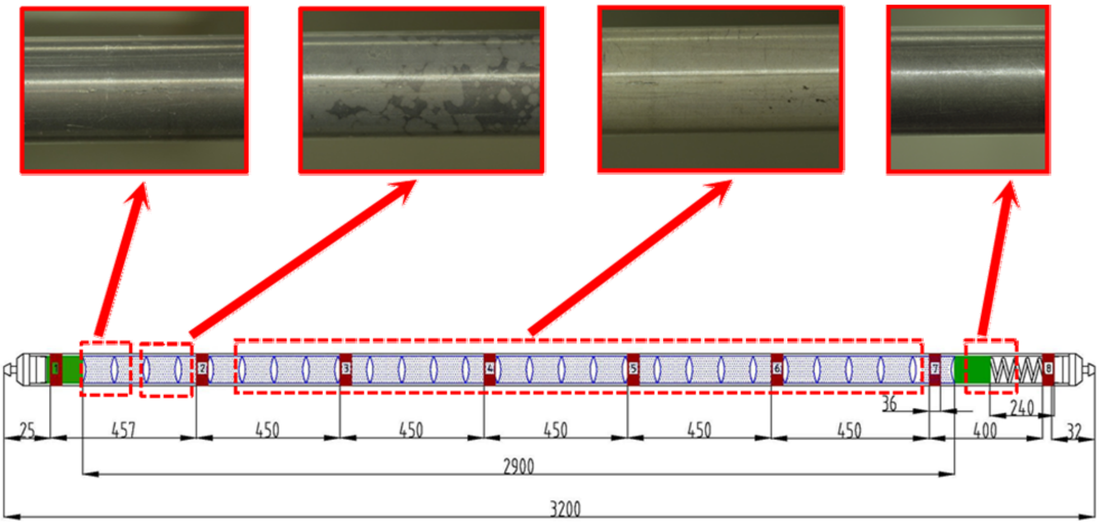

Fig. 2 Typical appearance of fuel rod

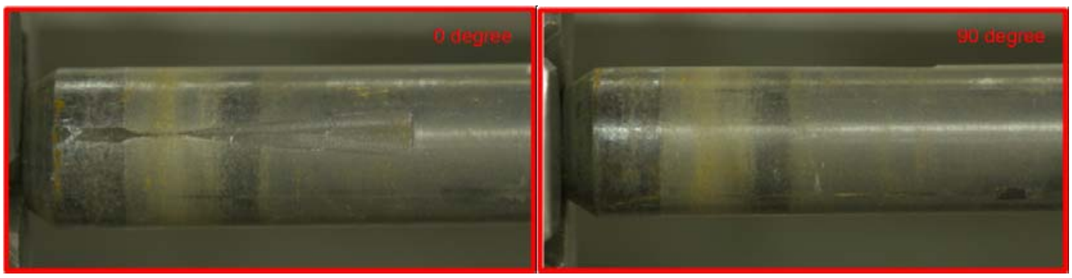

Fig. 3 Fretting Mark for YQ-005U-N04 fuel rod

2.2 Crud analysis

Crud sample was collected with polyethylene scraper. The total amount of the crud sample was too small for chemical composition analysis. This means that the crud thickness was negligible and the water chemistry control during reactor operation was excellent.

2.3 Eddy current testing

Eddy current testing was performed toeight fuel rods. A multi-frequency encircling differential coil was used to inspect the cladding for anomalies or defects. Calibration of the eddy-current system was achieved by scanning a defect standard that contains a variety of simulated inside and outside diameter defects.

Typical measured traces are shown in Fig.4. It was confirmed that the cladding integrity had been maintained during irradiation. No through-wall defects were found, however, several small indications were noted for outside wear marks. It is very obvious for the spacer grid.

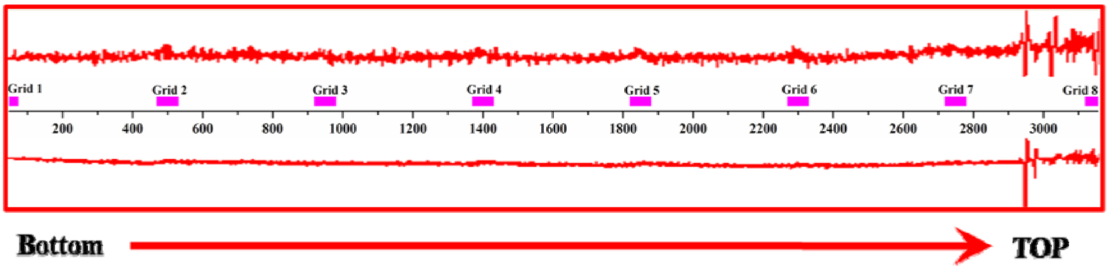

Fig. 4 Typical results of eddy current inspection

2.4 Oxide film thickness measurement

The nondestructive eddy-current technique was used to measure oxide film thickness on the eight fuel rods. Axial line scans of the surface oxide layer were made at four azimuthal orientations (0, 90, 180, and 270 degrees) on each of the eight rods. Oxide thickness data were recorded with the data acquisition system at one millimeter intervals during scanning.

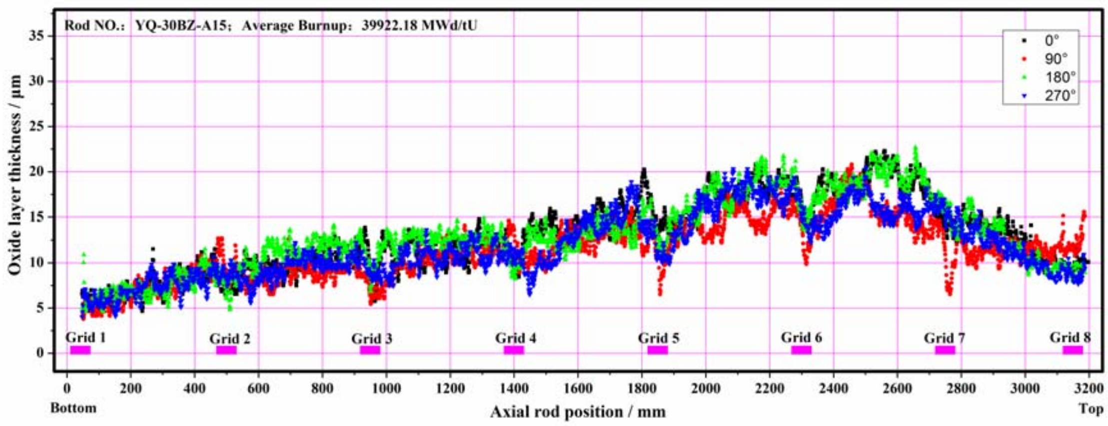

Fig. 5 Typical oxide profiles of rod YQ-30BZ-A15 at four orientations

Typical oxide thickness profiles are shown in Fig. 5.Span-average oxide thickness for these rods is listed in table 2. The profiles show oxide thickness increasing from the bottom to the top of the rod, with reductions occurring in the areas of the intermediate spacer grids. The maximum of oxide film thickness was observed in the region from the fifth to sixth span, and the axial profile of oxide layer thickness was depressed at seventh span. The maximum value of the oxide thickness was less than 25μm. The oxide film was thinner in thegrid region than in the middle of the span. This phenomenon was caused by two factors [3], first, the spacer grids are made of Inconel-718, which is a neutron absorber and decreasesthe power. Second, these grids increase thecoolant mixing which causes the local coolingof fuel rod surface.

However, the oxide thickness profile of two fuel rods from assembly YQ-005U was abnormal. Typical measured traces are shown in Fig. 6. This phenomenon can be explainedfrom the out diameter profiles in section 2.6.

Table 2 Span-average oxide film thickness

Fuel assembly No.	YQ-30BZ			YQ-30C6			YQ-005U	
Fuel rod No.	A15	K08	N04	A15	K08	N04	K08	N04
Burnup(MWd/tU)	39922.18			36006.96			33956.02	
Max/μm	22.69	23.10	23.13	22.23	15.80	20.14	20.80	19.01
Mean/μm	12.31	9.78	10.17	7.85	7.28	9.71	7.28	7.31
Span 1	7.33	4.33	3.56	3.64	3.13	4.03	3.94	3.75
Span 2	9.88	6.95	6.94	5.45	4.96	6.63	5.72	5.27
Span 3	11.21	9.34	9.23	7.05	6.61	8.64	6.77	6.86
Span 4	13.31	11.03	11.69	8.96	7.67	10.95	8.02	7.94
Span 5	16.31	13.62	14.93	10.69	10.18	13.56	9.80	10.19
Span 6	17.18	14.53	15.83	11.55	10.93	14.55	10.10	10.31
Span 7	11.84	9.42	9.60	8.41	7.88	10.52	7.37	7.35

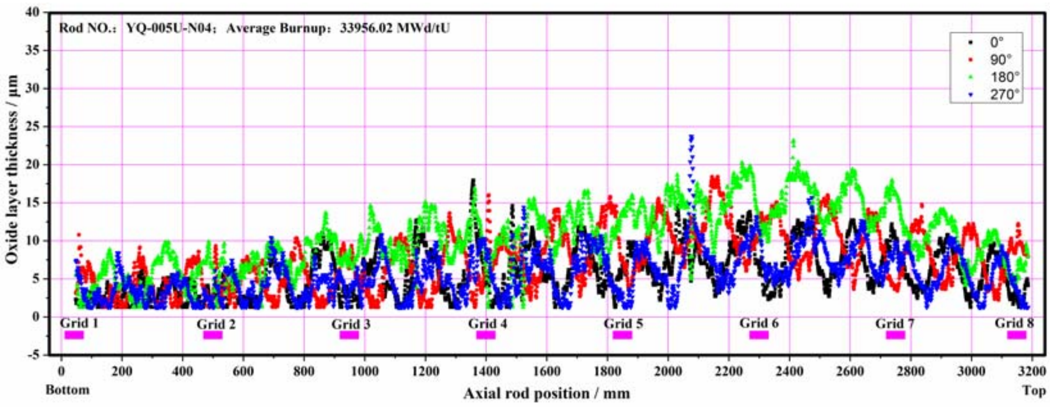

Fig. 6 Typical oxide profiles of rod YQ-005U-N04 at four orientations

2.5 Fuel rod length measurement

The total length of eight fuel rods wasdetermined by measuring the difference in elevation between a standard rod of known length and the fuel rod. The estimated uncertainty in the measured growth of the rods is ±0.5mm. Elongation data for all fuel rods are shown inFig.7. The minimum elongation was 10.14mm(0.32%) and the maximum one was 13.63mm(0.43%). The eight fuel rod elongation was within the range of the design criteria(35mm) [2]

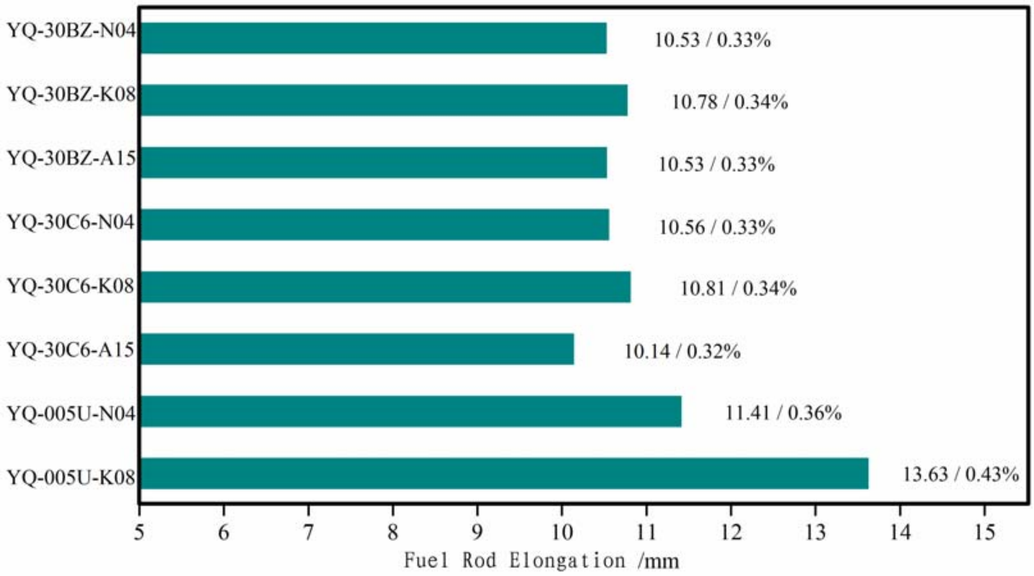

Fig. 7 Chart of eight fuel rods elongation

2.6 Outer diameter of cladding

Fuel rods outside diameters were measured with a contacting linear variable differential transducer(LVDT) system. Data were recorded at one millimeter axial increments from full length linear diameter scans taken at four azimuthal orientations 45 degrees apart. The four measured diameters were used to calculate maximum, minimum, and average diameters and the rod ovality (maximum diameter minus minimum diameter) at each axial increment. The diameter measurement error was no more than ±5µm. The diameter change was calculated as a difference between the average diameter values in the gas plenum and the fuel area. The difference of average diameter values in gas plenum minus the fuel area is 10~15µm.The obtained results are shown in Table 3.Creep down is the OD reduction from the as-fabricated value. The maximum creep down of at the all eight fuel rods was from51.1μm to 83.6μm. The maximum ovality was 28.1μm~82.9μm. Fig. 7 is the distribution of diameter value along fuel rod(YQ-30BZ-A15). Fig. 8 is the diameter diagram for YQ-005U-N04 with maximum creep down and ovality value.

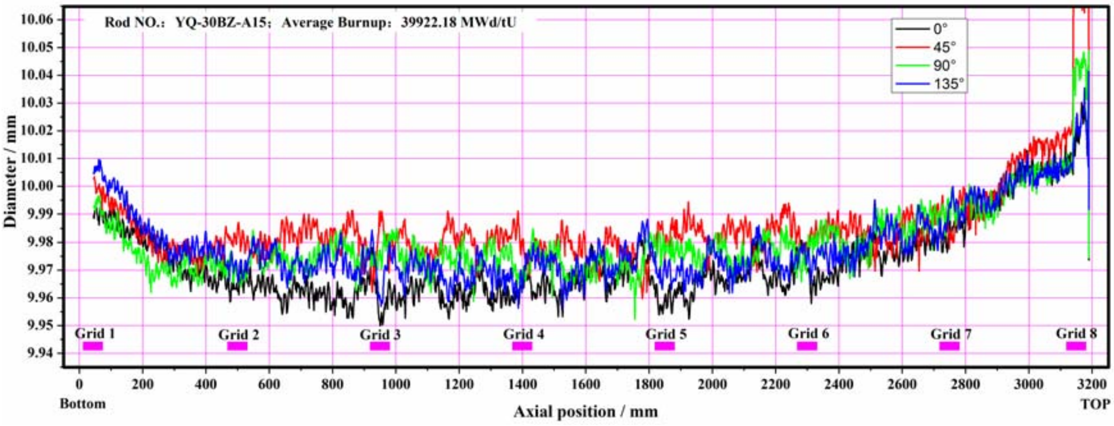

Fig. 7 Distribution of diameter value along fuel rod(YQ-30BZ-A15)

Table 3 Diameters of fuel rod claddings

Fuel assembly No.	YQ-30BZ			YQ-30C6			YQ-005U	
Fuel rod No.	A15	K08	N04	A15	K08	N04	K08	N04
Burnup(MWd/tU)	39922.18			36006.96			33956.02	
Average diameter in the gas plenum region(mm)	9.986	9.968	9.978	9.967	9.964	9.965	9.963	9.963
Average diameter in the fuel region(mm)	9.976	9.957	9.963	9.956	9.953	9.954	9.953	9.951
Difference between diameters in the fuel and gas plenum region(μm)	10	11	15	11	11	11	10	12
Maximum ovality(μm)	38.9	39.6	33.8	28.1	29.5	35.9	54.17	82.9
Average ovality(μm)	15.6	11.3	13.5	10.7	10.7	9.1	15.8	17.3
Maximum creep down/μm	50.1	63.1	51.3	62.9	66.7	56.2	77.2	83.6

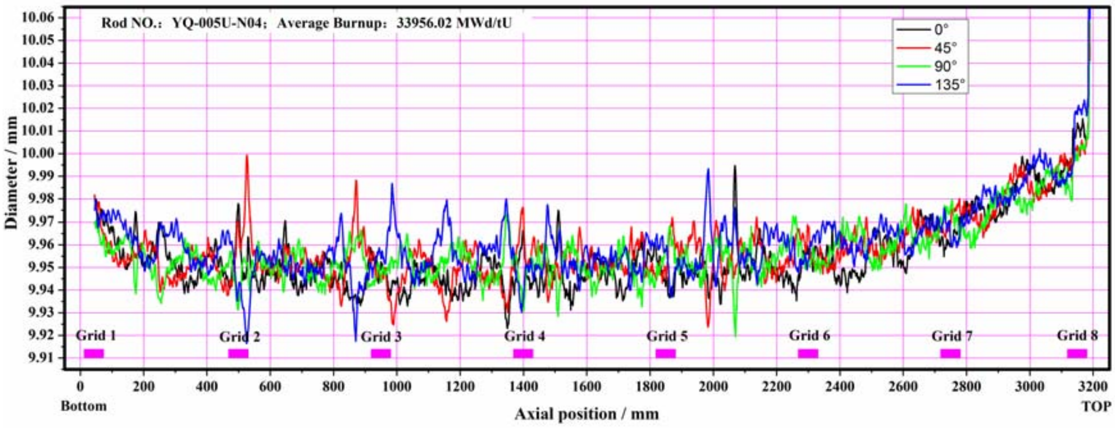

Fig. 8Distribution of diameter value along fuel rod

2.7 Axial gamma scanning

Axial gamma activity measurements were made on eight fuel rods, in which ^{137}Cs was used as the burnup monitor. The experimental apparatus for gamma spectroscopyconsists of collimator, lead shielding, high-purity germanium (HPGe) detector together with fast suitable electronics and an on-linemicrocomputer data acquisition module. The collimator with a 0.5mm slit is positioned between the irradiatedfuel element and the detector in order to enable thedetermination of the gamma emission rate of a specific fuel volume, as well as to avoid the systemoverflow concerning data acquisition.

Gamma acquisition along the fuel rod was performed at regular intervals of 25mm, each measurement had the duration of 30s of live time.Typical profiles of gamma-ray intensity are shown in Fig. 9. A prominent depression of count rate at fuel pellet interfaces is observed, which means there is no interaction between the pellets. This gamma activity profile highlights practically a symmetric loading of the fuel rod.

This figure also shows that the axial burnup profile was nearly flat at the center region.

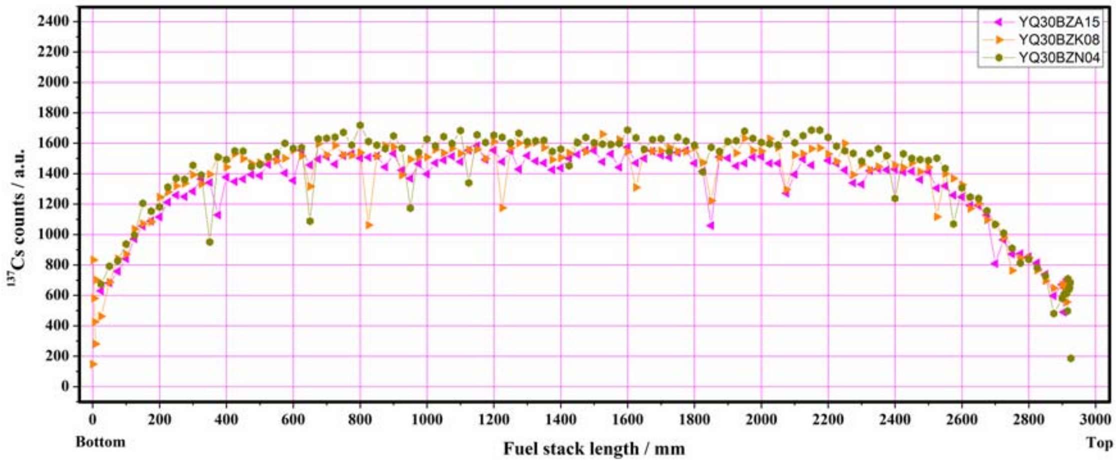

Fig. 9 Typical profiles of gamma-ray intensity

2.8 X radiography

X radiography was performed to eight fuel rods.No unusual deformation and unfavorable behavior, which might have a harmful influence on the fuel rod integrity, were observed. The typical image of X radiography for the YQ-30BZ-A15 fuel rod is shown in Fig. 10 and Fig. 11. As shown in these figures, the pellets in the bottom of rod have broken. The axial gaps between pellets were observed. The plenum spring is in good condition.

Fig. 10 The typical image of X radiography for YQ-30BZ-A15(bottom of rod)

Fig. 11 The typical image of X radiography for YQ-30BZ-A15(upper of rod)

3. CONCLUSION

The fuel rods werestored in the reactor poolafter removed from the reactor, cooling for a period of time and then transferred to the hot cells of CIAE where it was subjected to detailed examinations. A full process of nondestructive examinations concerning the integrity, dimensional changes, and oxidation of the cladding was performed. The obtained results are typical for PWR fuel rod.Summary of non-destructive examinations is as follows:

(1) No unusual bending and twisting, significant corrosion, remarkable deformation and defect were observed in the visual examinations for the fuel rods. The difference in appearance among cladding was not clear from the results of visual examination. Except for YQ-005U-NO4 fuel rod, with big fretting mark was observed.

(2) No crack and defect were detected in the eddy current examination.

(3) As the result of measurement of oxide layer thickness on the cladding surface, themaximum of oxide film thickness was observed in the region from the fifth to sixth span, and axial profile of oxide layer thickness was depressed at seventh span. The maximum value of the oxide thickness was less than 25μm, which was within the design criteria.

(4) The maximum axial elongation of the fuel rod was 0.43% to the as-fabricated, which was within the design criteria. The rod diameter was much decreased in the fuel region in contrast to the gas plenum. Fuel rod of YQ-005U-N04 has the maximum ovality.

(5) Axial burnup profile was nearly flat at the center regionof the fuel rod throughγ-scanning,.

(6) Axial gap between pellets were observed during X radiography. Pellets in the bottom region of rod have broken.

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