Maximum Oxide Thickness Determination Method and Evaluation of the Irradiated Fuel Rod Obtained from Pool Side Examination and Post Irradiation Examination

Oh-Hyun Kwon *, Hee-Hun Lee, Hong-Jin Kim, Jung-Cheol Shin
KEPCO Nuclear Fuel Co. Ltd., 989beon-gil 242, Daedeok-daero, Yuseong-gu, Daejeon 305-353, Korea
**Corresponding author: ohkwon@knfc.co.kr*

1. Introduction

Generally, the zirconium metal is resistant to a wide range of inorganic and organic acids. Recently, complete treatment such as heat treatment and alloy element adjustment for more advanced chemical corrosion resistance could be found and applied to the commercialized fabrication until now. Furthermore, the typical corrosion mechanisms are previously studied well in zirconium alloys. In some paper, the uniform corrosion usually occurs in PWRs (Pressurized Water Reactors) under non-boiling and hydrogenated conditions [1]. And the zirconium oxide growth has been shown to occur by inward diffusion of oxygen ions through the oxide layer continuously and the new oxide formed at the metal/oxide interface evenly [2]. Therefore, it is generally accepted that the oxide thickness forms by uniform corrosion at the surface of fuel rod at low burnup.

However, the zirconium alloys has corrosion acceleration due to the thermal feedback effect at a much larger oxide thickness and shows variable oxide thickness with wide variation at high burnup [3,4]. Therefore, recently, for the evaluation of high burnup performance of the fuel rod, oxide thickness data are continuously gathered and the study of the corrosion mechanism is ongoing worldwide. Moreover, for the corrosion study and evaluation of high burnup performance, it is especially important to correctly measure the maximum oxide thickness in each fuel rod at high burnup.

In this study, the two representative oxide thickness measurements method of PSE (Pool Side Examination) and PIE (Post Irradiation Examination) are introduced. In addition, the detailed maximum oxide thickness determination method which also considers the characteristics and differences due to the measurements methods and equipment is described. Finally, based on the above-mentioned determination method, the summarized maximum oxide thickness data obtained from irradiated fuel rod measurements are evaluated for the performance analysis at high burnup.

2. Measurement Methods

2.1. PSE Measurement

PSE is performed at the spent fuel pool during the overhaul period and should usually be completed within the very limited time frame because of the tight overhaul schedule. Therefore, it is essential to have skillful engineers and automated measurement tools to complete the work within the given time. The oxide thickness is measured with ECT (Eddy Current Test) in PSE. The oxide thickness measurements are processed in two steps. At first step, oxide thickness is measured for all the most outer rods on the face with the highest burnup distribution among four faces of the fuel assembly over 10 axial positions to acquire axial distribution of cladding oxide thickness. After determining the axial elevation which shows the peak oxide thickness, as the second step, all targeted rods are measured at that elevation to obtain the maximum oxide thickness [5]. In the second step, the ECT prove inserts from outer specific face of fuel assembly into the space between the fuel rods at the axial elevation selected in the first step, 10 mm higher, and 10mm lower than the selected location to secure the averaged value around approximately 1 inch height. Therefore, all the measured data from PSE in this study averaged value around approximately 1 inch height distance. For the more accurate average calculation, the second step is performed once again to acquire the oxide thickness data for in the 90^{o} angle of fuel rod. And then, the maximum oxide thickness data are averaged from two position-measurements of the fuel rod data.

2.2. PIE Measurement

The other close investigation (PIE : Post Irradiation Examination)for the oxide thickness is the measurement in hotcell facility. The principles for the measurement method using the eddy-current with microprocessor control are also the same as the case of PSE. However, contrary to the PSE point measurement, the oxide thickness measurement in hot-cell could obtain the data continuously with scanning through axial height of the rod and for all circumferential angles of fuel rod, which also enables closer observations. The typical configuration of oxide thickness distribution along with the circumferential angle directions is shown in Fig.1.

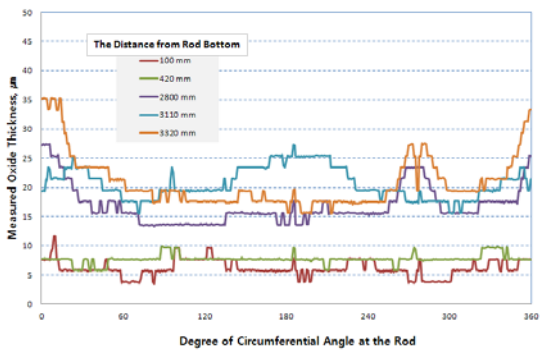

Fig. 1. The typical configurations of oxide thickness on the surface of fuel rod with circumferential angle

Fig. 2 shows the continuous oxide thickness data measured with the axial elevation of fuel rod. The figure includes information on the oxide thickness along with circumferential angle and distance from the rod bottom.

Generally, the maximum value, as shown in the Fig. 2, appears at around 80% of fuel rod axial height, which shows the similar results from the first step in PSE. However, as shown Fig. 2, even though it is capable of identifying the oxide thickness data at each specific local point, there are certain abnormal peaks data at certain axial elevation (around 2800 mm and 3300 mm from the rod bottom) and specific angle (Zero degree). It is considered that the abnormal certain peak data does not mean the local oxide thickness by examination through the metallurgical analysis.

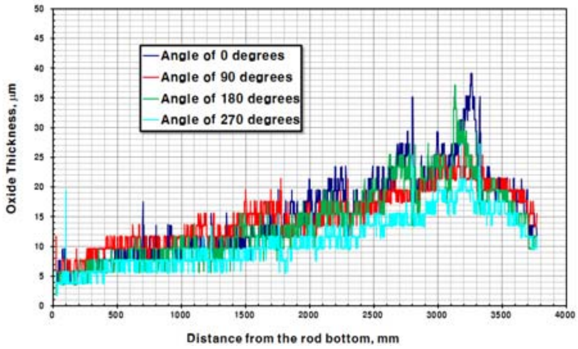

Fig. 2. The oxide thickness along with the axial elevation of the fuel rod with various angles

In addition, even though the PIE oxide thickness data are measured locally and selectively, those data at certain axial elevation can't be directly compared with criteria.

Therefore, it is needed to modify the data from PIE for the normalization of the peak data. Based on the measurement method of PSE, it is recommended that averaged oxide thickness in PIE is analyzed with approximately covered height (about 1 inch) and cladding surface area which covers 360^{o} circumferential angle. The calculation method of oxide thickness in PIE is shown below equation. By using the equation with standard interval distance and several circumferential angles, the maximum oxide thickness in irradiated fuel rod can be obtained through the whole distance from the bottom.

$$\frac{1}{n}\times\frac{\int_{x-d}^{x+d}(t_{oxide,\alpha^\circ}+t_{oxide,\beta^\circ}+\cdots+t_{oxide,n^\circ})dx}{2d}$$

Where,

x = Distance from fuel rod bottom
n = Total numbers of angle, (n≥ 2)
d = the interval distance for average calculation
$t_{oxide,\,\alpha}{}^{o}$ = oxide thickness at angle α and x

Through the calculation with the oxide thickness data, the maximum oxide thickness can be also acquired at every irradiated fuel rod respectively at approximately around 80% of fuel rod axial height. For the calculation, the *d* value could be considered as 10 mm, to which the method measured from the second step of PSE are also identical.

3. Results and Evaluation

Fig. 3 shows all the maximum oxide thickness data obtained from PIE and PSE. All the data shown in Fig.3 are summarized based on the suggested calculation determination mentioned above. Because PIE results and PSE results has the equivalent averaging calculation, those are able to be summarized in the same figure.

For the evaluation of corrosion in the irradiated fuel rod, it is generally accepted that PWR fuel rods retain their mechanical integrity during normal operation up to a corrosion layer thickness of 100 μm with sufficient safety margin against failure. According to the generally accepted criteria, all the summarized data in Fig.3 are able to be met within the criteria. For the further study and performance analysis at high burnup, the data would be accumulated continuously based on the suggested calculation.

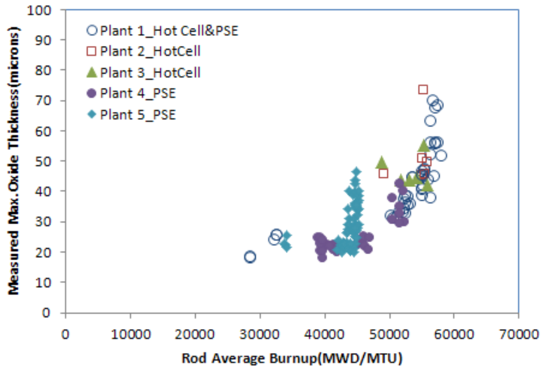

Fig. 3. The measured maximum oxide thickness results from the PSE and PIE

4. Conclusions

The two representative oxide thickness measurements method of PSE (Pool Side Examination) and PIE (Post Irradiation Examination) are introduced. And the detailed maximum oxide thickness determination method which also considers the characteristics and differences due to the measurements methods and equipment is suggested. Finally, based on the above-mentioned determination method the summarized maximum oxide thickness data obtained from irradiated fuel rod measurements are evaluated well with meeting within the oxide thickness criteria.

REFERENCES

[1] Adamson, "Corrosion in Zirconium Alloys", Garzarolli in IZNA2 Special Topic Report, 2002.
[2] A. Grandjean and Y. Serruys, "Metal and oxygen mobilities during zircaloy-4 oxidation at high temperature", J. Nucl. Mater., vol. 273, 1999, pp. 111-115
[3] Ron Adamson, "Corrosion Mechanisms in Zirconium Alloys", IZNA7 Special Topic Report, 2007, pp.3-50.
[4] A. Grandjean and Y. Serruys, "Cladding to Sustain Corrosion, Creep and Growth at High Burn-Ups", Nuclear Engineering and Technology, vol. 41, No.2, 2009, pp. 143-148
[5] Young Ki Jang, "Irradiation Performance Update on Advanced Nuclear Fuel of PLUS7TM", Proceedings of ASME 2011 Pressure Vessels & Piping Conference, 2011.