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⟨Technical Note⟩

Water-Side Oxide Layer Thickness Measurement of the Irradiated PWR Fuel Rod by ECT Method

Kwang-June Park and Yong-Bum Chun
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon 305-353, Korea

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Abstract

It has been known that water-side corrosion of fuel rods in nuclear reactor is accompanied with the metallic loss of wall thickness and hydrogen pickup in the fuel cladding tube. The fuel clad corrosion is one of the major factors to be controlled to maintain the fuel integrity during reactor operation. An oxide layer thickness measuring device equipped with ECT probe system was developed by KAERI, and whose performance test was carried out in NDT(Non-Destructive Test) hot-cell of PIE(Post Irradiation Examination) Facility. At first, the calibration/performance test was executed for the unirradiated standard specimen rod fabricated with several kinds of plastic thin films whose thickness were predetermined, and the result of which showed a good precision within 10% of discrepancy. And then, hot test was performed for the irradiated fuel rod selectively extracted from J44 fuel assembly dicharged from Kori Unit-2. The data obtained with this device were compared with the metallographic results obtained from destructive examination in PIEF hot-cell on the same fuel rod to verify the validity of the measurement data.

1. Introduction

An eddy current testing method was appiled to the measurement of oxide layers formed on the irradiated PWR fuel cladding tube surface. The eddy current coil carries a high frequency current which induces an eddy current flow in the Zircaloy cladding substrate. This produces alternately an opposing electrical field which affects the impedance of the coil. The net coil impedance is changed according to the proximity of the coil to the metal, and therefore the coil impedance could provide an estimation of the distance of the coil from the metal substrate. The distance from the coil to the metal substrate could be expressed as the sum of the thickness of the insulating oxide layer and the separation gap of the coil from the wear resistant diamond probe tip.

The water-side corrosion of Zircaloy fuel cladding does not matter in the normal reactor operation under normal coolant conditions and design burnups of around 35 GWD/MTU. But the current trends of power operation in the nuclear industry are increasing coolant inlet temperatures to improve thermal efficiency and extending design burnups up to 50 GWD/MTU to lower fuel cycle costs and to reduce spent fuel storage requirements. Since such modifications would accelerate Zircaloy water-side corrosion, it is essential to estimate the amount of corrosion under those conditions and to evaluate its effects on the design limits of fuels for the next generation[1].

Oxide layer thickness data of Zircaloy cladding tube have been obtained through destructive test of hot-cell examination. Careful preparation of metallographic specimens could provide a very precise oxide thickness data. This method is, however, rather expensive and time-consuming, and very limited number of data could be obtained from this metallographic examination. It also prevents the possibility of tracing the further progress of oxidation behaviour based on the exposure of individual fuel rods during successive irradiation cycles.

In this work, an eddy current method was introduced for the oxide layer thickness measurement and a comprehensive ECT probe was designed and fabricated to be mounted on the existing hot-cell features without any interferences. The function of this device was verified through the comparison of the measured data with the destructive test result of the H-08 fuel rod extracted from J-44 fuel assembly discharged from Kori Unit-2.

2. Descriptions

2.1. Hot Cell Installation on the Device

It is important to arrange the existing equipment to install the ECT device on the NDT bench and to confirm whether the device could be operated in normal way without any interference with other existing devices in hot-cell. Enough discussions were made in design and fabrication stage to escape the interference with other devices. A specially designed control cable was embedded on the hot-cell rear door to supply electric power to the system and to transfer

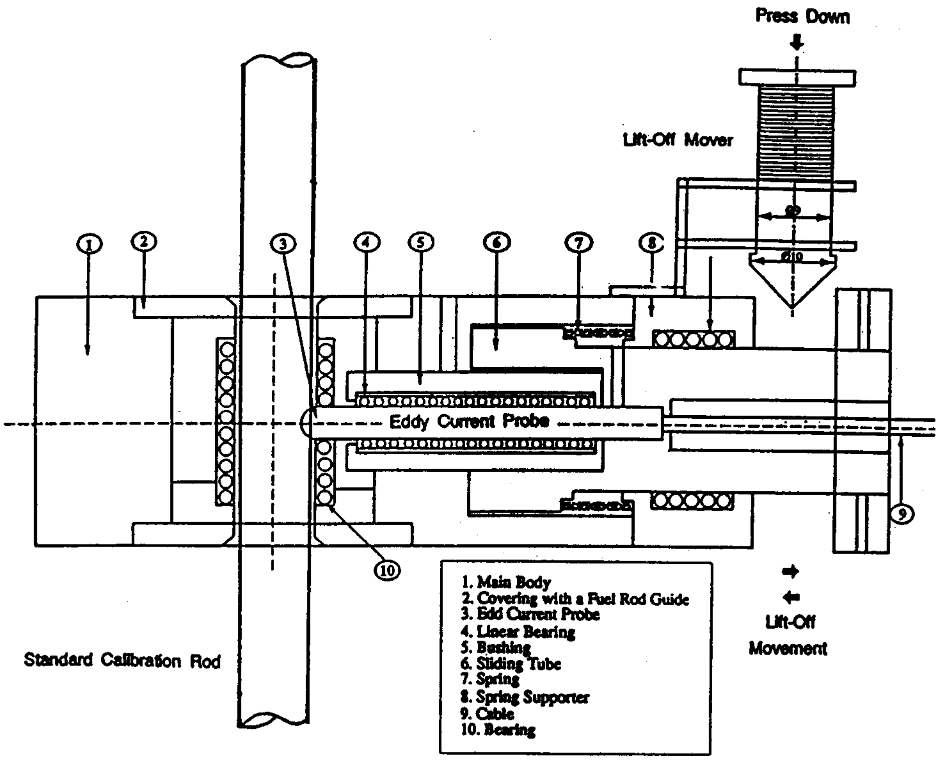

Fig. 1. Schematic Drawing of the Oxide Layer Thickness Measuring Device Assembled with the Component Parts.

measured data signal to the analysing system.

2.2. Design and Fabrication of the Device

A mechanical positioning device was designed to locate the eddy current probe exactly perpendicular to the fuel rod surface during the scanning of the fuel rod with the eddy current test device. Since a high degree of precision is required to maintain orthogonality, several special components of the oxide layer thickness measuring device were designed and fabricated as shown in Fig. 1. A geometrical structure of the main body was modified according to the external shape and dimension of the eddy current testing device. The rectangular hole of the eddy current testing package was fabricated to set up the oxide layer thickness measuring device. To reduce the weight and to handle the manupulator easily, the prominence and depression were made in the front side of the oxide layer thickness measuring device.

The main body has two holes, one of which is for inserting the eddy current probe and the other is for putting the nuclear fuel rod into the guide hole.

2.2.1. Parts for Eddy Current Probe Moving

A linear bearing is used to minimize the friction of the eddy current probe during the lift-off movement, and to cope with a sudden displacement from the irregularity of the fuel rod surface conditions. In order to satisfy those conditions, the size of a linear bearing must be exactly equal to that of eddy current probe. The longer the length of the bearing is, the more stable the movement is. An additional bearing bushing attached to the original bearing bushing plays a role of preventing the secession of the ball cage. It is composed of two parts and their connections are made by screw fastening device by putting the ball cage and bearing bushing into the additional bushing housing. A coil spring was used for the lift-off movement of the probe. Sliding tube was used for smooth operation and incorporated with the probe by fixing pin.

The function of the spring is to actuate the lift-off movement and to keep on soft contacting of the probe to the fuel rod. A spring supporter plays a role in supporting the spring as well as skidding the sliding tube incorporated with the eddy current probe. The friction between the sliding tube and the supporter hole is reduced by attaching a bearing in the supporter.

2.2.2. Part for Fuel Rod Guiding

The fuel rod is scanned in contact condition to the guide parts which is composed of a bearing and coverings. A friction could be reduced by the bearing and coverings which are not only to prevent the damage on the fuel rod but also to afford a smooth scanning movement. The size of the bearing was determined according to the dimension of fuel rod of 14×14 and 17×17 PWR fuel assemblies.

Coverings of this oxide layer thickness measuring device play a role of the fuel rod guide and bearing. Its dimension is limited to the size of the main body.

2.2.3. Part for Lift-Off Movement

It is not easy to lift-off the eddy current probe with the manipulator in hot-cell. Thus a lift-off mover was designed and adopted for easy handling with manipulator system. This part is connected to the main body of the oxide layer thickness measuring device in consideration of lift-off distance.

After all of the components of the oxide layer thickness measuring device have been designed and fabricated, they were assembled for the cold performance test and hot-cell examination.

3. Experiments and Results

3.1. Performance Evaluation

3.1.1. Cold Performance Test of Equipment

The preliminary cold performance test of the oxide layer thickness measuring device before installing in the NDT hot-cell was carried out with the standard calibration rod. The amplitude of the eddy current signal generated from the probe was collected and the signal change depending on the materials and the frequencies used in the test was identified. Since the cladding material of the PWR fuel rod is zirconium base alloy, it is preferable that the standard calibration rod has the same material characteristics with the fuel cladding tube to convert the eddy current signal obtained from the examination directly into the real oxide layer thickness values. In order to obtain these thickness data from the signal, the calibration was carried out through the cold test by using the standard calibration rod having three different thicknesses of film that are $12\pm0.5\mu m$, $24.5\pm1.0\mu m$ and $35\pm1.0\mu m$, respectively. Although it was difficult to attach the films precisely on the surface of standard calibration rod without using any adhesive, the problem was solved by making a groove on the surface of clad, putting the films in the groove and fixing a rectangular pin with small screw.

After preparing the standard rod and calibrating the thickness, the performance evaluation was carried out for the standard rod. The result of the test is depicted in Fig. 2 which shows a good correspondence within 10% error.

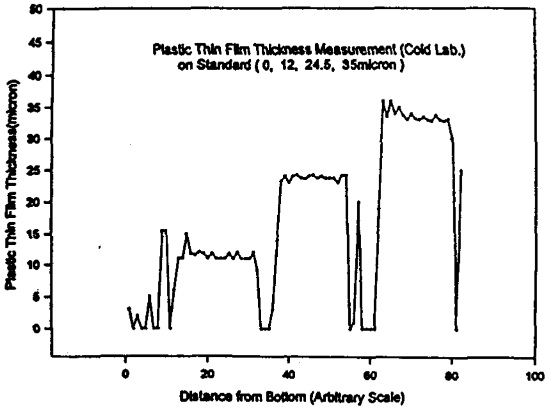

Fig. 2. Thickness Calibration Curve of the Oxide Layer Thickness Measuring System in Cold Laboratory.

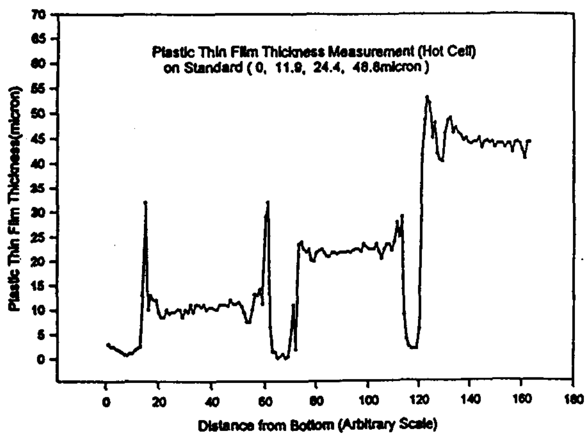

Fig. 3. Thickness Calibration Curve of the Oxide Layer Thickness Measuring System in NDT Hot-Cell.

3.1.2. Performance Evaluation Test in Hot-Cell

The thickness calibration standard rod having the thicknesses of $11.9\pm0.5\mu m$, $24.4\pm1.0\mu m$ and $48.8\pm1.5\mu m$, was mounted on the examination bench of the NDT hot-cell and then it was inserted in the guide hole of the eddy current package. The location of each film on the calibration rod could be identified by the reference position mark. After finishing the calibration test, the performance evaluation test was carried out by scanning the whole length of calibration standard rod. Fig. 3 shows the test result with a good precision that is in compliance with the results of the cold laboratory test.

3.2. Application to the Irradiated Fuel Rod

A fuel rod which was extracted from J-44 assembly discharged from Kori Unit-2, has been selected for the verification of the obtained oxide layer thickness measurement result. The thickness was measured along the whole length of the rod and the data were stored in personal computer and plotted by strip chart recorder. The result shows a good typical shape of oxide layers formed on the fuel rod cladding

Table 1. Measured Values of Oxide Layer Thickness of the H-08 Fuel Rod by Means of NDT and DT Methods

		Measured Values along the Fuel Rod Position, μm												
measuring position, mm		160 ~ 180	490 ~ 510	830 ~ 850	990 ~ 1010	1290 ~ 1310	1490 ~ 1510	1760 ~ 1780	1990 ~ 2010	2290 ~ 2310	2490 ~ 2510	2790 ~ 2810	2990 ~ 3010	3290 ~ 3310
testing method	NDT	1.0 ±0.5	3.0 ±0.5	2.0 ±0.5	5.0 ±0.5	2.0 ±0.5	13.0 ±0.5	8.0 ±0.5	13.0 ±0.5	15.0 ±0.5	20.0 ±1.0	16.0 ±0.5	23.0 ±1.0	17.0 ±0.5
	DT	2.08 ±0.10	3.21 ±0.96	2.86 ±1.28	3.71 ±1.32	3.70 ±1.64	8.45 ±1.33	6.35 ±1.83	12.24 ±1.31	11.73 ±2.33	20.05 ±2.36	17.34 ±1.94	24.74 ±2.62	21.89 ±0.70

* Error in NDT method is based on that of standard films. And error in the DT refers to the sample standard deviation.

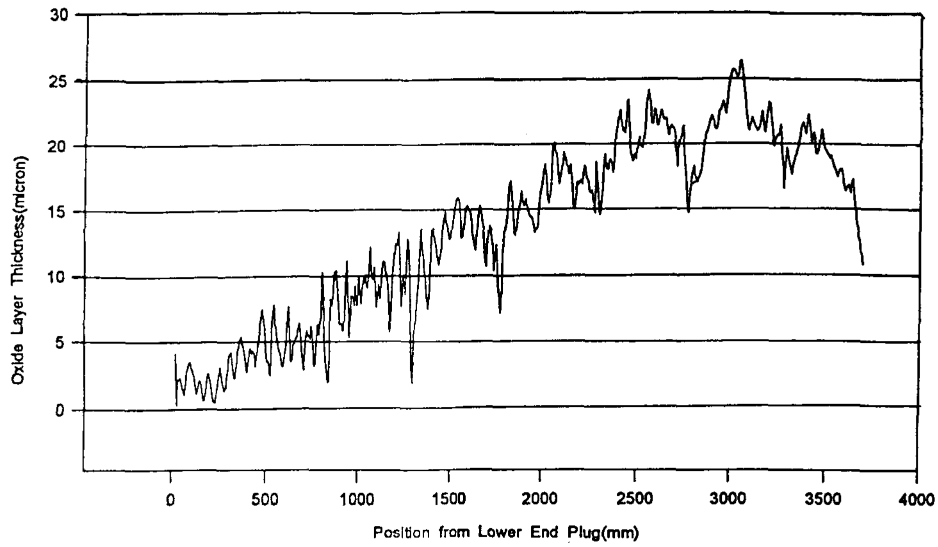

Fig. 4. Distribution of Oxide Layer Thickness along the Axis of HO8 Fuel Rod at O Degree.

tube which vary with the elevation of the rod. The minimum value of oxide thickness is shown near the bottom of the rod while the maximum one is shown close to 3,000mm from the bottom as presented in Fig. 4. Also it shows several downward spectrum peaks corresponding to the grid position of fuel assembly. The measured thicknesses were compared with those of the destructive test results to confirm the real thicknesses as shown in Table 1. In Fig. 5, Microscopic photographs of eight specimens taken at 2490~2510mm from the bottom of the fuel rod was drawn with oxide layers on the Zircaloy cladding. There are some differences between the nondestructive test results and the destructive ones with 10μm of discrepancy. In the case of Germany and Japan, it was reported that the maximum error was within ± 5μm and standard deviation of error was 2.8μm[1,2], which says the equipment developed in this work seems to be sufficiently applicable.

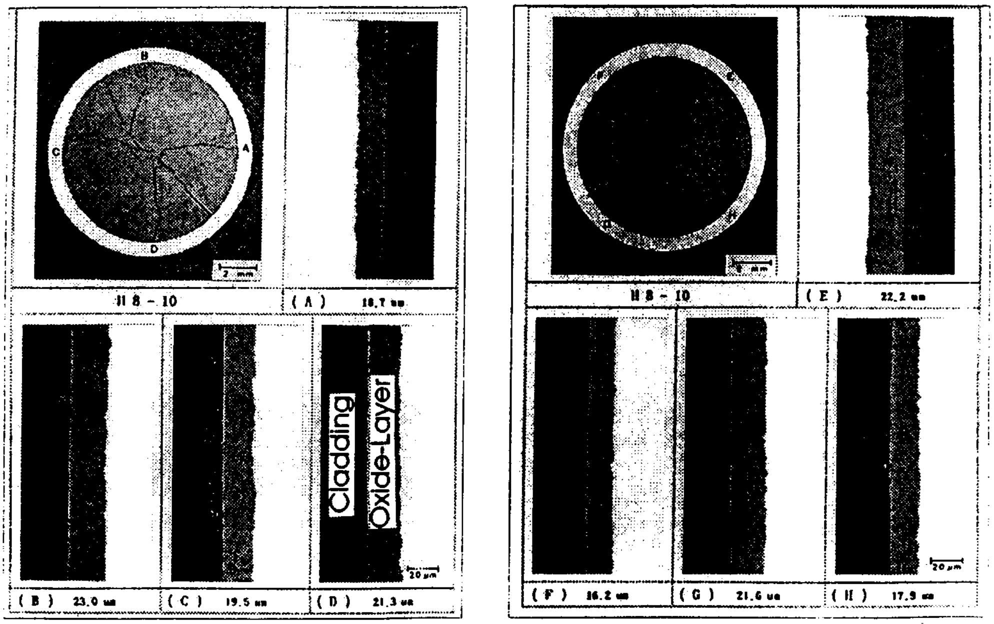

Fig. 5. Photographs of Oxide-Layer Thickness of Eight Specimens Taken at 2490~2510mm from Bottom of H-08 Fuel Rod.

4. Conclusions

The nondestructive oxide-layer thickness measuring device which adopts eddy current methods was developed and installed in PIE facility of KAERI. The data obtained through the cold and hot-cell test of the device to verify the precision showed practically good accuracy. And this technique was applied to the irradiated fuel rod selected from J-44 assembly discharged from Kori Unit-2. Those measured thicknesses data were compared with those of the destructive testing results to verify the real zirconium oxide layer thicknesses formed on the fuel rod cladding. These comparative results says that the newly developed oxide layer thickness measuring device could be employed for the irradiated fuels.

References

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