Development of Low Cyclic Fatigue Test Technique for Irradiated Cladding Tube in Hot Laboratory

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ABSTRACT

KAERI's R&D group had produced a lot of low cycle fatigue data for an un-irradiated fuel cladding tube using a cyclic pressurization device. However, the infrastructures and fatigue test techniques, which can produce the fatigue data on the irradiated fuel cladding tube, are still worse off in Korea. Therefore, the objectives of this study are to develop low cycle fatigue test techniques for irradiated fuel cladding tube, as well as produce a stress-life curve of the irradiated cladding tube under the cyclic pressurization. The cyclic pressurization fatigue test machine was newly developed and installed in hot laboratory at KAERI's post irradiation examination facility. Radiation shielding system that surround the irradiated cladding specimen and the electric furnace was installed to protect the tester and minimize the radiation exposure from the spent fuel cladding specimens. To exert an internal pressure inside the irradiated cladding tube specimen, it is essential to remove the spent fuel pellet from the fuel rod. So defueling machine which can remove the spent fuel pellet from 300 mm long irradiated cladding tube specimen was developed. In Addition, remote handling fitting fastening apparatus was equipped in hot cell. This apparatus was designed to fasten the high pressure fitting to defueled cladding tube specimen remotely using manipulator. The fatigue test specimen clamped with high pressure fitting guaranteed the non-leakage performance during cyclic pressurization. Using these developed test systems, fatigue behavior data of the un-irradiated advanced Zircaloy cladding tube w/ and w/o hydrogen have been produced from this study. In addition, the preliminary fatigue test for an irradiated advanced Zircaloy cladding tube was also carried out successively.

1. Introduction

Nuclear fuel cladding undergoes a cyclic deformation from various kinds of external parameters during in-reactor operation. Nowadays, the potential occurrences of high cycle fatigue are considerably decreased by virtue of an improvement of the spacer grid in the fuel design. However, it is well known that the possibility of low cycle fatigue along the radial direction caused by power oscillations still remains in the fuel cladding.[1,2] If the utility adopts a load following operation, the cyclic changes of the diameter causing a low-cycle fatigue will occur more frequently. Although failures regarding radial fatigue in the fuel cladding have not been reported yet, it is essential to accumulate a fatigue life database for use in a fuel design. Since Soniak's proposal for low cycle radial fatigue under cyclic pressurization of the fuel cladding, KAERI's R&D group has also produced a lot of low cycle fatigue data for an un-irradiated fuel cladding tube using a cyclic pressurization device [3]. However, fatigue data regarding irradiated fuel cladding under cyclic pressurization has not been obtained around the country until now. In addition, the infrastructures and fatigue test techniques, which can produce the fatigue data on the irradiated fuel cladding, are still worse off.

The objectives of this study are to develop low cycle fatigue test techniques for irradiated fuel cladding, as well as produce a stress-life curve of the irradiated cladding under the cyclic pressurization.

2. Methods and Experiment

2.1 Development of cyclic pressurization fatigue tester

The cyclic pressurization fatigue test machine consists of five major components, a main frame, electric furnace, control system, hydraulic supply module, and data acquisition system. Figure 1 shows a schematic diagram of the cyclic pressurization fatigue tester for an irradiated fuel cladding tube. The hydraulic booster cylinder moves up and down to load a cyclic pressure to the irradiated cladding specimen. The pressure of the cladding can be controlled within a range of 0 to 126 MPa by a hydraulic servo valve, and the resultant hoop stress ranges up to 992 MPa. Silicon oil, which is resistant to boiling, degradation, and reactivity under high temperature, was used as a medium to exert an internal pressure into the irradiated cladding tube. The loading frequency can be controlled in a range of 0.5 to 2 Hz with a sawtooth and sinusoidal waveform. The electric furnace heater was divided into two independent control zone to maintain the uniform temperature distribution axially along the irradiated cladding specimen.

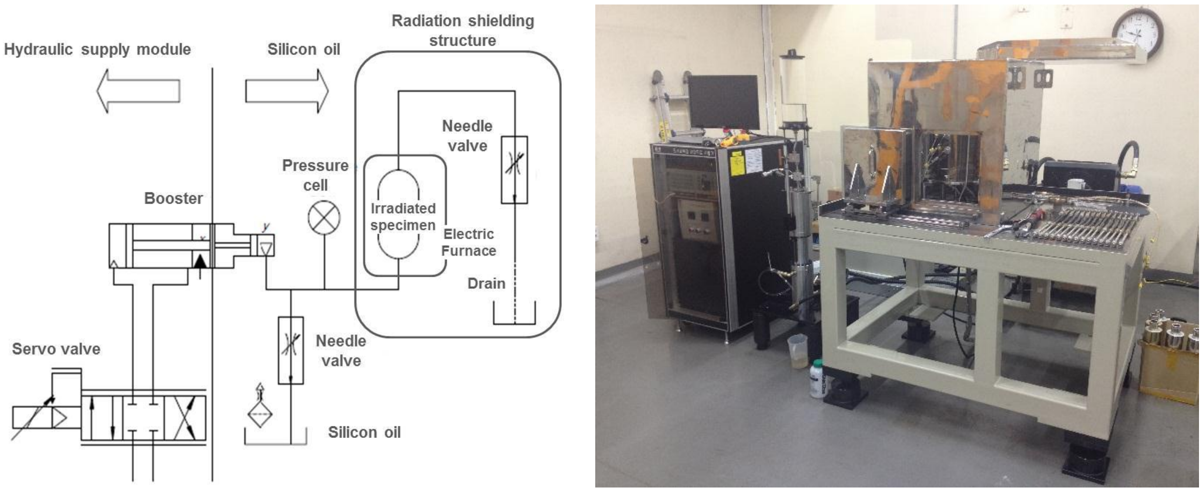

Figure 1. Schematic diagram and image of cyclic pressurization fatigue tester

2.2 Radiation shielding system

Radiation shielding structures that surround the irradiated cladding specimen and the electric furnace were installed to protect the tester and minimize the radiation exposure from the spent fuel cladding specimens. The history of spent fuel cladding for a source term analysis is as follows:

- Initial enrichment of U-235: ≤5 wt%
- Rod average discharge burn-up: 60 GWd/tU
- Cooling period: ≥ 2 years
- Cladding material: Zirlo
- Defueled cladding with 250mm length

Based on the shielding calculation results produced by the MCNP5 code system, the shielding material is determined to be rectangular shaped pure lead with a 50 mm thickness. In addition, the lead structure is covered with a 5 mm thick stainless steel casing.

According to the calcuation results, it has appear that the radiation level of the hot laboratory meet the radiation physical protection regulatory safely. And the radiation source terms were assumed to be conservative enough to cover all kind of irradiated specimens.

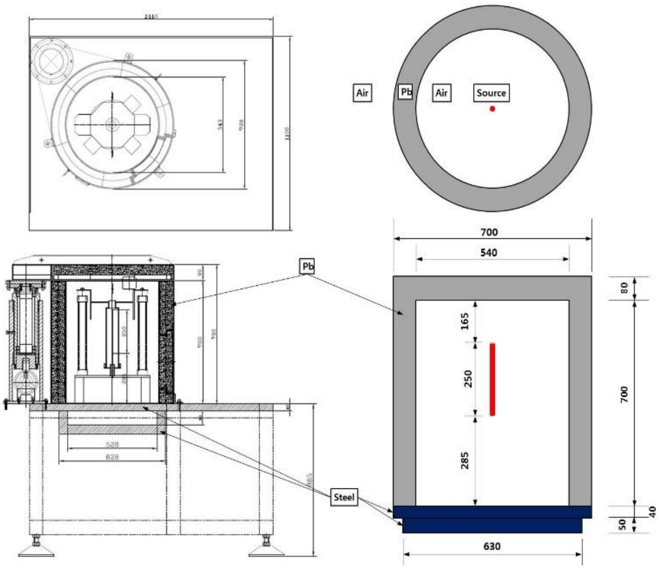

Figure 2. Geometrical modeling for radiation shielding analysis of fatigue test machine

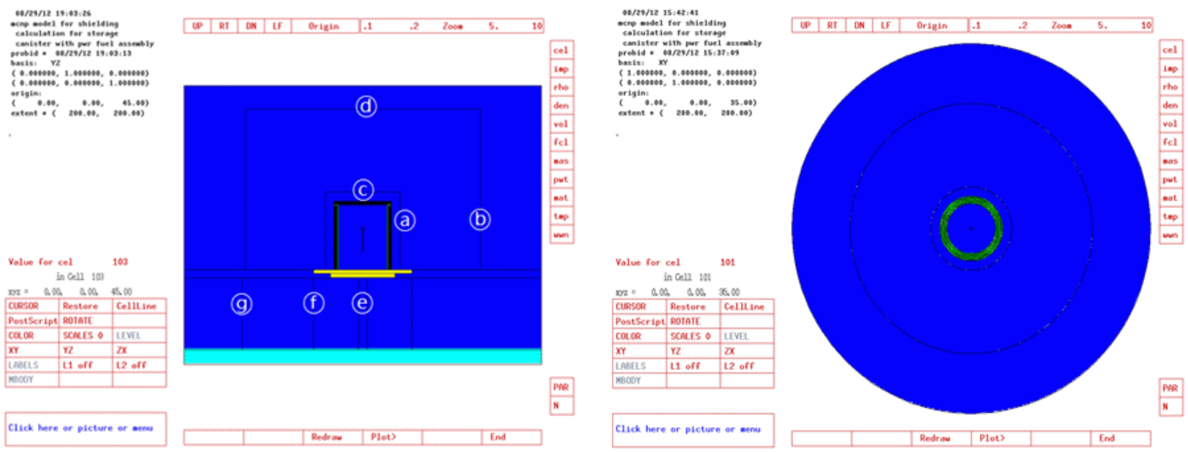

Figure 3. MCNP model for radiation shielding calculation

2.3 Development of remote handling fitting fastening apparatus

It is essential to connect and to fasten the high pressure fittings to the spent fuel specimens remotely in hot cell before fatigue test of irradiated specimens. Therefore, remote handling fitting fastening apparatus was equipped in hot cell. This apparatus was designed to fasten the high pressure fitting to defueled cladding tube specimen remotely using manipulator. The fatigue test specimen clamped with high pressure fitting guaranteed the non-leakage performance during cyclic pressurization. Figure 4 shows the schematic diagram and the principle of apparatus.

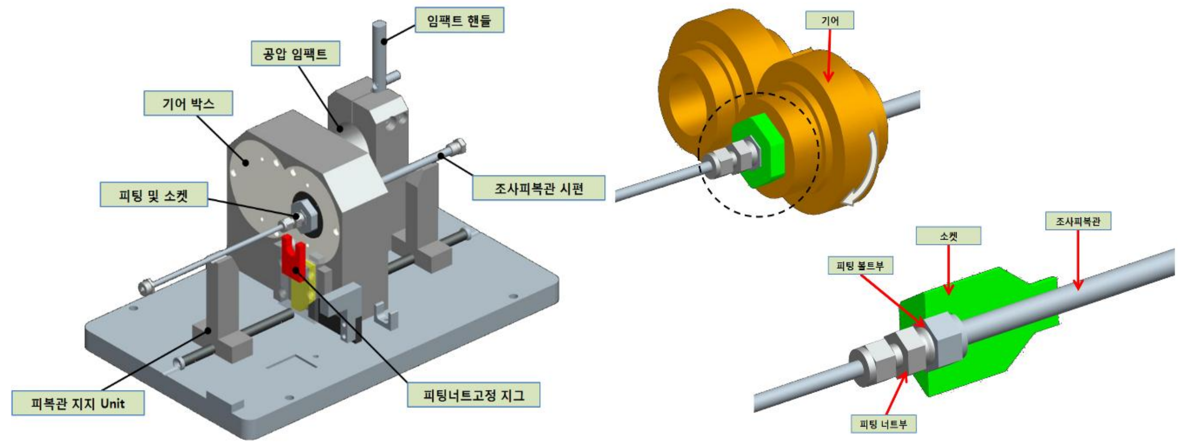

Figure 4. Schematic diagram of fitting fastening apparatus in hot cell

2.4 Performance test of fatigue tester

A performance test of the newly developed cyclic pressurization fatigue tester was carried out on the un-irradiated cladding tube specimens. A constant pressure difference was applied to the un-irradiated zircaloy fuel cladding tube. A sawtooth waveform was applied, where the maximum internal pressure was varied from 44.8 MPa to 64.1 MPa, while the minimum internal pressure was held constant at 10 MPa. The durability of the tester was good up to 10^6 cycles with a 1 Hz frequency.

To ensure the uniform temperature distribution along the specimen, seven thermocouples were attached on the surface of the cladding specimen at every 1 inch. As shown in figure 5, the temperature gradients at a 100 mm distance around the middle of specimen are within ±2℃.

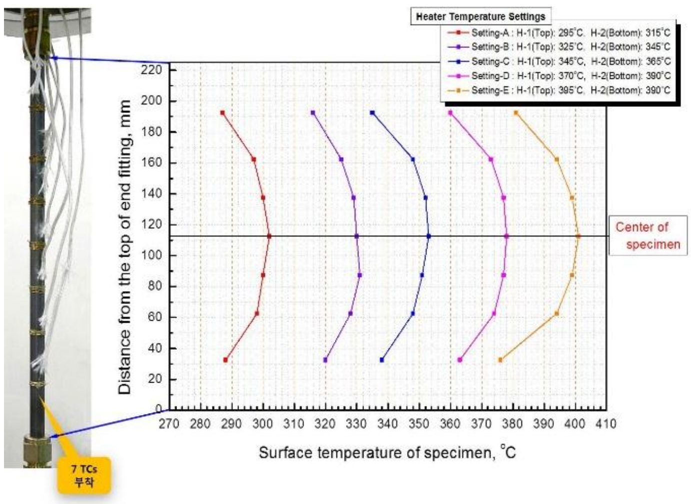

Figure 5. Axial temperature distribution along the cladding specimen

2.5 Low cycle fatigue test under cyclic pressurization

Using the developed test machine, fatigue behavior data of the un-irradiated advanced zircaloy cladding tube w/ and w/o hydrogen have been produced from this study. In addition, the preliminary fatigue test for an irradiated advanced zircaloy cladding tube was also carried out.

A low-cycle fatigue test, where a constant pressure difference was applied to the un-irradiated advanced fuel cladding (PLUS7, 17ACE7) tube, was performed. A sawtooth waveform was applied, where the maximum hoop stress was varied from 350 MPa to 500 MPa, while the minimum hoop stress was held constant at 78 MPa. The temperature was maintained at 400℃ during the fatigue test. The failure cycle, which corresponds to the maximum hoop stress, was measured to construct the S-N curve of each cladding tube. A preliminary low-cycle fatigue test for the irradiated PLUS7 cladding tube was carried out in this study. The rod average discharge burn-up of the PLUS7 spent fuel is about 57 GWd/tU. In addition, the cooling period is about 6 years. The low cycle fatigue test for the irradiated PLUS7 cladding specimen was performed under sawtooth waveform cyclic stress, where the maximum hoop stress was 400 MPa and the minimum hoop stress was held constant at 78 MPa, with a frequency of 1 Hz in a 400℃ air environment.

3. Results

Figure 6 shows the stress-life diagram of an un-irradiated and irradiated Advanced Zircaloy cladding tube under cyclic pressurization. An open mark means that a cladding tube specimen ruptured at the given cycle. A closed mark with an arrow means that a cladding tube specimen survived after the given cycles. As shown in the figure, the failure cycle increased with a decrease in applied stress. In addition, it was found that the failure cycle of a hydrided un-irradiated cladding tube specimen decreased drastically at the same level of maximum hoop stress in comparison with non-hydrided samples.

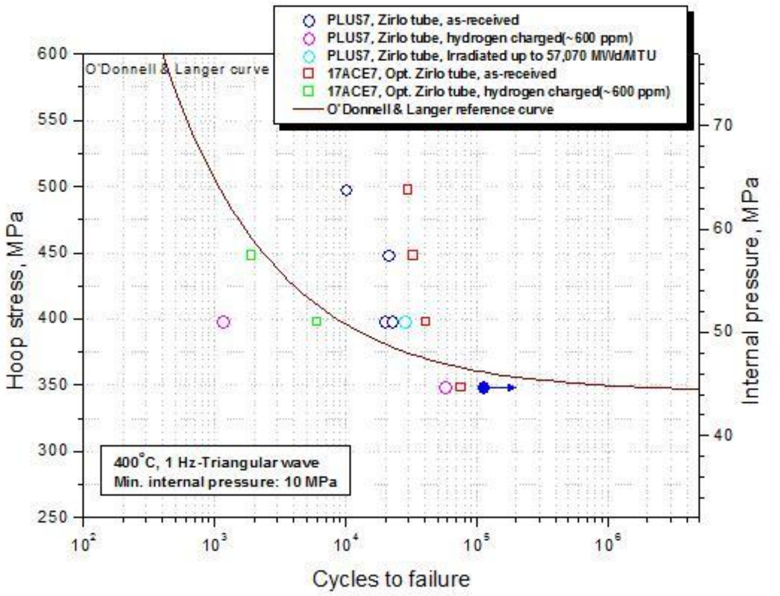

Figure 6. Stress-life curve of advanced Zircaloy cladding

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