Fast Neutron Irradiation Test of Metal Fuel Cladding

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1. Introduction

Evaluating in-pile property of cladding tube is essential for not only usage in fuel design code but also demonstrating integral performance under operating condition. KAERI has developed metal fuel cladding tube (FC92) for PGSFR which has higher creep strength compared to HT9 cladding [1]. To verify its performance, KAERI has successively finished the irradiation test program of fuel cladding tube under fast neutron fluence. Obtained dataset has been used for formulating creep strain model of cladding tube, together with out-of pile creep data.

2. Outline of irradiation test

As the design targets of PGSFR fuel are 650°C in maximum temperature and 100dpa in fast neutron fluence, it was attempted to use foreign reactor for the irradiation test. BOR-60 located in RIAR, Russia has been selected for fast neutron irradiation test because of its availability and achievability of testing parameters. Irradiation test of cladding tube consists of 2 test rigs (Material Test Rig, MTR-1 and 2), which have been characterized by the differences of irradiation temperature (600°C in MTR-1, 650°C in MTR-2). Maximum attainable dose of MTR-1 and MTR-2 at the end of the irradiation test has been set as 45 and 75dpa, respectively. Irradiation test rig is designed to be untightened type so that specimen can be pulled out for either inspection or replacement during the reactor overhaul period.

2.1. Irradiation test items

Irradiation test consists of following items; 1) Irradiation creep (diametral measurement of pressurized cladding tube), 2) Irradiation swelling (density measurement of material rod), 3) Tensile test, and 4) microstructure test. Irradiation creep and swelling test has been planned both at the interim inspection period when each MTR reaches predetermined dpa level, where tensile test and microstructural observation will be performed through the Post Irradiation Examination (PIE) stage after irradiation. Configuration of MTR-1 and 2 is identical, where 36 creep specimens, 18 swelling specimens, 72 tensile specimens, and 6 microstructure specimens are included in a single MTR. Half of the tensile specimens was replaced into new ones during the 1st interim inspection stage (equivalent to 15dpa of dose achieved in each MTR).

Table 1 Irradiation test items

Test Items	Available data (dpa)	MTR-1 (600℃, 45dpa)				Available data (dpa)	MTR-2 (650℃, 75dpa)			
		Total	HT9	FC92B	FC92N		Total	HT9	FC92B	FC92N
Tensile	15	36	12	12	12	15	36	12	12	12
	30	36	12	12	12	30	36	12	12	12
	45	36	12	12	12	45	36	12	12	12
Creep	15	36	10	13	13	15	36	10	13	13
	45					45				
						60				
						75				
Swelling	15	18	6	6	6	15	18	6	6	6
	45					45				
						60				
						75				
Microstructure	45	6	2	2	2	75	6	2	2	2

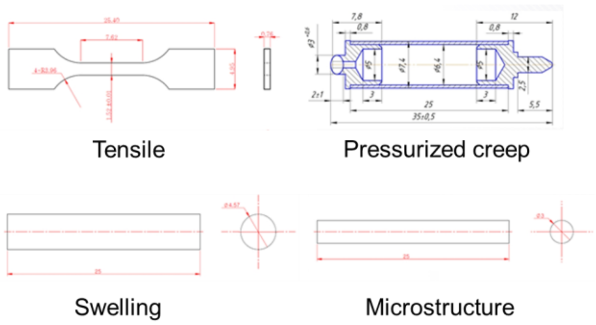

Fig. 1 Design of irradiation test specimen

2.2. Test matrix and specimen manufacture

Setting up the hoop stress value of the pressurized creep specimen (HT9) was made by referring previous irradiation data of Ferritic-Martensitic Steel (FMS) cladding tested in EBR-II as well as FFTF [2-6], where the hoop stress of FC92 was set 30% higher than that of HT9 based on the result of out-of pile creep-rupture data. As the distribution of fast neutron flux varied along the axial direction, specimens with identical hoop stress were located along the different axial location so that the effect of neutron fluence could be modeled. Manufacture of pressurized creep specimen was done by RIAR, after nondestructive examination (UT) over the cladding sample was conducted by KAERI. Specimen manufacturing includes welding at each ends with end plugs, pressurized seal welding, post weld heat treatment, and leak test. Pressurization was done by RIAR at room temperature, where the compensation of pressure due to the differences between manufacturing and test temperature was made [7]. Specimens other than creep (tensile specimen with 25.4mm in total length, 7.52mm in gage length and 0.76mm in thickness, swelling specimen with 4.57mm in diameter, 25mm in length, microstructure specimen with 3mm in diameter, 25mm in length) were manufactured by KAERI and have been sent to RIAR for the irradiation test.

3. Cladding Irradiation test

3.1. Adjustment of irradiation parameters

Along with the specimen manufacture, design and fabrication of irradiation test rig has been progressed. Specimen temperature could be adjusted by controlling gap distance between capsule and rig wall as well as locating number of tungsten rods to cause gamma heating inside the rig. Fusion-type temperature monitors and neutron fluence monitors has been installed inside MTR and validation of irradiation parameters (maximum irradiation temperature, neutron fluence) was performed during interim inspection. Irradiation test rig was non-instrumented type so that prediction of irradiation temperature inside MTR during test period is of importance. Estimated irradiation temperature normally has a variation according to uncertainty of reactor power, coolant flow rate, specimen orientation, gap thickness, calculation errors, and so on. To verify uncertainty value of the temperature inside the test rig, in-core verification test over the manufactured MTR took place after assembling procedure. Thermocouples with different axial position have been installed at the central part of MTR and it has inserted at the instrumentation position inside the BOR-60 core. Test ran for 12 days and temperature inside MTR was monitored with the reactor operation, to acquire relationships between irradiation temperature and reactor power. Based on the result of verification test, additional adjustment was carried out so that the variation of irradiation temperature could be validated by the value of ±5% in uncertainty, namely 600±30ºC in MTR-1 and 650±32ºC in MTR-2.

3.2. Irradiation test

After finishing in-core verification test, irradiation test launched at March 2015, finished in the mid of 2020. Figure 2 shows the accumulated neutron fluence of each MTR during the irradiation test, where accumulated cladding damage dose by fast neutron could be achieved 46.7dpa in MTR-1 and 77.5dpa in MTR-2 at the end of the test. Inspection characterized by the irradiation creep and swelling of the test specimen have been investigated in the hotcell during the test period. Four and two sets of inspection data have been secured from MTR-2 and MTR-1, where it was revealed that in-reactor creep strength of FC92 was 30% higher than HT9, while swelling behavior of FC92 was within the boundary of FMS. Extension of fast neutron fluence is being progressed up to 100dpa by means of metal fuel irradiation test.

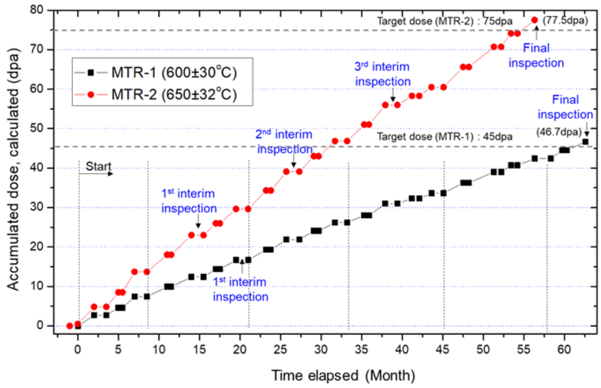

Fig. 2 Accumulated neutron fluence of metal fuel cladding from BOR-60 Irradiation test

4. Summary and Future work

KAERI has developed advanced cladding tube (FC92) prototype in cooperation with the domestic steelmaking company. Out-of pile property revealed that FC92 cladding exhibits superior mechanical property to conventional HT9 cladding. To demonstrate in-reactor property, irradiation tests were carried out in BOR-60 reactor up to 75dpa level in maximum. Obtained dataset of irradiation creep strain has been used as the cladding creep strain model for the fuel performance code in PGSFR. PIE of cladding materials are planned, including shipping back of irradiated materials, setting up relevant test items and conditions, and evaluating mechanical and microstructural property.

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