Fabrication and Evaluation of Advanced Cladding Tube for PGSFR

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Abstract. KAERI has developed cladding material (FC92) which has superior thermal creep property to HT9. In order to verify the performance of cladding tube, KAERI has manufactured FC92 cladding tube in connection with the steelmaking industry. Out-of pile tests like mechanical tests (uniaxial tensile, biaxial burst, pressurized creep) and simulated transient test are now being conducted. Thermo-physical properties (density, Young's modulus, Poisson's ratio, thermal expansion, specific heat capacity and thermal conductivity) of FC92 material is being performed for the usage in fuel design. Quality assurance program has been introduced in all out-of pile tests to acquire reliability of the test data. Evaluating in-pile property of cladding has been launched by an irradiation test program of fuel cladding tube using an experimental fast reactor (BOR-60), where irradiation creep and swelling will be mainly performed. Interim inspection revealed that in-reactor creep strength of FC92 cladding tube was higher than that of HT9 cladding by 30%.

Key Words: Cladding tube, Out-of-pile test, In-pile test

1. Introduction

Ferritic-martensitic steel (FMS) has been chosen as a candidate cladding material for the prototype sodium-cooled fast reactor (PGSFR) in Korea because of its superior swelling resistance against high-energy neutron. KAERI has developed cladding material (FC92) which has superior thermal creep property to HT9. Alloy design and screening test has been performed so that candidate material can be selected. In order to verify the performance of cladding tube, KAERI has manufactured FC92 cladding tube in connection with the steelmaking industry. Out-of pile tests like mechanical tests (uniaxial tensile, biaxial burst, pressurized creep) and simulated transient test are now being carried out. Thermo-physical properties (density, Young's modulus, Poisson's ratio, thermal expansion, specific heat capacity and thermal conductivity) of FC92 material is being performed to use in fuel design. Quality assurance program has been introduced in all out-of pile tests to acquire reliability of the test data. Evaluating in-pile property of cladding tube is essential for not only usage in fuel design but also demonstrating integral performance of developed cladding under irradiation condition. To verify its in-core performance, KAERI has launched irradiation test program of fuel cladding tube using an experimental fast reactor. In 2014, irradiation test using BOR-60 reactor in RIAR has been initiated, where irradiation creep and swelling will be mainly performed. Obtained dataset will be used for developing creep model of FC92 cladding tube, together with out-of pile creep data.

2. Fabrication of cladding tubes

FC92 alloy has been designed to increase thermal creep property by optimizing microstructure inside the FMS. Chemical composition of FC92 alloy is based on the Gr.92 (9Cr-2WVNb) stainless steel, and optimized alloying elements by decreasing C content to the lower range, increasing Nb content to initiate the number of MX (Nb-rich carbonitride and V-rich carbonitride) precipitates, adding Ta, and balancing B / N content to increase the stability of precipitates. Out-of pile thermal creep property of FC92 material under 650ºC air environment has revealed that creep strength of FC92 is higher than HT9 material by 30%, which indicates the increase of thermal margin of metal fuel rod, as shown in FIG. 1.

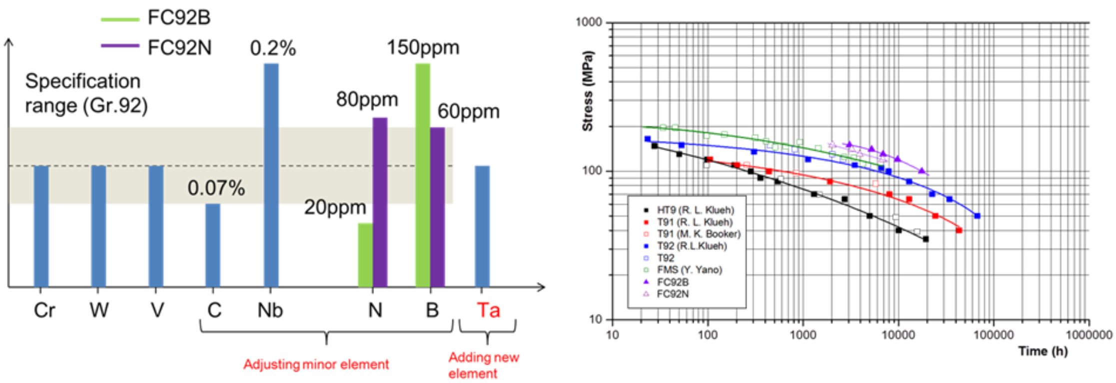


FIG. 1. Design and out-of pile thermal creep property of FC92 alloy.

Besides the material development, manufacturing process technologies of cladding tube have been scoped. Parametric studies like effect of the cold work, and the heat treatment (intermediate / final heat treatment) have been performed to find out the optimum range of cold work and the heat treatment parameters. Based on the parametric studies, fabrication of FC92 cladding tube has been initiated in collaboration with the domestic steelmaking company. 2 tons of ingot was made through the vacuum induction melting (VIM), followed by the refinement as the electro-slag remelting (ESR) process. The ingot was extruded into the mother tubes having 46mm outer diameter and 3.5mm thickness by hot extrusion and subsequent annealing process. The mother tubes were drawn into seamless cladding tube by 5 times of cold works and intermediate heat treatment (Bright Annealing). The intermediate tubes were finally cold drawn into cladding tubes with 7.4mm outer diameter and 0.5mm thickness, followed by the final heat treatment. Final heat treatment condition was 1038^{o}C for 6 minutes as a normalization and 760^{o}C for 40 minutes as a tempering. FIG. 2 summarizes the manufacture of FC92 cladding tube.

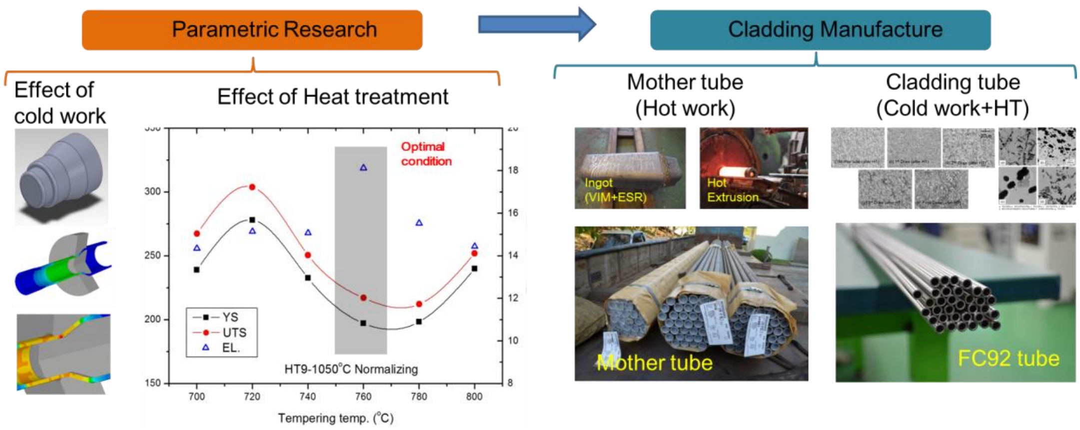


FIG. 2. Manufacture of FC92 cladding tube.

3. Evaluation of cladding tubes

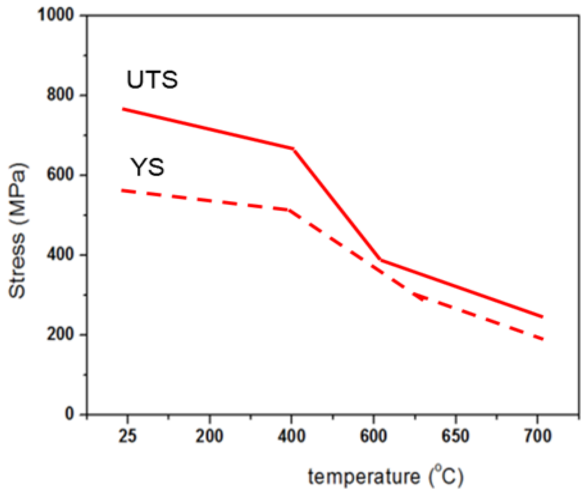
3.1. Out-of-pile test of cladding tubes

Manufactured cladding tubes have been transferred into KAERI. Dimensional measurement (Outer/inner diameter, thickness, ovality, straightness and roughness) has been carried out, which revealed that manufactured cladding tube fitted within the manufacturing specification. Mechanical and thermo-physical properties over the manufactured FC92 cladding tube have been evaluated to establish a database for the fuel performance code. Mechanical tests of the cladding tube have been carried out. Axial tension test, biaxial burst test, and pressurized creep test have been performed. Quality Assurance (QA) program (Establishing QA plan, test procedure, personnel certification, calibration of measuring devices, and so on) has been introduced in all kinds of out-of pile tests in order to acquire reliability of the test data. Status of dimensional and mechanical tests of FC92 cladding is summarized at TABLE I.

TABLE I: OUT-OF-PILE TEST LISTS OF FC92 CLADDING TUBE.

Test items	Subitems	Description	Status
Dimensional deviation	Diameter (outer, inner)	OD / ID measurement by LWR cladding procedure	Done
	Wall thickness	Derivation from the difference between OD and ID	Done
	Ovality	Tested by laser scanning	Done
	Straightness	Evaluation by LWR cladding procedure	Done
Surface & Internal condition	Surface roughness	OD / ID measurement by LWR cladding procedure	Done
	Surface defect	Visual inspection followed by LWR cladding procedure	Done
	Internal defect	Nondestructive examination (UT) over the cladding sample	Done
Mechanical performance	Tensile test	Axial tensile test (RT~700℃)	Done
	burst test	Short-term burst test (700~790℃)	Progress
	Creep test	Long-term creep test of pressurized cladding (570~680℃)	Progress
	Transient test	Thermal ramp / ramp and hold test of pressurized cladding	Progress
	Fatigue	Low / High cycle fatigue test (Axial, RT, 650℃)	Done

Temperature dependency of tensile property of FC92 cladding tube behaved similar trend to HT9 cladding tube as shown in FIG.3. Biaxial burst test and pressurized cladding test of FC92 cladding tube showed that burst and creep strengths of FC92 tube were 30% higher than HT9 tube (refer to FIG. 4).



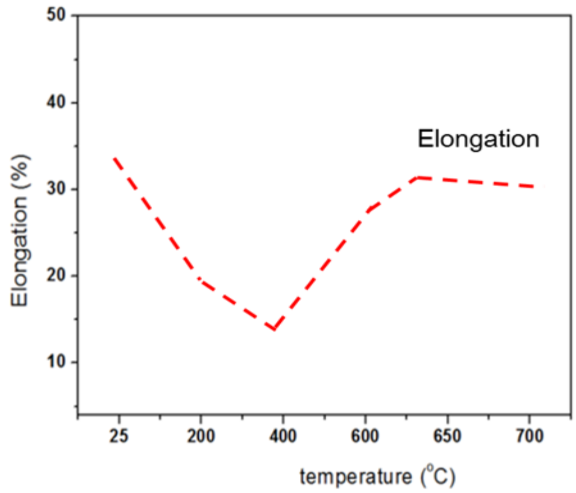


FIG. 3. Uniaxial tensile test property of FC92 cladding with test temperature.

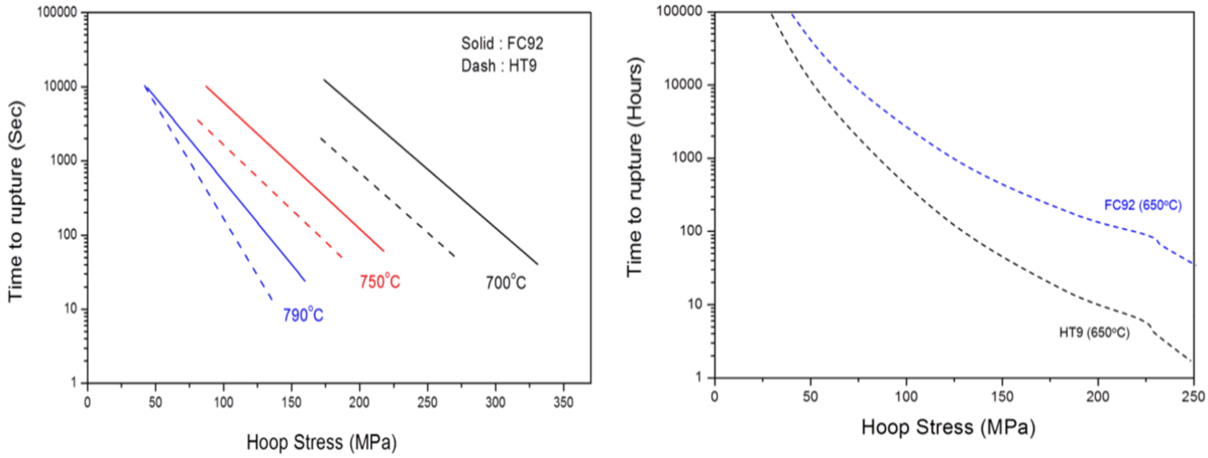


FIG. 4. Biaxial burst (left) and pressurized creep test (right) of FC92 cladding tube.

Cladding should show proper performance not only in the normal case, but also in the postulate transient condition. Thermal ramp test as well as ramp and hold test according to FFTF fuel cladding design [1-2] have been applied in FC92 cladding tube. FIG. 5 showed the transient condition test mode and the stress-temperature diagram of FC92 cladding tube under transient conditions, collated with the HT9 data.

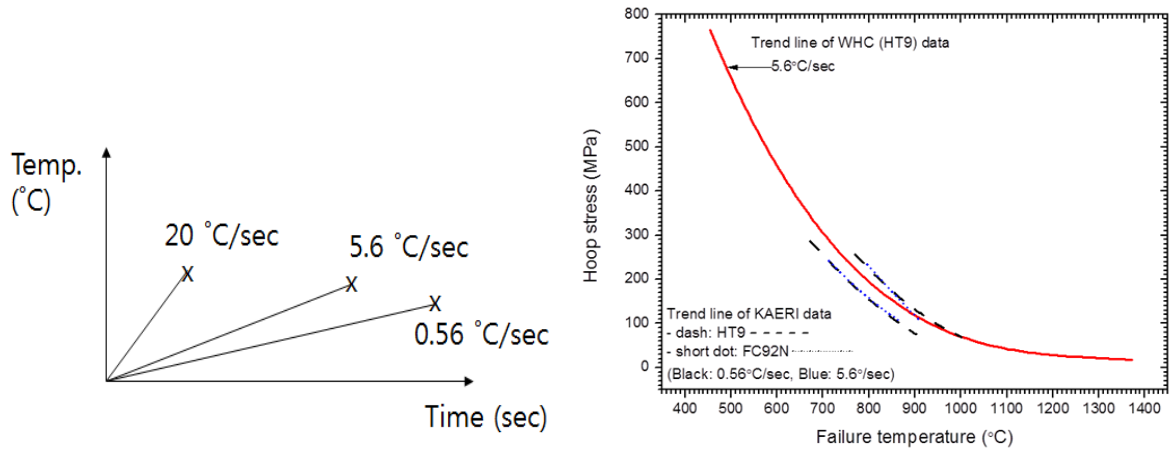


FIG. 5. Transient performance of FC92 cladding tube (Ramp mode).

Thermo-physical property of FC92 cladding material has been performed. Thermal properties like density, thermal expansion coefficient, specific heat capacity, thermal diffusivity, phase transformation, and physical properties like Young's modulus, shear modulus, Poisson's ratio have been conducted over KAERI-heat HT9 and FC92 cladding tubes, which showed that properties of FC92 material behaved similar trend to HT9 cladding material. All of the test items followed after QA program to secure reliability. Status of thermo-physical properties of FC92 cladding material is summarized at TABLE II.

TABLE II: STATUS OF THERMO-PHYSICAL PROPERTY TEST OF FC92 CLADDING.

Test items	Subitems	Description	Status
Thermo-physical property	Density	Tested at RT, compensation for thermal expansion (~900°C)	Done
	Thermal expansion coeff.	Tested by TMA (20~1000°C)	Done
	Specific heat capacity	Tested by DSC (RT~900°C)	Done
	Thermal conductivity	Derivation from thermal diffusivity (by Laser flash method) (RT~900°C)	Done
	Phase transformation	Tested both TMA and DSC	Done
	Young's modulus	Tested by resonant frequency method (RT~900°C)	Done
	Shear modulus	Tested by resonant frequency method (RT~900°C)	Done
	Poisson's ratio	Derived from Young's modulus and shear modulus	Done

3.2.In-pile test of cladding tubes

3.2.1.Description of BOR-60 irradiation tests

Evaluating in-pile property of cladding tube is essential for not only usage in fuel design but also demonstrating integral performance of developed cladding under the irradiation condition. To verify its performance, KAERI has launched irradiation test program of the fuel cladding tube using an experimental fast reactor. In 2014, irradiation test was initiated by using research reactor (BOR-60), where irradiation creep and swelling will be mainly performed. Irradiation tests of cladding tube consist of 2 test rigs (Material Test Rig (MTR)-1 and 2), which are characterized by irradiation temperatures (600±30^{o}C in MTR-1, 650±32^{o}C in MTR-2). Maximum attainable doses of MTR-1 and MTR-2 at the end of the irradiation test will be 45 and 75dpa, respectively. Irradiation tests will be ended at the end of 2019. Irradiation test rigs were designed to be untightened type so that interim inspections of dimensional change of specimens are able during the overhaul period of BOR-60, where post irradiation examination (PIE) over the irradiated specimen will be planned at 2020. FIG. 6 summarizes the irradiation test schedule of FC92 cladding tube.

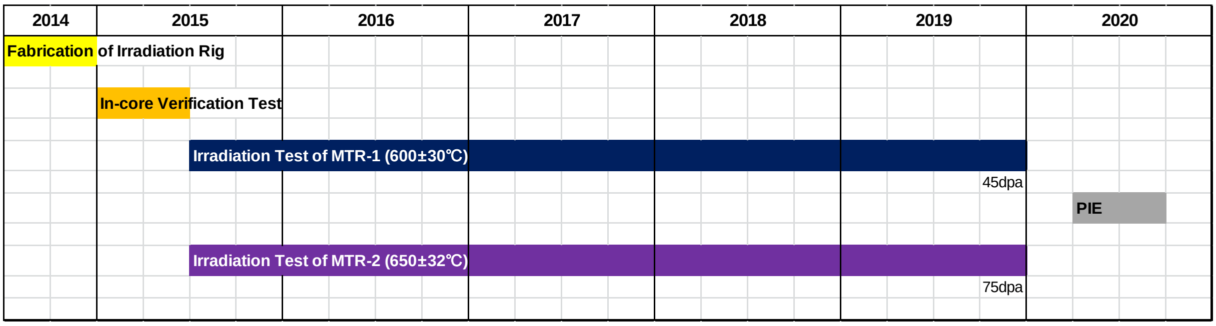


FIG. 6. Irradiation test schedule of FC92 cladding tube.

Irradiation test items consist as follows; 1) In-reactor creep (diametral measurement of pressurized cladding tube), 2) Irradiation swelling (density measurement of material rod), 3) Tensile test, and 4) microstructure test, where the measurements of creep and swelling specimens will be planned at the interim inspection period when each MTR reaches 15 and 30dpa, and after the irradiation test. Tensile test and microstructural observation will be performed through the Post Irradiation Examination (PIE), which will be scheduled after the irradiation test. Configurations of MTR-1 and 2 are identical, where it contains 36 creep specimens, 18 swelling specimens, 72 tensile specimens, and 6 microstructure specimens in each MTR. Regarding tensile specimens, half of the specimens will be replaced into new ones during the 1st interim inspection stage (equivalent to 15dpa of dose achieved in each MTR). TABLE III summarizes the test items and specimen sets.

TABLE III: IRRADIATION TEST ITEMS AND SPECIMEN SETS.

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	60	36	12	12	12
	45	36	12	12	12	75	36	12	12	12
Creep**	15	36	10	13	13	15	36	10	13	13
	30					30				
	45					75				
Swelling**	15	18	6	6	6	15	18	6	6	6
	30					30				
	45					75				
Microstructure	45	6	2	2	2	75	6	2	2	2

* Half of specimens (12 per each materials) will be replaced into new ones during the 1st interim inspection (15dpa)

** 15 and 30dpa data will be obtained through the 1st, 2nd interim inspection

Determination of hoop stress values of the pressurized creep specimens (HT9) was made by referring the previous irradiation data of ferritic-martensitic steel cladding tubes in EBR-II as well as FFTF [3-7]. Manufacturing creep specimen was done, including welding end plugs, pressurized seal welding, post weld heat treatment, and leak test. 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 sent to RIAR for the irradiation test.

3.2.2.BOR-60 irradiation test status

Along with specimen manufacture, design and fabrication of irradiation test rigs have been finished in 2014. Specimen temperature can be attained by adjusting the gap size between capsule and rig wall as well as the number of tungsten rods inside the specimen holders. Fusion-type temperature monitors and neutron fluence monitors have been installed inside the MTR and validation of irradiation parameters (temperature, neutron fluence) will be performed during the inspection period. Irradiation test rigs were non-instrumentation type so that precise estimation of irradiation temperature inside MTR during test period is of importance. Irradiation temperature in BOR-60 normally has ±5% uncertainty depending on the reactor power, the sodium flow rate, the configuration of rig itself, and the calculation errors. To minimize calculation errors and verify the temperature inside the test rig, an in-core verification test of MTR took place, where thermocouples with the different axial position have been installed at the central part of MTR and the MTR has inserted at the instrumented position inside BOR-60 core. The verification test of the MTR ran for 12 days and temperatures inside MTR were monitored with the reactor operation. After finishing in-core verification test, irradiation test of MTR-1 and 2 started in the March of 2015. Accumulated neutron dose in December 2016 could be achieved 16.7±2.2dpa in MTR-1 and 29.6±1.0dpa in MTR-2, as in FIG. 7.

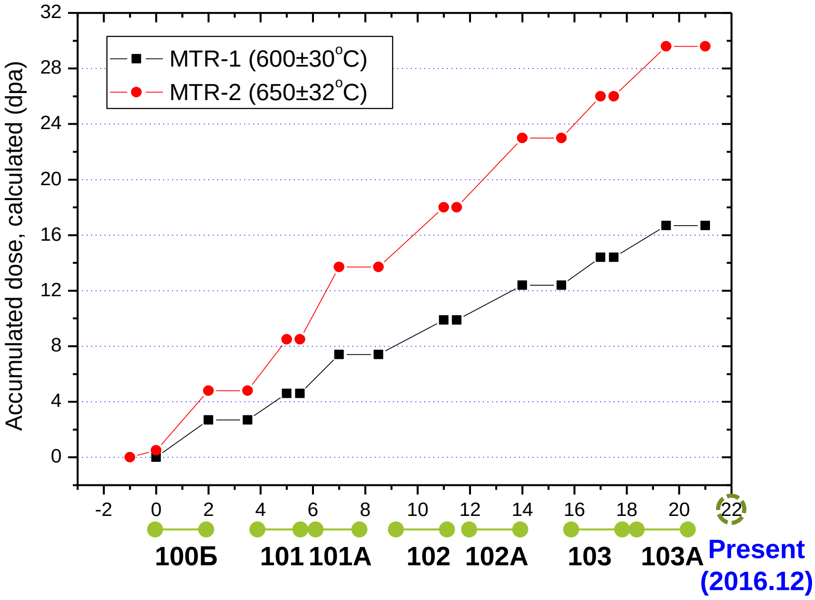


FIG. 7. Status of accumulated fast neutron dose in irradiation test.

3.2.3.Interim inspection

Interim inspection has been performed over MTR-2 in May 2016, when the neutron dose of MTR-2 achieves 22.7±0.7dpa (at the end of reactor cycle 102A). Interim inspection consists of 1) visual inspection of the irradiated specimen (Pressurized creep, swelling, microstructure), 2) diametral measurement of the creep specimen, 3) density measurement of swelling specimen, 4) examination of temperature/neutron fluence monitor, and 5) the replacement of tensile specimen. Visual examination of FC92 specimen showed good surface condition, where no failure or rupture was observed in pressurized creep specimen during the interim inspection, as shown in FIG. 8. Preliminary evaluation of creep data revealed that in-reactor creep strength of FC92 was 30% higher than that of HT9. Further interim inspection will be consecutively scheduled until 2020.

FIG. 8. Visual inspection of FC92 specimen after the interim inspection

4. Further works

Comprehensive thermal creep model of FC92 cladding tube will be established by collecting various kinds of out-of pile creep testing data, such as long-term creep-rupture tests (~50,000hrs), secondary creep rates of pressurized cladding specimens under air environment, and in-situ measurement of primary creep strains using instrumented creep tester under pressurized loading. Establishing further database of FC92 cladding tube under transient conditions will be performed, in order to fit the CDF (Cumulative Damage Fraction) correlation of FC92 cladding tube under the postulated transient condition.

Obtained dataset of the in-reactor creep will be used as the development of creep model for the fuel performance code in PGSFR. Relevant creep model will be established according to the result of interim inspections, and then the modification of creep model to fit the data will be performed at the next stage. On account of the limitation of the lifetime in BOR-60, maximum neutron dose is limited at 75dpa until now. Further irradiation test (~100dpa) is planned to be done in BOR-60 or MBIR next to the irradiation test.

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