Post-Irradiation Examination Supporting the Transformational Challenge Reactor

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INTRODUCTION

Accelerated irradiation testing in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) allows data on advanced manufactured materials for the Transformational Challenge Reactor (TCR) program to be quickly acquired. This approach is consistent with the TCR's agile design and advanced manufacturing process, which aims to develop, build, and operate structural components within a high-temperature gas-cooled microreactor core [1–2]. Some materials in the TCR core are intended to be fabricated using advanced manufacturing routes or are novel materials that are not currently used in light water or advanced reactors. Those materials require irradiation testing to assess their behavior under dose and temperature conditions relevant to the reactor design.

Three different non-fueled irradiation test series, corresponding to three materials used in the TCR core, have been performed in the HFIR using a total of 24 irradiation capsules: additively manufactured silicon carbide (SiC), additively manufactured 316L stainless steel, and yttrium hydride (YH_x). This summary describes the status of the TCR irradiation testing and the post-irradiation examination (PIE) plan for these three test series.

IRRADIATION TESTING

SiC Irradiation Testing

Additively manufactured SiC material is intended to be used as the TCR core fuel matrix. To collect data on this additively manufactured material, six irradiation capsules containing SiC disk specimens were irradiated in the HFIR flux trap during HFIR cycle 486 (February 2020). All capsules were irradiated for 1 full cycle, corresponding to 2 dpa, with a target temperature of either 400°C, 650°C, or 900°C. Table I shows the corresponding irradiation test matrix. 3D-printed SiC [3] specimens of two different orientations (x-y and z) as well as chemical vapor deposition (CVD) SiC [4] control specimens were placed in each capsule. The specimens are 0.5 mm thick disks with a 6 mm diameter.

The six capsules were disassembled at the Irradiation Materials Examination and Testing (IMET) hot cell facility at ORNL. All capsule components were recovered; Figure 1 shows a set of SiC disk specimens recovered from a capsule after disassembly. SiC disks specimens, as well as passive SiC temperature monitors (TMs), were shipped to the Low Activation Materials Development and Analysis (LAMDA) laboratory for PIE.

TABLE I. SiC irradiation test matrix

Capsule ID	Irradiation Temperature	Dose (dpa)	Material
SDTR01	400°C	2	3D-printed SiC (x-y and z orientations) and CVD SiC
SDTR02	650°C		
SDTR03	900°C		
SDTR04	400°C		
SDTR05	650°C		
SDTR06	900°C		

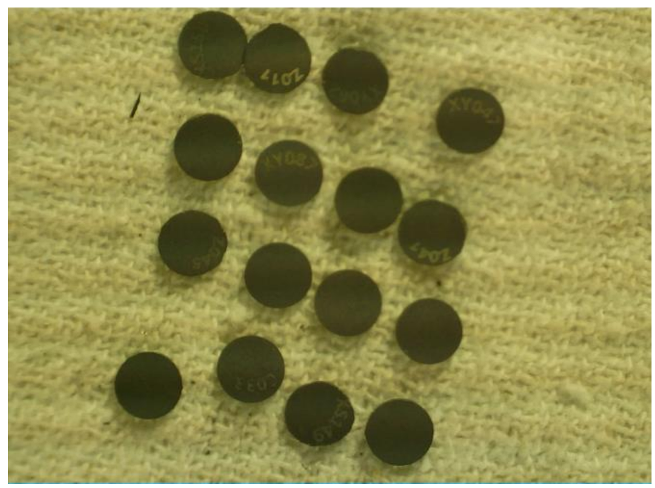

Fig. 1. Disks specimens from SDTR05 recovered after hot cell disassembly of the capsule.

TMs will be analyzed via dilatometry measurements to confirm the irradiation temperature [5]. The PIE on the SiC disks specimens includes swelling assessment, thermal diffusivity measurements, monotonic equibiaxial flexural strength test, and microscopy analysis. Dimensional measurements are planned to be performed and compared with the data collected before irradiation; this will provide an initial assessment of the specimens swelling during irradiation. Thermal diffusivity measurements will be performed on two disks specimens per irradiation temperature and per printed orientation using the laser flash methodology (ASTM E1461) via a Netzsch LFA 467 instrument. Every specimen will finally go through equibiaxial ring-on-ring mechanical testing in conformance to the standard test procedure specified in ASTM C1499.

The data collected from the 3D-printed SiC specimens will be analyzed against the data collected from reference CVD SiC specimens. In addition, the data collected on irradiated specimens will be compared with those collected for the non-irradiated specimens. It is expected that 3D-printed SiC specimens will provide tolerance to in-core irradiation damage and resistance to thermal creep similar to that provided using CVD SiC. This PIE campaign is expected to be completed by the end of the summer of 2020.

316L Irradiation Testing

Additively manufactured 316L material is considered in the TCR design for structural components of the fuel assembly. The irradiation testing of this material consists of six capsules, with a specimen target temperature of either 300 or 600°C. Four capsules were irradiated during cycle 486 (February 2020) or cycle 487 (May 2020), for either 1 or 0.1 cycle, corresponding to 2 or 0.2 dpa, respectively. The last two capsules started irradiation in HFIR during cycle 487 and will complete irradiation after cycle 490 (September 2020), which will provide a 4-cycle irradiation, corresponding to an exposure of 8 dpa. Table II presents the irradiation test matrix.

Each capsule contains additively manufactured [6] and wrought 316L tensile specimens, with dimensions of 16×4×0.5 mm. Some additively manufactured specimens were annealed at either 650°C or 1,050°C for 1 hour in a vacuum environment.

TABLE II. 316L Irradiation Test Matrix

Capsule ID	Irradiation temperature	Dose (dpa)	Material
GTCR01	300°C	0.2	Wrought 316L and
GTCR02		2	3D-printed 316L
GTCR03		8	(as-printed, or
GTCR04	600°C	0.2	printed+650°C or
GTCR05		2	1,050°C heat
GTCR06		8	treatment)

The four capsules that have completed irradiation have been shipped to IMET for disassembly. Figure 2 shows a set of tensile specimens and TMs recovered during disassembly from one capsule. TMs will be shipped to LAMDA to determine the average irradiation temperature of each capsule using the dilatometry method. PIE includes hot cell tensile testing at room and irradiation temperatures, microscopy, and in situ deformation testing in a scanning electron microscopy (SEM). PIE data will be collected with a high degree of spatial selectivity, to eventually correlate material and component performance data to the digital data collected during the fabrication process. The PIE results for these four capsules are expected during the fall of 2020.

The data obtained for 316L specimens produced through additive manufacturing will be compared with data on the wrought specimens. The impacts of heat treatment on 3D-printed specimen properties will also be assessed.

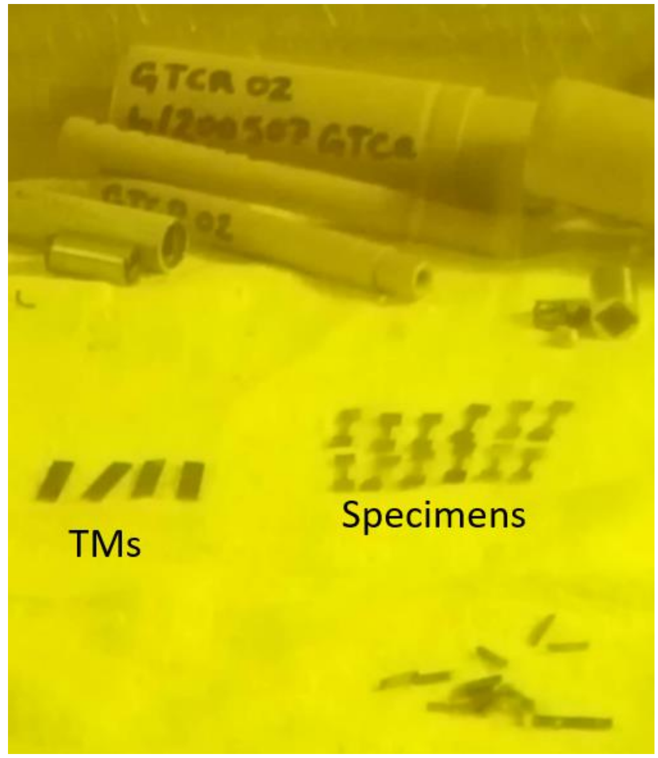

Fig. 2. One set of tensile specimens and TMs recovered during disassembly of the GTCR02 capsule.

YH_x Irradiation Testing

YH_x is the material selected for use as the TCR core moderator, because of its high hydrogen atom density and its exceptional thermal stability [7]. Irradiation testing is performed on YH_x specimens to acquire data on this material's performance and properties under irradiation and ultimately allow for future use of this high-temperature moderator in advanced reactors.

Twelve capsules were irradiated in the HFIR flux trap during cycle 487 (May 2020) and cycle 488 (June 2020). This irradiation test series targets temperatures of 600°C and 900°C and three different doses, 0.1, 1, and 2 dpa, which correspond to approximately 0.05, 0.5, and 1 irradiation cycle. The capsules contain disk specimens with a hydrogen concentration of either $YH_{1.72}$ or $YH_{1.87}$. The disk specimens are 0.5 mm thick and have a diameter of 6 mm. The irradiation test matrix is presented in Table III.

To date, eight of the twelve YH_x capsules have been shipped to IMET for disassembly. TMs and specimens will be shipped to LAMDA for PIE. PIE will focus on assessing the thermophysical and thermomechanical properties of YH_x, such as swelling, density, thermal diffusivity, specific heat, Vickers hardness, and flexural strength. Microstructure and metallography (optical microscopy) analyses will also be performed. Density measurements will be performed using the helium pycnometry technique. Finally, the average irradiation temperature of each capsule will be determined using the dilatometry method on TM specimens in each rabbit.

TABLE III. YH Irradiation Test Matrix

Capsule ID	Irradiation Temperature	Dose (dpa)	Material
YHXT01	600°C	0.1	$YH_{1.72}$
YHXT02		1	
YHXT03		2	
YHXT04	900°C	0.1	
YHXT05		1	
YHXT06		2	
YHXT07	600°C	0.1	$YH_{1.87}$
YHXT08		1	
YHXT09		2	
YHXT10	900°C	0.1	
YHXT11		1	
YHXT12		2	

The PIE results are expected during the fall of 2020. The data collected will be compared with those collected pre-irradiation to assess the YH_x material behavior under irradiation.

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CONCLUSIONS

This summary presents the irradiation testing being performed on additively manufactured SiC, additively manufactured 316L, and YH_x specimens to support the development and demonstration of the Transformational Challenge Reactor. Most of the irradiation capsules addressing these objectives have completed irradiation and have begun PIE. The PIE plan for each material being tested will provide critical material properties data for the design and licensing of the TCR's core. The status of each irradiation, progress on PIE, and analyzed average temperatures of irradiation vehicles are reported.

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