HFIR Irradiation Testing Supporting the Transformational Challenge Reactor

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INTRODUCTION

The objective of the Transformational Challenge Reactor (TCR) program is to rapidly demonstrate the application of advancements in materials, manufacturing, and computational techniques to alleviate high costs and lengthy timelines currently required to develop advanced nuclear energy systems [1–2]. TCR exploits an agile design and advanced manufacturing process to develop, build, and operate structural components within a high-temperature gas cooled microreactor core. The novel materials and manufacturing routes used in the TCR core differ from conventional constituents of light-water or advanced reactor cores and thus require irradiation testing. The goal of these irradiations is to verify expectations of the materials' behavior under irradiation based on the current understanding in radiation materials science.

Three different non-fueled irradiation test series, corresponding to three materials used in the core, will be performed in ORNL's High Flux Isotope Reactor (HFIR): 3D-printed silicon carbide (SiC), 3D-printed 316L stainless steel, and yttrium hydride (YH_x with 1.7 < × < 1.9). This summary describes the design of the capsules to be used for irradiation testing of these three types of materials, as well as the current status of the irradiation testing.

SiC Irradiation Testing

The TCR fuel matrix will be formed using additively manufactured SiC which will be binderjet printed and chemical vapor infiltrated (CVI) [3]. This process offers an ideal level of freedom in component design and geometrical complexity. The 3D-printed SiC is a high purity, fully crystalline material and is expected to provide tolerance to in-core irradiation damage and resistance to thermal creep similar to that provided using chemical vapor deposition (CVD) SiC [4].

The experiment design for irradiation testing of 3D-printed SiC material uses disk specimens that are 0.5 mm thick and 6 mm in diameter. These specimens are inserted into a holder which is inserted inside the capsule housing that is directly cooled on the outer surface by HFIR's primary coolant. The specimen temperature is controlled by varying the concentration of a helium/argon gas mixture and the size of the holder-to-housing gap. Temperature monitors (TMs) are also inserted into the capsule and will be analyzed via dilatometry measurements post irradiation to confirm the irradiation temperature [5]. Each capsule accommodates 32 disk specimens; those disks are either SiC disks 3D-printed in two different orientations (x-y or z), or CVD SiC disks as controls. Figure 1 shows the parts layout for one capsule.

Six irradiation capsules were assembled and are planned for irradiation in the HFIR flux trap in early 2020. They will be irradiated for 1 cycle, or 2 dpa. The target temperature will be either 400°C, 650°C, or 900°C to assess the performance of these advanced manufactured materials under the point defect swelling saturation regime [3]. Table I shows the corresponding irradiation test matrix.

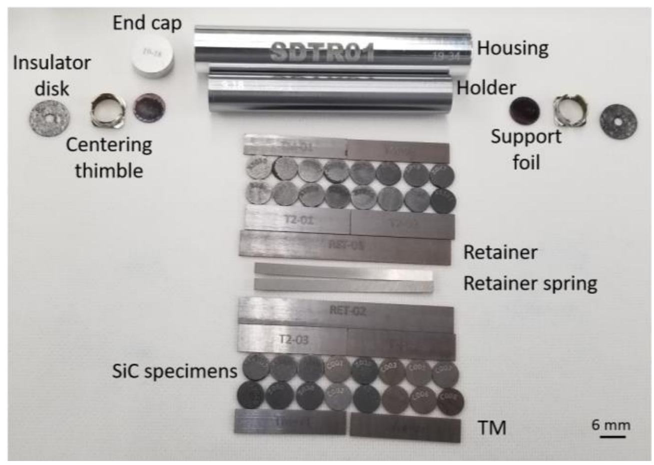

Fig. 1. Parts layout for SiC disks capsule.

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		

Post-irradiation examination (PIE) will include dimensional inspection to assess swelling, thermal diffusivity measurements, and equibiaxial ring-on-ring flexural strength testing on these SiC disk specimens. The data collected from the 3D-printed SiC specimens will be analyzed against the data collected from the reference CVD SiC specimens.

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316L Irradiation testing

The TCR core lattice is intended to be formed by laser powder bed fusion (LPBF)–derived austenitic stainless-steel grade 316L metal structures [6]. Neutron irradiation data on LPBF-derived 316L material, particularly with good manufacturing pedigree, is sparse and requires assessment.

The experiment design accommodates 36 tensile specimens that are 0.5 mm thick. The specimens are stacked inside holders with outside diameters that are optimized to create the gas gaps to control capsule temperature. Other capsule components include SiC TMs, chevrons, and spring pins. Performance details on this design can be found in references [7-9]. Figure 2 shows the parts layout for a tensile capsule assembly.

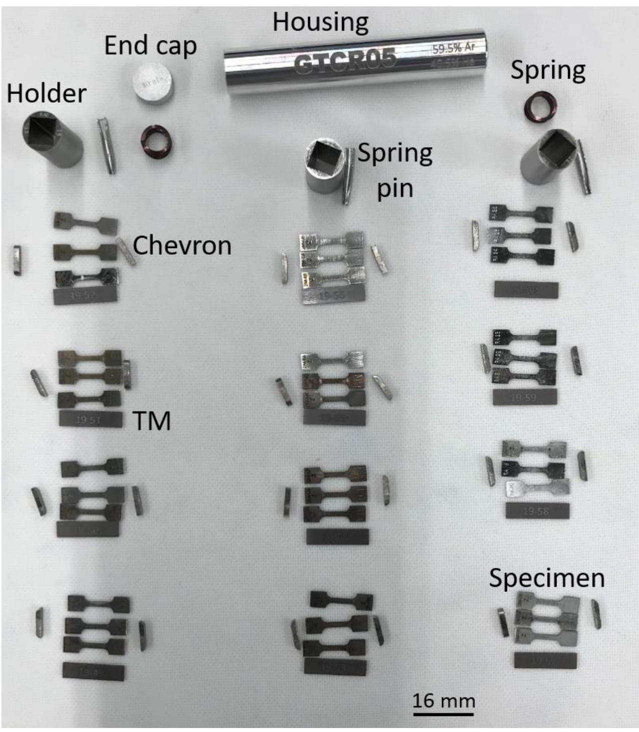

Fig. 2. Parts layout for a 316L tensile capsule.

Tensile specimens have been machined from wrought and additively manufactured blocks of 316L stainless steel. Some 3D-printed specimens were annealed at either 650°C or 1,050°C for one hour in a vacuum environment. During specimen machining, the location of each specimen in the blocks was recorded to establish eventual correlation between material properties and in situ manufacturing data collected during the LPBF process. This is a key feature of the TCR program - the objective is to correlate material and component performance data to the digital data collected during advanced manufacturing using data analytics approaches. Therefore, post irradiation data must be collected with a high degree of spatial selectivity.

Six capsules are planned to be assembled and irradiated in the HFIR flux trap at 300 and 600°C for 0.1, 1 and 4 irradiation cycles corresponding to exposures of about 0.2, 2, and 8 dpa. Each capsule will contain additively manufactured and wrought 316L tensile specimens. Table II presents the irradiation test matrix. To date, the two 1-cycle irradiation capsules have been assembled and are ready for insertion in HFIR for cycle 486 (February 2020).

PIE will focus on mechanical testing as a function of temperature and dose, as well as assessing microstructure evolution after accumulation of neutron irradiation damage. The data obtained for 316L specimens produced through additive manufacturing will be compared to data on wrought specimens. The impacts of heat treatment on 3D-printed specimen properties will also be assessed.

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)

YH_x Irradiation Testing

YH_x is the material selected for use as the TCR core moderator. YH_x has high hydrogen atom density, and it exhibits exceptional thermal stability [10], so it is a good moderator for high-temperature nuclear energy systems. Data on YH_x performance and properties under neutron irradiation currently do not exist, so they must be compiled to allow for future use of this high-temperature moderator in advanced reactors.

The capsule design will accommodate 16 disk specimens that are 0.5 mm thick and 6.0 mm in diameter. The disks will be stacked inside a holder. Welded end caps will seal the holder to minimize potential hydrogen release from the specimens to the external capsule housing and thus to HFIR coolant. SiC TMs are placed against the specimens, and retainer springs press the specimen assemblies to the holder wall. Figure 3 shows the YH_x irradiation capsule design.

The capsules will be irradiated in the HFIR flux trap at 600°C and 900°C at three different doses, 0.1, 1 and 2 dpa, which correspond to approximately 0.05, 0.5 and 1 irradiation cycle, and for specimens with two different hydrogen concentrations of $YH_{1.72}$ and $YH_{1.87}$. The irradiation test matrix is presented in Table III.

To date, YH_x rods with the two different hydrogen concentrations have been fabricated (see example on Fig. 4), and specimens are being machined from these rods. The YH_x capsules are expected to be inserted in the HFIR flux trap by summer of 2020.

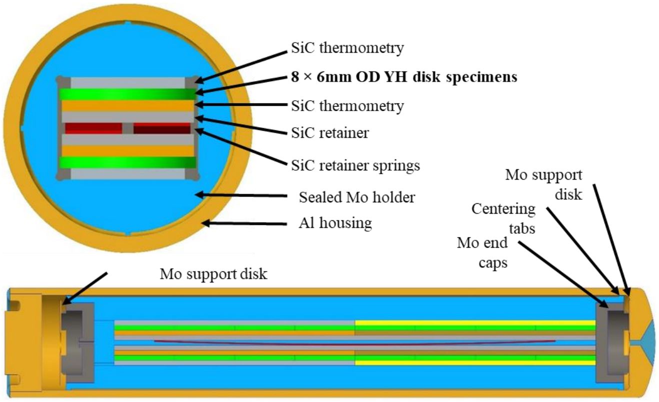

Fig. 3. Design of YH_x irradiation capsule.

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	

Fig. 4. As-fabricated YH_x rod.

PIE will be used to assess the thermophysical and thermomechanical properties of YH_x such as swelling, heat capacity, thermal diffusivity, thermal expansion, hardness, and fracture toughness.

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CONCLUSIONS

This summary presents the planned irradiations and successful assembly of irradiation capsules supporting development and demonstration of the Transformational Challenge Reactor. These capsules will be used for irradiation testing of additively manufactured 316L and SiC specimens. Additional capsules bearing YH_x specimens will be built in early 2020. The first PIE results are expected by summer 2020 and will provide critical material properties data for the design and licensing of the TCR's core.

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