Capsule and Specimen Geometries for HFIR Irradiation Testing Supporting the Transformational Challenge Reactor

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OAK RIDGE NATIONAL LABORATORY
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Transformational Challenge Reactor

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SUMMARY

This report provides a summary of irradiation capsule design and analysis for the three main categories of materials to be used in the Transformational Challenge Reactor (TCR) core. These materials are yttrium hydride as the moderator, silicon carbide, and Grade 316L austenitic stainless steel. No neutron irradiation data exists on the former and the latter two are derived from advanced manufacturing techniques and therefor need to undergo rigorous testing to assess their behavior as function of dose and temperature. The detailed design and analysis summarized in this report is the critical step to facilitate safe and relevant irradiation of these materials to be conducted at the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR). These irradiations will ultimately yield critical materials properties data for reactor design and licensing purposes.

ACRONYMS

BOC	beginning of cycle
CAD	computer-aided design
CVD	chemical vapor deposited
DAC	design and analysis calculation
DOE	US Department of Energy
EOC	end of cycle
FTT	flux trap target
GENBEN	general bend bar
GENTEN	general tensile
HFIR	High Flux Isotope Reactor
HT	hydraulic tube
LCS	limiting condition scenario
MCNP	Monte Carlo N-Particle
OD	outer diameter
ORNL	Oak Ridge National Laboratory
PTP	peripheral target position
SiC	silicon carbide
SNAP	Systems Nuclear Auxiliary Power
TCR	Transformational Challenge Reactor
TM	temperature monitor
TRIGA	Training, Research, Isotopes, General Atomic
TRRH	target rod rabbit holder
YH_x	yttrium hydride
ZrH_x	zirconium hydride

1. INTRODUCTION

The Transformational Challenge Reactor (TCR) program intends to rapidly demonstrate application of advanced manufacturing to build and operate an advanced nuclear energy system. The TCR core will comprise novel, advanced manufactured materials, so its core materials will differ from the pre-1970s conventionally manufactured materials used to date in light water or other advanced nuclear reactor cores [1]. As a result, these materials must be thoroughly tested. This comprehensive testing campaign must include irradiation testing to provide material properties data as a function of displacement damage dose and temperature. These data are necessary to inform performance and safety analysis tools used during design and licensing of the TCR core.

The TCR core materials envisioned at this stage of the program can be divided into three main categories: (1) laser powder bed fusion derived austenitic stainless steel (Grade 316L) metal structures forming the core lattice, (2) additively manufactured (binderjet printed and chemical vapor infiltrated) silicon carbide (SiC) forming the fuel matrix, with fuel being microencapsulated (TRISO) fuel particles, and (3) the hydrogen-bearing moderator for which the TCR core is the cubic phase of yttrium hydride (YH_x with $1.5 < x < 2$).

This report provides a brief background of neutron irradiation capabilities at the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR), followed by a detailed description of irradiation test capsule design and conditions for the three categories of TCR core materials.

2. HIGH FLUX ISOTOPE REACTOR (HFIR)

HFIR is a beryllium-reflected, pressurized, light-water–cooled and moderated flux trap–type reactor located at ORNL. HFIR's core consists of aluminum-clad involute-fuel plates which currently use highly enriched ^{235}U fuel to maintain steady state at a power level of 85 MW [2]. Most experiments performed in HFIR are conducted in the flux trap, typically in small, uninstrumented "rabbit" capsules. As many as 7–9 rabbits can be stacked axially inside a single peripheral target position (PTP) holder, a target rod rabbit holder (TRRH), or the hydraulic tube (see Figure 1). Orifices in the TRRH and PTP holders establish the capsule heat transfer boundary conditions. Positions are numbered in increasing order from the bottom to the top of a PTP or TRRH. Positions TRRH-4 and PTP-5 are closest to the reactor's midplane.

Neutron and gamma radiation from HFIR fuel causes heating of experiment materials. This heating is accurately determined using neutronics models of the HFIR core and is used as an input to thermal analyses that predict component temperatures during irradiation. Experiments in the flux trap are almost always uninstrumented. Either passive silicon carbide (SiC) temperature monitors (TMs) or thermometry can be used to determine the irradiation temperature post irradiation [3]. However, detailed neutronic and thermal analyses are required to ensure that design temperatures are achieved. Experiment designs typically use a small insulating gas gap between the capsule internal components and external housing in contact with reactor coolant. The size of the gap and the choice of fill gas (typically helium, neon, or argon) inside the experiment are chosen so that the heat generated in the experimental components passes through the gas gap and gives the desired temperature drop across the gap. The temperature drop is a function of the heat flux through the gap, the thermal conductivity of the fill gas, and the size of the gas gap. Each of these parameters is carefully selected and modeled to achieve design temperature in an experiment.
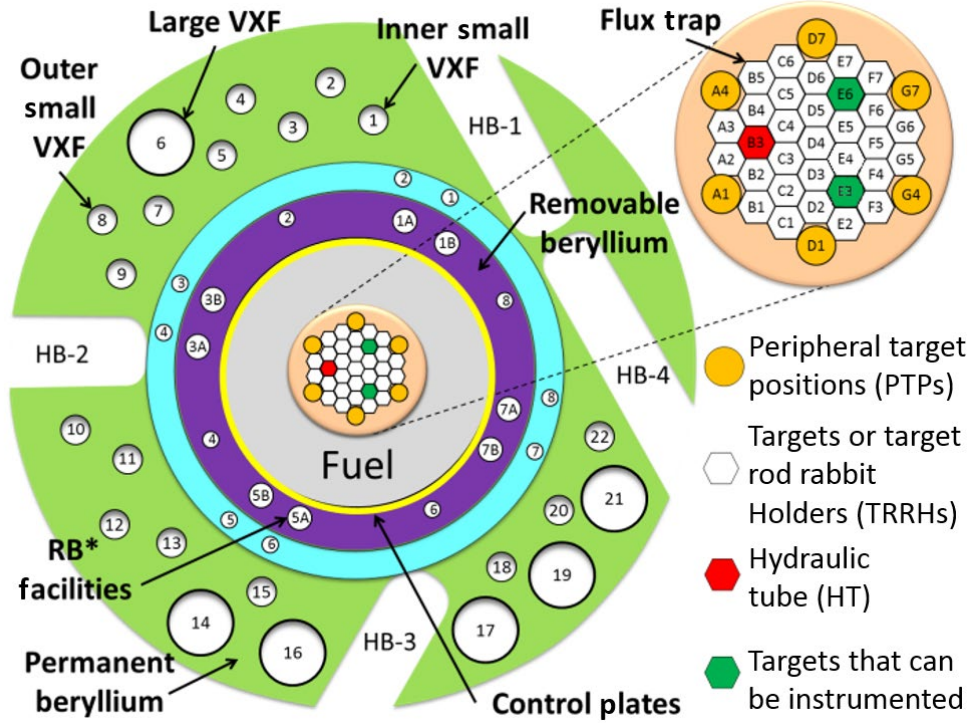
Figure 1. Schematic showing transverse section view of HFIR core, reflector, and experimental positions (not to scale) [4]

3.   HFIR IRRADIATION OF YTTRIUM HYDRIDE DISKS

3.1   BACKGROUND

Transition metals are known to absorb large quantities of hydrogen to form solid solutions at low hydrogen content, and the metals for hydrides at higher hydrogen content. The densities of hydrogen atoms in some transition metal hydrides are greater than those in water or in liquid hydrogen, enabling a variety of applications within nuclear and non-nuclear systems. Hydrogen is an outstanding moderator because of its substantial equivalence in mass to the neutron and its acceptably high neutron scattering cross section. This characteristic is useful for bringing the incident neutron energy to a level at which it has a greater probability of interacting with other fissile, fertile, and neutron-control atoms. For example, zirconium hydride (ZrH_x) is frequently used as a high-performance moderating material in advanced reactors. Examples include the Systems Nuclear Auxiliary Power (SNAP) Program [5], Training, Research, Isotopes, General Atomic (TRIGA) research reactors [6], and nuclear thermal propulsion reactors [7]. However, the application of ZrH_x to nuclear systems required careful management of the moderator temperature to avoid hydrogen desorption at elevated temperatures. In contrast, yttrium hydride (YH_x) is more attractive for such applications due to its significantly lower equilibrium hydrogen partial pressure at elevated temperatures. For example, the equilibrium hydrogen pressure for $YH_{1.6}$ at 900°C is only 8.8 torr [8] compared to an expected value of 3.3×10^3 torr for $ZrH_{1.6}$ at the same temperature.

The successful deployment of YH_x as a high-temperature moderator in advanced reactors requires a robust understanding of its response to neutron irradiation. However, the database of the physical and thermomechanical properties of neutron-irradiated YH_x is not yet available, so a campaign to irradiate YH_x in HFIR was initiated in FY19 under the TCR program. The current results of these efforts are reported below. Properties being investigated include swelling, heat capacity, thermal diffusivity, thermal expansion, hardness, and fracture toughness. Furthermore, as many of the properties are known to be strongly dependent on hydrogen content, both $YH_{1.5}$ and $YH_{1.7}$ are included in testing.

3.2   IRRADIATION CAPSULE DESIGN CONCEPT

In this experiment, the rabbit capsule is loaded with a sealed molybdenum holder that contains the disk-shaped YH_x specimens and their associated components, as shown in Figure 2. On each side of the holder's interior, eight 6 mm diameter specimens are lined with four silicon carbide (SiC) pieces that are 24 mm long. These are separated by two additional pieces of SiC retainers that are 48 mm long and two thin SiC retainer springs bent to press the specimen assemblies to the holder wall. Four SiC slabs 24 mm in length serving as thermometry are placed between the sample layer and the SiC retainers. The holder features welded end caps on each side to mitigate the potential of hydrogen release from the sample holder to the external Al housing, thus minimizing the amount of hydrogen diffusing into HFIR coolant. Molybdenum was specifically chosen due to its performance at high temperatures, frequency of use in similar experiments, and its anticipated resistance to hydrogen chemical interactions and leakage.
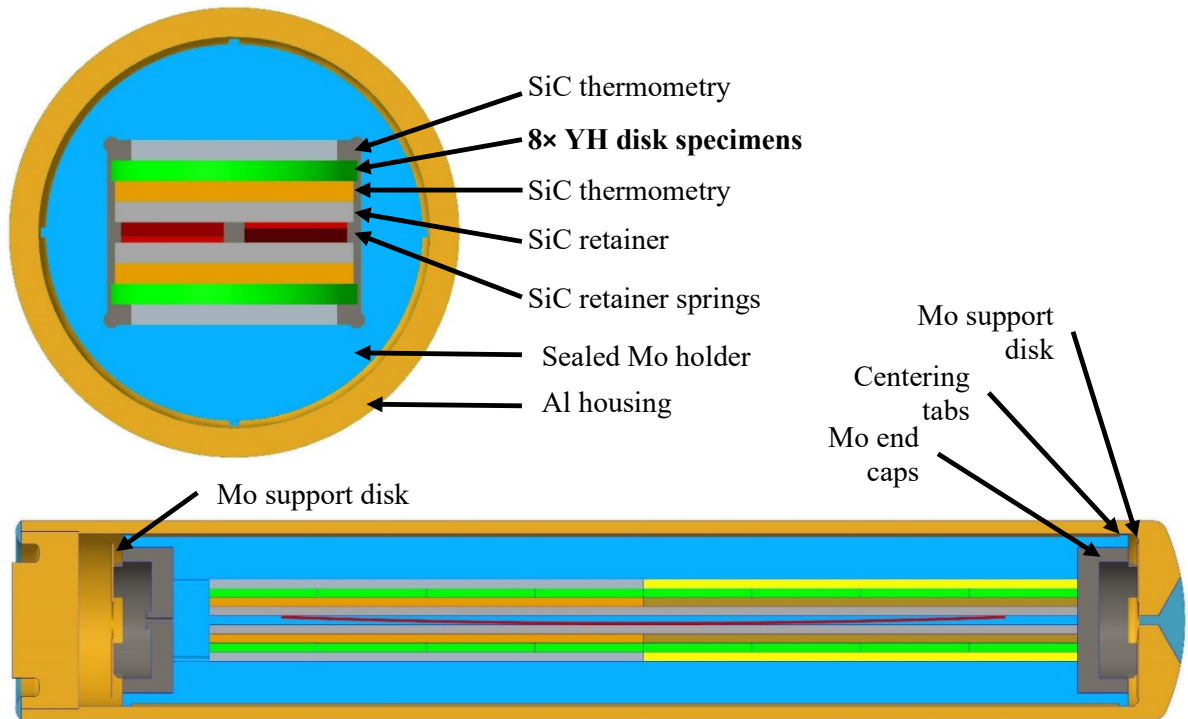
Figure 2. Design of YHx irradiation capsule.

This experiment will consist of twelve rabbits in total, representing two hydrogen concentrations of $YH_{1.5}$ and $YH_{1.7}$, two design temperatures of 600 and 900°C, and three specimen doses of 0.1, 1, and 2 dpa. The test matrix is shown in Table 1. This approach requires placing eight rabbits in the hydraulic tube for partial cycles and four in the permanent facilities for a single cycle. It is anticipated that these experiments will be at the centerline of the reactor or offset from the centerline by one position. To accomplish this, neutronic, thermal, and leak calculations must be performed to determine the design parameters and to ensure that conditions stay within their respective safety limits. The equilibrium pressure of hydrogen due to desorption is as follows:

- $YH_{1.5}$ at 600°C: 1.8×10^{-3} torr
- $YH_{1.7}$ at 600°C: 3.4×10^{-3} torr
- $YH_{1.5}$ at 900°C: 6.3 torr
- $YH_{1.7}$ at 900°C: 48 torr

Table 1. Irradiation test matrix

Capsule ID	Irradiation temperature	Dose (dpa)	Material
YHXT01		0.1	
YHXT02	600 °C	1	
YHXT03		2	$YH_{1.5}$
YHXT04		0.1	
YHXT05	900 °C	1	
YHXT06		2	
YHXT07		0.1	
YHXT08	600 °C	1	
YHXT09		2	$YH_{1.7}$
YHXT10		0.1	
YHXT11	900 °C	1	
YHXT12		2	

3.3   NEUTRONICS ANALYSIS

No historical reference exists for irradiation of YH_x materials in HFIR, and its behavior and performance in the reactor cannot be bound by existing safety-basis calculations with adequate confidence. Therefore, this gap requires a dedicated neutronic analysis of the irradiation capsule to assess nuclear heat generation in the samples and capsule structural components under anticipated operating conditions. This will enable thermal design studies of the capsule, as well as the ultimate approval of the experiment for insertion in HFIR. Heat is generated in the experiment capsule due to several contributions: fission neutrons from the HFIR fuel, prompt photons from fission in the fuel and (n,γ) reactions throughout the core, delayed photons from the decay of fission products accumulated in the fuel, α and β decay heat due to activation of capsule components under irradiation, and activation photons due to the decay of activation products in the capsule. Each source requires distinct neutronic treatment.

Standard safety-basis Monte Carlo N-Particle 5 (MCNP5) models of the HFIR core with cycle 400 experiment loading conditions at beginning and end of cycle (BOC/EOC) provide templates for the neutronics calculations carried out in this work. These models are modified to include the geometry and materials of the experiment capsule as described above; particular care is taken in these models to appropriately capture thermal neutron scattering physics in YH_x [9]. To cover a breadth of anticipated conditions to which the capsule may be exposed in the HFIR flux trap target (FTT) region, the capsule is modeled in three different peripheral target positions (PTPs), three different outer ring positions, and the hydraulic tube (HT). In all cases, the capsule is centered about the axial midplane of the core to maximize incident neutron and photon flux, thereby yielding bounding design- and safety-basis heat generation rates.

Heat generation from fission neutrons and prompt photons can be assessed from a single MCNP run in each FTT position in criticality mode with neutron and photon tracking enabled. Tallies are constructed to record the statistically estimated energy deposited by neutrons and photons in each capsule component. A separate MCNP calculation is run with a fixed photon source reflecting the photon emission rate and spectrum due to fission products accumulated in the HFIR fuel; this calculation determines heating contributed by these delayed photons. As MCNP is only capable of static transport calculations, additional tools are needed to assess decay heat, namely the COUPLE and ORIGEN modules of the SCALE code system. Fine-group neutron flux spectra are assessed for each capsule component in the initial MCNP run which are then passed to the COUPLE cross section processing module to generate reaction cross sections that are neutronically consistent across codes. These cross sections are then used for irradiation calculations using ORIGEN for each capsule component in each FTT position to determine locally deposited α and β decay heat. ORIGEN also outputs the spectrum and emission rates of decay photons from each activated material. This information is used to define a fixed photon source for a final MCNP calculation to determine the heat generation resulting from these photons.

Results from each of these contributions are summed for each component in each FTT position to determine design-basis heat generation rates for subsequent use in thermal analyses. Determination of safety-basis heat generation rates requires further manipulation that is relegated to this calculation document for the sake of concise presentation. Instead, Table 2 below shows the bounding design-basis heat generation results achieved in the A1 PTP position with $YH_{1.7}$.

Table 2. Bounding Design-Basis Nuclear Heat Generation

Component	Heat generation (W/g)	Relative error
TM-1	30.9	0.0037
TM-1	31.0	0.0037
TM-1	31.3	0.0037
TM-1	31.3	0.0036
TM-2	30.8	0.0034
TM-2	30.8	0.0034
TM-2	31.1	0.0034
TM-2	31.0	0.0034
Retainer	30.9	0.0024
Retainer	30.9	0.0024
Spring	31.2	0.0044
Spring	30.6	0.0043
Sample group 1	45.2	0.0033
Sample group 2	45.3	0.0033
Sample group 3	45.3	0.0032

Sample group 4	45.7	0.0032
Insulator	32.4	0.0077
Insulator	32.4	0.0079
Holder	46.6	0.0010
Housing	32.2	0.0023

3.4 CAPSULE THERMAL ANALYSIS

To determine the temperature distribution in the assembly, the ANSYS finite element software is utilized with custom, user-defined macros and inputs from the neutronics analysis. Descriptions of these macros can be found in Design and Analysis Calculation (DAC) 11-13-ANSYS02, Rev. 6, which is available by request [10]. Examples include algorithms that calculate the properties of gas mixtures [11] and approximate the effect of thermal expansion without requiring a coupled structural analysis [12]. Likewise, temperature-dependent (and in the case of SiC, dose-dependent) material properties are calculated using a database of DACs maintained by the ORNL Nuclear Experiments and Irradiation Testing Group. These properties are obtained from CINDAS [13], MatWeb [14], and a variety of literature sources. Table 3 lists previously approved DACs used in this calculation.

Table 3. YH$_x$ rabbit materials and material property references

Part	Material	Reference DAC
Holder, disks	Molybdenum	DAC-10-11-PROP_MOLY [15]
Housing	Aluminum	DAC-10-03-PROP_AL6061 [16]
Specimens	Yttrium hydride	DAC-19-03-PROP_YHX [17]
Thermometry, springs	Silicon carbide	DAC-10-06-PROP_SIC(IRR) [18]

For the specimens in particular, a new DAC was written to determine the properties of the hydride material. This macro accepts a given hydrogen content and calculates the phase and properties of the material at several reference temperatures. The phase diagram used is recommended by Khatamian and Manchester [19], while thermal and structural properties are from experiments by Ito et al. and Setoyama et al., respectively [20] [21]. The remaining values can be found in commonly available sources [14] [22]. For safety calculations, the macro can also be set to provide conservative values for each property. Other inputs, such as the convection boundary conditions for each case and the axial power profile, can be found in Table 4.

Table 4. YH$_x$ rabbit thermal boundary conditions [23] [24] [25]

Parameter	Unit	Design	LCS*	0.5 gpm flow
Convective coefficient	kW/m^2·K	31.6–48.4	22.5	4.968
Bulk coolant temperature	°C	52–54	77	182
Power scaling factor	---	1.03	1.30	1.03
Power profile	cm	29.70, 30.39	Flat	Flat

*Limiting condition scenario

When considering all potential placement configurations, this experiment represents 48 possible scenarios to analyze and optimize. To aid in managing this, the model is parameterized and used to construct a response surface with the ANSYS DesignXplorer software package. This is a fitted model of the system's response to many inputs, allowing for the quick, accurate estimation of results. This in turn enables optimization studies which are used to fine-tune the design to enhance performance and minimize the number of parts required.

Temperature profiles for specimens and rabbit internals are presented in Figure 3 for the illustrative case of $YH_{1.7}$ specimens in the centerline position of a target rod rabbit holder, with an average specimen temperature of 896°C compared to a design temperature of 900°C and an overall maximum temperature of 914°C. To achieve this, the holder has an outer diameter (OD) of 9.18 mm, and the housing is filled with a mixture of 64% helium and 36% argon. This case is one of many that could be generated by the response surface of the system, which is shown in Figure 4 for the average specimen temperature as a function of its two most sensitive parameters: the diameter of the holder and the fill gas composition. Other parameters analyzed include the design temperature, the hydrogen concentration in the specimens, the dose to the specimens, the irradiation location, and the axial position of the rabbit in the reactor. Initial safety calculations show the margin to melt in all components: ongoing is in process to confirm this finding. The impact of the hydrogen content on the thermal analysis of YH_x capsules is very limited due to the small difference in thermal conductivity. Detailed images for the 600°C irradiation capsule design is omitted here.
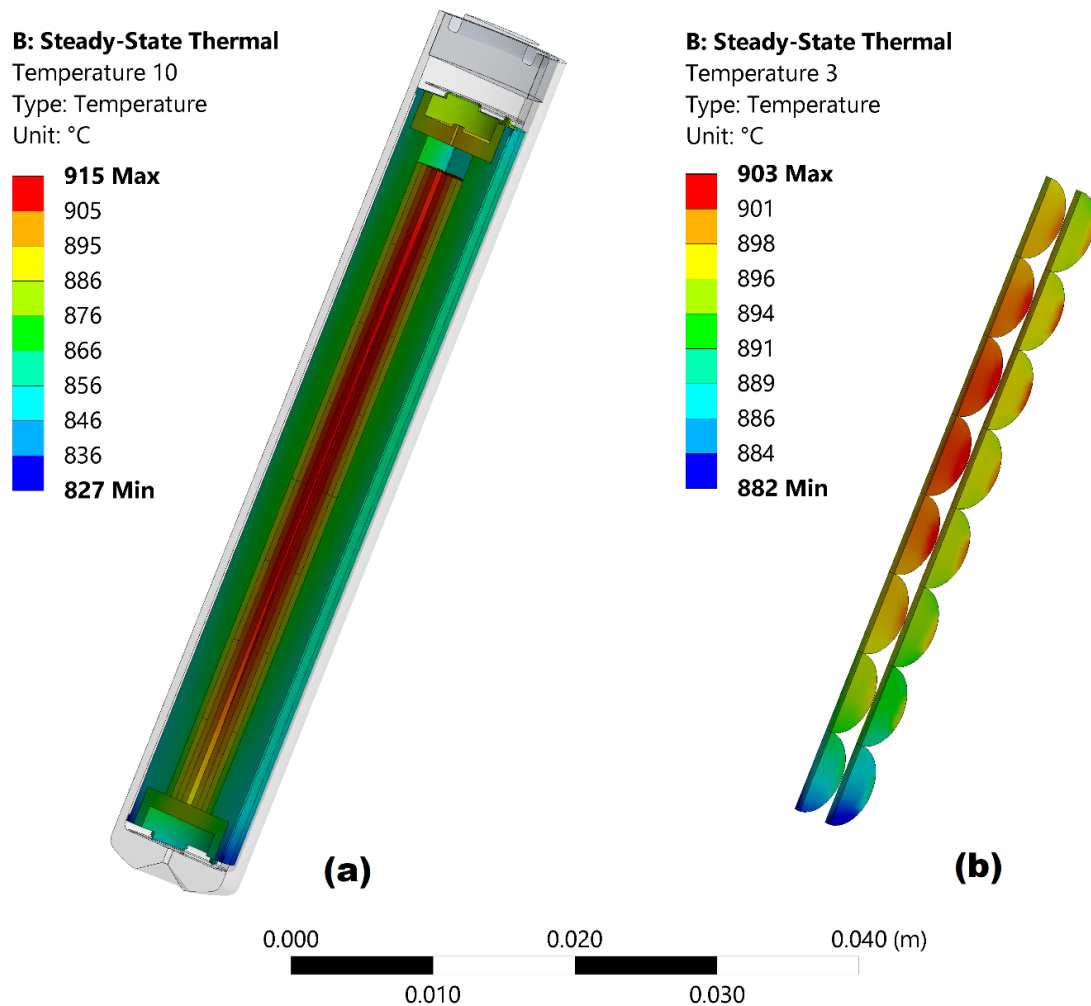
Figure 3. Temperatures in (a) the rabbit internals and (b) specimens for a 9.18 mm diameter holder and 64% helium + 36% argon fill gas for the YH$_{1.7}$ irradiation capsule with a targeted temperature of 900°C.
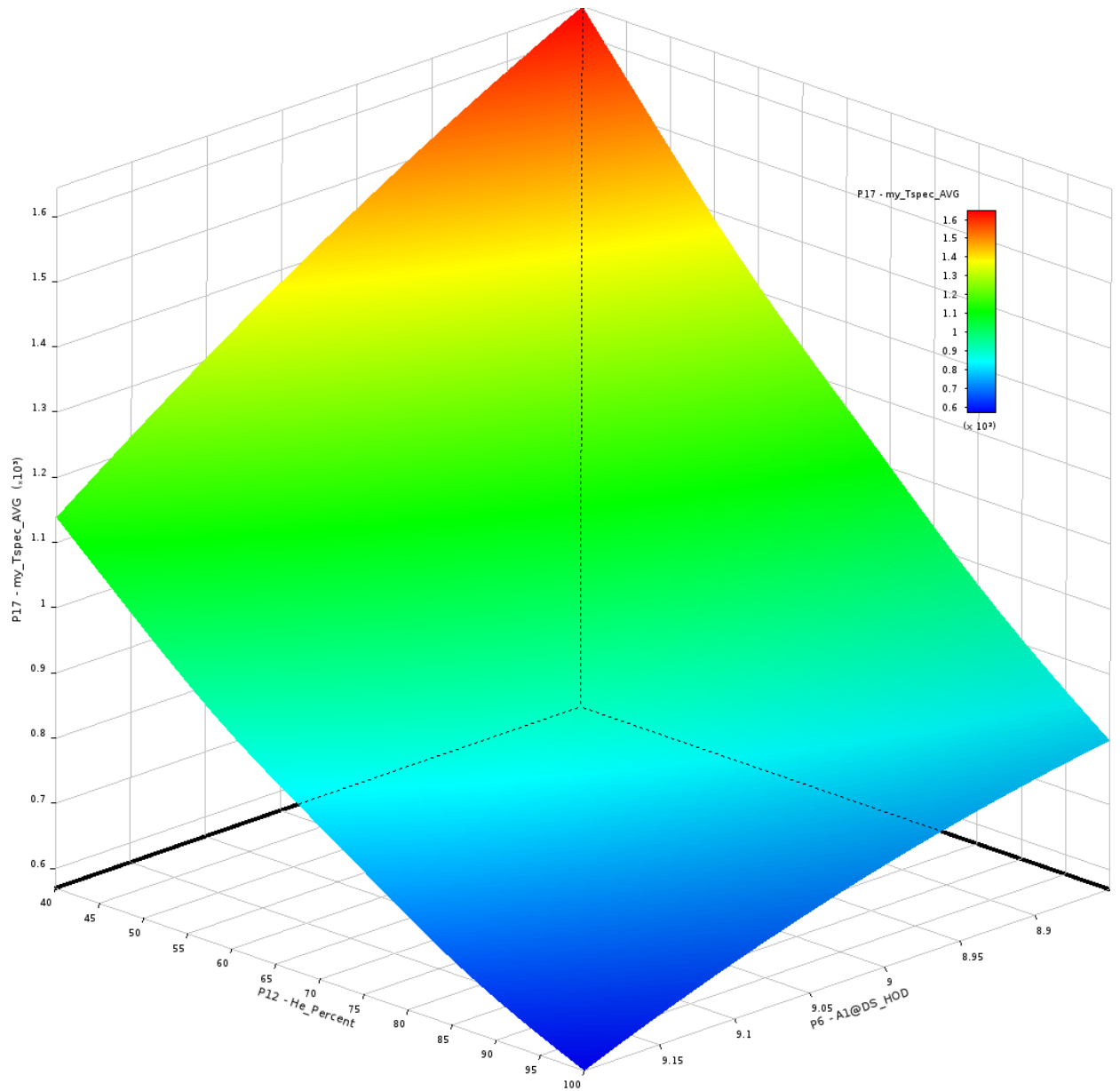
Figure 4. YH$_x$ specimen average temperature as a function of holder diameter and helium concentration in the housing (Vertical axis is temperature in °C; left axis is He gas fraction (%), and right axis is holder diameter in mm).

4. HFIR IRRADIATION OF 3D PRINTED SIC DISKS IRRADIATIONS

4.1 BACKGROUND

Advanced manufacturing of SiC (powder binderjet) combined with chemical vapor infiltration (3D-printed SiC-CVI) provides an attractive level of freedom in component design due to the high-temperature performance of these materials and allowances for geometrical complexity. 3D-printed SiC-CVI results in a high purity material with crystallinity which will likely provide tolerance to in-core atom displacement damage and resistance to thermal creep similar to that provided by bulk reference material (chemical vapor deposited [CVD] SiC). A HFIR irradiation is planned for FY20 with 3D-printed SiC-CVI disks and bulk CVD-SiC to evaluate the material's property response to temperature and irradiation dose, including various printing techniques and powders.

4.2 EXPERIMENT DESIGN

The overall design concept is summarized in Figure 5. The outer containment for all experiments is the rabbit capsule housing, which is directly cooled on the outer surface by HFIR's primary coolant. These rabbits include 32 disk specimens that are nominally 0.5 mm thick. There are two sets of 16 specimens located on either side of the center retainer spring. Each set has 2 layers of 8 specimens stacked between the inner and outer TMs. The TMs are SiC slabs that are evaluated using dilatometry post-irradiation to confirm the irradiation temperature [26]. The SiC retainer specimens keep the internal contents of the experiment pressed against the inner walls of the specimen holder. Insulator discs at the top and bottom of the assembly reduce axial heat losses. Temperature is controlled by varying the concentration of a helium/argon gas mixture and the size of the gas gap between the holder and the housing. Varying the gas mixture changes the effective thermal conductivity of the gas gap. Centering thimbles are inserted into the ends of the specimen holder to keep it centered within the rabbit capsule, ensuring a constant gas gap around the perimeter of the specimen holder.
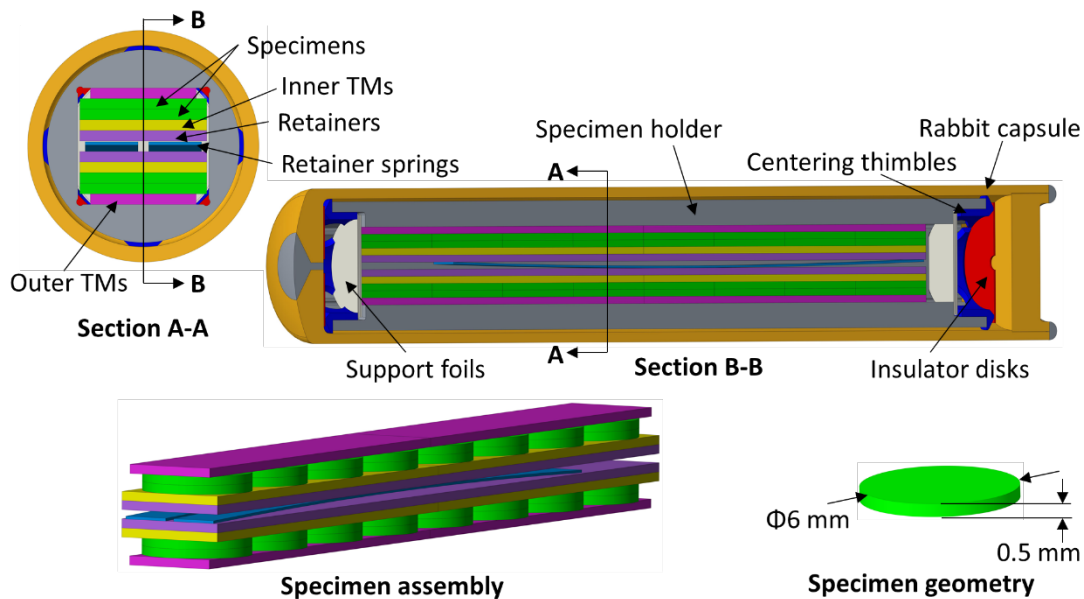

Figure 5. Schematic showing the irradiation capsule design.

4.3   CAPSULE THERMAL ANALYSIS

The computer-aided design (CAD) models were imported into the ANSYS finite element software package for thermal analysis to ensure that the specimens would be irradiated at the desired temperatures. This is accomplished by calculating the gamma heating generated within the capsule components and sizing an insulating gas gap through which the internal heat must pass before being rejected to the HFIR primary coolant, which flows around the outer surface of the capsules. Similar approaches have been used for previous HFIR irradiation experiments [27] [28] [29] [30] [31] [32] [33] [34]. For the experiments described herein, the variables adjusted to achieve the design temperatures are the size and composition of the gas gap between the specimen holder and the rabbit housing, as well as the specimen holder material (different materials have different gamma heating rates).

Figure 6 through Figure 8 show the temperature contours predicted by the thermal analyses for nominal specimen temperatures of 400, 650, and 900°C, respectively. These temperatures are for capsules positioned in TRRH position 6 within the HFIR flux trap. Axial positions are numbered 1 through 7 within the TRRHs from the bottom to the top of the core. Position 4 is closest to the core's midplane, and position 6 is centered ~12.7 cm above the core's midplane.

Figure 6. Predicted temperature contours (in °C) for the nominally 400°C design with ¼-symmetry showing (a) the entire capsule assembly, (b) the specimens, and (c) the passive temperature monitors.
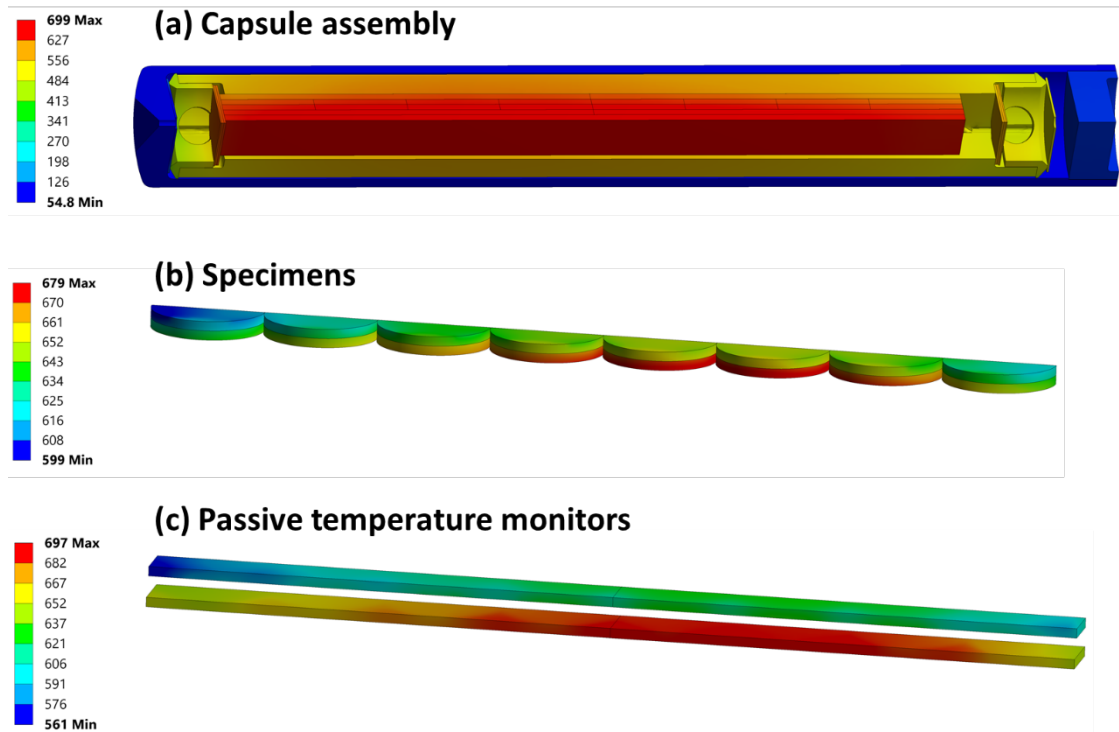
Figure 7. Predicted temperature contours (in °C) for the nominally 650°C design with ¼-symmetry showing (a) the entire capsule assembly, (b) the specimens, and (c) the passive temperature monitors.
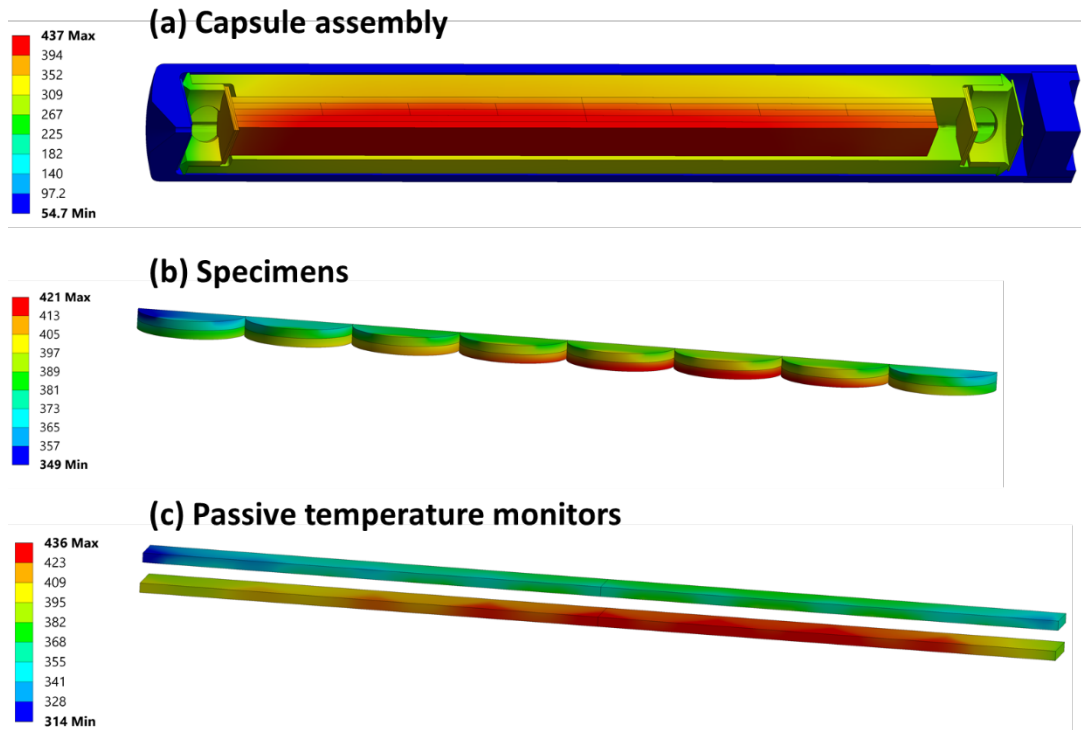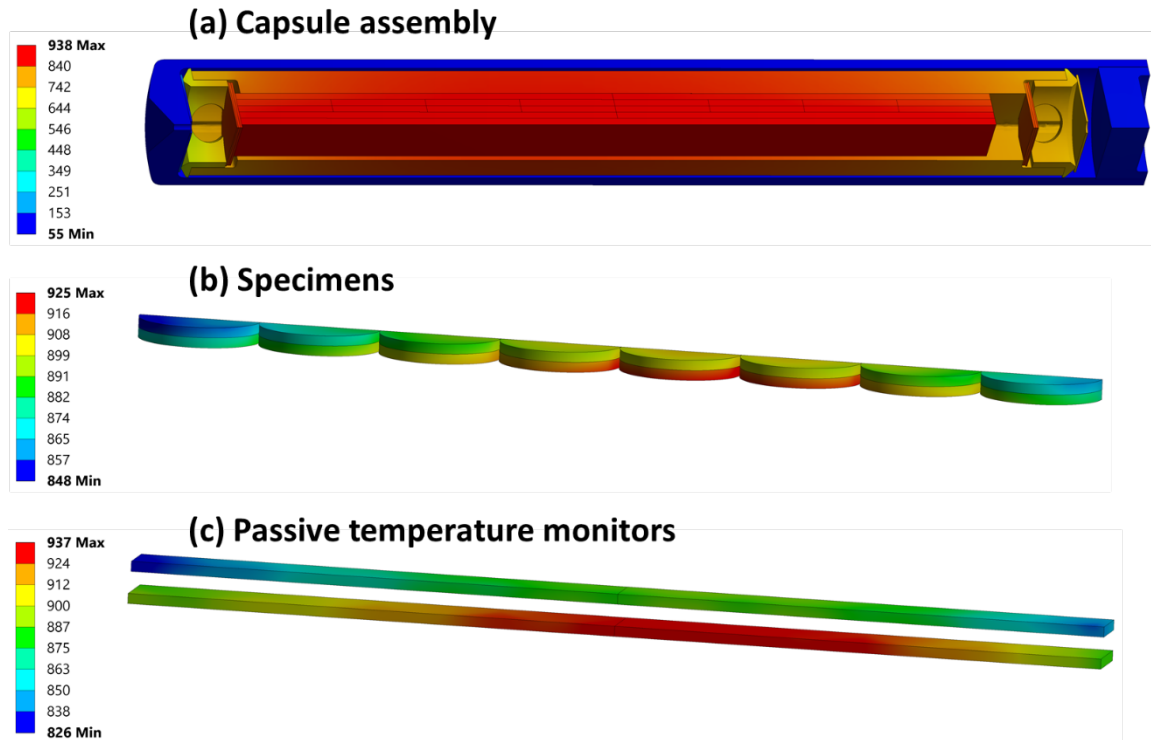
Figure 8. Predicted temperature contours (in °C) for the nominally 900°C design with ¼-symmetry showing (a) the entire capsule assembly, (b) the specimens, and (c) the passive temperature monitors.

The inner and outer TMs provide bounds on the specimen temperatures, with the inner TM temperatures being closer to the temperature of the inner specimens, and the outer TM temperatures being closer to the temperature of the outer specimens. Table 5 summarizes average, minimum, and maximum temperatures for all important components, in addition to other design parameters such as the irradiation position, holder material, fill gas, and size of the primary gas gap. The irradiation positions include TRRH positions, as well as PTPs, which are numbered axially 1 through 8 from the bottom to the top of core. Position 5 is closest to the axial midplane. The lower temperature capsules use a vanadium alloy holder. The higher temperature capsules use a niobium holder with 1% zirconium. Simulations are performed for multiple positions because it is not known at the time of the analysis which HFIR positions will be available when the capsules are inserted into the reactor. Analyzing for multiple positions increases the likelihood that the assembled capsules can be immediately inserted into the reactor.

Table 5. Summary of component temperatures, irradiation position, holder material, fill gas, and cold gas gaps for SiC disk specimens

Nominal temperature	Position	Holder material	Fill gas	Gas gap	Part	Temperature (°C)		
						Average	Minimum	Maximum
400°C	TRRH-6	V-4Cr4Ti	He	170 μm	Specimens	395	349	421
					Inner TMs	416	384	436
					Outer TMs	364	314	385
	PTP-3				Specimens	401	343	429
					Inner TMs	423	363	446
					Outer TMs	368	315	391
650°C	TRRH-6	V-4Cr4Ti	40.5% He, 59.5% Ar	135 μm	Specimens	650	599	679
					Inner TMs	676	645	697
					Outer TMs	614	561	636
	PTP-3				Specimens	658	591	690
					Inner TMs	685	617	709
					Outer TMs	619	560	644
900°C	TRRH-6	Nb-1Zr	40.5% He, 59.5% Ar	210 μm	Specimens	896	848	925
					Inner TMs	916	885	937
					Outer TMs	873	826	894
	PTP-3				Specimens	916	840	952
					Inner TMs	938	863	965
					Outer TMs	892	818	921

5.   HFIR IRRADIATION OF 3D PRINTED 316L

5.1   BACKGROUND

Irradiated material property measurements of 3D printed materials are needed to support modeling efforts of TCR design concepts. TCR design concepts include 3D printed 316L stainless steel (SS316L) cans, lattice structures, and SS316L bristle or springs as core components. The yield stress as a function of temperature and dose for SS316L produced through additive manufacturing may differ from commonly produced SS316L [35]. Neutron irradiations will be performed to understand these differences using HFIR rabbit irradiation vehicles designed for tensile specimens and ORNL hot cell facilities' infrastructure to support mechanical testing and advanced characterization techniques.

5.2   EXPERIMENT DESIGN

This report details two capsule designs for two flexible capsule designs that accommodate either (1) the miniature tensile specimen, or (2) the M4CVN "bend bar" specimen. The flexible tensile design, referred to as the *general tensile* (GENTEN) capsule design, consists of three specimen holders stacked axially within the rabbit housing, as shown in Figure 9. The flexible bend bar design, referred to as the *general bend* (GENBEN) bar capsule design, has four M4CVNs contained within a single holder within the rabbit housing, as shown in Figure 10.

The outer containment for the irradiation experiment is the rabbit capsule housing, which is directly cooled on the outer surface by HFIR's primary coolant. The specimens are placed in holders with ODs optimized to create gas gaps to control temperature performance. These holders can either be Al-6061 or molybdenum, for low and high target temperatures, respectively. Centering tabs with a slightly larger diameter are machined into the holders to keep the assemblies centered inside the housing and to maintain a constant gas gap between the holder and the housing. Stainless steel spring pins are used in the GENTEN design to hold the internal specimen in contact with the holder's inner walls. The chevrons are used as filler pieces that form a rectangular "coupon" shape to produce a uniform thermal load. Stainless steel wave springs are placed on the ends of the internal assembly between the housing and the holders to minimize axial heat loss.

The GENBEN design uses molybdenum wires to ensure that the specimens remain captured in the holder. The SiC spring ensures that the specimens remain in contact with the holder wall, also maintaining constant heat transfer. Stainless steel liners are used to insulate the specimens from the high thermally conductive holder. This feature is meant to reduce thermal gradients in the specimen. Stainless steel wave springs are also used in the bend bar design to isolate the holder from the capsule's ends and to minimize axial heat loss.
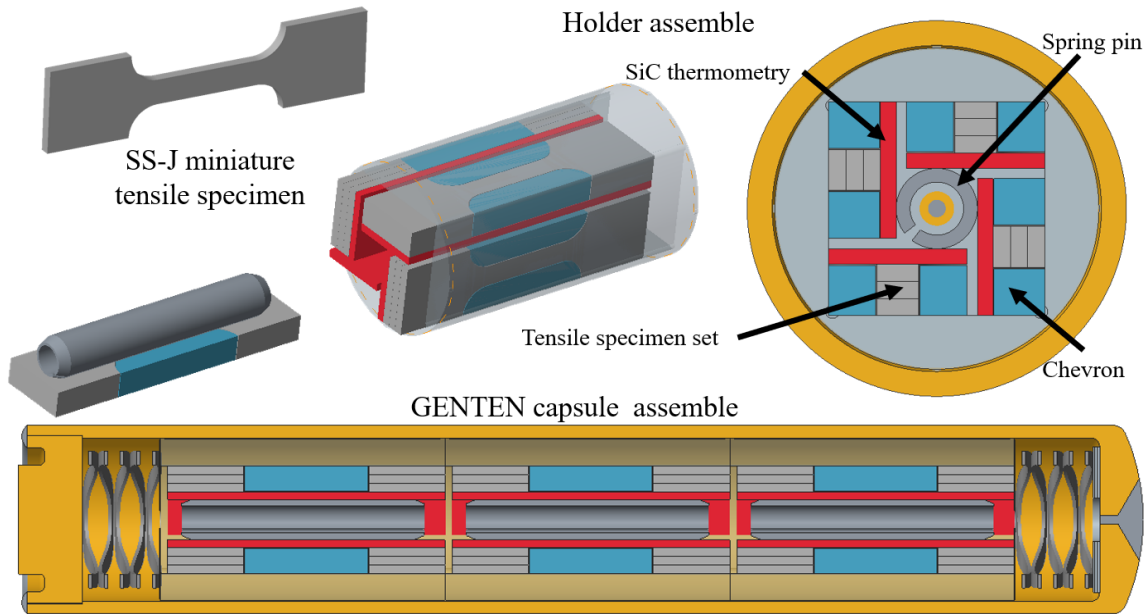

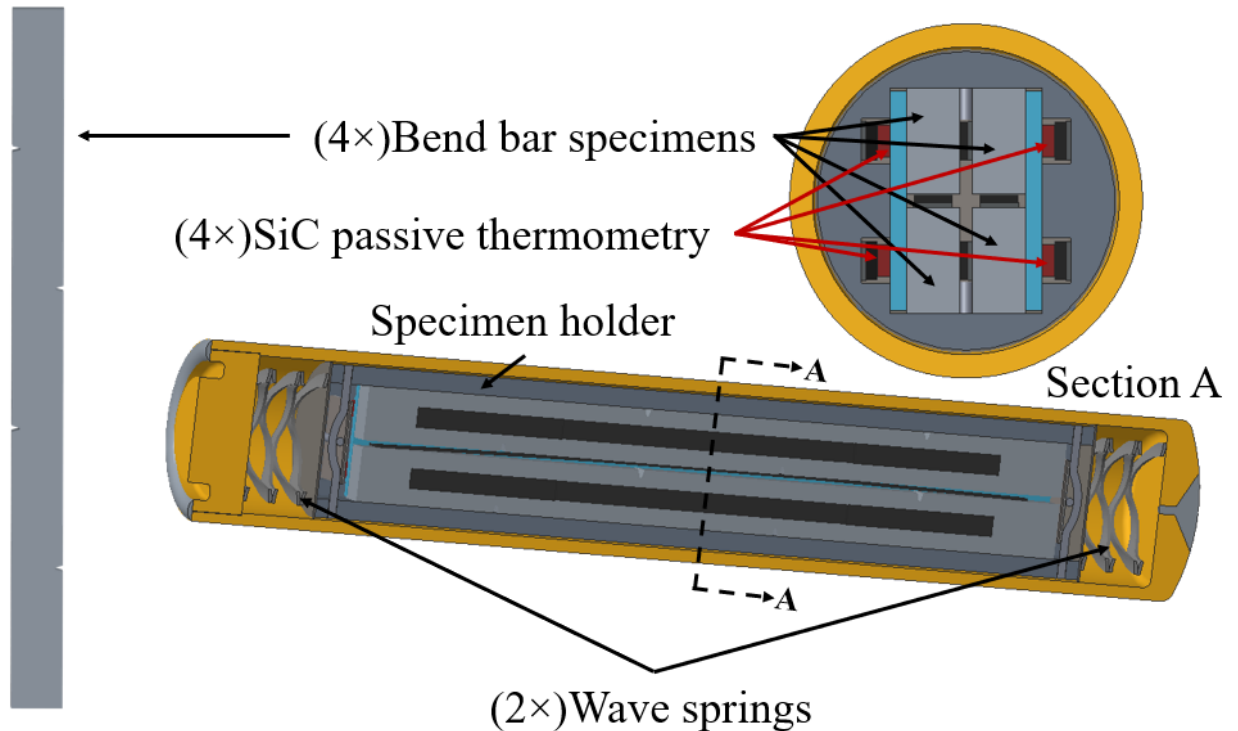**Figure 9. Section view of the GENTEN capsule design concept.**

Figure 10. Section view of the GENBEN capsule showing the design concept.

5.3 CAPSULE THERMAL ANALYSIS

ANSYS finite element analysis software was used to predict temperature distributions inside the experiments. These analyses use material-dependent heat generation rates (heat per unit mass) as inputs; these rates were calculated from previously determined neutronics analyses. CAD models are imported into ANSYS and are used to perform thermal analyses and to optimize gas gap dimensions. Convection boundary conditions are applied to the outer surface of the housing. The heat generation rates vary in each irradiation location and as a function of axial distance from the reactor core midplane. As shown in Figure 1, multiple irradiation facilities are designated in the HFIR flux trap. These various degrees of freedom for analysis inputs can create large numbers of single irradiation conditions. These GENTEN and GENBEN designs are intended to be easily deployed throughout the flux trap, but analyzing all these cases explicitly is impractical. Therefore, a series of surface response calculations was performed for these two capsule designs. This approach effectively maps the target temperature design space for a given set of conditions.

The GENTEN and GENBEN designs were set up to achieve target temperatures ranging from 200–1,000°C to be available for irradiation within the TRRH, PTP, and HT irradiation facilities. Varying the holder's OD was not sufficient to achieve this broad temperature range. Further degrees where established, including holder material and capsule elemental fill gas, to provide the remaining flexibility needed to map out the full temperature range. Al-6061 and molybdenum were selected as holder materials because they are very stable under neutron irradiation. Al-6061 is intended for specimen target temperatures below 400°C because of its low melting point, and molybdenum is used for all other conditions. Likewise, helium backfill gas is used for designs with specimen target temperatures below ~600°C, and neon is used for all other conditions.

The full list of design inputs for the surface response mapping analysis is as follows:
- Flux trap axial position (1–7) and thermal hydraulic boundary conditions,
- Material specific heat generation rates
- Holder material (either Al-6061 or molybdenum
- Fill gas composition (either helium or neon)
- Holder diameter (9.15–9.45 mm)

Representative sets of surface response maps for both the GENTEN and GENBEN designs placed in the TRRH facility can be seen in Figure 11 and Figure 12, respectively. The legend indicates XX-YY-TRRHN, where XX is the holder material, YY is the fill gas, and N is the axial position of the capsule numbered from bottom (1) to top (7), with position 4 located at the vertical midplane of the core. This tool allows for specific capsule designs to be chosen from a table of data based on parameters such as target temperature and HFIR core availability. Furthermore, safety basis calculations have been produced and approved to bound these designs. Currently, GENTEN is approved for specimen target temperatures less than 1,000°C in the PTP and TRRH facilities, and temperatures less than 650°C are approved in the HT facility. The GENBEN design is approved for specimen target temperatures of less than 1,000°C in the PTP and TRRH facilities only.
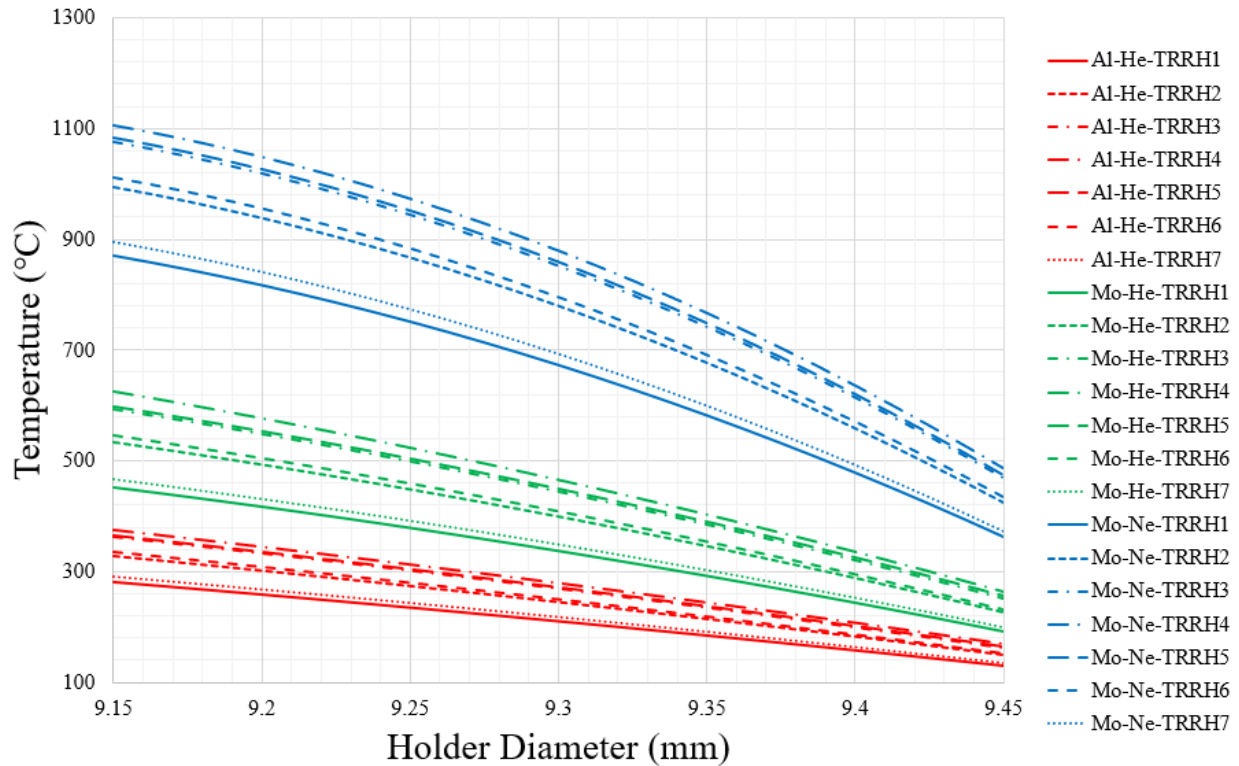
Figure 11. Representative GENTEN surface response reporting average specimen temperature as a function of holder diameter and fill gas.
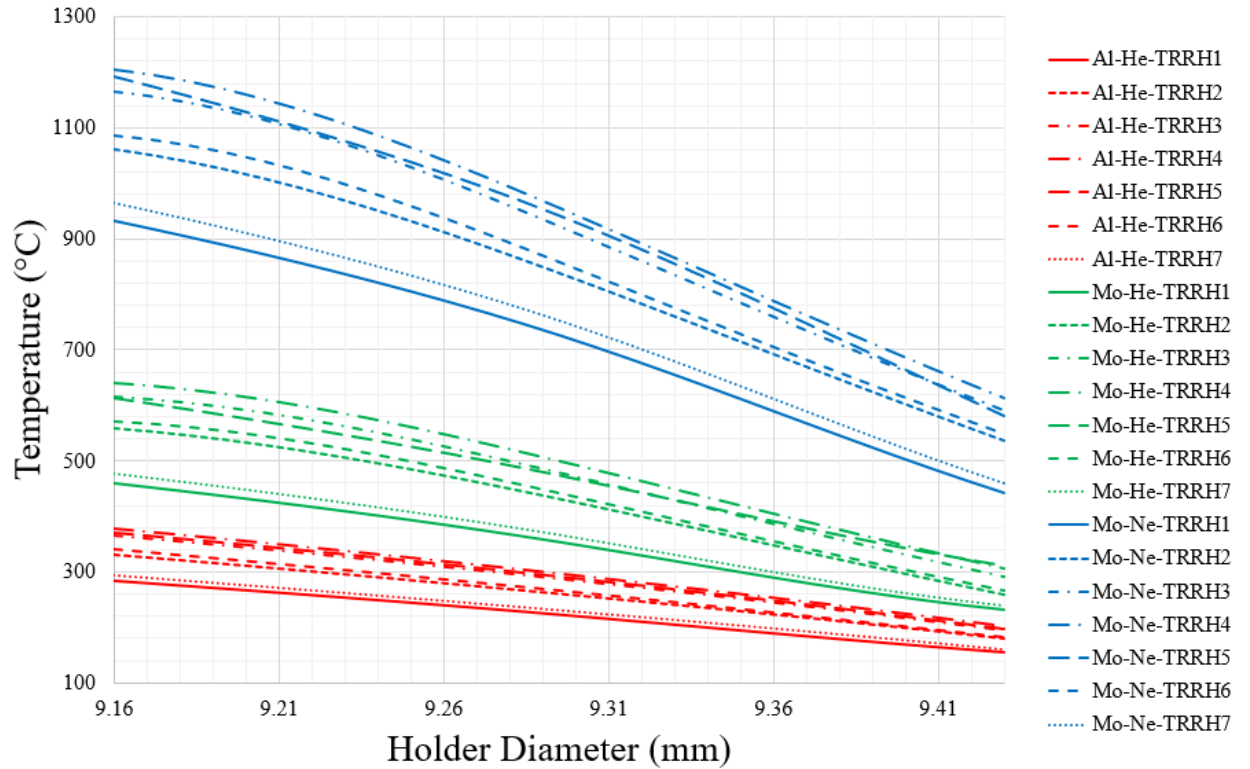
Figure 12. Representative GENBEN surface response reporting average specimen temperature as a function of holder diameter and fill gas.

5.4 3D PRINTED SS316L TEST MATRIX

Table 6 summarizes the irradiation condition of six rabbit capsules, each of which contains 32 tensile specimens. Additively manufactured 316L will be studied with slight variations in fabrication orientation. Table 7 shows the number of specimens planned for irradiation in each rabbit by orientation.

Table 6. Irradiation test matrix

Capsule ID	Irradiation temperature	Dose (dpa)	Material
GTCR01		0.2	
GTCR02	300 °C	2	
GTCR03		8	3D-printed 316L
GTCR04		0.2	
GTCR05	600 °C	2	
GTCR06		8	

Table 7. Materials loading plan in different capsules

Material type	Base alloy	ID*	Number of specimens per capsule					
			#1	#2	#3	#4	#5	#6
AM	316L	TXXX	8	8	8	8	8	8
		TZXX	8	8	8	8	8	8
		3XXX	8	8	8	8	8	8
		3ZXX	8	8	8	8	8	8

XX: ID number (01, 02, 03, …)

6.   SUMMARY AND CONCLUSIONS

Rigorous design and analysis activities for irradiation of the three main categories of TCR core materials—namely yttrium hydride and additively manufacture SiC and SS316L—are summarized in this report. The results of these planned irradiations provide confidence that the use of HFIR rabbits will be a viable path to obtaining important data on the material properties in support of the TCR program. Specifically, initial design and safety analyses show temperatures in the desired ranges for several placement options and conditions. Work is underway to order parts, assemble the rabbits, and finalize safety calculations for insertion into HFIR. This work includes reviews of both the neutronics and thermal calculations, as well as the calculations to ensure that any hydrogen released from the yttrium hydride specimens will be sufficiently contained by the sealed holder. The rapid execution of these irradiation experiments under this program will be critical to supply the necessary information to support TCR demonstration and relevant data for many other advanced reactor concepts, including various industry-led micro-reactor designs.

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