ORNL/TM-2017/433

Assembly and Delivery of Rabbit Capsules for Irradiation of Silicon Carbide Cladding Tube Specimens in the High Flux Isotope Reactor

Christian M. Petrie
Takaaki Koyanagi

September 6, 2017

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OAK RIDGE NATIONAL LABORATORY
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Reactor and Nuclear Systems Division

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Date Published: September 6, 2017

NSUF Work Package #: UF-17OR020711
Work Package Manager: Kory Linton
Milestone #: M3UF-17OR0207112

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGMENTS

This research was sponsored by the Nuclear Science User Facilities (NSUF) Program of the US Department of Energy (DOE), Office of Nuclear Energy. Neutron irradiation in the High Flux Isotope Reactor (HFIR) is made possible by the Office of Basic Energy Sciences, US DOE. The report was authored by UT-Battelle under Contract No. DE-AC05-00OR22725 with the DOE. The contributions of Kurt Terrani, ORNL program manager for the NSUF program, Kory Linton, the project manager for this work, and Yutai Katoh, the principal investigator for this work, are gratefully acknowledged. Caen Ang coordinated all coating of the cladding tube specimens. David Bryant performed most of the capsule assembly work and managed the welding and nondestructive examinations. Cladding specimens were provided by Christian Deck (General Atomics, San Diego, CA), Weon-Ju Kim (Korean Atomic Energy Research Institute, South Korea), and Cédric Sauder (Commissariat à l'Energie Atomique, France).

ABSTRACT

Neutron irradiation of silicon carbide (SiC)-based fuel cladding under a high radial heat flux presents a critical challenge for SiC cladding concepts in light water reactors (LWRs). Fission heating in the fuel provides a high heat flux through the cladding, which, combined with the degraded thermal conductivity of SiC under irradiation, results in a large temperature gradient through the thickness of the cladding. The strong temperature dependence of swelling in SiC creates a complex stress profile in SiC-based cladding tubes as a result of differential swelling. The Nuclear Science User Facilities (NSUF) Program within the US Department of Energy Office of Nuclear Energy is supporting research efforts to improve the scientific understanding of the effects of irradiation on SiC cladding tubes. Ultimately, the results of this project will provide experimental validation of multi-physics models for SiC-based fuel cladding during LWR operation. The first objective of this project is to irradiate tube specimens using a previously developed design that allows for irradiation testing of miniature SiC tube specimens subjected to a high radial heat flux. The previous "rabbit" capsule design uses the gamma heating in the core of the High Flux Isotope Reactor (HFIR) to drive a high heat flux through the cladding tube specimens. A compressible aluminum foil allows for a constant thermal contact conductance between the cladding tubes and the rabbit housing despite swelling of the SiC tubes. To allow separation of the effects of irradiation from those due to differential swelling under a high heat flux, a new design was developed under the NSUF program. This design allows for irradiation of similar SiC cladding tube specimens without a high radial heat flux. This report briefly describes the irradiation experiment design concepts, summarizes the irradiation test matrix, and reports on the successful delivery of six rabbit capsules to the HFIR. Rabbits of both low and high heat flux configurations have been assembled, welded, evaluated, and delivered to the HFIR along with a complete quality assurance fabrication package. These rabbits contain a wide variety of specimens including monolith tubes, SiC fiber SiC matrix (SiC/SiC) composites, duplex specimens (inner composite, outer monolith), and specimens with a variety of metallic or ceramic coatings on the outer surface. The rabbits are targeted for insertion during HFIR cycle 475, which is scheduled for September 2017.

1. INTRODUCTION

Silicon carbide (SiC) is a candidate material for a variety of nuclear applications because of its high-temperature strength, oxidation resistance, and stability under irradiation [1-6]. Although SiC has been under consideration for various nuclear applications since the 1960s, the more recent focus has been on using SiC as a fuel cladding for light water reactors (LWRs) to increase the accident tolerance of the fuel [7-13]. One of the major technical feasibility issues for SiC-based cladding is whether the cladding can survive the evolving stress state over the lifetime of the fuel [14-16]. A large amount of heat is generated as a result of fission occurring in the fuel, and that heat passes through the cladding before ultimately being rejected to the reactor coolant. As the cladding thermal conductivity degrades under irradiation, the high heat flux passing through the cladding results in significant temperature gradients through the cladding thickness. Because of the strong temperature dependence of swelling in SiC, the radial temperature gradients result in differential swelling, which creates a complex stress state in the cladding. This stress, combined with internal pressurization due to gaseous fission product accumulation inside the fuel rod, could result in cracking and fission product release.

The Nuclear Science User Facilities (NSUF) Program within the US Department of Energy (DOE) Office of Nuclear Energy (DOE-NE) is funding Oak Ridge National Laboratory (ORNL) to experimentally investigate irradiation effects on the stress state in SiC cladding subjected to LWR conditions. The results obtained from this irradiation testing will provide experimental validation of thermomechanical models that are used to predict cladding performance during LWR operation. “Rabbit” capsules have been designed to allow miniature SiC tube specimens to be irradiated in the core of the High Flux Isotope Reactor (HFIR) at ORNL. Post-irradiation examination of the irradiated cladding tubes will include optical microscopy (to check for cracking), Raman temperature mapping, resonant ultrasound spectroscopy (for determining changes in elastic modulus), gas permeability measurements, and destructive c-ring testing (to determine residual stresses) [17]. This work summarizes the assembly and delivery of six rabbits containing a variety of SiC cladding tube specimens to the HFIR. The specimens include chemical vapor deposition (CVD) monolith tubes, SiC fiber SiC matrix (SiC/SiC) composite tubes, and duplex specimens (inner composite, outer monolith). In addition, some specimens were coated with a metallic or ceramic layer with the intention of improving hermeticity and/or hydrothermal corrosion resistance. Some of the rabbits that are to be irradiated use a previous design that allows for the cladding tubes to be tested under a representative high heat flux. Others use a new design developed under the NSUF program that allows for irradiation of tube specimens at representative LWR temperatures without a high heat flux so that the effects of differential swelling can be separated from other irradiation effects. This report provides a brief overview of the irradiation test matrix, the capsule design concepts, and the successful delivery of all irradiation capsules to the HFIR.

2. EXPERIMENT DESIGNS AND TEST MATRIX

2.1 HIGH–HEAT FLUX DESIGN

The high–heat flux irradiation capsule designed previously is shown in Figure 1 [18]. This design places the specimens around a molybdenum heater (dense gamma absorbing cylinder) at the center of the rabbit housing. The heater generates significant gamma heating, which passes through the cladding tube, resulting in a heat flux of approximately 0.6 MW/m^2 at the outer surface of the cladding. The outside of the specimen is surrounded by an aluminum sleeve, an embossed aluminum foil, and an aluminum housing, which is directly cooled by the reactor primary coolant. The embossed foil allows the specimen to swell under irradiation while maintaining good thermal contact between the sleeve and the housing. The sleeve prevents large circumferential temperature variations on the outer surface of the cladding due to the periodic contact that would otherwise exist between the cladding and the foil. The cladding surface was estimated to be 300–350°C, based on finite element analysis (FEA) [18]. The FEA results were validated using passive SiC temperature monitors located inside the molybdenum heaters.

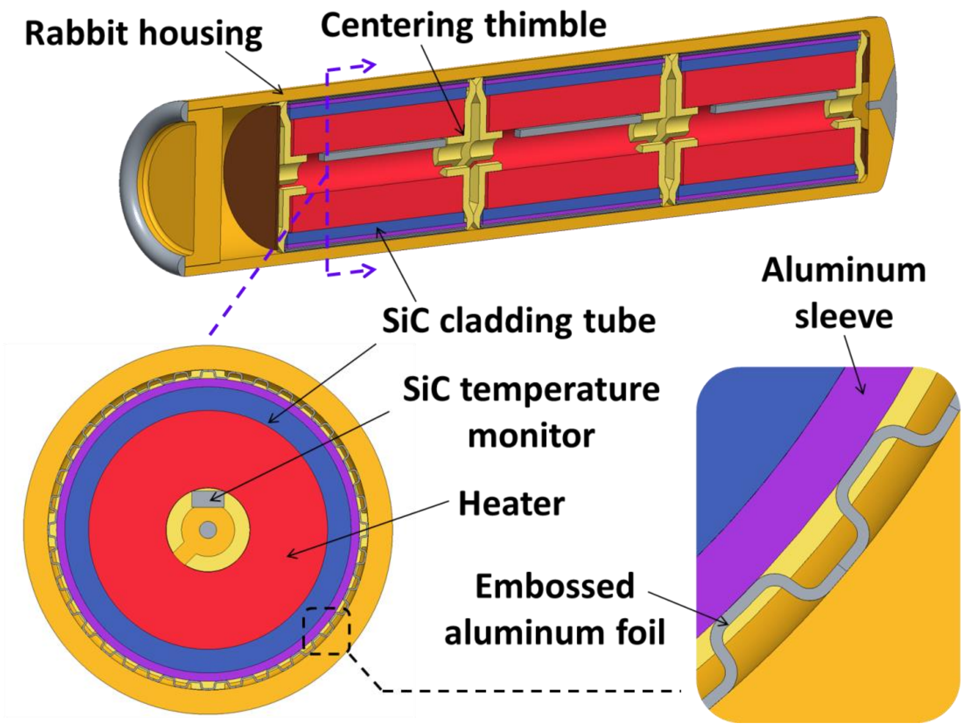

Figure 1. Previously developed design concept for irradiating SiC cladding tubes under a high radial heat flux.

2.2 LOW–HEAT FLUX DESIGN

As mentioned previously, the low–heat flux design was developed under the NSUF program to provide SiC cladding tube specimens that have been irradiated without differential swelling stresses resulting from the high radial heat flux and associated temperature gradients [19]. This allows for the separation of differential swelling effects from effects related to radiation damage. Figure 2 shows the concept for the low (~0.08 MW/m^2) heat flux design. Three cladding tubes are stacked in the vertical direction inside the rabbit housing. Each tube specimen has centering thimbles inserted on either end to keep the specimens centered within the housing. A compression spring is placed at the top of the rabbit to prevent the centering thimbles from dislodging from the cladding specimens. All centering thimbles are made of aluminum, except for the bottom thimble, which is made of a titanium alloy. The low density and high thermal conductivity of aluminum minimizes temperature extremes on the ends of the specimens due to increased gamma heating in the thimbles. To further reduce axial temperature gradients along the length of the specimens, graphite inserts are placed inside the cladding between the two centering thimbles to provide a more uniform heat loading along the length of the cladding tubes. The bottom thimble is made of titanium because of its low thermal conductivity, which reduces axial heat losses from the bottom cladding specimen to the cool bottom surface of the capsule housing. Figure 3 shows predicted temperatures for a SiC/SiC composite specimen during irradiation in both the high– and low–heat flux design configurations. Temperatures for the high–heat flux configuration were replotted from the data in Petrie et al. [18]. Clearly the low–heat flux design allows for much lower temperature gradients within the specimens.

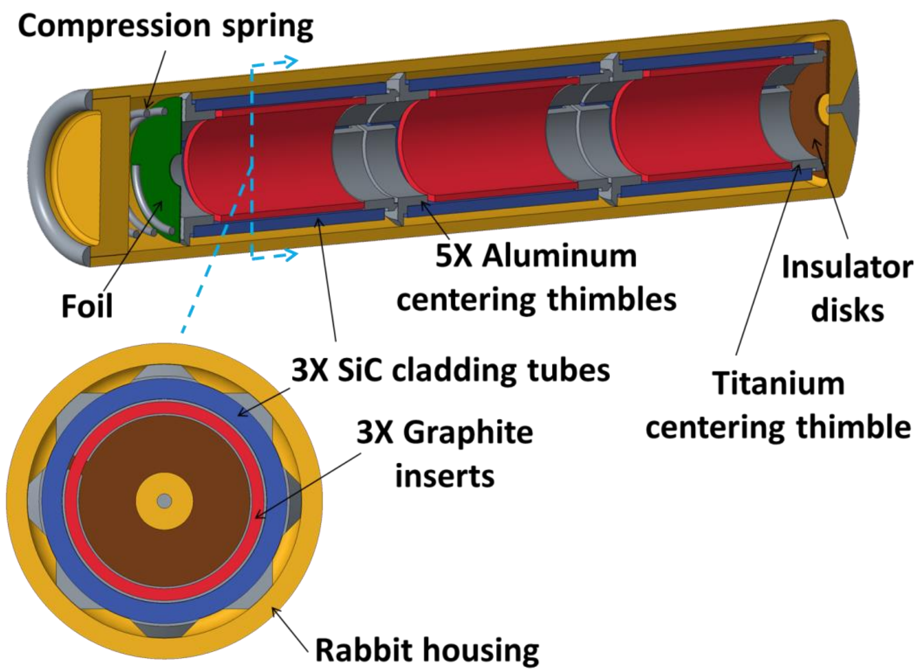

Figure 2. Section view showing low–heat flux design concept developed under the NSUF project.

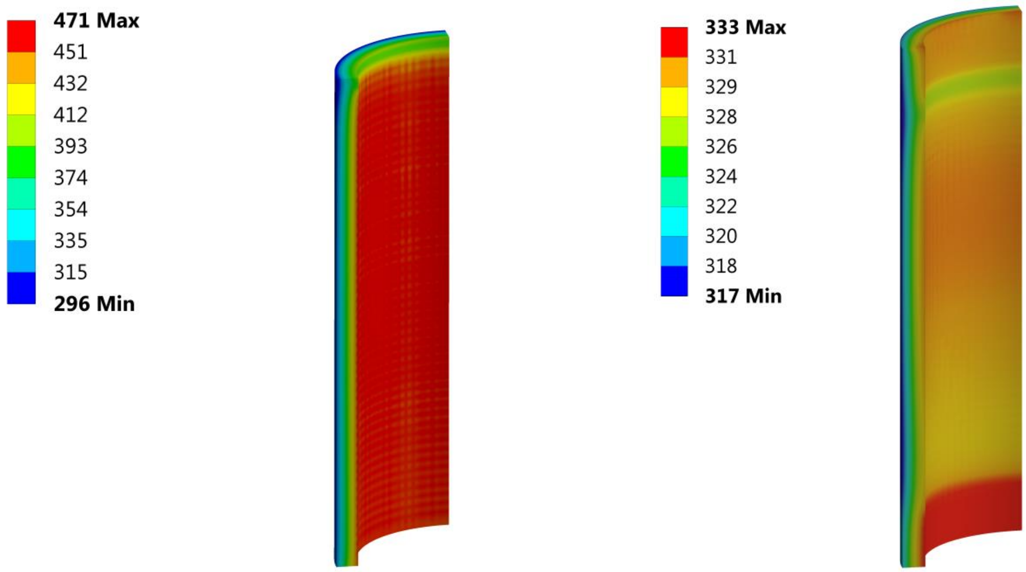

Figure 3. SiC/SiC composite cladding specimen temperature (°C) contours during irradiation in the high (left) and low (right) heat flux design configurations.

2.3 IRRADIATION TEST MATRIX

Table 1 and Table 2 summarize the irradiation test matrix. The specimens come from a variety of manufacturers, including The Dow Chemical Company (Dow), General Atomics (GA), the Korean Atomic Energy Research Institute (KAERI) in South Korea, and the Commissariat à l'Energie Atomique (CEA) in France. Coating was performed by two companies: Richter Precision Inc. (RP) and Techmetals Inc. (TM). Coatings included Cr, CrN, and TiN. Table 1 shows the loading of specimens in each rabbit along with the irradiation positions and fill gases. Each rabbit contains three specimens. Table 2 summarizes all specimens by specimen manufacturer, type, coating, and heat flux (high– or low–heat flux design). All specimens will be irradiated for one cycle (cycle 475) in the HFIR, which will result in a radiation dose of approximately 2.3 dpa [18]. The targeted cladding surface temperature is approximately 300–350°C for all rabbits. Temperature gradients through the thickness depend on the heat flux and the specimen thermal conductivity, which varies with specimen type and neutron fluence. The nominal specimen dimensions are 8.5 mm outer diameter, 7.1 mm inner diameter, and 16 mm length.

Table 1. Rabbit irradiation test matrix showing the loading of specimens within each rabbit, the irradiation positions, and fill gases

Rabbit	Heat flux	Cladding 1	Cladding 2	Cladding 3	Irradiation position	Fill gas
ATFSC06	High	CVD-E	GA-TGI-C-1	N1N3(8)	G4-4	He
ATFSC07	High	CVD-H	TYPE S-1	SA3-2	A1-4	He
ATFSC09	High	CVD-G	1-TM-CrN	4-RP-CrN	A4-4	He
SCL01	Low	CVD-L	SA3-1	N1N3(1)	A1-5	85% He, Ar bal.
SCL05	Low	CVD-Q	6-RP-Cr	2-TM-CrN	D1-5	85% He, Ar bal.
SCL06	Low	CVD-R	3-RP-CrN	7-TM-TiN	G7-4	85% He, Ar bal.

Table 2. Specimen irradiation test matrix showing number of specimens to be irradiated according to specimen manufacturer, type, coating, and heat flux (high or low heat flux design).

Manufacturer	Type	Coating	Specimen ID	Heat flux	
				High	Low
Dow	Monolith	None	CVD-X (X=E, G, H, L, Q, R)	3	3
GA	SiC/SiC composite	None	GA-TGI-C-1	1	0
GA	Duplex: inner composite, outer monolith	CrN	1-TM-CrN, 3-RP-CrN	1	1
GA	Duplex: inner composite, outer monolith	Cr	6-RP-Cr	0	1
KAERI	Duplex: inner composite, outer monolith	None	TYPE S-1, SA3-1, SA3-2	2	1
CEA	SiC/SiC composite	None	N1N3(1), N1N3(8)	1	1
CEA	SiC/SiC composite	CrN	2-TM-CrN, 4-RP-CrN	1	1
CEA	SiC/SiC composite	TiN	7-TM-TiN	0	1

3. RABBIT CAPSULE ASSEMBLY AND DELIVERY TO THE HFIR

3.1 HIGH–HEAT FLUX RABBITS ASSEMBLY

The three high–heat flux rabbits (ATFSC06, ATFSC07, and ATFSC09) were assembled. Pictures of the parts layout and specimen sub-assemblies for rabbit ATFSC06 are shown in Figure 4. Figure 5 shows the parts layout for rabbits ATFSC07 and ATFSC09. Figure 6 shows a top-down view of CEA SiC/SiC composite specimen N1N3(8) assembled inside the rabbit housing ATFSC06 with the heater, sleeve, foil, and thermometry surrounded by quartz wool. The signed capsule fabrication request forms are provided in APPENDIX A. Figure 7 shows an example of the pre-irradiation optical microscopy that is performed on each specimen (SA3-2 in this case) so that defects that exist in the specimen before irradiation are not attributed to radiation damage. The top of the specimen shows engraving marks for identifying the specimen. A surface defect is clearly visible in the bottom right picture.

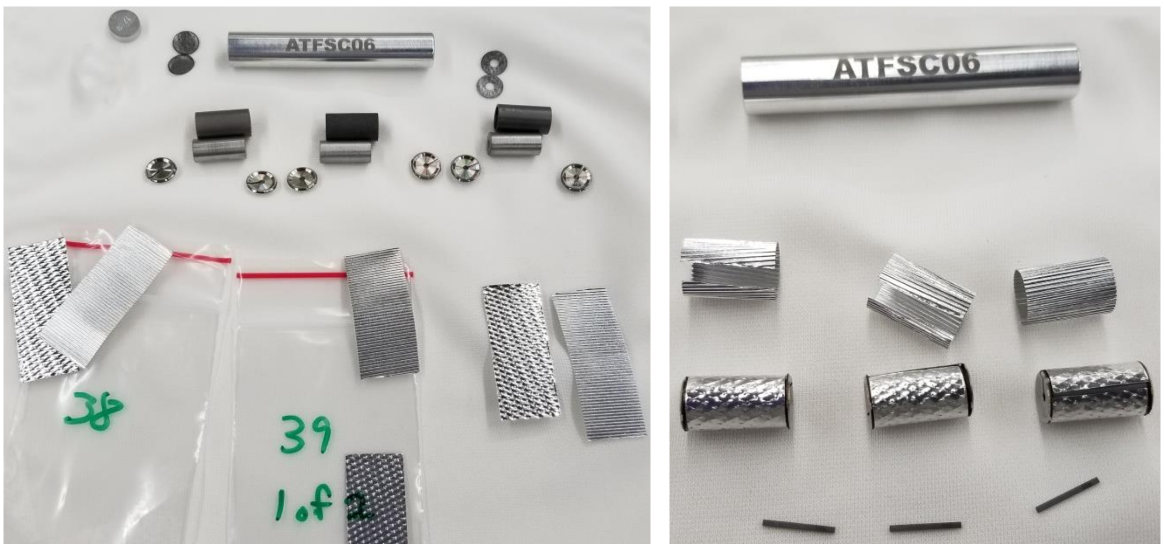

Figure 4. Parts (left) and assembly (right) of rabbit ATFSC06.

Figure 5. Parts for assembly of rabbits ATFSC07 (left) and ATFSC09 (right).

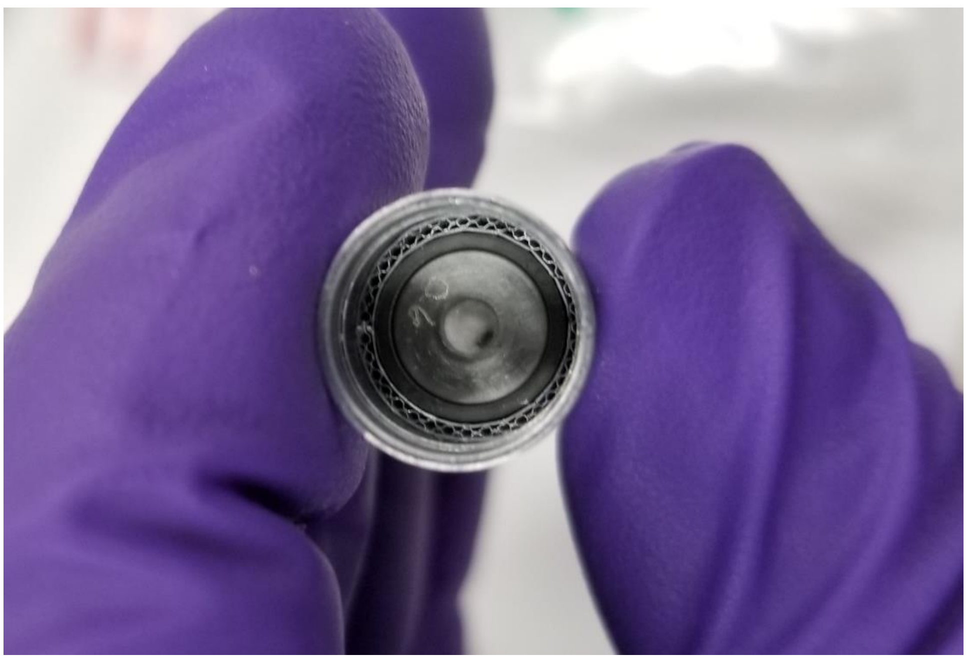

Figure 6. Top-down view of CEA SiC/SiC composite specimen N1N3(8) assembled inside rabbit housing ATFSC06 with the heater, sleeve, foil, and thermometry surrounded by quartz wool.

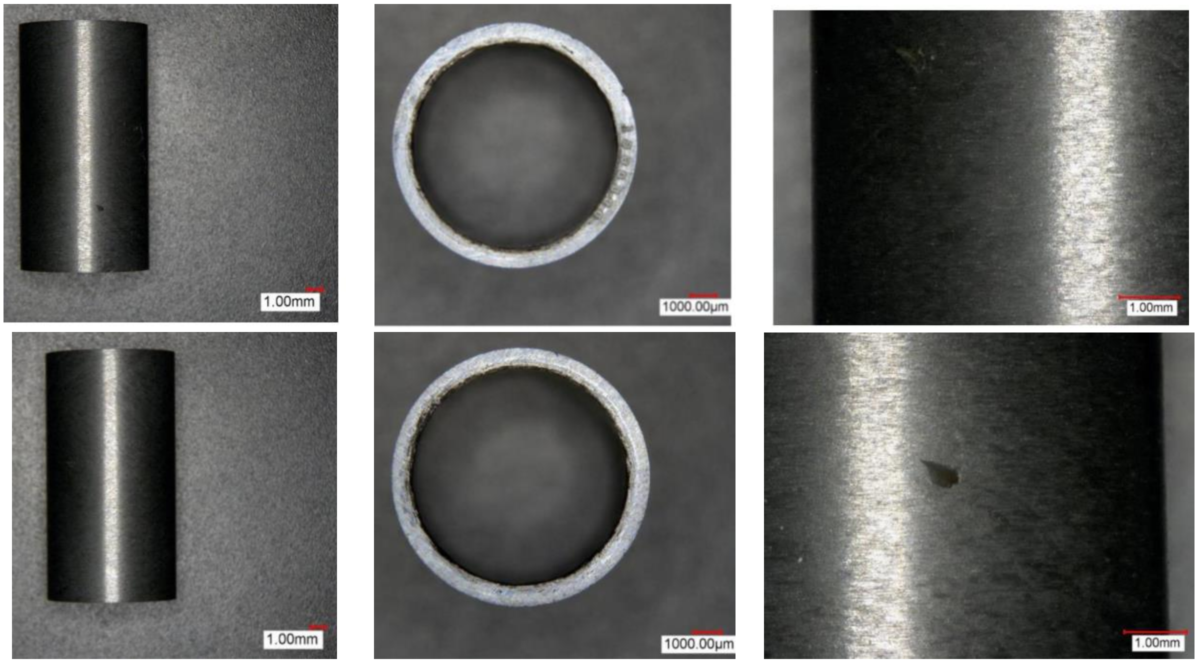

Figure 7. Example of optical microscopy performed on each specimen (SA3-2 in this case) before irradiation.

All capsule components were dimensionally inspected and cleaned according to HFIR-approved procedures, drawings, and sketches. After assembly of the internal components, all rabbit housing end caps were welded to the housings using an electron beam weld. The capsules were then placed inside sealed chambers that were evacuated and backfilled with ultra-high-purity helium gas three times to ensure a pure helium environment. The chambers were placed inside a glove box, which was also evacuated and backfilled with helium. Each rabbit had a small hole in the bottom of the housing that was sealed using a gas tungsten arc welding procedure. All welds passed visual examination. Each capsule was then sent for nondestructive examination, which included a helium leak test, hydrostatic compression at a pressure of 1,035 psi, mass comparisons before and after hydrostatic compression to ensure no water penetrated the capsule housing, and a final post-compression helium leak test. All rabbits passed helium leak testing and hydrostatic compression.

3.2 LOW–HEAT FLUX RABBITS ASSEMBLY

Three low–heat flux rabbits (SCL01, SCL05, and SCL06) were assembled. Pictures of the layout for each rabbit before irradiation are shown for these three rabbits in Figure 8. Figure 9 shows an example of cladding specimens assembled with centering thimbles. Figure 10 shows an example of optical microscopy performed on a coated specimen (7-TM-TiN) that was included in low–heat flux irradiation capsule SCL06. The low–heat flux rabbits and rabbit components were inspected, cleaned, assembled, and tested using the same processes and procedures as the high–heat flux rabbits, except that the backfill gas was an 85% He–Ar balance mixture instead of pure helium. All rabbits passed weld examination, helium leak testing, and hydrostatic compression.

Figure 8. Capsule parts for low–heat flux rabbits SCL01, SCL05, and SCL06.


Figure 9. Cladding specimens assembled with centering thimbles for the low–heat flux design configuration.

Figure 10. Example of optical microscopy performed on coated specimen 7-TM-TiN before irradiation in low–heat flux rabbit SCL06.

3.3 QUALITY ASSURANCE, FABRICATION PACKAGE, AND DELIVERY TO THE HFIR

Each rabbit irradiation experiment requires a fabrication package that is reviewed by an independent design engineer, a lead quality assurance (QA) representative, and a HFIR QA representative before acceptance for insertion into the HFIR. The fabrication package must satisfy the requirements of the Experiment Authorization Basis Document (EABD). Rabbit capsules fall under document EABD-HFIR-2009-004. This document specifies a number of requirements that the rabbits must satisfy in the areas of

- thermal safety analyses,
- material certification,
- dimensional inspection,
- cleaning,
- assembly procedure,
- sample loading,
- fill gas,
- welding, and
- nondestructive evaluation.

A separate fabrication package was prepared for the low– and high–heat flux rabbit capsules. These packages were reviewed and approved by an independent design engineer, lead QA representative, and HFIR QA representative and accepted by HFIR on August 14, 2017. The final signed acceptance page of the EABD is provided in APPENDIX A. All six rabbits are scheduled for insertion during HFIR cycle 475 (September 2017).

4. SUMMARY AND CONCLUSIONS

This work summarizes the capsule design concepts and the irradiation test matrix for six rabbit capsules, which were successfully assembled and delivered to the HFIR for insertion during cycle 475 (September 2017). Each rabbit contains three SiC cladding tube specimens, which will be evaluated post-irradiation as part of an NSUF-funded project investigating the effects of irradiation with a high radial heat flux on the stress state in SiC-based fuel cladding. Three rabbits use a previous design that provides the required radial heat flux through the specimens during irradiation. A new design was developed under the NSUF program to allow for irradiation at LWR temperatures without a significant radial heat flux to allow the separation of effects related to differential swelling from other irradiation effects. A wide variety of specimens were included in the test matrix, including monolith tubes, SiC/SiC composites, duplex specimens (inner composite, outer monolith), and specimens with a variety of metallic or ceramic coatings on the outer surfaces. The rabbits were successfully assembled, welded, evaluated, and delivered to the HFIR along with a complete QA fabrication package. Pictures of the rabbit assembly process and optical microscopy of select specimens are included in this report. Documentation of the capsule fabrication and final acceptance by HFIR is provided in an appendix. Ultimately, the results of this project will provide experimental validation of multi-physics models of the stress state of SiC-based fuel cladding during LWR operation.

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APPENDIX A. FABRICATION AND QUALITY ASSURANCE DOCUMENTATION FOR COMPLETED RABBITS

APPENDIX A. FABRICATION AND QUALITY ASSURANCE DOCUMENTATION FOR COMPLETED RABBITS

Caps[illegible] Fabrication Request Sheet

Page 1 of 1
Dat[illegible] [illegible]/2017

Capsu[illegible] umber: ATFSC06

Irradiation Conditions

Irradiation Location	TRRH 4
Target Fluence	2.4E+21
First Cycle Goal	474
Irradiation Time	1.0 cycles
Irradiation Temperature	325°C
Fill Gas	Helium
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	[signature] 7-24-17	[signature] 7/14/17
Checked by:	[signature] 7/24/17	[signature] 7/12/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		20654	20654	16-36	4.3396
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-66	0.5092
Cladding	S15-28-SIC-CLAD-02	C	3	SiC	3	Cladding 1	19502	20681	CVD-E	0.8909
						Cladding 2	20669	20669	GA-TGI-C-1	0.7713
						Cladding 3			N1N3(8)	0.7908
Heater	S15-28-SIC-CLAD-02	C	4	Moly	2	Match to cladding 1	20153	20670	16-10	5.4481
						Match to cladding 2			16-11	5.3290
						Match to cladding 3			16-12	5.4324
Centering thimble	S15-28-SIC-CLAD-02	C	2	Ti-6Al4V	6		20369	20419	ARM00001	0.1711
									ARM00015	0.1706
									ARM00016	0.1704
									ARM00021	0.1694
									ARM00064	0.1690
									ARM00065	0.1687
Sleeve	S15-28-SIC-CLAD-02	C	5	Al 1100	3	8 µm RMS: Clad 1	20379	20671	38	.146
						8 µm RMS: Clad 2			39	.147
						8 µm RMS: Clad 3			38	.149
Foil	S15-28-SIC-CLAD-02	C	6	Al 1100	3	Match to cladding 1	20388	20473	3 total from F01	.071
						Match to cladding 2				.072
						Match to cladding 3				.073
Small thermometry	X3E020977A540	1	3	SiC	3	Match to cladding 1	19502	20680	15A	0.0182
						Match to cladding 2			13A	0.0182
						Match to cladding 3			14A	0.0187
Insulator disc with hole	S15-28-SIC-CLAD-02	C	17	Grafoil	2	.13 mm thick	19812	19812	2 total	.014
Insulator disc w/o hole	S15-28-SIC-CLAD-02	C	18	Grafoil	2	.13 mm thick	19812	19812	2 total	.016
Quartz wool	S15-27-SIC-CLAD-01	0	NA	SiO2	AR	See notes 5 & 6	20679	20679	NA	.101
									Total Mass	24.5856
									Specimen Mass	2.4530
									Internal Mass	19.7368

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-27-SIC-CLAD-01-2	0	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	Helium		

Caps[illegible] Fabrication Request Sheet

Capsul[illegible] Number: ATFSC07

Irradiation Conditions

Irradiation Location	TRRH 4
Target Fluence	2.4E+21
First Cycle Goal	474
Irradiation Time	1.0 cycles
Irradiation Temperature	325°C
Fill Gas	Helium
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 7-24-17	[signature] 7/14/17
Checked by:	[signature] 7/24/17	[signature] 7/19/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		20654	20654	16-47	4.3314
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-51	0.5230
Cladding	S15-28-SIC-CLAD-02	C	3	SiC	3	Cladding 1	19502	20681	CVD-H	0.8914
						Cladding 2	20669	20669	TYPE S-1	0.8267
						Cladding 3			SA3-2	0.7955
Heater	S15-28-SIC-CLAD-02	C	4	Moly	2	Match to cladding 1	20153	20420	ARM00019	5.4309
						Match to cladding 2		20670	16-16	~~5.4310~~ 5.452
						Match to cladding 3			16-17	~~5.4320~~ 5.431 CMP 7-27-17
Centering thimble	S15-28-SIC-CLAD-02	C	2	Ti-6Al4V	6		20369	20419	ARM00058	0.1687
									ARM00047	0.1712
									ARM00024	0.1712
									ARM00005	0.1701
									ARM00053	0.1709
									ARM00012	0.1702
Sleeve	S15-28-SIC-CLAD-02	C	5	Al 1100	3	8 µm RMS: Clad 1	20379	20671	41	.141
						8 µm RMS: Clad 2			41	.143
						8 µm RMS: Clad 3			39	.146
Foil	S15-28-SIC-CLAD-02	C	6	Al 1100	3	Match to cladding 1	20388	20473	3 total from F01	.072
						Match to cladding 2				.073
						Match to cladding 3				.071
Small thermometry	X3E020977A540	1	3	SiC	3	Match to cladding 1	19502	20680	17A	~~0.0187~~ .0181
						Match to cladding 2			16A	0.0186
						Match to cladding 3			18A	0.0186 CMP 7-27-17
Insulator disc with hole	S15-28-SIC-CLAD-02	C	17	Grafoil	2	.13 mm thick	19812	19812	2 total	.013
Insulator disc w/o hole	S15-28-SIC-CLAD-02	C	18	Grafoil	2	.13 mm thick	19812	19812	2 total	.015
Quartz wool	S15-27-SIC-CLAD-01	0	NA	SiO2	AR	See notes 5 & 6	20679	20679	NA	.076
									Total Mass	24.7491
									Specimen Mass	2.5136
									Internal Mass	19.0857

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-27-SIC-CLAD-01-2	0	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	Helium		

Caps Fabrication Request Sheet

Capsule Number: ATFSC09

Irradiation Conditions

Irradiation Location	TRRH 4
Target Fluence	2.4E+21
First Cycle Goal	474
Irradiation Time	1.0 cycles
Irradiation Temperature	325°C
Fill Gas	Helium
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	Chris Robin 7-24-17	[signature] 7/14/17
Checked by:	[signature] 7/24/17	Jordan Hosinger 7/1/12

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		20713	20713	17-89	4.3338
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-39	0.5164
Cladding	S15-28-SIC-CLAD-02	C	3	SiC	3	Cladding 1	19502	20681	CVD-G	0.8925
						Cladding 2	20669	20747	1-TM-CrN	0.8097
						Cladding 3			4-RP-CrN	0.8515
Heater	S15-28-SIC-CLAD-02	C	4	Moly	2	Match to cladding 1	20153	20420	ARM00010	5.4299
						Match to cladding 2		20670	16-02	5.2790
						Match to cladding 3		20420	ARM00016	5.4440
Centering thimble	S15-28-SIC-CLAD-02	C	2	Ti-6Al4V	6		20369	20419	ARM00019	0.1683
									ARM00028	0.1710
									ARM00040	0.1715
									ARM00041	0.1718
									ARM00042	0.1712
									ARM00070	0.1694
Sleeve	S15-28-SIC-CLAD-02	C	5	Al 1100	3	8 µm RMS: Clad 1	20379	20671	32	.147
						8 µm RMS: Clad 2			37	.148
						8 µm RMS: Clad 3			33	.146
Foil	S15-28-SIC-CLAD-02	C	6	Al 1100	3	Match to cladding 1	20388	20473	3 total from F01	.075
						Match to cladding 2				.076
						Match to cladding 3				.073
Small thermometry	X3E020977A540	1	3	SiC	3	Match to cladding 1	19502	20680	8A	0.0184
						Match to cladding 2			21A	0.0177
						Match to cladding 3			22A	0.0183
Insulator disc with hole	S15-28-SIC-CLAD-02	C	17	Grafoil	2	.13 mm thick	19812	19812	2 total	.013
Insulator disc w/o hole	S15-28-SIC-CLAD-02	C	18	Grafoil	2	.13 mm thick	19812	19812	2 total	.015
Quartz wool	S15-27-SIC-CLAD-01	0	NA	SIO2	AR	See notes 5 & 6	20679	20679	NA	.094
									Total Mass	24.6344
									Specimen Mass	2.5537
									Internal Mass	19.7542

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-27-SIC-CLAD-01-2	0	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	Helium		

Caps[illegible] Fabrication Request Sheet

Capsule Number: SCL01

Irradiation Conditions

Irradiation Location	PTP 4
Target Fluence	2.4E+21
First Cycle Goal	473
Irradiation Time	1.0 cycles
Irradiation Temperature	340ºC
Fill Gas	85%He, Ar bal
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	[signature] 4.12.17	[signature] 4/17/17
Checked by:	Chris Petrie 4-12-17	[signature] 4/17/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		20654	20654	16-31	4.3321
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-22	0.5087
Centering Thimble	S15-35-SIC-CLAD-NOHF	1	2	DISPAL AL	5		16941	20672	A21	0.0948
									A22	0.0966
									A34	0.0961
									A35	0.0958
									A42	0.0964
	S15-35-SIC-CLAD-NOHF	1	7	Ti6Al4V	1	bottom of assy	20093	20673	T01	0.1585
Cladding	S15-28-SIC-CLAD-02	B	3	SiC	3	CVD-L	19502	20681	CVD-L	0.8822
						1000000	20669	20669	SA3-1	0.8186
						10	20669	20669	N1N3(1)	0.7853
Insert	S15-35-SIC-CLAD-NOHF	1	3	Graphite	3	CMP	5-4-17 19463	20660	54	0.1750
									53	0.1720
									40	0.1780
Foil	S15-35-SIC-CLAD-NOHF	1	4	Ti	1		20612	20612	1 total	0.022
Insulator Disk	S15-35-SIC-CLAD-NOHF	1	5	Grafoil	2		19812	19812	2 total	0.018
Compression Spring	S15-35-SIC-CLAD-NOHF	1	6	Stainless Steel	1		20659	20659	1B	0.1040

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-35-SIC-CLAD-NOHF	1	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	85% He, Ar bal.		

Caps Fabrication Request Sheet

Capsule Number: SCL05

Irradiation Conditions

Irradiation Location	PTP 4
Target Fluence	2.3E+21
First Cycle Goal	474
Irradiation Time	1.0 cycles
Irradiation Temperature	325°C
Fill Gas	85% He, Ar bal.
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 7-3-17	[signature] 6/28/17
Checked by:	[signature] 7/3/17	[signature]

Capsule Fabrication

20713 17-90

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		~~20654~~	~~20654~~	~~16-42~~	~~4.3237~~ 4.3336 cap 7-3-17
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-72	.5050
Centering thimble	S15-35-SIC-CLAD-NOHF	1	2	Dispal Al	5	All thimbles except bottom	16941	20672	A01	.096
									A08	.097
									A19	.096
									A20	.096
									A28	.097
Centering thimble	S15-35-SIC-CLAD-NOHF	1	7	Ti-6Al4V	1	Bottom thimble	20093	20673	T06	.156
Cladding	S15-28-SIC-CLAD-02	C	3	SiC	3		19502	20681	CVD-Q	.883
							20669	20747	6-RP-Cr	.757
									2-TM-CrN	.819
Insert	S15-35-SIC-CLAD-NOHF	1	3	Graphite	3		19463	20660	55	.173
									22	.175
									57	.178
Foil	S15-35-SIC-CLAD-NOHF	1	4	Ti-6Al4V	1		20612	20612	1 total	0.022
Insulator disk	S15-35-SIC-CLAD-NOHF	1	5	Grafoil	2		19812	19812	2 total	0.014
Compression spring	S15-35-SIC-CLAD-NOHF	1	6	304 SS	1		20659	20659	1 total	0.109
									Total Mass	0.0000
									Specimen Mass	0.0000
									Internal Mass	0.0000

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-35-SIC-CLAD-NOHF	1	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	85% He, Ar bal.		

Capsule Fabrication Request Sheet

Capsule Number: SCL06

Irradiation Conditions

Irradiation Location	PTP 4
Target Fluence	2.3E+21
First Cycle Goal	474
Irradiation Time	1.0 cycles
Irradiation Temperature	325°C
Fill Gas	85% He, Ar bal.
Cladding Design Diameter	8.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 7-3-17	[signature] 6/28/17
Checked by:	[signature] 7/3/17	[signature]

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	A	1	Al 6061	1		20654	20654	16-06	~~4.3108~~ 4.2984 cap 7-3-17
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20533	15-02	.4916
Centering thimble	S15-35-SIC-CLAD-NOHF	1	2	Dispal Al	5	All thimbles except bottom	16941	20672	A12	.097
									A13	.096
									A14	.096
									A31	.096
									A51	.097
Centering thimble	S15-35-SIC-CLAD-NOHF	1	7	Ti-6Al4V	1	Bottom thimble	20093	20673	T07	.157
Cladding	S15-28-SIC-CLAD-02	C	3	SiC	3		19502	20681	CVD-R	.890
							20669	20747	3-RP-CrN	.714
									7-TM-TiN	.807
Insert	S15-35-SIC-CLAD-NOHF	1	3	Graphite	3		19463	20660	47	.174
									20	.176
									8	.178
Foil	S15-35-SIC-CLAD-NOHF	1	4	Ti-6Al4V	1		20612	20612	1 total	.022
Insulator disk	S15-35-SIC-CLAD-NOHF	1	5	Grafoil	2		19812	19812	2 total	.011
Compression spring	S15-35-SIC-CLAD-NOHF	1	6	304 SS	1		20659	20659	1 total	0.101
									Total Mass	0.0000
									Specimen Mass	0.0000
									Internal Mass	0.0000

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S15-35-SIC-CLAD-NOHF	1	
Welding & Cleaning	X3E020977A633	0	
Fill Gas	85% He, Ar bal.		

Section 6: Acceptance for Use of As-Built Experiment Capsule

Note: This section is used to document acceptance of the as-built experiment for reactor installation and irradiation. This section is completed **after** completion of Section 2. See notes for explanation of signatures.

1. List Applicable Rabbit Identification and Heat Generation Classification (High or Low)

User I.D.	HFIR I.D.*	Heat Classification
ATFSC03		High
ATFSC04		↓
ATFSC05		
ATFSC06		
ATFSC07		
ATFSC08		
ATFSC09		

* Quality Assurance to verify correlation of User ID and HFIR ID noted above are consistent with markings presented on product body.

Independent Verification of User I.D. and HFIR I.D. : [signature]

2. Attach Capsule Fabrication Request Sheet or Equivalent : Chris Petrie Lead Experimenter

3. Approvals (see notes for explanation of signature responsibilities)

Christian Petrie Lead Experimenter	[signature] Lead Experimenter (signature)	8-1-17 Date
M.C. Vance Lead QA	[signature] Lead QA (signature)	8/2/17 Date
L.C. Smith RRD QA	[signature] RRD QA (signature)	8/3/17 Date
Greg Hirtz RRD EA&C Staff	[signature] RRD EA&C Staff (signature)	8/11/17 Date
N.A. No NCS Requirements RRD Criticality Safety Officer	N.A. No NCS Requirements RRD Criticality Safety Officer (signature)	NA Date
N.A. No MBA Requirements HFIR MBA Representative	N.A. No MBA Requirements HFIR MBA Representative (signature)	NA Date
BRIAN E FULLER HFIR Operations (print name)	[signature] HFIR Operations (signature)	8-15-17 Date

Section 6: Acceptance for Use of As-Built Experiment Capsule

Note: This section is used to document acceptance of the as-built experiment for reactor installation and irradiation. This section is completed **after** completion of Section 2. See notes for explanation of signatures.

1. List Applicable Rabbit Identification and Heat Generation Classification (High or Low)

User I.D.	HFIR I.D.*	Heat Classification
SCL01		Low
SCL02		↓
SCL03		↓
SCL04		↓
SCL05		↓
SCL06		↓

* Quality Assurance to verify correlation of User ID and HFIR ID noted above are consistent with markings presented on product body.
Independent Verification of User I.D. and HFIR I.D. : L C Smith

2. Attach Capsule Fabrication Request Sheet or Equivalent : Chris Petrie Lead Experimenter

3. Approvals (see notes for explanation of signature responsibilities)

Christian Petrie Lead Experimenter	Chris Petrie Lead Experimenter (signature)	8-1-17 Date
M.C. Vance Lead QA	[signature] Lead QA (signature)	8/2/17 Date
L. C. Smith RRD QA	L C Smith RRD QA (signature)	8/3/17 Date
Greg Hirtz RRD EA&C Staff	Greg Hirtz RRD EA&C Staff (signature)	8/4/17 Date
N.A. No NCS Requirements RRD Criticality Safety Officer	N.A. No NCS Requirements RRD Criticality Safety Officer (signature)	NA Date
N.A. No MBA Requirements HFIR MBA Representative	N.A. No MBA Requirements HFIR MBA Representative (signature)	NA Date
FULLER, BRIAN E HFIR Operations (print name)	Brian E Fuller HFIR Operations (signature)	08/15/2017 Date