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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Reactor and Nuclear Systems Division

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

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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 SiCbased 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/m² 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/m²) 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.

Manufacturer	Туре	Coating	Specimen ID	<u>Heat</u> High	<u>flux</u> 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

 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).

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 postirradiation 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**



A-3

Helium

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oil S15-26-SIC-CLAD-02 C 5 3 8 µm RMS: Clad 2 20379 20671 41 1/42 oil S15-26-SIC-CLAD-02 C 6 Al 1100 Al match to cladding 1 2038 20473 3 total from F01 2073 mall thermometry X35020977A540 1 3 Match to cladding 2 20388 20473 3 total from F01 2073 mall thermometry X35020977A540 1 3 3 Match to cladding 2 20388 20473 3 total from F01 2073 mall thermometry X35020977A540 1 3 3 Match to cladding 2 19802 20473 3 total from F01 2073 malter disc with hole S15-28-SIC-CLAD-02 C 17 3 Match to cladding 2 19802 2 total 2 2018 2073 sullator disc with hole S15-27-SIC-CLAD-02 C 18 3 18812 2 total 2 2 total 2<	oil 515-28-SIC-CLAD-02 C 5 3 8 µm RMS: Clad 2 9 µm	AI 1100	8 µm RMS: Clad 1			41	1 141.		
Oil Oil Natch to clading 2 Coach O Natch to clading 2 So and throm For Natch to clad	oill S15-28-SIC-CLAD-02 C 6 AI 1100 Match to cladding 1 mall thermometry X3E0209774540 1 3 Match to cladding 2 mall thermometry X3E0209774540 1 3 Match to cladding 2 mall thermometry X3E0209774540 1 3 Match to cladding 2 match tole S15-28-SIC-CLAD-02 C 17 3 Match to cladding 2 match tole S15-28-SIC-CLAD-02 C 17 3 Match to cladding 2 match tole S15-28-SIC-CLAD-02 C 18 3 Match to cladding 2 match tole S15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mm thick usutator disc with hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick usutator wol S15-27-SIC-CLAD-01 0 N SIO2 AR See notes 5 & 6	ß	3 8 µm RMS: Clad 2	20379	20671	41	.143		
Match in classing S15-28-SIC-CLAD-02 C 6 Match in classing 20388 20473 3 tatal from F01 2024 imall thermometry X3E020977A540 1 3 Match to classing 20388 20473 3 tatal from F01 2024 imall thermometry X3E020977A540 1 3 Natch to classing 20388 20473 3 tatal from F01 272 isulator disc with hole S15-28-SIC-CLAD-02 C 17 3 match to classing 18912 19802 20680 18A 0.0188 9018 isulator disc with hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick 19812 2 total 2/2 10.0188 <	Offer S15-28-SIC-CLAD-02 C 6 Match to cladding 1 imall thermometry X3E0209774540 1 3 Match to cladding 2 imall thermometry X3E0209774540 1 3 Match to cladding 2 isulator disc with hole S15-28-SIC-CLAD-02 C 17 3 Match to cladding 2 isulator disc with hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick usutator disc with hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick usutator disc with hole S15-27-SIC-CLAD-01 0 NA SIO2 AR See notes 5 & 6 usariz wool S15-27-SIC-CLAD-01 0 NA SIO2 AR See notes 5 & 6 usariz wool S15-27-SIC-CLAD-01 0 NA SIO2 AR See notes 5 & 6 usariz wool S15-27-SIC-CLAD-01 0 NA SIO2 AR See notes 5 & 6 seembly Drawing S15-27-SIC-CLAD-01 0 NA SIO2 AR	A1 1100	Match to clouding 4			200	146		
mail thermometry X3E020877A540 1 3 SiC Match to cladding 2 15602 20680 17A 60473 Match to cladding 2 13A 0.0186 13A 0.0186 Match to cladding 2 13A 0.0186 13A 0.0186 Match to cladding 2 13B 13A 0.0186 13A 0.0186 Match to cladding 2 13B 13B 13B 13B 0.0186 Match to cladding 2 13B	mail thermometry X3E020977A540 1 3 SiC Match to cledding 1 sulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mtch to cladding 3 sulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mtch to cladding 3 sulator disc with hole \$15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mt thick sulator disc with hole \$15-28-SIC-CLAD-012 0 NA \$502 AR See notes 5 & 6 utartz wool \$15-27-SIC-CLAD-012 0 NA \$502 AR See notes 5 & 6 stembly Drawing \$15-27-SIC-CLAD-012 0 NA \$502 AR See notes 5 & 6 delding & Cleaning \$16-27 \$10-27 0 \$102 AR See notes 5 & 6 ssembly Drawing \$15-27-SIC-CLAD-01-2 0 NA \$102 AR See notes 5 & 6 ssembly Drawing \$15-27-SIC-CLAD-01-2 0 NA \$102 AR See notes 5 & 6 <td>9</td> <td>3 Match to cladding 2 Match to cladding 2</td> <td>20388</td> <td>20473</td> <td>3 total from F01</td> <td>510.</td> <td></td>	9	3 Match to cladding 2 Match to cladding 2	20388	20473	3 total from F01	510.		
X3E0209774540 1 3 Match to clading 2 15602 20680 15A 0.0188 V rsulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 -13 mm thick 19812 19812 2 total $\sqrt{3}$ $\sqrt{3}$ rsulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 -13 mm thick 19812 19812 2 total $\sqrt{3}$ $\sqrt{3}$ sulatize wool \$15-28-SIC-CLAD-02 C 18 Grafoil 2 -13 mm thick 19812 19812 2 total $\sqrt{3}$ Juartz wool \$15-27-SIC-CLAD-01 0 NA SIO2 2 total $\sqrt{3}$ $\sqrt{3}$ Seembly Total whick 19812 19812 2 total $\sqrt{3}$ $\sqrt{3}$ static wool SIS-27-SIC-CLAD-01 0 NA SIO2 2 0579 2 0579 NA $\sqrt{3}$ Static wool SIS-27-SIC-CLAD-012 0 NA SIO3 2 0579 $\sqrt{3}$ $\sqrt{3}$ <	X3E0209774540 1 3 Match to cladding 2 rsulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 13 mm thick rsulator disc with hole \$15-28-SIC-CLAD-02 C 17 Grafoil 2 13 mm thick rsulator disc with hole \$15-28-SIC-CLAD-02 C 18 Grafoil 2 13 mm thick subartz wool \$15-27-SIC-CLAD-01 0 NA \$SiO2 AR See notes 5 & 6 variatz wool \$15-27-SIC-CLAD-01 0 NA \$SiO2 AR See notes 5 & 6 Assembly Tawing \$SiO2 AR See notes 5 & 6 Velding & Cleaning \$S15-27-SIC-CLAD-01-2 0 NA \$SiO2 AR See notes 5 & 6	SiC	Match to cladding 3			17A	1/0.	1819	
sulator disc with hole S15-28-S1C-CLAD-02 C 17 Grafoil 2 -13 mm thick 19812 19812 2 total 0.0168 V/V isulator disc w/o hole S15-28-S1C-CLAD-02 C 17 Grafoil 2 -13 mm thick 19812 19812 2 total 0.0168 V/V isulator disc w/o hole S15-28-S1C-CLAD-02 C 18 Grafoil 2 -13 mm thick 19812 2 total 0.0168 V/V tuartz wool S15-27-S1C-CLAD-01 0 NA S102 AR See notes 5 & 6 20679 2 total .076 V/V ssembly Total Wasing S15-27-S1C-CLAD-01-2 0 NA S102 2 total .076 ssembly Total Wasing S16-CLAD-01-2 0 NA S102 2 total .076 ssembly Total Wasing S16-CLAD-01-2 0 NA S16-S10-S10-S10 .078 .078 ssembly Total Wasing S16-S10-S10-S10 0 NA .078	sulator disc with hole S15-28-SIC-CLAD-02 C 17 Match to cladding 3 isulator disc w/o hole S15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mm thick isulator disc w/o hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick ium trick S15-27-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 item trick Seembly Drawing Rev. SiO2 AR See notes 5 & 6 seembly Drawing S15-27-SIC-CLAD-01-2 0 NA SiO2 AR See notes 5 & 6 delding & Cleaning S15-27-SIC-CLAD-01-2 0 NA SiO2 AR See notes 5 & 6	5	3 Match to cladding 2	19502	20680	16A	0.0186	-	
Instalator disc with hole S15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mm thick 19812 19812 2 total \scretchedges}/23 \scretchedges \scretchedges 	Isulator disc with hole S15-28-SIC-CLAD-02 C 17 Grafoil 2 .13 mm thick reulator disc w/o hole S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick reulator disc w/o hole S15-28-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 Juartz wool S15-27-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 Assembly Drawing Rev. Comment Velding & Cleaning S15-27-SIC-CLAD-01-2 0 Velding & Cleaning S15-27-SIC-CLAD-01-2 0 NA SiO2 AR See notes 5 & 6		Match to cladding 3			18A	0.0186	25	
Instant of the work of the state S15-28-SIC-CLAD-02 C 18 Grafoil 2 .13 mm thick 19812 19812 2 total .0/5 Juartz wool S15-27-SIC-CLAD-01 0 NA S102 AR See notes 5 & 6 20679 NA .0/5 Assembly S15-27-SIC-CLAD-01 0 NA S102 AR See notes 5 & 6 20679 NA .0/5 Assembly Drawing Rev. Comment S15-27-SIC-CLAD-01-2 0 Na .0/5 Velding & Cleaning X3E020977A633 0 Na .0/5 .0/5 .0/5	Instant of the control S15-28-SIC-CLAD-02 C 18 Grafoli 2 .13 mm thick Juartz wool S15-27-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 Assembly S15-27-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 Assembly Drawing S15-27-SIC-CLAD-01-2 0 NA SiO2 AR See notes 5 & 6 Velding & Cleaning S15-27-SIC-CLAD-01-2 0 Na SiO2 AR See notes 5 & 6 Velding & Cleaning S15-22-SIC-CLAD-01-2 0 Na SiO2 AR See notes 5 & 6 Assembly Drawing S15-22-SIC-CLAD-01-2 0 Na SiO2 AR See notes 5 & 6 Assembly Drawing S15-22-SIC-CLAD-01-2 0 Na SiO2 AR See notes 5 & 6 Assembly S16-30 A Comment Comment SiO2 AR Assembly S16-30 A S10 S10 S10 S10	17 Grafoil	2 .13 mm thick	19812	19812	2 total	·2/3	1-1	
Juartz wool S15-27-SIC-CLAD-01 0 NA S/02 AR See notes 5 & 6 20679 NA • 7/4 Assembly Total Mass 247401 Total Mass 247401 Total Mass 247401 Assembly Drawing Rev. Comment Specimen Mass 25167 10401455 25167 Velding & Cleaning S15-27-SIC-CLAD-01-2 0 X3E020977A533 0 Nedding & Cleaning X3E020977A533 0	Juartz wool S15-27-SIC-CLAD-01 0 NA SiO2 AR See notes 5 & 6 Assembly Drawing Rev. Comment sesembly Drawing S15-27-SIC-CLAD-01-2 0 NA SiO2 AR See notes 5 & 6 Image: Si	18 Grafoil	2 .13 mm thick	19812	19812	2 total	.015		
Assembly Total Mass 247401 Total Mass 247401 Total Mass 247401 Specimen Mass 515-21-51C-CLAD-01-2 0 19.0001 Velding & Cleaning X3E020977A633 0 19.0001	Assembly Drawing Drawing Rev. Comment seembly Drawing S15-27-SIC-CLAD-01-2 0 Velding & Cleaning X3E020977A633 0 Fill Gas Heilum	NA Si02	AR See notes 5 & 6	20679	20679	AA	020.		
Assembly Drawing Rev. Comment Specimen Mass 2.5/16 Assembly Drawing \$15-27-SIC-CLAD-01-2 0 10.6657 10.6657 Velding & Cleaning X3E020977A633 0 10.6657 10.6657	Assembly Assembly Drawing Drawing Rev. Comment Assembly Drawing S15-27-SIC-CLAD-01-2 0 Nelding & Cleaning X3E020977A633 0 Fill Gar Helium					Total Mass	24,7401		
Drawing Drawing New. Comment Assembly Drawing \$15-27-SIC-CLAD-01-2 0 10.0001 Welding & Cleaning X3E020977A633 0 10.0001	Assembly Drawing S15-27-SIC-CLAD-01-2 0 Nelding & Cleaning X15-22-SIC-CLAD-01-2 0 X10 A Cleaning X15020977A633 0 Till Gas Helium					Specimen Mass	2.5136		
Seemby Jrawing S15-27-SIC-CLAD-01-2 0 Velding & Cleaning X3E020977A633 0	velding & Cleaning X15-2C-CLAD-01-2 0 X15-2C-CLAD-01-2 0 X3E020977A633 0 X3E020977A633 0 X3E01204 Helium	Comment				Internal Mass	19.4357		
Velding & Cleaning X3E020977A633 0 X3E020977A633 0	Velding & Cleaning X3E020977A633 0 Helium								
	Fill Gas Helium								

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Request
Fabrication
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Capsule ...umber:

ATFSC09

Irradiation Conditions	Irradiation Location	E F

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

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Performed by: Approvals

Checked by:

Page 1 of 1 Dat /2017



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	E C	4
	MAT II	07400
	Comment	
	Count	
	Material	10001
mm	Part	,
8.50	Rev.	~
	Irawing	1000100000

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	Q	Mass (g)
Housing	X3E020977A634	A	-	AI 6061	-		20713	20713	17-89	4.3338
Housing end cap	X3E020977A634	A	2	AI 4047	+		20311	20533	15-39	0.5164
Cladding				SiC		Cladding 1	19502	20681	CVD-G	0.8925
2	S15-28-SIC-CLAD-02	υ	m		m	Cladding 2	Daare	TATAC	1-TM-CrN	0.8097
						Cladding 3	20009	20/4/	4-RP-CrN	0.8515
Heater	*.			Moly		Match to cladding 1		20420	ARM00010	5.4299
	S15-28-SIC-CLAD-02	υ	4		2	Match to cladding 2	20153	20670	16-02	5.2790
						Match to cladding 3		20420	ARM00016	5.4440
Centering thimble				Ti-6AI4V					ARM00019	0.1683
									ARM00028	0.1710
		(c		9		00000	OFFOC	ARM00040	0.1715
	20-02-010-02-010	כ	N		D		20203	20413	ARM00041	0.1718
					*				ARM00042	0.1712
									ARM00070	0.1694
Sleeve				AI 1100		8 µm RMS: Clad 1			32	147
	S15-28-SIC-CLAD-02	0	S		e	8 µm RMS: Clad 2	20379	20671	37	144
						8 µm RMS: Clad 3			33	Jel.
Foil				AI 1100		Match to cladding 1				-x0.
	S15-28-SIC-CLAD-02	υ	9		3	Match to cladding 2	20388	20473	3 total from F01	.076
						Match to cladding 3				523
Small thermometry				SiC		Match to cladding 1			8A	0.0184
	X3E020977A540	-	ო		3	Match to cladding 2	19502	20680	21A	0.0177
						Match to cladding 3			22A	0.0183
Insulator disc with hole	S15-28-SIC-CLAD-02	o	17	Grafoil	2	.13 mm thick	19812	19812	2 total	210.
Insulator disc w/o hole	S15-28-SIC-CLAD-02	υ	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	1200.
									Total Mass	24,6344
Assembly					1				Specimen Mass	2.5537
	Drawing	Rev.		Comment					Internal Mass	133,3542
Assembly Drawing	S15-27-SIC-CLAD-01-2	0								
Welding & Cleaning	X3E020977A633	0			Г					

Assembly Drawing Welding & Cleaning Fill Gas

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Caps Fabrication Request Sheet

Capsule Number:

C

85%He, Ar bal 8.50 mm PTP 4 2.4E+21 340°C 473 1.0 cycles SCL01 Irradiation Conditions Irradiation Location Target Fluence First Cycle Goal Irradiation Time Irradiation Temperature Fill Gas Cladding Design Diameter

	Request	Build
Performed by:	JURU4.12.9-	The My Mint
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capsule raprication	Drawing	Rev.	Part	Material	Count	Comment	MATIR	FAB IR	9	Mass (a)
Housing	X3E020977A634	A	-	AI 6061	-		20654	20654	16-31	4.3321
Housing end cap	X3E020977A634	A	2	AI 4047	1		20311	20533	15-22	0.5087
									A21	0.0948
		-	ŝ						A22	0.0966
Centering Thimble	S15-35-SIC-CLAD-NOHF	-	2	DISPAL AL	ю		16941	20672	A34	0.0961
									A35	0.0958
									A42	0.0964
	S15-35-SIC-CLAD-NOHF	1	7	TIGAI4V	+	bottom of assy	20093	20673	T01	0.1585
						CVD-L	20561	18702	CVD-L	0.8822
Cladding	S15-28-SIC-CLAD-02	ш	ო	SiC	ო	0000001	20699 44	20669	SA3-1	0.8186
			5			0	20169	PUNOL	N1N3(1)	0.7853
Insert						CMP	L1-1-5		54	0.1750
	S15-35-SIC-CLAD-NOHF	-	0	Graphite	ო		19463	20660	53	0.1720
									40	0.1780
Foil	S15-35-SIC-CLAD-NOHF	۲	4	F	1		20612	20612	1 702	0.022
Insulator Disk	S15-35-SIC-CLAD-NOHF	1	2	Grafoil	2		19812	19812	2 total	\$100
Compression Spring	S15-35-SIC-CLAD-NOHF	-	9	Stainless Steel	-		20659	20659	18	0.1040

Assembly

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

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1233, 122/9 175 178 101.094 06-LÍ Total Mass Specimen Mass Internal Mass /In/ 106 CVD-Q 2-TM-CrN (6-RP-Cr 1 total 2 total Build 22 52 20713 21 -MAT IR FAB IR 20633 20612 19812 20659 20672 20673 20681 20747 20660 1/2/2 Chris Patrice 20054 20311 20612 19812 20659 Request 16941 20093 19502 19463 20669 All thimbles except bottom Bottom thimble Comment Performed by: Approvals Checked by: Count **r**--*** S -0 3 N Ti-6AI4V Grafoil AI 4047 Dispal AI Ti-6AI4V SiC Material 304 SS Graphite AI 6061 Comment 474 1.0 cycles 325°C 85% He, Ar bal. 8.50 mm 2.3E+21 Rev. Part 4 3 3 9 -2 2 ~ S Rev. PTP < -< 0 ---S15-35-SIC-CLAD-NOHF S15-35-SIC-CLAD-NOHF S15-35-SIC-CLAD-NOHF Drawing S15-35-SIC-CLAD-NOHF X3E020977A633 85% He, Ar bal. S15-35-SIC-CLAD-NOHF S15-35-SIC-CLAD-NOHF S15-35-SIC-CLAD-NOHF S15-28-SIC-CLAD-02 X3E020977A634 X3E020977A634 Drawing SCL05 Irradiation Conditions Cladding Design Diameter **Capsule Fabrication** Irradiation Temperature Capsule Number: Compression spring Irradiation Location Housing Housing end cap Centering thimble First Cycle Goal Irradiation Time Centering thimble Target Fluence Insulator disk Assembly Cladding Fill Gas Insert Foil

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Assembly Drawing Welding & Cleaning Fill Gas

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Caps Fabrication Request Sheet

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Part of 1 Da. 2017

Caps > Fabrication Request Sheet

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Capsule Number:	SCLO6			
Irradiation Conditions		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	
Capsule Fabrication				
	Drawing	Rev.	Part	Material
Housing	X3E020977A634	A	۲	AI 6061
Hamilton and and	V9E000077A634	<	c	AL ADAT

4/12

Build

Chris Retrie Request

Performed by: Approvals

Checked by:

Capsule raprication										4.2	484
	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	Q	Mass (g)	(wo
Housing	X3E020977A634	A	٢	AI 6061	Ļ		20654	20654	16-06	4:3108	2.2
Housing end cap	X3E020977A634	A	2	AI 4047	٣		20311	20533	15-02	4916	140 .
Centering thimble				Dispal Al					412	1097	
						All definition of the second			A13	2016	`
	S15-35-SIC-CLAD-NOHF	~	2		ŋ	All thimbles except	16941	20672	AIY	.096 %	
									431	.0960	
		_							1SH	.097 6	
Centering thimble	S15-35-SIC-CLAD-NOHF	-	7	TI-6AI4V	-	Bottom thimble	20093	20673	107	.157	3
Cladding				SiC			19502	20681	CVD-R	1 062	`
1	S15-28-SIC-CLAD-02	0	ო		ო		00000	11100	3-RP-CrN	PIC.	
					8		20002	20/4/	7-TM-TIN	\$ 20%	
Insert				Graphite					47	174 .	
	S15-35-SIC-CLAD-NOHF	٣	б		ო		19463	20660	20	176 6	
									ø	178 2	1
Foil	S15-35-SIC-CLAD-NOHF	-	4	Ti-6AI4V	-		20612	20612	1 total	3 520.	5
Insulator disk	S15-35-SIC-CLAD-NOHF	-	2	Grafoil	2		19812	19812	2 total	110.	
Compression spring	S15-35-SIC-CLAD-NOHF	-	ø	304 SS			20659	20659	1 total	0.101	
									Total Mass	0,0000	
Assembly					-				Specimen Mass	0,0000	
	Drawing	Rev.		Comment					Internal Mass	0.0000	
Accambly Drawing	STERSENCICI AD-NOHE										

S15-35-SIC-CLAD-NOHF

X3E020977A63 85% He, Ar bal

Assembly Drawing Welding & Cleaning Fill Gas

Experiment Authorization Bases Document: EABD-HFIR-2009-004 Rev 13 Page 10 of 36 Date:01/12/2017 Title: Rabbit Irradiations in the HFIR Target Region Prepared By: G. J. Hirtz 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** High ATFSC03 ATFSC04 ATESC05 ATESCOL ATTESCO7 ATFSC 08 ATTES(09 * 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. : Alat 2. Attach Capsule Fabrication Request Sheet or Equivalent : _____ etrie Lead Experimenter 3. Approvals (see notes for explanation of signature responsibilities) Christian Petrie Lead Experimenter ne Experimenter (signature) Date M.C. VANG Lead QA Lead QA (signature) 8/3 L.C. Smith mall Date RRD QA RRD QA (signature) RRD EA&C Staff RRD EA&C Staff (signature) N.A. No NCS Requirements RRD Criticality Safety Officer (signature) NA Date N.A. No NCS Requirements **RRD** Criticality Safety Officer <u>N.A. No MBA Requirements</u> HFIR MBA Representative (signature) N.A. No MBA Requirements HFIR MBA Representative NA Date Bin E Filly HFIR Operations (signature) 8-15-17 BRIAN E FULLER HFIR Operations (print name) Date

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