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Irradiation of Wrought FeCrAl Tubes in the High Flux Isotope Reactor

Nuclear Technology Research and Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign

C.M. Petrie, K.G. Field, K. Linton
Oak Ridge National Laboratory

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SUMMARY

The Advanced Fuels Campaign within the Nuclear Technology Research and Development program of the Department of Energy Office of Nuclear Energy is seeking to improve the accident tolerance of light water reactors. Alumina-forming ferritic alloys (e.g., FeCrAl) are one of the leading candidate materials for fuel cladding to replace traditional zirconium alloys because of the superior oxidation resistance of FeCrAl. However, there are still some unresolved questions regarding irradiation effects on the microstructure and mechanical properties of FeCrAl at end-of-life dose levels. In particular, there are concerns related to irradiation-induced embrittlement of FeCrAl alloys due to secondary phase formation. To address this issue, Oak Ridge National Laboratory has developed a new experimental design to irradiate shortened cladding tube specimens with representative 17×17 array pressurized water reactor diameter and thickness in the High Flux Isotope Reactor (HFIR) under relevant temperatures (300–350°C). Post-irradiation examination will include studies of dimensional change, microstructural changes, and mechanical performance. This report briefly summarizes the capsule design concept and the irradiation test matrix for six rabbit capsules. Each rabbit contains two FeCrAl alloy tube specimens. The specimens include Generation I and Generation II FeCrAl alloys with varying processing conditions, Cr concentrations, and minor alloying elements. The rabbits were successfully assembled, welded, evaluated, and delivered to the HFIR along with a complete quality assurance fabrication package. Pictures of the rabbit assembly process and detailed dimensional inspection of select specimens are included in this report. The rabbits were inserted into HFIR starting in cycle 472 (May 2017).

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TABLES

ACRONYMS

AFC	Advanced Fuels Campaign
Al	aluminum
Ar	argon
Cr	chromium
DOE-NE	US Department of Energy, Office of Nuclear Energy
dpa	displacements per atom
EABD	experiment authorization basis document
He	helium
HFIR	High Flux Isotope Reactor
LWR	light water reactor
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PWR	pressurized water reactor
QA	quality assurance
SiC	silicon carbide
Zr	zirconium

ACKNOWLEDGMENTS

This work was supported by the US Department of Energy Office of Nuclear Energy (DOE-NE) Advanced Fuels Campaign (AFC). 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 US DOE. The contributions of Kurt Terrani, ORNL program manager for the AFC, are gratefully acknowledged. Doug Stringfield, Jordan Massengale, and David Bryant performed most of the capsule assembly work and managed the welding and nondestructive examinations.

1. OBJECTIVE

The objective of this work is to irradiate wrought FeCrAl tubes in the High Flux Isotope Reactor (HFIR) that have a geometry and microstructure representative of what would be used in a 17×17 array pressurized water reactor (PWR). The FeCrAl tube specimens are to be irradiated at typical PWR temperatures of 300–350°C at radiation doses ranging from 1.8 to >20 displacements per atom (dpa).

2. INTRODUCTION

Despite a long history of successful operation, traditional light water reactor (LWR) fuel systems with UO_2 fuel and zirconium (Zr)-alloy cladding are susceptible to high-temperature steam oxidation, hydrogen generation, and radiation-induced embrittlement, particularly after the Zr-alloy cladding forms hydrides [1-3]. A number of advanced nuclear fuel cladding concepts are currently being investigated to improve the accident tolerance of LWRs, primarily by identifying cladding materials with improved high-temperature steam oxidation resistance during accident scenarios [4, 5]. Other potential benefits of accident-tolerant fuels include enhanced fission product retention, reduced hydrogen generation, and improved thermomechanical properties. Performance under normal operating conditions (e.g., high fuel burnup, long fuel cycle length, high reliability) remains important for economic viability.

Alumina-forming ferritic alloys (e.g., FeCrAl) are some of the leading candidates to replace traditional Zr-based cladding because of their superior oxidation resistance and high-temperature strength compared with Zr alloys [6-8]. However, FeCrAl alloys are known to experience embrittlement under irradiation as a result of secondary-phase formations [9-11]. New information regarding the irradiation performance of FeCrAl alloys with representative LWR geometry, microstructure, and temperature would be invaluable for qualifying these materials for use in commercial reactors. Accelerated irradiation testing is preferred so that a large test matrix can be evaluated and down-selection of specific alloys and processing parameters can occur within a reasonable time and cost. This report describes the successful irradiation of six "rabbit" capsules, each containing two FeCrAl tube specimens, in the HFIR at Oak Ridge National Laboratory (ORNL). Two of the six rabbits have completed irradiation and are awaiting shipping before being disassembled in a hot cell. The remaining four rabbits will finish irradiation in late calendar year 2018. The irradiated samples will allow the severity of the cladding degradation under irradiation to be determined through post-irradiation examination (PIE), which will include mechanical and microstructural evaluations.

3. TUBE IRRADIATION EXPERIMENT DESIGN

3.1 Summary of Capsule Design

The cladding tube specimens are packaged inside a HFIR-approved irradiation vehicle so that they can accumulate the desired radiation dose at the design temperature. A detailed summary of the irradiation capsule design and analysis can be found in a previous report [12]. A brief description of the capsule design is provided here. A section view of the rabbit capsule is shown in Figure 1. Predicted temperatures for rabbit FCF04 are shown in Figure 2. The details of the various rabbits and the test matrix are provided in Section 3.2. The outer containment for the irradiation experiment is the rabbit capsule housing, which is directly cooled on the outer surface by the HFIR primary coolant. Rabbits are stacked vertically inside aluminum (Al) targets that are placed in the flux trap (radial center region with highest neutron flux) of the HFIR core. The specimen temperature is controlled by varying the concentration of a helium/argon gas mixture according to the heat generated in the internal components and the size of the gas gap between the cladding and the housing. Varying the gas mixture changes the effective thermal conductivity of the gas gap. Neutron and gamma heating from the HFIR fuel is accurately determined using neutronics models of the HFIR core. The cladding tube specimens are placed over molybdenum sleeves. Centering thimbles are inserted inside the sleeves to keep the assemblies centered inside the housing and to maintain a constant gas gap between the cladding and the housing. Wires are inserted through the thimbles and small radial holes in the sleeves to keep the thimbles from being able to dislodge from the sleeves. Grafoil insulators are stacked on both ends of the capsule to reduce axial heat losses. Passive silicon carbide (SiC) temperature monitors are placed inside slots that are machined near the inner surfaces of the sleeves. These SiC temperature monitors are used to determine the actual irradiation temperature using a dilatometric technique [13].

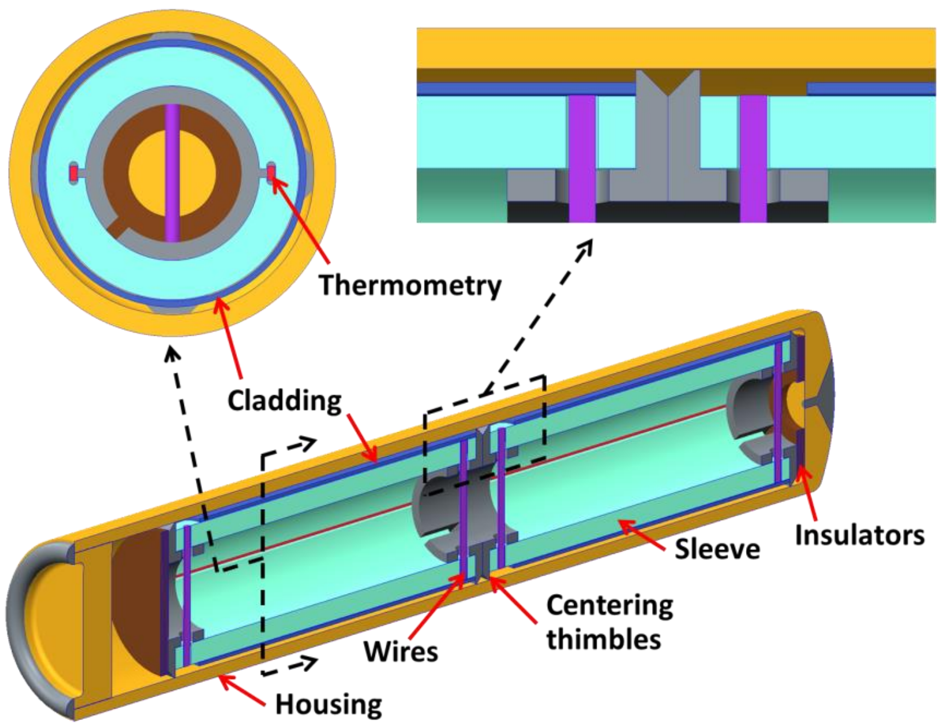

Figure 1. Section view showing irradiation capsule design concept.

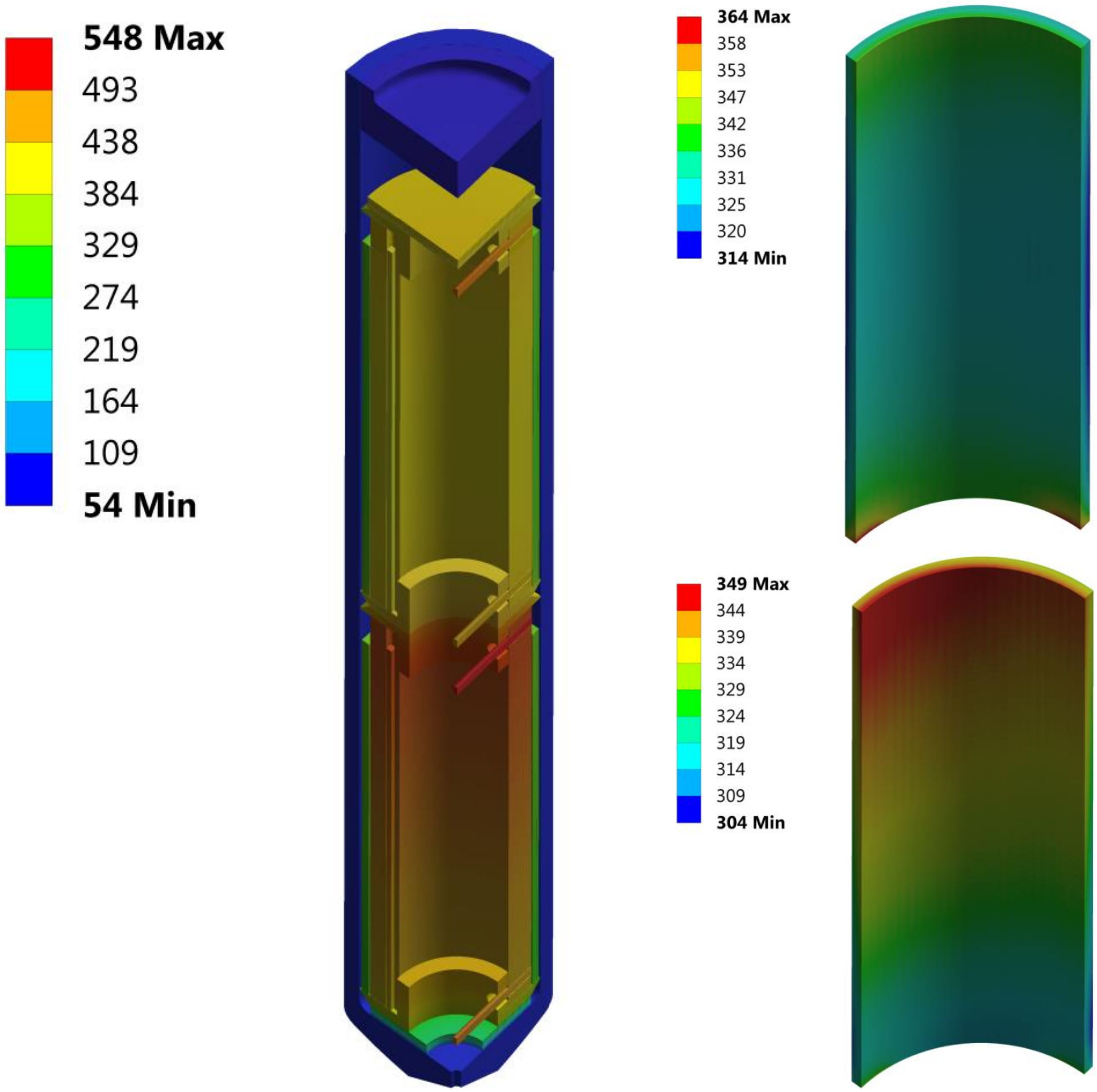

Figure 2. Temperature (°C) contours for the FCF04 rabbit assembly (left), bottom FeCrAl specimen (bottom right), and top FeCrAl specimen (top right).

3.2 Irradiation Test Matrix

The irradiation test matrix shown in Table 1 includes a variety of FeCrAl alloys. The irradiation positions correspond to the HFIR grid position (see reference [12]) followed by the axial position (numbered 1–7 from bottom to top, with position 4 located at the core midplane). The specimen part numbers are in the format XMNY or XMMNY, where X indicates the alloy series, M (or MM) the chromium (Cr) concentration (mass percent), N the Al concentration (mass percent), and Y a minor alloying element. "B" series alloys are model FeCrAl alloys (Generation I) that span a wide range of Cr concentrations. These alloys have the XMMNY format. In this case, MM refers to the Cr concentration. For example, B136Y refers to a model FeCrAl alloy with 13% Cr, 6% Al, and minor alloying with yttrium. "C" series alloys are engineering-grade FeCrAl alloys (Generation II) with more focused Cr concentrations. These alloys have the XMNY format, with M referring to the Cr content minus 10%. For example, C06M refers to an engineering-grade alloy with 10% Cr, 6% Al, and minor alloying with molybdenum. All specimens were produced at ORNL. More details regarding the alloy refinement and selection can be found in previous documents [7, 9].

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

Rabbit	Specimens	Irradiation position	Fill gas	Number of cycles	Dose (dpa)
FCF01	C06M-01 B136Y-1	B1-3	92% He, Ar bal.	1	1.7
FCF02	C06M-02 B136Y-4	E7-5	97% He, Ar bal.	12	20.4
FCF03	B126Y-1 C36M3-4	C1-3	97% He, Ar bal.	1	1.7
FCF04	B126Y-2 C36M3-2	E5-5	97% He, Ar bal.	4	6.8
FCF05	B126Y-3 C36M3-3	F6-5	97% He, Ar bal.	8	13.6
FCF06	B126Y-4 C36M3-1	F7-5	97% He, Ar bal.	12	20.4

4. EXPERIMENT FABRICATION AND DELIVERY TO HFIR

4.1 Rabbit Assembly

The six rabbits (FCF01 through FCF06) were assembled in February 2017. Photographs of the parts layout for all rabbits are shown in Figure 3. Figure 4 shows views of a specimen subassembly and thermometry loaded inside a molybdenum sleeve with quartz wool packed in the center of the sleeve. The signed capsule fabrication request forms are provided in Appendix A. Figure 5 shows examples of the pre-irradiation dimensional inspection that is performed on each specimen outer diameter. The *x* and *y* values are scaled so that they are *x* and *y* distances from some reference radius (arbitrarily defined as 99% of the minimum measured inner radius of the cladding) that is unique to each specimen. This scale allows observation of the variations in the cladding outer diameter at various axial locations (*z*) compared with the nominal housing inner diameter of 9.70 mm. Both the cladding outer diameter values and the nominal housing inner diameter are scaled to the same reference radius. These measurements are required to ensure a proper gas gap between the specimen and the housing, which is used to control temperature. These measurements can also be compared with post-irradiation dimensional measurements to determine radiation swelling. Specimen B136Y-4 has a very uniform outer diameter along the entire axis. Specimen C06M-02 has a more significant variation in diameter, particularly at one end (*z*=0 mm). Because this nonuniformity would affect only the temperatures at the end of the specimen, specimen C06M-02 was considered acceptable.

Figure 3. Parts for rabbits FCF01 through FCF06.

Figure 4. Specimen subassembly (left), top-down view of specimen subassembly (top right), and top-down view of a sleeve with thermometry in slots (bottom right).

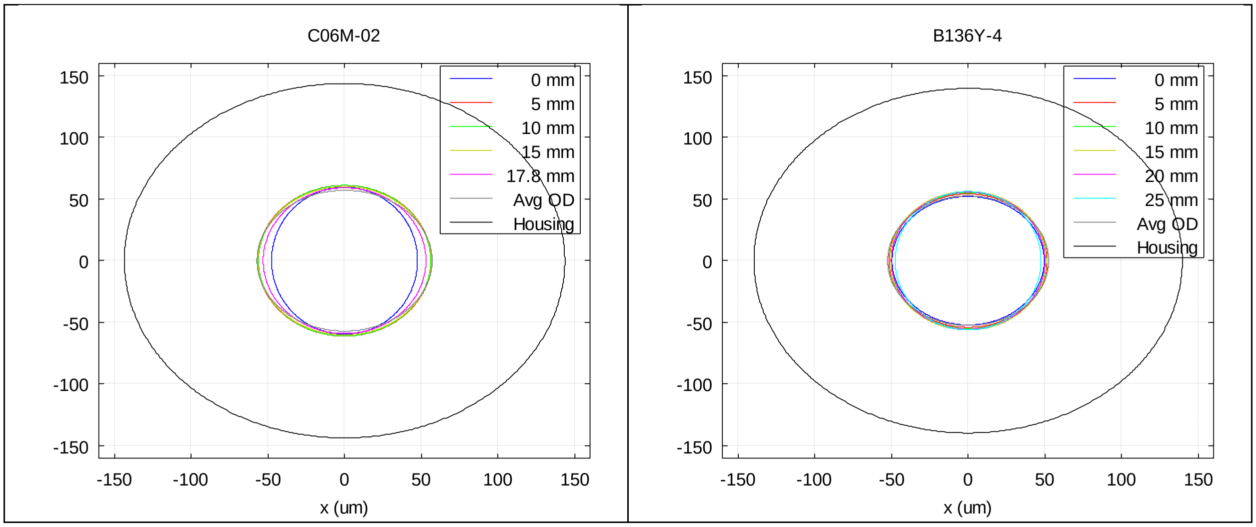

Figure 5. Examples (specimens C06M-02 and B136Y-4 shown) of dimensional inspection of specimen outer diameter at various lengths compared with the nominal 9.70 mm housing inner diameter. All *x* and *y* values are scaled so that they are x and y distances from some arbitrary reference radius that is unique to each specimen.

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/argon gas mixtures (see Table 1) three times to ensure a pure environment. The chambers were placed inside a glove box, which was also evacuated and backfilled with the same gas used in the sealed chambers. Each rabbit has a small hole in the bottom of the housing that was seal-welded 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.

4.2 Fabrication Package and Delivery to 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.

The fabrication packages for rabbits FCF01 through FCF06 were reviewed and approved by an independent design engineer, lead QA representative, and HFIR QA representative and accepted by HFIR on April 12, 2017. The final signed acceptance page of the EABD is provided in Appendix A. All six rabbits were inserted during HFIR cycle 472 (May 2017).

5. SUMMARY AND CONCLUSIONS

This report briefly summarizes the capsule design concept and the irradiation test matrix for six rabbit capsules that were successfully assembled and delivered to the HFIR for insertion during cycle 472 (May 2017). Each rabbit contains two FeCrAl alloy tube specimens, which will be evaluated post-irradiation as part of the Advanced Fuels Campaign to understand irradiation effects on the microstructure and mechanical properties of accident-tolerant FeCrAl fuel cladding. A new rabbit design was developed to accommodate the large diameter of standard 17×17 array PWR cladding tubes with a sufficient gap between the cladding tubes and the rabbit housing to allow fine temperature control. A wide variety of specimens were included in the test matrix, including Generation I and Generation II FeCrAl alloys with varying processing conditions, Cr concentrations, and minor alloying elements. 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 the detailed dimensional inspection of select specimens are included in this report. Documentation of the capsule fabrication and final acceptance by HFIR is provided in an appendix. The data that will be obtained from PIE of the irradiated cladding tubes will help support the qualification of FeCrAl fuel cladding for commercial applications to ultimately improve the accident tolerance of LWRs.

6. REFERENCES

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APPENDIX A. FABRICATION AND QUALITY ASSURANCE DOCUMENTATION FOR COMPLETED RABBITS

APPENDIX A. FABRICATION AND QUALITY ASSURANCE DOCUMENTATION FOR COMPLETED RABBITS

Capsule Fabrication Request Sheet

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Date /2017

Capsule Number: FCF01

Irradiation Conditions

Irradiation Location	TRRH ~~5~~ 3 CMP 3-3-17
Target Fluence	2.4E+21
First Cycle Goal	471
Irradiation Time	1.0 cycles
Irradiation Temperature	340ºC
Fill Gas	92% He, Ar bal.
Cladding Design Diameter	9.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 2-9-17	D. Sease 2/9/17
Checked by:	2.9.17	2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-16	4.6834
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-26	0.5140
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	2 marks	20625	20625	C06M-01	1.3527
						1 mark	20628	20628	B136Y-1	1.9545
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 1	20153	20630	16-02	5.3710
						Group 3		20632	16-06	7.5330
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	01	0.1900
									02	0.1920
									03	0.1900
									04	0.1910
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4	16mm	19502	20636	1	0.0050
									6	0.0070
						24mm		20635	25	0.0110
									26	0.0090
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0860
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0900
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0480
									Total Mass	22.4276
									Specimen Mass	3.3072
									Internal Mass	17.2302

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	92% He, Ar bal.		

Capsule Fabrication Request Sheet

Capsule Number: FCF02

Irradiation Conditions

Irradiation Location	TRRH 5
Target Fluence	2.83E+22
First Cycle Goal	471
Irradiation Time	12.0 cycles
Irradiation Temperature	340°C
Fill Gas	97% He, Ar bal.
Cladding Design Diameter	9.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 2-9-17	[illegible] 2/9/17
Checked by:	[illegible] 2.9.17	[illegible] 2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-06	4.6483
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-04	0.5150
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	2 marks	20625	20625	C06M-02	1.3362
						4 marks	20628	20628	B136Y-4	1.9517
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 1	20153	20630	16-03	5.3610
						Group 2		20631	16-06	7.8051
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	05	0.1930
									06	0.1930
									07	0.1920
									08	0.1890
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4		19502	20636	3	0.0060
									4	0.0070
								20635	1	0.0100
									11	0.0090
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0870
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0900
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0510
									Total Mass	22.6443
									Specimen Mass	3.2879
									Internal Mass	17.4810

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	97% He, Ar bal.		

Caps‿le Fabrication Request Sheet

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Da‿ ‿3/2017

Capsule Number: FCF03

Irradiation Conditions

Irradiation Location	TRRH ~~5~~ 3
Target Fluence	2.4E+21
First Cycle Goal	471
Irradiation Time	1.0 cycles
Irradiation Temperature	340°C
Fill Gas	97% He, Ar bal.
Cladding Design Diameter	9.50 mm

CMP 3-3-17

Approvals

	Request	Build
Performed by:	Chris Petrie 2-9-17	D. [illegible] 2/9/17
Checked by:	[illegible] 2.9.17	[illegible] 2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-07	4.6591
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-28	0.5140
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	1 mark	20626	20626	B126Y-1	1.9514
						4 marks	20627	20627	C36M3-4	1.9515
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 3	20153	20632	16-01	7.5660
						Group 2		20631	16-01	7.8006
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	09	0.1910
									10	0.1920
									11	0.1890
									12	0.1890
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4		19502	20635	3	0.0100
									4	0.0110
									5	0.0110
									8	0.0110
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0860
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0880
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0950
									Total Mass	25.5156
									Specimen Mass	3.9029
									Internal Mass	20.3425

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	97% He, Ar bal.		

Caps"'e Fabrication Request Sheet

Capsule Number: FCF04

Irradiation Conditions

Irradiation Location	TRRH 5
Target Fluence	9.4E+21
First Cycle Goal	471
Irradiation Time	4.0 cycles
Irradiation Temperature	340°C
Fill Gas	97% He, Ar bal.
Cladding Design Diameter	9.50 mm

Approvals

	Request	Build
Performed by:	Chris Petrie 2-9-17	D. [illegible] 2/9/17
Checked by:	[illegible] 2-9-17	[illegible] 2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-12	4.6529
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-35	0.5160
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	2 marks	20626	20626	B126Y-2	1.8000
						3 marks	20627	20627	C36M3-2	1.7970
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 3	20153	20632	16-02	7.6100
						Group 2		20631	16-02	7.7972
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	13	0.1940
									14	0.1930
									15	0.1920
									16	0.1940
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4		19502	20635	12	0.0100
									13	0.0100
									18	0.0090
									15	0.0110
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0870
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0890
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0790
									Total Mass	25.2411
									Specimen Mass	3.5970
									Internal Mass	20.0722

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	97% He, Ar bal.		

Caps[illegible]e Fabrication Request Sheet

Capsule Number: FCF05

Irradiation Conditions

Irradiation Location	TRRH 5
Target Fluence	1.88E+22
First Cycle Goal	471
Irradiation Time	8.0 cycles
Irradiation Temperature	340°C
Fill Gas	97% He, Ar bal.
Cladding Design Diameter	9.50 mm

Approvals

	Request	Build
Performed by:	[signature] 2-7-17	[signature] 2/9/17
Checked by:	[signature] 2.9.17	[signature] 2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-03	4.6692
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-29	0.5150
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	3 marks	20626	20626	B126Y-3	1.7840
						4 marks	20627	20627	C36M3-3	1.7930
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 3	20153	20632	16-03	7.5520
									16-05	7.5260
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	17	0.1910
									18	0.1920
									19	0.1920
									20	0.1940
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4		19502	20635	16	0.0100
									20	0.0100
									21	0.0110
									47	0.0110
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0850
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0940
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0940
									Total Mass	24.9232
									Specimen Mass	3.5770
									Internal Mass	19.7390

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	97% He, Ar bal.		

Capsule Fabrication Request Sheet

Capsule Number: FCF06

Irradiation Conditions

Irradiation Location	TRRH 5
Target Fluence	2.83E+22
First Cycle Goal	471
Irradiation Time	12.0 cycles
Irradiation Temperature	340°C
Fill Gas	97% He, Ar bal.
Cladding Design Diameter	9.50 mm

Approvals

	Request	Build
Performed by:	[signature] 2-9-17	[signature] 2/9/17
Checked by:	[signature] 2.9.17	[signature] 2/9/17

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A690	0	1	Al 6061	1		19348	20642	16-01	4.6524
Housing end cap	X3E020977A634	A	2	Al 4047	1		20311	20640	16-06	0.5170
Cladding	S16-11-FLEXCLAD02	1	2	FeCrAl	2	4 marks	20626	20626	B126Y-4	1.7950
						1 mark	20627	20627	C36M3-1	1.7920
Sleeve	S16-11-FLEXCLAD02	1	3	Moly	2	Group 3	20153	20632	16-04	7.6180
						Group 2		20631	16-05	7.8359
Centering thimble	S16-11-FLEXCLAD02	1	4	Ti-6Al4V	4		20634	20634	21	0.1900
									22	0.1930
									23	0.1880
									24	0.1920
Thermometry	S16-11-FLEXCLAD02	1	5	SiC	4		19502	20635	50	0.0110
									51	0.0100
									52	0.0100
									53	0.0110
Wire	S16-11-FLEXCLAD02	1	6	Moly	4	.020" diameter	19600	19600	4 total	0.0870
Grafoil, .13 mm thick	S16-10-FLEXCLAD01	1	2	Grafoil	10	.005" thick	19812	19812	10 total	0.0950
Quartz wool	S16-11-FLEXCLAD02	1	7	SiO2	AR	See note 12	20679	20679	N/A	0.0750
									Total Mass	25.2723
									Specimen Mass	3.5870
									Internal Mass	20.1029

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S16-10-FLEXCLAD01	1	specimen marks are inscribed on the end
Welding & Cleaning	X3E020977A689	0	
Fill Gas	97% He, Ar bal.		

Experiment Authorization Bases Document: EABD-HFIR-2009-004	Rev 13
Title: Rabbit Irradiations in the HFIR Target Region Prepared By: G. J. Hirtz Date: 01/12/2017	Page 10 of 36

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
FCF01		High
FCF02		↓
FCF03		↓
FCF04		↓
FCF05		↓
FCF06		↓
FCZ01		↓
FCZ02		↓
FCZ03		↓
FCZ04		↓
FCZ05		↓
~~FCZ06~~ CNP 3-14-17		

* 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. : LC 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	Christian Petrie Lead Experimenter (signature)	4-10-17 Date
Mark C. Vance Lead QA	MCV Lead QA (signature)	4/11/17 Date
Lee C. Smith RRD QA	LC Smith RRD QA (signature)	4/11/17 Date
Greg Hirtz RRD EA&C Staff	Greg Hirtz RRD EA&C Staff (signature)	4/12/17 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)	FULLER, BRIAN HFIR Operations (signature)	04/13/2017 Date