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Assembly of Capsules for Irradiation of Absorber Material Specimens in the High Flux Isotope Reactor

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OAK RIDGE NATIONAL LABORATORY
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Reactor and Nuclear Systems Division

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SUMMARY

This report provides a summary of the thermal analysis, test matrix, and assembly of two capsules containing absorber material specimens. Four different absorber materials are inserted in the same capsule: hafnium carbide, hafnium carbide with a molybdenum silicide additive, samarium hafnate, and europium hafnate. The two capsules are planned for irradiation in the flux trap of the High Flux Isotope Reactor at two different neutron fluence levels and with a target specimen temperature of 300°C. In addition, this report shows the pre-characterization performed on the absorber material specimens. The goal of this experiment is to investigate the neutron irradiation effects on the absorber materials and characterize irradiation-induced swelling.

ACRONYMS

BOC	beginning of cycle
EOC	end of cycle
HFIR	High Flux Isotope Reactor
HGR	heat generation rate
ORNL	Oak Ridge National Laboratory

1. INTRODUCTION

Current commercial nuclear reactors use silver-indium-cadmium (AIC) and boron carbide (B_4C) as the primary neutron absorber materials for safely shutting down the reactor and for controlling reactor power. Recently, there has been increased interest in advanced accident-tolerant absorber materials that can survive for extended periods of time during beyond-design-basis accidents.

Framatome has developed alternative absorber materials with increased stability at temperatures higher than those predicted for severe accident conditions: hafnium carbide, hafnium carbide with a molybdenum silicide additive, samarium hafnate, and europium hafnate. The purpose of this project is to perform experimental irradiation testing of these alternative absorber material specimens in order to understand the effects of irradiation with realistic temperature gradients. Post-irradiation experimental results will quantify irradiation-induced swelling of the four absorber materials.

The absorber material specimens will be inserted into the Oak Ridge National Laboratory's (ORNL) High Flux Isotope Reactor (HFIR) using irradiation capsules, or rabbits, designed to achieve the desired specimen temperatures during irradiation. Swelling will be measured by comparing specimen dimensions before and after irradiation to two different neutron fluence levels. The experiment design concept is detailed in Cetiner et al. [1] and shown in Figure 1. This report presents the updated neutronics and thermal analyses, the pre-irradiation characterization of the specimens, and summarizes the assembly of two rabbits containing absorber material specimens.

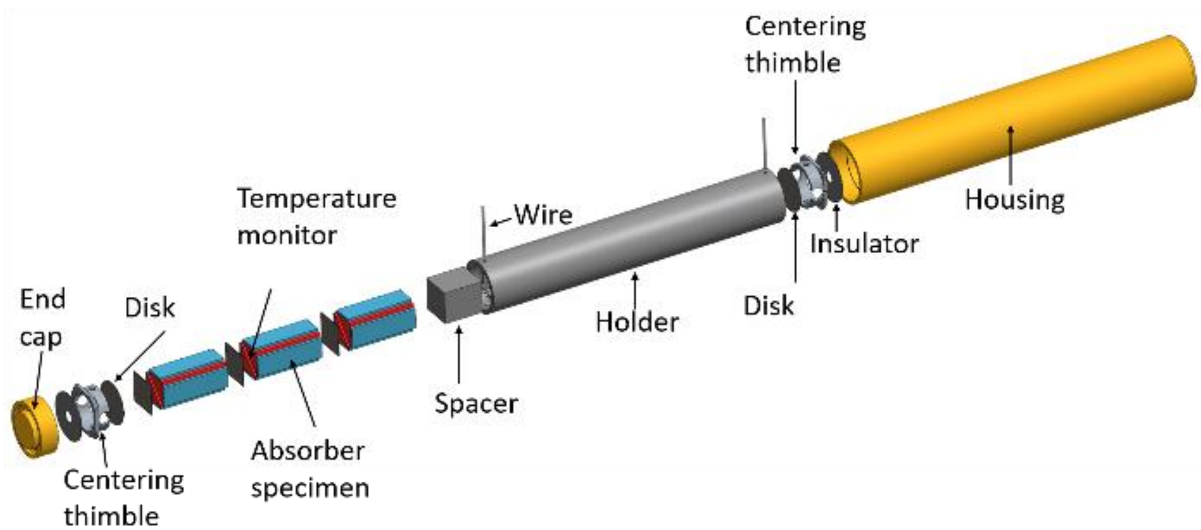


Figure 1. Exploded view of the irradiation capsule design.

2. COMPUTATIONAL METHODS

2.1 NEUTRONICS CALCULATIONS

While HFIR irradiations of strongly neutron-absorbing materials have been carried out in the past, existing safety calculations could not be assumed to bound the thermal and neutronic behavior of the materials under investigation in this work with adequate confidence. A neutronic analysis of the experiment capsule was therefore undertaken to assess nuclear heat generation in the capsule components. The heat generation rates (HGR) are used as inputs to thermal design calculations, as well as the ultimate safety-basis approval of the irradiation campaign. Neutronics calculations were executed using the MCNP code for static Monte Carlo transport and SCALE for depletion and decay, leveraging the standard MCNP HFIR core models historically used for safety-basis irradiation analyses [2]. Five distinct contributions to nuclear heat generation must be accounted for in the neutronic assessment: (1) fission neutrons released from the HFIR fuel, (2) prompt photons released from fission in the fuel and neutron capture reactions throughout the core, (3) delayed photons emitted from the decay of fission products accumulated in the fuel, (4) local α and β decay heat from decay of activated capsule components, and (5) photons emitted from decay of activated capsule components.

Running criticality source calculations with MCNP allows for the determination of fission neutron and prompt photon heat deposition in the experiment capsule. Particular care must be taken to appropriately treat photons emitted from capture reactions by the absorber materials. Specifically, some transmutation products that build up in the samples over the course of irradiation have no gamma production data available in the safety-qualified ENDF/B-VII cross section libraries – potentially producing erroneous heat generation estimates if these cross sections are used. Instead, a cross section library constructed with holistic gamma production data for the necessary nuclides was employed [3]. It was confirmed that this cross section library does not significantly perturb calculated core conditions such as the fuel fission rate distribution, enabling its use for this particular safety-basis analysis. Heat deposition from delayed photons was assessed separately with a fixed-source MCNP calculation using previously characterized delayed photon source definitions [4]. Flux spectra and reaction rates calculated from these MCNP static transport runs were then provided to the COUPLE and ORIGEN modules of the SCALE code suite to assess locally deposited decay heat (α and β) as well as the activation photon source energy distribution and intensity. These depletion calculations were carried out for up to 12 irradiation cycles to determine the timing of maximum decay heat in the absorber samples, informing the safety-basis thermal conditions. Finally, the activation photon source characterized with ORIGEN was provided to MCNP for a final fixed-source calculation evaluating the heat generation attributable to these photons.

Design-basis heat generation rates (HGR) for each component at beginning-of-cycle and end-of-cycle (BOC/EOC) are reported in Table 1. These values represent the average of peak values from each axial level in the capsule, over 12 cycles of irradiation. The maximum HGR at EOC was observed after the first cycle for all the absorber material specimens except samarium hafnate, which had a maximum HGR at the end of the second cycle.

Table 1. Design-basis heat generation rates.

Component	Heat generation rate (W/g)	
	BOC	**EOC**
Housing	37.1	34.9
Holder	50.0	48.8
SiC spacer	36.1	34.4
Mo disk	77.2	69.1
SiC TM	44.9	39.1
Hafnium carbide	116.3	109.7
Hafnium carbide with additive	116.7	109.0
Europium hafnate	159.3	131.7
Samarium hafnate	130.7	110.7

2.2 THERMAL ANALYSES

The thermal analyses described in Cetiner et al. [1] were revised to consider the peak HGRs calculated in the previous section (see Table 1). Table 2 shows the absorber materials properties used in this calculation. The capsules have a holder-to-housing gas gap of 40 µm, are filled with helium, and are irradiated in the HFIR peripheral target position 5.

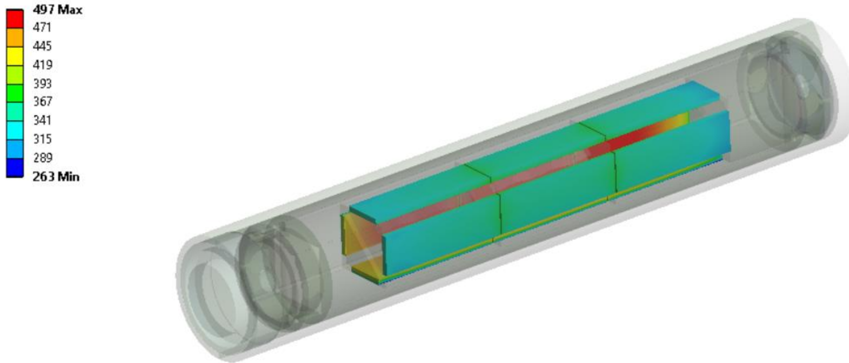
Table 2. Properties of the absorber materials.

Absorber material	Density (g/cm^3)	Thermal conductivity (W/m-°C)
Hafnium carbide	11.94	17.3
Hafnium carbide + additive	11.96	15.7
Samarium hafnate	7.97	1.32
Europium hafnate	7.86	1.32

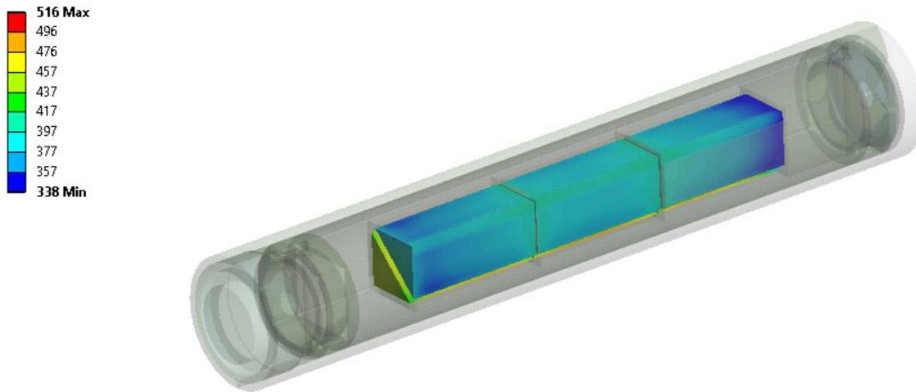
Table 3 shows the temperatures reached by the specimens and the thermometry at BOC and EOC. Figure 2 and Figure 3 show the temperature contours for BOC and EOC, respectively. The temperatures of the europium hafnate and samarium hafnate specimens are higher than those of the specimens of hafnium carbide and hafnium carbide with additive because of a higher HGR and lower thermal conductivity. The europium and samarium hafnate specimens have temperature gradients across their thickness as high as 227°C. Hafnium carbide specimens, with or without additives, have higher thermal conductivities, which results in temperature gradients closer to 80°C. The temperatures of the thermometry are lower on the side where the monitor is in contact with the hafnium carbide and hafnium carbide with additive specimens, than on the side in contact with the other specimens. On average, the specimens' temperature at EOC is 349 °C, slightly above the desired range of 300 ± 25°C. More details are provided in the complete ANSYS report provided in 0 for EOC.

Table 3. Specimens and thermometry temperatures at BOC and EOC.

Component	Average temperature (min-max)(°C)	
	BOC	EOC
All absrober specimens	373 (263 - 497)	349 (248 - 449)
Europium hafnate	402 (270 - 497)	367 (253 - 449)
Samarium hafnate	388 (263 - 486)	357 (248 - 440)
Hafnium carbide	354 (309 - 388)	336 (296 - 365)
Hafnium carbide with additive	355 (310 - 389)	337 (297 - 366)
Thermometry	442 (338 - 516)	408 (321 - 468)



(a) Absorber specimens

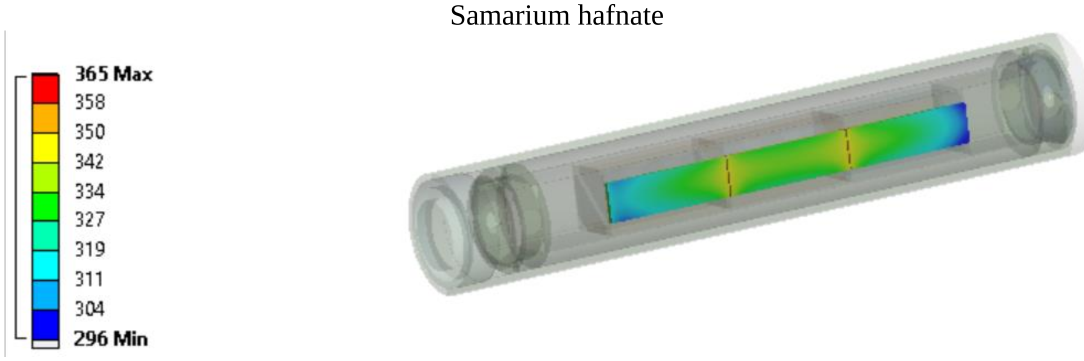


(b) Thermometry

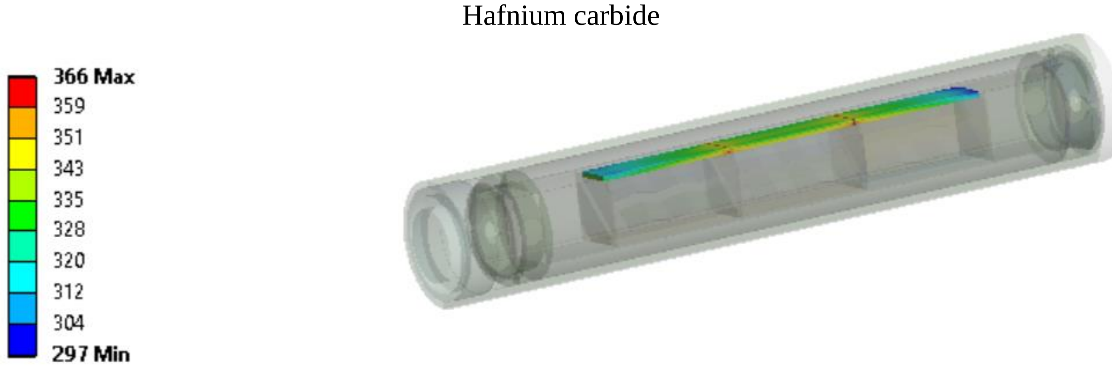
Figure 2. Predicted temperature contours (°C) at BOC showing (a) the specimens and (b) the SiC thermometry.

Europium hafnate

Samarium hafnate



Hafnium carbide



Hafnium carbide with additive

Figure 3. Predicted temperature contours (°C) at EOC for the different types of absorber materials.

Calculations have also been performed considering cases where one samarium hafnate specimen is replaced with a SiC one, and where one samarium and one europium hafnate specimens are replaced by SiC. The SiC specimens are placed at the center of the axial stack of specimens. Table 4 shows the temperatures reached by the specimens are thermometry and Figure 4 shows the temperature contours for samarium and europium hafanate specimens in the case where each stack of these materials is made with a SiC specimen in the middlde. These results show that the presence of one or two SiC specimens instead of one samarium or/and one europium hafnate specimens will reduce the temperatures by about 10°C.

Table 4. Specimens and thermometry temperatures at BOC and EOC for cases with SiC specimen(s)

Component	Case with 1 SiC specimen		Case with 2 SiC specimens	
	Average temperature (min-max)(°C)			
	BOC	EOC	BOC	EOC
All absorber specimens	365 (263 - 484)	341 (248 - 438)	371 (262 – 479)	341 (247 – 434)
Europium hafnate	386 (270 - 484)	354 (253 - 438)	386 (270 – 479)	353 (253 – 434)
Samarium hafnate	378 (263 - 472)	348 (248 - 429)	373 (262 – 468)	344 (247 – 425)
Hafnium carbide	349 (309 - 375)	332 (296 - 355)	346 (309 – 367)	329 (295 – 348)
Hafnium carbide with additive	351 (310 - 379)	333 (296 - 358)	346 (310 – 368)	330 (296 – 349)
Thermometry	420 (310 - 501)	390 (289 - 456)	401 (277 – 496)	374 (262 – 451)
SiC specimen	299 (261 – 379)	280 (246 – 352)	270 (240 – 347)	256 (228 – 324)

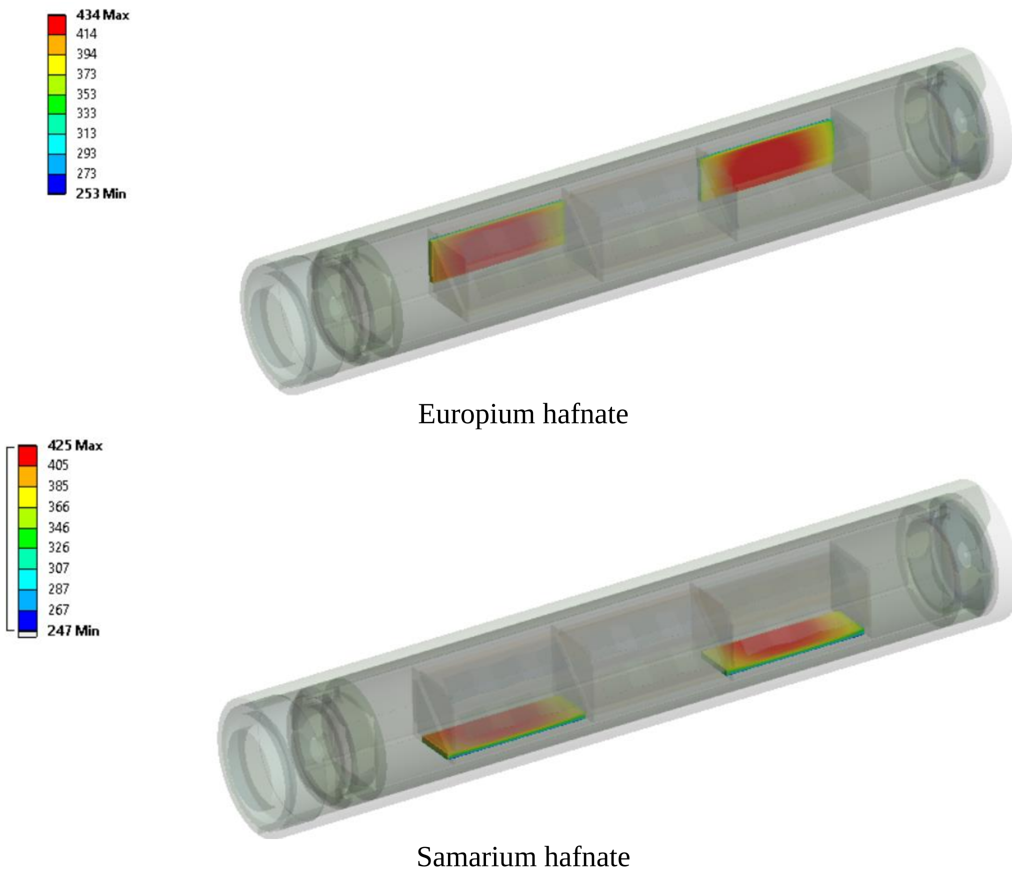


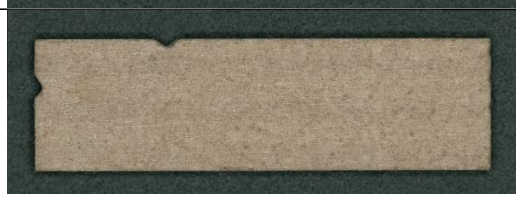
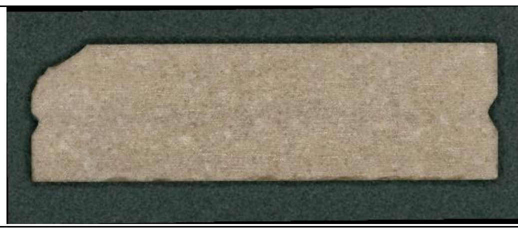
Figure 4. Temperature contours at EOC for europium hafnate and samarium hafnate for the case with 2 SiC specimens in the capsule.

3. SPECIMEN PRE-CHARACTERIZATION

3.1 SPECIMEN IDENTIFICATION

The hafnium carbide and hafnium carbide with additive specimens were laser-engraved with unique IDs. The samarium and europium hafnate specimens proved to be too fragile for laser engraving; instead, one or two notches were made on each specimen. The notch patterns allow for identification of the specimens and their orientations for dimensional inspection. Figure 5 shows the IDs and pictures of the different specimens.

Specimen ID	**Front picture (ID upward)**	**Back picture**
	Samarium hafnate	
S1		
S2		
S3		
S5		
	Europium hafnate	
E6		

Specimen ID	Front picture (ID upward)	Back picture
E7		
E8		
E9		
E21		
Hafnium carbide		
H15		
H16		
H17		
H18		

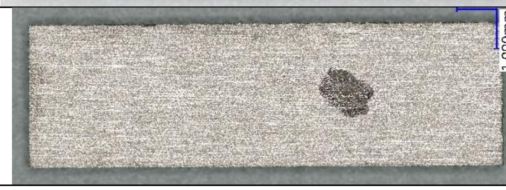
Specimen ID	Front picture (ID upward)	Back picture
H23		
H24		
Hafnium carbide with additive		
M10		
M11		
M12		
M13		
M14		
M22		

Figure 5. Specimen IDs and pictures.

3.2 SPECIMEN INSPECTION

Pre-irradiation inspection of the specimens was performed to record their dimensions and masses. These data will be compared with the dimensions and masses post-irradiation. For each specimen, the length, width, and thickness were measured at different locations along the specimen; a total of 3 length measurements, 6 width measurements, and 12 thickness measurements were performed on each specimen. Figure 6 shows the locations of the different measurements.

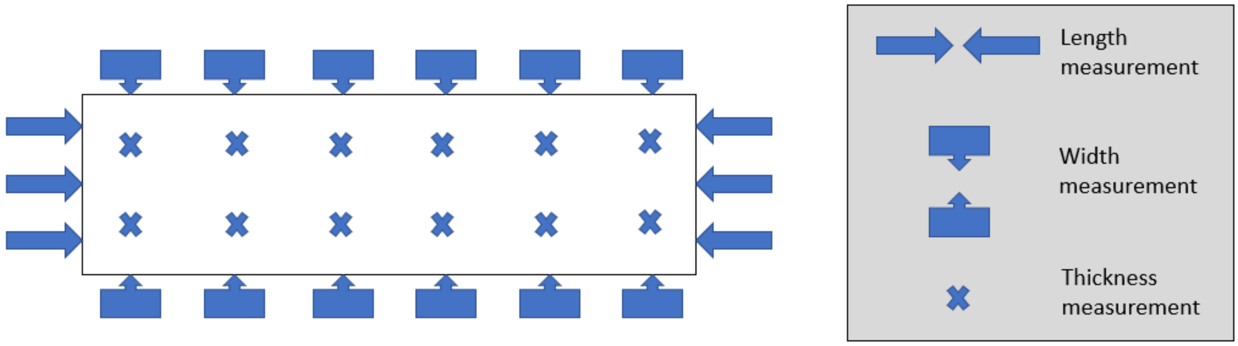


Figure 6. Locations of the different dimensional measurements on one specimen.

A jaw gauge (Dorsey/Mitutoyo ID#12030426, see Figure 7) was used to perform these measurements. Reference gauge blocks were used to check and calibrate the instrument before and after each set of dimension measurements, and after every few measurements. A reference gauge block whose thickness was close to the expected measured dimension was used (see APPENDIX B).

Figure 7. Jaw gage used to perform dimensional inspection of the absorber material.

Three length measurements were performed per specimen; looking at the front side of the specimen, L1 is measured in the middle of the specimen, L2 at the top of the specimen, and L3 at the bottom of the specimen. The locations of the different measurements are shown in Figure 8. The front sides and orientations of the specimens with notches are identified in Figure 5.

L1	L2	L3

Figure 8. Length measurements of the specimens.

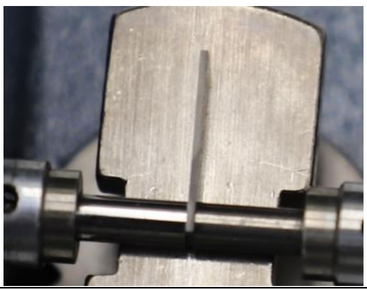
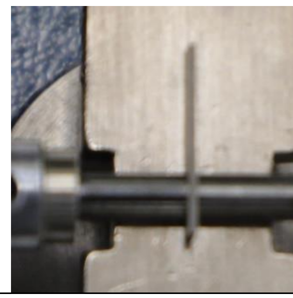
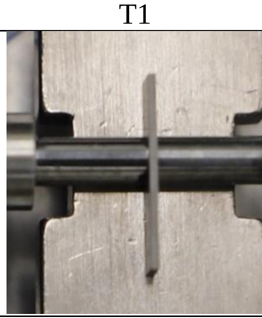
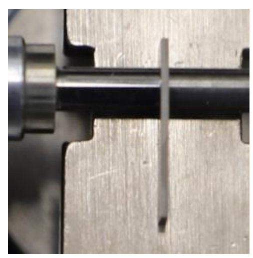
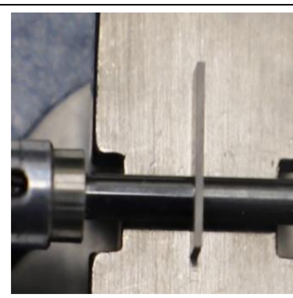
Six width measurements were performed per specimen, from bottom to top of the specimen with the front face visible to the inspector. The locations of the different measurements are shown in Figure 9.

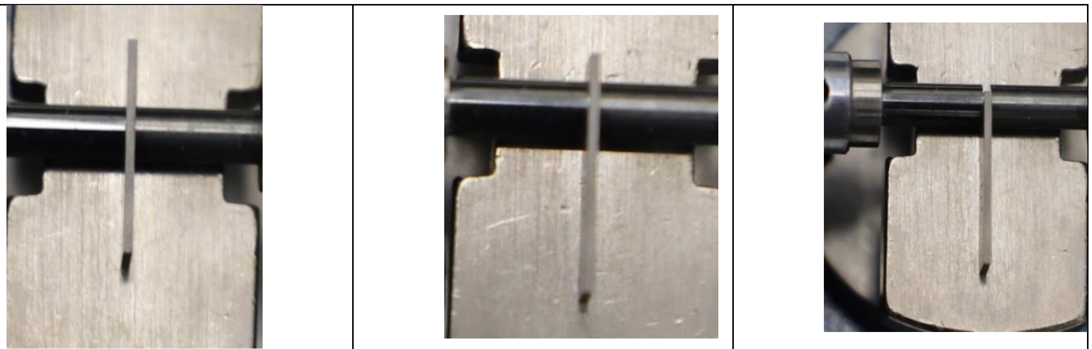
W1	W2	W3

W4	W5	W6

Figure 9. Width measurements of the specimens.

Twelve thickness measurements were performed per specimen: 6 thickness measurements (T1 to T6) were performed with the specimen sitting on the plate, ID upward and on the right side, with the first measurement (T1) on the closest edge of the specimen from the inspector; the other 6 measurements (T7 to T12) were performed after flipping the specimen 180° along its long axis, having the specimen sitting on the plate, its ID upside down on the left side, and the first measurement (T7) on the closest edge of the specimen from the inspector. The locations of the different measurements are shown in Figure 10.

 		
T1	T2	T3
		
T4	T5	T6
		
T7	T8	T9



T10	T11	T12

Figure 10. Thickness measurements of the specimens.

The nominal results of the specimens' dimensional inspections are presented in Table 5. The instrument provides dimensions with a tolerance of ± 0.002 mm. To investigate the repeatability of the measurements, one specimen per material was chosen to go through the dimensional measurements a second time. The specimens selected were S3, E9, M11, and H15. The average variation of measurements between the first inspection and the second one was 0.02% for the length of the specimens, 0.03% for their width, and 0.16% for their thickness.

Table 5. Dimensional measurement results.

Material	Samarium hafnate				Europium hafnate				
Specimen	S1	S2	S3	S5	E6	E7	E8	E9	E21
Length measurements (mm)									
L1	11.999	11.998	12.000	11.998	11.992	12.003	11.989	11.997	11.892
L2	11.999	11.997	11.998	11.996	11.995	12.005	11.990	11.999	11.892
L3	11.998	11.998	12.001	11.998	11.992	12.003	11.987	11.997	11.890
average L	11.999	11.998	12.000	11.997	11.993	12.004	11.989	11.998	11.891
Width measurements (mm)									
W1	3.594	3.592	3.598	3.594	3.586	3.606	3.584	3.590	3.489
W2	3.594	3.593	3.599	3.594	3.589	3.607	3.586	3.590	3.491
W3	3.594	3.593	3.599	3.595	3.590	3.606	3.585	3.600	3.491
W4	3.595	3.593	3.598	3.596	3.590	3.607	3.588	3.593	3.491
W5	3.594	3.593	3.598	3.596	3.590	3.608	3.605	3.590	3.492
W6	3.594	3.593	3.598	3.596	3.589	3.607	3.593	3.591	3.490
average W	3.594	3.593	3.598	3.595	3.589	3.607	3.590	3.592	3.491
Thickness measurements (mm)									
T1	0.519	0.517	0.517	0.519	0.521	0.518	0.521	0.518	0.521
T2	0.519	0.518	0.519	0.520	0.523	0.520	0.521	0.519	0.521
T3	0.520	0.519	0.519	0.520	0.524	0.520	0.522	0.520	0.521
T4	0.519	0.519	0.519	0.520	0.523	0.520	0.523	0.521	0.521
T5	0.518	0.519	0.519	0.520	0.523	0.521	0.522	0.522	0.520
T6	0.516	0.518	0.518	0.518	0.522	0.522	0.521	0.521	0.520

Material	Samarium hafnate				Europium hafnate				
Specimen	S1	S2	S3	S5	E6	E7	E8	E9	E21
T7	0.519	0.517	0.517	0.519	0.521	0.518	0.521	0.518	0.520
T8	0.520	0.519	0.519	0.520	0.522	0.520	0.521	0.519	0.521
T9	0.519	0.520	0.520	0.520	0.524	0.520	0.522	0.520	0.521
T10	0.518	0.519	0.519	0.520	0.522	0.521	0.522	0.521	0.520
T11	0.518	0.520	0.519	0.521	0.522	0.521	0.523	0.522	0.520
T12	0.516	0.518	0.518	0.519	0.522	0.521	0.521	0.521	0.520
average T	0.518	0.519	0.519	0.520	0.522	0.520	0.522	0.520	0.521

Material	Hafnium carbide						Hafnium carbide + additive					
Specimen	H15	H16	H17	H18	H23	H24	M10	M11	M12	M13	M14	M22
Length measurements (mm)												
L1	11.960	11.963	11.964	11.963	11.963	11.962	11.970	11.964	11.971	11.965	11.966	11.964
L2	11.965	11.964	11.962	11.962	11.963	11.962	11.969	11.964	11.972	11.965	11.967	11.965
L3	11.963	11.963	11.964	11.964	11.963	11.962	11.972	11.961	11.972	11.964	11.965	11.965
average L	11.963	11.963	11.963	11.963	11.963	11.962	11.970	11.963	11.972	11.965	11.966	11.965
Width measurements (mm)												
W1	3.606	3.607	3.598	3.605	3.612	3.610	3.632	3.600	3.627	3.607	3.571	3.619
W2	3.611	3.609	3.603	3.606	3.614	3.616	3.632	3.603	3.627	3.617	3.571	3.620
W3	3.615	3.614	3.606	3.609	3.618	3.619	3.633	3.604	3.627	3.619	3.571	3.618
W4	3.618	3.618	3.608	3.612	3.621	3.625	3.629	3.602	3.624	3.619	3.570	3.615
W5	3.621	3.620	3.610	3.614	3.622	3.628	3.625	3.599	3.622	3.618	3.568	3.611
W6	3.624	3.622	3.612	3.617	3.623	3.629	3.620	3.593	3.617	3.611	3.565	3.606
average W	3.616	3.615	3.606	3.611	3.618	3.621	3.629	3.600	3.624	3.615	3.569	3.615
Thickness measurements (mm)												
T1	0.520	0.517	0.515	0.517	0.516	0.532	0.517	0.514	0.515	0.514	0.515	0.531
T2	0.520	0.517	0.517	0.517	0.521	0.533	0.521	0.519	0.522	0.525	0.525	0.532
T3	0.519	0.518	0.516	0.516	0.518	0.533	0.527	0.523	0.530	0.532	0.529	0.543
T4	0.521	0.518	0.516	0.516	0.516	0.535	0.524	0.519	0.531	0.530	0.531	0.543
T5	0.521	0.518	0.517	0.516	0.517	0.534	0.519	0.519	0.520	0.522	0.520	0.536
T6	0.518	0.519	0.518	0.515	0.518	0.533	0.517	0.516	0.517	0.517	0.518	0.532
T7	0.519	0.517	0.516	0.517	0.517	0.533	0.516	0.514	0.515	0.514	0.517	0.533
T8	0.520	0.517	0.518	0.516	0.518	0.533	0.521	0.517	0.520	0.528	0.527	0.536
T9	0.520	0.517	0.516	0.516	0.520	0.533	0.525	0.522	0.531	0.530	0.529	0.539
T10	0.520	0.518	0.517	0.516	0.517	0.535	0.524	0.520	0.527	0.528	0.527	0.539
T11	0.519	0.518	0.517	0.515	0.517	0.534	0.518	0.518	0.517	0.523	0.519	0.534
T12	0.518	0.519	0.518	0.515	0.518	0.533	0.516	0.514	0.517	0.516	0.517	0.532
average T	0.520	0.518	0.517	0.516	0.518	0.533	0.520	0.518	0.522	0.523	0.523	0.536

The masses of the specimens were measured with a Mettler Toledo scale (ID#A006629) with reference weights TROEMNER Serial No. 29511 (ID#M212163). This instrument provides the masses with a tolerance of ± 0.0007 g. The nominal mass of each specimen is presented in Table 6. This table also shows the densities of the specimens calculated with the average dimensions from Table 5. Specimen E21 was damaged on the corner (see Figure 5) and the dimensional inspection procedure was not capable of reflecting this damage; thus, the calculated volume was overestimated, leading to an underestimated density. Excluding the E21 specimen, the calculated density for the specimens of the same absorber material presented a constant shift compared with the nominal density provided by Framatome. In addition, the calculated density was below the nominal density for all the specimens. The difference between nominal and calculated density was comprised between 0.80% and 4.70%.

Table 6. Density of the specimens calculated from the inspection data.

Specimen	**H15**	**H16**	**H17**	**H18**	**H23**	**H24**	**M10**	**M11**	**M12**
Mass (g)	0.2623	0.2621	0.2600	0.2600	0.2611	0.2684	0.2618	0.2595	0.2621
Volume (mm^3)	22.47	22.39	22.29	22.29	22.41	23.11	22.60	22.31	22.64
Density (g/cm^3)	11.67	11.71	11.66	11.67	11.65	11.62	11.58	11.63	11.58
Density compared with nominal value	-1.09%	-0.80%	-1.16%	-1.14%	-1.27%	-1.56%	-1.85%	-1.41%	-1.89%
Specimen	**M13**	**M14**	**M22**	**E6**	**E7**	**E8**	**E9**	**E21**	**S1**
Mass (g)	0.2618	0.2588	0.2701	0.1711	0.1712	0.1708	0.1707	0.1606	0.1683
Volume (mm^3)	22.63	22.33	23.17	22.49	22.52	22.45	22.42	21.61	22.36
Density (g/m^3)	11.57	11.59	11.65	7.61	7.60	7.61	7.61	7.43	7.53
Density compared with nominal value	-1.97%	-1.78%	-1.23%	-2.45%	-2.54%	-2.48%	-2.38%	-4.70%	-2.24%
Specimen	**S2**	**S3**	**S5**						
Mass (g)	0.1681	0.1686	0.1696						
Volume (mm^3)	22.35	22.39	22.41						
Density (g/m^3)	7.52	7.53	7.57						
Density compared with nominal value	-2.34%	-2.21%	-1.73%						

4. RABBIT CAPSULE ASSEMBLY

4.1 TEST MATRIX

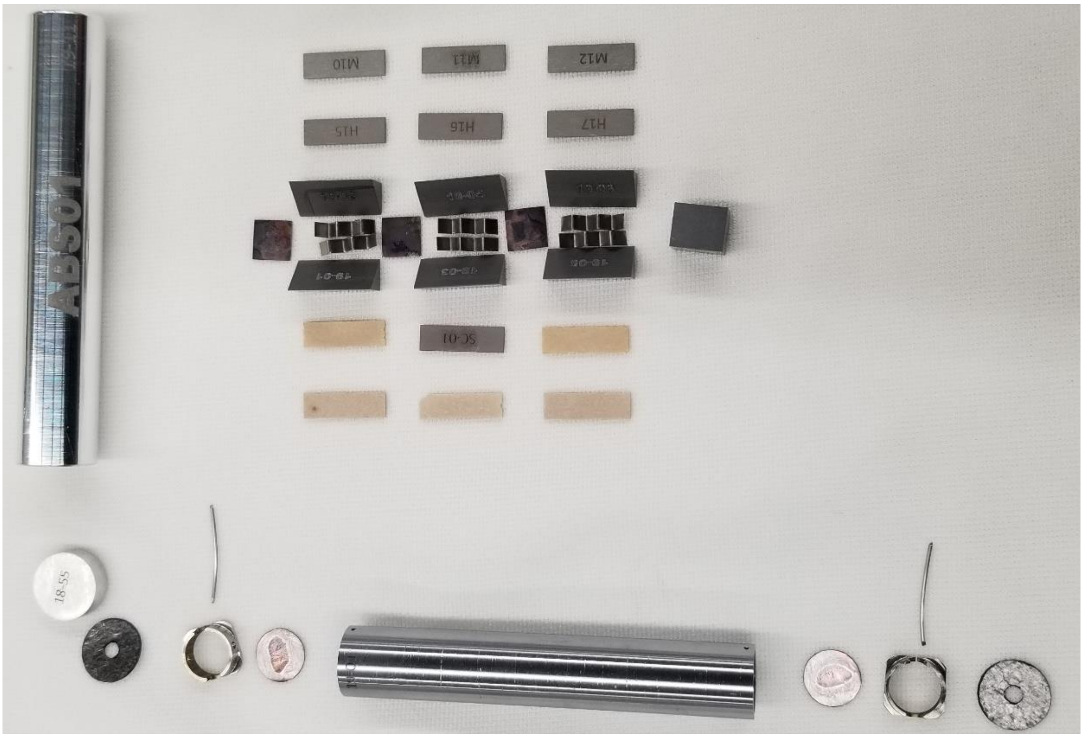
Table 7 summarizes the irradiation test matrix, with the irradiation conditions and the specimens being inserted in the capsules. Each of the two capsules contains two or three specimens from each absorber material, as well as one or two SiC specimens that replace absorber material specimens that were damaged before assembly. One capsule will undergo a 6-cycle irradiation (corresponding to an approximate dose of 6 dpa) and the other a 12-cycle irradiation (corresponding to an approximate dose of 12 dpa). Both capsules have nominal design temperatures of 300°C.

Table 7. Irradiation test matrix.

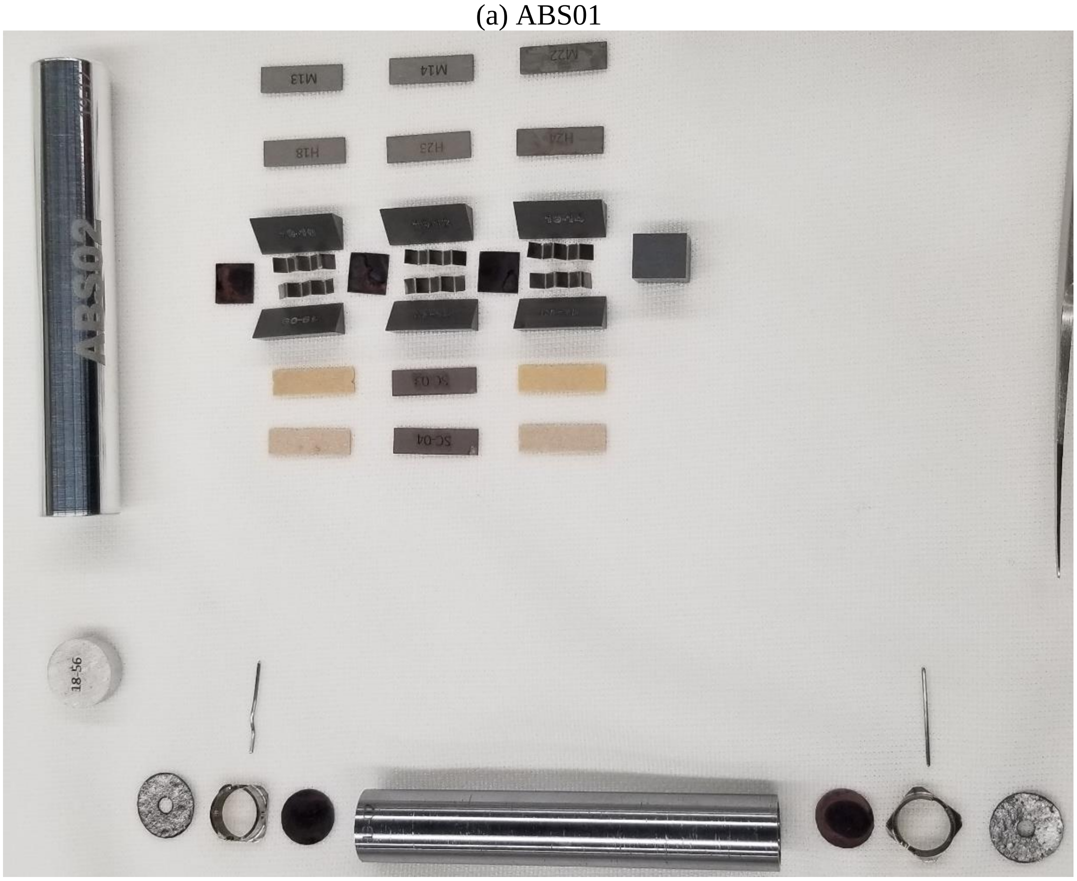
Capsule ID	Number of cycles	Specimen material	Number of specimens	Specimen ID
ABS01	6	Hafnium carbide	3	H15 H16 H17
		Hafnium carbide + additive	3	M10 M11 M12
		Samarium hafnate	2	S1 S3
		Europium hafnate	3	E6 E7 E21
		SiC	1	SC-01
ABS02	12	Hafnium carbide	3	H18 H23 H24
		Hafnium carbide + additive	3	M13 M14 M22
		Samarium hafnate	2	S2 S5
		Europium hafnate	2	E8 E9
		SiC	2	SC-03 SC-04

4.2 CAPSULE ASSEMBLY AND HFIR FABRICATION

The two rabbits (ABS01 and ABS02) were assembled. Pictures of the complete parts layout are shown in Figure 11. Figure 12 shows a top-down view of the specimens assembled inside the rabbit housing. Housings were chosen so that the as-built holder-to-housing gas gap matches the desired 40 µm gap as closely as possible; the holders' nominal outer diameter is 9.44 mm. A fill gas of 100% helium will be used for these capsules. The signed capsule fabrication request forms are provided in APPENDIX C.



(a) ABS01



(b) ABS02

Figure 11. Parts layout for (a) capsule ABS01 and (b) capsule ABS02.

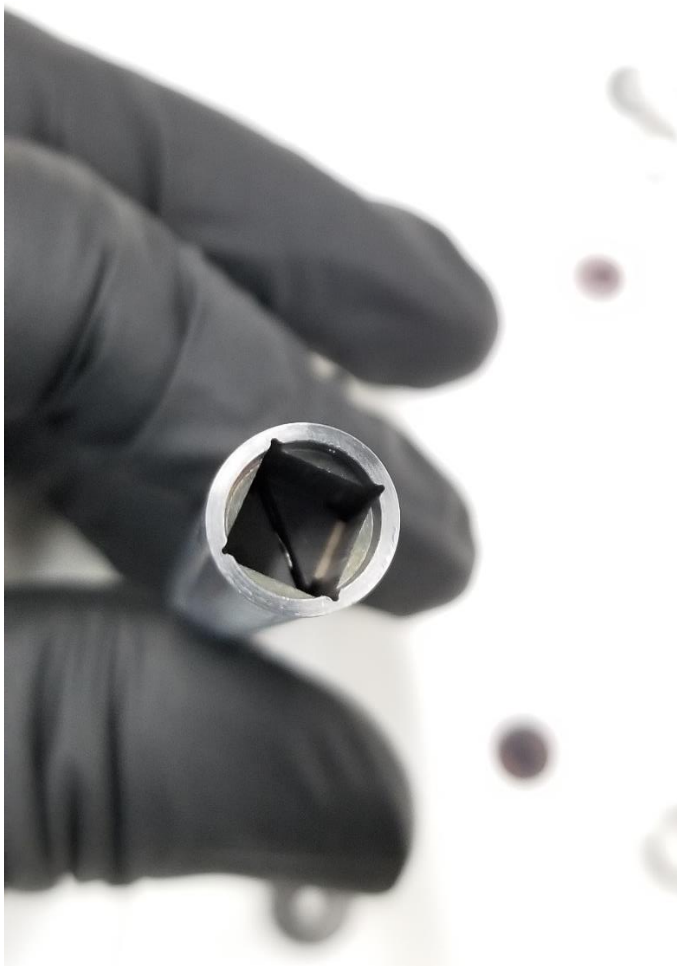


Figure 12. Top-down view of the internal assembly.

5. SUMMARY AND CONCLUSIONS

This report summarizes the thermal analyses that were performed for irradiation testing of absorber material plate specimens in the HFIR, the pre-characterization of the specimens, and the assembly of the capsules. Four different absorber materials were inserted in the same capsule: hafnium carbide, hafnium carbide with additive, samarium hafnate, and europium hafnate. Thermal analyses of this design show that an average design temperature of 336°C at EOC can be achieved for the absorber material specimens. Ultimately, the data gathered from this experiment will assist in quantifying the irradiation-induced swelling of the different absorber materials, which is needed to demonstrate their performance under irradiation.

6. WORKS CITED

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[2] G. Ilas et al., "Modeling and Simulations for the High Flux Isotope Reactor Cycle 400," ORNL/TM-2015/36, Oak Ridge National Laboratory, Oak Ridge, TN, 2015.

[3] C. R. Daily and D. Chandler, "Development and Testing of Nculear Data Libraries for Improved Energy Deposition Modeling," in *ANS RPSD 2014*, Knoxville, TN, September 14-18 2014.

[4] D. Chandler, "Activation and Heat Generation Calculation to Support Pu-238 Fully Loaded Target Irradiations in Inner Small VXFs for up to Three Cycles," C-HFIR-2015-014, Oak Ridge National Laboratory, Oak Ridge, TN, 2015.

APPENDIX A. THERMAL ANALYSIS REPORT

APPENDIX A. THERMAL ANALYSIS REPORT

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**************************************************************************

   TEMPERATURE DESIGN AND SAFETY BASIS SOLUTION FOR ABSORBER MATERIAL RABBITS

 **************************************************************************

  * Temperature Design Solution at the End of Cycle (EOC)

  -------------------------------------------------------------------------------

  DESCRIPTION


  * Design dose = 12.00 dpa

  * Helium fill gas

  * Holder diameter =  9.44 mm (0.3717 in)

  * Thermal-only solution with calculated gaps

  * PTP, Axial position 5.

 --------------------------------------------------------------------------------

  COLD MODEL DIMENSIONS


  Outer housing diameter  =  10.96 mm (0.4313 in)

  Inner housing diameter  =   9.52 mm (0.3747 in)

  Outer holder diameter   =   9.44 mm (0.3717 in)

  Cold gap                =   0.04 mm (0.0015 in)

  -------------------------------------------------------------------------------

  BOUNDARY CONDITIONS


  Heat transfer coefficient =  48400. W/m²·°C

  Bulk coolant temperature  =    54.0 °C


 --------------------------------------------------------------------------------

  HEAT GENERATION


                                                     Heat Gen.   ------ Heat Load -----
```

Part	Material	@Midplane (W/kg)	@Midplane (W)	@Location (W)
1) Housing	AL-6061	34933.	74.6	74.2
2) Housing	AL-6061	34933.	74.6	74.2
3) EndCap	AL-6061	34933.	21.6	21.2
4) Holder	V-4Cr4Ti	48800.	17.6	17.5
5) Holder	V-4Cr4Ti	48800.	17.6	17.3
6) Holder	V-4Cr4Ti	48800.	504.7	502.6
7) Disk_bottom	Moly	69133.	3.7	3.7
8) HfCMo_bottom	HFO2	109667.	28.3	28.3
9) TM1_bottom	SiC(Irr)	39050.	15.2	15.2
10) TM2_bottom	SiC(Irr)	39050.	15.2	15.2
11) Spring.1	Ti-6Al4V	35600.	0.3	0.3
12) Spacer.1	Moly	69133.	3.1	3.1
13) Disk_up	Moly	69133.	3.7	3.7
14) Spacer.2	Moly	69133.	3.1	3.1
15) Spacer.3	Moly	69133.	3.1	3.1
16) Wire_up	Moly	69133.	1.3	1.3
17) Wire_bottom	Moly	69133.	1.3	1.3
18) Insulator_bottom	GRAFOIL	33800.	0.2	0.2
19) EuHf_bottom	HFO2	131667.	22.7	22.7
20) SmHf_bottom	HFO2	110667.	18.8	18.8
21) HfC_bottom	HFO2	109667.	28.3	28.3
22) Spring.2	Ti-6Al4V	35600.	0.3	0.3
23) Insulator_top	GRAFOIL	33800.	0.2	0.2
24) Thimble_top	Ti-6Al4V	35600.	5.0	4.9
25) Thimble_bottom	Ti-6Al4V	35600.	5.0	5.0
26) Block	SiC(Irr)	34400.	26.0	26.0
27) HfCMo_middle	HFO2	109667.	28.3	28.2

28) EuHf-middle	HFO2	131667.	22.7	22.6
29) SmHf_middle	HFO2	110667.	18.8	18.8
30) HfC_middle	HFO2	109667.	28.3	28.2
31) TM1_middle	SiC(Irr)	39050.	15.2	15.2
32) TM2_middle	SiC(Irr)	39050.	15.2	15.2
33) Spring.3	Ti-6Al4V	35600.	0.3	0.3
34) Spring.4	Ti-6Al4V	35600.	0.3	0.3
35) HfCMo_top	HFO2	109667.	28.3	28.1
36) EuHf_top	HFO2	131667.	22.7	22.5
37) SmHf_top	HFO2	110667.	18.8	18.7
38) HfC_top	HFO2	109667.	28.3	28.1
39) TM1_top	SiC(Irr)	39050.	15.2	15.1
40) TM2_top	SiC(Irr)	39050.	15.2	15.1
41) Spring.5	Ti-6Al4V	35600.	0.3	0.3
42) Spring.6	Ti-6Al4V	35600.	0.3	0.3
			1153.6	1148.4

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	66.	57.	72.	58.	71.
2) Housing	AL-6061	66.	57.	72.	58.	70.
3) EndCap	AL-6061	93.	90.	96.	91.	96.
4) Holder	V-4Cr4Ti	154.	140.	174.	144.	167.
5) Holder	V-4Cr4Ti	149.	141.	161.	144.	156.
6) Holder	V-4Cr4Ti	211.	143.	274.	155.	258.
7) Disk_bottom	Moly	281.	265.	295.	267.	294.

8)	HfCMo_bottom	HFO2	319.	285.	351.	299.	338.
9)	TM1_bottom	SiC(Irr)	354.	310.	391.	326.	379.
10)	TM2_bottom	SiC(Irr)	426.	336.	451.	373.	448.
11)	Spring.1	Ti-6Al4V	396.	341.	432.	353.	428.
12)	Spacer.1	Moly	393.	359.	423.	363.	421.
13)	Disk_up	Moly	217.	205.	226.	207.	225.
14)	Spacer.2	Moly	392.	358.	422.	362.	420.
15)	Spacer.3	Moly	374.	345.	398.	349.	396.
16)	Wire_up	Moly	249.	222.	267.	223.	267.
17)	Wire_bottom	Moly	255.	228.	274.	229.	274.
18)	Insulator_bottom	GRAFOIL	78.	69.	96.	69.	89.
19)	EuHf_bottom	HFO2	350.	243.	431.	314.	364.
20)	SmHf_bottom	HFO2	340.	238.	422.	306.	355.
21)	HfC_bottom	HFO2	319.	284.	351.	298.	338.
22)	Spring.2	Ti-6Al4V	393.	339.	428.	352.	424.
23)	Insulator_top	GRAFOIL	168.	165.	170.	166.	170.
24)	Thimble_top	Ti-6Al4V	163.	142.	170.	157.	168.
25)	Thimble_bottom	Ti-6Al4V	152.	106.	230.	118.	198.
26)	Block	SiC(Irr)	302.	256.	366.	267.	344.
27)	HfCMo_middle	HFO2	330.	312.	352.	322.	340.
28)	EuHf-middle	HFO2	361.	273.	436.	351.	367.
29)	SmHf_middle	HFO2	350.	266.	427.	339.	360.
30)	HfC_middle	HFO2	329.	312.	351.	322.	340.
31)	TM1_middle	SiC(Irr)	366.	341.	392.	350.	383.
32)	TM2_middle	SiC(Irr)	440.	399.	456.	419.	454.
33)	Spring.3	Ti-6Al4V	412.	387.	437.	389.	433.
34)	Spring.4	Ti-6Al4V	408.	384.	433.	386.	429.
35)	HfCMo_top	HFO2	320.	293.	351.	306.	337.
36)	EuHf_top	HFO2	351.	242.	430.	330.	362.
37)	SmHf_top	HFO2	341.	237.	421.	322.	354.

38) HfC_top		HFO2	319.	293.	350.	306.	337.
39) TM1_top		SiC(Irr)	357.	323.	391.	336.	379.
40) TM2_top		SiC(Irr)	430.	380.	449.	403.	447.
41) Spring.5		Ti-6Al4V	405.	375.	429.	379.	427.
42) Spring.6		Ti-6Al4V	401.	372.	425.	377.	422.
	All Specimens	ABSMAT	336.	237.	436.	305.	364.
	Thermometry	SiC	395.	310.	456.	337.	450.
	EuHfSpecimens	EuHf	354.	242.	436.	325.	366.
	SmHfSpecimens	SmHf	344.	237.	427.	315.	358.
	HfCSpecimens	HfC	322.	284.	351.	301.	339.
	HfCMoSpecimens	HfCMo	323.	285.	352.	302.	339.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.422	24.21	0.050
2) Housing	AL-6061	167.369	0.00	0.050
3) EndCap	AL-6061	170.477	0.00	0.050
4) Holder	V-4Cr4Ti	31.547	9.57	0.350
5) Holder	V-4Cr4Ti	31.498	0.00	0.350
6) Holder	V-4Cr4Ti	32.053	0.00	0.350
7) Disk_bottom	Moly	127.857	0.00	0.056
8) HfCMo_bottom	HFO2	17.300	0.00	0.310
9) TM1_bottom	SiC(Irr)	6.928	3.42	0.900

10)	TM2_bottom	SiC(Irr)	8.031	3.60	0.900
11)	Spring.1	Ti-6Al4V	14.496	0.00	0.391
12)	Spacer.1	Moly	123.351	0.00	0.067
13)	Disk_up	Moly	130.388	0.00	0.049
14)	Spacer.2	Moly	123.392	0.00	0.067
15)	Spacer.3	Moly	124.102	0.00	0.065
16)	Wire_up	Moly	129.139	0.00	0.052
17)	Wire_bottom	Moly	128.869	0.00	0.053
18)	Insulator_bottom	GRAFOIL	38.000	1.00	0.500
19)	EuHf_bottom	HFO2	1.320	0.00	0.310
20)	SmHf_bottom	HFO2	1.320	0.00	0.310
21)	HfC_bottom	HFO2	17.300	0.00	0.310
22)	Spring.2	Ti-6Al4V	14.425	0.00	0.391
23)	Insulator_top	GRAFOIL	38.000	1.00	0.500
24)	Thimble_top	Ti-6Al4V	9.771	0.00	0.320
25)	Thimble_bottom	Ti-6Al4V	9.556	0.00	0.320
26)	Block	SiC(Irr)	6.091	3.27	0.900
27)	HfCMo_middle	HFO2	17.300	0.00	0.310
28)	EuHf-middle	HFO2	1.320	0.00	0.310
29)	SmHf_middle	HFO2	1.320	0.00	0.310
30)	HfC_middle	HFO2	17.300	0.00	0.310
31)	TM1_middle	SiC(Irr)	7.112	3.45	0.900
32)	TM2_middle	SiC(Irr)	8.241	3.63	0.900
33)	Spring.3	Ti-6Al4V	14.802	0.00	0.395
34)	Spring.4	Ti-6Al4V	14.731	0.00	0.394
35)	HfCMo_top	HFO2	17.300	0.00	0.310
36)	EuHf_top	HFO2	1.320	0.00	0.310
37)	SmHf_top	HFO2	1.320	0.00	0.310
38)	HfC_top	HFO2	17.300	0.00	0.310
39)	TM1_top	SiC(Irr)	6.968	3.43	0.900

40) TM2_top	SiC(Irr)	8.099	3.61	0.900	
41) Spring.5	Ti-6Al4V	14.660	0.00	0.393	
42) Spring.6	Ti-6Al4V	14.589	0.00	0.392	

STORED ENERGY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Mass (g)	Tavg (°C)	Specific Heat (J/kg°C)	Stored Energy (J)
1) Housing	AL-6061	2.137	66.	890.	88.
2) Housing	AL-6061	2.137	66.	889.	87.
3) EndCap	AL-6061	0.619	93.	911.	41.
4) Holder	V-4Cr4Ti	0.360	154.	515.	25.
5) Holder	V-4Cr4Ti	0.360	149.	515.	24.
6) Holder	V-4Cr4Ti	10.341	211.	521.	1028.
7) Disk_bottom	Moly	0.054	281.	265.	4.
8) HfCMo_bottom	HFO2	0.258	319.	266.	21.
9) TM1_bottom	SiC(Irr)	0.390	354.	1048.	137.
10) TM2_bottom	SiC(Irr)	0.390	426.	1084.	171.
11) Spring.1	Ti-6Al4V	0.007	396.	727.	2.
12) Spacer.1	Moly	0.045	393.	270.	5.
13) Disk_up	Moly	0.054	217.	263.	3.
14) Spacer.2	Moly	0.045	392.	270.	4.
15) Spacer.3	Moly	0.045	374.	270.	4.
16) Wire_up	Moly	0.019	249.	264.	1.
17) Wire_bottom	Moly	0.019	255.	264.	1.
18) Insulator_bottom	GRAFOIL	0.007	78.	700.	0.
19) EuHf_bottom	HFO2	0.172	350.	500.	28.

20)	SmHf_bottom	HFO2	0.170	340.	560.	30.
21)	HfC_bottom	HFO2	0.258	319.	266.	20.
22)	Spring.2	Ti-6Al4V	0.007	393.	726.	2.
23)	Insulator_top	GRAFOIL	0.007	168.	700.	1.
24)	Thimble_top	Ti-6Al4V	0.140	163.	636.	13.
25)	Thimble_bottom	Ti-6Al4V	0.140	152.	631.	12.
26)	Block	SiC(Irr)	0.756	302.	1019.	217.
27)	HfCMo_middle	HFO2	0.258	330.	266.	21.
28)	EuHf-middle	HFO2	0.172	361.	500.	29.
29)	SmHf_middle	HFO2	0.170	350.	560.	31.
30)	HfC_middle	HFO2	0.258	329.	266.	21.
31)	TM1_middle	SiC(Irr)	0.390	366.	1055.	142.
32)	TM2_middle	SiC(Irr)	0.390	440.	1090.	178.
33)	Spring.3	Ti-6Al4V	0.007	412.	733.	2.
34)	Spring.4	Ti-6Al4V	0.007	408.	732.	2.
35)	HfCMo_top	HFO2	0.258	320.	266.	21.
36)	EuHf_top	HFO2	0.172	351.	500.	29.
37)	SmHf_top	HFO2	0.170	341.	560.	31.
38)	HfC_top	HFO2	0.258	319.	266.	21.
39)	TM1_top	SiC(Irr)	0.390	357.	1050.	138.
40)	TM2_top	SiC(Irr)	0.390	430.	1086.	174.
41)	Spring.5	Ti-6Al4V	0.007	405.	730.	2.
42)	Spring.6	Ti-6Al4V	0.007	401.	729.	2.
			--------			--------
			22.242			2814.

CONTACT SUMMARY FOR CONTACT ID 85: Multiple To Multiple {Frictionless}

Contact surface material: V-4Cr4Ti

Target surface material: AL-6061

Interstitial gas: Helium

Effective surface roughness: 2.514 µm

Effective asperity slope: 0.223 rad

Effective microhardness: 1.220 GPa

	Average	Minimum	Maximum
~~ direct results ~~~~~~~~~~			
Contact status	1.000	1.000	1.000
Contact temperature (°C)	193.215	141.053	229.814
Target temperature (°C)	68.328	60.108	72.203
Geometric gas gap (µm)	39.249	39.090	39.256
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m²)	596.630	337.462	794.647
Radiation heat flux (kW/m²)	0.098	0.044	0.146
Contact conduction heat flux (kW/m²)	0.000	0.000	0.000
Total heat flux (kW/m²)	596.728	337.506	794.793
Thermal contact conductance (W/m²·C)	4739.991	4325.660	5044.322
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	36.893	35.626	38.707
Contact thermal jump distance (µm)	1.464	1.251	1.618
Target thermal jump distance (µm)	1.193	1.079	1.271
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	18.260	18.242	18.286
Gas thermal conductivity (W/m·°C)	0.187	0.177	0.194
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	4741.132	4328.420	5042.302

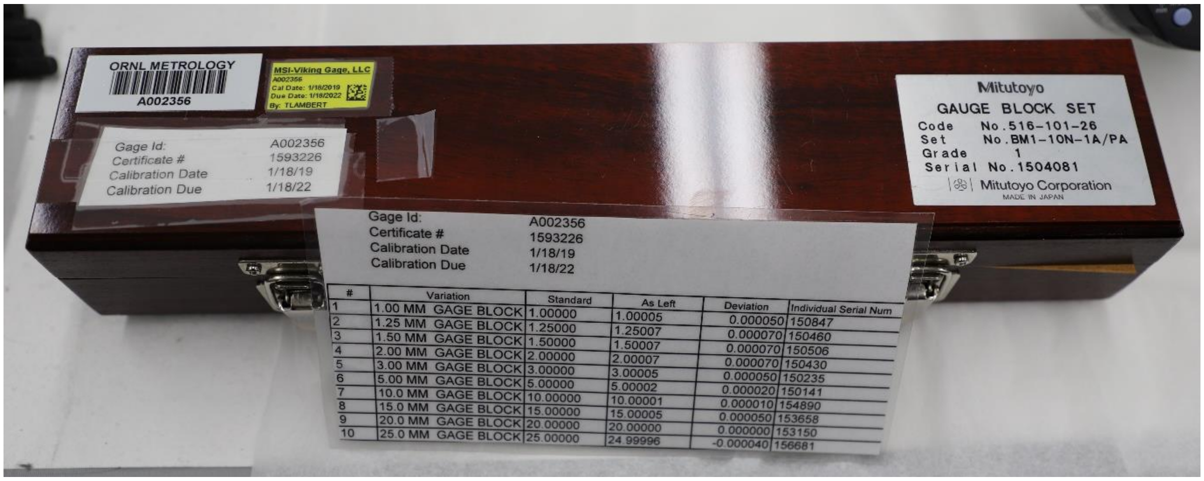
Contact status codes:

```
0=open/no heat transfer, 1=near-field contact

2=closed and sliding,    3=closed and sticking
```

APPENDIX B. REFERENCE MEASUREMENTS FOR DIMENSIONAL INSPECTION

APPENDIX B. REFERENCE MEASUREMENTS FOR DIMENSIONAL INSPECTION



Gauge block specifications for the jaw gauge

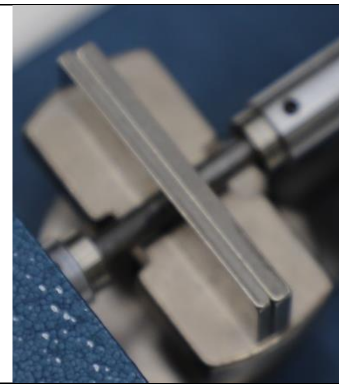
The length of the specimens is expected to be 12 mm (nominal value). Thus, for the length measurements, a total gauge block of 12 mm (10 mm block + 2 mm block) is used for the reference measurement (see below).

(a) Reference measurement

(b) Reference gauge block (12 mm)

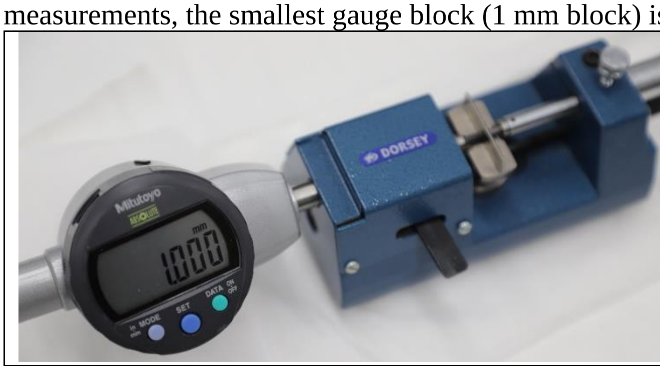
Reference measurement with a 12 mm total gauge block (10 mm block + 2 mm block)

The width of the specimens is expected to be 3.6 mm (nominal value). Thus, for the width measurements, a total gauge block of 3.5 mm (2 mm block + 1.5 mm block) is chosen for the reference measurement (see below).

	
(a) Reference measurement	(b) Reference gauge block (3.5 mm)

Reference measurement with a 3.5 mm total gauge block (2 mm block + 1.5 mm block)

The thickness of the specimens is expected to be 0.5 mm (nominal value). Thus, for the thickness measurements, the smallest gauge block (1 mm block) is used for the reference measurement (see below).

	
(a) Reference measurement	(b) Reference gauge block (1 mm)

Reference measurement with a 1 mm gauge block

APPENDIX C. FABRICATION REQUEST SHEETS

APPENDIX C. FABRICATION REQUEST SHEETS

Capsule Number: ABS01

Irradiation Conditions

Irradiation Location	PTP 5
Design Temperature	300
First Cycle Goal	484
Irradiation Time	6.0 cyc.
Fill Gas	Helium

Approvals

	Request	Build
Performed by:	[illegible] 5/21/19	[illegible] 9/27/19
Checked by:	Chris [illegible] 9-30-19	[illegible] 09/27/19

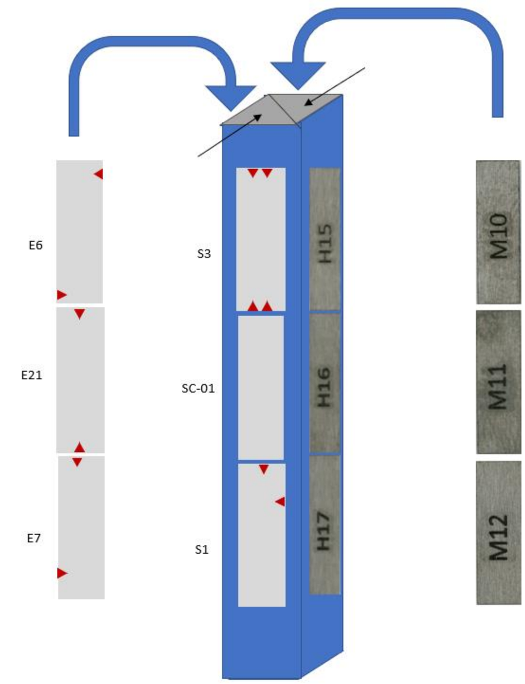
Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	C	1	Al 6061	1		20930	20930	19-11	4.3145
End Cap	X3E020977A634	C	2	Al 4047	1		20823	20850	18-55	0.6153
Support disk	S17-40-ABS_MATL	0	2	Mo	2	Ø7.5 x .05- .13 thk	19593	19593	2 pcs	0.0762
Support disk	S17-40-ABS_MATL	0	3	Mo	3	5.8 SQx .05- .13 thk	19593	19593	3 pcs	0.0735
Wire	S17-40-ABS_MATL	0	4	Mo	2	Ø .5	19600	19600	2 pcs	0.0548
Insulator disk	S17-40-ABS_MATL	0	5	Grafoil	2	Ø8.5 x .05- .13 thk	19812	19812	2 pcs	0.0164
Quartz wool	S17-40-ABS_MATL	0	6	High purity SiO2	AR		20279	20279	As Needed	0.0270
Specimen	S17-41-ABS_MATL	0	1	Samarium hafnate	2		21030	21030	S1	0.1683
									S3	0.1686
				Europium hafnate	3				E6	0.1711
									E7	0.1712
									E21	0.1606
				HfC+MoSi2	3				M10	0.2618
									M11	0.2595
									M12	0.2621
				HfC	3				H15	0.2623
									H16	0.2621
									H17	0.2600
				SiC	1		19759	20980	SC-01	0.0662
Holder	S17-41-ABS_MATL	0	2	Vanadium alloy	1		19599	21028	19-01	11.0711
Thermometry	S17-41-ABS_MATL	0	3	SiC	6	19-01 thru 19-06	19759	20986	6 pcs	2.4022
Spring	S17-41-ABS_MATL	0	4	Ti alloy	6		20094	20094	6 pcs	0.0597
Spacer	S17-41-ABS_MATL	0	5	SiC	1		19759	19759	1 pcs	0.7712
Centering thimble	X3E020977A540	1	1	Ti alloy	2	ARM00027 & ARM00028	20536	20553	2 pcs	0.2729
									total mass	22.2286
									specimen mass	2.4738

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S17-40-ABS_MATL	0	
Welding & Cleaning	X3E020977A633	2	
Fill Gas			Helium

ABS01



Capsule Number: ABS02

Irradiation Conditions

Irradiation Location	PTP 5
Design Temperature	300
First Cycle Goal	484
Irradiation Time	12.0 cyc.
Fill Gas	Helium

Approvals

	Request	Build
Performed by:	[signature] 9/30/19	[signature] 9/27/19
Checked by:	Chris Petrie 9-30-19	[signature] 09/27/19

Capsule Fabrication

	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Housing	X3E020977A634	C	1	Al 6061	1		20930	20930	19-12	4.3124
End Cap	X3E020977A634	C	2	Al 4047	1		20823	20850	18-56	0.6147
Support disk	S17-40-ABS_MATL	0	2	Mo	2	Ø7.5 x .05- .13 thk	19593	19593	2 pcs	0.0807
Support disk	S17-40-ABS_MATL	0	3	Mo	3	5.8 SQx .05- .13 thk	19593	19593	3 pcs	0.0735
Wire	S17-40-ABS_MATL	0	4	Mo	2	Ø .5	19600	19600	2 pcs	0.0512
Insulator disk	S17-40-ABS_MATL	0	5	Grafoil	2	Ø8.5 x .05- .13 thk	19812	19812	2 pcs	0.0168
Quartz wool	S17-40-ABS_MATL	0	6	High purity SiO2	AR		20279	20279	As Needed	0.0336
Specimen	S17-41-ABS_MATL	0	1	Samarium hafnate	2		21030	21030	S2	0.1681
									S5	0.1696
				Europium hafnate	2				E8	0.1708
									E9	0.1707
				HfC+MoSi2	3				M13	0.2618
									M14	0.2588
									M22	0.2701
				HfC	3				H18	0.2600
									H23	0.2611
									H24	0.2684
				SiC	2		19759	20980	SC-03	0.0654
									SC-04	0.0650
Holder	S17-41-ABS_MATL	0	2	Vanadium alloy	1		19599	21028	19-02	11.0640
Thermometry	S17-41-ABS_MATL	0	3	SiC	6	19-09 thru 19-14	19759	20986	6 pcs	2.4078
Spring	S17-41-ABS_MATL	0	4	Ti alloy	6		20094	20094	6 pcs	0.0615
Spacer	S17-41-ABS_MATL	0	5	SiC	1		19759	19759	1 pcs	0.7715
Centering thimble	X3E020977A540	1	1	Ti alloy	2	ARM00029 & ARM00030	20536	20553	2 pcs	0.2734
									total mass	22.1509
									specimen mass	2.3898

Assembly

	Drawing	Rev.	Comment
Assembly Drawing	S17-40-ABS_MATL	0	
Welding & Cleaning	X3E020977A633	2	
Fill Gas			Helium

ABS02