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Design and Thermal Analysis for Irradiation of Absorber Material Specimens in the High Flux Isotope Reactor

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November 2018

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Reactor and Nuclear Systems Division

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SUMMARY

This report provides a summary of the irradiation vehicle design and thermal analysis of absorber material specimens planned for irradiation in the flux trap of the High Flux Isotope Reactor (HFIR). Four different absorber materials will be inserted in the same capsule: hafnium carbide without additive (HfC), hafnium carbide with molybdenum silicide additive (HfC + $MoSi_2$), samarium hafnate (Sm_2HfO_5), and europium hafnate (Eu_2HfO_5). The capsule design, with target temperatures of 300°C, will accommodate twelve specimens. Two capsules are planned to be built and irradiated to two different neutron fluence levels.

1. INTRODUCTION

Current commercial nuclear reactors use silver-indium-cadmium (AIC) and boron carbide (B_4C) as the primary neutron absorber materials. These absorbers are used to safely shut down the reactor and, for some designs, for controlling reactor power. Recently, there has been increased interest on advanced accident tolerant absorber materials that can survive for extended periods of time during beyond design basis accidents. AIC and B_4C form low-melting eutectics with the fuel cladding. They can also melt and partially vaporize during accident scenarios.

Alternative absorber materials are being considered that do not form low-melting eutectics with the fuel cladding and are more stable at higher temperatures than those predicted for severe accident conditions. These alternative materials would ideally have equivalent reactivity worth and control rod drop times to minimize the impact on reactor operation.

The purpose of this project is to perform experimental irradiation testing of novel absorber material specimens to understand the effects of irradiation with realistic temperature gradients. The experimental results will quantify irradiation-induced swelling of four absorber materials: hafnium carbide without an additive (HfC), hafnium carbide with molybdenum silicide additive (HfC + $MoSi_2$), samarium hafnate (Sm_2HfO_5), and europium hafnate (Eu_2HfO_5).

The absorber material specimens will be inserted into the Oak Ridge National Laboratory (ORNL)'s 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. This report summarizes the HFIR irradiation experiments that are being performed to assess performance under irradiation, including the irradiation capsule design concept and thermal analyses.

2. EXPERIMENTAL METHODS

2.1 HFIR IRRADIATION EXPERIMENTS

The irradiation experiment described in this document will be performed in the flux trap of ORNL's HFIR. The HFIR is a beryllium-reflected, pressurized, light water–cooled and moderated flux trap–type reactor [1]. The core consists of aluminum-clad involute-fuel plates which currently use highly enriched ^{235}U fuel at a power level of 85 MW. The reactor core consists of two concentric annular regions, each approximately 61 cm in height. The flux trap region is located inside the fuel region. The HFIR fuel and all experiment vessels are cooled by the reactor's primary coolant, which is approximately 50–60°C. A typical HFIR cycle is 25 days.

The goal of this work is to design experiments to contain the absorber material specimens inside HFIR-approved irradiation vehicles so that they can accumulate the desired dose while being irradiated at the design temperature. Neutron and gamma radiation from the HFIR fuel cause heating of the experiment materials. This heating is accurately determined using neutronics models of the HFIR core. These data are used as inputs to thermal analyses to predict component temperatures during irradiation [2-11]. Experiments in the flux trap are almost always un-instrumented; passive SiC temperature monitors (TMs) can be used to determine the irradiation temperature post-irradiation [12]. However, detailed neutronic and thermal analyses are required to ensure that capsule design temperatures are achieved. Experiment designs typically use a small insulating gas gap between the holder and the housing. The size of the gap and the choice of the fill gas (typically helium (He), neon (Ne), argon (Ar), or a mixture) inside the experiment are established so that the heat generated in the experimental components passes through the gas gap and results in the desired temperature drop across the gap. The temperature drop is a function of the heat flux through the gap, the thermal conductivity of the fill gas, and the size of the gas gap.

2.2 EXPERIMENT DESIGN CONCEPTS

The irradiation capsule developed in this work is shown in the section views of Figure 1 and Figure 2. The outer containment for the irradiation experiment is the capsule housing, made from aluminum, and is directly cooled on the outer surface by the HFIR's primary coolant. Grafoil insulator disks are placed on both ends inside the housing to reduce axial heat losses. One vanadium alloy holder, placed in the housing, contains 12 plate specimens, 6 passive SiC temperature monitor (TM) and a SiC block for a space filler. The nominal dimensions of the specimens are 12 mm × 3.6 mm × 0.50 mm. Retainer springs inserted in between the SiC TMs keep the specimens pressed against the inner walls of the holder to provide adequate heat transfer. Quartz wool (not shown) is packed to fill the void space at the top of the internal stack inside the holder to keep the specimens from falling out in the case of a spring failure. Support disks provide a platform on which the specimens sit. The titanium centering thimbles are inserted in the ends of the holder and secured by wires to prevent dislodging from the holder. The main function of the thimbles is to keep the holder centered inside the housing and to maintain a constant gas gap between the holder and the housing. Temperature is controlled by varying the size of the gas gap between the holder and the housing. Helium is used as the fill gas.

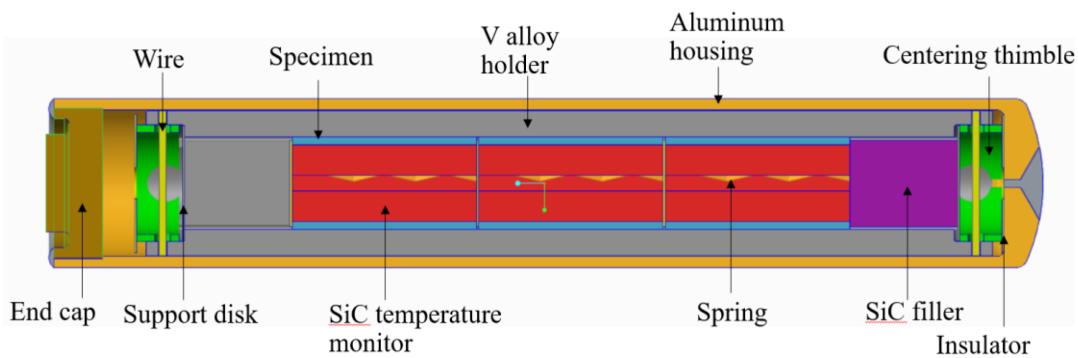

Figure 1. Section view showing irradiation capsule design concept.

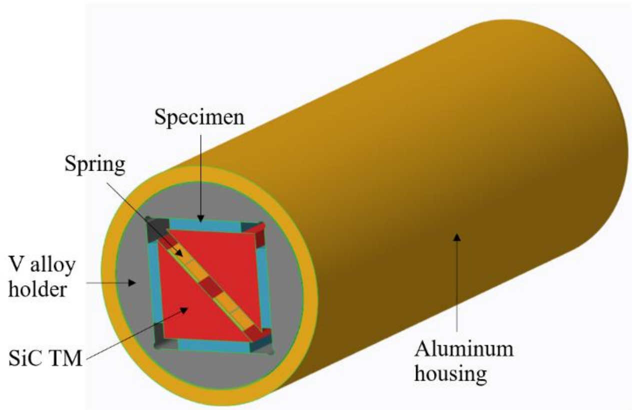

Figure 2. Radial section view of the irradiation capsule design

2.3 TEST MATRIX

Table 1 summarizes the different specimens that will be included in the irradiation test matrix. Four absorber materials will be studied: HfC, HfC + $MoSi_2$, Sm_2HfO_5, and Eu_2HfO_5. A total of 2 capsules, containing 12 specimens each, will be irradiated: 1 capsule will undergo a 6-cycle irradiation (corresponding to an approximated dose of 6 dpa), and the other a 12-cycle irradiation (corresponding to an approximated dose of 12 dpa). Both capsules have a nominal design temperature of 300 °C.

Table 1. Irradiation test matrix.

Capsule number	Absorber material specimens	Irradiation dose	Irradiation temperature
Capsule #1	HfC	6 dpa	300 °C ± 25°C
	HfC + $MoSi_2$		
	Sm_2HfO_5		
	Eu_2HfO_5		
Capsule #2	HfC	12 dpa	
	HfC + $MoSi_2$		
	Sm_2HfO_5		
	Eu_2HfO_5		

3. COMPUTATIONAL METHODS

3.1 NEUTRONICS CALCULATIONS

Neutronics calculations were performed to determine the heat generation rates for the four absorber materials and the surrounding capsule materials. The standard MCNP model of the HFIR core with cycle 400 experimental loading [13] was modified to include the absorber irradiation assembly described above to assess neutron and photon transport through the materials of interest. For these calculations, the capsules were located in a peripheral target position (PTP) of the HFIR flux trap centered about the axial midplane (PTP position 5). This position results in a conservative estimate of photon flux and therefore provides bounding heating values.

Heat generation assessment must account for heating from several sources: prompt fission neutrons and photons, delayed photons from fission product decay in the HFIR fuel, and decay heat in the absorbers themselves. Prompt fission neutron and photon heating is assessed directly from heat deposition tallies in the absorbers from an MCNP criticality calculation under beginning of cycle conditions. Delayed photon heating is assessed using a separate fixed source MCNP calculation with a photon source definition representative of the fission product distribution in the HFIR fuel at the end of one day of operation [14]. For activation and decay calculations, the static MCNP analysis must be coupled to the ORIGEN depletion and decay module of the SCALE code system [15]. To this end, during the MCNP criticality calculations, tallies are also defined for the group-wise neutron fluxes and nuclide-specific capture reaction rates in the absorbers; these results are then used to explicitly calculate capture cross sections to be passed to ORIGEN for consistency with MCNP. Given these cross sections and the flux magnitudes and spectra, the ORIGEN calculation is then run to deplete each absorber material over one day of irradiation and assess the resulting decay heat. It is assumed that the portion of decay heat attributed to gamma photon energy is deposited locally. Summing the heating from each of these sources then gives the total heat generation rates reported in Table 2 (as well as the absorber material densities). These results were then used as inputs to the thermal analyses to predict the thermal behavior of the capsule (see next section).

Table 2. Density and heat generation rate results for the absorber materials.

Absorber material	Density (g/cm^3)	Heat generation rate (W/g)
HfC	11.77	95.0
HfC + $MoSi_2$	11.76	94.1
Sm_2HfO_5	7.99	115.5
Eu_2HfO_5	8.17	82.4
V4Cr4Ti	6.11	46.0

3.2 THERMAL ANALYSES

The remainder of this document describes the three-dimensional (3D) thermal analyses that were performed using the ANSYS finite element software package to predict temperature distributions inside the capsule. These analyses use material-dependent heat generation rates (heat per unit mass) determined in previous neutronics analyses. Computer aided design (CAD) models are imported into ANSYS and meshed using 20-node hexagonal and tetrahedral elements with a nominal mesh size of 0.5 mm. Thermal contacts are defined to allow heat to be transferred between multiple bodies. Gas gap heat transfer was assumed to include conduction and radiation only, as there is very little space available for natural convection to occur. The contact conductance of components in contact or separated by the small gas gaps are calculated with user-defined macros [16]. In this way, gas gaps are not directly meshed, which significantly reduces computational time. Gaps for this design are approximately 40 µm, and the total internal length of the capsule is less than 60 mm. The solver accounts for thermal expansion, though it does not explicitly modify the model geometry. Instead, an effective gap is determined using the initial (cold) dimensions, temperature-dependent thermal expansion data, and the temperatures of the contact and target surface nodes.

The ORNL Nuclear Experiments and Irradiation Testing (NEIT) group maintains a database of design and analysis calculations (DACs) that include temperature-dependent thermophysical material properties used in thermal analyses. Most of the properties are obtained from CINDAS [17], MatWeb [18], and various literature sources. Material properties for this calculation are included in the DACs, as shown in Table 3 and are available upon request.

Table 3. Experiment materials and material property references

Part	Material	Reference
Holder	Vanadium	DAC-10-05-PROP_V4CR4TI [19]
Centering thimbles, springs	Titanium	DAC-11-14-PROP_TI6AL4V [20]
Housing, endcap	Aluminum	DAC-10-03-PROP_AL6061 [21]
Insulators	Grafoil	DAC-11-16-PROP_GRAFOIL [22]
TMs, block	SiC	DAC-10-06-PROP_SIC(IRR) [23]
Support disks	Molybdenum	DAC-10-11-PROP_MOLY [24]
Fill gas	Helium	DAC-10-02-PROP_HELIUM [25]

Convection boundary conditions were applied to the outer surface of the housing. Details of the calculation of the convective heat transfer coefficients and bulk coolant temperatures are summarized in DAC-11-01-RAB03 [26]. These parameters were calculated using turbulent flow correlations and the axial power profile (resulting from neutron and gamma heat generation in the coolant) specific to the peripheral target position in the HFIR flux trap. Temperatures calculated in the thermal analyses are not extremely sensitive to the convection heat transfer coefficient, as the housing surface temperatures are typically only ~10°C warmer than the bulk coolant temperature.

The heat generation rates vary as a function of axial position from the midplane of the reactor core. Peak heat generation rates (at the core midplane), parameters for determining the axial profile, and convection parameters are summarized in Table 4. Heat generation rates for aluminum, graphite, molybdenum and SiC were determined in the HFIR safety basis calculation C-HFIR-2012-035 [27]. The titanium heat generation rate was determined in calculation C-HFIR-2013-003 [28]. Other heat generation rates are calculated for this capsule configuration as described in Section 3.1. These heat generation rates include contributions from prompt neutrons, fission photons and secondary photons produced by the fission neutrons, fission product decay photons, and decay (primarily due to beta emission) of activation sources. Nuclear heating in the HFIR is dominated by photon absorption in the materials used in this experiment.

Table 4. Thermal boundary conditions for target holder irradiation experiments

Parameter	Value
Heat transfer coefficient	48.4 kW m^{-2} K^{-1}
Bulk coolant temperature	54°C
Peak heat generation rate for aluminum	32.1 W/g
Peak heat generation rate for grafoil	33.8W/g
Peak heat generation rate for titanium	35.6 W/g
Peak heat generation rate for molybdenum	42.9 W/g
Peak heat generation rate for SiC	34.9 W/g
Correlating parameter (σ)	30.07 cm

The local heat generation rate is estimated using the following profile:

$$q(\text{material}, z) = q_{\text{peak}}(\text{material}) \cdot \exp\left[-\left(\frac{z}{\sigma}\right)^2\right],$$

where:

q	=	local heat generation rate as a function of the material and axial location,
q_{peak}	=	heat generation rate at the HFIR midplane as a function of material,
z	=	axial location in the HFIR, where the midplane is at z = 0, and
σ	=	correlating parameter

4. THERMAL ANALYSIS RESULTS

4.1 TEMPERATURE CONTOURS

Figure 3 shows temperature contours predicted by the thermal analyses. The specimens' average temperatures are within the desired range of 300 ± 25°C. However, the temperature gradients within the specimens are quite large. For both Sm_2HfO_5 and Eu_2HfO_5 specimens, the temperature gradients are as high as 150°C. The large temperature gradients are due to the low thermal conductivity and the high heat generation rates of the specimens. For the other absorber materials, with higher thermal conductivity, the temperature gradients are much lower (closer to 70°C).

More details are provided in the complete ANSYS reports provided in APPENDIX A. A fill gas with 100% He was chosen for this design. The holder's 9.44 mm outer diameter, combined with a nominal housing inner diameter of 9.52 mm, results in a nominal cold (room temperature) holder-to-housing gas gap of 40 µm. Depending on the as-inspected value of the holder, a suitable housing will be selected so that the as-built holder-to-housing gas gap matches the desired 50 µm gap as close as possible.

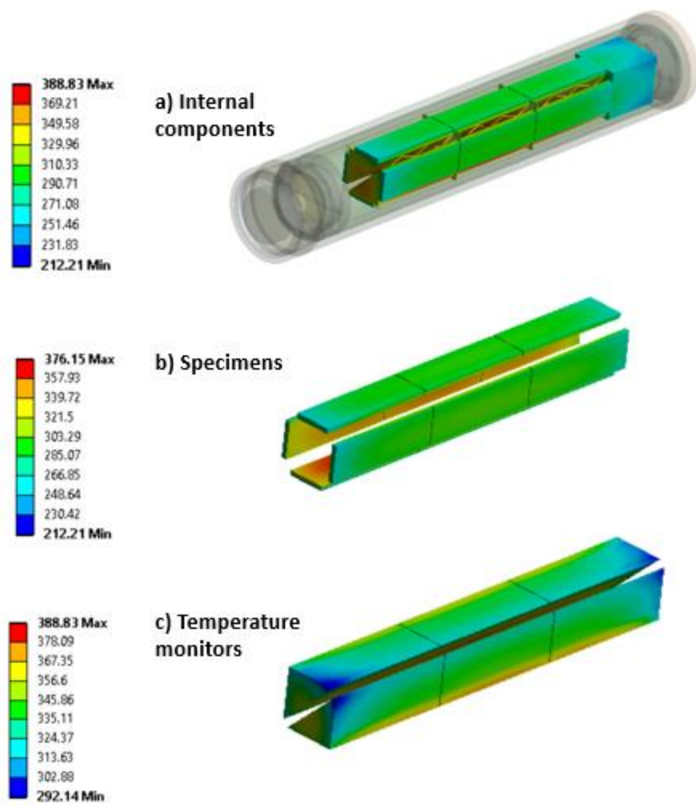

Figure 3. Predicted temperature contours (°C) showing (a) the internal components, (b) the specimens, and (c) SiC temperature monitors.

4.2 TEMPERATURE SUMMARY

Table 5 summarizes average, minimum, and maximum temperatures for all important components, in addition to other design parameters such as the irradiation position, fill gas, and gas gap.

Table 5. Summary of component temperatures, irradiation position, fill gas, and gas gap

Position	Fill gas	Gas gap	Part	Temperature (°C)		
				Average	Minimum	Maximum
PTP-5	He	40 µm	HfC specimen	306	258	329
			HfC + $MoSi_2$ specimen	302	256	323
			Sm_2HfO_5 specimen	314	222	376
			Eu_2HfO_5 specimen	296	212	355
			TM	358	292	389
			Holder	197	135	256
			Housing	65	57	71

5. SUMMARY AND CONCLUSIONS

This report summarizes the capsule design and thermal analyses that were performed for irradiation testing of absorber material plate specimens in the HFIR. Four different absorber materials will be inserted in the same capsule: HfC, HfC + $MoSi_2$, Sm_2HfO_5, and Eu_2HfO_5. The capsule design allows the loading of 12 specimens in a holder, which is centered inside the rabbit housing using centering thimbles. Neutronics calculations were performed to estimate the heat generation rates of the absorber materials. Thermal analyses of this design show that an average design temperature of 300 ± 25°C 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 performance under irradiation.

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APPENDIX A. THERMAL ANALYSIS REPORT

APPENDIX A. THERMAL ANALYSIS REPORT

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   TEMPERATURE DESIGN AND SAFETY BASIS SOLUTION FOR ABSORBER MATERIAL RABBITS

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* Temperature Design Solution for Normal Design Case

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 DESCRIPTION


 * Design dose = 12.00 dpa

 * Helium fill gas

 * Holder diameter =  9.44 mm (0.3717 in)

 * Thermal-only solution method

 * Hydraulic Tube (HT), 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)

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 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	32100.	5.2	5.1
3) Housing	AL-6061	32100.	117.7	117.1
5) Housing	AL-6061	32100.	14.6	14.6
7) EndCap	AL-6061	32100.	1.7	1.6
9) EndCap	AL-6061	32100.	4.1	4.0
11) EndCap	AL-6061	32100.	14.1	13.8
13) Holder	V-4Cr4Ti	46021.	497.4	495.4
15) Holder	V-4Cr4Ti	46021.	16.6	16.3
17) Disk_bottom	Moly	42900.	2.3	2.3
18) EuHafnate.1	HFO2	82360.	14.5	14.5
19) TMa.1	SiC(Irr)	34900.	13.6	13.6
20) TMb.1	SiC(Irr)	34900.	13.6	13.6
21) Springa.1	Ti-6Al4V	35600.	0.3	0.3
22) Spacer.1	SiC(Irr)	34900.	0.5	0.5
23) Disk_up	Moly	42900.	2.3	2.3
24) Spacer.2	SiC(Irr)	34900.	0.5	0.5
25) Spacer.3	SiC(Irr)	34900.	0.5	0.5
26) Wire_up	Moly	42900.	0.8	0.8
27) Wire_bottom	Moly	42900.	0.8	0.8
28) Insulator_bottom	GRAFOIL	33800.	0.2	0.2
29) SmHafnate.1	HFO2	115465.	19.9	19.9
30) HfC.1	HFO2	94965.	24.1	24.1
31) HfCMoSi2.1	HFO2	94965.	24.1	24.1
32) Spring_b.1	Ti-6Al4V	35600.	0.3	0.3
33) Insulator_top	GRAFOIL	33800.	0.2	0.2
34) Thimble_top	Ti-6Al4V	35600.	5.0	4.9
35) Thimble_bottom	Ti-6Al4V	35600.	5.0	5.0
36) Block	SiC(Irr)	34900.	26.4	26.4

37) EuHafnate.2	HFO2	82360.	14.5	14.5
38) SmHafnate.2	HFO2	115465.	19.9	19.9
39) HfC.2	HFO2	94965.	24.1	24.1
40) HfCMoSi2.2	HFO2	94965.	24.1	24.1
41) TMa.2	SiC(Irr)	34900.	13.6	13.6
42) TMb.2	SiC(Irr)	34900.	13.6	13.6
43) Spring_a.2	Ti-6Al4V	35600.	0.3	0.3
44) Spring_b.2	Ti-6Al4V	35600.	0.3	0.3
45) EuHafnate.3	HFO2	82360.	14.5	14.4
46) SmHafnate.3	HFO2	115465.	19.9	19.8
47) HfC.3	HFO2	94965.	24.1	24.0
48) HfCMoSi2.3	HFO2	94965.	24.1	24.0
49) TMa.3	SiC(Irr)	34900.	13.6	13.5
50) TMb.3	SiC(Irr)	34900.	13.6	13.5
51) Spring_a.3	Ti-6Al4V	35600.	0.3	0.3
52) Spring_b.3	Ti-6Al4V	35600.	0.3	0.3
			1047.5	1042.8

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	58.	58.	59.	58.	59.
3) Housing	AL-6061	65.	57.	71.	58.	69.
5) Housing	AL-6061	65.	61.	67.	62.	67.
7) EndCap	AL-6061	88.	87.	89.	88.	88.
9) EndCap	AL-6061	92.	91.	93.	92.	93.
11) EndCap	AL-6061	90.	88.	92.	88.	92.
13) Holder	V-4Cr4Ti	197.	135.	256.	146.	242.

15) Holder	V-4Cr4Ti	143.	136.	152.	139.	148.
17) Disk_bottom	Moly	262.	247.	276.	250.	275.
18) EuHafnate.1	HFO2	295.	221.	353.	277.	303.
19) TMa.1	SiC(Irr)	350.	296.	373.	319.	370.
20) TMb.1	SiC(Irr)	360.	297.	386.	322.	384.
21) Springa.1	Ti-6Al4V	371.	332.	386.	341.	385.
22) Spacer.1	SiC(Irr)	350.	294.	384.	310.	381.
23) Disk_up	Moly	185.	177.	191.	179.	190.
24) Spacer.2	SiC(Irr)	349.	293.	382.	309.	380.
25) Spacer.3	SiC(Irr)	324.	267.	361.	280.	357.
26) Wire_up	Moly	205.	185.	217.	186.	217.
27) Wire_bottom	Moly	210.	194.	222.	194.	222.
28) Insulator_bottom	GRAFOIL	76.	68.	94.	68.	87.
29) SmHafnate.1	HFO2	312.	229.	374.	290.	322.
30) HfC.1	HFO2	305.	266.	329.	285.	314.
31) HfCMoSi2.1	HFO2	301.	265.	322.	283.	310.
32) Spring_b.1	Ti-6Al4V	349.	318.	367.	326.	363.
33) Insulator_top	GRAFOIL	162.	159.	164.	160.	164.
34) Thimble_top	Ti-6Al4V	157.	133.	164.	151.	162.
35) Thimble_bottom	Ti-6Al4V	146.	103.	217.	115.	189.
36) Block	SiC(Irr)	289.	244.	338.	256.	327.
37) EuHafnate.2	HFO2	301.	237.	355.	295.	305.
38) SmHafnate.2	HFO2	319.	249.	376.	313.	324.
39) HfC.2	HFO2	312.	290.	329.	304.	316.
40) HfCMoSi2.2	HFO2	308.	287.	323.	301.	311.
41) TMa.2	SiC(Irr)	358.	321.	376.	332.	373.
42) TMb.2	SiC(Irr)	370.	324.	389.	336.	387.
43) Spring_a.2	Ti-6Al4V	382.	369.	388.	375.	388.
44) Spring_b.2	Ti-6Al4V	359.	345.	369.	350.	367.
45) EuHafnate.3	HFO2	293.	212.	351.	275.	302.
46) SmHafnate.3	HFO2	311.	222.	372.	291.	321.

47)	HfC.3	HFO2	302.	258.	328.	279.	313.
48)	HfCMoSi2.3	HFO2	298.	256.	321.	276.	309.
49)	TMa.3	SiC(Irr)	349.	292.	372.	317.	369.
50)	TMb.3	SiC(Irr)	360.	295.	384.	323.	382.
51)	Spring_a.3	Ti-6Al4V	375.	365.	384.	367.	383.
52)	Spring_b.3	Ti-6Al4V	352.	336.	365.	337.	363.

All Specimens	ABSMAT	305.	212.	376.	280.	322.
Thermometry	SiC	358.	292.	389.	324.	384.

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	166.453	0.00	0.050
3) Housing	AL-6061	167.301	24.21	0.050
5) Housing	AL-6061	167.266	0.00	0.050
7) EndCap	AL-6061	169.879	0.00	0.050
9) EndCap	AL-6061	170.336	0.00	0.050
11) EndCap	AL-6061	170.124	0.00	0.050
13) Holder	V-4Cr4Ti	31.927	9.62	0.350
15) Holder	V-4Cr4Ti	31.443	0.00	0.350
17) Disk_bottom	Moly	128.596	0.00	0.054
18) EuHafnate.1	HFO2	1.338	0.00	0.310
19) TMa.1	SiC(Irr)	6.857	3.41	0.900
20) TMb.1	SiC(Irr)	7.023	3.44	0.900
21) Springa.1	Ti-6Al4V	14.005	0.00	0.384

22) Spacer.1	SiC(Irr)	6.860	3.41	0.900
23) Disk_up	Moly	131.662	0.00	0.046
24) Spacer.2	SiC(Irr)	6.843	3.41	0.900
25) Spacer.3	SiC(Irr)	6.449	3.34	0.900
26) Wire_up	Moly	130.874	0.00	0.048
27) Wire_bottom	Moly	130.671	0.00	0.049
28) Insulator_bottom	GRAFOIL	38.000	1.00	0.500
29) SmHafnate.1	HFO2	1.404	0.00	0.310
30) HfC.1	HFO2	10.000	0.00	0.310
31) HfCMoSi2.1	HFO2	10.000	0.00	0.310
32) Spring_b.1	Ti-6Al4V	13.525	0.00	0.376
33) Insulator_top	GRAFOIL	38.000	1.00	0.500
34) Thimble_top	Ti-6Al4V	9.652	0.00	0.320
35) Thimble_bottom	Ti-6Al4V	9.458	0.00	0.320
36) Block	SiC(Irr)	5.953	3.23	0.900
37) EuHafnate.2	HFO2	1.338	0.00	0.310
38) SmHafnate.2	HFO2	1.404	0.00	0.310
39) HfC.2	HFO2	10.000	0.00	0.310
40) HfCMoSi2.2	HFO2	10.000	0.00	0.310
41) TMa.2	SiC(Irr)	6.984	3.43	0.900
42) TMb.2	SiC(Irr)	7.166	3.46	0.900
43) Spring_a.2	Ti-6Al4V	14.221	0.00	0.388
44) Spring_b.2	Ti-6Al4V	13.740	0.00	0.380
45) EuHafnate.3	HFO2	1.338	0.00	0.310
46) SmHafnate.3	HFO2	1.404	0.00	0.310
47) HfC.3	HFO2	10.000	0.00	0.310
48) HfCMoSi2.3	HFO2	10.000	0.00	0.310
49) TMa.3	SiC(Irr)	6.837	3.40	0.900
50) TMb.3	SiC(Irr)	7.014	3.44	0.900
51) Spring_a.3	Ti-6Al4V	14.087	0.00	0.386
52) Spring_b.3	Ti-6Al4V	13.585	0.00	0.377

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	0.163	58.	883.	6.
3) Housing	AL-6061	3.667	65.	889.	148.
5) Housing	AL-6061	0.456	65.	889.	18.
7) EndCap	AL-6061	0.052	88.	907.	3.
9) EndCap	AL-6061	0.128	92.	910.	8.
11) EndCap	AL-6061	0.439	90.	908.	28.
13) Holder	V-4Cr4Ti	10.808	197.	520.	992.
15) Holder	V-4Cr4Ti	0.360	143.	514.	23.
17) Disk_bottom	Moly	0.054	262.	265.	3.
18) EuHafnate.1	HFO2	0.176	295.	650.	32.
19) TMa.1	SiC(Irr)	0.390	350.	1046.	135.
20) TMb.1	SiC(Irr)	0.390	360.	1052.	140.
21) Springa.1	Ti-6Al4V	0.007	371.	717.	2.
22) Spacer.1	SiC(Irr)	0.014	350.	1046.	5.
23) Disk_up	Moly	0.054	185.	262.	2.
24) Spacer.2	SiC(Irr)	0.014	349.	1045.	5.
25) Spacer.3	SiC(Irr)	0.014	324.	1032.	4.
26) Wire_up	Moly	0.019	205.	262.	1.
27) Wire_bottom	Moly	0.019	210.	263.	1.
28) Insulator_bottom	GRAFOIL	0.007	76.	700.	0.
29) SmHafnate.1	HFO2	0.173	312.	650.	33.
30) HfC.1	HFO2	0.254	305.	650.	47.
31) HfCMoSi2.1	HFO2	0.254	301.	650.	46.

32)	Spring_b.1	Ti-6Al4V	0.007	349.	708.	2.
33)	Insulator_top	GRAFOIL	0.007	162.	700.	1.
34)	Thimble_top	Ti-6Al4V	0.140	157.	633.	12.
35)	Thimble_bottom	Ti-6Al4V	0.140	146.	629.	11.
36)	Block	SiC(Irr)	0.756	289.	1011.	206.
37)	EuHafnate.2	HFO2	0.176	301.	650.	32.
38)	SmHafnate.2	HFO2	0.173	319.	650.	34.
39)	HfC.2	HFO2	0.254	312.	650.	48.
40)	HfCMoSi2.2	HFO2	0.254	308.	650.	48.
41)	TMa.2	SiC(Irr)	0.390	358.	1050.	138.
42)	TMb.2	SiC(Irr)	0.390	370.	1057.	144.
43)	Spring_a.2	Ti-6Al4V	0.007	382.	721.	2.
44)	Spring_b.2	Ti-6Al4V	0.007	359.	712.	2.
45)	EuHafnate.3	HFO2	0.176	293.	650.	31.
46)	SmHafnate.3	HFO2	0.173	311.	650.	33.
47)	HfC.3	HFO2	0.254	302.	650.	47.
48)	HfCMoSi2.3	HFO2	0.254	298.	650.	46.
49)	TMa.3	SiC(Irr)	0.390	349.	1045.	134.
50)	TMb.3	SiC(Irr)	0.390	360.	1051.	139.
51)	Spring_a.3	Ti-6Al4V	0.007	375.	719.	2.
52)	Spring_b.3	Ti-6Al4V	0.007	352.	709.	2.
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			22.270			2795.

CONTACT SUMMARY FOR CONTACT ID 95: Multiple To Housing {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)	182.025	136.206	216.828
Target temperature (°C)	66.887	59.851	70.495
Geometric gas gap (μm)	39.497	39.169	39.757
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m²)	536.081	316.576	717.568
Radiation heat flux (kW/m²)	0.081	0.040	0.119
Contact conduction heat flux (kW/m²)	0.000	0.000	0.000
Total heat flux (kW/m²)	536.161	316.616	717.686
Thermal contact conductance (W/m²·C)	4622.704	4267.443	4903.506
~~ derived results ~~~~~~~~~~			
Effective gas gap (μm)	37.498	36.291	39.099
Contact thermal jump distance (μm)	1.417	1.233	1.560
Target thermal jump distance (μm)	1.169	1.071	1.242
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	18.266	18.248	18.289
Gas thermal conductivity (W/m·°C)	0.185	0.176	0.192
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	4623.958	4268.854	4901.654

Contact status codes:

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

2=closed and sliding, 3=closed and sticking