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Design and Thermal Analysis for Irradiation of Silicon Carbide Joint Specimens in the High Flux Isotope Reactor

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August 31, 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

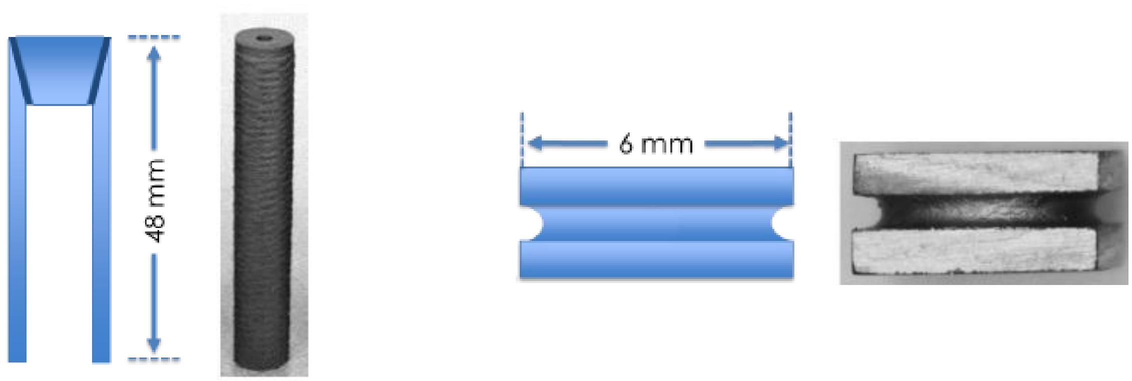
This report provides a summary of the irradiation vehicle design and thermal analysis of SiC joint specimens planned for irradiation in the flux trap of the High Flux Isotope Reactor (HFIR). Two different capsule designs will be used to accommodate the two different specimen geometries: a small torsion joint specimen geometry to measure mechanical and thermal properties, and joint end plug representative cladding geometry to demonstrate strength and integrity. The capsule designs, with target temperatures of 350°C ± 50°C and 750°C ± 50°C, will accommodate either sixteen torsion joint specimens or one joint end plug specimen. Three joint variations will be studied in each capsule design: a hybrid SiC (preceramic polymer with chemical vapor deposition (CVD) SiC), a transient eutectic phase (TEP) process, and an oxide process.

1. INTRODUCTION

Silicon Carbide (SiC) fiber reinforced, SiC matrix composites (SiC-SiC) are of interest for fuel cladding and structural components in current and advanced nuclear reactor designs [1], as they offer strength retention at high temperatures, high temperature steam oxidation resistance, and stability under irradiation. To enable the use of these materials in current and advanced reactor designs, comparable performance of their joining methods with respect to the parent material under high temperatures and irradiation conditions must be demonstrated. Oak Ridge National Laboratory (ORNL) has worked on several joining technologies and the SiC-based joints have shown reliable mechanical performance after irradiation [2].

However, thermo-mechanical simulations have predicted that application-specific geometries (i.e., end plugs that seal the ends of cladding tubes) can show higher stresses than those in simplified joint test specimen designs. In addition, in an environment with high neutron radiation damage and high temperature, the thermal conductivity of SiC rapidly degrades, resulting in large temperature gradients. These temperature gradients can drive significant stresses in SiC components during irradiation due to the highly temperature-dependent irradiation-induced swelling [3]. In addition, many joint formulations may also contain sintering aides or other phases which are compositionally different from either the cladding tube or end plug; this can cause additional stresses as the non-SiC phases can undergo dissimilar irradiation swelling. Ultimately, the irradiation swelling-induced stresses in SiC-based cladding-end plug joints can contribute to failure of the joint.

The purpose of this project is to perform experimental irradiation testing of representative joint specimens to understand the effects of irradiation with realistic temperature gradients. The experimental results will provide joint-specific properties that will help validate thermomechanical models of the joint performance. Three joint variations will be investigated in this work: transient eutectic phase (TEP) SiC-based joints, oxide joints, and high purity SiC-based hybrid (preceramic polymer with chemical vapor deposition (CVD) SiC) joints. Representative sealed tube specimens will be fabricated using SiC-SiC composite tubes with prototypical cladding architectures. One end of each tube will be sealed with a CVD SiC end plug while the other end will remain open. These one-end sealed tubes are referred as the joint end plug specimens. The total length of the specimens will be around 48 mm, which allows for end plug push-out testing during post-irradiation examination. Torsion specimens will be fabricated as well, using two square plates of monolithic CVD SiC, joined together using the different joint processes. The geometry of these specimens is comparable to other torsion specimens previously irradiated in the High Flux Isotope Reactor (HFIR). Figure 1 shows schematics and pictures of the two specimen geometries.



(a) (b)

Figure 1. Specimen schematic and picture for (a) the joint end plug specimen, and (b) the square torsion specimen

The joint end plug and torsion specimens will be inserted into the HFIR using irradiation capsules, or rabbits, designed around accumulated dose and temperatures so that the irradiation performance of the joining processes can be evaluated post-irradiation. The influence of irradiation will be investigated through a comparative study of as-fabricated and irradiated specimens. This report summarizes the HFIR irradiation experiments that are being performed to assess joint-specific performance under irradiation, including the irradiation capsule design concepts and thermal analyses.

2. EXPERIMENTAL METHODS

2.1 HFIR IRRADIATION EXPERIMENTS

The irradiation experiments 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 [4]. The core consists of aluminum-clad involute-fuel plates which currently use highly enriched ^{235}U fuel at a power level of 85 MW. A typical HFIR cycle is 25 days. 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.

The goal of this work is to design experiments to contain the SiC-based joint 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 [5-10]. 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 [11]. 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 internal components (in this case the torsion joint holder or the joint end plug specimen) 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

2.2.1 Joint end plug specimens

The overall design of the irradiation experiments developed in this work is shown in the section view of Figure 2. The outer containment for the irradiation experiment is the rabbit capsule housing, which is directly cooled on the outer surface by the HFIR's primary coolant. One joint end plug specimen is placed in each capsule, with a cylindrical passive SiC TM inside of the tube specimen. The nominal dimensions of the tube specimen are 8.5 mm outer diameter × 6.3 mm inner diameter with a length of 48 mm and an end plug thickness of 4.5 mm. Temperature is controlled by varying the concentration of a He/Ar gas mixture and the size of the gas gap between the tube specimen and the housing. Varying the gas mixture changes the effective thermal conductivity of the gas gap. Centering thimbles are inserted in the ends of the joint end plug specimen to keep it centered inside the housing and to maintain a constant gas gap between the specimen and the housing. A compression spring inserted at the top of the capsule keeps the specimen pressed on the bottom of the capsule and ensures that the thimbles cannot dislodge from the specimen.

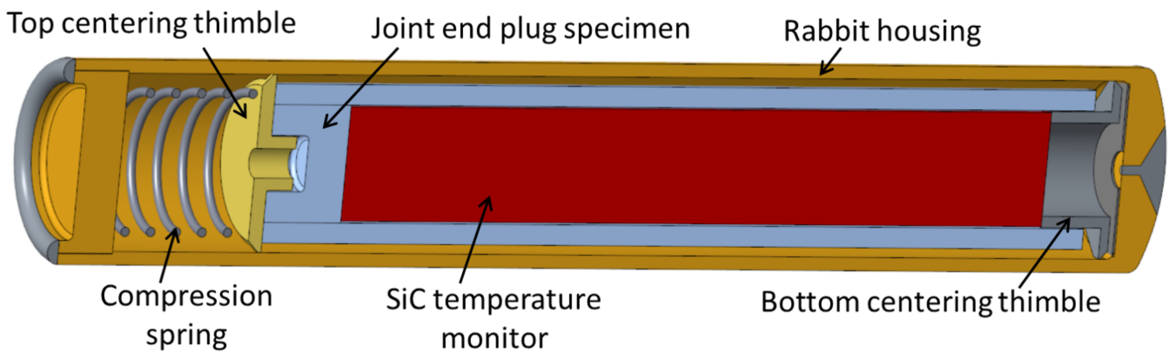


Figure 2. Section view showing irradiation capsule design concept.

2.2.2 Torsion joint specimens

Figure 3 shows the concept for the torsion rabbit design. Two rows of eight torsion joint specimens stacked in the vertical direction are set inside a vanadium or niobium alloy holder. A grafoil center spacer presses the two rows of specimens against the inner walls of the holder. Two SiC passive TMs are pressed against the specimens inside of small slots in the holder using SiC retainer springs. Grafoil insulator disks are placed at the top and bottom of the specimen stack and the housing assembly to reduce axial heat losses. Centering thimbles are placed on either end of the holder to keep the holder centered within the capsule housing.

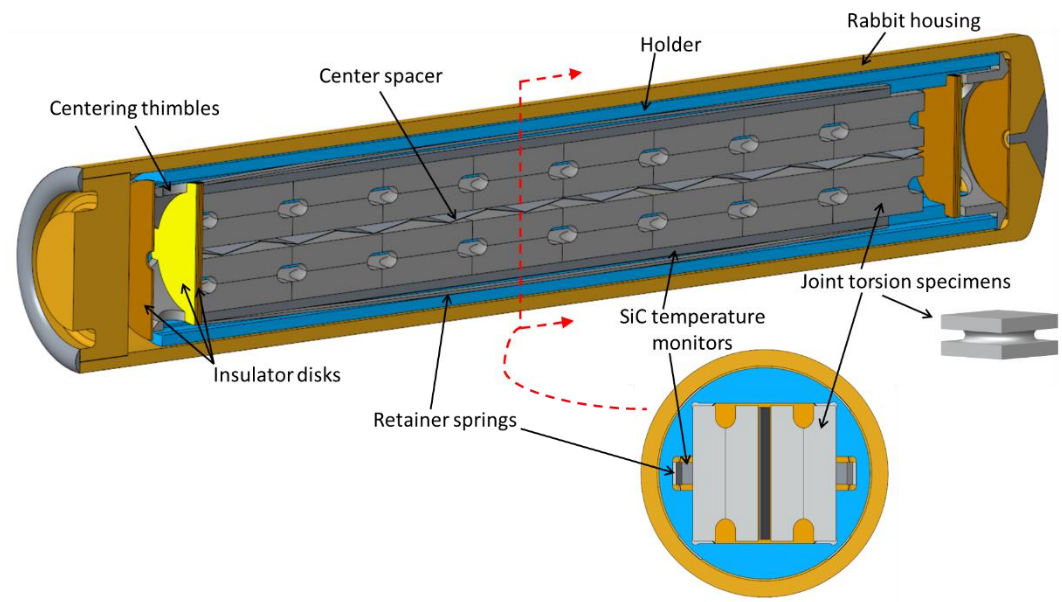


Figure 3. Capsule design concept for irradiating SiC-based joint torsion specimens.

2.3 TEST MATRIX

Table 1 summarizes the different specimens that will be included in the irradiation test matrix. Three joint variations will be studied: a hybrid SiC (preceramic polymer with CVD SiC), a TEP process, and an oxide process. All three variations will be irradiated in both torsion joint and joint end plug geometries. All irradiations will be performed with a dose of approximately 2 dpa (approximately one cycle in HFIR) and a nominal design temperature of 350 ± 50°C or 750 ± 50°C. Each joint variation and each specimen geometry will be irradiated at both temperatures. A total of 14 capsules will be irradiated: 12 capsules containing one joint end plug specimen per capsule, and two capsules containing sixteen torsion specimens per capsule.

Table 1. Irradiation test matrix.

Capsule number	Specimen geometry	Joint variation	Irradiation dose	Irradiation temperature
Capsules #1-6	Joint end plug	Hybrid	2 dpa	350 °C ± 50°C
		TEP		
		Oxide		
Capsule #7	Torsion joint	Hybrid		
		TEP		
		Oxide		
Capsules #8-13	Joint end plug	Hybrid		750 °C ± 50°C
		TEP		
		Oxide		
Capsule #14	Torsion joint	Hybrid		
		TEP		
		Oxide		

3. COMPUTATIONAL METHODS

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 joint end plug capsules. These analyses use material-dependent heat generation rates (heat per unit mass) determined in previous neutronics analyses. The contact conductance of components in contact or separated by small gas gaps are calculated with user-defined macros [13]. In this way, gas gaps are not directly meshed, which significantly reduces computational time. Computer aided design (CAD) models are imported into ANSYS and meshed using 20-node hexagonal and tetrahedral elements with a nominal mesh size of 0.4 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. Gaps for this design are on the order of 100 µm, and the total internal length of the capsule is less than 60 mm. The solver accounts for thermal expansion, though does not explicitly modify the model geometry, using 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. Some properties for SiC also include radiation dose-dependence. Properties are primarily obtained from CINDAS [14], MatWeb [15], and various literature sources. The monolithic SiC components were assumed to be of theoretical density, with properties obtained from reference [16]. The SiC/SiC composite generally used the same thermal properties except that the density was assumed to be 2.9 g/cm^3 and the thermal conductivity ranged from 3.5 W/m-K at 350°C to 5.8 W/m-K at 750°C based on the available literature data [17]. Properties of gas mixtures are calculated using the methods described by Wahid et al. [18]. Material properties for this calculation are included in the DACs, as shown in Table 2 and are available upon request.

Table 2. Experiment materials and material property references

Part	Material	Reference
Housing, end cap	Aluminum	DAC-10-03-PROP_AL6061 [19]
Centering thimbles	Titanium	DAC-11-14-PROP_TI6AL4V [20]
Insulators	Grafoil	DAC-11-16-PROP_GRAFOIL [21]
Joint end plug specimens and TMs	SiC	DAC-10-06-PROP_SIC(IRR) [22]
Fill gas	Argon	DAC-10-09-PROP_ARGON [23]
Fill gas	Helium	DAC-10-02-PROP_HELIUM [24]

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 [25]. 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 target rod rabbit holders 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 3. All heat generation rates were determined in the HFIR safety basis calculation C-HFIR-2012-035 [26], except for the titanium heat generation rate, which was determined in calculation C-HFIR-2013-003 [27]. 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 3. Thermal boundary conditions for target holder irradiation experiments

Parameter	Value
Heat transfer coefficient	47.1 kW m^{-2} K^{-1}
Bulk coolant temperature	52°C
Peak heat generation rate for aluminum	31.3 W/g
Peak heat generation rate for grafoil	32.5 W/g
Peak heat generation rate for titanium	35.2 W/g
Peak heat generation rate for SiC	31.7 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

4.1.1 Joint end plug specimens

Figure 4 and Figure 5 show temperature contours predicted by the thermal analyses for the joint end plug 350°C and 750°C designs, respectively. The reductions in temperature at the bottom of the specimen are due to axial heat losses through the tabs of the centering thimbles. The specimen temperatures remain close to the desired range of 350 ± 50°C or 750 ± 50°C. It should be noted that for the 350°C case, specimen temperatures cannot be reduced any further without modifying the specimen or capsule geometry. This is because the capsules are located as far away from the core midplane as possible (to reduce heat generation rates), and the fill gas (helium) is the most conductive inert gas that is allowable in HFIR capsules. For both capsules, there are somewhat significant temperature gradients (as high as 120°C) within the specimen. However, for a large portion of the specimen (above the lower section where axial heat conduction is significant), the temperature gradients are much lower (closer to 60°C or less). Within the joint region, the temperatures are within, or at least very close to, the desired temperature ranges.

More details are provided in the complete ANSYS reports provided in APPENDIX A. A fill gas with 100% He and a 46% He, Ar balance was chosen for the 350°C design and the 750°C design, respectively. The specimen's 8.50 mm outer diameter, combined with a nominal housing inner diameter of 9.52 mm, results in a nominal cold (room temperature) specimen-to-housing gas gap of 510 µm. Depending on the as-inspected value of the specimen, a suitable housing will be selected so that the as-built specimen-to-housing gas gap matches the desired 510 µm gap as close as possible.

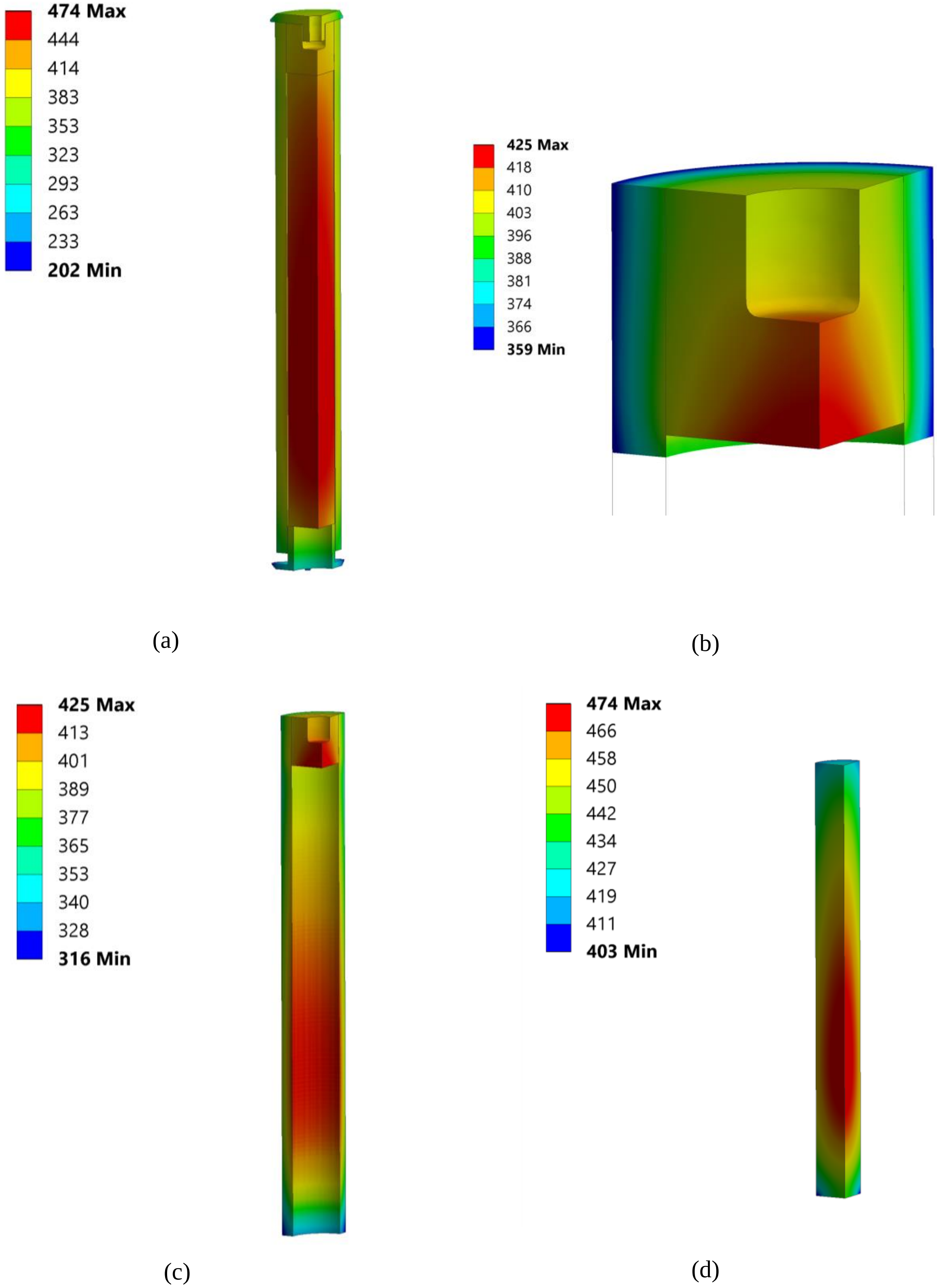


Figure 4. Predicted temperature contours (°C) for the 350°C design, showing (a) the internal components, (b) the joint region, (c) the specimen, and (d) the SiC temperature monitors.

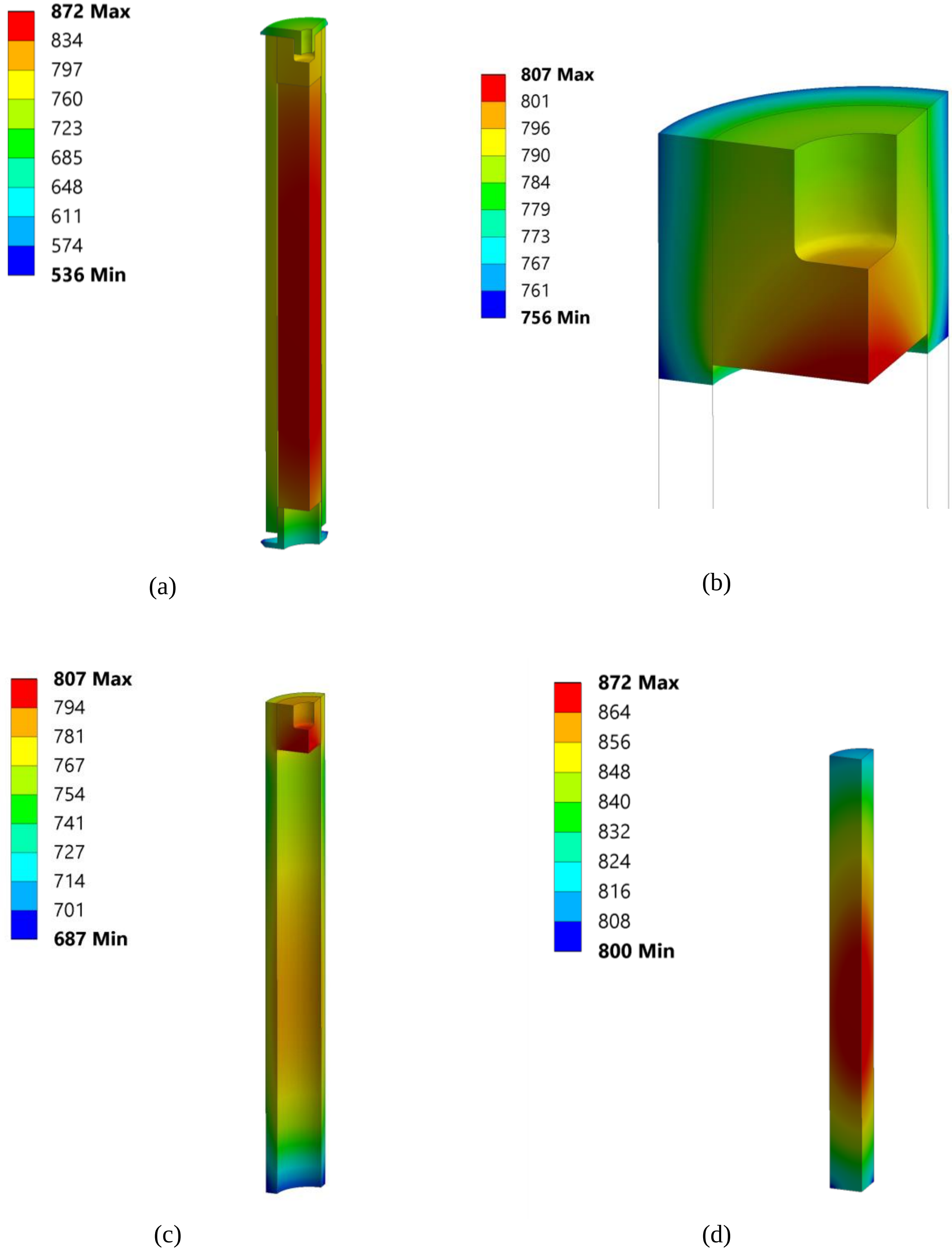
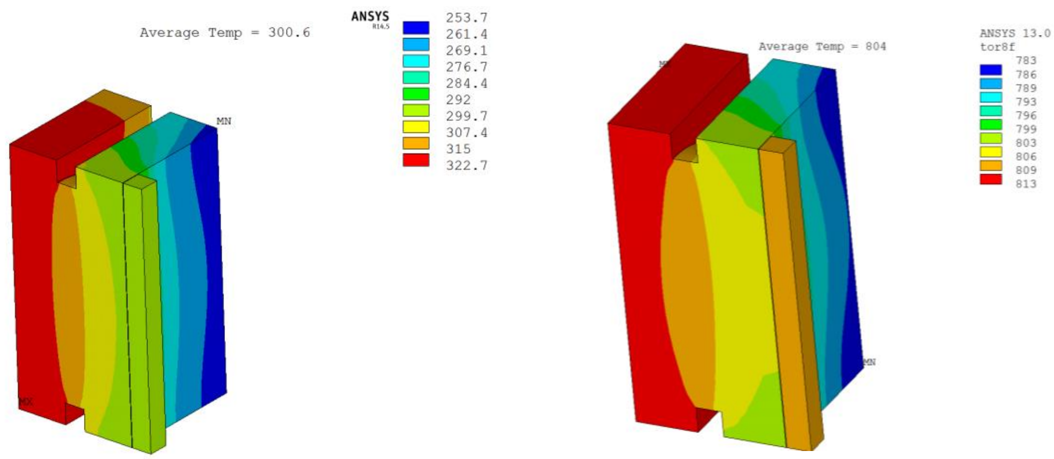


Figure 5. Predicted temperature contours (°C) for the 750°C design, showing (a) the internal components, (b) the joint region, (c) the specimen, and (d) the SiC temperature monitors.

4.1.2 Torsion joint specimens

The torsion joint specimen designs were based on, and nearly identical to, previous irradiation experiments [12]. Finite element modeling of the previous designs predicted 300°C and 800°C average specimen temperatures, respectively. These predicted temperatures are within the desired temperature ranges of 350°C ± 50°C and 750°C ± 50°C. The thermal performance will be validated by the SiC TMs, post-irradiation. Figure 6 shows temperature contour plots for torsion joint specimens from the previously designed capsules. Both the 300°C and the 800°C capsules will be irradiated in target rod rabbit holders within the flux trap in axial position 7 (the top position within the target holder). The 300°C design utilizes a vanadium alloy holder with a holder-to-housing radial gas gap of 131 µm and a helium fill gas. The 800°C design utilizes a niobium alloy holder with a holder-to-housing radial gas gap of 83 µm and an argon fill gas.



(a) **(b)**

Figure 6. Temperature contour plots (°C) for cross section of a torsion specimen and SiC TM in the 300°C capsule design (a) and the 800°C capsule design (b).

4.2 TEMPERATURE SUMMARY

Table 4 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 4. Summary of component temperatures, irradiation position, fill gas, and gas gap

Position	Fill gas	Gas gap	Part	Temperature (°C)		
				Average	Minimum	Maximum
TH-7	He	510 µm	Specimen plug	407	395	425
			Specimen tube	385	316	420
			TM	452	403	474
			Housing	56	53	62
TH-7	46% He, Ar balance	510 µm	Specimen plug	792	783	807
			Specimen tube	761	687	791
			TM	852	800	872
			Housing	56	53	63
TH-7	He	131 µm	Torsion specimen	301	254	323
			TM	295	293	297
			Housing	60	60	61
TH-7	Ar	83 µm	Torsion specimen	804	783	813
			TM	807	807	807
			Housing	61	61	62

5. SUMMARY AND CONCLUSIONS

This report summarizes the capsule designs and thermal analyses that were performed for irradiation testing of SiC-based joint specimens in the HFIR. Two specimen geometries are being considered to study the performance of three joint variations (hybrid, TEP, and oxide): a small torsion joint specimen geometry to measure mechanical and thermal properties, and a joint end plug specimen geometry to demonstrate strength and integrity in a representative cladding geometry. Ultimately, the data gathered from these experiments will assist in the development of accurate models and codes for fuel cladding performance, which are needed to evaluate the use of SiC-based materials for cladding and structural components in nuclear reactor designs. A new rabbit capsule design allows for one joint end plug specimen to be loaded and centered inside the rabbit housing using titanium centering thimbles. Temperature is controlled by varying the backfill gas (He or He/Ar mixture). The rabbit capsule designs for torsion specimens use existing designs, which allow the loading of 16 specimens per capsule. Thermal analyses show that design temperatures of 350 ± 50°C and 750 ± 50°C can be achieved for joint end plug specimens as well as for torsion specimens.

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APPENDIX A. THERMAL ANALYSIS REPORTS

APPENDIX A. THERMAL ANALYSIS REPORTS

****
OUTPUT SUMMARY FILE
****

INPUTS

* Thermal only solution with calculated gaps
* Symmetry angle: 90.00 degrees
* Radiative heat transfer excluded
* 3D problem geometry
* Target temperature: 350.0 deg C
* Target dose (in SiC):   2.800 dpa
* Capsule pressure: 215.45 kPa
* Cladding: OD = 8.5000 mm, ID = 6.3000 mm, density = 0.0000 g/cc
* Housing: ID = 9.5200 mm
* Backfill gas: 100.00% He,   0.00% Ar
* Irradiation facility: TRRH
* Axial position: 7
* Capsule centerline position = 19.16 cm (7.54 in)
* Axial peaking factor above the core midplane: 30.070 cm
* Axial peaking factor below the core midplane: 30.070 cm

BOUNDARY CONDITIONS

Heat generation rate scaling factor = 1.0000
Heat transfer coefficient = 47100. W/m2-K
Bulk coolant temperature =   52.0 deg C

HEAT GENERATION

Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	31300.	134.1	90.5
2) Cap	AL-6061	31300.	16.5	9.6
3) Grafoil	GRAFOIL	32500.	0.3	0.2
4) TM	SiC(Irr)	31700.	121.9	83.1
5) Thimble.1	Ti-6Al4V	35200.	8.5	6.3
6) Thimble.2	Ti-6Al4V	35200.	8.4	5.1
7) Plug	SiC(Irr)	31700.	12.7	7.8
9) Tube	SiC_COMP	31700.	112.8	76.6
			415.2	279.2

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	56.	53.	62.	53.	62.
2) Cap	AL-6061	70.	68.	71.	69.	71.
3) Grafoil	GRAFOIL	69.	64.	87.	64.	73.
4) TM	SiC(Irr)	452.	403.	474.	423.	471.
5) Thimble.1	Ti-6Al4V	329.	202.	393.	253.	387.
6) Thimble.2	Ti-6Al4V	374.	265.	404.	346.	403.
7) Plug	SiC(Irr)	407.	395.	425.	397.	421.
9) Tube	SiC_COMP	385.	316.	420.	341.	413.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Thermal Cond.	Thermal Exp. Coeff.	Emis

Name	Material	(W/m·°C)	(µm/m·°C)	(---)
1) Housing	AL-6061	166.128	24.21	0.050
2) Cap	AL-6061	167.838	0.00	0.050
3) Grafoil	GRAFOIL	38.000	1.00	0.500
4) TM	SiC(Irr)	10.075	3.66	0.900
5) Thimble.1	Ti-6Al4V	13.094	9.92	0.368
6) Thimble.2	Ti-6Al4V	14.060	10.00	0.385
7) Plug	SiC(Irr)	9.433	3.56	0.900
9) Tube	SiC_COMP	3.512	3.51	0.900

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	4.285	56.	881.	134.
2) Cap	AL-6061	0.527	70.	892.	23.
3) Grafoil	GRAFOIL	0.008	69.	700.	0.
4) TM	SiC(Irr)	3.846	452.	1096.	1821.
5) Thimble.1	Ti-6Al4V	0.240	329.	700.	52.
6) Thimble.2	Ti-6Al4V	0.239	374.	718.	61.
7) Plug	SiC(Irr)	0.401	407.	1076.	167.
9) Tube	SiC_COMP	3.560	385.	1065.	1385.
		13.106			3643.

GAP REPORTS

Cladding to housing gap

CONTACT SUMMARY FOR CONTACT ID 10: Tube To Housing (Frictionless)

Contact surface material: SiC_COMP
Target surface material: AL-6061
Interstitial gas: 1000HE_0
Effective surface roughness: 2.263 µm
Effective asperity slope: 0.214 rad
Effective microhardness: 1.220 GPa

	Average	Minimum	Maximum
~~ direct results ~~~~~~~~~~			
Contact status	1.000	1.000	1.000
Contact temperature (°C)	367.311	317.566	381.406
Target temperature (°C)	55.513	54.963	55.848
Geometric gas gap (µm)	509.883	509.748	509.943
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m^2)	130.226	105.165	137.478
Radiation heat flux (kW/m^2)	0.000	0.000	0.000
Contact conduction heat flux (kW/m^2)	0.000	0.000	0.000
Total heat flux (kW/m^2)	130.226	105.165	137.478
Thermal contact conductance (W/m^2·C)	417.484	401.598	422.064
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	508.433	508.125	509.413
Contact thermal jump distance (µm)	1.858	1.681	1.910
Target thermal jump distance (µm)	1.370	1.285	1.395
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	22.827	22.771	22.842
Gas thermal conductivity (W/m·°C)	0.214	0.206	0.216
Solid spot conductance (W/m^2·C)	0.000	0.000	0.000
Gas gap conductance (W/m^2·C)	417.395	401.489	421.971

Contact status codes:

0=open/no heat transfer, 1=near-field contact
2=closed and sliding, 3=closed and sticking

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******************************************************************************
                             OUTPUT SUMMARY FILE
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 INPUTS

* Thermal only solution with calculated gaps
* Symmetry angle:  90.00 degrees
* Radiative heat transfer excluded
* 3D  problem geometry
* Target temperature:  750.0 deg C
* Target dose (in SiC):   2.800 dpa
* Capsule pressure:  353.77 kPa
* Cladding: OD =  8.5000 mm, ID =  6.3000 mm, density =  0.0000 g/cc
* Housing: ID =  9.5200 mm
* Backfill gas:   46.00% He,   54.00% Ar
* Irradiation facility: TRRH
* Axial position: 7
* Capsule centerline position =  19.16 cm (  7.54 in)
* Axial peaking factor above the core midplane: 30.070 cm
* Axial peaking factor below the core midplane: 30.070 cm

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 BOUNDARY CONDITIONS

 Heat generation rate scaling factor = 1.0000
 Heat transfer coefficient =  47100. W/m2-K
 Bulk coolant temperature  =    52.0 deg C

-------------------------------------------------------------------------------
 HEAT GENERATION

                                          Heat Gen.   ------ Heat Load -----
                                          @Midplane   @Midplane    @Location
  Part                           Material  (W/kg)        (W)          (W)
----------------------------------- --------  ---------   ---------    ---------
  1) Housing                      AL-6061     31300.      134.1         90.5
  2) Cap                          AL-6061     31300.       16.5          9.6
  3) Grafoil                      GRAFOIL     32500.        0.3          0.2
  4) TM                           SiC(Irr)    31700.      121.9         83.1
  5) Thimble.1                    Ti-6Al4V    35200.        8.5          6.3
  6) Thimble.2                    Ti-6Al4V    35200.        8.4          5.1
  7) Plug                         SiC(Irr)    31700.       12.7          7.8
  9) Tube                         SiC_COMP    31700.      112.8         76.6
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                                                          415.2        279.2

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 CAPSULE TEMPERATURE SUMMARY

Name                                 Material   Tavg   Tmin   Tmax  T.025  T.975
------------------------------------ --------  -----  -----  -----  -----  -----
  1) Housing                         AL-6061     56.    53.    63.    53.    63.
  2) Cap                             AL-6061     95.    93.    96.    94.    96.
  3) Grafoil                         GRAFOIL     84.    71.   116.    72.    93.
  4) TM                              SiC(Irr)   852.   800.   872.   818.   870.
  5) Thimble.1                       Ti-6Al4V   687.   536.   761.   603.   754.
  6) Thimble.2                       Ti-6Al4V   723.   604.   758.   694.   757.
  7) Plug                            SiC(Irr)   792.   783.   807.   784.   803.
  9) Tube                            SiC_COMP   761.   687.   791.   703.   784.

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 PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

                                                         Thermal
                                              Thermal     Exp.
                                               Cond.     Coeff.    Emis
Name                                 Material (W/m·°C) (µm/m·°C)  (---)
--------------------------------     -------- --------- --------- ---------
  1) Housing                         AL-6061    166.136     24.21     0.050
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2) Cap	AL-6061	170.621	0.00	0.050
3) Grafoil	GRAFOIL	38.000	1.00	0.500
4) TM	SiC(Irr)	22.290	4.25	0.900
5) Thimble.1	Ti-6Al4V	19.633	10.68	0.529
6) Thimble.2	Ti-6Al4V	19.664	10.77	0.531
7) Plug	SiC(Irr)	20.650	4.19	0.900
9) Tube	SiC_COMP	5.767	4.16	0.900

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	4.285	56.	881.	135.
2) Cap	AL-6061	0.527	95.	912.	36.
3) Grafoil	GRAFOIL	0.008	84.	700.	0.
4) TM	SiC(Irr)	3.846	852.	1224.	3915.
5) Thimble.1	Ti-6Al4V	0.240	687.	928.	149.
6) Thimble.2	Ti-6Al4V	0.239	723.	972.	163.
7) Plug	SiC(Irr)	0.401	792.	1209.	374.
9) Tube	SiC_COMP	3.560	761.	1201.	3168.
		13.106			7939.

GAP REPORTS

Cladding to housing gap

CONTACT SUMMARY FOR CONTACT ID 10: Tube To Housing (Frictionless)

Contact surface material: SiC_COMP
Target surface material: AL-6061
Interstitial gas: 460HE_54
Effective surface roughness: 2.263 µm
Effective asperity slope: 0.214 rad
Effective microhardness: 1.220 GPa

	Average	Minimum	Maximum
~~ direct results ~~~~~~~~~~			
Contact status	1.000	1.000	1.000
Contact temperature (°C)	750.444	688.029	765.277
Target temperature (°C)	55.468	54.994	56.570
Geometric gas gap (µm)	509.883	509.748	509.943
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m²)	127.902	112.393	131.644
Radiation heat flux (kW/m²)	0.000	0.000	0.000
Contact conduction heat flux (kW/m²)	0.000	0.000	0.000
Total heat flux (kW/m²)	127.902	112.393	131.644
Thermal contact conductance (W/m²·C)	183.996	177.819	185.484
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	500.657	500.233	502.078
Contact thermal jump distance (µm)	0.522	0.487	0.530
Target thermal jump distance (µm)	0.372	0.352	0.376
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	23.028	22.998	23.035
Gas thermal conductivity (W/m·°C)	0.092	0.089	0.093
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	183.924	177.775	185.414

Contact status codes:

0=open/no heat transfer, 1=near-field contact
2=closed and sliding, 3=closed and sticking