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Design and Thermal Analysis for Irradiation of Pyrolytic Carbon / Silicon Carbide Diffusion Couples in the High Flux Isotope Reactor

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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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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

Tristructural-isotropic (TRISO)–coated particle fuel is a promising advanced fuel concept being considered for several advanced reactor applications and for accident-tolerant fuel for light water reactors. Accurate models and codes for TRISO fuel performance must be developed to ensure safe, efficient operation using this fuel form. One of the unresolved safety and maintenance concerns for TRISO fuel is the release of specific fission products (Ag, Eu, and Sr). The silicon carbide (SiC) layer of TRISO fuel serves as the primary barrier to metallic fission products and actinides not retained in the fuel kernel. Recent experimental evidence suggests that diffusion of these fission products may be accelerated by irradiation. The objective of this effort is to improve the understanding of Ag, Ag-Pd, Eu, and Sr diffusion in the SiC layers of TRISO fuel particles by performing reactor irradiations and out-of-pile thermal experiments to separate the effects of irradiation and temperature. Small diffusion couple specimens with slab geometry and representative pyrolytic carbon (PyC) and SiC layers will be fabricated using processes and equipment similar to those used to make TRISO particles. The PyC layer of these particles will be implanted with the desired fission products using ion accelerators, thus allowing for characterization of the diffusion profiles before and after heating and/or irradiation. This report summarizes the design and thermal analysis for the irradiation experiments, which will be performed in the flux trap of the High Flux Isotope Reactor (HFIR). Up to 40 specimens can be loaded into each rabbit capsule and irradiated in a hydraulic tube facility in the HFIR. Thermal analyses show that a specimen design temperature of 1,100°C ± 50°C can be achieved by placing the specimens inside a holder fabricated from a Nb alloy and backfilling the rabbit capsule with a custom He/Ar gas mixture.

1. INTRODUCTION

Tristructural-isotropic (TRISO)–coated particle fuel is a promising advanced fuel concept consisting of a spherical fuel kernel made of uranium oxide and uranium carbide, surrounded by a porous carbonaceous buffer layer and successive layers of dense inner pyrolytic carbon (IPyC), silicon carbide (SiC) deposited by chemical vapor , and dense outer pyrolytic carbon (OPyC). This fuel concept is being considered for advanced reactor applications such as high temperature gas-cooled reactors (HTGRs) and molten salt reactors (MSRs), as well as for accident-tolerant fuel for light water reactors (LWRs). Development and implementation of TRISO fuel for these reactor concepts support the US Department of Energy (DOE) Office of Nuclear Energy mission to promote safe, reliable nuclear energy that is sustainable and environmentally friendly. During operation, the SiC layer serves as the primary barrier to metallic fission products and actinides not retained in the kernel. It has been observed that certain fission products are released from TRISO fuel during operation, notably, Ag, Eu, and Sr [1]. Release of these radioisotopes causes safety and maintenance concerns.

Accurate models and codes for TRISO fuel performance must be developed to ensure safe, efficient operation using this fuel form. These models require a thorough understanding of fission product diffusion kinetics in the various coating layers. Most diffusion kinetics parameters that are currently available originate from fractional release measurements from irradiated TRISO fuel particles. These measurements (particularly those for Ag) have large uncertainties due to the indirect nature of the analysis, the varying pedigrees of the fuel particles, the uncertainty of fission product production, a limited understanding of boundary conditions, and the complex, time-dependent nature of fuel irradiations. Recent efforts have focused on providing diffusion kinetics of fission product elements in SiC through simplified surrogate diffusion systems. The transport of Ag in SiC has received the most attention due to the magnitude of the release and the complex release behavior from TRISO fuel. Most experiments have focused on surrogate diffusion couple designs, which differ from TRISO fuel systems due to SiC variations, diffusion species source effects (direct ion implantation, high activity sources), and the lack of neutron irradiation. Results from surrogate diffusion couple experiments show no consistency in diffusion kinetics or possible mechanisms [2].

Recent ion implantation diffusion studies showed the potential influence of radiation damage on Ag transport in SiC [3]. The influence of irradiation on fission product transport is also noted from post-irradiation examination (PIE) safety testing of AGR-1 TRISO fuel. After irradiation, high fractional Ag release from irradiated particles with intact TRISO coatings was observed [1]. Post-irradiation heating of the compacts up to 1700°C did not result in significant additional Ag release [4]. On the other hand, Eu and Sr fission product release through intact TRISO particles at temperatures below 1800°C could not be conclusively confirmed due to retention of these fission product species in the compact matrix. Similar observations were made after comparing in-pile release with release during post-irradiation heating of HRB-15B fuel [5]. These observations suggest the likely influence of neutron radiation on fission product diffusion in the TRISO SiC layer, and they provide motivation to study the effect of neutron radiation-enhanced diffusion to obtain representative diffusion kinetic parameters.

The optimal approach to obtaining accurate diffusion kinetic data on fission product release is to analyze irradiated TRISO fuel particles. However, the large variation in irradiation conditions across fuel compacts and the complex, time-dependent diffusion sources and thermal histories do not allow for accurate diffusion analysis. Additionally, the spherical geometry of the TRISO fuel particle does not lend itself to the sensitive techniques required to measure the precise depth profiles needed to determine diffusion behavior. Separate effects testing of representative fission product diffusion from the IPyC layer through the SiC layer could provide accurate measurements of diffusion kinetics without the complications of integral TRISO particle testing. For these separate effects tests to be relevant to TRISO fuel performance models, the tests must include representative TRISO fuel construction and fission products, and they must account for the influence of neutron irradiation. At this writing, no surrogate system has been able to provide such a system to study diffusion of select species in SiC.

Oak Ridge National Laboratory (ORNL) is leveraging coating systems developed to fabricate fuel for the AGR-1 irradiation campaign to produce diffusion couple systems with the unique PyC/SiC interface and a SiC microstructure identical to the SiC found in TRISO fuel. The diffusion couple coupon specimens will have slab geometry to simplify the fabrication process and the post-irradiation depth profiling. Fig. 1 shows a schematic of the diffusion couple specimen.

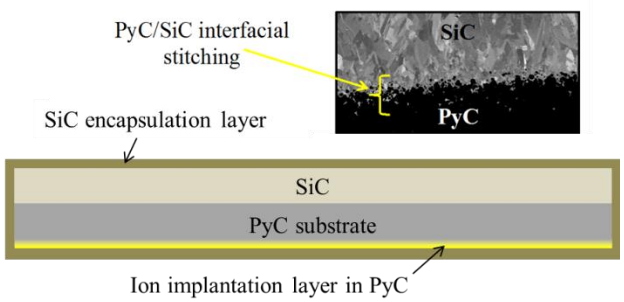

Fig. 1. Schematic of PyC/SiC diffusion couple with inset showing interfacial stitching.

The diffusing fission product species will be introduced into the PyC layer, which mitigates any issues resulting from implantation effects in the SiC [6]. The implantation energy and dose will be tailored to reflect the concentrations present in TRISO fuel particles at the end of life. This approach also allows for multiple species to be introduced so that the potential of Pd-assisted Ag diffusion can be further understood. The diffusion couples will reflect the encapsulated nature of TRISO fuel, allowing for insertion into the High Flux Isotope Reactor (HFIR) so that neutron radiation-enhanced diffusion can be studied. The influence of neutron radiation-enhanced diffusion will be investigated through a comparative study of neutron-irradiated diffusion couples and thermally exposed diffusion couples. This report summarizes the HFIR irradiation experiment to be used to assess neutron radiation-enhanced diffusion, including the irradiation capsule design concept and thermal analyses.

2. EXPERIMENTAL METHODS

2.1 HFIR IRRADIATION EXPERIMENTS

The irradiation experiments described in this document will be performed in the hydraulic tube facility inside the flux trap of ORNL's HFIR. The HFIR is a beryllium-reflected, pressurized, light water–cooled and moderated flux trap–type reactor [7]. 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. Most experiments are conducted in the flux trap in small, un-instrumented rabbit capsules. The hydraulic tube (HT) allows for short-term (less than a full cycle) irradiations to be performed. As many as 9 rabbits can be stacked vertically and irradiated simultaneously inside the hydraulic tube. Positions are numbered from the bottom to the top of the hydraulic tube. Position HT-5 aligns with the axial midplane of the reactor. The irradiations described in this document are designed for the HT-6 position, which is located just above the axial midplane, or the HT-4 position, which is located just below the axial midplane.

The goal of this work is to design an experiment to contain the PyC/SiC diffusion couple specimens inside a HFIR-approved irradiation vehicle 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. As mentioned previously, 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 [8]. However, detailed neutronic and thermal analyses are required to ensure that design temperatures are achieved. Experiment designs typically use a small insulating gas gap. The size of the gap and the choice of the fill gas (typically helium, neon, or argon) 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 CONCEPT

The overall design of the irradiation experiments developed in this work is shown in the section views of Fig. 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. As many as 40 diffusion couple specimens (3 mm × 4 mm × 0.25 mm) are placed inside small cutouts in a graphite container. The container is then placed inside a square cutout in a cylindrical holder made from a Nb-1Zr alloy. Passive SiC TMs line the inside of the holder cutout, and SiC retainer springs keep the graphite container pressed into one corner of the cutout. Temperature is controlled by varying the concentration of a helium/argon gas mixture and the size of the gas gap between the holder and the housing. Varying the gas mixture changes the effective thermal conductivity of the gas gap. Centering thimbles are inserted inside counterbores in the ends of the holder to keep the holder centered inside the housing and to maintain a constant gas gap between the holder and the housing. Wires are inserted through the thimbles and the radial holes in the holder to ensure that the thimbles cannot dislodge from the holder. The small raised features above and below the base of the centering thimble (see Fig. 2) reduce the contact area between the centering thimble and the contacting components (the holder and the bottom of the housing). These features significantly reduce axial heat losses through the thimbles. Grafoil insulator disks are also stacked on both ends of the capsule to further reduce axial heat losses. Quartz wool (not shown) is packed into the ends of the cutouts in the graphite container to keep the specimens from falling out.

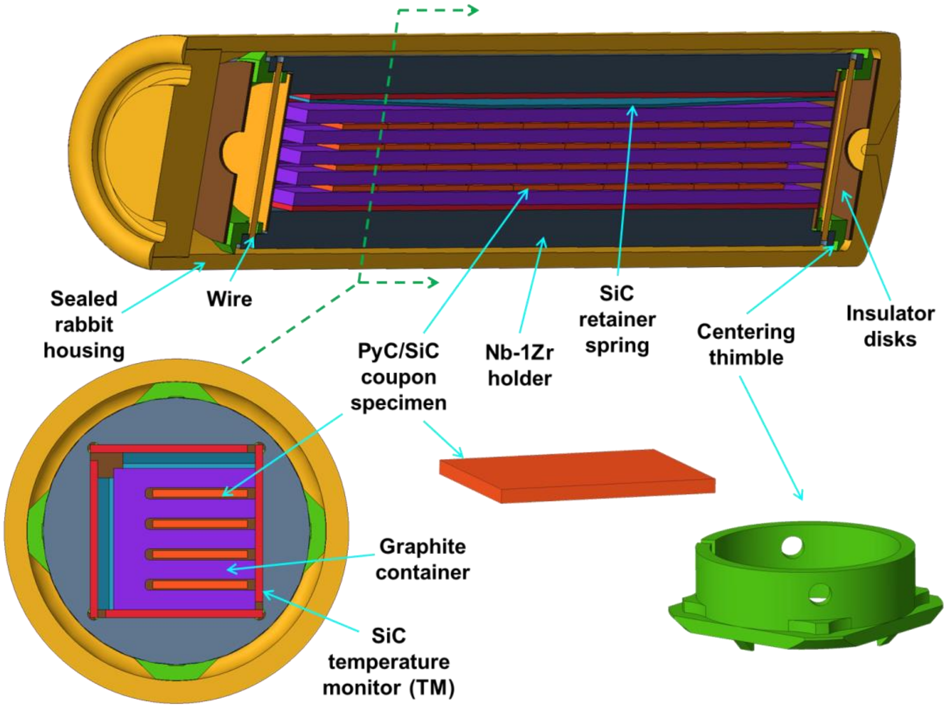

Fig. 2. Section view showing irradiation capsule design concept.

3. COMPUTATIONAL METHODS

Three-dimensional (3D) thermal analyses are performed using the ANSYS finite element software package to predict temperature distributions inside the experiment. These analyses use material-dependent heat generation rates (heat per unit mass) calculated from neutronics analyses. Custom user-defined macros have been incorporated into ANSYS to determine thermal contact conductance between components either in contact or separated by small gas gaps that expand or contract due to thermal expansion [9]. 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 elements with a mesh size ranging from 0.2–0.7 mm. Thermal contacts are defined to allow heat to be transferred between multiple bodies. Gas gap heat transfer is assumed to only result from conduction and radiation, as there is very little space available for natural convection to occur. Gaps are typically on the order of microns to a few millimeters, and the total internal length of the capsule is less than 60 mm. The solver accounts for thermal expansion using temperature-dependent thermal expansion data and the temperatures of contact and target surface nodes.

The ORNL Thermal Hydraulic and Irradiation Engineering 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 and PyC also include radiation dose-dependence. Properties are primarily obtained from CINDAS [10], MatWeb [11], and various literature sources. Properties of gas mixtures are calculated using the methods described by Wahid et al. [12]. Material properties for this calculation are included in the DACs, as shown in Table 1 and are available upon request. Specimens are modeled as 100% PyC. However, because of their small size, the specimens do not have much effect on the total heat load inside the capsule, and temperature gradients within the specimens are very small.

Table 1. Experiment materials and material property references

Part	Material	Reference
Housing, end cap	Aluminum	DAC-10-03-PROP_AL6061 [13]
Specimen	PyC/SiC	DAC-16-07-PROP_PYROLYTIC_CARBON [14]
Container	Graphite	DAC-10-15-PROP_POCO-GRAPHITE [15]
Holder	Nb-1Zr	DAC-10-12-PROP_NB1ZR [16]
Centering thimbles	Titanium	DAC-11-14-PROP_TI6AL4V [17]
Insulators	Grafoil	DAC-11-16-PROP_GRAFOIL [18]
Temperature monitors and retainer springs	SiC	DAC-10-06-PROP_SIC(IRR) [19]
Wires and support disks	Molybdenum	DAC-10-11-PROP_MOLY [20]
Fill gas	Argon	DAC-10-09-PROP_ARGON [21]
Fill gas	Helium	DAC-10-02-PROP_HELIUM [22]

Convection boundary conditions are 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 [23]. 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 hydraulic tube facility 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 2. All heat generation rates were determined in DAC-10-18-RAB02 [24] except for the titanium heat generation rate, which was determined in HFIR safety basis calculation C-HFIR-2013-003 [25]. 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 HFIR is dominated by photon absorption in the materials used in this experiment.

Table 2. Thermal boundary conditions for hydraulic tube irradiation experiments

Parameter	Value
Heat transfer coefficient	31.6 kW m^{-2} K^{-1}
Bulk coolant temperature	53°C
Peak heat generation rate for aluminum	31.5 W/g
Peak heat generation rate for PyC, graphite, and grafoil	32.3 W/g
Peak heat generation rate for Nb-1Zr	44.0 W/g
Peak heat generation rate for titanium	34.7 W/g
Peak heat generation rate for SiC	31.9 W/g
Peak heat generation rate for molybdenum	42.3 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 TEST MATRIX

Table 3 summarizes all possible specimen combinations that could be included in the irradiation test matrix. All specimen types to be included in the irradiation testing will also be included in high-temperature furnace testing in the absence of irradiation. This will separate the effects of thermal and irradiation-assisted diffusion. The baseline specimen condition will be produced with AGR-2 layer properties. Other specimen variants will include a tailored SiC microstructure with larger grains (SiC variant), a controlled PyC/SiC interface with minimal stitching compared to the AGR-2 baseline (PyC variant), and a specimen (RH-SiC) that uses commercially available chemical vapor deposition (CVD) SiC from Dow Chemical Company (formerly Rohm and Haas). All irradiations will be performed with a nominal design temperature of 1,100°C with dose ranging from 0.5–1.0 dpa. Because there are two irradiation dose levels and one design temperature, a total of two rabbits will be irradiated. Each rabbit can contain up to 40 specimens. Therefore, with 10 different types of specimens (condition + implanted species), as many as 4 specimens of each type can be accommodated in each rabbit.

Table 3. Potential specimen types that could be included in the irradiation test matrix

Specimen condition	Implanted species	Irradiation dose	Irradiation temperature
Baseline	Ag Ag+Pd Eu Sr	0.5 dpa, 1.0 dpa	1,100±50°C
IPyC variant	Ag Ag+Pd		
SiC variant	Ag Eu Sr		
RH-SiC	Ag		

4.2 TEMPERATURE CONTOURS

Fig. 3 shows temperature contours predicted by the thermal analyses. The reductions in temperature at the ends of the specimen holder and the specimens themselves are due to axial heat losses through the tabs of the centering thimbles. However, the small raised features of the centering thimbles described in Section 2.2 keep the axial temperature reductions very low (~45°C in the specimens). The specimen temperatures remain within the desired range of 1,100±50°C. Furthermore, the temperatures of the passive SiC TMs (1,050–1,115°C) are close to the temperatures of the specimens (1,089–1,135°C), which assures that the TMs will give a good indication of the actual specimen temperature. The difference in temperature between the four TMs is because the graphite specimen container is pressed against two of the four interior walls of the specimen holder. This forces more heat to pass through the two walls that are in contact compared to the other two walls that are not in direct contact. The greater amount of heat passing through these two walls (and through two of the four TMs) results in slightly higher temperatures for these two TMs.

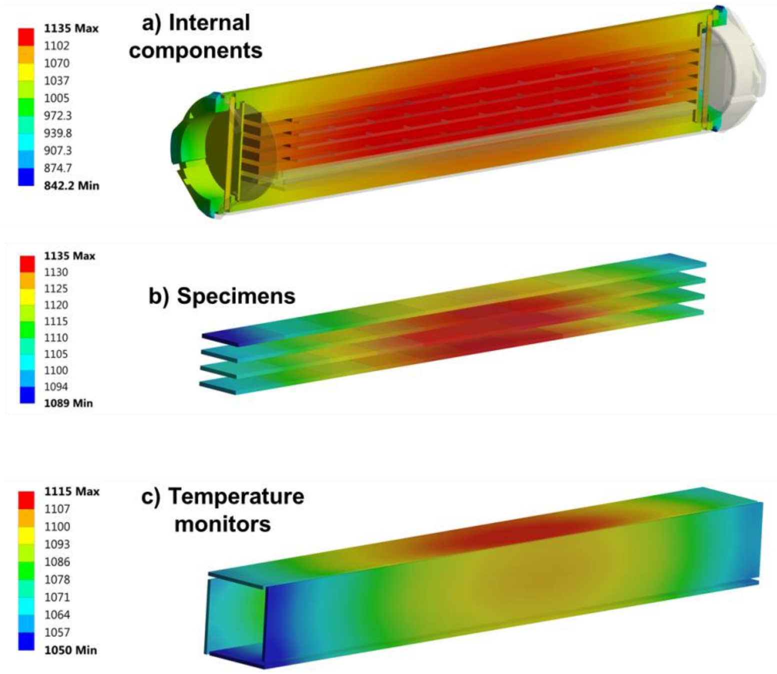

Fig. 3. Predicted temperature contours showing (a) a section view of the internal components, (b) the specimens, and (c) the SiC temperature monitors.

4.3 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 outer diameter of the holder. More details are provided in the complete ANSYS reports provided in APPENDIX A. A fill gas with a 40.5% He, Ar balance was chosen. This is a standard gas composition that results in a thermal conductivity essentially equivalent to neon gas. Neon is not used often due to the higher cost. The holder's 9.01 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 255 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 255 µm gap as close as possible.

Table 4. Summary of component temperatures, irradiation position, fill gas, and cold holder-to-housing gas gap

Position	Fill gas	Gas gap	Part	Temperature (°C)		
				Average	Minimum	Maximum
HT-4 or HT-6	40.5% He, Ar balance	255 µm	Specimens	1,120	1,089	1,135
			TM1	1,096	1,059	1,113
			TM2	1,085	1,050	1,101
			TM3	1,084	1,050	1,101
			TM4	1,097	1,060	1,115
			Container	1,113	1,064	1,133
			Holder	1,077	1,009	1,106
			Housing	66	57	73

5. SUMMARY AND CONCLUSIONS

This report summarizes the capsule design and thermal analysis that was performed for irradiation testing of PyC/SiC diffusion couple specimens in the hydraulic tube facility of the HFIR. This design will allow for separation of the effects of radiation and temperature on the diffusion of select metallic fission products in the SiC layers of TRISO fuel particles. Ultimately, the data gathered from these experiments will assist in the development of accurate models and codes for TRISO fuel performance, which are needed to ensure safe and efficient operation of this fuel for advanced reactor applications or for use as an accident-tolerant fuel for LWRs. The rabbit capsule design allows for up to 40 PyC/SiC diffusion couple specimens to be loaded inside a rectangular graphite container, with small slots to accommodate the specimens. The graphite container is placed inside a Nb-1Zr specimen holder that is centered inside the rabbit housing using titanium centering thimbles. Temperature is controlled by varying the backfill gas (a He/Ar gas mixture) and the size of the gas gap between the holder and the rabbit housing. Thermal analyses show that a design temperature of 1,100°C can be achieved in the specimens with temperature gradients of ~45°C. These analyses show that a 40.5% He (Ar balance) gas mixture and a holder-to-housing gas gap of 255 μm are required to achieve the desired temperatures.

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APPENDIX A. THERMAL ANALYSIS REPORT

APPENDIX A. THERMAL ANALYSIS REPORT

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

* Thermal only solution with calculated gaps
* Symmetry angle: 360.00 degrees
* Fill gas: 405HE_59
* Radiative heat transfer included
* 3D  problem geometry
* Target temperature: 1100.0 °C
* Target dose (in SiC):   0.500 dpa
* Capsule pressure:  474.81 kPa
* Specimen material: PyC
* Holder OD =  9.0100 mm, Housing ID =  9.5199 mm
* Gas gap:    0.25 mm
* Backfill gas:   40.50% He,   59.50% Ar
* Irradiation facility: HT
* Axial position: 6
* Capsule centerline position =   6.49 cm (  2.56 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 =  31600. W/m²·°C
 Bulk coolant temperature  =    53.0 °C

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

                                                 Heat Gen.   ------ Heat Load -----
                                                 @Midplane   @Midplane    @Location
  Part                                Material     (W/kg)       (W)          (W)
----------------------------------- --------   ---------   ---------    ---------
  1) Grafoil.1                       GRAFOIL       32300.         0.2          0.2
  3) Grafoil.2                       GRAFOIL       32300.         0.2          0.2
  5) Holder                          NB-1ZR        44000.       637.3        609.1
  7) Foil.1                          Moly          42300.         1.5          1.5
  9) Foil.2                          Moly          42300.         1.5          1.4
 11) Grafoil.3                       GRAFOIL       32300.         0.2          0.2
 13) Grafoil.4                       GRAFOIL       32300.         0.2          0.2
 15) TM.1                            SiC(Irr)      31900.         6.0          5.7
 17) TM.2                            SiC(Irr)      31900.         6.0          5.7
 19) TM.3                            SiC(Irr)      31900.         6.0          5.7
 21) TM.4                            SiC(Irr)      31900.         6.0          5.7
 23) Wire.1                          Moly          42300.         0.7          0.7
 25) Wire.2                          Moly          42300.         0.7          0.7
 27) Spring.1                        SiC(Irr)      31900.         3.0          2.9
 28) Spring.2                        SiC(Irr)      31900.         3.0          2.9
 29) Housing                         AL-6061       31500.       135.0        128.9
 31) Cap                             AL-6061       31500.        20.0         18.1
 33) Thimble.1                       Ti-6Al4V      34700.         5.2          5.1
 35) Thimble.2                       Ti-6Al4V      34700.         5.2          4.8
 37) Container                       POCO          32300.        41.7         39.9
 39) Specimen.1                      PyC           32300.         0.2          0.2
 40) Specimen.2                      PyC           32300.         0.2          0.2
 41) Specimen.3                      PyC           32300.         0.2          0.2
 42) Specimen.4                      PyC           32300.         0.2          0.2
 43) Specimen.5                      PyC           32300.         0.2          0.2
 44) Specimen.6                      PyC           32300.         0.2          0.2
 45) Specimen.7                      PyC           32300.         0.2          0.2
 46) Specimen.8                      PyC           32300.         0.2          0.2
 47) Specimen.9                      PyC           32300.         0.2          0.2
```

48) Specimen.10	PyC	32300.	0.2	0.2
49) Insulator.1	GRAFOIL	32300.	0.2	0.2
51) Insulator.2	GRAFOIL	32300.	0.2	0.2
53) Specimen.11	PyC	32300.	0.2	0.2
54) Specimen.12	PyC	32300.	0.2	0.2
55) Specimen.13	PyC	32300.	0.2	0.2
56) Specimen.14	PyC	32300.	0.2	0.2
57) Specimen.15	PyC	32300.	0.2	0.2
58) Specimen.16	PyC	32300.	0.2	0.2
59) Specimen.17	PyC	32300.	0.2	0.2
60) Specimen.18	PyC	32300.	0.2	0.2
61) Specimen.19	PyC	32300.	0.2	0.2
62) Specimen.20	PyC	32300.	0.2	0.2
63) Specimen.21	PyC	32300.	0.2	0.2
64) Specimen.22	PyC	32300.	0.2	0.2
65) Specimen.23	PyC	32300.	0.2	0.2
66) Specimen.24	PyC	32300.	0.2	0.2
67) Specimen.25	PyC	32300.	0.2	0.2
68) Specimen.26	PyC	32300.	0.2	0.2
69) Specimen.27	PyC	32300.	0.2	0.2
70) Specimen.28	PyC	32300.	0.2	0.2
71) Specimen.29	PyC	32300.	0.2	0.2
72) Specimen.30	PyC	32300.	0.2	0.2
73) Specimen.31	PyC	32300.	0.2	0.2
74) Specimen.32	PyC	32300.	0.2	0.2
75) Specimen.33	PyC	32300.	0.2	0.2
76) Specimen.34	PyC	32300.	0.2	0.2
77) Specimen.35	PyC	32300.	0.2	0.2
78) Specimen.36	PyC	32300.	0.2	0.2
79) Specimen.37	PyC	32300.	0.2	0.2
80) Specimen.38	PyC	32300.	0.2	0.2
81) Specimen.39	PyC	32300.	0.2	0.2
82) Specimen.40	PyC	32300.	0.2	0.2
			887.5	847.2

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Grafoil.1	GRAFOIL	93.	86.	100.	87.	97.
3) Grafoil.2	GRAFOIL	114.	96.	158.	98.	131.
5) Holder	NB-1ZR	1077.	1009.	1106.	1025.	1102.
7) Foil.1	Moly	1066.	1055.	1077.	1058.	1076.
9) Foil.2	Moly	1043.	1042.	1044.	1042.	1044.
11) Grafoil.3	GRAFOIL	1037.	1035.	1039.	1035.	1038.
13) Grafoil.4	GRAFOIL	1037.	1036.	1039.	1036.	1038.
15) TM.1	SiC(Irr)	1096.	1059.	1113.	1065.	1112.
17) TM.2	SiC(Irr)	1085.	1050.	1101.	1055.	1101.
19) TM.3	SiC(Irr)	1084.	1050.	1101.	1054.	1100.
21) TM.4	SiC(Irr)	1097.	1060.	1115.	1066.	1114.
23) Wire.1	Moly	1070.	1064.	1073.	1064.	1073.
25) Wire.2	Moly	1060.	1056.	1063.	1056.	1063.
27) Spring.1	SiC(Irr)	1103.	1054.	1129.	1063.	1128.
28) Spring.2	SiC(Irr)	1107.	1060.	1130.	1065.	1129.
29) Housing	AL-6061	66.	57.	73.	58.	71.
31) Cap	AL-6061	148.	146.	150.	146.	150.
33) Thimble.1	Ti-6Al4V	994.	842.	1039.	926.	1032.
35) Thimble.2	Ti-6Al4V	1003.	855.	1028.	947.	1026.
37) Container	POCO	1113.	1064.	1133.	1083.	1132.
39) Specimen.1	PyC	1109.	1104.	1115.	1104.	1114.
40) Specimen.2	PyC	1120.	1115.	1125.	1116.	1124.
41) Specimen.3	PyC	1128.	1124.	1131.	1124.	1130.
42) Specimen.4	PyC	1131.	1129.	1133.	1129.	1133.
43) Specimen.5	PyC	1132.	1130.	1133.	1130.	1133.
44) Specimen.6	PyC	1130.	1128.	1133.	1128.	1132.
45) Specimen.7	PyC	1127.	1123.	1130.	1124.	1129.
46) Specimen.8	PyC	1121.	1117.	1125.	1117.	1124.
47) Specimen.9	PyC	1113.	1108.	1118.	1109.	1117.
48) Specimen.10	PyC	1104.	1099.	1109.	1099.	1108.

49) Insulator.1	GRAFOIL	1070.	1060.	1082.	1062.	1080.
51) Insulator.2	GRAFOIL	1040.	1036.	1042.	1038.	1041.
53) Specimen.11	PyC	1111.	1106.	1116.	1106.	1116.
54) Specimen.12	PyC	1122.	1117.	1126.	1118.	1126.
55) Specimen.13	PyC	1129.	1126.	1132.	1126.	1132.
56) Specimen.14	PyC	1133.	1131.	1135.	1131.	1134.
57) Specimen.15	PyC	1134.	1133.	1135.	1133.	1135.
58) Specimen.16	PyC	1133.	1130.	1134.	1131.	1134.
59) Specimen.17	PyC	1129.	1126.	1131.	1126.	1131.
60) Specimen.18	PyC	1123.	1119.	1126.	1119.	1126.
61) Specimen.19	PyC	1115.	1110.	1119.	1111.	1118.
62) Specimen.20	PyC	1105.	1101.	1110.	1101.	1109.
63) Specimen.21	PyC	1109.	1104.	1115.	1105.	1114.
64) Specimen.22	PyC	1120.	1115.	1124.	1116.	1124.
65) Specimen.23	PyC	1128.	1124.	1130.	1125.	1130.
66) Specimen.24	PyC	1132.	1129.	1133.	1130.	1133.
67) Specimen.25	PyC	1132.	1131.	1133.	1131.	1133.
68) Specimen.26	PyC	1131.	1129.	1132.	1129.	1132.
69) Specimen.27	PyC	1127.	1124.	1129.	1124.	1129.
70) Specimen.28	PyC	1121.	1117.	1124.	1118.	1124.
71) Specimen.29	PyC	1113.	1108.	1117.	1109.	1116.
72) Specimen.30	PyC	1103.	1099.	1108.	1099.	1107.
73) Specimen.31	PyC	1102.	1096.	1108.	1096.	1107.
74) Specimen.32	PyC	1113.	1107.	1118.	1108.	1117.
75) Specimen.33	PyC	1120.	1116.	1124.	1117.	1123.
76) Specimen.34	PyC	1124.	1122.	1126.	1122.	1126.
77) Specimen.35	PyC	1125.	1123.	1126.	1124.	1126.
78) Specimen.36	PyC	1123.	1121.	1126.	1121.	1125.
79) Specimen.37	PyC	1120.	1116.	1123.	1117.	1122.
80) Specimen.38	PyC	1113.	1109.	1118.	1110.	1117.
81) Specimen.39	PyC	1105.	1100.	1110.	1100.	1109.
82) Specimen.40	PyC	1095.	1089.	1100.	1090.	1099.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Grafoil.1	GRAFOIL	38.000	1.00	0.500
3) Grafoil.2	GRAFOIL	38.000	1.00	0.500
5) Holder	NB-1ZR	64.571	8.09	0.211
7) Foil.1	Moly	101.524	0.00	0.142
9) Foil.2	Moly	102.098	0.00	0.139
11) Grafoil.3	GRAFOIL	38.000	1.00	0.500
13) Grafoil.4	GRAFOIL	38.000	1.00	0.500
15) TM.1	SiC(Irr)	40.813	4.41	0.900
17) TM.2	SiC(Irr)	40.638	4.40	0.900
19) TM.3	SiC(Irr)	40.625	4.40	0.900
21) TM.4	SiC(Irr)	40.831	4.41	0.900
23) Wire.1	Moly	101.434	0.00	0.142
25) Wire.2	Moly	101.673	0.00	0.141
27) Spring.1	SiC(Irr)	41.094	4.41	0.900
28) Spring.2	SiC(Irr)	41.355	4.42	0.900
29) Housing	AL-6061	167.424	24.21	0.050
31) Cap	AL-6061	175.671	0.00	0.050
33) Thimble.1	Ti-6Al4V	19.897	8.91	0.466
35) Thimble.2	Ti-6Al4V	19.905	8.94	0.466
37) Container	POCO	29.600	8.40	0.800
39) Specimen.1	PyC	19.548	5.56	0.800
40) Specimen.2	PyC	19.657	5.57	0.800
41) Specimen.3	PyC	19.730	5.57	0.800
42) Specimen.4	PyC	19.766	5.57	0.800
43) Specimen.5	PyC	19.773	5.58	0.800
44) Specimen.6	PyC	19.758	5.57	0.800
45) Specimen.7	PyC	19.722	5.57	0.800
46) Specimen.8	PyC	19.666	5.57	0.800
47) Specimen.9	PyC	19.587	5.56	0.800
48) Specimen.10	PyC	19.491	5.55	0.800

49) Insulator.1	GRAFOIL	38.000	1.00	0.500
51) Insulator.2	GRAFOIL	38.000	1.00	0.500
53) Specimen.11	PyC	19.565	5.56	0.800
54) Specimen.12	PyC	19.674	5.57	0.800
55) Specimen.13	PyC	19.748	5.57	0.800
56) Specimen.14	PyC	19.785	5.58	0.800
57) Specimen.15	PyC	19.794	5.58	0.800
58) Specimen.16	PyC	19.778	5.58	0.800
59) Specimen.17	PyC	19.741	5.57	0.800
60) Specimen.18	PyC	19.683	5.57	0.800
61) Specimen.19	PyC	19.602	5.56	0.800
62) Specimen.20	PyC	19.508	5.55	0.800
63) Specimen.21	PyC	19.548	5.56	0.800
64) Specimen.22	PyC	19.656	5.57	0.800
65) Specimen.23	PyC	19.730	5.57	0.800
66) Specimen.24	PyC	19.768	5.57	0.800
67) Specimen.25	PyC	19.777	5.58	0.800
68) Specimen.26	PyC	19.761	5.57	0.800
69) Specimen.27	PyC	19.723	5.57	0.800
70) Specimen.28	PyC	19.664	5.57	0.800
71) Specimen.29	PyC	19.582	5.56	0.800
72) Specimen.30	PyC	19.486	5.55	0.800
73) Specimen.31	PyC	19.473	5.55	0.800
74) Specimen.32	PyC	19.584	5.56	0.800
75) Specimen.33	PyC	19.658	5.57	0.800
76) Specimen.34	PyC	19.695	5.57	0.800
77) Specimen.35	PyC	19.704	5.57	0.800
78) Specimen.36	PyC	19.688	5.57	0.800
79) Specimen.37	PyC	19.650	5.57	0.800
80) Specimen.38	PyC	19.590	5.56	0.800
81) Specimen.39	PyC	19.506	5.55	0.800
82) Specimen.40	PyC	19.409	5.55	0.800

STORED ENERGY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Mass (g)	Tavg (°C)	Specific Heat (J/kg°C)	Stored Energy (J)
1) Grafoil.1	GRAFOIL	0.007	93.	700.	0.
3) Grafoil.2	GRAFOIL	0.007	114.	700.	0.
5) Holder	NB-1ZR	14.485	1077.	351.	5372.
7) Foil.1	Moly	0.035	1066.	313.	12.
9) Foil.2	Moly	0.035	1043.	311.	11.
11) Grafoil.3	GRAFOIL	0.007	1037.	700.	5.
13) Grafoil.4	GRAFOIL	0.007	1037.	700.	5.
15) TM.1	SiC(Irr)	0.187	1096.	1276.	257.
17) TM.2	SiC(Irr)	0.187	1085.	1274.	254.
19) TM.3	SiC(Irr)	0.187	1084.	1274.	253.
21) TM.4	SiC(Irr)	0.187	1097.	1277.	257.
23) Wire.1	Moly	0.017	1070.	314.	6.
25) Wire.2	Moly	0.017	1060.	313.	6.
27) Spring.1	SiC(Irr)	0.094	1103.	1278.	130.
28) Spring.2	SiC(Irr)	0.094	1107.	1278.	131.
29) Housing	AL-6061	4.285	66.	890.	177.
31) Cap	AL-6061	0.635	148.	949.	77.
33) Thimble.1	Ti-6Al4V	0.149	994.	616.	90.
35) Thimble.2	Ti-6Al4V	0.149	1003.	493.	72.
37) Container	POCO	1.290	1113.	1963.	2767.
39) Specimen.1	PyC	0.006	1109.	1769.	11.
40) Specimen.2	PyC	0.006	1120.	1774.	11.
41) Specimen.3	PyC	0.006	1128.	1777.	12.
42) Specimen.4	PyC	0.006	1131.	1778.	12.
43) Specimen.5	PyC	0.006	1132.	1779.	12.
44) Specimen.6	PyC	0.006	1130.	1778.	12.
45) Specimen.7	PyC	0.006	1127.	1776.	12.
46) Specimen.8	PyC	0.006	1121.	1774.	11.
47) Specimen.9	PyC	0.006	1113.	1770.	11.
48) Specimen.10	PyC	0.006	1104.	1766.	11.
49) Insulator.1	GRAFOIL	0.005	1070.	700.	4.

51)	Insulator.2	GRAFOIL	0.005	1040.	700.	4.
53)	Specimen.11	PyC	0.006	1111.	1770.	11.
54)	Specimen.12	PyC	0.006	1122.	1774.	11.
55)	Specimen.13	PyC	0.006	1129.	1778.	12.
56)	Specimen.14	PyC	0.006	1133.	1779.	12.
57)	Specimen.15	PyC	0.006	1134.	1780.	12.
58)	Specimen.16	PyC	0.006	1133.	1779.	12.
59)	Specimen.17	PyC	0.006	1129.	1777.	12.
60)	Specimen.18	PyC	0.006	1123.	1775.	12.
61)	Specimen.19	PyC	0.006	1115.	1771.	11.
62)	Specimen.20	PyC	0.006	1105.	1767.	11.
63)	Specimen.21	PyC	0.006	1109.	1769.	11.
64)	Specimen.22	PyC	0.006	1120.	1774.	11.
65)	Specimen.23	PyC	0.006	1128.	1777.	12.
66)	Specimen.24	PyC	0.006	1132.	1778.	12.
67)	Specimen.25	PyC	0.006	1132.	1779.	12.
68)	Specimen.26	PyC	0.006	1131.	1778.	12.
69)	Specimen.27	PyC	0.006	1127.	1777.	12.
70)	Specimen.28	PyC	0.006	1121.	1774.	11.
71)	Specimen.29	PyC	0.006	1113.	1770.	11.
72)	Specimen.30	PyC	0.006	1103.	1766.	11.
73)	Specimen.31	PyC	0.006	1102.	1765.	11.
74)	Specimen.32	PyC	0.006	1113.	1770.	11.
75)	Specimen.33	PyC	0.006	1120.	1774.	11.
76)	Specimen.34	PyC	0.006	1124.	1775.	12.
77)	Specimen.35	PyC	0.006	1125.	1776.	12.
78)	Specimen.36	PyC	0.006	1123.	1775.	12.
79)	Specimen.37	PyC	0.006	1120.	1773.	11.
80)	Specimen.38	PyC	0.006	1113.	1771.	11.
81)	Specimen.39	PyC	0.006	1105.	1767.	11.
82)	Specimen.40	PyC	0.006	1095.	1763.	11.
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			22.308			10349.

GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 117: Thimble.1 To Housing (Frictionless)

Contact surface material: Ti-6Al4V
Target surface material: AL-6061
Interstitial gas: 405HE_59
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)	855.943	845.426	865.195
Target temperature (°C)	69.326	68.811	69.833
Geometric gas gap (µm)	9.999	9.999	10.000
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m²)	7191.804	7064.618	7304.316
Radiation heat flux (kW/m²)	5.164	4.977	5.331
Contact conduction heat flux (kW/m²)	0.000	0.000	0.000
Total heat flux (kW/m²)	7196.968	7069.596	7309.647
Thermal contact conductance (W/m²·C)	9142.429	9107.236	9173.519
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	8.878	8.878	8.878
Contact thermal jump distance (µm)	0.414	0.410	0.418
Target thermal jump distance (µm)	0.281	0.279	0.283
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	16.918	16.918	16.918
Gas thermal conductivity (W/m·°C)	0.088	0.087	0.088
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	9060.913	9028.388	9090.734

Contact status codes:

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

-------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 119: Thimble.2 To Housing (Frictionless)
   Contact surface material:     Ti-6Al4V
   Target surface material:       AL-6061
   Interstitial gas:             405HE_59
   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)                   871.231      858.487      881.338
   Target temperature (°C)                     65.366       64.558       66.055
   Geometric gas gap (µm)                       9.999        9.999       10.000
   Contact pressure (MPa)                       0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          7397.596     7242.348     7522.041
   Radiation heat flux (kW/m²)                  5.445        5.211        5.634
   Contact conduction heat flux (kW/m²)         0.000        0.000        0.000
   Total heat flux (kW/m²)                   7403.041     7247.559     7527.675
   Thermal contact conductance (W/m²·C)      9179.367     9136.944     9212.236
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                       8.878        8.878        8.878
   Contact thermal jump distance (µm)           0.419        0.414        0.423
   Target thermal jump distance (µm)            0.283        0.280        0.285
   Effective contact pressure (MPa)             0.000        0.000        0.000
   Pressure index                              16.918       16.918       16.918
   Gas thermal conductivity (W/m·°C)            0.088        0.088        0.088
   Solid spot conductance (W/m²·C)              0.000        0.000        0.000
   Gas gap conductance (W/m²·C)              9096.745     9055.447     9129.167

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

-------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 175: Holder To Housing (Frictionless)
   Contact surface material:       NB-1ZR
   Target surface material:       AL-6061
   Interstitial gas:             405HE_59
   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)                  1071.570     1008.972     1098.282
   Target temperature (°C)                     67.823       62.185       68.605
   Geometric gas gap (µm)                     254.999      254.556      255.362
   Contact pressure (MPa)                       0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)           433.189      393.323      451.043
   Radiation heat flux (kW/m²)                  9.057        7.394        9.821
   Contact conduction heat flux (kW/m²)         0.000        0.000        0.000
   Total heat flux (kW/m²)                    442.246      400.717      460.865
   Thermal contact conductance (W/m²·C)       431.453      416.205      438.572
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     220.972      219.970      223.320
   Contact thermal jump distance (µm)           0.708        0.664        0.726
   Target thermal jump distance (µm)            0.328        0.312        0.335
   Effective contact pressure (MPa)             0.000        0.000        0.000
   Pressure index                              13.809       13.809       13.809
   Gas thermal conductivity (W/m·°C)            0.096        0.093        0.097
   Solid spot conductance (W/m²·C)              0.000        0.000        0.000
```

```
Gas gap conductance (W/m²·C)             431.387      416.166      437.930

Contact status codes:
 ---------------------------------------------
 0=open/no heat transfer, 1=near-field contact
 2=closed and sliding,    3=closed and sticking
```