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Analysis and Experimental Qualification of an Irradiation Capsule Design for Testing Pressurized Water Reactor Fuel Cladding in the High Flux Isotope Reactor

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ORNL/TM-2017/67

Reactor and Nuclear Systems Division

ANALYSIS AND EXPERIMENTAL QUALIFICATION OF AN IRRADIATION CAPSULE DESIGN FOR TESTING PRESSURIZED WATER REACTOR FUEL CLADDING IN THE HIGH FLUX ISOTOPE REACTOR

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ACRONYMS

3D	three dimensional
BOC	beginning of cycle
CAD	computer-aided design
DAC	design and analysis calculations
DOE	US Department of Energy
EOC	end of cycle
HFIR	High Flux Isotope Reactor
LWR	light water reactor
MCNP	Monte Carlo N-Particle
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PTP	peripheral target position
PWR	pressurized water reactor
RB	removable beryllium
SiC	silicon carbide
TRRH	target rod rabbit holder
WFL	water flow loop
Zr	zirconium

ACKNOWLEDGMENTS

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ABSTRACT

The Advanced Fuels Campaign within the Fuel Cycle Research and Development program of the Department of Energy Office of Nuclear Energy is currently investigating a number of advanced nuclear fuel cladding concepts to improve the accident tolerance of light water reactors. Alumina-forming ferritic alloys (e.g., FeCrAl) are some of the leading candidates to replace traditional zirconium alloys due to their superior oxidation resistance, provided no prohibitive irradiation-induced embrittlement occurs. Oak Ridge National Laboratory has developed experimental designs to irradiate thin-walled cladding tubes with representative pressurized water reactor geometry in the High Flux Isotope Reactor (HFIR) under relevant temperatures. These designs allow for post-irradiation examination (PIE) of cladding that closely resembles expected commercially viable geometries and microstructures. The experiments were designed using relatively inexpensive rabbit capsules for the irradiation vehicle. The simplistic designs combined with the extremely high neutron flux in the HFIR allow for rapid testing of a large test matrix, thus reducing the time and cost needed to advanced cladding materials closer to commercialization. The designs are flexible in that they allow for testing FeCrAl alloys, stainless steels, Inconel alloys, and zirconium alloys (as a reference material) both with and without hydrides. This will allow a direct comparison of the irradiation performance of advanced cladding materials with traditional zirconium alloys. PIE will include studies of dimensional change, microstructure variation, mechanical performance, etc. This work describes the capsule design, neutronic and thermal analyses, and flow testing that were performed to support the qualification of this new irradiation vehicle.

1. INTRODUCTION

Nuclear power produces approximately 20% of the electricity in the United States. Nearly all reactors that are either under construction or being considered in the short to near term are light water cooled and moderated. While traditional light water reactors (LWRs) with UO_2 fuel and zirconium (Zr)-alloy cladding have a long history of successful operation, the accident tolerance of this fuel-cladding system has recently been questioned due to high-temperature steam oxidation, hydrogen generation, and radiation-induced embrittlement, particularly after the Zr-alloy cladding forms hydrides [1-3]. In order to improve the accident tolerance of LWRs, a number of advanced nuclear fuel cladding concepts are currently being investigated [4, 5]. These advanced cladding materials would provide enhanced fission product retention, slower high-temperature reaction kinetics with steam, reduced hydrogen generation, and improved thermomechanical properties. Of course performance under normal operating conditions including high fuel burnup, long fuel cycle length, and high reliability remain important for economic viability.

Some of the leading candidates to replace traditional Zr-based cladding are alumina-forming ferritic alloys (e.g., FeCrAl) [6-8]. FeCrAl alloys have shown superior oxidation resistance compared to Zr alloys, and they could also provide an additional margin for burst failure if they can retain superior high-temperature strength after irradiation. However, FeCrAl alloys are known to experience embrittlement under irradiation due to secondary-phase formations [9-11]. New information regarding the irradiation performance of FeCrAl alloys with representative LWR geometry and microstructure would be invaluable for qualifying these materials for use in commercial reactors. Ideally these materials would be irradiated in tube geometry at prototypic LWR temperatures (300–350°C). Accelerated irradiation testing is preferred so that a large test matrix can be evaluated and down-selection of specific alloys and processing parameters can occur within a reasonable time and cost.

This report describes work that was done at Oak Ridge National Laboratory (ORNL) to develop and qualify experimental designs to irradiate thin-walled cladding tubes with the required LWR geometry and temperatures in the High Flux Isotope Reactor (HFIR). The design is flexible in that it can accommodate FeCrAl alloys, stainless steels, nickel (Ni)-based alloys, and Zr-based alloys (as reference materials) with an outer diameter (9.50 mm) equivalent to that of a 17 × 17 array pressurized water reactor (PWR). Some advanced cladding materials would require reduced wall thickness (compared to traditional Zr-alloy cladding) to reduce parasitic neutron absorption in the cladding. Therefore, the HFIR irradiation design can accommodate a range of cladding thicknesses from 0.3–0.7 mm. The irradiated samples will allow the severity of the cladding degradation under irradiation to be determined through post-irradiation examination (PIE), which will include mechanical and microstructural evaluations. The experiments were designed using relatively inexpensive rabbit capsules for the irradiation vehicle. The simplistic designs combined with the extremely high neutron flux in the HFIR allow for rapid testing of a large test matrix. This work describes the capsule design, thermal and neutronic analyses, and other work such as flow testing to support experimental qualification in the HFIR.

2. EXPERIMENTAL METHODS

2.1 CAPSULE DESIGN

2.1.1 HFIR Irradiation and Experiment Design Concept

2.1.1.1 HFIR Irradiation

The HFIR is a beryllium-reflected, pressurized, light water–cooled and moderated flux trap–type reactor located at ORNL [12]. 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. Moving radially outward from the fuel, there are control plates, a removable beryllium (RB) reflector, which includes RB* irradiation facilities, and a permanent beryllium reflector with large and small vertical experiment facilities (VXFs). The water coolant for the reactor provides cooling for the fuel as well as for all experiment containments. The majority of experiments are conducted in the flux trap, typically in small, un-instrumented rabbit capsules, or less often in full length targets that span the entire length of the core. The flux trap has the highest fast and thermal neutron flux of all available facilities. As many as seven to nine rabbits can be stacked axially inside of a single peripheral target position (PTP) holder, a target rod rabbit holder (TRRH), or the hydraulic tube. The hydraulic tube allows short-term (less than a full cycle) irradiations to be performed. Orifices in the target rod and PTP holders allow for the outer surfaces of rabbits to be exposed to reactor coolant, which is approximately 50–60°C. Positions are numbered in increasing order from bottom to top of a PTP or TRRH. Positions TRRH-4 and PTP-5 are closest to the reactor midplane (Figure 1).

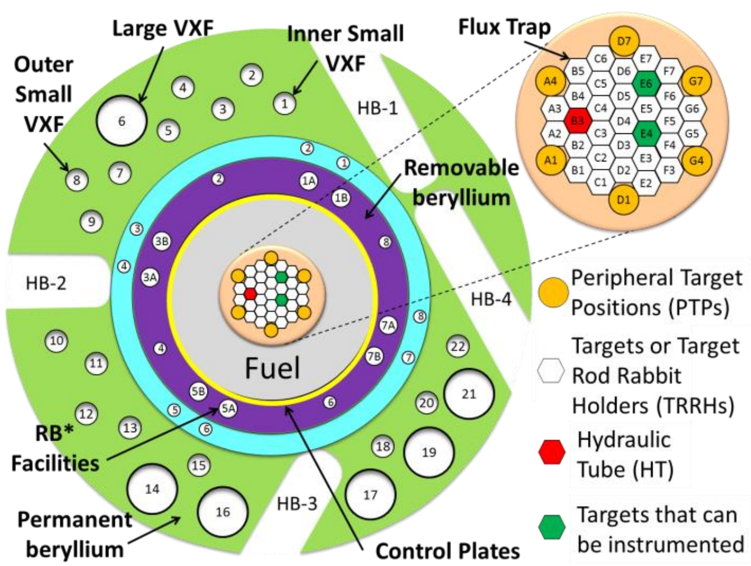

Figure 1. Schematic (not to scale) showing transverse section view of HFIR core, reflector, and experimental positions.

2.1.1.2 Experiment Design Concept

The goal of this work is to design an experiment to contain the cladding tube specimens inside a HFIR-approved irradiation vehicle so that they can accumulate the desired amount of radiation damage, or dose, while being irradiated at the design temperature. Neutron and gamma radiation from the HFIR fuel cause heating of the experiment materials. Heat generation rates are accurately determined using neutronics models of the HFIR core (Section 3.1) and are input to thermal models that are used to predict component temperatures during irradiation. As mentioned previously, experiments in the flux trap are almost always un-instrumented. Passive silicon carbide (SiC) temperature monitors, or thermometry, can be used to determine the irradiation temperature post-irradiation [13]. However, neutronic and thermal analyses are still required to ensure that the design temperatures are achieved. Section 3.2 summarizes the thermal models in more detail. However, the methodology is briefly discussed here so that the experimental design can be better understood. Typically HFIR irradiation experiments utilize a small insulating gas gap to achieve the desired component temperatures. The gap is established by the inner surface of the primary containment, which is actively cooled, and the outer surface of the internal components. The size of the gap and the choice of the fill gas (typically helium, neon, or argon) inside the experiment are chosen such that the heat generated in the experimental components passes through the gas gap, giving 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.

The overall design of the irradiation experiments developed in this work is shown in the section views of Figure 2. Design drawings of the experiment assembly and part details are summarized in Table 1. The outer containment for the irradiation experiment is the rabbit capsule housing, which is directly cooled on the outer surface by the HFIR primary coolant. The cladding tube specimens are placed over molybdenum sleeves with slots on the inner surface and radial thru-holes drilled kat each end. In this design, the temperature is controlled by varying the concentration of a helium/argon gas mixture according to the measured size of the gas gap between the cladding and the housing. Varying the gas mixture changes the effective thermal conductivity of the gas gap. Centering thimbles are inserted inside the sleeves to keep the assemblies centered inside the housing and to maintain a constant gas gap between the cladding and the housing. Wires are inserted through the thimbles and the radial holes in the sleeves to keep the thimbles from being able to dislodge from the sleeves. Grafoil insulators are stacked on both ends of the capsule to reduce axial heat losses.

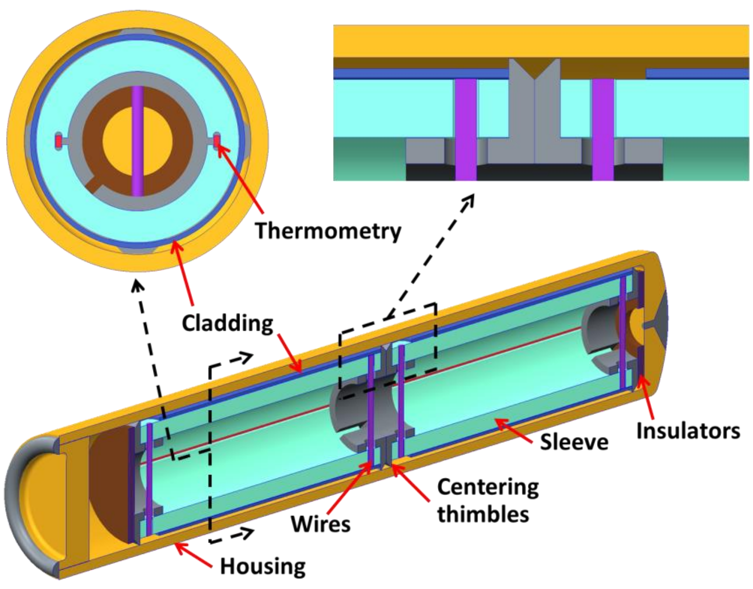

Figure 2. Section view showing irradiation capsule design concept.

Table 1. Summary of the experiment assembly and part detail drawings

Drawing	Title
X3E020977A689, Rev. 0	Target Capsule Housing Assembly [14]
X3E020977A690, Rev. 0	Target Capsule Housing Details [15]
X3E020977A634, Rev. A	Target Capsule Housing/End Cap Detail [16]
S16-10-FLEXCLAD01, Rev. 0	Flexible Cladding Rabbits Assembly [17]
S16-11-FLEXCLAD02, Rev. 0	Flexible Cladding Rabbits Assembly and Part Details [18]

2.1.2 Metrology

It is critically important that the temperature of the cladding tubes during irradiation be as close as possible to the temperature (300–350°C) of fuel cladding in PWRs. As mentioned previously, the size of the gas gap is one of the parameters that determines the temperature drop through the gap. Therefore, very precise measurement of the cladding outer diameter and the housing inner diameter is required. High-precision Mitutoyo 293-765-30 micrometers are used to measure the major and minor diameters (the cladding is circular but µm-scale eccentricities are often observed) at five or six points along the length of the specimens, which are typically 15–23 mm long. Similarly, the inner diameter of the housing is measured at five axial locations using a Mitutoyo Crysta-Apex 920 coordinate-measuring machine (CMM) with Renishaw Modus 1.7 software. This level of detail is necessary to ensure that there are no significant eccentricities or axial variations in diameter that would affect the uniformity of the insulating gas gap.

2.2 FLOW TESTING

Standard HFIR rabbit housings (nominally 10.96 mm outer diameter, 9.52 mm inner diameter) are not large enough to accommodate 17 × 17 array PWR cladding tubes (9.50 mm nominal outer diameter) with a sufficiently large gas gap to control temperature. Therefore, this experiment required developing larger rabbit housings with nominal dimensions of 11.24 mm outer diameter and 9.71 mm inner diameter. The larger outer diameter of these new rabbits could potentially restrict flow through the channel between the rabbits and the PTPs or TRRHs in which the rabbits are contained during irradiation. Therefore, it was necessary to prove that adequate flow through the TRRHs could be achieved with a core pressure drop that is within the allowable range for HFIR operation. Engineering drawings of both the standard and large-bore rabbits are available upon request.

2.2.1 Description of Flow Test Facility

Flow testing was conducted at 22°C in the Water Flow Loop (WFL) facility, which is managed by the Thermal Hydraulics and Irradiation Engineering group at ORNL. A general schematic of the test loop is shown in

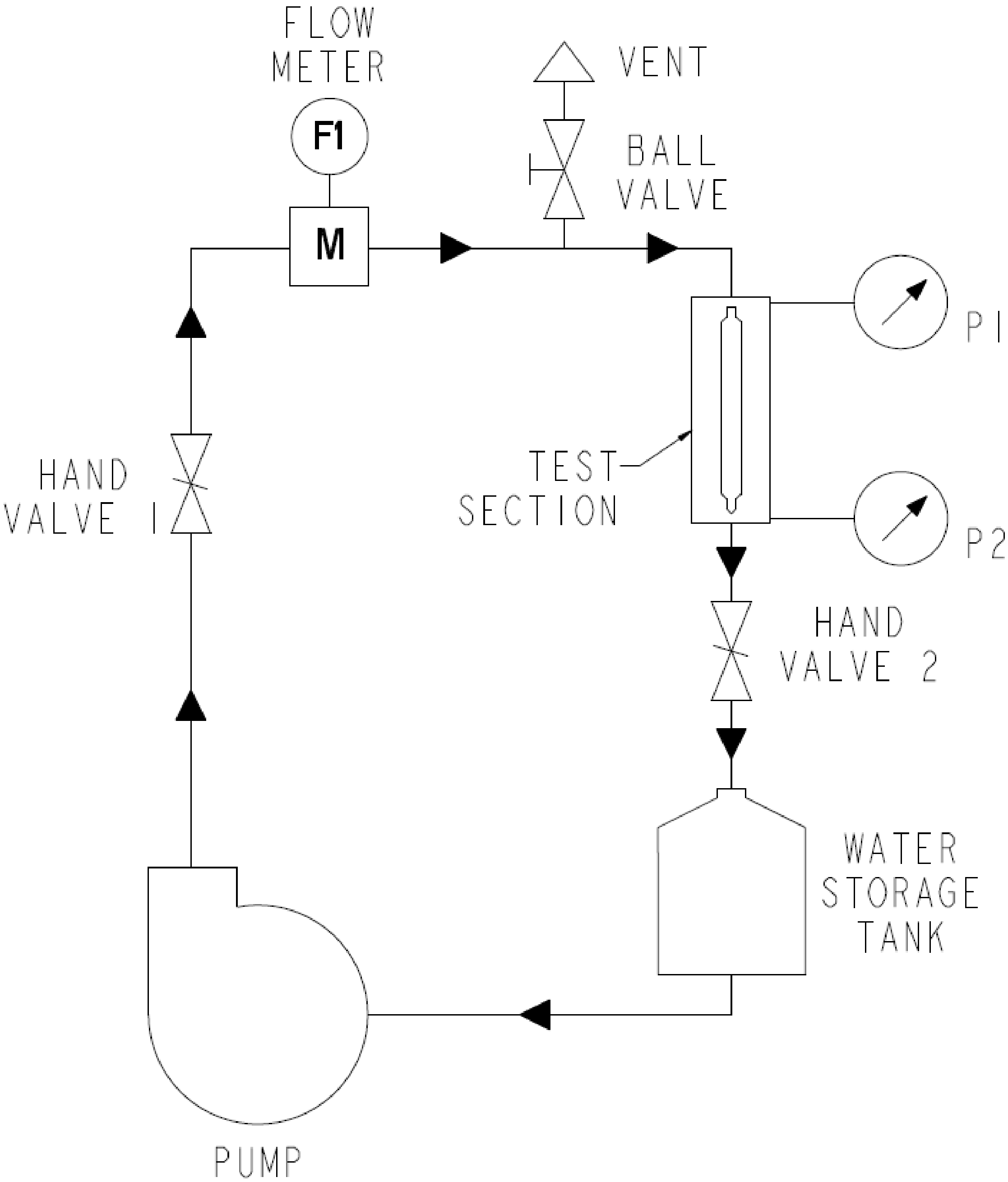

Figure 3. The WFL is essentially a pump and a water storage tank with a return line. A modular test region was added with hand valves in between the pump and the test section and between the test section and the water storage tank. In this experiment a PTP flow test section was used. Figure 4 and Figure 5 show computer-aided design (CAD) section views of the loop with the test section. A HFIR-issued PTP holder (serial number 11-02) was used for these tests. The PTP holder was loaded with a train of seven dummy rabbits (sealed rabbits containing aluminum slugs instead of cladding tubes and other experimental components) as shown in Figure 5. Both standard size and large-bore rabbits were tested. Dimensional inspection data for the dummy rabbits as well as other relevant information can be found in the attachments in Appendix A. Data on the PTP holder are available upon request.

The WFL pump speed can be controlled using a variable frequency controller. A magnetic flowmeter (Azbil model MTG18A) was incorporated to measure the flow rate through the experiment. An Omegadyne DPG409-100DWU pressure gauge was used to measure pressure drop across the test assembly. Pressure measurements were taken at locations P1 and P2 as shown in Figure 4 and Figure 5. Engineering drawings of the PTP holder and the flow test section can be can be obtained by contacting the author. Calibration data for the pressure gauges and the flowmeter can be found in APPENDIX A, exhibits 1 and 2, respectively. The pressure gauge calibration data indicate that the maximum error observed over the entire calibration range (0–689 kPa, or 0–100 psid) is 0.55 kPa (0.08 psid). The flowmeter calibration data indicate a maximum error of 2.78 cc/s (0.044 gpm) over the testing range (roughly 210–610 cc/s, or 3.33–9.67 gpm). It should be noted that the instrumentation was calibrated and set to acquire data in customary English units (psid and gpm, as is typically done for HFIR experiments). These data are later converted and reported in SI units.

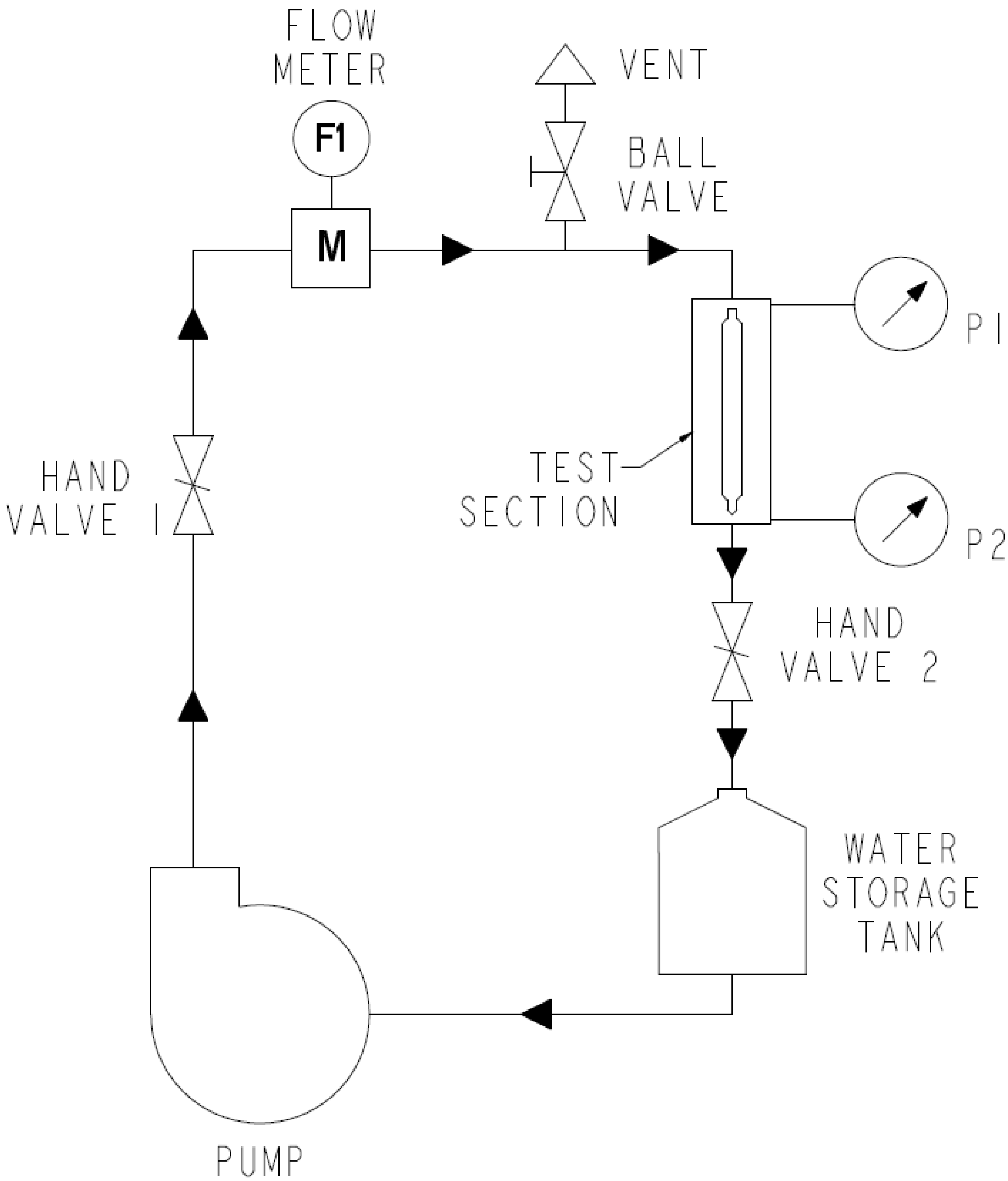

Figure 3. Schematic of the WFL with test section to measure flow through a PTP holder loaded with rabbits.

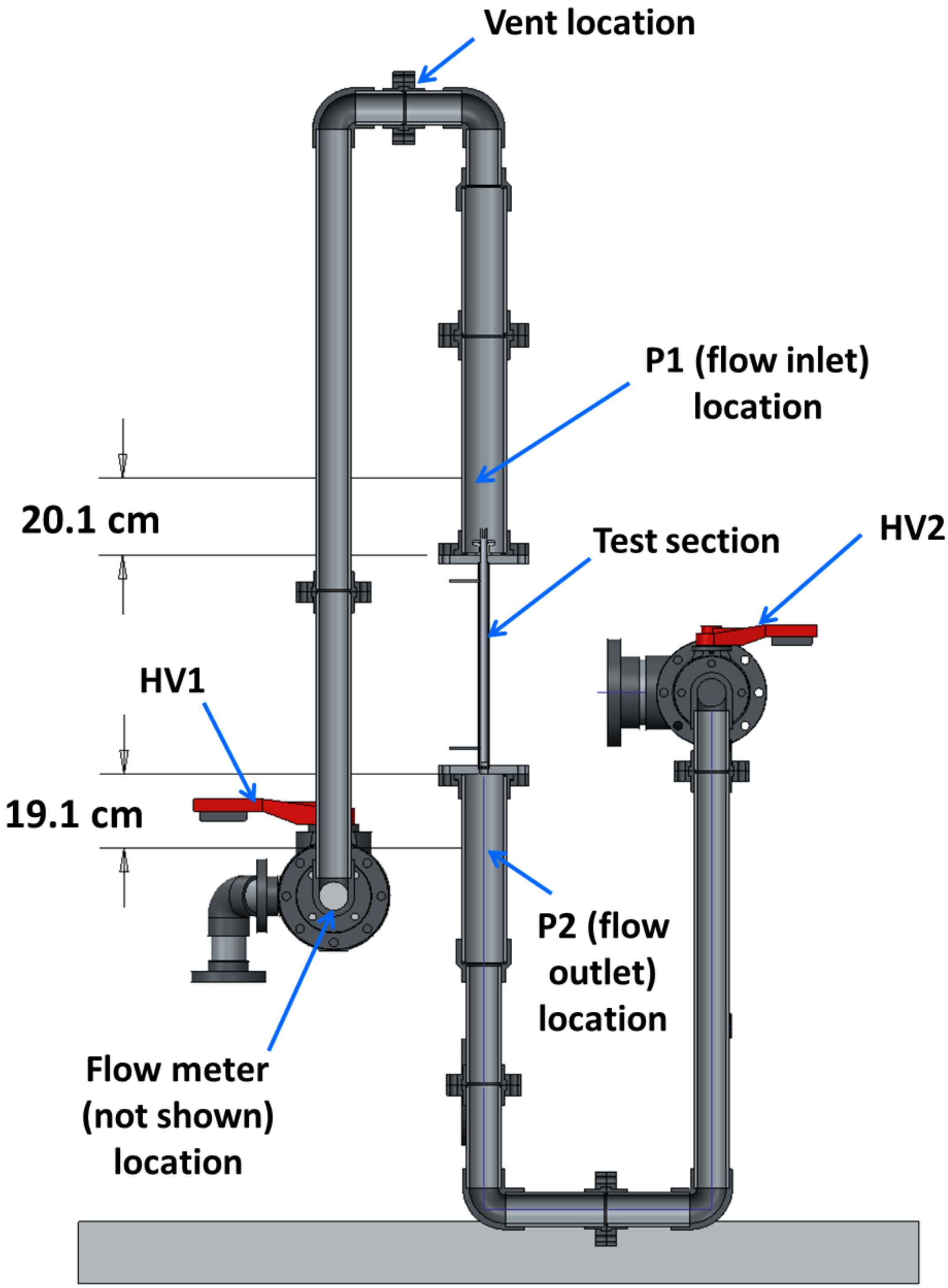

Figure 4. Flow loop schematic detailing specific parts and elevations.

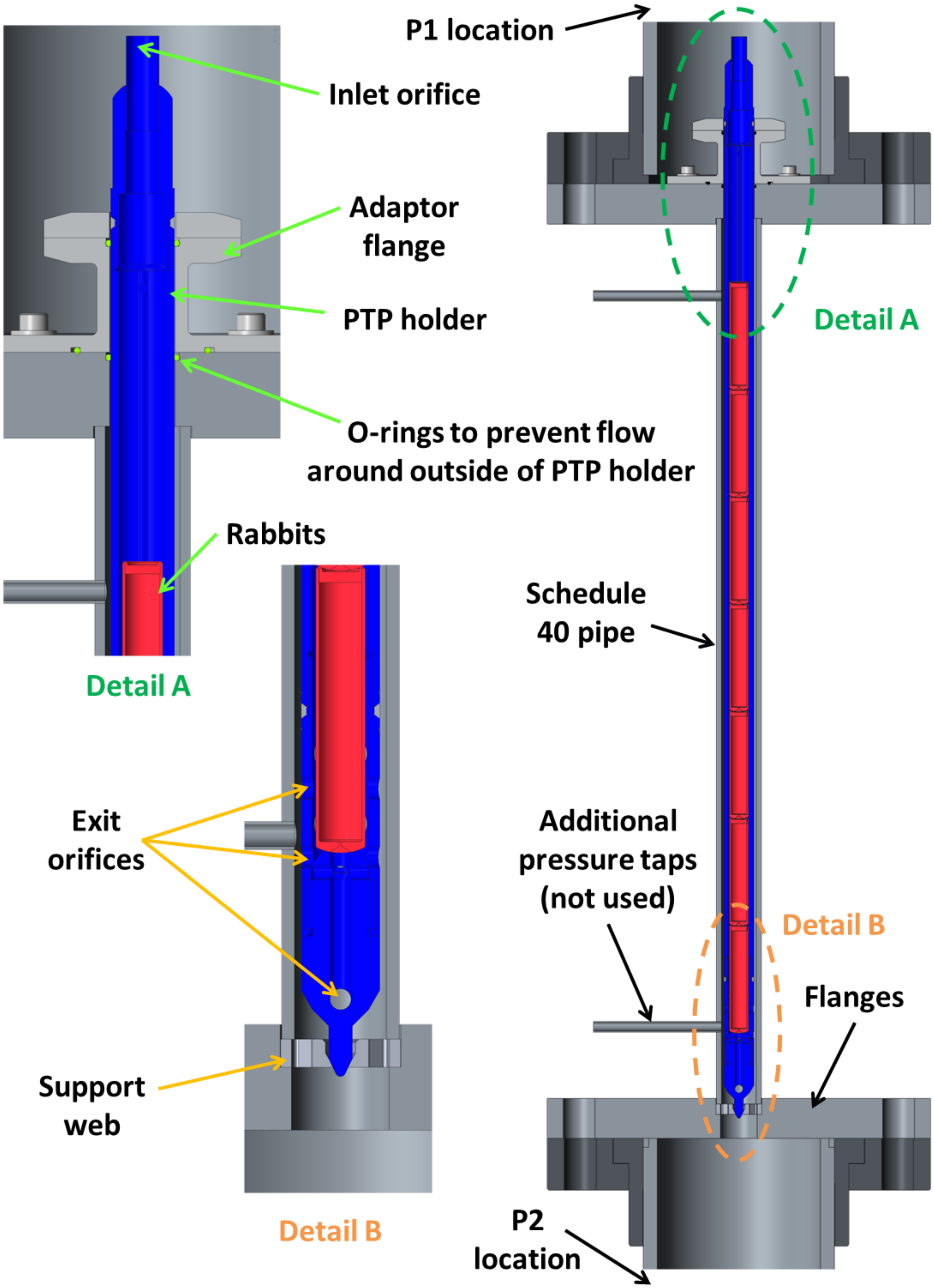

Figure 5. Section view of test section.

2.2.2 Test Procedure

The facility was filled with water by starting the pump and circulating water through the test section and piping until no bubbles were observed exiting a bleed valve located at the top of the flow loop (Figure 4). Lines connecting the pressure gauges were also bled of air to ensure that all lines were full of water and free of air pockets. Flow testing was conducted by adjusting the pump speed to achieve the desired flow rate to the test section. The pump speed (and thus the flow rate) was increased in steps, and the system was allowed to reach a steady state after each increment in pump speed. Flow rates and pressure drops were recorded continuously using data acquisition software. The real-time data were verified against the gauge displays on both the pressure and flow rate readouts.

Steady-state measurements of pressure drop vs. flow rate were obtained by analyzing subsets of the data after a sufficiently long time after the pump speed was increased in each step. Small oscillations can be observed in both the pressure and flow rate data, so each data set was averaged over some time after reaching steady state. Figure 6 shows one example of data from an entire experiment and the corresponding steady-state subsets that were used to calculate average data points for each step in flow rate.

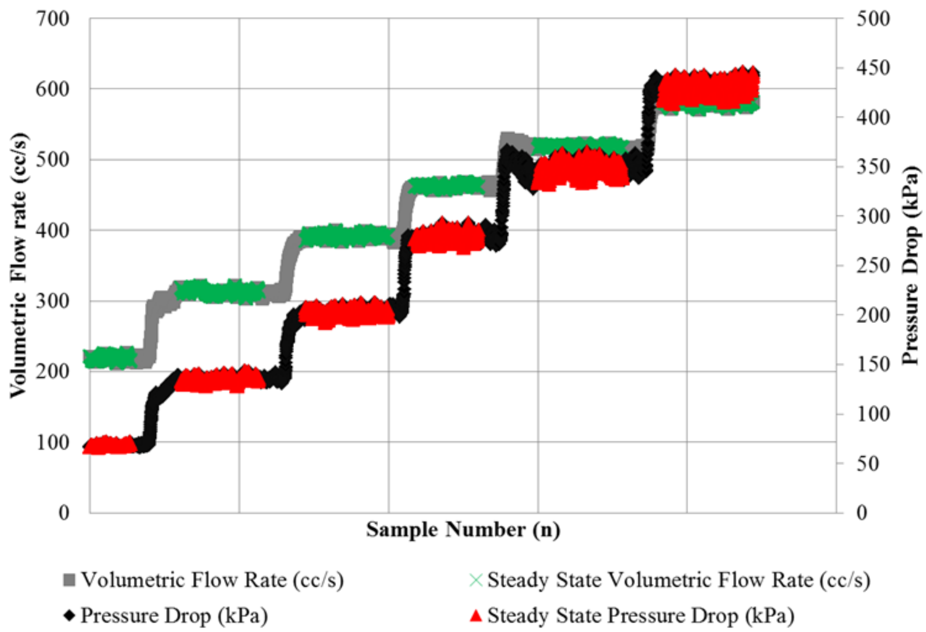

Figure 6. Flow rate and pressure drop data from one experiment and the corresponding steady-state subsets that were used to calculate average data points for each step in flow rate.

3. COMPUTATIONAL METHODS

3.1 NEUTRONICS ANALYSIS

Heat generation rates have four major components: (1) prompt neutron heating, (2) heating caused by fission photons and secondary photons produced by the fission neutrons (prompt photon heating), (3) heating due to fission product decay photons (fission product heating), and (4) heating due to the decay (primarily due to beta emission) of activation sources. Nuclear heating in HFIR is typically dominated by photon absorption in most materials. One exception is water, in which neutron scattering from hydrogen results in significant energy transfer to the scattered hydrogen nucleus, which produces substantial levels of neutron heat generation. Heat generation due to photon absorption is dependent on the atomic number of the absorbing element with higher-Z elements typically having higher heat generation rates due to increased pair production and photoelectric interactions. Photon absorption also depends on the magnitude and spectrum of the capture gammas released as a result of neutron absorption. For isotopes with a significant neutron absorption cross section, or at least one or more large resonance absorption peaks, the heat generation within the sample can be significantly affected by the shape of the specimen. This is because these isotopes often de-excite to their ground state by emitting a cascade of lower energy photons following neutron absorption. The low-energy photons may or may not deposit their energy locally in the material, depending on the component geometry.

Because of the geometric dependence of heat generation in some materials, the rabbit geometry was explicitly modeled using the Monte Carlo N-Particle (MCNP) to determine neutron and gamma heat generation rates in the experimental components including the aluminum housing, cladding tubes (FeCrAl and Zircaloy-4), and the molybdenum sleeves. The model does not consider minor components such as SiC thermometry, centering thimbles, wires, insulator disks, etc. The MCNP models of the HFIR core at beginning of cycle (BOC) and end of cycle (EOC) were developed previously [19]. These models include variations in fuel composition, control plate position, and fission density within the fuel at the two extremes of a HFIR cycle. Further modifications were made to these models to calculate heat generation rates. Prompt neutron and photon heating are modeled in MCNP. Fission product photon heating is also modeled in MCNP using a fixed photon source distributed throughout the HFIR fuel. The photon energy spectrum and steady-state photon yields for fission product decay photons were calculated using the ORIGEN software package. Heating due to local alpha and beta decay of components is also calculated using ORIGEN assuming 100% local energy deposition.

3.2 THERMAL ANALYSIS

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 the neutronics analyses as inputs. Custom user-defined macros were 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 [20]. In this way, gas gaps are not directly meshed, which significantly reduces computational time. CAD models are imported into ANSYS and meshed. Thermal contacts are defined to allow heat to be transferred between multiple bodies. Gas gap heat transfer is assumed to only include conduction 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 includes temperature-dependent (and in some cases radiation dose-dependent) thermophysical material properties that are used in thermal analyses. Properties are primarily obtained from CINDAS [21], MatWeb [22], and various literature sources. Properties of gas mixtures are calculated using the methods described by Wahid et al. [23]. Material properties for this calculation are included in the DACs shown in Table 2, which are available upon request.

Table 2. Experiment materials and material property references

Part	Material	Reference
Housing, end cap	Aluminum	DAC-10-03-PROP_AL6061 [24]
Cladding	FeCrAl	DAC-16-02-PROP_FeCrAl [25]
Cladding	Zircaloy-4 or ZIRLO	DAC-11-03-PROP_ZIRCALOY [26]
Centering thimbles	Grade 5 titanium	DAC-11-14-PROP_TI6AL4V [27]
Insulators	Grafoil	DAC-11-16-PROP_GRAFOIL [28]
Thermometry	Silicon carbide	DAC-10-06-PROP_SIC(IRR) [29]
Sleeves and wires	Molybdenum	DAC-10-11-PROP_MOLY [30]
Fill gas	Argon	DAC-10-09-PROP_ARGON [31]
Fill gas	Helium	DAC-10-02-PROP_HELIUM [31]

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 [32]. These parameters were calculated using turbulent flow correlations and the axial power profile (due to neutron and gamma heat generation in the coolant) specific to TRRHs in the HFIR flux trap. The 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 in each irradiation location (PTP vs. TRRH) and 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. Some minor components were not explicitly included in the neutronics calculations described in Section 3.1. However, similar calculations were performed previously [33, 34] for other experiments that included the materials that make up these minor components. Results from these previous calculations were used in the analyses for this experiment for materials that were not explicitly modeled in the neutronics analysis. Although the geometries for previous experiments were different, the results are on a per-unit-mass basis, and therefore they provide a reasonable estimate of heat generation in this experiment. Aluminum heat generation rates were not modified based on whether the cladding was made of FeCrAl or Zircaloy-4. Minor discrepancies in aluminum heat generation rates with FeCrAl vs. Zircaloy-4 cladding were observed due to differences in attenuation of gammas that pass radially through the cladding and then generate heat in the aluminum housing on the opposite side. Aluminum heat generation rates between those calculated for FeCrAl and Zircaloy-4 cladding were used. This resulted in at most a 0.6 W/g discrepancy, which has little effect on component temperatures because all of the heat generated in the aluminum housing is dissipated to the reactor coolant and does not affect internal temperatures.

Table 3. Thermal boundary conditions

Parameter	Value in PTP	Value in TRRH
Heat transfer coefficient	48.4 kW m^{-2} K^{-1}	47.1 kW m^{-2} K^{-1}
Bulk coolant temperature	54°C	52°C
Peak heat generation rate for aluminum	29.9 W/g	28.8 W/g
Peak heat generation rate for titanium	35.6 W/g	35.2 W/g
Peak heat generation rate for FeCrAl	34.4 W/g	33.5 W/g
Peak heat generation rate for Zr-alloys	46.1 W/g	45.1 W/g
Peak heat generation rate for SiC	34.0 W/g	32.9 W/g
Peak heat generation rate for grafoil	35.0 W/g	33.7 W/g
Peak heat generation rate for molybdenum with FeCrAl cladding	43.6 W/g	42.5 W/g
Peak heat generation rate for molybdenum with Zr-alloy cladding	41.0 W/g	39.8 W/g
Correlating parameter (σ)	30.07 cm	
Note: PTP = Peripheral Target Position, TRRH = Target Rod Rabbit Holder		

The local heat generation rate is estimated with 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.

Figure 7 shows one example of a fully meshed 3D finite-element model. The model utilizes ¼ symmetry to reduce computational time. The majority of the components were meshed using 20 node hexagonal elements with a mesh size of 0.3 mm. The centering thimbles and housing end cap used 20 node tetrahedral elements. The housing and end cap used mesh sizes of 0.5 and 0.7 mm, respectively. As-built specimen, sleeve, and housing dimensions obtained from metrology were used in the model to give the best estimates of component temperatures.

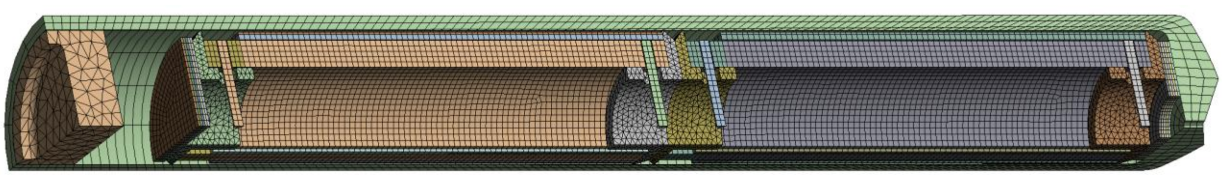

Figure 7. Meshed 3D thermal finite-element model with ¼ symmetry.

4. RESULTS AND DISCUSSION

4.1 METROLOGY

As mentioned in Section 2.1.2, high-precision dimensional inspection of the cladding specimens and the capsule housings was necessary to ensure that the cladding-to-housing gas gap, which is used to control temperature, is uniform around the circumference of the cladding. Table 4 summarizes average dimensional measurements for all cladding specimens that were included in the irradiation experiments. The average gas gap is calculated using the averaged measured housing inner diameter and the cladding/housing pairing that is introduced later in Section 4.4. Figure 8 and Figure 9 show examples of the cladding outer diameter measurements that were made. The *x* and *y* values are scaled such that they are *x* and *y* distances from some reference radius (arbitrarily defined as 99% of the minimum measured inner radius of the cladding) that is unique to each specimen. This allows one to observe the variations in the cladding outer diameter at various axial locations (*z*) compared to the nominal housing inner diameter of 9.70 mm. Both the cladding outer diameter values and the nominal housing inner diameter are scaled to the same reference radius.

Figure 8 shows that specimen B136Y-4 has a very uniform outer diameter along the entire axis. Specimen C06M-02 has more significant variation in diameter, particularly at one end (z=0 mm). Because this nonuniformity would only affect temperatures at the end of the specimen, specimen C06M-02 was considered acceptable. Using similar logic, specimen Zirlo-HH-1 (Figure 9) is also acceptable because the most significant diameter nonuniformity is observed only on one end of the specimen (z=0 mm) and the remainder of the specimen shows a variation of <9 µm. Specimen Zirlo-MH-1 has an oval shape that is constant along its axis. This oval shape was explicitly modeled in the thermal analysis (Section 4.4) and was found to have no significant effect on the part temperatures. Cladding outer diameter measurements for all specimens used in the irradiation experiment can be found in APPENDIX B.

Table 4. Summary of average cladding dimensional measurements

Cladding Part	Material (Grade)	Avg Length (mm)	ID (mm)	Avg OD (mm)	Max OD Deviation (mm)	Avg Gas Gap (mm)	Max OD Deviation / Avg Gas Gap (%)
C06M-01	FeCrAl (C06M)	15.885	8.79	9.533	0.008	0.096	8.4%
C06M-02	FeCrAl (C06M)	15.750	8.79	9.527	0.010	0.100	9.5%
B126Y-1	FeCrAl (B126Y)	23.498	8.76	9.509	0.008	0.109	7.5%
B126Y-2	FeCrAl (B126Y)	23.481	8.76	9.509	0.005	0.109	4.5%
B126Y-3	FeCrAl (B126Y)	23.305	8.76	9.510	0.004	0.108	4.1%
B126Y-4	FeCrAl (B126Y)	23.410	8.76	9.511	0.007	0.107	6.3%
C36M3-1	FeCrAl (C36M3)	23.359	8.79	9.535	0.002	0.095	2.5%
C36M3-2	FeCrAl (C36M3)	23.423	8.79	9.535	0.003	0.096	2.7%
C36M3-3	FeCrAl (C36M3)	23.364	8.77	9.535	0.003	0.096	3.5%
C36M3-4	FeCrAl (C36M3)	23.494	8.79	9.533	0.003	0.097	3.6%
B136Y-1	FeCrAl (B136Y)	23.399	8.78	9.528	0.005	0.098	5.6%
B136Y-4	FeCrAl (B136Y)	23.356	8.79	9.526	0.005	0.100	4.9%
Zirlo-1	ZIRLO	23.374	8.35	9.493	0.005	0.116	4.0%
Zirlo-2	ZIRLO	23.436	8.35	9.493	0.004	0.117	3.8%
Zirlo-HH-1	ZIRLO (1000 weight ppm H)	23.476	8.35	9.508	0.021	0.096	21.7%
Zirlo-MH-1	ZIRLO (500 weight ppm H)	23.476	8.37	9.511	0.014	0.095	14.7%
Zirc-4H-1	Zircaloy-4 (150 weight ppm H)	23.475	8.36	9.481	0.004	0.109	3.3%
Zirc-4H-2	Zircaloy-4 (150 weight ppm H)	23.434	8.36	9.480	0.003	0.110	2.8%
Zirc-4H-3	Zircaloy-4 (150 weight ppm H)	23.437	8.36	9.481	0.003	0.110	2.5%
ZIRLO-H-3	ZIRLO (250 weight ppm H)	23.511	8.35	9.505	0.004	0.098	3.9%
ZIRLO-H-4	ZIRLO (250 weight ppm H)	23.347	8.35	9.505	0.008	0.097	8.7%
ZIRLO-H-5	ZIRLO (250 weight ppm H)	23.441	8.35	9.504	0.002	0.098	2.5%

Note: Avg = Average, Max = Maximum, OD = Outer Diameter, ID = Inner Diameter

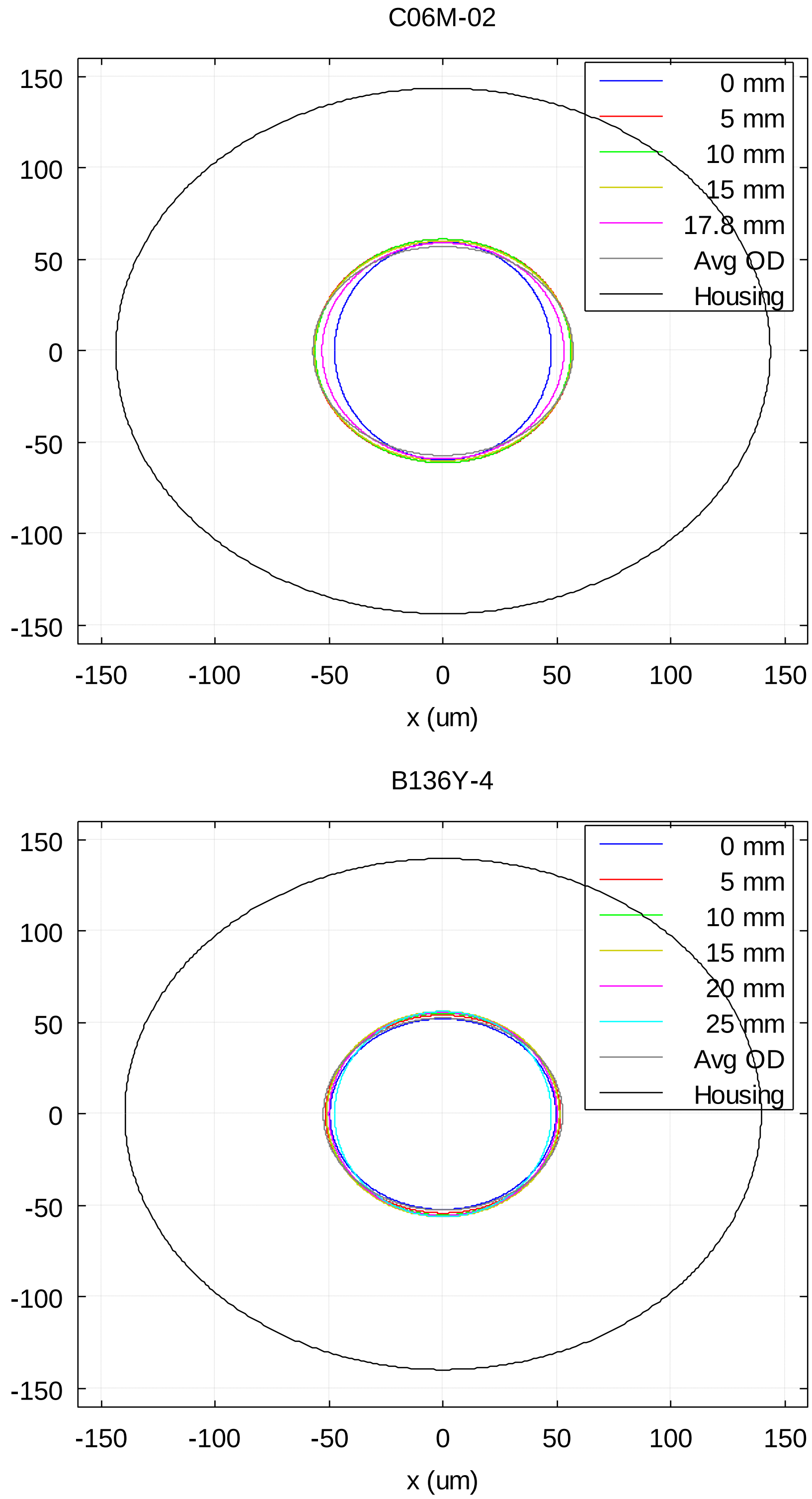

Figure 8. Cladding outer diameter measurements for two FeCrAl specimens compared to the nominal 9.70 mm housing inner diameter. All *x* and *y* values are scaled such that they are *x* and *y* distances from some arbitrary reference radius that is unique to each specimen.

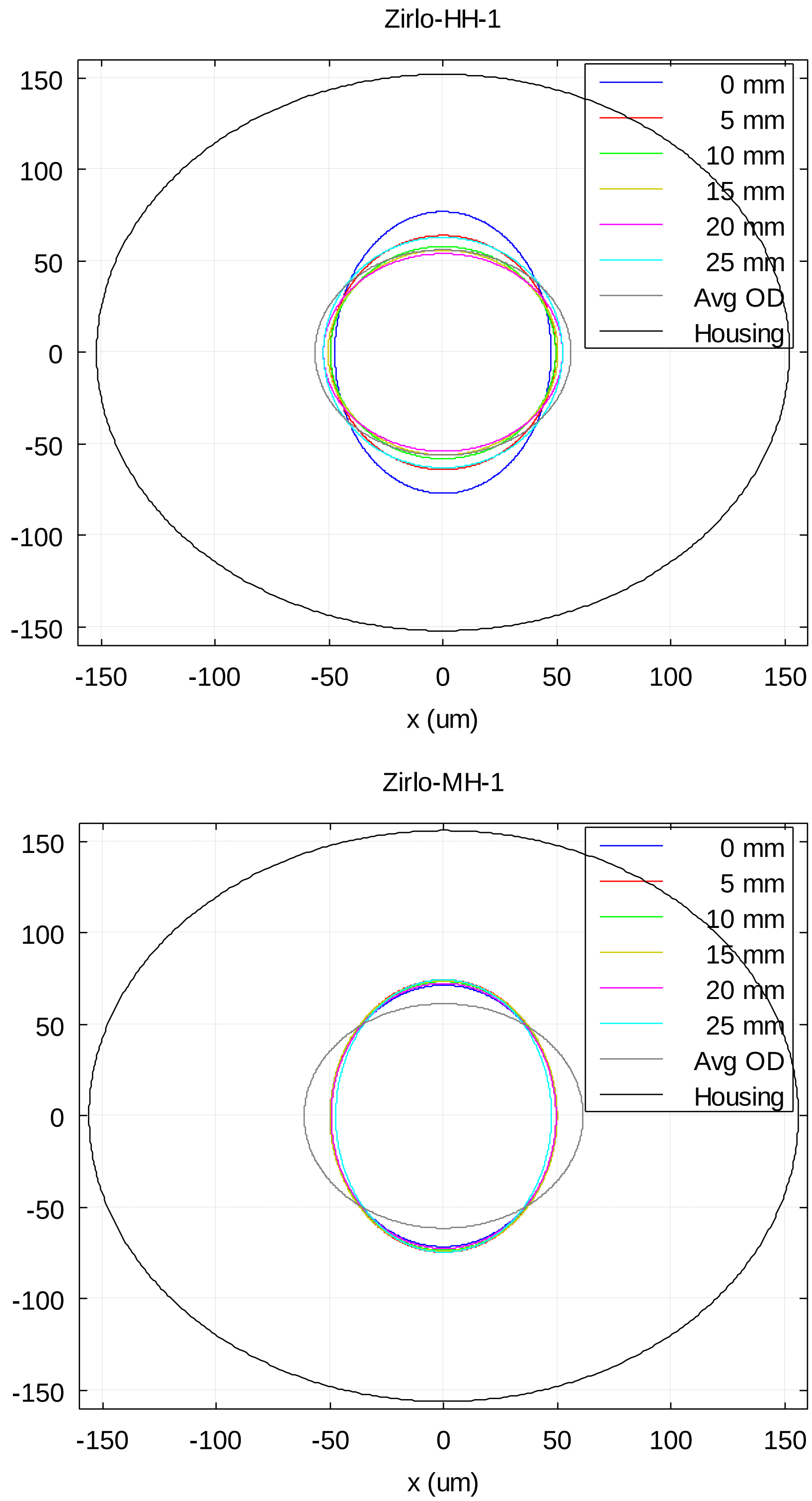

Figure 9. Cladding outer diameter measurements for two Zr-alloy specimens compared to the nominal 9.70 mm housing inner diameter. All *x* and *y* values are scaled such that they are *x* and *y* distances from some arbitrary reference radius that is unique to each specimen.

The inner diameters of the housings were inspected in a similar manner. Table 5 summarizes average dimensional measurements for all housings. The ratio of housing inner diameter deviation to gas gap assumes a nominal gas gap of 0.100 mm for all cases. The exact gas gap will depend on the specific pairing of housing and cladding. Section 4.4 shows that this nominal gap is typical for the cladding/housing pairing that was selected. Figure 10 shows one example of housing inner diameter measurements at five axial locations. Similar to the data for the cladding specimens in Figure 8 and Figure 9, the *x* and *y* values in Figure 10 are scaled such that they are *x* and *y* distances from some arbitrary reference radius that is unique to each housing. This allows one to observe the variations in the housing inner diameter at various axial locations (*z*) compared to the nominal cladding outer diameter of 9.50 mm. Both the housing inner diameter values and the nominal cladding outer diameter are scaled to the same reference radius. Figure 10 shows that housing 16-12 has an inner diameter that is constant to within ±5 μm along the entire length of the part. Housing inner diameter measurements for all parts can be found in APPENDIX B.

Table 5. Summary of average housing dimensional measurements.

Part #	**Avg ID (mm)**	**ID Max Deviation (mm)**	**ID Max Deviation / Nominal Gas gap**
16-01	9.725	0.005	5.1%
16-02	9.733	0.007	6.7%
16-03	9.726	0.004	4.3%
16-04	9.722	0.003	3.3%
16-05	9.730	0.002	1.7%
16-06	9.726	0.003	3.2%
16-07	9.727	0.006	5.5%
16-08	9.726	0.006	5.6%
16-09	9.724	0.003	3.1%
16-10	9.726	0.004	4.4%
16-11	9.719	0.002	2.0%
16-12	9.727	0.005	4.6%
16-13	9.720	0.004	4.4%
16-14	9.722	0.004	3.6%
16-15	9.723	0.003	3.3%
16-16	9.724	0.003	2.9%
16-17	9.724	0.004	4.0%
16-18	9.724	0.003	3.2%
Note: Avg = Average, Max = Maximum, ID = Inner Diameter			

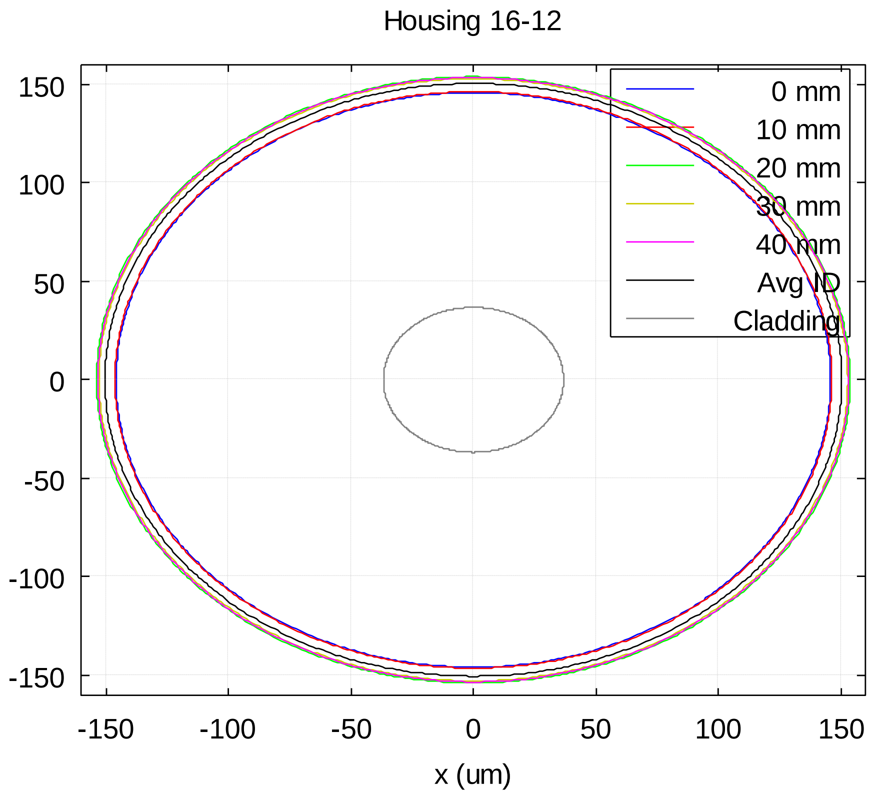

Figure 10. Measurements of one housing inner diameter at various axial locations as well as the nominal housing inner diameter. All *x* and *y* values are scaled such that they are *x* and *y* distances from some arbitrary reference radius that is unique to each specimen.

4.2 FLOW TESTING

4.2.1 Test Results

Flow tests were performed to determine flow through a PTP holder for two cases: (1) a PTP holder loaded with seven standard size rabbits and (2) a PTP holder loaded with seven large-bore rabbits. Table 6 shows the time-averaged values with errors for the flow rate (Q) and pressure drop (P) for each step in flow rate. This data is plotted in Figure 11 along with a curve fit using the bulk loss coefficient described later in this section. Measurement errors are quantified by calculating the standard deviation of the data for each interval of interest. In addition to the measurement variability, there are errors due to (1) elevation differences between the pressure transducers and the test section and (2) calibration error in the instrumentation. The error due to pressure transducer elevation effects was quantified in an earlier calculation to be 0.69 kPa (0.10 psid) [35]. As described earlier in Section 2.2.1, the calibration errors in the pressure transducers and flow meter are 0.55 kPa (0.08 psid) and 2.78 cc/s (0.044 gpm) for the differential pressure gage and flow meter, respectively. These elevation and calibration errors are of similar magnitude compared to the measurement variability. Note that the uncertainty and errors are only a few percent of the measured values.

Table 6. Averaged flow and pressure drop data for the two tests that were performed

Case 1 (seven standard rabbits)		Case 2 (seven large-bore rabbits)	
Flow rate, *Q* (cc/s)	**Pressure drop, *P* (kPa)**	**Flow rate, *Q* (cc/s)**	**Pressure drop, *P* (kPa)**
228.7±4.2	67.0±1.1	218.8±4.0	68.1±1.3
333.1±4.7	136.2±3.1	312.6±3.9	135.0±3.1
408.3±3.9	199.1±3.0	391.5±3.4	202.4±3.7
470.0±2.9	262.2±4.2	462.5±2.8	279.0±4.8
542.9±2.4	344.5±5.5	517.9±2.6	347.7±6.2
605.2±2.6	427.3±5.9	578.5±2.6	430.8±6.5

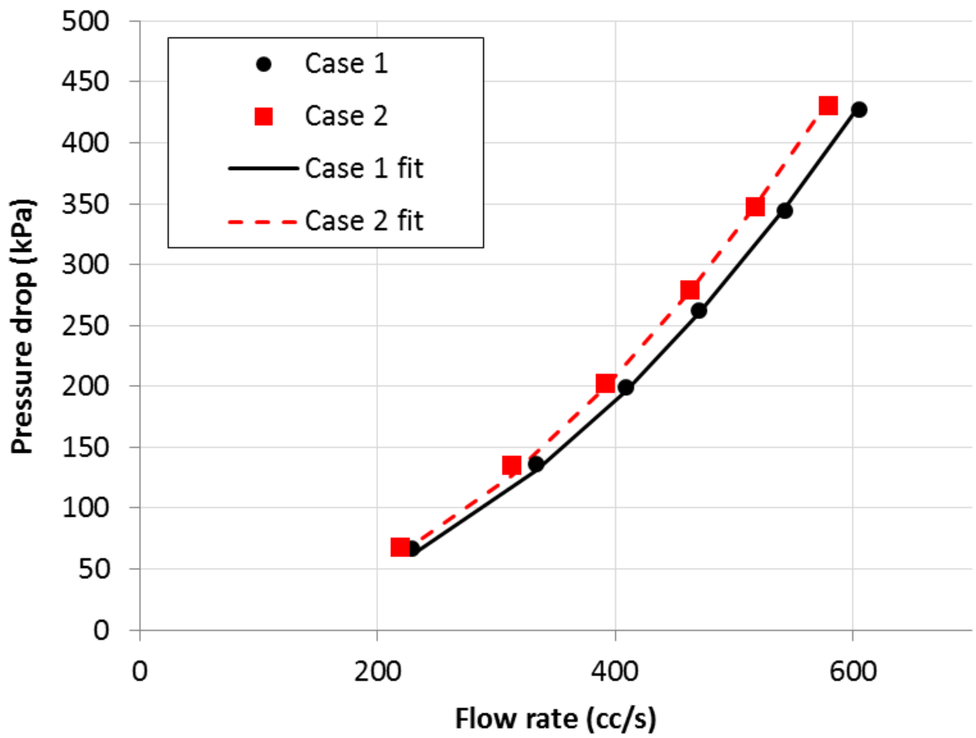

Figure 11. Pressure drop vs. flow rate data with curve fits.

The bounding limit for flow in a PTP holder is 246 cc/s (3.9 gpm) [36]. This amount of flow must be achieved when the pressure drop across the flux trap bundle (which is essentially equivalent to the pressure drop measured in the experiments described in this document) is as low as 228 kPa (33 psig) [32, 37]. Table 6 shows that for a PTP holder loaded with seven large-bore rabbits (Case 2) a flow rate of 312.6 cc/s (4.95 gpm), which is greater than the 246 cc/s requirement, can be achieved with a much lower pressure drop of 135.0 kPa (19.6 psig). Interpolation between the tabulated data gives a flow rate of 415 cc/s (6.6 gpm) at a pressure drop of 228 kPa (33 psig). Therefore, the large-bore rabbits do not have any issues with flow restriction in a PTP holder.

Additional efforts were made to determine a bulk loss coefficient for these rabbits. The functional form for the pressure drop is

$$P = \mathrm{k} \times \frac{\rho}{2} \times \left(\frac{Q}{A}\right)^2 ,$$

where k is the bulk loss coefficient for the test section (unitless), ρ is the fluid density (997.7 kg/m^3 at 22°C [38]), and A is the channel flow area (m^2). The flow channel is an annulus with four tabs in the PTP holder that keep the rabbits centered in the channel. The Creo CAD software package is used to calculate flow areas and hydraulic diameters (calculated as four times the flow area divided by the wetted perimeter) for both cases. These parameters are summarized in Table 7.

Table 7. Flow areas and hydraulic diameters for the two experiment cases

Case	Flow area (mm^2)	Hydraulic Diameter (mm)
Case 1 (7 standard rabbits)	68.99	3.40
Case 2 (7 large bore rabbits)	64.11	3.12

The single unknown in the expression for pressure drop is the bulk loss term, k. The dynamic pressure term (i.e., $\frac{\rho}{2} \times \left(\frac{Q}{A}\right)^2$) is calculated for all flow rates and all cases using the fluid density and flow areas described above. Table 8 shows the calculated dynamic pressure and the measured pressure drop for all measured flow rates and both test cases. Ignoring uncertainty in the fluid density and the channel flow area, uncertainties in the dynamic pressures (as a percent) are equal to twice those of the flow rates listed in Table 6 due to the dependence of dynamic pressure on the square of the flow rate. Figure 12 shows pressure drop vs. dynamic pressure for Cases 1 and 2, along with linear least-squares fits that determine the scaled bulk loss coefficient k. The loss coefficients (i.e., k) for Cases 1 and 2 are calculated to be 11.22 and 10.71, respectively. This means that for a given dynamic pressure, the system pressure drop is higher for Case 1 compared to Case 2.

Table 8. Dynamic pressure and pressure drop (loss pressure) for the two experiment cases

Case 1 (seven standard rabbits)		Case 2 (seven large-bore rabbits)	
Dynamic pressure (kPa)	**Pressure drop (kPa)**	**Dynamic pressure (kPa)**	**Pressure drop (kPa)**
5.5	67.0	5.8	68.1
11.6	136.2	11.9	135.0
17.5	199.1	18.6	202.4
23.2	262.2	26.0	279.0
30.9	344.5	32.6	347.7
38.4	427.3	40.6	430.8

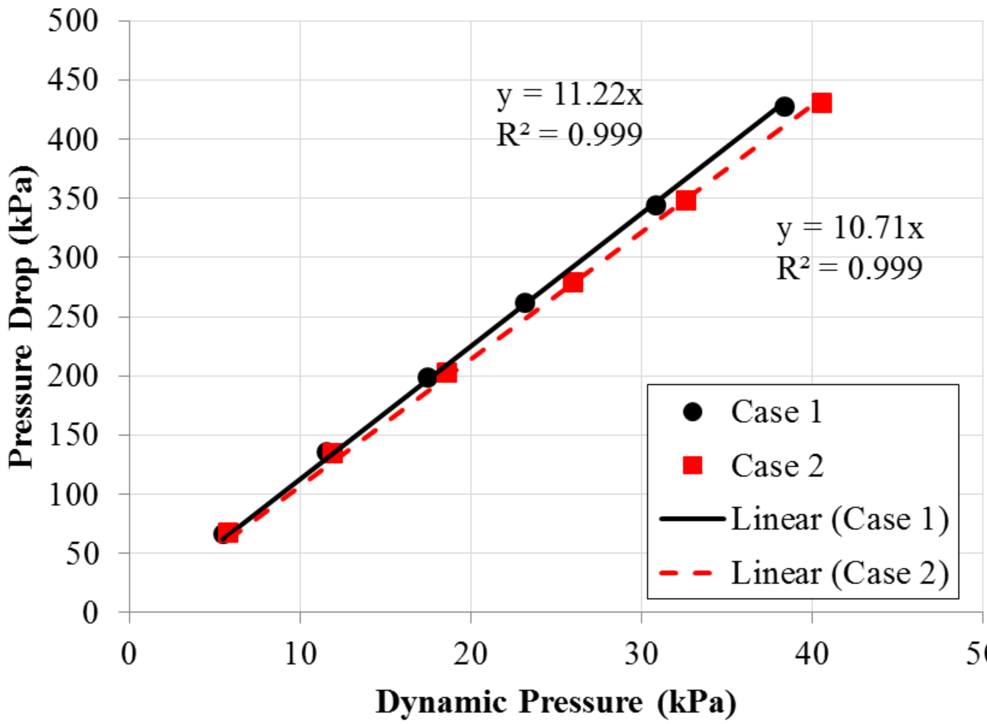

Figure 12. Pressure drop vs. dynamic pressure for Cases 1 and 2.

4.2.2 Convective Heat Transfer Coefficients

The results from this flow experiment and analysis show that large-bore rabbit capsules have a slight reduction in flow rate inside a PTP holder, when compared to standard rabbit capsules in a PTP holder. However, the benchmark flow characteristics for the standard rabbit case, as detailed in C-HFIR-2001-026, are 231.91 cc/s (3.66 gpm) at 228 kPa (33 psid) [36]. It is clear that the improved flow test data from the present experiment show flow that greatly outperforms the benchmark data. At 228 kPa (33 psid) Case 1 yields 437 cc/s (6.9 gpm) and Case 2 yields 415 cc/s (6.6 gpm).

While this improvement in flow satisfies concerns regarding flow restrictions with the large-bore rabbits, there is some concern that the significantly increased flow could affect the thermal analyses that were performed using convective heat transfer coefficients that assumed benchmark flow data. The average convective heat transfer coefficient for the PTP facility was calculated to be 48.4 kW/m^2-K with a volumetric flow rate of 306 cc/s [32]. This is the value that is used later in the thermal analyses described in Section 4.4. This value was determined using a Nusselt number calculated using the following correlation:

$$Nu = 0.027\, Re^{0.8}\, Pr^{1/3} \left(\frac{\mu_b}{\mu_w}\right)^{0.14},$$

where *Nu* is the Nusselt number, *Re* the Reynolds number, *Pr* the Prandtl number, μ_b the bulk liquid viscosity, and μ_w the wall liquid viscosity. For the large-bore rabbit case (LB), the average Reynolds number (Re_{LB}) can be scaled from the reference (ref) value (Re_{ref}) using the volumetric flow rates (Q_{lb} and Q_{ref}), hydraulic diameters (D_{lb} and D_{ref}), and flow areas (A_{lb} and A_{ref}). This way, the calculated value for Re_{LB} is

$$Re_{LB} = \frac{\frac{Q_{lb}D_{lb}}{A_{lb}}}{\frac{Q_{ref}D_{ref}}{A_{ref}}} Re_{ref} = \frac{\frac{[415\ \text{cm}^3/\text{s}][3.12\ \times 10^{-3}\ \text{m}]}{[6.41 \times 10^{-5}\ \text{m}^2]}}{\frac{[306\ \text{cm}^3/\text{s}][2.15\ \times 10^{-3}\ \text{m}]}{[4.06 \times 10^{-5}\ \text{m}^2]}} [30{,}865] = 38{,}475\ .$$

Note that there is a significant difference in the flow areas and hydraulic diameters for the large-bore case compared to the reference case. The primary reason for this difference is that the large-bore rabbits were tested with the latest PTP holder design with centering tabs. The new PTP holder results in significantly larger flow areas and hydraulic diameters. The average Nusselt number for the large-bore case (Nu_{LB}) can be calculated from the average Nusselt number for the reference case (Nu_{ref}) scaled by the ratio of Reynolds number to the 0.8 power. Nu_{LB} is calculated to be

$$Nu_{LB} = \frac{{Re_{LB}}^{0.8}}{{Re_{ref}}^{0.8}} Nu_{ref} = \frac{[38{,}475]^{0.8}}{[30{,}865]^{0.8}} [160] = 191\ .$$

Finally, the convective heat transfer coefficient for the large-bore case (D_{lb}) is calculated using Nu_{LB}, D_{lb}, and the average thermal conductivity of the coolant ($k_{coolant}$) to be

$$h_{LB} = \frac{Nu_{LB}k_{coolant}}{D_{lb}} = \frac{[191][0.65 \frac{\text{W}}{\text{m K}}]}{[3.12\ \times 10^{-3}\ \text{m}]} = 39{,}792\ \frac{\text{W}}{\text{m}^2\text{K}}\ .$$

These calculations show that the large-bore convective heat transfer coefficient is roughly 18% lower than the reference case. However, this will not significantly affect capsule component temperatures as the temperature drop from the housing outer surface to the bulk coolant is ~2°C. Changing this temperature drop by 18% will result in less than a 0.4°C difference in component temperatures.

4.3 NEUTRONICS ANALYSIS

Table 9 summarizes the total peak heat generation rates for the aluminum housing, molybdenum sleeve, FeCrAl cladding, and Zircaloy-4 cladding during irradiation in PTP and TRRH positions. Results are shown at BOC and EOC, as well as the average of BOC and EOC values. Variations from BOC to EOC are relatively small (in the range of 3–6%). These variations are primarily due to the region within the HFIR fuel with the highest fission density moving radially outward toward the EOC. As a result, gammas born during the fission process experience increased attenuation as they must travel a longer distance before reaching the experiment materials. PTP heat generation rates are higher than those in TRRH positions because of the closer proximity of PTP positions to the fuel. As expected, heat generation rates increase with atomic number due to increased gamma absorption. Increased gamma absorption in the Zircaloy-4 cladding also explains why molybdenum (located inside the cladding) heat generation rates are lower for Zircaloy-4 cladding compared to FeCrAl cladding.

Table 9. Heat generation rates (W/g) for various materials at BOC and EOC in PTP and TRRH centerline positions

		BOC		EOC		Average	
Cladding Material	**Component**	**PTP**	**TRRH**	**PTP**	**TRRH**	**PTP**	**TRRH**
FeCrAl	Aluminum housing	30.7	29.6	29.3	28.3	30.1	29.0
	Molybdenum sleeve	44.3	43.3	42.9	41.6	43.6	42.5
	FeCrAl cladding	35.2	34.4	33.6	32.6	34.4	33.5
Zircaloy-4	Aluminum housing	30.0	29.0	28.5	27.7	29.3	28.3
	Molybdenum sleeve	41.7	40.5	40.2	39.1	41.0	39.8
	Zircaloy-4 cladding	47.4	46.2	44.8	44.0	46.1	45.1

Table 10 summarizes the percentage contributions from the various source of heat generation. Results are shown for aluminum, molybdenum, FeCrAl, and Zircaloy-4 in a PTP position at BOC and EOC. Aluminum and molybdenum results are shown only for the case with a FeCrAl cladding. Percentages do not change significantly with varying position or cladding material. Clearly, prompt photons and fission product decay photons are the dominant sources of heat generation in these materials. Neutron heating decreases with increasing atomic number. Therefore, neutron heating is most significant in aluminum (the material with the lowest atomic number); however, even for aluminum, this contribution is less than 4% of the total heat generation rate. Local decay heat is mostly negligible except for aluminum, which has a somewhat significant contribution from local decay heat due to the rapid beta decay of aluminum-28, which is produced from the (n,g) reaction in aluminum-27.

Table 10. Contributions to heat generation rates in experiment materials from various sources at BOC and EOC in PTP positions

Material	**Fission Neutrons**		**Fission Photons**		**Fission Product Photons**		**Local Decay Heating**	
	BOC	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**
Al6061	3.3%	3.0%	66.3%	66.6%	27.2%	26.6%	3.3%	3.8%
FeCrAl	3.0%	3.1%	67.9%	68.3%	28.9%	28.3%	0.3%	0.3%
Molybdenum	0.1%	0.1%	68.9%	68.8%	30.8%	30.7%	0.2%	0.5%
Zirc4	0.7%	0.6%	66.3%	66.5%	33.0%	32.9%	0.0%	0.0%

4.4 THERMAL ANALYSIS

4.4.1 Test Matrix and Evaluation Cases

Thermal analyses were performed for each rabbit that is to be irradiated. These analyses determine temperature distributions within the experiment using as-built housing and specimen dimensions and the desired fill gas (i.e., the specific helium/argon mixture). The cladding specimens were modeled as ovals with major and minor diameters equal to the average major and minor diameters, respectively, over the entire length of the part. In this way, the ovality of the specimens is considered but variations in the ovality are not. However, as summarized in Section 4.1, the specimens generally showed little diameter variations along the length except for a few specimens that showed significant variations that were limited to one end of the specimen. The housings were modeled as plain cylinders because the dimensional measurements did not show any significant variations in the housing inner diameter.

Table 11 summarizes the irradiation test matrix, cladding specimen, housing, and sleeve pairing, gas gaps (using average cladding and housing dimensions), and gas mixtures for each rabbit. Cladding specimens were paired with specific housings so that rabbits could be grouped together with others that have a similar gas gap (and thus a similar gas mixture, assuming the heat flux through the cladding-to-housing gas gap is approximately the same). Each rabbit can accommodate two cladding specimens, so efforts were made to pair specimens with similar outer diameters. However, in order to irradiate a wide variety of materials to varying dose levels, two different specimen material grades (with slightly different geometry) were often loaded into a single rabbit to reduce the total number of rabbits (for cost reasons). Because the different specimen material grades produced slightly different outer diameters, it was sometimes impossible to achieve the same gas gap for both specimens within each rabbit.

Previous irradiations of Zr-alloy cladding with molybdenum on the inside resulted in the molybdenum parts getting stuck inside the cladding [39]. In this work, the molybdenum sleeves were machined such that the gap between the sleeve and the cladding was large enough that it would not close due to sleeve swelling and cladding shrinkage (for the case of Zr-alloy cladding specimens). Zr-alloys are known to grow in the axial (<a> axis) direction during irradiation in a constant-volume process, resulting in a concomitant shrinkage in the radial direction with a magnitude that is approximately half of the <a> axis growth. The observed growth rate in the <a> axis for both an as-extruded Zr-alloy and a cold-worked Zircaloy-2 tube during neutron irradiation was 0.06% per dpa [40]. Growth rates for annealed Zircaloy-2 and cold-worked Zircaloy-2 in other geometries were much less and in some cases were as low as 0.012% per dpa. Growth rates for the Zr-alloy tubes that are to be irradiated in this experiment are conservatively assumed to be 0.06% per dpa. The maximum dose to which the specimens will be exposed is 26 dpa, which results in an <a> axis growth strain of 1.6%, or a radial shrinkage of ~0.8%.

Radiation-induced dimensional changes in FeCrAl (a ferritic alloy) are expected to be negligible [41, 42], with the possibility of very minor swelling, which would increase the sleeve-to-cladding gap. Volumetric radiation swelling of molybdenum was assumed to be at most 2% (0.67% linear swelling), which is the maximum observed swelling for low-carbon arc cast molybdenum in the literature [43]. For Zr-alloy cladding with a maximum inner diameter of 8.79 mm (4.40 mm inner radius), gap closure due to both Zr-alloy radial shrinkage and molybdenum swelling would be at most 4.40 mm × (0.8% + 0.67%) = 0.065 mm. This calculation is also conservative because it assumes that the molybdenum sleeve outer diameter is equal to the cladding inner diameter. For FeCrAl cladding with a maximum cladding inner diameter of 8.37 mm (4.19 mm inner radius), gap closure due to molybdenum swelling would be at most 4.19 mm × 0.67% = 0.028 mm. Table 11 shows that all sleeve-to-cladding gaps are greater than 0.065 mm and 0.028 mm for Zr-alloy and FeCrAl cladding, respectively.

Table 11. Irradiation test matrix, cladding specimen, housing, and sleeve pairing, gas gaps (using average cladding and housing dimensions), and gas mixtures for each rabbit

Case	Loc	Hous Part #	Specimen Part #	Avg hous ID (mm)	Clad ID (mm)	Avg clad minor OD (mm)	Avg clad major OD (mm)	Sleeve OD (mm)	Avg clad-to-hous gap (mm)	Sleeve-to-clad gap (mm)	Fill gas He fraction
FCF01	TRRH-3	16-16	C06M-01	9.724	8.79	9.528	9.538	8.69	0.095	0.050	0.92
			B136Y-1		8.78	9.524	9.532	8.67	0.098	0.055	
FCF02	TRRH-5	16-06	C06M-02	9.726	8.79	9.521	9.533	8.69	0.099	0.050	0.97
			B136Y-4		8.79	9.521	9.531	8.71	0.100	0.040	
FCF03	TRRH-3	16-07	B126Y-1	9.727	8.76	9.498	9.520	8.65	0.109	0.055	0.97
			C36M3-4		8.79	9.530	9.536	8.70	0.097	0.045	
FCF04	TRRH-5	16-12	B126Y-2	9.727	8.76	9.503	9.515	8.66	0.109	0.050	0.97
			C36M3-2		8.79	9.531	9.539	8.71	0.096	0.040	
FCF05	TRRH-5	16-03	B126Y-3	9.726	8.76	9.503	9.517	8.66	0.108	0.050	0.97
			C36M3-3		8.77	9.531	9.539	8.66	0.096	0.055	
FCF06	TRRH-5	16-01	B126Y-4	9.725	8.76	9.501	9.520	8.66	0.107	0.050	0.97
			C36M3-1		8.79	9.531	9.539	8.71	0.095	0.040	
FCZ01	TRRH-3	16-17	Zirlo-1	9.724	8.35	9.490	9.496	8.20	0.116	0.075	1
			ZIRLO-MH-1		8.37	9.487	9.535	8.21	0.107	0.080	
FCZ02	PTP-6	16-05	Zirlo-2	9.730	8.35	9.490	9.496	8.21	0.119	0.070	1
			ZIRLO-HH-1		8.35	9.497	9.520	8.21	0.111	0.070	
FCZ03	TRRH-3	16-13	Zirc-4H-1	9.720	8.36	9.477	9.485	8.21	0.120	0.075	1
			ZIRLO-H-3		8.35	9.500	9.510	8.21	0.108	0.070	
FCZ04	PTP-6	16-15	Zirc-4H-2	9.723	8.36	9.477	9.483	8.20	0.122	0.080	1
			ZIRLO-H-4		8.35	9.502	9.508	8.20	0.109	0.075	
FCZ05	PTP-6	16-14	Zirc-4H-3	9.722	8.36	9.477	9.484	8.21	0.121	0.075	1
			ZIRLO-H-5		8.35	9.502	9.507	8.18	0.109	0.085	

Note: TRRH = Target Rod Rabbit Holder, PTP = Peripheral Target Position, Avg = Average,
OD = Outer Diameter, ID = Inner Diameter, Loc = Location, Hous = Housing, Clad = Cladding

4.4.2 Predicted Temperatures

Figure 13 and Figure 14 show examples of temperature contours for the rabbit assembly and specimens for rabbits FCF04 and FCZ03, respectively. The FCF04 rabbit is in a TRRH-5 position, which is just above the core midplane. Therefore, there is a small (<10%) reduction in heat generation moving from the bottom to the top of the rabbit. On the other hand, the bottom components are in direct contact with the cool bottom of the rabbit housing. The net effect is that the bottom specimen is at a slightly lower temperature than the top specimen, indicating that axial heat losses are more significant than the axial power profile effects. However, the effects of the axial variation in heat generation can be observed in the temperatures of the sleeves, centering thimbles, and wires. The FCZ03 rabbit is just below the core midplane. In this case, heat generation increases moving from the bottom to the top of the rabbit. Therefore, the effects of the axial variation in heat generation act in the same direction as the axial heat losses at the bottom of the rabbit. This explains why for rabbit FCZ03 the top sleeve and specimen are at higher temperatures compared to the bottom sleeve and specimen.

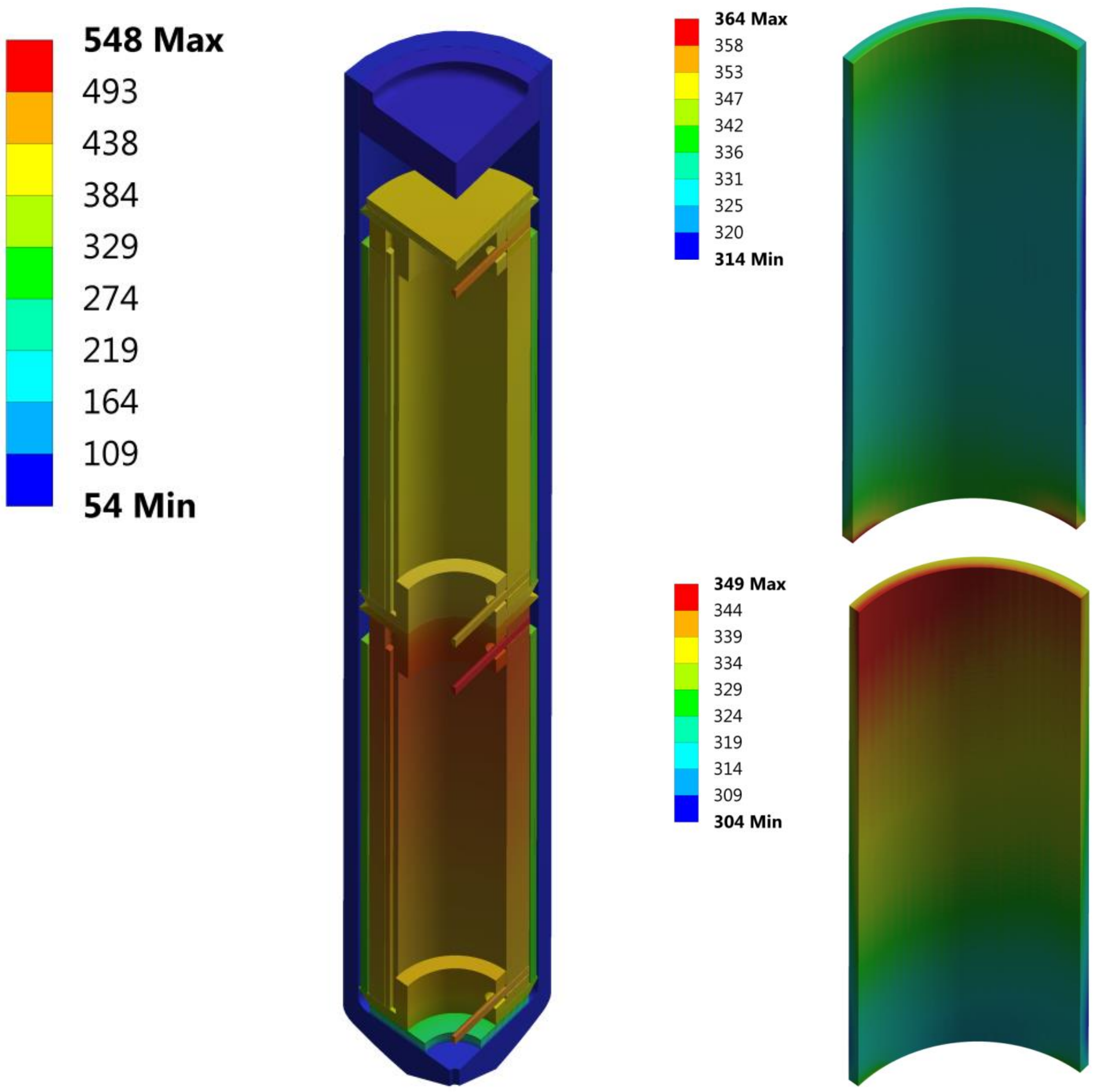

Figure 13. Temperature contours for the FCF04 rabbit assembly (left), bottom FeCrAl specimen (bottom right), and top FeCrAl specimen (top right).

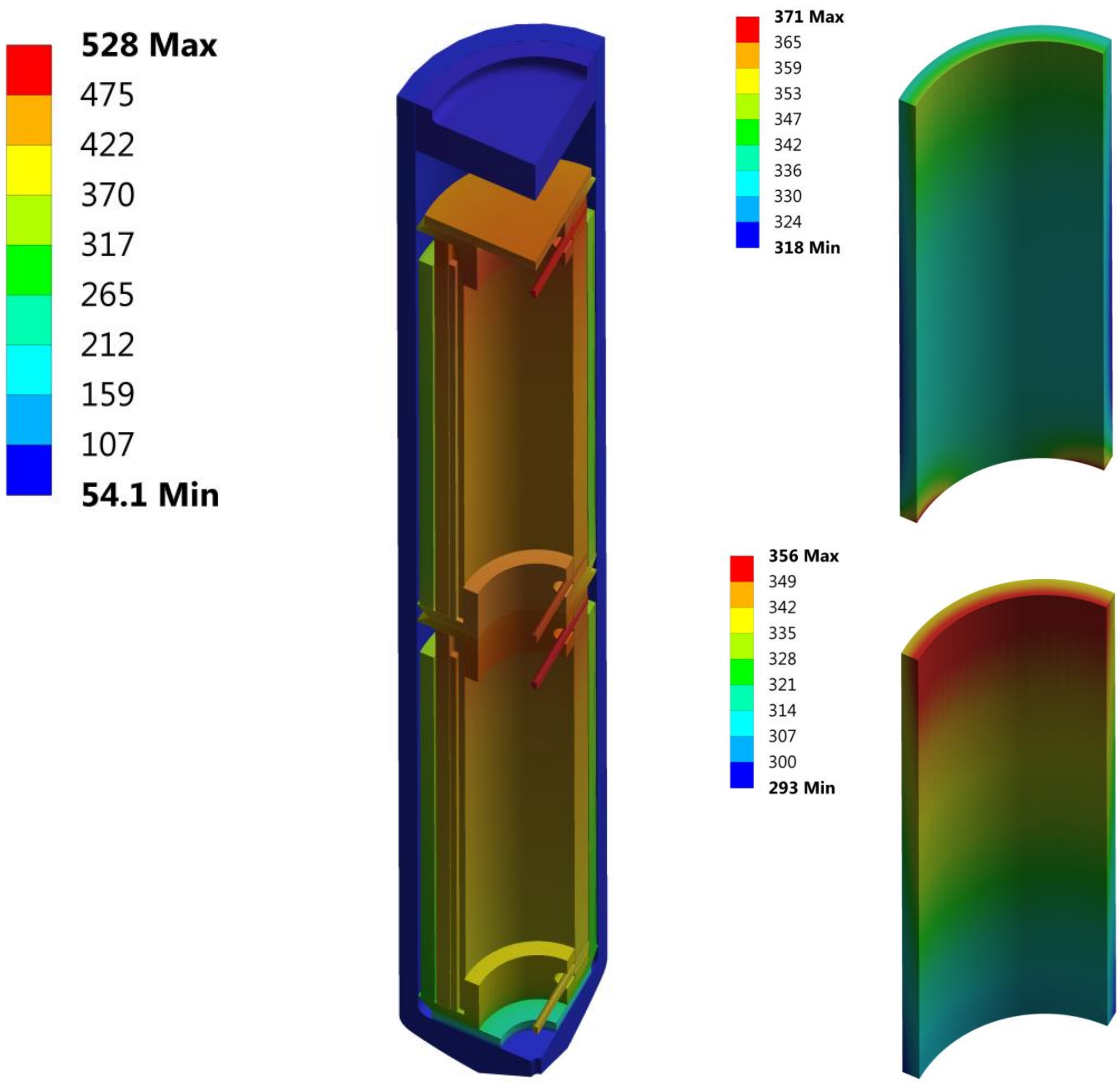

Figure 14. Temperature contours for the FCZ03 rabbit assembly (left), bottom Zr-alloy specimen (bottom right), and top Zr-alloy specimen (top right).

Table 12 summarizes average, minimum, and maximum temperatures for the specimens in each rabbit capsule. Table 13 summarizes average, minimum, and maximum temperatures for the thermometry, which will be compared to temperatures determined post-irradiation using dilatometry. More details are provided in the full ANSYS output files that can be found in APPENDIX C. Average specimen temperatures range from 315–345°C, which is within the desired range of 300–350°C. Minimum temperatures are as low as 288°C at the bottom of the bottom-most specimen. Maximum temperatures are as high as 384°C, although these temperatures are typically limited to small regions at the bottom of the top specimen close to the tabs of the centering thimbles. Although it was not explicitly modeled, closure of the sleeve-to-cladding gap due to sleeve swelling and (for Zr-alloy cladding) cladding growth will slightly increase the cladding temperatures, particularly for the bottom cladding specimen. The reason for this is that before gap closure there is some amount of heat generated in the sleeve that is lost due to conduction through the bottom centering thimble and the grafoil insulators. These heat losses reduce the amount of heat that is transferred to the cladding through the sleeve-to-cladding gas gap and thus reduce the cladding temperature. As the sleeve-to-cladding gap closes, heat will be more encouraged to pass through the sleeve-to-cladding gap instead of traveling down to the housing bottom, which will increase the heat flux through the cladding-to-housing gap and increase the cladding temperature. As a point of comparison, the top cladding specimen does not show significant axial temperature gradients, indicating that axial heat losses in the top specimen are negligible. Therefore, it is reasonable to assume that the temperature of the bottom cladding specimen will be somewhere between the calculated temperatures of the bottom and top specimens after sleeve-to-cladding gap closure.

Table 12. Predicted cladding temperatures for each rabbit

					Temperature (°C)		
Rabbit	**Cladding material**	**Position**	**He %**	**Part**	**Average**	**Minimum**	**Maximum**
FCF01	FeCrAl	TRRH-3	92	C06M-01	322	295	354
				B136Y-1	345	332	384
FCF02	FeCrAl	TRRH-5	97	C06M-02	317	293	343
				B136Y-4	329	318	366
FCF03	FeCrAl	TRRH-3	97	B126Y-1	315	289	340
				C36M3-4	330	317	364
FCF04	FeCrAl	TRRH-5	97	B126Y-2	328	304	349
				C36M3-2	326	314	364
FCF05	FeCrAl	TRRH-5	97	B126Y-3	330	305	355
				C36M3-3	318	307	363
FCF06	FeCrAl	TRRH-5	97	B126Y-4	324	301	347
				C36M3-1	324	312	361
FCZ01	Zr-alloy	TRRH-3	100	Zirlo-1	316	288	344
				ZIRLO-MH-1	331	311	375
FCZ02	Zr-alloy	PTP-6	100	Zirlo-2	341	312	367
				ZIRLO-HH-1	336	322	383
FCZ03	Zr-alloy	TRRH-3	100	Zirc-4H-1	326	293	356
				ZIRLO-H-3	332	318	371
FCZ04	Zr-alloy	PTP-6	100	Zirc-4H-2	344	314	369
				ZIRLO-H-4	331	319	379
FCZ05	Zr-alloy	PTP-6	100	Zirc-4H-3	344	313	371
				ZIRLO-H-5	328	317	377

Table 13. Predicted passive temperature monitor (TM) temperatures for each rabbit

					Temperature (°C)		
Rabbit	**Cladding material**	**Position**	**He (%)**	**Part**	**Average**	**Minimum**	**Maximum**
FCF01	FeCrAl	TRRH-3	92	Bottom TM	447	383	490
				Top TM	509	496	535
FCF02	FeCrAl	TRRH-5	97	Bottom TM	444	385	477
				Top TM	445	439	463
FCF03	FeCrAl	TRRH-3	97	Bottom TM	461	396	493
				Top TM	430	422	452
FCF04	FeCrAl	TRRH-5	97	Bottom TM	474	411	500
				Top TM	416	409	435
FCF05	FeCrAl	TRRH-5	97	Bottom TM	462	400	494
				Top TM	452	446	469
FCF06	FeCrAl	TRRH-5	97	Bottom TM	471	409	497
				Top TM	414	407	432
FCZ01	Zr-alloy	TRRH-3	100	Bottom TM	437	368	475
				Top TM	452	445	474
FCZ02	Zr-alloy	PTP-6	100	Bottom TM	450	384	484
				Top TM	455	449	470
FCZ03	Zr-alloy	TRRH-3	100	Bottom TM	430	362	469
				Top TM	458	451	480
FCZ04	Zr-alloy	PTP-6	100	Bottom TM	458	389	492
				Top TM	462	456	476
FCZ05	Zr-alloy	PTP-6	100	Bottom TM	453	386	489
				Top TM	470	465	485

5. SUMMARY AND CONCLUSIONS

This work summarizes the capsule design, neutronic and thermal analyses, and flow testing that were performed to support the qualification of a new irradiation vehicle for testing representative PWR fuel cladding in the HFIR under relevant temperatures. This design allows for PIE of cladding that closely resembles expected commercially viable geometries and microstructures. PIE will include studies of dimensional change, microstructure variation, and mechanical performance for both advanced cladding materials (primarily FeCrAl alloys) and traditional Zr-alloys, both with and without hydriding. The experiments were designed using relatively inexpensive HFIR rabbit capsules, which will allow for rapid testing of a large test matrix. Coupled MCNP + ORIGEN calculations were performed to give accurate estimates of neutron and gamma heating of the capsule components during irradiation. Thermal calculations were performed using finite-element analysis software to determine temperatures of the capsule components during irradiation. Inputs to these calculations include the calculated heating rates, geometry determined from high-precision dimensional inspection, and convection parameters determined from fluid dynamics calculations. Flow testing was performed to show that the new irradiation vehicles would have adequate cooling during irradiation. This work will help support the qualification of advanced fuel cladding materials, which will ultimately improve the accident tolerance of operating nuclear reactors.

6. WORKS CITED

1. Northwood, D.O. and U. Kosasih, *Hydrides and delayed hydrogen cracking in zirconium and its alloys,* International Metals Reviews, **28** (1983) p. 92-121.
2. Cathcart, J.V., et al., Zirconium metal-water oxidation kinetics. IV. Reaction rate studies, ORNL/NUREG-17, Oak Ridge National Laboratory: Oak Ridge, TN (1977).
3. Garzarolli, F., et al. *Oxide growth mechanism on zirconium alloys*. in *Zirconium in the Nuclear Industry: Ninth International Symposium*. 1991. Kobe, Japan: ASTM International.
4. Zinkle, S.J., et al., *Accident tolerant fuels for LWRs: A perspective,* Journal of Nuclear Materials, **448** (2014) p. 374-379.
5. Pint, B.A., et al., *Material Selection for Accident Tolerant Fuel Cladding,* Metallurgical and Materials Transactions E, **2** (2014) p. 190-196.
6. Terrani, K.A., S.J. Zinkle, and L.L. Snead, *Advanced Oxidation-Resistant Iron-Based Alloys for LWR Fuel Cladding,* Journal of Nuclear Materials, **448** (2014) p. 420-435.
7. Yamamoto, Y., et al., *Development and property evaluation of nuclear grade wrought FeCrAl fuel cladding for light water reactors,* Journal of Nuclear Materials, **467** (2015) p. 703-716.
8. Rebak, R., *Ferritic Alloys as Accident Tolerant Fuel Cladding Material for Light Water Reactors,* Metallurgical and Materials Transactions E, **2** (2014) p. 74.
9. Field, K.G., et al., Database on Performance of Neutron Irradiated FeCrAl Alloys, ORNL/TM(2016/335, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
10. Field, K.G., et al., *Radiation Tolerance of Neutron-Irradiated Model Fe-Cr-Al Alloys,* Journal of Nuclear Materials, **465** (2015) p. 746-755.
11. Field, K.G., et al., *Heterogeneous dislocation loop formation near grain boundaries in a neutron-irradiated commercial FeCrAl alloy,* Journal of Nuclear Materials, **483** (2017) p. 54-61.
12. *High Flux Isotope Reactor Technical Parameters*. [cited 2016 27 July]; Available from: http://neutrons.ornl.gov/hfir/parameters.
13. Campbell, A., et al., *Method for analyzing passive silicon carbide thermometry with a continuous dilatometer to determine irradiation temperature,* Nuclear Instruments and Methods in Physics Research B, **370** (2016) p. 49-58.
14. Petrie, C.M., *X3E020977A689, Rev. 0*, Target Capsule Housing Details, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
15. Petrie, C.M., *X3E020977A690, Rev. 0*, Target Capsule Housing Details, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
16. McDuffee, J.L., *X3E020977A634, Rev. B*, Target Capsule Housing/End Cap Detail, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2017).
17. Petrie, C.M., *S16-10-FLEXCLAD01, Rev. 1*, Flexible Cladding Rabbits Assembly, Oak Ridge National Laboratory: Oak Ridge, TN (2017).
18. Petrie, C.M., *S16-11-FLEXCLAD02, Rev. 1*, Flexible Cladding Rabbits Assembly and Part Details, Oak Ridge National Laboratory: Oak Ridge, TN (2017).
19. Xoubi, N. and R.T. Primm III, *ORNL/TM-2004/251*, Modeling of the High Flux Isotope Reactor Cycle 400, Oak Ridge, TN (2005).
20. McDuffee, J.L., Thermophysical Properties for AL6061, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2013).
21. *CINDAS, LLC: Global Benchmark for Critically Evaluated Materials Properties Data*. 27 July [cited 2016 27 July]; Available from: http://cindasdata.com.
22. *MatWeb: Material Property Data*. MatWeb.com [cited 2016 27 July]; Available from: http://matweb.com/.

23. Wahid, S.M.S. and C.V. Madhusudana, *Gap conductance in contact heat transfer,* International Journal of Heat and Mass Transfer, **43** (2000) p. 4483-4487.
24. McDuffee, J.L., *DAC-10-03-PROP_AL6061, Rev.2*, Thermophysical Properties for AL6061, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2013).
25. Petrie, C.M., *DAC-16-02-PROP_FeCrAl, Rev. 0*, Thermophysical Properties for FeCrAl, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
26. McDuffee, J.L., *DAC-11-03-PROP_ZIRCALOY, Rev. 2*, Thermophysical Properties for Zircaloy, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
27. McDuffee, J.L., *DAC-11-14-PROP_TI6AL4V, Rev. 1*, Thermophysical Properties for Titanium Alloy Ti-6Al4V, Oak Ridge National Laboratory: Oak Ridge, TN (2013).
28. McDuffee, J.L., *DAC-11-16-PROP_GRAFOIL, Rev. 0*, Thermophysical Properties for Flexible Graphite, Oak Ridge National Laboratory: Oak Ridge, TN (2013).
29. McDuffee, J.L., *DAC-10-06-PROP_SIC(IRR), Rev. 2*, Thermophysical Properties for Irradiated SiC, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2013).
30. McDuffee, J.L., *DAC-10-11-PROP_MOLY, Rev. 1*, Thermophysical Properties for Molybdenum, Oak Ridge National Laboratory: Oak Ridge, TN (2013).
31. McDuffee, J.L., *DAC-10-02-PROP_HELIUM, Rev. 0*, Thermophysical Properties for Helium, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2010).
32. McDuffee, J.L., *DAC-11-01-RAB03, Rev. 0*, Heat Transfer Coefficients and Bulk Temperatures for HFIR Rabbit Facilities, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2011).
33. Daily, C., *C-HFIR-2013-003, Rev. 0*, Heat Generation Rates for Various Titanium and Silicon Compounds in the Flux Trap of HFIR, Oak Ridge National Laboratory: Oak Ridge, TN (2013).
34. McDuffee, J.L., *DAC-10-18-RAB02, Rev. 0*, Heat Generation Rates for Various Rabbit Materials in the Flux Trap of HFIR, Oak Ridge National Laboratory, Thermal Hydraulics and Irradiation Engineering Group: Oak Ridge, TN (2011).
35. Howard, R.H., *C-HFIR-2015-002, Rev. 0*, FlowTest to Support Light Curium Targets in a Seven Hole Large VXF Holder, Oak RIdge National Laboratory: Oak RIdge, TN (2015).
36. Carbajo, J.J., *C-HFIR-2001-026, Rev. 0*, RELAP analysis of the PTT Irradiation Facility, Oak RIdge National Laboratory: (2002).
37. Hobbs, R.W., *C-HFIR-1994-052, Rev. 0*, Calculation of target-region flow and pressure-drop perturbations due to increased use of solid dummy target rods, Oak Ridge National Laboratory: Oak Ridge, TN (1994).
38. Lide, D.R., *Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Phyical Data*. 71st Edition ed, ed. R.C. Weast. 1990: CRC Press.
39. Ott, L.J., et al. *Preparation of Prototypic Irradiated Hydrided-Zircaloy Cladding*. in *Proceedings of Top Fuel 2013*. 2013. Charlotte.
40. Holt, R.A., *Mechanisms of irradiation growth of alpha-zirconium alloys,* Journal of Nuclear Materials, **159** (1988) p. 310-338.
41. Terrani, K.A., T.M. Karlsen, and Y. Yamamoto, Input Correlations for Irradiation Creep of FeCrAl and SiC Based on In-Pile Halden Test Results, ORNL/TM-2016/191, Oak Ridge National Laboratory: Oak Ridge, TN (2016).
42. Garner, F.A., M.B. Toloczko, and B.H. Sencer, *Comparison of swelling and irradiation creep behavior of fcc-austenitic and bcc-ferritic/martensitic alloys at high neutron exposure,* Journal of Nuclear Materials, **276** (2000) p. 123-142.
43. Cockeram, B.V., et al., *The swelling, microstructure, and hardening of wrought LCAC, TZM, and ODS molybdenum following neutron irradiation*, Journal of Nuclear Materials, **418** (2011) p. 121-136.

APPENDIX A. SELECT ATTACHMENTS

APPENDIX A. SELECT ATTACHMENTS

Exhibit 1 – Pressure Gauge Calibration

Pressure Gage Calibration Check: Omegadyne DPG409-100DWU (S/N 426085)

Range: 0-100 psid

Fluke Model 718 300G Pressure Calibrator

ORNL Metrology ID No. A001516

Cal. Date: 5/6/2016

Cal. Due Date: 5/6/2017

Calibration by: J.R. Massengale 06/28/16

Note: Pressure applied to high side of differential pressure transmitter, low side vented to atmosphere

Fluke Calibrator Applied Pressure (psig)	DPT_1 DAS Reading (psid)	Error (psid)	Error (%)	Local Display (psig)
0.00	-0.03	-0.03		0.0
5.00	4.95	-0.05	-1.0	5.0
10.00	9.96	-0.04	-0.4	10.0
15.00	14.96	-0.04	-0.3	15.0
20.00	19.96	-0.04	-0.2	20.0
30.00	29.96	-0.04	-0.1	30.0
40.00	39.95	-0.05	-0.1	40.0
50.00	49.95	-0.05	-0.1	50.0
60.00	59.96	-0.04	-0.1	60.0
70.00	69.95	-0.05	-0.1	70.0
80.00	79.95	-0.05	-0.1	80.0
90.00	89.94	-0.06	-0.1	90.0
100.00	99.92	-0.08	-0.1	100.0
50.00	49.95	-0.05	-0.1	50.0
0.04	-0.03	-0.07		0.0

Exhibit 2 – Flow Meter Calibration

UT-BATTELLE
Management Contractor for DOE's Oak Ridge National Laboratory

Subcontracted Calibration Results

Oak Ridge National Laboratory
ORNL Metrology Laboratory
Bethel Valley Rd. Bldg. 5510A
Oak Ridge, TN 37831-6366

Unit Under Test Information	Customer Information	Test Information
Manufacturer: Azbil Corporation Description: Electromagnetic Flowmeter Model Number: MTG18A Serial Number: R-9A7KD-41-0S1 Asset / ID Number: A001657 Custodian: David K Felde Work Order Number: 2016002458	David K Felde Building: 5800 Room: A119 Mail Stop: 6051 865-241-2653	Certificate Number: **2016002458** Overall Result: Pass Performed on: 9/7/2016 Next Cal Due: 9/7/2018 Performed by: Subcontract Vendor Environment: N/A N/A Received: In Tolerance

Notes:

Asset No.

Work Order No.

ORNL ML subcontracts calibrations when the requirements of the calibration cannot be technically, economically or safely met by the laboratory, or for temporary incapacity, workload, etc. ORNL ML policy and the terms of its accreditation agreements require that any subcontracted calibrations be placed with a competent subcontractor. A competent subcontractor is one that complies with the requirements of ISO 17025. ORNL ML makes every effort to seek out and place its contracts with laboratories accredited to ISO 17025 by an accrediting body with which the International Laboratory Accreditation Cooperation (ILAC) has a mutual recognition agreement. Laboratories that have been approved as a Commercial Calibration Laboratory (CCL) or a Designated Calibration Source (DCS) by the DOE Nuclear Weapons Complex are deemed compliant with ISO 17025. Other prospective subcontractor laboratories must claim compliance with ISO 17025 and provide sufficient evidence to support that claim to the satisfaction of the management of ORNL ML. If an ISO 17025 compliant subcontractor cannot be found, ORNL ML may have subcontracted the calibration with a non-compliant laboratory. In this event, the subcontracted calibration results have been cross checked by ORNL ML to provide assurance of traceability to SI units.

Colorado Engineering Experiment Station Inc.
54043 WCR 37
Nunn, CO 60648
970-897-2711

FOUND_LEFT

See the Vendor supplied Report or Certificate #16ORL-0004_1 (As Found) and 16ORL-0005_1 (As Left) from Colorado Engineering Experiment Station Inc. (4 each, 8 total pages).

ORNL Purchase Order Number = CE25146 (CC)

CALIBRATION RECEIVING CHECKLIST

Instrument Checkout

---

1. Instrument ID Correct?
YES

2. Accessories accounted for (manuals, power cords, test leads, case, accessories, etc.)?
YES

3. Instrument damaged in shipment? (Does the instrument or the packing material show any evidence of shipping damage such as cracks, cuts, dents, dirt, water-stains, missing/loose screws/ fasteners, etc.)?
NO

4. Are all of the instrument's features operational, insofar as we have the ability to test functions and ranges? Attach documentation of the operational test if applicable.
YES

5. Does the vendor supplied service, material and/or documentation have all the information that was specified in the ORNL purchasing documents, (name and address of the laboratory performing the calibration; method used; "As Found/Left" results, instrument identification, description and condition;, data tables, accreditation logo, conversion factors, traceability information, statement that results relate only to the items tested/calibrated, etc.)?
YES

6. Have all coefficients, calibration factors correction tables, etc. been updated as needed?
N/A

7. For supplies and reagents: Do they comply with standard specifications or requirements (defined in the calibration methods for which they will be used)?
N/A

Checklist performed by: Joe Keck (908866) Date: 09/20/16

Approved By: Joe Keck
Metrology Engineer/Operations Coordinator

LABORATORY/OFFICE:
54043 County Rd. 37
Nunn, Colo. 80648
Phone: 970-897-2711
FAX: 970-897-2710

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NVLAP LAB CODE 200377-0

CERTIFICATE OF CALIBRATION

Traceable to the
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Customer:	**Oak Ridge National Laboratory**	**Item Calibrated:**	**Magmeter**
Address:	**1 Bethel Valley Rd**		
	Oak Ridge, TN 37831	**Serial Number:**	**R-9A7KD-41-0S1**
Date:	**September 07, 2016**	**Order:**	**CC**
		Job Number:	**CE25146**
CEESI Data File(s):	**16ORL-0005_1**	**Report Number:**	

The uncertainty in the flowrate indicated by CEESI standards is contained in this report under *Statement of Uncertainties.*

The calibration(s) identified by the above CEESI DATA FILE (S) were performed using standards that are traceable to the National Institute of Standards and Technology. The calibration(s) were performed in accordance with any or all of the following: The current revision of CEESI PROCEDURE NO. 10 ; NIST Handbook 150 (NVLAP accreditation under NVLAP lab code 200377-0); ISO/IEC 17025:1999; ANSI/NCSL Z540-1-1994; and Former MIL-STD-45662A. The stated uncertainties were calculated in accordance with the current revision of CEESI Report "Calibration Services Uncertainty Analyses".

Calibration Method	[X] Primary	[ ] Secondary
This calibration is:	[ ] As Found	[X] As Left

Bryan Trostel - Engineering Manager of Data Quality

NOTES:

1. Re-calibration intervals should be determined by the user and based on meter type, conditions of use, and the degree of risk associated with the measurement. Please contact CEESI for guidance in establishing adequate re-calibration intervals.
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CEESI Form 140 8-8-06

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IOWA HIGH FLOW FACILITY
2365 240th St.
Garner, IA 50438
Phone: 641-923-3664
FAX: 641-923-3693

Calibration of a Magmeter
Model: MTG18A-040P21LSDAAJT2-XX-X Serial Number: R-9A7KD-41-0S1
For: Oak Ridge National Laboratory Order: CC
Data File: 16ORL-0005_1 Job Number: CE25146 Date: 07 September 2016
Inlet Diameter: 1.610 Inches Throat Diameter: 1.610 Inches
Test Fluid: WATER

True Rate: gallons per minute, as measured by Static Weigh - Time - Temperature
MtrRead1: meter output in milliamps
Vel: Fluid velocity in feet per second
Temp: Temperature of fluid in degrees F
Rho: Density of fluid in pounds mass per cubic foot
Visc: Viscosity of fluid in pounds mass per inch seconds
MtrRead2: Meter panel output in gallons per minute
IndRate: (MtrRead1-Z)/16*30
Diff: TrueRate-IndRate

Pt.	TrueRate [gpm]	MtrRead1 [mA]	Vel [ft/sec]	Temp [°F]	Rho [lbm/cuft]	Visc [lbm/(in*sec)]	MtrRead2 [gpm]	IndRate [gpm]	Diff [gpm]
1	30.259	20.142	4.77	85.751	62.167	4.478E-05	30.280	30.265	0.006
2	5.979	7.194	0.94	85.699	62.168	4.481E-05	5.980	5.988	0.008
3	27.029	18.429	4.26	85.706	62.167	4.480E-05	27.030	27.054	0.025
4	24.046	16.834	3.79	85.816	62.166	4.475E-05	24.090	24.063	0.016
5	20.907	15.159	3.29	85.804	62.166	4.475E-05	20.930	20.921	0.014
6	17.973	13.603	2.83	85.786	62.167	4.476E-05	18.020	18.004	0.032
7	14.973	12.000	2.36	85.774	62.167	4.477E-05	15.030	14.999	0.025
8	12.119	10.473	1.91	85.767	62.167	4.477E-05	12.150	12.135	0.016
9	9.166	8.893	1.44	85.741	62.167	4.478E-05	9.200	9.174	0.008
10	2.959	5.603	0.47	85.596	62.169	4.486E-05	2.990	3.004	0.044

LABORATORY/OFFICE:
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Nunn, Colo. 80648
Phone: 970-897-2711
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Garner, IA 50438
Phone: 641-923-3664
FAX: 641-923-3693

STATEMENT OF UNCERTAINTIES

Calibration of a Magmeter
Model: MTG18A-040P21LSDAAJT2-XX-X Serial Number: R-9A7KD-41-0S1
For: Oak Ridge National Laboratory Order: CC
Data File: 16ORL-0005_1 Job Number: CE25146 Date: 07 September 2016
Inlet Diameter: 1.610 Inches Throat Diameter: 1.610 Inches
Test Fluid: WATER

TrueRate: Uncertainty in volumetric flowrate at a 95% confidence in percent of reading
MtrRead1: Uncertainty in milliamps at a 95% confidence in percent of reading
Vel: Uncertainty in velocity at a 95% confidence in percent of reading
Temp: Uncertainty in temperature at a 95% confidence in percent of reading
Rho: Uncertainty in density at a 95% confidence in percent of reading
Visc: Uncertainty in viscosity at a 95% confidence in percent of reading
MtrRead2: -
IndRate: -
Diff: -

Pt.	TrueRate [%]	MtrRead1 [%]	Vel [%]	Temp [%]	Rho [%]	Visc [%]	MtrRead2	IndRate	Diff
1	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
2	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
3	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
4	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
5	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
6	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
7	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
8	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
9	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-
10	0.12	0.017	0.12	0.034	0.060	0.25	-	-	-

LABORATORY/OFFICE:
54043 County Rd. 37
Nunn, Colo. 80648
Phone: 970-897-2711
FAX: 970-897-2710

COLORADO ENGINEERING EXPERIMENT STATION INC.

...the primary source for flow measurement solutions...

IOWA HIGH FLOW FACILITY
2365 240th St.
Garner, IA 50438
Phone: 641-923-3664
FAX: 641-923-3693

Calibration Checklist

Checklist ID: [illegible]

Job #:	CE25146	**Data File #:**	16ORL-0006
Customer Name:	Oak Ridge National Laboratory	**Purchase Order:**	CC
Serial #:	R-9A7KD-41-0S1	**Model #:**	MTG18A-040P21LSDAAJT2-XX-X
Part #:		**Tag #:**	
Meter Type:	MAGMETER	**Description:**	1.5

Cal. Conditions: Inlet Pressure, Inlet Temperature
Data Acquisition: CEESI047

List of Instruments Used:

Q/C Number	Instrument Description	Cal. Due Date
1000	Primary 1000 hz Time Signal	09/21/2016
1564	DAQ	02/24/2017
1661	Transducer	11/12/2016
1780	70lb digital scale	02/07/2017
1782	1200lb digital scale	02/07/2017

List of Standards Used:

Standard(s) Number
PRIWL3
PRIWL2

Quality Control Supervisor: **John Reiner on 9/7/2016**

		Length	OD	(Housing) Mass		Total Mass	
RABBIT	Test 1	2.521	.442	4.655 g		15.591 g	
	Test 2	2.522	.442	4.640 g		15.689 g	
	Test 3	2.521	.442	4.651 g		15.703 g	
	Test 4	2.521	.442	4.652 g		15.702 g	
	Test 5	2.522	.441	4.665 g		15.709 g	
	Test 6	2.521	.442	4.649 g		15.673 g	
	Test 7	2.522	.442	4.641 g		15.728	
SLUG		Length	OD	Mass			
	Test 1	2.094	.378	10.407 g			
	Test 2	2.120	.379	10.535 g			
	Test 3	2.120	.378	10.534 g			
	Test 4	2.123	.377	10.535			
	Test 5	2.119	.379	10.528			
	Test 6	2.116	.378	10.508			
	Test 7	2.128	.378	10.571			

D. [signature] 10/10/16

Lengths and outer diameters (ODs) in inches

(FLOW TEST ONLY
NOT APPROVED FOR
REACTOR USE)

FLOW TEST RABBITS		LENGTH	OD	MASS		
T29		2.5245	.431	16.100		
T30		2.523	.431	16.087		
T31		2.525	.431	16.086		
T32		2.523	.432	16.125		
T33		2.525	.431	16.109		
T34		2.525	.431	16.096		
T35		2.524	.432	16.110		
T36		2.524	.432	16.129		
T37		2.524	.431	16.127		

Lengths and outer diameters (ODs) in inches, mass in grams

	Rabbit housing	Outer surface roughness (Ra)				
	A	B	C	D	E	F
1	T30	17 μin				
2	T31	16 μin				
3	T32	14 μin				
4	T33	16 μin				
5	T34	18 μin				
6	T35	14 μin				
7	T36	16 μin				
8	T37	17 μin				
9	TEST 1	5 μin				
10	TEST 2	6 μin				
11	TEST 3	5 μin				
12	TEST 4	4 μin				
13	TEST 5	7 μin				
14	TEST 6	14 μin				
15	TEST 7	16 μin				
16						
17						
18		D. [illegible]				
19		12/12/16				

MATERIAL ISSUE

TicketID: 35906			**Issue Date:** 10-03-2016		**Requester:** Deichert, Geoffrey			**Group:** Systems Engineering		**Work document:** N/A		
End Use: Flow testing Kurt Smith												
	InvID	**SubID**	**Noun**	**Description**	**Bldg Loc.**	**Req.**	**Heat #**	**Stock End Use SR/Non**	**Notes**	**Qty**	**Units**	**Remarks**
1	17738	24155	Plug	Plug, Lower Plug, Peripheral Target Holder Type 2, P/N: 1-21-3	7910 ZZ8			SR2 / NON		1	Each	Serial No: 11-01, 11-02, 11-03
2	13861	19058	Holder	Holder, PTP Rabbit Holder, Peripheral Target Holder Type 2	7990 D7	HFIR-HE-FT-584		SR2 / NON		1	Each	Serial Numbers 11-01,11-02,11-03,11-05,11-07,11-11,11-13 and 11-15 NOT FINISHED MACHINED per DWG R2 and NOT CERTIFIED
3												
4												
5												
6												
7												
8												
9												
10												
11												

Filled By: TM Ingram

APPENDIX B. DIMENSIONAL INSPECTION

APPENDIX B. DIMENSIONAL INSPECTION

Table B-1. Cladding dimensions

Material	Cladding Part #	ID (mm)	Minor OD (mm)	Major OD (mm)	Avg OD (mm)	Min OD (mm)	Max OD (mm)	Length (mm)	Avg length (mm)
FeCrAl	C06M-01	8.79	9.526	9.534	9.533	9.526	9.549	15.897	15.885
C06M	C06M-01		9.528	9.534				15.875	
	C06M-01		9.530	9.536				15.878	
	C06M-01		9.528	9.539				15.890	
	C06M-01		9.526	9.549					
	C06M-01								
FeCrAl	C06M-02	8.79	9.508	9.532	9.527	9.508	9.535	15.747	15.750
C06M	C06M-02		9.526	9.535				15.751	
	C06M-02		9.525	9.535				15.747	
	C06M-02		9.526	9.533				15.756	
	C06M-02		9.519	9.531					
	C06M-02								
FeCrAl	B126Y-1	8.76	9.497	9.521	9.509	9.493	9.522	23.502	23.498
B126Y	B126Y-1		9.500	9.518				23.495	
	B126Y-1		9.501	9.522				23.502	
	B126Y-1		9.501	9.522				23.494	
	B126Y-1		9.498	9.521					
	B126Y-1		9.493	9.517					
FeCrAl	B126Y-2	8.76	9.501	9.511	9.509	9.500	9.519	23.481	23.481
B126Y	B126Y-2		9.504	9.514				23.481	
	B126Y-2		9.506	9.514				23.482	
	B126Y-2		9.504	9.519				23.480	
	B126Y-2		9.503	9.516					
	B126Y-2		9.500	9.518					
FeCrAl	B126Y-3	8.76	9.505	9.515	9.510	9.501	9.518	23.304	23.305
B126Y	B126Y-3		9.502	9.516				23.307	
	B126Y-3		9.502	9.518				23.302	
	B126Y-3		9.501	9.518				23.307	
	B126Y-3		9.504	9.517					
	B126Y-3		9.501	9.518					
FeCrAl	B126Y-4	8.76	9.500	9.520	9.511	9.500	9.524	23.406	23.410
B126Y	B126Y-4		9.500	9.518				23.417	
	B126Y-4		9.500	9.522				23.408	
	B126Y-4		9.500	9.520				23.408	
	B126Y-4		9.501	9.518					
	B126Y-4		9.504	9.524					

Material	**Cladding Part #**	**ID (mm)**	**Minor OD (mm)**	**Major OD (mm)**	**Avg OD (mm)**	**Min OD (mm)**	**Max OD (mm)**	**Length (mm)**	**Avg length (mm)**
FeCrAl	C36M3-1	8.79	9.530	9.538	9.535	9.530	9.539	23.355	23.359
C36M3	C36M3-1		9.530	9.538				23.363	
	C36M3-1		9.531	9.538				23.364	
	C36M3-1		9.533	9.538				23.352	
	C36M3-1		9.533	9.537					
	C36M3-1		9.532	9.539					
FeCrAl	C36M3-2	8.79	9.530	9.539	9.535	9.530	9.540	23.429	23.423
C36M3	C36M3-2		9.530	9.540				23.426	
	C36M3-2		9.531	9.538				23.416	
	C36M3-2		9.533	9.539				23.419	
	C36M3-2		9.531	9.539					
	C36M3-2		9.531	9.536					
FeCrAl	C36M3-3	8.77	9.536	9.541	9.535	9.528	9.541	23.363	23.364
C36M3	C36M3-3		9.529	9.537				23.351	
	C36M3-3		9.530	9.539				23.380	
	C36M3-3		9.531	9.541				23.360	
	C36M3-3		9.528	9.536					
	C36M3-3		9.530	9.539					
FeCrAl	C36M3-4	8.79	9.526	9.534	9.533	9.526	9.538	23.495	23.494
C36M3	C36M3-4		9.528	9.537				23.499	
	C36M3-4		9.530	9.538				23.492	
	C36M3-4		9.532	9.538				23.489	
	C36M3-4		9.532	9.536					
	C36M3-4		9.530	9.535					
FeCrAl	B136Y-1	8.78	9.526	9.531	9.528	9.517	9.535	23.401	23.399
B136Y	B136Y-1		9.528	9.533				23.401	
	B136Y-1		9.528	9.533				23.402	
	B136Y-1		9.524	9.535				23.391	
	B136Y-1		9.522	9.531					
	B136Y-1		9.517	9.527					
FeCrAl	B136Y-4	8.79	9.520	9.525	9.526	9.516	9.533	23.348	23.356
B136Y	B136Y-4		9.524	9.529				23.358	
	B136Y-4		9.523	9.531				23.358	
	B136Y-4		9.523	9.533				23.360	
	B136Y-4		9.521	9.532					
	B136Y-4		9.516	9.533					
ZIRLO	Zirlo-1	8.35	9.487	9.495	9.493	9.484	9.499	23.350	23.374
	Zirlo-1		9.491	9.499				23.388	
	Zirlo-1		9.493	9.498				23.375	

Material	Cladding Part #	ID (mm)	Minor OD (mm)	Major OD (mm)	Avg OD (mm)	Min OD (mm)	Max OD (mm)	Length (mm)	Avg length (mm)
	Zirlo-1		9.493	9.498				23.382	
	Zirlo-1		9.493	9.497					
	Zirlo-1		9.484	9.491					
ZIRLO	Zirlo-2	8.35	9.485	9.490	9.493	9.485	9.502	23.429	23.436
	Zirlo-2		9.491	9.495				23.459	
	Zirlo-2		9.495	9.500				23.423	
	Zirlo-2		9.493	9.499				23.432	
	Zirlo-2		9.493	9.502					
	Zirlo-2		9.485	9.491					
ZIRLO	Zirlo-HH-1	8.35	9.491	9.550	9.508	9.491	9.550	23.510	23.476
1000 wt	Zirlo-HH-1		9.495	9.524				23.433	
ppm H	Zirlo-HH-1		9.495	9.512				23.506	
	Zirlo-HH-1		9.497	9.508				23.455	
	Zirlo-HH-1		9.501	9.504					
	Zirlo-HH-1		9.501	9.522					
ZIRLO	Zirlo-MH-1	8.37	9.488	9.531	9.511	9.483	9.537	23.445	23.476
500 wt	Zirlo-MH-1		9.487	9.537				23.508	
ppm H	Zirlo-MH-1		9.487	9.535				23.447	
	Zirlo-MH-1		9.488	9.536				23.503	
	Zirlo-MH-1		9.487	9.533					
	Zirlo-MH-1		9.483	9.537					
Zircaloy-4	Zirc-4H-1	8.36	9.474	9.481	9.481	9.474	9.487	23.467	23.475
150 wt	Zirc-4H-1		9.478	9.487				23.458	
ppm H	Zirc-4H-1		9.475	9.482				23.515	
	Zirc-4H-1		9.482	9.487				23.458	
	Zirc-4H-1		9.478	9.486					
	Zirc-4H-1		9.477	9.487					
Zircaloy-4	Zirc-4H-2	8.36	9.479	9.484	9.480	9.474	9.486	23.438	23.434
150 wt	Zirc-4H-2		9.476	9.483				23.440	
ppm H	Zirc-4H-2		9.477	9.482				23.429	
	Zirc-4H-2		9.478	9.486				23.430	
	Zirc-4H-2		9.476	9.482					
	Zirc-4H-2		9.474	9.482					
Zircaloy-4	Zirc-4H-3	8.36	9.476	9.484	9.481	9.476	9.486	23.441	23.437
150 wt	Zirc-4H-3		9.477	9.485				23.434	
ppm H	Zirc-4H-3		9.479	9.486				23.441	
	Zirc-4H-3		9.478	9.484				23.430	
	Zirc-4H-3		9.476	9.482					
	Zirc-4H-3		9.476	9.484					
ZIRLO	ZIRLO-H-3	8.35	9.497	9.512	9.505	9.497	9.512	23.563	23.511

Material	Cladding Part #	ID (mm)	Minor OD (mm)	Major OD (mm)	Avg OD (mm)	Min OD (mm)	Max OD (mm)	Length (mm)	Avg length (mm)
250 wt	ZIRLO-H-3		9.503	9.512				23.496	
ppm H	ZIRLO-H-3		9.500	9.508				23.479	
	ZIRLO-H-3		9.500	9.507				23.505	
	ZIRLO-H-3		9.500	9.512					
	ZIRLO-H-3		9.498	9.507					
ZIRLO	ZIRLO-H-4	8.35	9.501	9.505	9.505	9.500	9.522	23.353	23.347
250 wt	ZIRLO-H-4		9.503	9.506				23.331	
ppm H	ZIRLO-H-4		9.503	9.505				23.363	
	ZIRLO-H-4		9.501	9.505				23.340	
	ZIRLO-H-4		9.500	9.506					
	ZIRLO-H-4		9.504	9.522					
ZIRLO	ZIRLO-H-5	8.35	9.500	9.505	9.504	9.500	9.509	23.455	23.441
250 wt	ZIRLO-H-5		9.500	9.506				23.427	
ppm H	ZIRLO-H-5		9.503	9.507				23.454	
	ZIRLO-H-5		9.502	9.506				23.426	
	ZIRLO-H-5		9.502	9.507					
	ZIRLO-H-5		9.502	9.509					
Note: Avg = Average, Min = Minimum, Max = Maximum, OD = Outer Diameter, ID = Inner Diameter									

Table B-2. Housing dimensions.

Housing Part #	OD (mm)	ID 1 (mm)	ID 2 (mm)	ID 3 (mm)	ID 4 (mm)	ID 5 (mm)	Max ID (mm)	Min ID (mm)	Avg ID (mm)	ID Deviation (mm)
16-01	11.237	9.716	9.717	9.725	9.731	9.735	9.735	9.716	9.725	+0.005/-0.004
16-02	11.240	9.720	9.725	9.743	9.740	9.739	9.743	9.720	9.733	+0.005/-0.007
16-03	11.235	9.717	9.719	9.727	9.732	9.733	9.733	9.717	9.726	+0.004/-0.004
16-04	11.236	9.718	9.720	9.720	9.725	9.729	9.729	9.718	9.722	+0.003/-0.002
16-05	11.232	9.732	9.727	9.730	9.732	9.731	9.732	9.727	9.730	+0.001/-0.002
16-06	11.230	9.720	9.720	9.731	9.730	9.731	9.731	9.720	9.726	+0.002/-0.003
16-07	11.235	9.716	9.720	9.736	9.733	9.730	9.736	9.716	9.727	+0.005/-0.006
16-08	11.232	9.718	9.720	9.725	9.729	9.737	9.737	9.718	9.726	+0.006/-0.004
16-09	11.234	9.718	9.719	9.723	9.729	9.730	9.730	9.718	9.724	+0.003/-0.003
16-10	11.235	9.717	9.720	9.729	9.731	9.732	9.732	9.717	9.726	+0.003/-0.004
16-12	11.236	9.718	9.719	9.734	9.732	9.733	9.734	9.718	9.727	+0.003/-0.005
16-13	11.231	9.715	9.715	9.720	9.722	9.729	9.729	9.715	9.720	+0.004/-0.003
16-14	11.233	9.717	9.719	9.720	9.724	9.729	9.729	9.717	9.722	+0.004/-0.002
16-15	11.232	9.720	9.720	9.722	9.725	9.730	9.730	9.720	9.723	+0.003/-0.002
16-16	11.242	9.720	9.720	9.723	9.728	9.730	9.730	9.720	9.724	+0.003/-0.002
16-17	11.236	9.718	9.720	9.722	9.728	9.732	9.732	9.718	9.724	+0.004/-0.003
16-18	11.235	9.720	9.720	9.722	9.726	9.730	9.730	9.720	9.724	+0.003/-0.002
Note: Avg = Average, Min = Minimum, Max = Maximum, OD = Outer Diameter, ID = Inner Diameter										

APPENDIX C. ANSYS DESIGN REPORTS

APPENDIX C. ANSYS DESIGN REPORTS

FCF01:

```
******************************************************************************
                            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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7240 mm
 * Bottom cladding: ID =  8.7900 mm, minor OD =  9.5280 mm, major OD =  9.5380 mm, sleeve OD =
8.6900 mm
 * Top cladding: ID =  8.7800 mm, minor OD =  9.5240 mm, major OD =  9.5320 mm, sleeve OD =
8.6700 mm
 * Backfill gas:   92.00% He,    8.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 3
 * Capsule centerline position =  -6.99 cm ( -2.75 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·°C
  Bulk coolant temperature  =    52.0 °C

 ------------------------------------------------------------------------------
  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	28800.	133.0	125.0
2) Cap	AL-6061	28800.	15.2	14.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	6.5
8) Clad1	FeCrAl	33500.	41.4	38.0
9) Clad1	FeCrAl	33500.	19.3	17.7
10) Thimble1b	Ti-6Al4V	35200.	7.2	6.8
11) Sleeve1	Moly	42500.	309.1	284.0
13) Sleeve1	Moly	42500.	26.1	24.6
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.8
17) Clad2	FeCrAl	33500.	40.6	39.0
18) Clad2	FeCrAl	33500.	18.9	18.1
19) Thimble2b	Ti-6Al4V	35200.	7.2	7.0
20) Sleeve2	Moly	42500.	306.4	294.0
22) Sleeve2	Moly	42500.	25.9	25.2
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7

29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2
32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			971.5	914.0

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	78.	54.	75.
2) Cap	AL-6061	87.	85.	88.	86.	88.
3) Grafoil1	GRAFOIL	116.	109.	123.	115.	117.
4) Grafoil2	GRAFOIL	161.	154.	169.	159.	162.
5) Grafoil6	GRAFOIL	525.	515.	531.	517.	529.
6) Grafoil7	GRAFOIL	522.	514.	526.	516.	526.
7) Thimble1a	Ti-6Al4V	373.	288.	413.	336.	412.
8) Clad1	FeCrAl	324.	298.	354.	303.	347.
9) Clad1	FeCrAl	318.	295.	345.	298.	341.
10) Thimble1b	Ti-6Al4V	497.	383.	504.	470.	503.
11) Sleeve1	Moly	444.	399.	489.	405.	484.
13) Sleeve1	Moly	491.	486.	494.	488.	494.
15) TM1	SiC(Irr)	447.	383.	490.	404.	488.
16) Thimble2a	Ti-6Al4V	500.	368.	509.	460.	509.
17) Clad2	FeCrAl	347.	336.	384.	340.	359.
18) Clad2	FeCrAl	341.	332.	375.	334.	353.
19) Thimble2b	Ti-6Al4V	536.	415.	544.	509.	544.
20) Sleeve2	Moly	507.	494.	534.	497.	530.
22) Sleeve2	Moly	536.	531.	538.	533.	537.
24) TM2	SiC(Irr)	509.	496.	535.	499.	534.
25) Wire1	Moly	439.	425.	448.	426.	448.
26) Wire2	Moly	534.	522.	544.	522.	544.
27) Wire3	Moly	531.	515.	541.	516.	541.
28) Wire4	Moly	579.	566.	589.	566.	589.
29) Grafoil3	GRAFOIL	203.	193.	213.	199.	206.
30) Grafoil4	GRAFOIL	244.	228.	258.	232.	250.
31) Grafoil5	GRAFOIL	283.	252.	305.	255.	295.
32) Grafoil8	GRAFOIL	520.	513.	525.	514.	525.
33) Grafoil9	GRAFOIL	519.	512.	525.	513.	524.
34) Grafoil10	GRAFOIL	518.	511.	524.	512.	524.

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	166.992	24.21	0.050
2) Cap	AL-6061	169.774	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.044	10.00	0.385
8) Clad1	FeCrAl	15.717	11.30	0.143
9) Clad1	FeCrAl	15.630	11.27	0.143
10) Thimble1b	Ti-6Al4V	16.574	10.25	0.404
11) Sleeve1	Moly	121.314	5.15	0.072
13) Sleeve1	Moly	119.433	0.00	0.076
15) TM1	SiC(Irr)	8.679	3.65	0.900
16) Thimble2a	Ti-6Al4V	16.629	10.25	0.404
17) Clad2	FeCrAl	16.073	11.39	0.143
18) Clad2	FeCrAl	15.981	11.36	0.143
19) Thimble2b	Ti-6Al4V	17.268	10.33	0.416
20) Sleeve2	Moly	118.818	5.21	0.078

22)	Sleeve2	Moly	117.743	0.00	0.082
24)	TM2	SiC(Irr)	8.630	3.79	0.900
25)	Wire1	Moly	121.529	0.00	0.071
26)	Wire2	Moly	117.777	0.00	0.081
27)	Wire3	Moly	117.895	0.00	0.081
28)	Wire4	Moly	116.437	0.00	0.087
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.618	63.	887.	175.
2) Cap	AL-6061	0.527	87.	906.	32.
3) Grafoil1	GRAFOIL	0.006	116.	700.	0.
4) Grafoil2	GRAFOIL	0.006	161.	700.	1.
5) Grafoil6	GRAFOIL	0.008	525.	700.	3.
6) Grafoil7	GRAFOIL	0.008	522.	700.	3.
7) Thimble1a	Ti-6Al4V	0.205	373.	718.	52.
8) Clad1	FeCrAl	1.235	324.	603.	227.
9) Clad1	FeCrAl	0.577	318.	601.	103.
10) Thimble1b	Ti-6Al4V	0.205	497.	769.	75.
11) Sleeve1	Moly	7.274	444.	273.	841.
13) Sleeve1	Moly	0.615	491.	275.	80.
15) TM1	SiC(Irr)	0.019	447.	1093.	9.
16) Thimble2a	Ti-6Al4V	0.205	500.	770.	76.
17) Clad2	FeCrAl	1.212	347.	611.	242.
18) Clad2	FeCrAl	0.564	341.	609.	110.
19) Thimble2b	Ti-6Al4V	0.205	536.	790.	84.
20) Sleeve2	Moly	7.209	507.	275.	965.
22) Sleeve2	Moly	0.609	536.	277.	87.
24) TM2	SiC(Irr)	0.019	509.	1120.	11.
25) Wire1	Moly	0.017	439.	272.	2.
26) Wire2	Moly	0.017	534.	277.	2.
27) Wire3	Moly	0.017	531.	276.	2.
28) Wire4	Moly	0.017	579.	279.	3.
29) Grafoil3	GRAFOIL	0.006	203.	700.	1.
30) Grafoil4	GRAFOIL	0.006	244.	700.	1.
31) Grafoil5	GRAFOIL	0.006	283.	700.	1.
32) Grafoil8	GRAFOIL	0.008	520.	700.	3.
33) Grafoil9	GRAFOIL	0.008	519.	700.	3.
34) Grafoil10	GRAFOIL	0.008	518.	700.	3.
		25.442			3197.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: FeCrAl
Target surface material: AL-6061
Interstitial gas: 920HE_80
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)	316.581	294.578	340.780

```
   Target temperature (°C)                  63.793       61.686       64.697
   Geometric gas gap (µm)                   95.381       92.846       97.836
   Contact pressure (MPa)                    0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)        488.348      430.285      562.374
   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)                 488.348      430.285      562.374
   Thermal contact conductance (W/m²·C)   1930.269     1830.457     2047.934
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                   84.395       80.448       87.855
   Contact thermal jump distance (µm)        1.285        1.222        1.351
   Target thermal jump distance (µm)         0.931        0.904        0.959
   Effective contact pressure (MPa)          0.000        0.000        0.000
   Pressure index                           19.925       19.876       19.969
   Gas thermal conductivity (W/m·°C)         0.167        0.164        0.170
   Solid spot conductance (W/m²·C)           0.000        0.000        0.000
   Gas gap conductance (W/m²·C)           1930.380     1830.182     2048.048

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:             920HE_80
   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)                339.161      332.199      365.103
   Target temperature (°C)                  64.458       61.097       65.177
   Geometric gas gap (µm)                   97.881       95.844       99.860
   Contact pressure (MPa)                    0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)        531.618      510.095      612.264
   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)                 531.618      510.095      612.264
   Thermal contact conductance (W/m²·C)   1935.077     1882.316     2048.442
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                   85.614       82.053       87.821
   Contact thermal jump distance (µm)        1.350        1.331        1.425
   Target thermal jump distance (µm)         0.960        0.949        0.991
   Effective contact pressure (MPa)          0.000        0.000        0.000
   Pressure index                           19.879       19.826       19.894
   Gas thermal conductivity (W/m·°C)         0.170        0.169        0.173
   Solid spot conductance (W/m²·C)           0.000        0.000        0.000
   Gas gap conductance (W/m²·C)           1935.078     1882.232     2048.760

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

FCF02:

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******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7260 mm
 * Bottom cladding: ID =  8.7900 mm, minor OD =  9.5210 mm, major OD =  9.5330 mm, sleeve OD =
8.6900 mm
 * Top cladding: ID =  8.7900 mm, minor OD =  9.5210 mm, major OD =  9.5310 mm, sleeve OD =
8.7100 mm
 * Backfill gas:   97.00% He,    3.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 5
 * Capsule centerline position =   6.09 cm (  2.40 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·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION
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Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	28800.	132.9	127.5
2) Cap	AL-6061	28800.	15.2	13.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	7.1
8) Clad1	FeCrAl	33500.	40.6	39.8
9) Clad1	FeCrAl	33500.	18.8	18.4
10) Thimble1b	Ti-6Al4V	35200.	7.2	7.0
11) Sleeve1	Moly	42500.	309.1	302.6
13) Sleeve1	Moly	42500.	26.1	25.2
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.9
17) Clad2	FeCrAl	33500.	40.6	38.5
18) Clad2	FeCrAl	33500.	18.7	17.7
19) Thimble2b	Ti-6Al4V	35200.	7.2	6.7
20) Sleeve2	Moly	42500.	311.9	295.3
22) Sleeve2	Moly	42500.	26.4	24.4
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			975.9	937.4

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	80.	54.	77.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	117.	109.	125.	116.	118.
4) Grafoil2	GRAFOIL	161.	154.	170.	160.	163.
5) Grafoil6	GRAFOIL	455.	447.	460.	449.	459.
6) Grafoil7	GRAFOIL	453.	446.	456.	447.	456.
7) Thimble1a	Ti-6Al4V	376.	287.	417.	336.	415.
8) Clad1	FeCrAl	319.	296.	343.	301.	336.
9) Clad1	FeCrAl	313.	293.	334.	296.	330.
10) Thimble1b	Ti-6Al4V	476.	366.	486.	447.	485.
11) Sleeve1	Moly	442.	402.	476.	408.	473.
13) Sleeve1	Moly	477.	473.	479.	475.	479.
15) TM1	SiC(Irr)	444.	385.	477.	406.	476.
16) Thimble2a	Ti-6Al4V	457.	344.	469.	426.	466.
17) Clad2	FeCrAl	331.	321.	366.	326.	340.
18) Clad2	FeCrAl	325.	318.	356.	320.	333.
19) Thimble2b	Ti-6Al4V	465.	361.	472.	442.	471.
20) Sleeve2	Moly	443.	435.	462.	436.	458.
22) Sleeve2	Moly	463.	459.	466.	461.	465.
24) TM2	SiC(Irr)	445.	439.	463.	439.	462.
25) Wire1	Moly	443.	428.	453.	429.	453.
26) Wire2	Moly	518.	505.	528.	505.	528.
27) Wire3	Moly	480.	464.	490.	465.	490.
28) Wire4	Moly	503.	491.	512.	491.	512.
29) Grafoil3	GRAFOIL	204.	193.	214.	199.	207.
30) Grafoil4	GRAFOIL	244.	227.	259.	232.	251.
31) Grafoil5	GRAFOIL	283.	251.	307.	254.	296.
32) Grafoil8	GRAFOIL	451.	444.	456.	446.	456.
33) Grafoil9	GRAFOIL	450.	444.	455.	445.	455.
34) Grafoil10	GRAFOIL	449.	443.	455.	444.	455.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.037	24.21	0.050
2) Cap	AL-6061	169.192	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.089	10.01	0.386
8) Clad1	FeCrAl	15.638	11.28	0.143
9) Clad1	FeCrAl	15.547	11.25	0.143
10) Thimble1b	Ti-6Al4V	16.164	10.20	0.404
11) Sleeve1	Moly	121.415	5.15	0.071
13) Sleeve1	Moly	119.991	0.00	0.075
15) TM1	SiC(Irr)	8.681	3.64	0.900
16) Thimble2a	Ti-6Al4V	15.756	10.16	0.402
17) Clad2	FeCrAl	15.827	11.32	0.143
18) Clad2	FeCrAl	15.732	11.30	0.143
19) Thimble2b	Ti-6Al4V	15.930	10.18	0.403
20) Sleeve2	Moly	121.375	5.15	0.071
22) Sleeve2	Moly	120.541	0.00	0.074
24) TM2	SiC(Irr)	8.680	3.65	0.900
25) Wire1	Moly	121.373	0.00	0.071

26) Wire2	Moly	118.365	0.00	0.080
27) Wire3	Moly	119.898	0.00	0.075
28) Wire4	Moly	118.962	0.00	0.078
29) Grafoil3	GRAFOIL	38.000	1.00	0.500
30) Grafoil4	GRAFOIL	38.000	1.00	0.500
31) Grafoil5	GRAFOIL	38.000	1.00	0.500
32) Grafoil8	GRAFOIL	38.000	1.00	0.500
33) Grafoil9	GRAFOIL	38.000	1.00	0.500
34) Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.613	63.	887.	177.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	117.	700.	0.
4) Grafoil2	GRAFOIL	0.006	161.	700.	1.
5) Grafoil6	GRAFOIL	0.008	455.	700.	2.
6) Grafoil7	GRAFOIL	0.008	453.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	376.	719.	52.
8) Clad1	FeCrAl	1.212	319.	602.	218.
9) Clad1	FeCrAl	0.562	313.	600.	99.
10) Thimble1b	Ti-6Al4V	0.205	476.	759.	71.
11) Sleeve1	Moly	7.274	442.	273.	836.
13) Sleeve1	Moly	0.615	477.	274.	77.
15) TM1	SiC(Irr)	0.019	444.	1092.	9.
16) Thimble2a	Ti-6Al4V	0.205	457.	750.	67.
17) Clad2	FeCrAl	1.212	331.	606.	228.
18) Clad2	FeCrAl	0.559	325.	604.	103.
19) Thimble2b	Ti-6Al4V	0.205	465.	754.	69.
20) Sleeve2	Moly	7.339	443.	273.	846.
22) Sleeve2	Moly	0.620	463.	273.	75.
24) TM2	SiC(Irr)	0.019	445.	1093.	9.
25) Wire1	Moly	0.017	443.	273.	2.
26) Wire2	Moly	0.017	518.	276.	2.
27) Wire3	Moly	0.017	480.	274.	2.
28) Wire4	Moly	0.017	503.	275.	2.
29) Grafoil3	GRAFOIL	0.006	204.	700.	1.
30) Grafoil4	GRAFOIL	0.006	244.	700.	1.
31) Grafoil5	GRAFOIL	0.006	283.	700.	1.
32) Grafoil8	GRAFOIL	0.008	451.	700.	2.
33) Grafoil9	GRAFOIL	0.008	450.	700.	2.
34) Grafoil10	GRAFOIL	0.008	449.	700.	2.
		25.535			2990.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material:	FeCrAl
Target surface material:	AL-6061
Interstitial gas:	970HE_30
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)	311.255	292.791	329.793
Target temperature (°C)	64.359	61.943	65.402
Geometric gas gap (µm)	99.381	96.347	102.331
Contact pressure (MPa)	0.000	0.000	0.000

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   Gap conduction heat flux (kW/m²)         510.919      458.427      573.557
   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)                  510.919      458.427      573.557
   Thermal contact conductance (W/m²·C)    2068.551     1966.546     2182.522
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (μm)                    88.783       84.680       92.510
   Contact thermal jump distance (μm)         1.553        1.488        1.615
   Target thermal jump distance (μm)          1.119        1.091        1.143
   Effective contact pressure (MPa)           0.000        0.000        0.000
   Pressure index                            19.936       19.898       19.973
   Gas thermal conductivity (W/m·°C)          0.189        0.186        0.192
   Solid spot conductance (W/m²·C)            0.000        0.000        0.000
   Gas gap conductance (W/m²·C)            2068.806     1966.429     2183.402

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:             970HE_30
   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)                 323.046      317.786      347.570
   Target temperature (°C)                   64.599       61.367       65.192
   Geometric gas gap (μm)                    99.881       97.345      102.336
   Contact pressure (MPa)                     0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)         540.183      520.365      622.541
   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)                  540.183      520.365      622.541
   Thermal contact conductance (W/m²·C)    2090.114     2029.454     2215.203
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (μm)                    88.606       84.664       91.195
   Contact thermal jump distance (μm)         1.595        1.578        1.682
   Target thermal jump distance (μm)          1.137        1.130        1.171
   Effective contact pressure (MPa)           0.000        0.000        0.000
   Pressure index                            19.912       19.862       19.923
   Gas thermal conductivity (W/m·°C)          0.191        0.190        0.194
   Solid spot conductance (W/m²·C)            0.000        0.000        0.000
   Gas gap conductance (W/m²·C)            2090.353     2029.735     2215.831

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

FCF03:

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******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7270 mm
 * Bottom cladding: ID =  8.7600 mm, minor OD =  9.4980 mm, major OD =  9.5200 mm, sleeve OD =
8.6500 mm
 * Top cladding: ID =  8.7900 mm, minor OD =  9.5300 mm, major OD =  9.5360 mm, sleeve OD =
8.7000 mm
 * Backfill gas:   97.00% He,    3.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 3
 * Capsule centerline position =  -6.99 cm ( -2.75 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·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	28800.	132.8	124.8
2) Cap	AL-6061	28800.	15.2	14.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	6.5
8) Clad1	FeCrAl	33500.	40.6	37.3
9) Clad1	FeCrAl	33500.	17.3	15.9
10) Thimble1b	Ti-6Al4V	35200.	7.2	6.8
11) Sleeve1	Moly	42500.	303.6	278.9
13) Sleeve1	Moly	42500.	25.6	24.1
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.8
17) Clad2	FeCrAl	33500.	42.9	41.2
18) Clad2	FeCrAl	33500.	19.3	18.5
19) Thimble2b	Ti-6Al4V	35200.	7.2	7.0
20) Sleeve2	Moly	42500.	310.5	298.0
22) Sleeve2	Moly	42500.	26.2	25.6
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			969.7	912.7

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	80.	54.	77.
2) Cap	AL-6061	84.	82.	85.	82.	85.
3) Grafoil1	GRAFOIL	118.	110.	126.	117.	119.
4) Grafoil2	GRAFOIL	164.	156.	172.	162.	165.
5) Grafoil6	GRAFOIL	447.	438.	451.	440.	450.
6) Grafoil7	GRAFOIL	444.	437.	448.	439.	448.
7) Thimble1a	Ti-6Al4V	385.	291.	429.	343.	427.
8) Clad1	FeCrAl	316.	292.	340.	296.	334.
9) Clad1	FeCrAl	311.	289.	332.	291.	329.
10) Thimble1b	Ti-6Al4V	484.	371.	499.	451.	499.
11) Sleeve1	Moly	459.	414.	492.	420.	489.
13) Sleeve1	Moly	492.	489.	493.	491.	493.
15) TM1	SiC(Irr)	461.	396.	493.	419.	492.
16) Thimble2a	Ti-6Al4V	448.	342.	465.	421.	462.
17) Clad2	FeCrAl	332.	321.	364.	326.	343.
18) Clad2	FeCrAl	325.	317.	353.	320.	336.
19) Thimble2b	Ti-6Al4V	455.	357.	461.	433.	461.
20) Sleeve2	Moly	427.	418.	451.	419.	447.
22) Sleeve2	Moly	453.	447.	455.	449.	455.
24) TM2	SiC(Irr)	430.	422.	452.	422.	450.
25) Wire1	Moly	450.	436.	459.	437.	459.
26) Wire2	Moly	531.	518.	540.	519.	540.
27) Wire3	Moly	462.	446.	472.	447.	472.
28) Wire4	Moly	495.	482.	504.	482.	504.
29) Grafoil3	GRAFOIL	207.	196.	218.	202.	211.
30) Grafoil4	GRAFOIL	249.	231.	264.	236.	256.
31) Grafoil5	GRAFOIL	289.	256.	313.	259.	302.
32) Grafoil8	GRAFOIL	443.	436.	447.	437.	447.
33) Grafoil9	GRAFOIL	442.	435.	447.	436.	446.
34) Grafoil10	GRAFOIL	441.	435.	446.	436.	446.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.002	24.21	0.050
2) Cap	AL-6061	169.424	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.277	10.02	0.389
8) Clad1	FeCrAl	15.596	11.26	0.143
9) Clad1	FeCrAl	15.515	11.24	0.143
10) Thimble1b	Ti-6Al4V	16.337	10.22	0.404
11) Sleeve1	Moly	120.709	5.16	0.073
13) Sleeve1	Moly	119.390	0.00	0.077
15) TM1	SiC(Irr)	8.667	3.68	0.900
16) Thimble2a	Ti-6Al4V	15.562	10.14	0.400
17) Clad2	FeCrAl	15.835	11.33	0.143
18) Clad2	FeCrAl	15.733	11.30	0.143
19) Thimble2b	Ti-6Al4V	15.717	10.16	0.401
20) Sleeve2	Moly	121.997	5.14	0.070
22) Sleeve2	Moly	120.976	0.00	0.072
24) TM2	SiC(Irr)	8.693	3.61	0.900
25) Wire1	Moly	121.087	0.00	0.072

26)	Wire2	Moly	117.882	0.00	0.081
27)	Wire3	Moly	120.600	0.00	0.073
28)	Wire4	Moly	119.296	0.00	0.077
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.611	63.	887.	175.
2) Cap	AL-6061	0.527	84.	903.	30.
3) Grafoil1	GRAFOIL	0.006	118.	700.	0.
4) Grafoil2	GRAFOIL	0.006	164.	700.	1.
5) Grafoil6	GRAFOIL	0.008	447.	700.	2.
6) Grafoil7	GRAFOIL	0.008	444.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	385.	723.	54.
8) Clad1	FeCrAl	1.212	316.	601.	216.
9) Clad1	FeCrAl	0.517	311.	599.	90.
10) Thimble1b	Ti-6Al4V	0.205	484.	763.	73.
11) Sleeve1	Moly	7.144	459.	273.	858.
13) Sleeve1	Moly	0.604	492.	275.	78.
15) TM1	SiC(Irr)	0.019	461.	1100.	9.
16) Thimble2a	Ti-6Al4V	0.205	448.	747.	66.
17) Clad2	FeCrAl	1.282	332.	606.	242.
18) Clad2	FeCrAl	0.577	325.	604.	106.
19) Thimble2b	Ti-6Al4V	0.205	455.	750.	67.
20) Sleeve2	Moly	7.307	427.	272.	809.
22) Sleeve2	Moly	0.617	453.	273.	73.
24) TM2	SiC(Irr)	0.019	430.	1086.	9.
25) Wire1	Moly	0.017	450.	273.	2.
26) Wire2	Moly	0.017	531.	276.	2.
27) Wire3	Moly	0.017	462.	273.	2.
28) Wire4	Moly	0.017	495.	275.	2.
29) Grafoil3	GRAFOIL	0.006	207.	700.	1.
30) Grafoil4	GRAFOIL	0.006	249.	700.	1.
31) Grafoil5	GRAFOIL	0.006	289.	700.	1.
32) Grafoil8	GRAFOIL	0.008	443.	700.	2.
33) Grafoil9	GRAFOIL	0.008	442.	700.	2.
34) Grafoil10	GRAFOIL	0.008	441.	700.	2.
		25.397			2980.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

```
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:             970HE_30
   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)	309.568	288.860	329.378
Target temperature (°C)	63.226	61.221	64.674
Geometric gas gap (µm)	108.882	103.353	114.325
Contact pressure (MPa)	0.000	0.000	0.000

```
   Gap conduction heat flux (kW/m²)          461.215      407.121      520.913
   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)                   461.215      407.121      520.913
   Thermal contact conductance (W/m²·C)     1871.926     1744.072     2009.509
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     98.262       91.874      104.448
   Contact thermal jump distance (µm)          1.545        1.473        1.612
   Target thermal jump distance (µm)           1.114        1.084        1.141
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             19.939       19.899       19.980
   Gas thermal conductivity (W/m·°C)           0.189        0.186        0.191
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1872.260     1744.204     2010.141

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:            970HE_30
   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)                  322.980      317.367      344.773
   Target temperature (°C)                    64.961       61.510       65.621
   Geometric gas gap (µm)                     96.880       95.343       98.385
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          557.419      536.590      633.678
   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)                   557.419      536.590      633.678
   Thermal contact conductance (W/m²·C)     2160.144     2112.350     2263.653
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     85.647       82.710       87.403
   Contact thermal jump distance (µm)          1.596        1.577        1.672
   Target thermal jump distance (µm)           1.137        1.130        1.167
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             19.912       19.868       19.924
   Gas thermal conductivity (W/m·°C)           0.191        0.190        0.194
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             2160.254     2111.968     2264.345

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

FCF04:

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****************************************************************************
                            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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7270 mm
 * Bottom cladding: ID =  8.7600 mm, minor OD =  9.5030 mm, major OD =  9.5150 mm, sleeve OD =
8.6600 mm
 * Top cladding: ID =  8.7900 mm, minor OD =  9.5310 mm, major OD =  9.5390 mm, sleeve OD =
8.7100 mm
 * Backfill gas:   97.00% He,    3.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 5
 * Capsule centerline position =   6.09 cm (  2.40 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·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	------ Heat Load ----- @Midplane (W)	@Location (W)
1) Housing	AL-6061	28800.	132.8	127.4
2) Cap	AL-6061	28800.	15.2	13.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	7.1
8) Clad1	FeCrAl	33500.	40.6	39.8
9) Clad1	FeCrAl	33500.	17.3	16.9
10) Thimble1b	Ti-6Al4V	35200.	7.2	7.0
11) Sleeve1	Moly	42500.	305.0	298.5
13) Sleeve1	Moly	42500.	25.8	24.9
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.9
17) Clad2	FeCrAl	33500.	42.9	40.6
18) Clad2	FeCrAl	33500.	19.5	18.4
19) Thimble2b	Ti-6Al4V	35200.	7.2	6.7
20) Sleeve2	Moly	42500.	311.9	295.3
22) Sleeve2	Moly	42500.	26.4	24.4
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			972.9	934.4

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	82.	54.	78.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	122.	113.	130.	120.	123.
4) Grafoil2	GRAFOIL	170.	161.	178.	168.	171.
5) Grafoil6	GRAFOIL	428.	420.	432.	422.	431.
6) Grafoil7	GRAFOIL	426.	419.	429.	421.	429.
7) Thimble1a	Ti-6Al4V	400.	303.	445.	357.	444.
8) Clad1	FeCrAl	329.	307.	349.	312.	343.
9) Clad1	FeCrAl	324.	304.	340.	307.	337.
10) Thimble1b	Ti-6Al4V	488.	372.	506.	453.	505.
11) Sleeve1	Moly	472.	430.	499.	436.	497.
13) Sleeve1	Moly	499.	495.	500.	497.	500.
15) TM1	SiC(Irr)	474.	411.	500.	435.	499.
16) Thimble2a	Ti-6Al4V	444.	341.	464.	419.	461.
17) Clad2	FeCrAl	328.	318.	364.	323.	337.
18) Clad2	FeCrAl	322.	314.	353.	316.	330.
19) Thimble2b	Ti-6Al4V	436.	344.	442.	416.	442.
20) Sleeve2	Moly	414.	405.	432.	406.	428.
22) Sleeve2	Moly	433.	428.	436.	430.	435.
24) TM2	SiC(Irr)	416.	409.	435.	409.	432.
25) Wire1	Moly	470.	455.	480.	456.	480.
26) Wire2	Moly	539.	526.	548.	526.	548.
27) Wire3	Moly	456.	441.	466.	442.	466.
28) Wire4	Moly	474.	462.	483.	462.	483.
29) Grafoil3	GRAFOIL	215.	203.	227.	210.	219.
30) Grafoil4	GRAFOIL	258.	240.	274.	245.	266.
31) Grafoil5	GRAFOIL	300.	266.	326.	269.	314.
32) Grafoil8	GRAFOIL	424.	418.	429.	419.	428.
33) Grafoil9	GRAFOIL	423.	417.	428.	418.	428.
34) Grafoil10	GRAFOIL	423.	417.	428.	418.	427.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.044	24.21	0.050
2) Cap	AL-6061	169.190	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.575	10.05	0.392
8) Clad1	FeCrAl	15.800	11.32	0.143
9) Clad1	FeCrAl	15.716	11.30	0.143
10) Thimble1b	Ti-6Al4V	16.410	10.23	0.404
11) Sleeve1	Moly	120.207	5.18	0.074
13) Sleeve1	Moly	119.120	0.00	0.077
15) TM1	SiC(Irr)	8.658	3.71	0.900
16) Thimble2a	Ti-6Al4V	15.474	10.14	0.400
17) Clad2	FeCrAl	15.785	11.31	0.143
18) Clad2	FeCrAl	15.683	11.29	0.143
19) Thimble2b	Ti-6Al4V	15.300	10.12	0.399
20) Sleeve2	Moly	122.535	5.12	0.069
22) Sleeve2	Moly	121.745	0.00	0.071
24) TM2	SiC(Irr)	8.703	3.58	0.900
25) Wire1	Moly	120.295	0.00	0.074

26) Wire2	Moly	117.654	0.00	0.082
27) Wire3	Moly	120.828	0.00	0.073
28) Wire4	Moly	120.133	0.00	0.075
29) Grafoil3	GRAFOIL	38.000	1.00	0.500
30) Grafoil4	GRAFOIL	38.000	1.00	0.500
31) Grafoil5	GRAFOIL	38.000	1.00	0.500
32) Grafoil8	GRAFOIL	38.000	1.00	0.500
33) Grafoil9	GRAFOIL	38.000	1.00	0.500
34) Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.611	63.	887.	177.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	122.	700.	0.
4) Grafoil2	GRAFOIL	0.006	170.	700.	1.
5) Grafoil6	GRAFOIL	0.008	428.	700.	2.
6) Grafoil7	GRAFOIL	0.008	426.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	400.	729.	57.
8) Clad1	FeCrAl	1.212	329.	605.	227.
9) Clad1	FeCrAl	0.517	324.	603.	95.
10) Thimble1b	Ti-6Al4V	0.205	488.	765.	73.
11) Sleeve1	Moly	7.176	472.	274.	888.
13) Sleeve1	Moly	0.606	499.	275.	80.
15) TM1	SiC(Irr)	0.019	474.	1105.	10.
16) Thimble2a	Ti-6Al4V	0.205	444.	745.	65.
17) Clad2	FeCrAl	1.282	328.	605.	239.
18) Clad2	FeCrAl	0.582	322.	603.	106.
19) Thimble2b	Ti-6Al4V	0.205	436.	742.	63.
20) Sleeve2	Moly	7.339	414.	271.	784.
22) Sleeve2	Moly	0.620	433.	272.	70.
24) TM2	SiC(Irr)	0.019	416.	1080.	8.
25) Wire1	Moly	0.017	470.	274.	2.
26) Wire2	Moly	0.017	539.	277.	3.
27) Wire3	Moly	0.017	456.	273.	2.
28) Wire4	Moly	0.017	474.	274.	2.
29) Grafoil3	GRAFOIL	0.006	215.	700.	1.
30) Grafoil4	GRAFOIL	0.006	258.	700.	1.
31) Grafoil5	GRAFOIL	0.006	300.	700.	1.
32) Grafoil8	GRAFOIL	0.008	424.	700.	2.
33) Grafoil9	GRAFOIL	0.008	423.	700.	2.
34) Grafoil10	GRAFOIL	0.008	423.	700.	2.
		25.473			2995.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: FeCrAl
Target surface material: AL-6061
Interstitial gas: 970HE_30
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)	322.327	304.456	337.058
Target temperature (°C)	63.959	61.620	65.591
Geometric gas gap (µm)	108.881	105.847	111.831
Contact pressure (MPa)	0.000	0.000	0.000

```
   Gap conduction heat flux (kW/m²)          491.399      443.884      538.091
   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)                   491.399      443.884      538.091
   Thermal contact conductance (W/m²·C)     1901.406     1816.091     1988.463
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     97.583       93.700      101.282
   Contact thermal jump distance (µm)          1.592        1.529        1.641
   Target thermal jump distance (µm)           1.134        1.108        1.154
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             19.914       19.884       19.949
   Gas thermal conductivity (W/m·°C)           0.191        0.188        0.193
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1901.722     1816.524     1989.083

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:             970HE_30
   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)                  319.731      314.096      344.729
   Target temperature (°C)                    64.882       61.421       65.456
   Geometric gas gap (µm)                     95.881       93.844       97.860
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          554.411      532.195      642.278
   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)                   554.411      532.195      642.278
   Thermal contact conductance (W/m²·C)     2175.308     2116.891     2301.353
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     84.832       81.279       87.030
   Contact thermal jump distance (µm)          1.584        1.565        1.672
   Target thermal jump distance (µm)           1.132        1.125        1.167
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             19.919       19.868       19.930
   Gas thermal conductivity (W/m·°C)           0.190        0.190        0.194
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             2175.407     2116.801     2302.023

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

FCF05:

```
*******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7260 mm
 * Bottom cladding: ID =  8.7600 mm, minor OD =  9.5030 mm, major OD =  9.5170 mm, sleeve OD =
8.6600 mm
 * Top cladding: ID =  8.7700 mm, minor OD =  9.5310 mm, major OD =  9.5390 mm, sleeve OD =
8.6600 mm
 * Backfill gas:   97.00% He,    3.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 5
 * Capsule centerline position =   6.09 cm (  2.40 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·°C
  Bulk coolant temperature  =    52.0 °C

 --------------------------------------------------------------------------------
  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	------ Heat Load ----- @Midplane (W)	@Location (W)
1) Housing	AL-6061	28800.	132.9	127.5
2) Cap	AL-6061	28800.	15.2	13.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	7.1
8) Clad1	FeCrAl	33500.	42.2	41.3
9) Clad1	FeCrAl	33500.	17.4	17.0
10) Thimble1b	Ti-6Al4V	35200.	7.2	7.0
11) Sleeve1	Moly	42500.	305.0	298.5
13) Sleeve1	Moly	42500.	25.8	24.9
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.9
17) Clad2	FeCrAl	33500.	42.9	40.6
18) Clad2	FeCrAl	33500.	19.5	18.4
19) Thimble2b	Ti-6Al4V	35200.	7.2	6.7
20) Sleeve2	Moly	42500.	305.0	288.7
22) Sleeve2	Moly	42500.	25.8	23.9
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			967.1	928.9

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	81.	54.	78.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	120.	111.	128.	119.	121.
4) Grafoil2	GRAFOIL	166.	158.	175.	165.	167.
5) Grafoil6	GRAFOIL	461.	452.	466.	454.	465.
6) Grafoil7	GRAFOIL	459.	451.	462.	453.	462.
7) Thimble1a	Ti-6Al4V	390.	296.	433.	348.	432.
8) Clad1	FeCrAl	332.	308.	355.	313.	349.
9) Clad1	FeCrAl	326.	305.	346.	308.	343.
10) Thimble1b	Ti-6Al4V	490.	373.	502.	458.	501.
11) Sleeve1	Moly	460.	418.	493.	424.	490.
13) Sleeve1	Moly	494.	490.	496.	492.	496.
15) TM1	SiC(Irr)	462.	400.	494.	423.	493.
16) Thimble2a	Ti-6Al4V	466.	347.	480.	433.	477.
17) Clad2	FeCrAl	320.	311.	363.	316.	328.
18) Clad2	FeCrAl	314.	307.	353.	309.	322.
19) Thimble2b	Ti-6Al4V	471.	364.	478.	447.	477.
20) Sleeve2	Moly	449.	442.	468.	443.	465.
22) Sleeve2	Moly	470.	465.	472.	467.	472.
24) TM2	SiC(Irr)	452.	446.	469.	446.	468.
25) Wire1	Moly	456.	441.	466.	442.	466.
26) Wire2	Moly	534.	521.	544.	522.	544.
27) Wire3	Moly	482.	465.	493.	467.	493.
28) Wire4	Moly	509.	497.	518.	497.	518.
29) Grafoil3	GRAFOIL	210.	199.	221.	205.	214.
30) Grafoil4	GRAFOIL	252.	234.	268.	240.	260.
31) Grafoil5	GRAFOIL	293.	260.	318.	263.	307.
32) Grafoil8	GRAFOIL	457.	450.	461.	451.	461.
33) Grafoil9	GRAFOIL	456.	449.	461.	450.	461.
34) Grafoil10	GRAFOIL	455.	448.	461.	449.	460.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.034	24.21	0.050
2) Cap	AL-6061	169.192	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.368	10.03	0.390
8) Clad1	FeCrAl	15.836	11.33	0.143
9) Clad1	FeCrAl	15.748	11.30	0.143
10) Thimble1b	Ti-6Al4V	16.447	10.23	0.404
11) Sleeve1	Moly	120.678	5.17	0.073
13) Sleeve1	Moly	119.316	0.00	0.077
15) TM1	SiC(Irr)	8.667	3.69	0.900
16) Thimble2a	Ti-6Al4V	15.957	10.18	0.403
17) Clad2	FeCrAl	15.662	11.28	0.143
18) Clad2	FeCrAl	15.562	11.26	0.143
19) Thimble2b	Ti-6Al4V	16.059	10.19	0.403
20) Sleeve2	Moly	121.101	5.16	0.072
22) Sleeve2	Moly	120.289	0.00	0.074
24) TM2	SiC(Irr)	8.675	3.66	0.900
25) Wire1	Moly	120.834	0.00	0.073

26)	Wire2	Moly	117.783	0.00	0.081
27)	Wire3	Moly	119.784	0.00	0.075
28)	Wire4	Moly	118.716	0.00	0.078
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.613	63.	887.	176.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	120.	700.	0.
4) Grafoil2	GRAFOIL	0.006	166.	700.	1.
5) Grafoil6	GRAFOIL	0.008	461.	700.	2.
6) Grafoil7	GRAFOIL	0.008	459.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	390.	724.	55.
8) Clad1	FeCrAl	1.258	332.	606.	238.
9) Clad1	FeCrAl	0.519	326.	604.	96.
10) Thimble1b	Ti-6Al4V	0.205	490.	765.	74.
11) Sleeve1	Moly	7.176	460.	273.	863.
13) Sleeve1	Moly	0.606	494.	275.	79.
15) TM1	SiC(Irr)	0.019	462.	1100.	9.
16) Thimble2a	Ti-6Al4V	0.205	466.	755.	69.
17) Clad2	FeCrAl	1.282	320.	602.	232.
18) Clad2	FeCrAl	0.582	314.	600.	103.
19) Thimble2b	Ti-6Al4V	0.205	471.	757.	70.
20) Sleeve2	Moly	7.176	449.	273.	841.
22) Sleeve2	Moly	0.606	470.	274.	75.
24) TM2	SiC(Irr)	0.019	452.	1096.	9.
25) Wire1	Moly	0.017	456.	273.	2.
26) Wire2	Moly	0.017	534.	277.	2.
27) Wire3	Moly	0.017	482.	274.	2.
28) Wire4	Moly	0.017	509.	275.	2.
29) Grafoil3	GRAFOIL	0.006	210.	700.	1.
30) Grafoil4	GRAFOIL	0.006	252.	700.	1.
31) Grafoil5	GRAFOIL	0.006	293.	700.	1.
32) Grafoil8	GRAFOIL	0.008	457.	700.	2.
33) Grafoil9	GRAFOIL	0.008	456.	700.	2.
34) Grafoil10	GRAFOIL	0.008	455.	700.	2.
		25.347			3044.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: FeCrAl
Target surface material: AL-6061
Interstitial gas: 970HE_30
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)	324.373	305.047	342.762
Target temperature (°C)	64.165	61.802	65.538
Geometric gas gap (µm)	107.881	104.348	111.330
Contact pressure (MPa)	0.000	0.000	0.000

```
   Gap conduction heat flux (kW/m²)         501.313      449.055      559.829
   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)                  501.313      449.055      559.829
   Thermal contact conductance (W/m²·C)    1925.907     1826.613     2033.142
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    96.484       91.926      100.758
   Contact thermal jump distance (µm)         1.600        1.531        1.662
   Target thermal jump distance (µm)          1.138        1.109        1.162
   Effective contact pressure (MPa)           0.000        0.000        0.000
   Pressure index                            19.909       19.872       19.948
   Gas thermal conductivity (W/m·°C)          0.191        0.188        0.193
   Solid spot conductance (W/m²·C)            0.000        0.000        0.000
   Gas gap conductance (W/m²·C)            1926.155     1827.002     2033.305

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:       FeCrAl
   Target surface material:       AL-6061
   Interstitial gas:             970HE_30
   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)                 312.035      306.997      342.934
   Target temperature (°C)                   64.518       61.267       65.048
   Geometric gas gap (µm)                    95.381       93.344       97.360
   Contact pressure (MPa)                     0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)         535.838      517.387      640.586
   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)                  535.838      517.387      640.586
   Thermal contact conductance (W/m²·C)    2164.767     2109.953     2310.329
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    84.752       80.884       86.881
   Contact thermal jump distance (µm)         1.556        1.539        1.666
   Target thermal jump distance (µm)          1.120        1.114        1.164
   Effective contact pressure (MPa)           0.000        0.000        0.000
   Pressure index                            19.934       19.872       19.944
   Gas thermal conductivity (W/m·°C)          0.189        0.189        0.194
   Solid spot conductance (W/m²·C)            0.000        0.000        0.000
   Gas gap conductance (W/m²·C)            2165.116     2110.388     2310.875

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

FCF06:

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******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: FeCrAl
 * Housing ID =  9.7250 mm
 * Bottom cladding: ID =  8.7600 mm, minor OD =  9.5010 mm, major OD =  9.5200 mm, sleeve OD =
8.6600 mm
 * Top cladding: ID =  8.7900 mm, minor OD =  9.5310 mm, major OD =  9.5390 mm, sleeve OD =
8.7100 mm
 * Backfill gas:   97.00% He,    3.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 5
 * Capsule centerline position =   6.09 cm (  2.40 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·°C
  Bulk coolant temperature  =    52.0 °C

 -------------------------------------------------------------------------------
  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	28800.	132.9	127.6
2) Cap	AL-6061	28800.	15.2	13.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	7.1
8) Clad1	FeCrAl	33500.	40.6	39.8
9) Clad1	FeCrAl	33500.	17.4	17.1
10) Thimble1b	Ti-6Al4V	35200.	7.2	7.0
11) Sleeve1	Moly	42500.	305.0	298.5
13) Sleeve1	Moly	42500.	25.8	24.9
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.9
17) Clad2	FeCrAl	33500.	42.9	40.6
18) Clad2	FeCrAl	33500.	19.5	18.4
19) Thimble2b	Ti-6Al4V	35200.	7.2	6.7
20) Sleeve2	Moly	42500.	311.9	295.3
22) Sleeve2	Moly	42500.	26.4	24.4
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	42500.	0.7	0.7
26) Wire2	Moly	42500.	0.7	0.7
27) Wire3	Moly	42500.	0.7	0.7
28) Wire4	Moly	42500.	0.7	0.7
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			973.1	934.6

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	63.	54.	81.	54.	78.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	122.	112.	129.	120.	122.
4) Grafoil2	GRAFOIL	169.	160.	178.	167.	170.
5) Grafoil6	GRAFOIL	426.	418.	430.	419.	429.
6) Grafoil7	GRAFOIL	424.	417.	427.	418.	427.
7) Thimble1a	Ti-6Al4V	398.	298.	443.	354.	441.
8) Clad1	FeCrAl	326.	304.	347.	309.	341.
9) Clad1	FeCrAl	321.	301.	338.	304.	335.
10) Thimble1b	Ti-6Al4V	485.	366.	503.	450.	502.
11) Sleeve1	Moly	469.	427.	496.	434.	494.
13) Sleeve1	Moly	496.	492.	497.	494.	497.
15) TM1	SiC(Irr)	471.	409.	497.	432.	496.
16) Thimble2a	Ti-6Al4V	442.	336.	462.	416.	458.
17) Clad2	FeCrAl	326.	316.	361.	321.	335.
18) Clad2	FeCrAl	320.	312.	351.	314.	328.
19) Thimble2b	Ti-6Al4V	434.	339.	440.	413.	439.
20) Sleeve2	Moly	411.	402.	429.	404.	426.
22) Sleeve2	Moly	431.	426.	433.	428.	433.
24) TM2	SiC(Irr)	414.	407.	432.	407.	429.
25) Wire1	Moly	467.	452.	477.	453.	477.
26) Wire2	Moly	536.	523.	545.	523.	545.
27) Wire3	Moly	454.	438.	464.	439.	464.
28) Wire4	Moly	471.	459.	481.	460.	481.
29) Grafoil3	GRAFOIL	214.	202.	225.	208.	217.
30) Grafoil4	GRAFOIL	257.	239.	273.	244.	265.
31) Grafoil5	GRAFOIL	299.	264.	324.	268.	312.
32) Grafoil8	GRAFOIL	422.	416.	426.	417.	426.
33) Grafoil9	GRAFOIL	421.	415.	426.	416.	425.
34) Grafoil10	GRAFOIL	420.	415.	425.	415.	425.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.044	24.21	0.050
2) Cap	AL-6061	169.190	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.528	10.05	0.392
8) Clad1	FeCrAl	15.750	11.30	0.143
9) Clad1	FeCrAl	15.665	11.28	0.143
10) Thimble1b	Ti-6Al4V	16.358	10.22	0.404
11) Sleeve1	Moly	120.322	5.17	0.074
13) Sleeve1	Moly	119.237	0.00	0.077
15) TM1	SiC(Irr)	8.660	3.71	0.900
16) Thimble2a	Ti-6Al4V	15.417	10.13	0.400
17) Clad2	FeCrAl	15.751	11.30	0.143
18) Clad2	FeCrAl	15.648	11.28	0.143
19) Thimble2b	Ti-6Al4V	15.250	10.11	0.399
20) Sleeve2	Moly	122.626	5.12	0.068
22) Sleeve2	Moly	121.834	0.00	0.070
24) TM2	SiC(Irr)	8.705	3.58	0.900
25) Wire1	Moly	120.404	0.00	0.074

26)	Wire2	Moly	117.741	0.00	0.082
27)	Wire3	Moly	120.925	0.00	0.073
28)	Wire4	Moly	120.221	0.00	0.074
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.616	63.	887.	177.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	122.	700.	0.
4) Grafoil2	GRAFOIL	0.006	169.	700.	1.
5) Grafoil6	GRAFOIL	0.008	426.	700.	2.
6) Grafoil7	GRAFOIL	0.008	424.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	398.	728.	56.
8) Clad1	FeCrAl	1.212	326.	604.	224.
9) Clad1	FeCrAl	0.520	321.	602.	94.
10) Thimble1b	Ti-6Al4V	0.205	485.	763.	73.
11) Sleeve1	Moly	7.176	469.	274.	882.
13) Sleeve1	Moly	0.606	496.	275.	79.
15) TM1	SiC(Irr)	0.019	471.	1104.	10.
16) Thimble2a	Ti-6Al4V	0.205	442.	744.	64.
17) Clad2	FeCrAl	1.282	326.	604.	237.
18) Clad2	FeCrAl	0.582	320.	602.	105.
19) Thimble2b	Ti-6Al4V	0.205	434.	741.	63.
20) Sleeve2	Moly	7.339	411.	271.	779.
22) Sleeve2	Moly	0.620	431.	272.	69.
24) TM2	SiC(Irr)	0.019	414.	1079.	8.
25) Wire1	Moly	0.017	467.	274.	2.
26) Wire2	Moly	0.017	536.	277.	2.
27) Wire3	Moly	0.017	454.	273.	2.
28) Wire4	Moly	0.017	471.	274.	2.
29) Grafoil3	GRAFOIL	0.006	214.	700.	1.
30) Grafoil4	GRAFOIL	0.006	257.	700.	1.
31) Grafoil5	GRAFOIL	0.006	299.	700.	1.
32) Grafoil8	GRAFOIL	0.008	422.	700.	2.
33) Grafoil9	GRAFOIL	0.008	421.	700.	2.
34) Grafoil10	GRAFOIL	0.008	420.	700.	2.
		25.481			2975.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: FeCrAl
Target surface material: AL-6061
Interstitial gas: 970HE_30
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)	319.082	300.939	335.165
Target temperature (°C)	63.973	61.611	65.651
Geometric gas gap (µm)	107.132	102.351	111.827
Contact pressure (MPa)	0.000	0.000	0.000

Gap conduction heat flux (kW/m²)	491.886	442.083	544.472
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)	491.886	442.083	544.472
Thermal contact conductance (W/m²·C)	1927.989	1812.215	2049.508
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	96.030	90.507	101.378
Contact thermal jump distance (µm)	1.580	1.517	1.634
Target thermal jump distance (µm)	1.129	1.103	1.151
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	19.920	19.888	19.956
Gas thermal conductivity (W/m·°C)	0.190	0.188	0.192
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	1928.319	1812.669	2050.337

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 71: Clad2 To Housing (Frictionless)

Contact surface material: FeCrAl
Target surface material: AL-6061
Interstitial gas: 970HE_30
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)	317.503	311.897	341.967
Target temperature (°C)	64.882	61.421	65.454
Geometric gas gap (µm)	94.881	92.844	96.860
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m²)	554.168	531.910	640.984
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)	554.168	531.910	640.984
Thermal contact conductance (W/m²·C)	2193.541	2134.248	2319.880
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	83.967	80.453	86.161
Contact thermal jump distance (µm)	1.576	1.558	1.662
Target thermal jump distance (µm)	1.129	1.122	1.163
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	19.923	19.874	19.935
Gas thermal conductivity (W/m·°C)	0.190	0.189	0.194
Solid spot conductance (W/m²·C)	0.000	0.000	0.000
Gas gap conductance (W/m²·C)	2193.678	2134.380	2319.960

Contact status codes:

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

FCZ01:

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******************************************************************************
                            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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Zircaloy
 * Housing ID =  9.7240 mm
 * Bottom cladding: ID =  8.3500 mm, minor OD =  9.4900 mm, major OD =  9.4960 mm, sleeve OD =
8.2000 mm
 * Top cladding: ID =  8.3700 mm, minor OD =  9.4870 mm, major OD =  9.5350 mm, sleeve OD =
8.2100 mm
 * Backfill gas:  100.00% He,    0.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 3
 * Capsule centerline position =  -6.99 cm ( -2.75 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·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION
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Part	Material	Heat Gen. @Midplane (W/kg)	------ Heat Load ----- @Midplane (W)	@Location (W)
1) Housing	AL-6061	28800.	133.0	125.0
2) Cap	AL-6061	28800.	15.2	14.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	6.5
8) Clad1	Zircaloy	45100.	89.2	82.0
9) Clad1	Zircaloy	45100.	19.7	18.1
10) Thimble1b	Ti-6Al4V	35200.	7.2	6.8
11) Sleeve1	Moly	39800.	227.7	209.2
13) Sleeve1	Moly	39800.	19.2	18.1
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.8
17) Clad2	Zircaloy	45100.	91.0	87.4
18) Clad2	Zircaloy	45100.	21.5	20.7
19) Thimble2b	Ti-6Al4V	35200.	7.2	7.0
20) Sleeve2	Moly	39800.	228.9	219.7
22) Sleeve2	Moly	39800.	19.3	18.8
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	39800.	0.7	0.6
26) Wire2	Moly	39800.	0.7	0.6
27) Wire3	Moly	39800.	0.7	0.6
28) Wire4	Moly	39800.	0.7	0.6
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			900.1	846.9

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	62.	54.	78.	54.	75.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	112.	104.	119.	111.	113.
4) Grafoil2	GRAFOIL	153.	146.	161.	152.	154.
5) Grafoil6	GRAFOIL	462.	452.	468.	454.	467.
6) Grafoil7	GRAFOIL	460.	451.	464.	453.	463.
7) Thimble1a	Ti-6Al4V	358.	262.	402.	309.	400.
8) Clad1	Zircaloy	317.	290.	344.	295.	339.
9) Clad1	Zircaloy	311.	288.	332.	290.	329.
10) Thimble1b	Ti-6Al4V	472.	350.	483.	435.	482.
11) Sleeve1	Moly	436.	386.	474.	392.	471.
13) Sleeve1	Moly	476.	472.	477.	473.	477.
15) TM1	SiC(Irr)	437.	368.	475.	391.	474.
16) Thimble2a	Ti-6Al4V	456.	329.	468.	413.	466.
17) Clad2	Zircaloy	333.	314.	375.	319.	349.
18) Clad2	Zircaloy	325.	311.	360.	313.	340.
19) Thimble2b	Ti-6Al4V	474.	355.	482.	443.	481.
20) Sleeve2	Moly	450.	442.	472.	443.	469.
22) Sleeve2	Moly	474.	470.	476.	472.	476.
24) TM2	SiC(Irr)	452.	445.	474.	445.	472.
25) Wire1	Moly	420.	408.	428.	409.	428.
26) Wire2	Moly	512.	501.	521.	502.	520.
27) Wire3	Moly	474.	459.	483.	461.	483.
28) Wire4	Moly	512.	501.	521.	501.	521.
29) Grafoil3	GRAFOIL	192.	182.	202.	188.	195.
30) Grafoil4	GRAFOIL	230.	214.	243.	219.	236.
31) Grafoil5	GRAFOIL	267.	237.	286.	239.	277.
32) Grafoil8	GRAFOIL	458.	450.	463.	451.	463.
33) Grafoil9	GRAFOIL	456.	449.	462.	450.	462.
34) Grafoil10	GRAFOIL	456.	449.	462.	450.	462.

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	166.915	24.21	0.050
2) Cap	AL-6061	169.217	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	13.706	9.97	0.379
8) Clad1	Zircaloy	16.374	4.83	0.699
9) Clad1	Zircaloy	16.295	0.00	0.699
10) Thimble1b	Ti-6Al4V	16.090	10.19	0.403
11) Sleeve1	Moly	121.651	5.14	0.071
13) Sleeve1	Moly	120.058	0.00	0.075
15) TM1	SiC(Irr)	8.686	3.63	0.900
16) Thimble2a	Ti-6Al4V	15.739	10.16	0.401
17) Clad2	Zircaloy	16.559	4.84	0.699
18) Clad2	Zircaloy	16.460	0.00	0.699
19) Thimble2b	Ti-6Al4V	16.116	10.20	0.404
20) Sleeve2	Moly	121.085	5.16	0.072
22) Sleeve2	Moly	120.115	0.00	0.075
24) TM2	SiC(Irr)	8.675	3.66	0.900
25) Wire1	Moly	122.276	0.00	0.069

26)	Wire2	Moly	118.589	0.00	0.079
27)	Wire3	Moly	120.124	0.00	0.075
28)	Wire4	Moly	118.585	0.00	0.079
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.618	62.	886.	172.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	112.	700.	0.
4) Grafoil2	GRAFOIL	0.006	153.	700.	1.
5) Grafoil6	GRAFOIL	0.008	462.	700.	3.
6) Grafoil7	GRAFOIL	0.008	460.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	358.	711.	49.
8) Clad1	Zircaloy	1.978	317.	325.	191.
9) Clad1	Zircaloy	0.437	311.	324.	41.
10) Thimble1b	Ti-6Al4V	0.205	472.	757.	70.
11) Sleeve1	Moly	5.721	436.	272.	648.
13) Sleeve1	Moly	0.483	476.	274.	60.
15) TM1	SiC(Irr)	0.019	437.	1089.	9.
16) Thimble2a	Ti-6Al4V	0.205	456.	750.	67.
17) Clad2	Zircaloy	2.018	333.	327.	207.
18) Clad2	Zircaloy	0.478	325.	326.	47.
19) Thimble2b	Ti-6Al4V	0.205	474.	758.	71.
20) Sleeve2	Moly	5.752	450.	273.	675.
22) Sleeve2	Moly	0.486	474.	274.	60.
24) TM2	SiC(Irr)	0.019	452.	1096.	9.
25) Wire1	Moly	0.017	420.	272.	2.
26) Wire2	Moly	0.017	512.	275.	2.
27) Wire3	Moly	0.017	474.	274.	2.
28) Wire4	Moly	0.017	512.	276.	2.
29) Grafoil3	GRAFOIL	0.006	192.	700.	1.
30) Grafoil4	GRAFOIL	0.006	230.	700.	1.
31) Grafoil5	GRAFOIL	0.006	267.	700.	1.
32) Grafoil8	GRAFOIL	0.008	458.	700.	2.
33) Grafoil9	GRAFOIL	0.008	456.	700.	2.
34) Grafoil10	GRAFOIL	0.008	456.	700.	2.
		23.496			2431.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	309.372	287.658	328.831
Target temperature (°C)	62.612	60.536	63.871
Geometric gas gap (µm)	115.380	113.841	116.888
Contact pressure (MPa)	0.000	0.000	0.000

Gap conduction heat flux (kW/m^2)	433.710	386.134	482.203
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)	433.710	386.134	482.203
Thermal contact conductance (W/m^2·C)	1756.652	1703.611	1809.964
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	113.627	111.453	115.662
Contact thermal jump distance (µm)	2.061	1.940	2.168
Target thermal jump distance (µm)	1.289	1.253	1.320
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	15.350	15.258	15.452
Gas thermal conductivity (W/m·°C)	0.206	0.202	0.209
Solid spot conductance (W/m^2·C)	0.000	0.000	0.000
Gas gap conductance (W/m^2·C)	1758.283	1705.130	1812.209

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 71: Clad2 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	323.411	310.737	353.886
Target temperature (°C)	63.779	60.510	64.866
Geometric gas gap (µm)	106.388	94.371	118.302
Contact pressure (MPa)	0.000	0.000	0.000
Gap conduction heat flux (kW/m^2)	502.298	458.135	613.172
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)	502.298	458.135	613.172
Thermal contact conductance (W/m^2·C)	1937.813	1740.579	2205.069
~~ derived results ~~~~~~~~~~			
Effective gas gap (µm)	104.433	91.953	116.237
Contact thermal jump distance (µm)	2.144	2.074	2.322
Target thermal jump distance (µm)	1.316	1.297	1.366
Effective contact pressure (MPa)	0.000	0.000	0.000
Pressure index	15.284	15.137	15.344
Gas thermal conductivity (W/m·°C)	0.208	0.206	0.213
Solid spot conductance (W/m^2·C)	0.000	0.000	0.000
Gas gap conductance (W/m^2·C)	1939.733	1742.407	2208.138

Contact status codes:

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

FCZ02:

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******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Zircaloy
 * Housing ID =  9.7300 mm
 * Bottom cladding: ID =  8.3500 mm, minor OD =  9.4900 mm, major OD =  9.4960 mm, sleeve OD =
8.2100 mm
 * Top cladding: ID =  8.3500 mm, minor OD =  9.4970 mm, major OD =  9.5200 mm, sleeve OD =
8.2100 mm
 * Backfill gas:  100.00% He,    0.00% Ar
 * Irradiation facility: PTP
 * Axial position: 6
 * Capsule centerline position =   8.00 cm (  3.15 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 =  48400. W/m²·°C
  Bulk coolant temperature  =    54.0 °C

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

                                               Heat Gen.  ------ Heat Load -----
                                               @Midplane  @Midplane    @Location
   Part                              Material   (W/kg)       (W)          (W)
 ----------------------------------- --------  ---------  ---------    ---------
   1) Housing                       AL-6061     29900.      137.6        128.4
   2) Cap                           AL-6061     29900.       15.8         13.8
   3) Grafoil1                      GRAFOIL     35000.        0.2          0.2
   4) Grafoil2                      GRAFOIL     35000.        0.2          0.2
   5) Grafoil6                      GRAFOIL     35000.        0.3          0.3
   6) Grafoil7                      GRAFOIL     35000.        0.3          0.3
   7) Thimble1a                     Ti-6Al4V    35600.        7.3          7.1
   8) Clad1                         Zircaloy    46100.       93.0         89.1
   9) Clad1                         Zircaloy    46100.       20.1         19.3
  10) Thimble1b                     Ti-6Al4V    35600.        7.3          6.9
  11) Sleeve1                       Moly        41000.      235.8        225.7
  13) Sleeve1                       Moly        41000.       19.9         18.7
  15) TM1                           SiC(Irr)    34000.        0.7          0.6
  16) Thimble2a                     Ti-6Al4V    35600.        7.3          6.8
  17) Clad2                         Zircaloy    46100.       93.0         85.2
  18) Clad2                         Zircaloy    46100.       21.8         19.9
  19) Thimble2b                     Ti-6Al4V    35600.        7.3          6.5
  20) Sleeve2                       Moly        41000.      235.8        215.8
  22) Sleeve2                       Moly        41000.       19.9         17.8
  24) TM2                           SiC(Irr)    34000.        0.7          0.6
  25) Wire1                         Moly        41000.        0.7          0.7
  26) Wire2                         Moly        41000.        0.7          0.6
  27) Wire3                         Moly        41000.        0.7          0.6
  28) Wire4                         Moly        41000.        0.7          0.6
  29) Grafoil3                      GRAFOIL     35000.        0.2          0.2
  30) Grafoil4                      GRAFOIL     35000.        0.2          0.2
  31) Grafoil5                      GRAFOIL     35000.        0.2          0.2
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32) Grafoil8	GRAFOIL	35000.	0.3	0.3
33) Grafoil9	GRAFOIL	35000.	0.3	0.3
34) Grafoil10	GRAFOIL	35000.	0.3	0.3
			928.6	867.0

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	56.	82.	56.	79.
2) Cap	AL-6061	81.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	118.	109.	125.	116.	119.
4) Grafoil2	GRAFOIL	161.	153.	169.	159.	162.
5) Grafoil6	GRAFOIL	459.	449.	464.	451.	463.
6) Grafoil7	GRAFOIL	456.	448.	460.	450.	460.
7) Thimble1a	Ti-6Al4V	374.	283.	419.	327.	417.
8) Clad1	Zircaloy	342.	315.	367.	320.	362.
9) Clad1	Zircaloy	335.	312.	354.	315.	351.
10) Thimble1b	Ti-6Al4V	482.	370.	492.	447.	491.
11) Sleeve1	Moly	448.	403.	483.	409.	480.
13) Sleeve1	Moly	485.	481.	486.	482.	486.
15) TM1	SiC(Irr)	450.	384.	484.	407.	483.
16) Thimble2a	Ti-6Al4V	465.	347.	477.	424.	475.
17) Clad2	Zircaloy	338.	325.	383.	329.	351.
18) Clad2	Zircaloy	330.	322.	368.	324.	342.
19) Thimble2b	Ti-6Al4V	470.	365.	478.	442.	477.
20) Sleeve2	Moly	453.	446.	469.	447.	466.
22) Sleeve2	Moly	470.	466.	472.	468.	472.
24) TM2	SiC(Irr)	455.	449.	470.	449.	468.
25) Wire1	Moly	439.	425.	447.	426.	447.
26) Wire2	Moly	522.	511.	531.	511.	531.
27) Wire3	Moly	483.	469.	492.	470.	492.
28) Wire4	Moly	506.	496.	514.	496.	514.
29) Grafoil3	GRAFOIL	202.	191.	212.	197.	205.
30) Grafoil4	GRAFOIL	241.	224.	255.	229.	248.
31) Grafoil5	GRAFOIL	280.	248.	301.	251.	291.
32) Grafoil8	GRAFOIL	454.	447.	459.	448.	459.
33) Grafoil9	GRAFOIL	453.	446.	458.	447.	458.
34) Grafoil10	GRAFOIL	452.	445.	458.	446.	458.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (µm/m·°C)	Emis (---)
1) Housing	AL-6061	167.170	24.21	0.050
2) Cap	AL-6061	169.183	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.055	10.00	0.385
8) Clad1	Zircaloy	16.664	4.84	0.699
9) Clad1	Zircaloy	16.578	0.00	0.699
10) Thimble1b	Ti-6Al4V	16.293	10.21	0.404
11) Sleeve1	Moly	121.145	5.15	0.072
13) Sleeve1	Moly	119.697	0.00	0.076
15) TM1	SiC(Irr)	8.676	3.66	0.900
16) Thimble2a	Ti-6Al4V	15.927	10.18	0.403
17) Clad2	Zircaloy	16.622	4.84	0.699
18) Clad2	Zircaloy	16.529	0.00	0.699
19) Thimble2b	Ti-6Al4V	16.033	10.19	0.403
20) Sleeve2	Moly	120.975	5.16	0.072
22) Sleeve2	Moly	120.266	0.00	0.074
24) TM2	SiC(Irr)	8.673	3.67	0.900
25) Wire1	Moly	121.534	0.00	0.071

26)	Wire2	Moly	118.187	0.00	0.080
27)	Wire3	Moly	119.744	0.00	0.076
28)	Wire4	Moly	118.822	0.00	0.078
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.604	64.	888.	181.
2) Cap	AL-6061	0.527	81.	902.	29.
3) Grafoil1	GRAFOIL	0.006	118.	700.	0.
4) Grafoil2	GRAFOIL	0.006	161.	700.	1.
5) Grafoil6	GRAFOIL	0.008	459.	700.	2.
6) Grafoil7	GRAFOIL	0.008	456.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	374.	718.	52.
8) Clad1	Zircaloy	2.018	342.	328.	213.
9) Clad1	Zircaloy	0.437	335.	327.	45.
10) Thimble1b	Ti-6Al4V	0.205	482.	762.	72.
11) Sleeve1	Moly	5.752	448.	273.	672.
13) Sleeve1	Moly	0.486	485.	274.	62.
15) TM1	SiC(Irr)	0.019	450.	1095.	9.
16) Thimble2a	Ti-6Al4V	0.205	465.	754.	69.
17) Clad2	Zircaloy	2.018	338.	328.	210.
18) Clad2	Zircaloy	0.472	330.	327.	48.
19) Thimble2b	Ti-6Al4V	0.205	470.	756.	70.
20) Sleeve2	Moly	5.751	453.	273.	679.
22) Sleeve2	Moly	0.486	470.	274.	60.
24) TM2	SiC(Irr)	0.019	455.	1097.	9.
25) Wire1	Moly	0.017	439.	272.	2.
26) Wire2	Moly	0.017	522.	276.	2.
27) Wire3	Moly	0.017	483.	274.	2.
28) Wire4	Moly	0.017	506.	275.	2.
29) Grafoil3	GRAFOIL	0.006	202.	700.	1.
30) Grafoil4	GRAFOIL	0.006	241.	700.	1.
31) Grafoil5	GRAFOIL	0.006	280.	700.	1.
32) Grafoil8	GRAFOIL	0.008	454.	700.	2.
33) Grafoil9	GRAFOIL	0.008	453.	700.	2.
34) Grafoil10	GRAFOIL	0.008	452.	700.	2.
		23.549			2506.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	333.273	312.981	350.724
Target temperature (°C)	65.203	62.766	66.538
Geometric gas gap (µm)	118.380	116.841	119.888
Contact pressure (MPa)	0.000	0.000	0.000

```
   Gap conduction heat flux (kW/m²)          469.077      419.101      514.598
   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)                   469.077      419.101      514.598
   Thermal contact conductance (W/m²·C)     1749.140     1697.165     1797.905
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    116.356      114.181      118.427
   Contact thermal jump distance (µm)          2.206        2.089        2.305
   Target thermal jump distance (µm)           1.337        1.303        1.364
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.236       15.152       15.333
   Gas thermal conductivity (W/m·°C)           0.210        0.207        0.212
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1750.664     1698.304     1800.095

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:     Zircaloy
   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)                  329.019      321.728      361.023
   Target temperature (°C)                    65.285       62.107       65.935
   Geometric gas gap (µm)                    110.632      104.853      116.320
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          491.693      466.932      585.924
   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)                   491.693      466.932      585.924
   Thermal contact conductance (W/m²·C)     1864.858     1772.422     2012.112
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    108.718      102.256      114.418
   Contact thermal jump distance (µm)          2.181        2.140        2.371
   Target thermal jump distance (µm)           1.330        1.319        1.383
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.257       15.102       15.292
   Gas thermal conductivity (W/m·°C)           0.209        0.208        0.214
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1866.672     1774.110     2014.245

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

FCZ03:

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*******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Zircaloy
 * Housing ID =  9.7200 mm
 * Bottom cladding: ID =  8.3600 mm, minor OD =  9.4770 mm, major OD =  9.4850 mm, sleeve OD =
8.2100 mm
 * Top cladding: ID =  8.3500 mm, minor OD =  9.5000 mm, major OD =  9.5100 mm, sleeve OD =
8.2100 mm
 * Backfill gas:  100.00% He,    0.00% Ar
 * Irradiation facility: TRRH
 * Axial position: 3
 * Capsule centerline position =  -6.99 cm ( -2.75 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·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION
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Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	28800.	133.3	125.3
2) Cap	AL-6061	28800.	15.2	14.9
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil6	GRAFOIL	33700.	0.3	0.3
6) Grafoil7	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.2	6.5
8) Clad1	Zircaloy	45100.	91.0	83.6
9) Clad1	Zircaloy	45100.	18.5	17.0
10) Thimble1b	Ti-6Al4V	35200.	7.2	6.8
11) Sleeve1	Moly	39800.	229.0	210.4
13) Sleeve1	Moly	39800.	19.3	18.2
15) TM1	SiC(Irr)	32900.	0.6	0.6
16) Thimble2a	Ti-6Al4V	35200.	7.2	6.8
17) Clad2	Zircaloy	45100.	90.1	86.5
18) Clad2	Zircaloy	45100.	20.9	20.1
19) Thimble2b	Ti-6Al4V	35200.	7.2	7.0
20) Sleeve2	Moly	39800.	228.9	219.7
22) Sleeve2	Moly	39800.	19.3	18.8
24) TM2	SiC(Irr)	32900.	0.6	0.6
25) Wire1	Moly	39800.	0.7	0.6
26) Wire2	Moly	39800.	0.7	0.6
27) Wire3	Moly	39800.	0.7	0.6
28) Wire4	Moly	39800.	0.7	0.6
29) Grafoil3	GRAFOIL	33700.	0.2	0.2
30) Grafoil4	GRAFOIL	33700.	0.2	0.2
31) Grafoil5	GRAFOIL	33700.	0.2	0.2

32) Grafoil8	GRAFOIL	33700.	0.3	0.3
33) Grafoil9	GRAFOIL	33700.	0.3	0.3
34) Grafoil10	GRAFOIL	33700.	0.3	0.3
			900.8	847.5

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	62.	54.	78.	54.	75.
2) Cap	AL-6061	82.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	112.	103.	118.	110.	112.
4) Grafoil2	GRAFOIL	152.	145.	159.	150.	153.
5) Grafoil6	GRAFOIL	468.	457.	474.	459.	473.
6) Grafoil7	GRAFOIL	465.	457.	469.	458.	469.
7) Thimble1a	Ti-6Al4V	352.	258.	395.	307.	394.
8) Clad1	Zircaloy	327.	296.	356.	301.	351.
9) Clad1	Zircaloy	320.	293.	343.	297.	341.
10) Thimble1b	Ti-6Al4V	468.	340.	477.	432.	477.
11) Sleeve1	Moly	428.	380.	468.	386.	465.
13) Sleeve1	Moly	470.	466.	472.	467.	471.
15) TM1	SiC(Irr)	430.	362.	469.	384.	468.
16) Thimble2a	Ti-6Al4V	458.	324.	468.	412.	467.
17) Clad2	Zircaloy	334.	321.	371.	325.	346.
18) Clad2	Zircaloy	326.	318.	355.	320.	335.
19) Thimble2b	Ti-6Al4V	480.	353.	489.	448.	488.
20) Sleeve2	Moly	456.	448.	479.	449.	476.
22) Sleeve2	Moly	481.	476.	483.	478.	482.
24) TM2	SiC(Irr)	458.	451.	480.	451.	479.
25) Wire1	Moly	412.	400.	420.	401.	420.
26) Wire2	Moly	507.	496.	515.	496.	515.
27) Wire3	Moly	480.	466.	489.	467.	489.
28) Wire4	Moly	519.	508.	528.	508.	528.
29) Grafoil3	GRAFOIL	190.	180.	200.	186.	193.
30) Grafoil4	GRAFOIL	227.	211.	240.	216.	233.
31) Grafoil5	GRAFOIL	263.	234.	283.	236.	274.
32) Grafoil8	GRAFOIL	463.	455.	468.	457.	468.
33) Grafoil9	GRAFOIL	462.	454.	468.	456.	468.
34) Grafoil10	GRAFOIL	461.	454.	467.	455.	467.

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	166.914	24.21	0.050
2) Cap	AL-6061	169.219	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	13.593	9.97	0.377
8) Clad1	Zircaloy	16.486	4.83	0.699
9) Clad1	Zircaloy	16.406	0.00	0.699
10) Thimble1b	Ti-6Al4V	16.004	10.19	0.403
11) Sleeve1	Moly	121.951	5.14	0.070
13) Sleeve1	Moly	120.295	0.00	0.074
15) TM1	SiC(Irr)	8.692	3.61	0.900
16) Thimble2a	Ti-6Al4V	15.778	10.17	0.402
17) Clad2	Zircaloy	16.566	4.84	0.699
18) Clad2	Zircaloy	16.473	0.00	0.699
19) Thimble2b	Ti-6Al4V	16.250	10.21	0.404
20) Sleeve2	Moly	120.832	5.16	0.073
22) Sleeve2	Moly	119.849	0.00	0.075
24) TM2	SiC(Irr)	8.670	3.68	0.900
25) Wire1	Moly	122.585	0.00	0.068

26)	Wire2	Moly	118.815	0.00	0.078
27)	Wire3	Moly	119.880	0.00	0.075
28)	Wire4	Moly	118.318	0.00	0.080
29)	Grafoil3	GRAFOIL	38.000	1.00	0.500
30)	Grafoil4	GRAFOIL	38.000	1.00	0.500
31)	Grafoil5	GRAFOIL	38.000	1.00	0.500
32)	Grafoil8	GRAFOIL	38.000	1.00	0.500
33)	Grafoil9	GRAFOIL	38.000	1.00	0.500
34)	Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.628	62.	886.	173.
2) Cap	AL-6061	0.527	82.	902.	29.
3) Grafoil1	GRAFOIL	0.006	112.	700.	0.
4) Grafoil2	GRAFOIL	0.006	152.	700.	1.
5) Grafoil6	GRAFOIL	0.008	468.	700.	3.
6) Grafoil7	GRAFOIL	0.008	465.	700.	3.
7) Thimble1a	Ti-6Al4V	0.205	352.	709.	48.
8) Clad1	Zircaloy	2.018	327.	326.	202.
9) Clad1	Zircaloy	0.409	320.	325.	40.
10) Thimble1b	Ti-6Al4V	0.205	468.	756.	69.
11) Sleeve1	Moly	5.753	428.	272.	639.
13) Sleeve1	Moly	0.486	470.	274.	60.
15) TM1	SiC(Irr)	0.019	430.	1086.	9.
16) Thimble2a	Ti-6Al4V	0.205	458.	751.	67.
17) Clad2	Zircaloy	1.998	334.	327.	205.
18) Clad2	Zircaloy	0.464	326.	326.	46.
19) Thimble2b	Ti-6Al4V	0.205	480.	761.	72.
20) Sleeve2	Moly	5.752	456.	273.	685.
22) Sleeve2	Moly	0.486	481.	274.	61.
24) TM2	SiC(Irr)	0.019	458.	1098.	9.
25) Wire1	Moly	0.017	412.	271.	2.
26) Wire2	Moly	0.017	507.	275.	2.
27) Wire3	Moly	0.017	480.	274.	2.
28) Wire4	Moly	0.017	519.	276.	2.
29) Grafoil3	GRAFOIL	0.006	190.	700.	1.
30) Grafoil4	GRAFOIL	0.006	227.	700.	1.
31) Grafoil5	GRAFOIL	0.006	263.	700.	1.
32) Grafoil8	GRAFOIL	0.008	463.	700.	3.
33) Grafoil9	GRAFOIL	0.008	462.	700.	2.
34) Grafoil10	GRAFOIL	0.008	461.	700.	2.
		23.519			2440.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	318.804	294.604	340.545
Target temperature (°C)	62.723	60.638	63.931
Geometric gas gap (μm)	119.380	117.342	121.361
Contact pressure (MPa)	0.000	0.000	0.000

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   Gap conduction heat flux (kW/m²)          438.996      380.777      492.468
   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)                   438.996      380.777      492.468
   Thermal contact conductance (W/m²·C)     1713.243     1648.920     1774.209
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    117.416      114.700      120.068
   Contact thermal jump distance (µm)          2.115        1.981        2.237
   Target thermal jump distance (µm)           1.306        1.266        1.340
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.305       15.202       15.419
   Gas thermal conductivity (W/m·°C)           0.207        0.203        0.210
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1714.782     1650.012     1775.841

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

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CONTACT SUMMARY FOR CONTACT ID 71: Clad2 To Housing (Frictionless)
   Contact surface material:     Zircaloy
   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)                  324.193      318.141      348.043
   Target temperature (°C)                    63.704       60.608       64.321
   Geometric gas gap (µm)                    107.381      104.844      109.835
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          497.834      479.352      565.810
   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)                   497.834      479.352      565.810
   Thermal contact conductance (W/m²·C)     1911.116     1863.256     1995.889
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    105.399      102.272      107.944
   Contact thermal jump distance (µm)          2.148        2.114        2.287
   Target thermal jump distance (µm)           1.317        1.308        1.357
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.280       15.165       15.309
   Gas thermal conductivity (W/m·°C)           0.208        0.207        0.212
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1913.033     1865.111     1998.545

   Contact status codes:
    ----------------------------------------------
    0=open/no heat transfer, 1=near-field contact
    2=closed and sliding,    3=closed and sticking
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FCZ04:

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******************************************************************************
                             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 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Zircaloy
 * Housing ID =  9.7230 mm
 * Bottom cladding: ID =  8.3600 mm, minor OD =  9.4770 mm, major OD =  9.4830 mm, sleeve OD =
8.2000 mm
 * Top cladding: ID =  8.3500 mm, minor OD =  9.5020 mm, major OD =  9.5080 mm, sleeve OD =
8.2000 mm
 * Backfill gas:  100.00% He,    0.00% Ar
 * Irradiation facility: PTP
 * Axial position: 6
 * Capsule centerline position =   8.00 cm (  3.15 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 =  48400. W/m²·°C
  Bulk coolant temperature  =    54.0 °C

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  HEAT GENERATION
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Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	29900.	138.2	128.9
2) Cap	AL-6061	29900.	15.8	13.8
3) Grafoil1	GRAFOIL	35000.	0.2	0.2
4) Grafoil2	GRAFOIL	35000.	0.2	0.2
5) Grafoil6	GRAFOIL	35000.	0.3	0.3
6) Grafoil7	GRAFOIL	35000.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35600.	7.3	7.1
8) Clad1	Zircaloy	46100.	93.0	89.1
9) Clad1	Zircaloy	46100.	18.8	18.0
10) Thimble1b	Ti-6Al4V	35600.	7.3	6.9
11) Sleeve1	Moly	41000.	234.5	224.5
13) Sleeve1	Moly	41000.	19.8	18.6
15) TM1	SiC(Irr)	34000.	0.7	0.6
16) Thimble2a	Ti-6Al4V	35600.	7.3	6.8
17) Clad2	Zircaloy	46100.	92.1	84.3
18) Clad2	Zircaloy	46100.	21.4	19.6
19) Thimble2b	Ti-6Al4V	35600.	7.3	6.5
20) Sleeve2	Moly	41000.	234.5	214.7
22) Sleeve2	Moly	41000.	19.8	17.7
24) TM2	SiC(Irr)	34000.	0.7	0.6
25) Wire1	Moly	41000.	0.7	0.7
26) Wire2	Moly	41000.	0.7	0.6
27) Wire3	Moly	41000.	0.7	0.6
28) Wire4	Moly	41000.	0.7	0.6
29) Grafoil3	GRAFOIL	35000.	0.2	0.2
30) Grafoil4	GRAFOIL	35000.	0.2	0.2
31) Grafoil5	GRAFOIL	35000.	0.2	0.2

32) Grafoil8	GRAFOIL	35000.	0.3	0.3
33) Grafoil9	GRAFOIL	35000.	0.3	0.3
34) Grafoil10	GRAFOIL	35000.	0.3	0.3
			923.7	862.4

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	56.	82.	56.	79.
2) Cap	AL-6061	81.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	119.	110.	126.	117.	120.
4) Grafoil2	GRAFOIL	162.	155.	171.	161.	163.
5) Grafoil6	GRAFOIL	463.	452.	469.	455.	468.
6) Grafoil7	GRAFOIL	461.	452.	464.	454.	464.
7) Thimble1a	Ti-6Al4V	379.	279.	425.	329.	423.
8) Clad1	Zircaloy	345.	317.	369.	322.	364.
9) Clad1	Zircaloy	337.	314.	356.	318.	354.
10) Thimble1b	Ti-6Al4V	488.	358.	499.	449.	499.
11) Sleeve1	Moly	456.	409.	491.	415.	488.
13) Sleeve1	Moly	492.	488.	493.	490.	493.
15) TM1	SiC(Irr)	458.	389.	492.	414.	490.
16) Thimble2a	Ti-6Al4V	471.	339.	483.	425.	481.
17) Clad2	Zircaloy	333.	322.	379.	326.	346.
18) Clad2	Zircaloy	325.	319.	363.	321.	338.
19) Thimble2b	Ti-6Al4V	475.	354.	484.	444.	483.
20) Sleeve2	Moly	460.	453.	475.	454.	472.
22) Sleeve2	Moly	477.	473.	478.	474.	478.
24) TM2	SiC(Irr)	462.	456.	476.	456.	475.
25) Wire1	Moly	444.	431.	453.	432.	453.
26) Wire2	Moly	529.	518.	538.	518.	538.
27) Wire3	Moly	491.	477.	500.	478.	500.
28) Wire4	Moly	513.	502.	521.	502.	521.
29) Grafoil3	GRAFOIL	204.	193.	215.	199.	207.
30) Grafoil4	GRAFOIL	244.	227.	258.	232.	251.
31) Grafoil5	GRAFOIL	283.	251.	304.	254.	294.
32) Grafoil8	GRAFOIL	458.	451.	464.	452.	463.
33) Grafoil9	GRAFOIL	457.	450.	463.	451.	463.
34) Grafoil10	GRAFOIL	456.	449.	463.	450.	462.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (µm/m·°C)	Emis (---)
1) Housing	AL-6061	167.166	24.21	0.050
2) Cap	AL-6061	169.183	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.155	10.01	0.387
8) Clad1	Zircaloy	16.696	4.84	0.699
9) Clad1	Zircaloy	16.612	0.00	0.699
10) Thimble1b	Ti-6Al4V	16.403	10.23	0.404
11) Sleeve1	Moly	120.841	5.16	0.073
13) Sleeve1	Moly	119.413	0.00	0.076
15) TM1	SiC(Irr)	8.670	3.68	0.900
16) Thimble2a	Ti-6Al4V	16.057	10.19	0.403
17) Clad2	Zircaloy	16.559	4.84	0.699
18) Clad2	Zircaloy	16.468	0.00	0.699
19) Thimble2b	Ti-6Al4V	16.147	10.20	0.404
20) Sleeve2	Moly	120.684	5.17	0.073
22) Sleeve2	Moly	120.014	0.00	0.075
24) TM2	SiC(Irr)	8.667	3.68	0.900
25) Wire1	Moly	121.301	0.00	0.072

26) Wire2	Moly	117.932	0.00	0.081
27) Wire3	Moly	119.438	0.00	0.076
28) Wire4	Moly	118.575	0.00	0.079
29) Grafoil3	GRAFOIL	38.000	1.00	0.500
30) Grafoil4	GRAFOIL	38.000	1.00	0.500
31) Grafoil5	GRAFOIL	38.000	1.00	0.500
32) Grafoil8	GRAFOIL	38.000	1.00	0.500
33) Grafoil9	GRAFOIL	38.000	1.00	0.500
34) Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.621	64.	888.	181.
2) Cap	AL-6061	0.527	81.	902.	29.
3) Grafoil1	GRAFOIL	0.006	119.	700.	0.
4) Grafoil2	GRAFOIL	0.006	162.	700.	1.
5) Grafoil6	GRAFOIL	0.008	463.	700.	3.
6) Grafoil7	GRAFOIL	0.008	461.	700.	2.
7) Thimble1a	Ti-6Al4V	0.205	379.	720.	53.
8) Clad1	Zircaloy	2.018	345.	328.	215.
9) Clad1	Zircaloy	0.407	337.	327.	42.
10) Thimble1b	Ti-6Al4V	0.205	488.	764.	73.
11) Sleeve1	Moly	5.721	456.	273.	681.
13) Sleeve1	Moly	0.483	492.	275.	63.
15) TM1	SiC(Irr)	0.019	458.	1098.	9.
16) Thimble2a	Ti-6Al4V	0.205	471.	757.	70.
17) Clad2	Zircaloy	1.998	333.	327.	204.
18) Clad2	Zircaloy	0.464	325.	326.	46.
19) Thimble2b	Ti-6Al4V	0.205	475.	759.	71.
20) Sleeve2	Moly	5.720	460.	273.	688.
22) Sleeve2	Moly	0.483	477.	274.	60.
24) TM2	SiC(Irr)	0.019	462.	1100.	9.
25) Wire1	Moly	0.017	444.	273.	2.
26) Wire2	Moly	0.017	529.	276.	2.
27) Wire3	Moly	0.017	491.	275.	2.
28) Wire4	Moly	0.017	513.	276.	2.
29) Grafoil3	GRAFOIL	0.006	204.	700.	1.
30) Grafoil4	GRAFOIL	0.006	244.	700.	1.
31) Grafoil5	GRAFOIL	0.006	283.	700.	1.
32) Grafoil8	GRAFOIL	0.008	458.	700.	2.
33) Grafoil9	GRAFOIL	0.008	457.	700.	2.
34) Grafoil10	GRAFOIL	0.008	456.	700.	2.
		23.441			2522.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	336.256	315.643	353.439
Target temperature (°C)	65.109	62.725	66.694
Geometric gas gap (µm)	121.380	119.841	122.888
Contact pressure (MPa)	0.000	0.000	0.000

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   Gap conduction heat flux (kW/m²)          464.108      413.359      507.860
   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)                   464.108      413.359      507.860
   Thermal contact conductance (W/m²·C)     1710.975     1659.722     1757.455
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    119.276      117.115      121.393
   Contact thermal jump distance (µm)          2.223        2.104        2.321
   Target thermal jump distance (µm)           1.342        1.307        1.369
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.222       15.139       15.321
   Gas thermal conductivity (W/m·°C)           0.210        0.207        0.213
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1712.466     1660.655     1759.488

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

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CONTACT SUMMARY FOR CONTACT ID 71: Clad2 To Housing (Frictionless)
   Contact surface material:     Zircaloy
   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)                  323.798      319.402      355.571
   Target temperature (°C)                    65.206       62.113       65.654
   Geometric gas gap (µm)                    108.880      107.341      110.388
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          487.052      473.626      570.353
   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)                   487.052      473.626      570.353
   Thermal contact conductance (W/m²·C)     1883.363     1853.085     1964.176
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    107.083      104.756      108.685
   Contact thermal jump distance (µm)          2.150        2.125        2.339
   Target thermal jump distance (µm)           1.320        1.314        1.375
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.282       15.128       15.303
   Gas thermal conductivity (W/m·°C)           0.208        0.208        0.213
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1885.105     1854.730     1966.253

   Contact status codes:
    ----------------------------------------------
    0=open/no heat transfer, 1=near-field contact
    2=closed and sliding,    3=closed and sticking
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FCZ05:

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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:  350.0 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Zircaloy
 * Housing ID =  9.7220 mm
 * Bottom cladding: ID =  8.3600 mm, minor OD =  9.4770 mm, major OD =  9.4840 mm, sleeve OD =
8.2100 mm
 * Top cladding: ID =  8.3500 mm, minor OD =  9.5020 mm, major OD =  9.5070 mm, sleeve OD =
8.1800 mm
 * Backfill gas:  100.00% He,    0.00% Ar
 * Irradiation facility: PTP
 * Axial position: 6
 * Capsule centerline position =   8.00 cm (  3.15 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 =  48400. W/m²·°C
  Bulk coolant temperature  =    54.0 °C

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  HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	Heat Load @Midplane (W)	Heat Load @Location (W)
1) Housing	AL-6061	29900.	138.2	128.9
2) Cap	AL-6061	29900.	15.8	13.8
3) Grafoil1	GRAFOIL	35000.	0.2	0.2
4) Grafoil2	GRAFOIL	35000.	0.2	0.2
5) Grafoil6	GRAFOIL	35000.	0.3	0.3
6) Grafoil7	GRAFOIL	35000.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35600.	7.3	7.1
8) Clad1	Zircaloy	46100.	93.0	89.1
9) Clad1	Zircaloy	46100.	18.8	18.0
10) Thimble1b	Ti-6Al4V	35600.	7.3	6.9
11) Sleeve1	Moly	41000.	235.8	225.7
13) Sleeve1	Moly	41000.	19.9	18.7
15) TM1	SiC(Irr)	34000.	0.7	0.6
16) Thimble2a	Ti-6Al4V	35600.	7.3	6.8
17) Clad2	Zircaloy	46100.	92.1	84.3
18) Clad2	Zircaloy	46100.	21.3	19.5
19) Thimble2b	Ti-6Al4V	35600.	7.3	6.5
20) Sleeve2	Moly	41000.	232.0	212.4
22) Sleeve2	Moly	41000.	19.6	17.5
24) TM2	SiC(Irr)	34000.	0.7	0.6
25) Wire1	Moly	41000.	0.7	0.7
26) Wire2	Moly	41000.	0.7	0.6
27) Wire3	Moly	41000.	0.7	0.6
28) Wire4	Moly	41000.	0.7	0.6
29) Grafoil3	GRAFOIL	35000.	0.2	0.2
30) Grafoil4	GRAFOIL	35000.	0.2	0.2
31) Grafoil5	GRAFOIL	35000.	0.2	0.2

32) Grafoil8	GRAFOIL	35000.	0.3	0.3
33) Grafoil9	GRAFOIL	35000.	0.3	0.3
34) Grafoil10	GRAFOIL	35000.	0.3	0.3
			922.5	861.3

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	56.	82.	56.	79.
2) Cap	AL-6061	81.	80.	83.	80.	83.
3) Grafoil1	GRAFOIL	118.	109.	125.	117.	119.
4) Grafoil2	GRAFOIL	161.	154.	169.	160.	162.
5) Grafoil6	GRAFOIL	471.	459.	477.	462.	475.
6) Grafoil7	GRAFOIL	468.	459.	472.	461.	472.
7) Thimble1a	Ti-6Al4V	376.	277.	421.	327.	419.
8) Clad1	Zircaloy	345.	316.	371.	322.	366.
9) Clad1	Zircaloy	338.	313.	358.	318.	356.
10) Thimble1b	Ti-6Al4V	487.	356.	497.	448.	496.
11) Sleeve1	Moly	452.	405.	488.	411.	484.
13) Sleeve1	Moly	489.	485.	491.	487.	490.
15) TM1	SiC(Irr)	453.	386.	489.	410.	487.
16) Thimble2a	Ti-6Al4V	475.	337.	486.	426.	484.
17) Clad2	Zircaloy	330.	320.	377.	323.	343.
18) Clad2	Zircaloy	322.	317.	361.	318.	335.
19) Thimble2b	Ti-6Al4V	483.	357.	492.	451.	492.
20) Sleeve2	Moly	468.	462.	484.	463.	481.
22) Sleeve2	Moly	485.	481.	487.	483.	487.
24) TM2	SiC(Irr)	470.	465.	485.	465.	483.
25) Wire1	Moly	441.	427.	450.	428.	450.
26) Wire2	Moly	527.	515.	535.	516.	535.
27) Wire3	Moly	497.	482.	506.	483.	506.
28) Wire4	Moly	522.	511.	530.	511.	530.
29) Grafoil3	GRAFOIL	203.	192.	213.	198.	206.
30) Grafoil4	GRAFOIL	242.	225.	256.	230.	249.
31) Grafoil5	GRAFOIL	281.	249.	302.	252.	292.
32) Grafoil8	GRAFOIL	466.	458.	471.	459.	471.
33) Grafoil9	GRAFOIL	464.	457.	470.	458.	470.
34) Grafoil10	GRAFOIL	464.	456.	470.	458.	470.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.164	24.21	0.050
2) Cap	AL-6061	169.183	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil6	GRAFOIL	38.000	1.00	0.500
6) Grafoil7	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	14.089	10.01	0.386
8) Clad1	Zircaloy	16.703	4.84	0.699
9) Clad1	Zircaloy	16.619	0.00	0.699
10) Thimble1b	Ti-6Al4V	16.386	10.22	0.404
11) Sleeve1	Moly	121.020	5.16	0.072
13) Sleeve1	Moly	119.522	0.00	0.076
15) TM1	SiC(Irr)	8.674	3.67	0.900
16) Thimble2a	Ti-6Al4V	16.147	10.20	0.404
17) Clad2	Zircaloy	16.522	4.84	0.699
18) Clad2	Zircaloy	16.433	0.00	0.699
19) Thimble2b	Ti-6Al4V	16.318	10.22	0.404
20) Sleeve2	Moly	120.352	5.17	0.074
22) Sleeve2	Moly	119.673	0.00	0.076
24) TM2	SiC(Irr)	8.661	3.70	0.900
25) Wire1	Moly	121.448	0.00	0.071

26) Wire2	Moly	118.013	0.00	0.081
27) Wire3	Moly	119.208	0.00	0.077
28) Wire4	Moly	118.214	0.00	0.080
29) Grafoil3	GRAFOIL	38.000	1.00	0.500
30) Grafoil4	GRAFOIL	38.000	1.00	0.500
31) Grafoil5	GRAFOIL	38.000	1.00	0.500
32) Grafoil8	GRAFOIL	38.000	1.00	0.500
33) Grafoil9	GRAFOIL	38.000	1.00	0.500
34) Grafoil10	GRAFOIL	38.000	1.00	0.500

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	4.623	64.	888.	181.
2) Cap	AL-6061	0.527	81.	902.	29.
3) Grafoil1	GRAFOIL	0.006	118.	700.	0.
4) Grafoil2	GRAFOIL	0.006	161.	700.	1.
5) Grafoil6	GRAFOIL	0.008	471.	700.	3.
6) Grafoil7	GRAFOIL	0.008	468.	700.	3.
7) Thimble1a	Ti-6Al4V	0.205	376.	719.	52.
8) Clad1	Zircaloy	2.018	345.	328.	215.
9) Clad1	Zircaloy	0.408	338.	327.	43.
10) Thimble1b	Ti-6Al4V	0.205	487.	764.	73.
11) Sleeve1	Moly	5.752	452.	273.	678.
13) Sleeve1	Moly	0.486	489.	275.	63.
15) TM1	SiC(Irr)	0.019	453.	1096.	9.
16) Thimble2a	Ti-6Al4V	0.205	475.	759.	71.
17) Clad2	Zircaloy	1.998	330.	327.	202.
18) Clad2	Zircaloy	0.463	322.	326.	46.
19) Thimble2b	Ti-6Al4V	0.205	483.	762.	72.
20) Sleeve2	Moly	5.659	468.	274.	694.
22) Sleeve2	Moly	0.478	485.	274.	61.
24) TM2	SiC(Irr)	0.019	470.	1103.	10.
25) Wire1	Moly	0.017	441.	273.	2.
26) Wire2	Moly	0.017	527.	276.	2.
27) Wire3	Moly	0.017	497.	275.	2.
28) Wire4	Moly	0.017	522.	276.	2.
29) Grafoil3	GRAFOIL	0.006	203.	700.	1.
30) Grafoil4	GRAFOIL	0.006	242.	700.	1.
31) Grafoil5	GRAFOIL	0.006	281.	700.	1.
32) Grafoil8	GRAFOIL	0.008	466.	700.	3.
33) Grafoil9	GRAFOIL	0.008	464.	700.	3.
34) Grafoil10	GRAFOIL	0.008	464.	700.	3.
		23.410			2524.

CLAD TO HOUSING GAP REPORTS

CONTACT SUMMARY FOR CONTACT ID 69: Clad1 To Housing (Frictionless)

Contact surface material: Zircaloy
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)	336.775	314.925	355.137
Target temperature (°C)	65.189	62.794	66.706
Geometric gas gap (µm)	120.630	118.841	122.375
Contact pressure (MPa)	0.000	0.000	0.000

```
   Gap conduction heat flux (kW/m²)          467.942      413.555      515.045
   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)                   467.942      413.555      515.045
   Thermal contact conductance (W/m²·C)     1722.283     1665.325     1774.236
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    118.523      116.092      120.909
   Contact thermal jump distance (µm)          2.227        2.103        2.331
   Target thermal jump distance (µm)           1.343        1.307        1.371
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.219       15.131       15.324
   Gas thermal conductivity (W/m·°C)           0.210        0.207        0.213
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1723.787     1666.316     1776.233

   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 71: Clad2 To Housing (Frictionless)
   Contact surface material:     Zircaloy
   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)                  320.815      316.753      353.728
   Target temperature (°C)                    65.099       62.061       65.516
   Geometric gas gap (µm)                    108.630      107.340      109.902
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          481.420      469.179      566.848
   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)                   481.420      469.179      566.848
   Thermal contact conductance (W/m²·C)     1882.514     1856.248     1961.778
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                    106.892      104.785      108.257
   Contact thermal jump distance (µm)          2.132        2.110        2.328
   Target thermal jump distance (µm)           1.315        1.309        1.372
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.296       15.137       15.315
   Gas thermal conductivity (W/m·°C)           0.208        0.207        0.213
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1883.953     1857.333     1963.933

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