A HIGH TEMPERATURE OUT-OF-PILE EXPERIMENT FOR TESTING NUCLEAR THERMAL PROPULSION SURROGATE FUELS

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Richard Harmon Howard
August 2019

ACKNOWLEDGMENTS

I would like to thank all my colleagues in the Nuclear Experiments and Irradiation Testing Group at the Oak Ridge National Laboratory. This work would not have been possible without their support. Specifically, thanks to Joel McDuffee and Kurt Smith who contributed their time to support me with advice and technical support. Others at ORNL who deserve my gratitude include Ken Tobin, Bob Sitterson, David Bryant, and Ryan Gallagher. To Jordan Rader, T. Jay Harrison, and Michael Smith – thanks for making me part of the team. To Dr. Kelsa Benensky, Dr. Mike Houts, and Sonny Mitchell at NASA – thank you for the funding opportunity, collaboration, and excellent comradery. Thanks also to Dr. Lou Qualls who introduced me to this outrageous project and provided me with a muse that allowed me to create something beautiful.

I also want to thank my committee. Dr. Ruggles – you are fantastic to work with, and your insights & conversations were invaluable. To the remaining members of my committee, who include Dr. J. I. Frankel, Dr. T. M. Moeller, Dr. T. J. Harrison: I give you my utmost respect and regards.

Lastly, I owe everything to my wife Amy. I was once told that there is no such thing as a self-made man. My achievement here is proof that this anecdote is true. I couldn't have done this without her. I dedicate this work to Amy and our wonderful children.

ABSTRACT

Nuclear Thermal Propulsion derives power from fission to heat hydrogen gas to produce thrust for propulsion. This technology dates to the 1950's and the early days of the space race between the United States and the Soviet Union, but much more development is required to bring it into a technologically mature state. The fuel and reactor component qualification remain incomplete and are crucial to developing engine designs that can reliably facilitate interplanetary space travel. This work describes a Nuclear Thermal Propulsion fuel test strategy that integrates nonradiological out-of-pile tests and in-pile radiation tests that utilize sub-scale specimen geometries to subject fuel materials to Nuclear Thermal Propulsion conditions. Earlier Nuclear Thermal Propulsion development efforts relied on full-scale prototype reactor tests to qualify fuels and reactor designs. The approach developed here reduces risk of the fuel qualification process.

This work includes the design, modeling, and testing of an experiment called "OUTSET" that exposes candidate fuel and reactor component materials to 2,300°C, which is typical of Nuclear Thermal Propulsion service conditions. The design requirements for OUTSET are established, construction & testing details for the experiment are described, experiment transient temperature results from thermocouples, short wave infrared camera response, and melt wire are reported. A thermal model for OUTSET is developed using ANSYS and data from experiments are used to validate this model following the American Society for Mechanical Engineers consensus standard Verification &Validation -20.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

ACRR	Annular Core Research Reactor
ANL	Argonne National Laboratory
APDL	ANSYS Parametric Design Language
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
C_δ	Insulation thickness proportionality constant
C_ε	Emissivity thickness proportionality constant
CFEET	Compact Fuel Element Environmental Test
CX	Critical Experiment
D	Nominal measured validation point
DC	Direct Current
E	Error
ESCORT	Excore Scalable Cermet Orbital Repositioning Technology
FEA	Finite Element Analysis
GE	General Electric
HFIR	High Flux Isotope Reactor
NASA	National Aeronautics and Space Administration
NERVA	Nuclear Engine for Rocket Vehicle Applications
NET	Nuclear Fuel Element Development Tests

NEIT	Nuclear Experiments and Irradiation Testing
NTP	Nuclear thermal propulsion
NTREES	Nuclear Thermal Rocket Element Environmental Simulator
NUC	Non-Uniformity Compensation
ORNL	Oak Ridge National Laboratory
OUTSET	OUT of pile experiment SET apparatus
PID	Proportional-integrator-differentiator
PIE	Post-irradiation Examination
PIPET	Particle-Bed Reactor Integral Performance Element Tester
POP	Period Of Progress
Poco	Pure Oil Company
PPPT	Peak Power Peak Temperature
PWR	Pressurized Water Reactor
S	Nominal tabulated simulation point
SDIO	Strategic Defense Initiative Organization
SNL	Sandia National Laboratory
SNTP	Space Nuclear Thermal Propulsion
SWIR	Short-Wave Infrared
TEM	Transmission Electron Microscopy
u_{input}	model input uncertainty
u_{num}	Numerical Uncertainty
$u_{To.D}$	Measurement Uncertainty

u_{val}	Validation Uncertainty
V&V	Verification & Validation
V&V 20-2009	Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

CHAPTER 1.
INTRODUCTION AND BACKGROUND

Nuclear thermal propulsion (NTP) technology is designed to provide propulsion after a vehicle is "in space" and derives thrust from a hydrogen propellant which is heated by a nuclear reaction. This technology generates a 900 s specific impulse and 1.1 MN thrust [1]. The specific impulse is estimated to be over twice of that of contemporary chemical combustion rockets [1], primarily as a result of the low atomic weight of hydrogen propellant, and the high temperature to which it is heated. Chemical rockets may have higher exhaust temperature, but the lower molecular weight of the hydrogen compared to chemical rocket propellants makes NTP a more efficient propulsion technology. Other technologies such as electric propulsion, solar sails, solar thermal propulsion, and fusion propulsion claim specific impulse generation from 1,000s – 100,000s, but the technical readiness of these technologies is low [2]. Domestic NTP research and development trace their roots to the Project Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) program that was in operation from 1955 through 1973. During that time, multiple NTP engines were developed and tested to withstand multiple firing cycles at "very high temperatures" ($T<2{,}127°C$) [3].

Great progress was made in the 1960s and 1970s to develop NTP technology. Initial NTP fuels were comprised of carbon/carbide composite materials developed by the Rover/NERVA program and were designed to withstand operating temperatures around 2,127°C while remaining intact after tens of firing cycles. Project Rover/NERVA employed a strategy of designing, building, and testing prototype nuclear reactors to develop and qualify NTP fuels. This work yielded tens of prototype reactors and "an overall system technical readiness level of about 6" [4], which corresponds with technology demonstration.

After the Rover/NERVA program was discontinued, lesser efforts were made to model and improve potential NTP fuel technology, but no significant concerted effort to revive this technology came to fruition. However, the 2010 United States' National Space Policy states that the US will, "by 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth," [5]. Work has resumed to qualify a propulsion system that uses nuclear fuel with a hydrogen working fluid to support this policy [1].

Current development programs expect the modern NTP fuel to withstand temperatures from 2,200-2600°C under duty cycle similar to that of Project Rover/NERVA [6] because higher operating temperatures of the reactor improve performance. This dissertation proposes an experiment and testing strategy that will subject fuel candidates to these new service conditions. Materials from these tests will then be subjected to materials testing to provide material performance data. This material performance data will be used for optimizing and potentially down-selecting the candidate materials for larger scale fuel qualification. The material testing is beyond the scope of this dissertation

This dissertation also describes the development of the OUT-of-pile experiment SET apparatus or OUTSET. OUTSET provides the basis for sub-scale reactor-based experiments and is engineered to facilitate a low risk transition to full-scale reactor-based testing. The OUTSET design requirements are based on NTP service conditions and other constraints provided by the experiment and testing strategy. Specific challenges include:

- understanding the experiment design requirements for both nonradiation (out-of-pile), and irradiation (in-pile) environments,
- preliminary modeling to quantify power and heat transfer requirements and transferring these to out-of-pile design parameters,
- identifying the appropriate materials for OUTSET that maximize the portability of outcomes from out-of-pile to in-pile environments, and
- the devising of a reliable instrumentation scheme for OUTSET to generate experiment data well suited to validate thermal performance.

OUTSET experiment data generated out-of-pile are then used to validate thermal performance models to be used to design future in-pile experiments; where combined gamma heating and fission sources provide the thermal power. Subsequent in-pile testing, that will occur at an existing research reactor, will subject fuel materials to NTP conditions including a hydrogen atmosphere and neutron/gamma irradiation fields. While different physics establishes heat input conditions for the out-of-pile experiments, the heat transfer characteristics are similar for OUTSET and the in-pile experiments. The thermal performance data from OUTSET are valuable for reducing uncertainties of in-pile designs.

1.1 Early Developments in Nuclear Thermal Propulsion (1950s-1970s)

The Project Rover/NERVA, General Electric (GE) 710, and Argonne National Laboratory (ANL) 200/2000 are the primary fuel types currently under consideration. The

Project Rover/NERVA design utilized a hexagonal binary/ternary carbon composite fuel type, where the GE and ANL designs used a hexagonal cermet fuel structure [7]. Images of the composite and cermet fuel geometries are seen in Figure 1-1 and Figure 1-2, respectively.

The base materials for both designs are derived from ceramics, refractory metals, and graphite structures; each with high melting points and resistance to degradation under NTP operating conditions. The Project Rover/NERVA incorporated zirconium and niobium refractory metals to form the metal carbides that coat a graphite structure with a base fuel of a solidified mixture of spherical uranium particles [8], [9]. The GE and ANL designs employed tungsten to form the tungsten metal-uranium ceramic, or cermet, fuel structure [7]. These metals and carbides have melting points over 2,700°C.

The Project Rover/NERVA was the earliest NTP effort, initiated in the early days of the space race between the United States and the Soviet Union. It had very strong support from both the American government and the general public. Amid the Cold War, funding and resources were relatively easy to obtain. Developing this technology required the invention of novel technologies especially in the realm of materials but also in nuclear reactor technology. This effort required many larger scale experiments that ultimately led to full-scale nuclear tests. Figure 1-3, shows the extensive number of major nuclear reactor tests that were undertaken throughout the Project Rover/NERVA. Fuel/reactor configurations under steadily increasing power ratings were tested, translating roughly to increasing reactor exit temperatures.

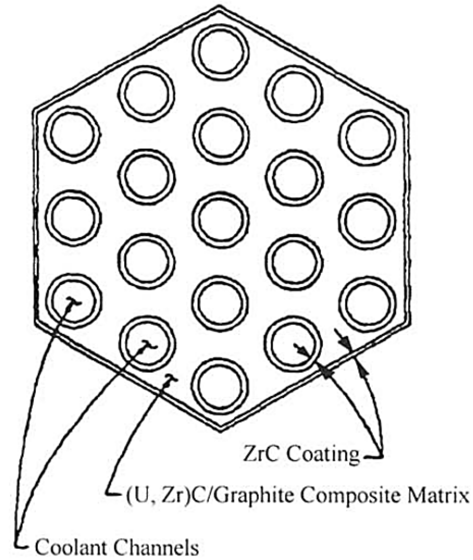


Figure 1-1. Project Rover/NERVA NF-1 carbide/graphite composite fuel element [10]

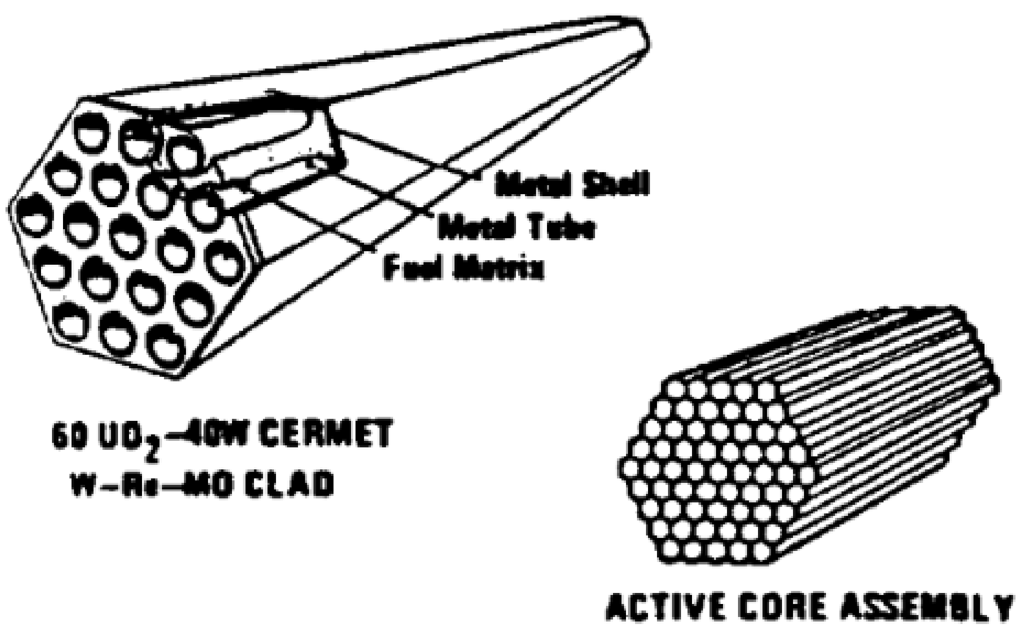


Figure 1-2. Cermet fuel schematic from the GE 710 testing program [11]

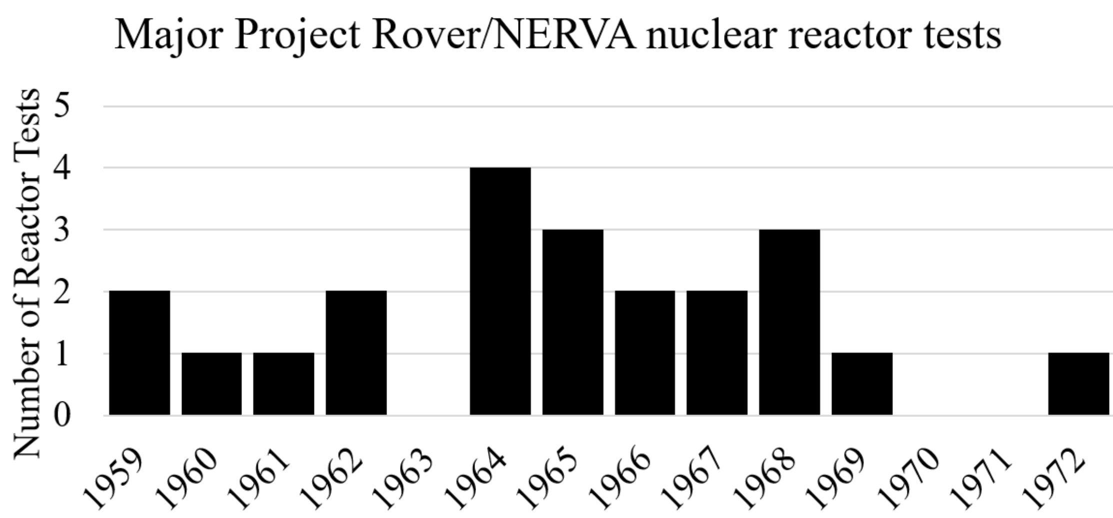


Figure 1-3. Major Project Rover/NERVA nuclear reactor tests [12].

The Project Rover/NERVA yielded successful fuel materials and good performance data [13] [14], but most of the fabrication data and technology for this fuel format has been lost over time. Likewise, the cermet fuel system was initially investigated in the 1960s by GE and ANL, but modern fabrication processes for the cermet fuel system such as Excore Scalable Cermet Orbital Repositioning Technology (ESCORT) [9] have yet to be qualified. The GE/ANL cermet fuel developments produced much in the way of analysis and material selection. However, only unfueled furnace testing was performed on the early GE/ANL cermet materials [7].

A major testing outcome for the Project Rover/NERVA was the linkage between the coefficient of thermal expansion and fuel corrosion. This phenomenon was of interest to the program given Project Rover/NERVA fuels were coated with materials that reduce reactions between the carbon-based fuel and the hydrogen NTP propellant/coolant [15]. A similar strategy was used to protect cermet fuels by cladding them with refractory metals

[7]. The thought was that a thermal expansion mismatch between the coating and the fuel led to cracks in the NERVA fuel coating or buckling in the cermet cladding; which exacerbated fuel degradation. Lyons showed the dependence of corrosion of the composite fuel structure as a function of thermal expansion as reproduced in Figure 1-4. Fuel elements with a thermal expansion coefficient of 6.1 μm/m-K (right, Figure 1-4) had a substantially larger mass loss than a fuel sample with 6.5 μm/m-K (left, Figure 1-4).

1.2 Space Nuclear Thermal Propulsion (the 1980s)

The space nuclear thermal propulsion (SNTP) program, sponsored by the Strategic Defense Initiative Organization (SDIO), set out to develop a nuclear thermal propulsion engine that utilized particle bed reactor technology. Although SNTP gained much from earlier works such as the Project Rover/NERVA and the high-temperature gas-cooled reactor, significant advancements were required to meet the SDIO objectives. The program decided to qualify a baseline fuel particle consisting of graphite coated fuel kernels that were encapsulated in Zirconium Carbide (ZrC), as shown in Figure 1-5, through nuclear fuel element development tests (NET) [16] and in the critical experiment (CX) [16]. This experimentation was to be performed simultaneous with the development of an advanced fuel particle with broader operating limits, particularly with a higher melting point and operating temperature (>2,700°C), expecting that this final fuel form would be used for the SNTP engine.

Initial tests for the baseline fuel included irradiated particles in the Annular Core Research Reactor (ACRR) at Sandia National Laboratory (SNL) for particle nuclear tests

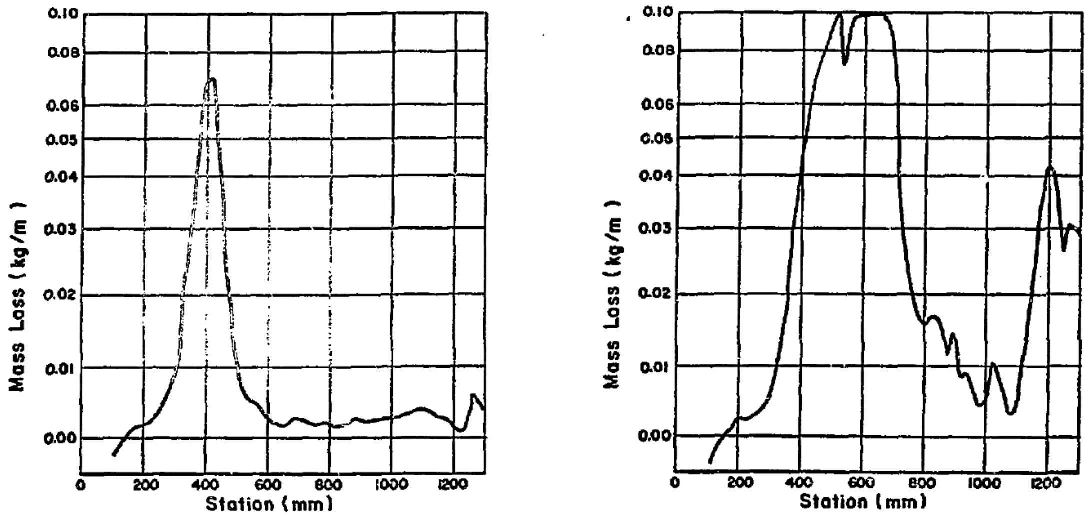


Figure 1-4. Mass loss of Project Rover/NERVA fuel structure over the length of the fuel element with graphite thermal expansion greater than 6.5 μm/m-K (left) and thermal expansion of 6.1 μm/m-K (right) [10]

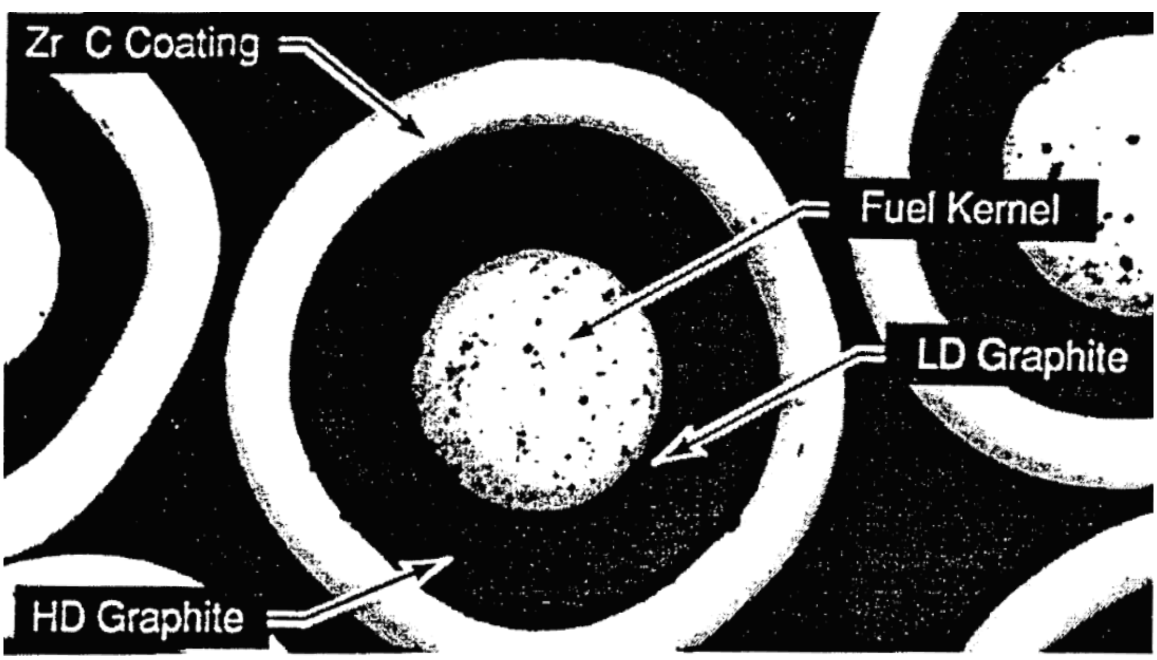


Figure 1-5. Space Nuclear Thermal Propulsion baseline fuel particle [16].

and heating particles in furnaces for particle heating tests. These early experiments were intended to gather nuclear and nonnuclear data on mechanical performance, cycling capabilities, and temperature capabilities to establish the limitations and failure modes of the fuel form [17]. The next phase of testing included both the baseline and advanced fuel forms and involved irradiating prototypic fueled pebbles in the CX, located at SNL, and fuel elements in NET capsules within the ACRR. The CX tests yielded data used to verify calculated neutronic performance of the particle bed and the NET experiments were used to learn about fuel element performance and verify concurrent simulation efforts of NET that would support future experiments [16].

The NET experiment phase was the high-water mark of the testing efforts for the SNTP program. This irradiation experiment plan was sectioned into four phases, where the research team methodically increased fuel-element powers/bulk-reactor operating temperatures in order to find a fuel element that could perform with advanced fuel particles at temperatures exceeding 2,700°C. Table 1-1 shows the NET test matrix. The NET 1.2 test was the only experiment completed before the termination of the project. It was heated by fuel fission and cooled with -123°C hydrogen. The literature indicates that an initial test was satisfactorily completed, but a second test was inadequate, causing cracks that led to the fuel particles migrating into the experiment's center channel and thereby causing power irregularities [16]. Corrections were made to the experiment design to alleviate these issues, but the SNTP program was terminated before additional in-pile testing took place.

The SNTP program was discontinued in 1994, but there remained a few other experimentation and testing facilities engaging in design or installation of the objectives of

Table 1-1. Nuclear fuel element development test (NET) matrix [16].

Test Condition	NET-1	NET-2	NET-3	NET-4
Max. H_2 Outlet Temp (K)	2300	2500	3000	>3000
H_2 Inlet Temp (K)	150	150	150	150
Specific Power (MW/l)	1.5	5	5	5
Fuel Bed Length (cm)	25	10.6	10.6	10.6
Fuel Type	UC_2/ZrC	UC_2/ZrC	UC_2/ZrC	UC_2/ZrC
Cycles to Maximum Temp	2	2	30-50	
Nom. ^{235}U Mass (g)	400	125	TBD	TBD
Nom. Fuel Volume (cm^3)	300	140	140	140

SNTP to some degree. The most important of these were the Particle-Bed Reactor Integral Performance Element Tester (PIPET) critical facility and the San Tan Hydrogen Test Facility. PIPET was to drive fuel to prototypic temperatures. PIPET never moved out of the design phase before SNTP was terminated. The San Tan Hydrogen Test Facility was intended to serve as a site for testing subsystems and components in high temperature flowing hydrogen. It was to be located San Tan test site in Arizona but was never used before the end of the SNTP program. Haslett's report [16] provides a full summary of these facilities.

Fuel thermophysical properties played a significant role in fuel failure during the ACRR NET tests. Like those experiments performed during the Project Rover/NERVA, a thermal expansion mismatch caused the fuel to fail and ultimately led to NET test failure [16]. The delay and expense of fuel failures in a reactor test contributed to the discontinuation of the NET test program. SNTP relied on designing and building custom facilities to support the qualification of the fuel assemblies. The CX, PIPET, and the San Tan hydrogen test facility are examples of this. Establishing these facilities took considerable time and project funding. Ultimately, “adequate funding support for the national ground test facility was not obtained,” [16].

1.3 Modern NTP Testing Facilities (the 2000s–Present)

The National Aeronautics and Space Administration (NASA) NTP program developed two nonreactor test facilities that are located at the Marshall Space Flight Center. The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) uses a 1.2 MW induction heater, to take unfueled NTP test articles to prototypic temperatures under vacuum or other gas atmospheric conditions [18]. The Compact Fuel Element Environmental Test (CFEET) can deliver 50kW of power for induction heating and is intended for hot hydrogen testing of sub-scale nuclear thermal propulsion fuels. These test facilities cannot utilize fission as a heat source. They are predominantly used to perform experiments to understand the separate effects of thermal cycling and atmospheric composition on fuel or fuel surrogate test articles.

1.4 Summarization of Historical NTP Testing Capabilities

The needs and methods for qualifying fuels remained consistent throughout the Project Rover/NERVA, GE/ANL, and SNTP Periods Of Progress (POP). For each project, the fundamental challenge remained to develop a fuel form that would survive prototypic NTP temperatures and corrosive/erosive hydrogen propellant atmospheres. The Project Rover/NERVA work was able to produce a working carbon/carbide composite fuel form that was able to survive multiple firing cycles at temperatures in excess of 2,127°C (2,400

K). Graphite readily reacts with hydrogen at high temperatures, requiring this fuel form be coated with a hydrogen resistant refractory carbide coating to reduce fuel mass loss during operation. Coating failures that exposed the carbon-based interior of the fuel were shown to be problematic for the Project Rover/NERVA development. Lyons' report [10] concluded that thermal expansion mismatch between the carbon composite and the carbide coating led to the thermally induced stress that resulted in cracked coatings. Likewise, thermal expansion mismatch between fuel and coating led to pebble fuel failure in the early iterations of the NET test during the SNTP program. These programs identified that understanding thermophysical properties are crucial to the success of developing a robust NTP fuel form. With the Project Rover/NERVA and SNTP programs, this data was gathered during radiation testing. Engineers learned about the issues with thermal expansion after fuel failures from in-pile tests.

The literature indicates that a capability for measurement of thermophysical, mechanical, and nuclear performance characteristics must be available to support the revitalization of fabrication capability and qualification of NTP fuels [19]. Moving forward, the NTP fuel qualification strategy must provide means to test fuel candidates to gather this data throughout the qualification process, including sub-scale specimen out-of-pile & in-pile testing, to ensure these parameters are well characterized and potential fuel systems can be either down selected or further optimized to maximize fuel performance in an efficient and cost-effective manner. Domestic research reactor capacity is greatly diminished from the days of Project Rover/NERVA and GE-700 [20]. To effectively select viable fuels for NTP systems, a method of rapidly testing these fuel materials must be established. NTREES and CFEET, both of which are out-of-pile experiment facilities, are capable of thermally cycling specimens and look for failures by analyzing the exhaust gas composition. Sub-scale out-of-pile experiments like OUTSET or CFEET also allow fuel developers to test various materials against established performance specifications and optimize or abandon candidates as necessary before proceeding to the more expensive in-pile experiments. OUTSET is also designed to transition to in-pile testing in a domestic research reactor. The CFEET design restricts that device to only out-of-pile test conditions, and in-pile data are required for fuel qualification.

It is estimated that testing of nuclear-fueled specimens of more prototypic sizes would cost in the range of tens to hundreds of millions of dollars [21]. NTP does not enjoy the government and public support of the early Project Rover/NERVA days and no program can sustain a fuel development process that requires potentially scores of large-scale critical test iterations. Therefore, a strategy for testing fuels in-pile is proposed that relies on the existing research reactor fleet. OUTSET provides a pathway to gather performance data, build design tools, and demonstrate the feasibility of future in-pile phases of the fuel NTP qualification process. Large-scale reactor tests remain necessary, but the utilization of sub-scale testing for producing optimized fuels and components can reduce project risk and lead to a more efficient fuel qualification process.

CHAPTER 2.
THE NTP FUEL AND COMPONENT MATERIAL TESTING STRATEGY

The strategy described in this chapter progresses from out-of-pile testing to in-pile testing by utilizing a general experiment design and an existing domestic host reactor. Most of the information in this chapter comes from a report, ORNL/TM-2017/376—"Technology Implementation Plan: Irradiation Testing and Qualification for Nuclear Thermal Propulsion Fuel" —which was primarily written by this author in 2017 [22]. Benensky and Qualls [6] authored an NTP fuel qualification plan that established several technical focus areas that needed to be addressed to develop NTP fuels successfully. The plan specifically calls for out-of-pile surrogate fuel testing, in-pile testing, and post-irradiation examination (PIE). These phases are the framework of the strategy laid out here.

2.1 Testing Strategy

Phase 1 of the strategy, which centers around the OUTSET experiment, consists of performing out-of-pile tests on sub-scale [6] surrogate fuel specimens; i.e. specimens that do not contain nuclear fuel. Current out-of-pile tests such as CFEET are already capable of testing fueled specimens. Therefore, the scope for OUTSET does not include fueled specimens to reduce the experiment complexity and focus on demonstrating OUTSET thermal performance. The testing methods include exposing the material to elevated temperatures so that researchers can generate test articles for subsequent thermophysical property and material property testing. While CFEET is capable of exposing specimens to hydrogen gas, OUTSET is not capable of delivering hydrogen to specimens. This challenge must be addressed in future work. Upon successful completion of the surrogate out-of-pile tests, the program will shift to phase 2 which includes performing in-pile sub-scale surrogate and fueled specimen tests. These tests shall emulate the conditions established under phase 1 so that researchers can understand the effects imparted by neutron irradiation on the samples. Phase 2 will have an experiment enclosure with a design that is based on the phase 1, OUTSET, enclosure. Under phase 2, further fuel optimization and down-selection occurs until researchers arrive at a viable NTP fuel form accompanied by an appropriate fabrication process of record.

A series of full-scale in-pile experiments are conducted during this last phase. This effort will expose fuel forms made to prototypic geometries to prototypic and limiting NTP service conditions to establish optimized fuel form performance data. This third phase will rely on both large-scale irradiation experiment facilities and full-scale reactor ground tests. Instrumentation and experiment design practices will evolve as the strategy unfolds, coupling phases one and two to the integral testing performed in phase 3. PIE will be conducted during phase 2 and 3 testing. This process will include a destructive and nondestructive examination of fuel samples to extract thermophysical and mechanical data, yielding the fuel material performance characteristics. A flow chart of the technology implementation plan can be seen in Figure 2-1. The focus of this dissertation is phase 1 of the fuel testing strategy; specifically, the blocks shaded in blue.

2.2 Experiment Requirements

OUTSET must be designed to meet NTP service conditions. Data and validated

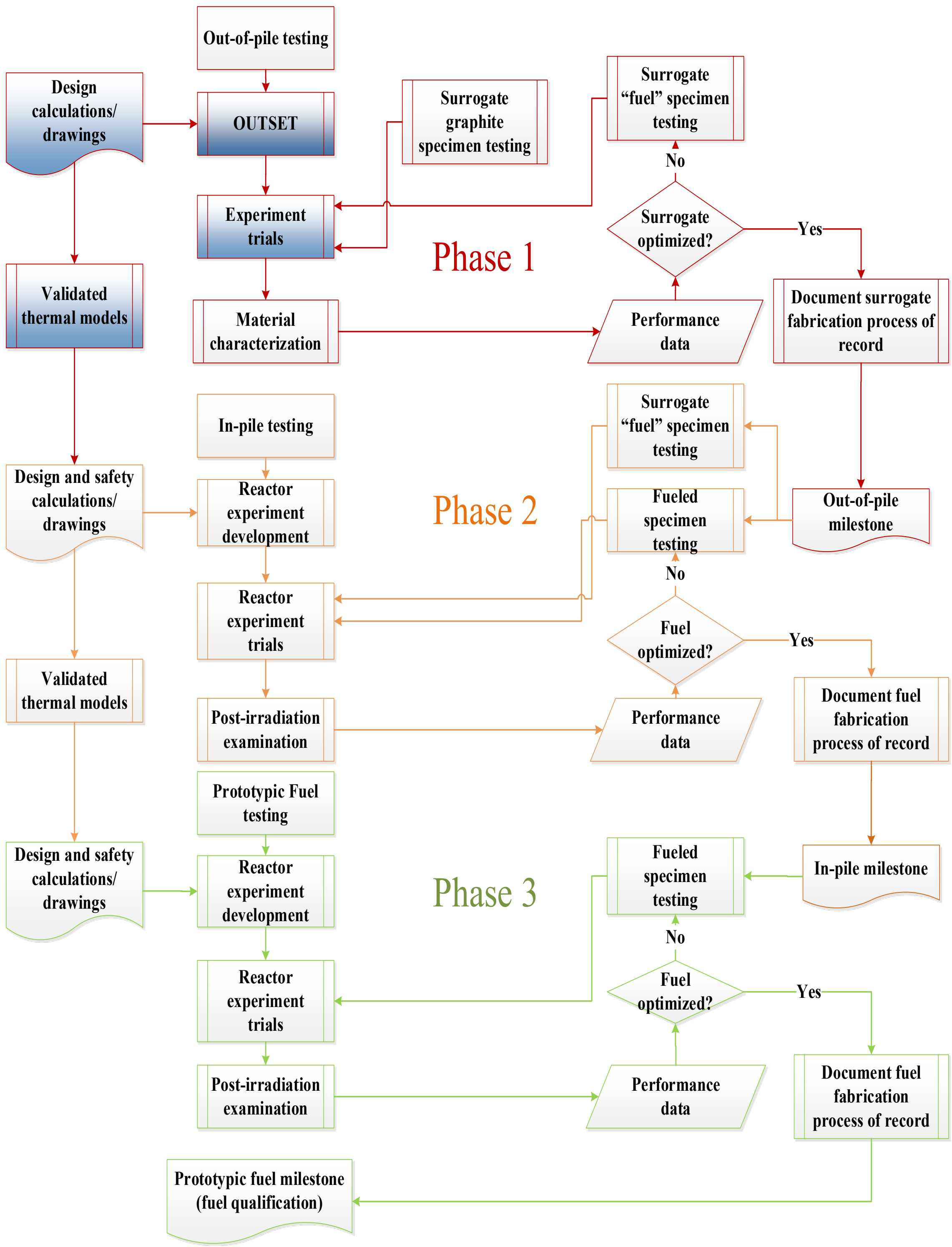


Figure 2-1. Flow chart for the NTP fuel and component testing strategy. Contributions of this dissertation are shown in the blue shaded regions. [22].

models of the thermal performance of OUTSET can then be used to design future experiments in the research reactor core. The design requirements for OUTSET are not limited strictly to attaining NTP service conditions out-of-pile, but also pertain to generating validation data for the performance of the in-pile experiment. OUTSET design requirements include:

1. **Materials selection:** OUTSET composition should be based on ease of fabrication, application compatibility, and reduced neutron activation. Although OUTSET will not be exposed to neutron irradiation, it is the basis for future versions of the in-pile experiments used in phase 2 of the testing strategy. Therefore, containment materials and internal components will be selected with fabrication, thermophysical property compatibility, and neutron activation in mind. Reducing fabrication costs and post-irradiation handling and processing costs for in-pile experiments aligns with the goals established in the NTP fuel testing strategy.
2. **Flexibility to accept various instrumentation techniques and electrical power delivery:** Obtaining reliable OUTSET performance is crucial to the phase 1 mission. Thermocouples are a common instrument for measuring temperature. High-temperature thermocouples made from tungsten-rhenium alloys have operating temperatures up to around 2,700°C [23], and commercial instrument interfaces are available. However, alternate instrumentation forms should be implemented to gather additional redundant temperature information.
3. **Ability to provide and maintain a well controlled atmosphere:** The gas atmosphere type and pressure may be modulated to control power rejection by

convection and sample temperature. Also a well-controlled atmosphere is required to protect the experiment samples from contamination.

4. **Provide thermal cycling:** OUTSET must be able to thermally cycle specimens at maximum rates on the order of 20-50°C/s. The NTP reactor is planned to operate predominantly at steady state conditions, but it is expected that the start-up and shutdown transients will be challenging to the NTP fuel forms.
5. **Temperature control and thermal management:** NTP fuel has a target power density of 5 MW/l and NTP fuel temperatures [1]. OUTSET must be designed to accommodate heat removal and attain steady state NTP component temperatures. Preliminary tests are conducted under vacuum conditions to demonstrate that the OUTSET enclosure and internal components can reliably survive these conditions. Vacuum conditions force the internal components of OUTSET to reject heat mostly through radiation. However, the apparatus shall be designed to also be operated under an inert gas atmosphere (helium or argon) to facilitate heat transfer through both convection and radiation for higher power experiments. The outside of the enclosure must have cooling and be compatible with water, given forced light water convection cooling is generally standard at the candidate research reactor sites that will be used for phase 2 testing.
6. **Standardization of specimen geometry:** OUTSET will seek to accommodate a general standard specimen geometry. The specimen geometry is designed to easily transition from OUTSET to subsequent thermophysical and mechanical property

testing. The sample size for the in-pile and out-of-pile experiments is set by the methods available for material property testing.

2.3 Chapter Summary

Qualifying NTP fuels requires a well-formulated strategy to effectively examine and optimize candidate fuel forms through out-of-pile testing, irradiation testing, and PIE. Out-of-pile experiments are designed to inform subsequent in-pile experiments. A precise set of design requirements is essential to ensuring OUTSET will produce thermal performance data that is suitable to validate future models used in later phases of the testing strategy. The OUTSET enclosure design must be easily fabricated and minimally activated by a neutron field. The experiment must be able to heat & cool the specimen region and interface with a standardized specimen geometry suited to facilitate NTP fuel characterization. Lastly, it must properly manage thermal loads and provide reliable instrumentation interfaces to the specimen region.

CHAPTER 3.
OUTSET EXPERIMENT DESIGN

3.1 Materials Selection

The OUTSET design is consolidated into four primary components: (1) the enclosure, (2) the insulation, (3) the power and instrumentation penetration points, and (4) the specimen. Figure 3-1 shows a hypothetical design of OUTSET and these primary components. The enclosure provides structure, atmosphere/vacuum conditions, and a heat transfer circuit. As a starting point, the initial OUTSET size constraints were selected to allow the experiment to fit into common irradiation sites at the High Flux Isotope Reactor (HFIR) and the Advanced Test Reactor (ATR), which are cylindrical with a diameter of 3.8 cm [24] [25]. Many materials may facilitate these functions, so an efficient method for down selection must be employed to find the optimal materials. Ashby developed a technique that includes translation, screening, and ranking of candidate materials to determine the most favorable option [26], based on specific criteria. The enclosure is the primary pressure boundary for the experiment. The maximum pressure loading that in-pile experiment enclosures will experience depends on the host reactor. Reactors such as the HFIR and ATR operate at less than 3.5 MPa. This loading condition yields a strength limited design which includes examples such as loaded cylinders and compression-loaded columns. Ashby states that a strength-limited design should optimize the specific failure stress $\left(\frac{\sigma_f}{\rho}\right)$ material index [26]. Note this proposed design does not consider H_2 gas, which will be corrosive to carbon. Accommodating for H_2 is left for future work. This material

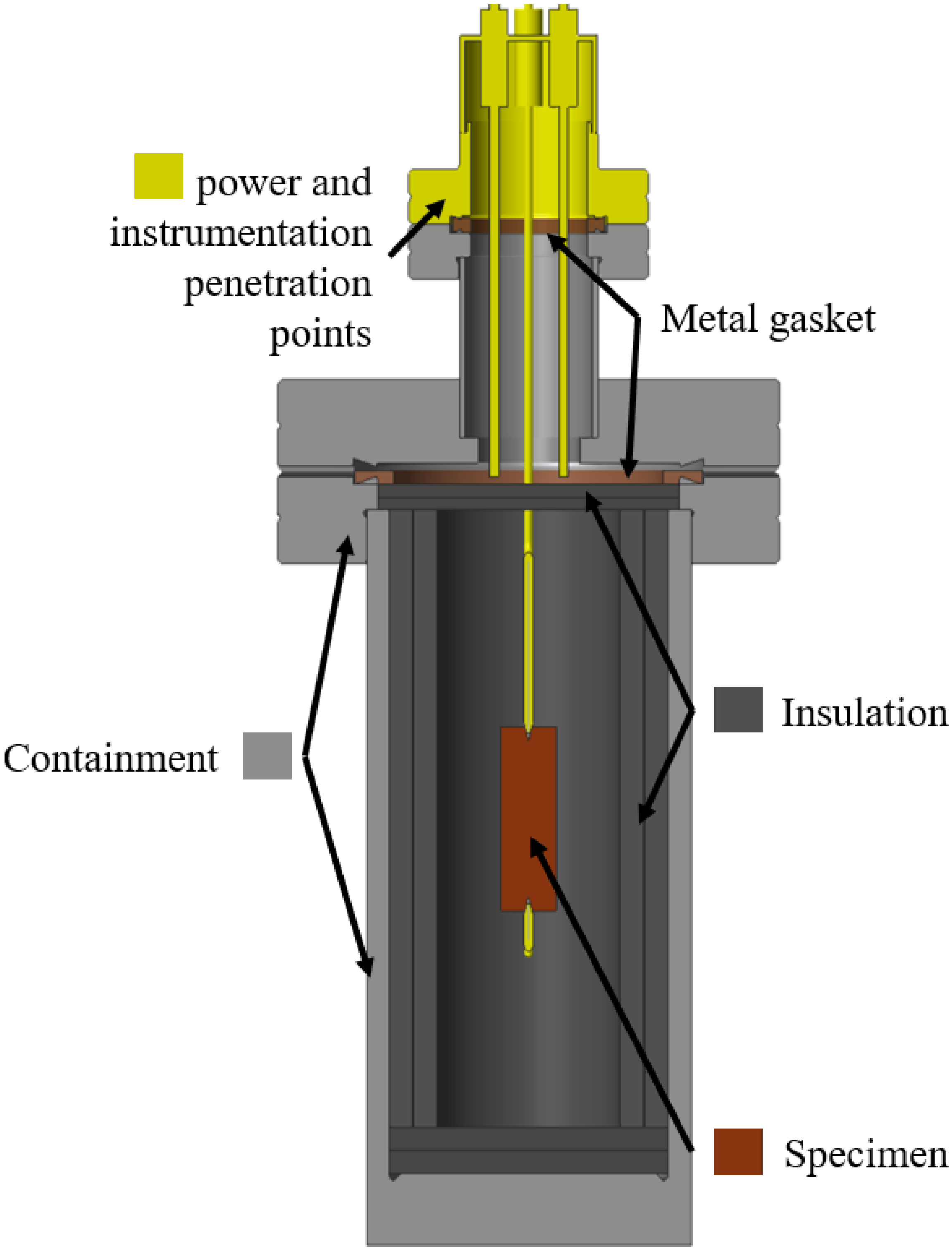


Figure 3-1. Notional OUTSET experiment design outlining the four primary components.

index normalizes failure stress (σ_f) to material density (ρ), which has units of (J/kg) and is the classical form of the index developed by Ashby and shows the failure stress to be of exponent order one. A discriminant line of slope of one can be used to evaluate materials in the Ashby charts produced by the CES Granta software [27]. The enclosure should be similar to the one used in a reactor for phase 2 in-pile testing, so only the metals family are considered for enclosure material candidates because other nonmetal materials are generally not compatible with reactor environments. The material optimization exercise yielded Mg alloys, Al alloys, Ti alloys, and low alloy steels as good candidates. Figure 3-2 shows the Ashby plot detailing these data.

Since magnesium and carbon steel alloys are not very resistant to water corrosion [28] [29], these materials were eliminated from the list and only aluminum and titanium alloys remain from the provided data set. Although they were eliminated during the material index phase, stainless steel alloys are very resistant to corrosion, have good strength, and have been used for earlier irradiation experiments [30] [31]. Therefore, stainless steel alloys were also considered as a potential candidate.

Further characterization of performance parameters must be performed to select the optimal material. Specific parameters of interest include weldability, thermophysical properties, and radiation tolerance. The weldability is important, as the bolt-on lid of the initial OUTSET enclosure design shown in Figure 3-1 may not be considered for use in in-pile experiments. The author chose to compare these alloys by rank using numeric assignments of -1 for *unfavorable*, 0 for *neutral*, and 1 for *favorable*. The evaluations are provided in Table 3-1.

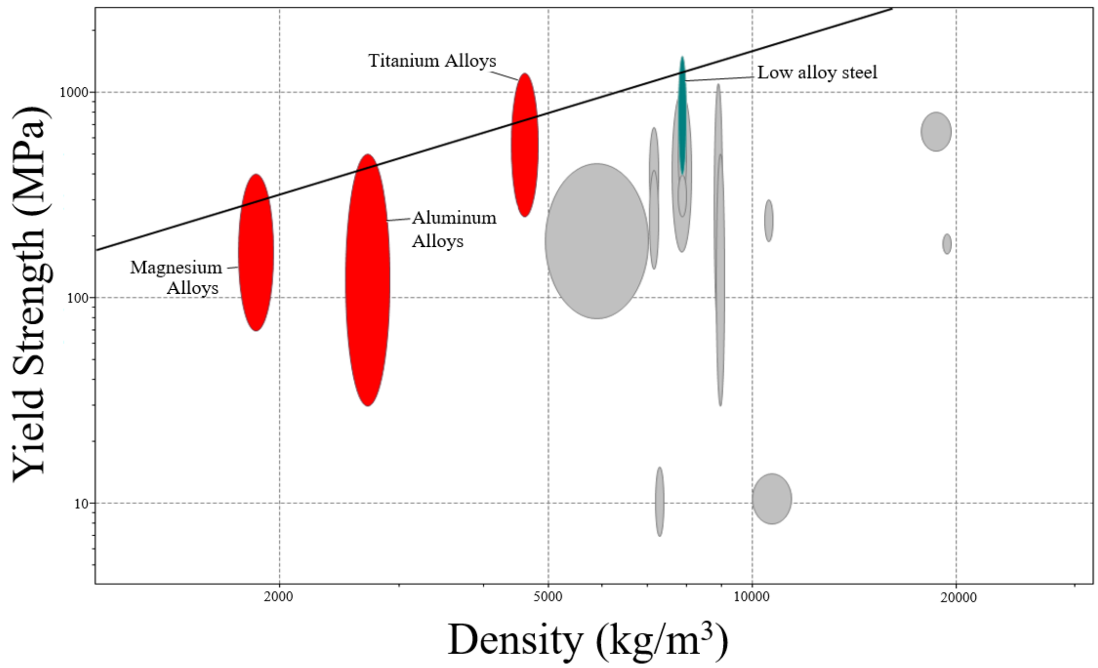


Figure 3-2. Optimized material selection for enclosure from material index σf/ρ (generated in CES Granta).

Table 3-1. Comparison and ranking of suggested containment materials.

Material	Weldability	Thermophysical properties	Radiation tolerance and activation	Rank
Aluminum alloys	-1	1	1	1
Stainless steel alloys	1	1	-1	1
Titanium alloys	1	0	1	2

Down-selection within these categories are based on a relative comparison of each of the parameters concerning the metal-specific performance. Specifically, welding aluminum alloys can be challenging due to the formation of porosity in the weld joint due to surface contaminations (Al_2O_3 corrosion layer, hydrocarbons, contaminated shield gas, etc.) and dissolution of hydrogen gas from the weld metal during solidification [32]. Conversely, stainless steel alloys have good weldability, as do titanium alloys that have been welded under a tightly controlled atmosphere [33] [34].

Thermal performance of containment material also needs consideration. Thermal conductivity of the container impacts OUTSET heat transfer. Aluminum alloys have values of thermal conductivity around 180 W/m-K, stainless steels are roughly 14 W/m-K, and titanium alloys are around 6 W/m-K [35]. Considering this comparison, aluminum and stainless steel are given a favorable ranking, while the titanium alloys are given a neutral ranking.

The final parameter considered is radiation tolerance and activation. While all materials have reasonably good resistance to irradiation damage (i.e., swelling and embrittlement), stainless steel tends to experience high neutron activation with relatively long-lived isotopes such as ^{59}Fe and ^{60}Co. The decay schemes of these two isotopes produce high energy gamma rays with more difficulties in shipping, handling, and disposal. Obtaining low-activation stainless steel is possible, but expensive. Based on this ranking system, a titanium alloy is the recommended choice for an in-pile enclosure, given that it is considered as a reduced activation material [36].

For in-pile experiments, the bulk material consists of titanium alloys, which are commercially available in a wide variety of shapes. Specifically, the likely candidates for containment materials are grades 9 and 5 titanium alloys. Most of the enclosure is fabricated from off-the-shelf components to reduce cost and complexity. Using this approach alleviates the need for custom tooling and fabrication processes. When welding is needed, grade 9 titanium (ASME Boiler and Pressure Vessel Code, section IX base metal designation P-53) is compatible with grade 5 titanium (base metal designation P-none, UNS R56400) [37]. Oak Ridge National Laboratory (ORNL) and others have demonstrated this capability; ORNL has weld parameters available from their welding program [38]. Grade 9 titanium can be used for the tubular section of the enclosure due to its availability in extruded tubular form. Sandvik, a metal tubing manufacturer, fabricates grade 9 titanium tubing to ASTM B338, which controls chemical composition, mechanical properties, etc. [39] [40]. Sandvik claims that many tubing/wall thickness combinations are feasible for fabrication. See Figure 3-3 for the principal size ranges for grade 9 titanium seamless tube; the target range for the enclosure wall is circled in white. Note that both stainless steel and titanium alloys are suitable out-of-pile enclosure material. Stainless steel 304L parts were used to fabricate OUTSET.

The containment enclosure must be sufficiently insulated to allow specimens to reach prototypic NTP temperatures greater than 2,500°C. The requirements for this insulation include:

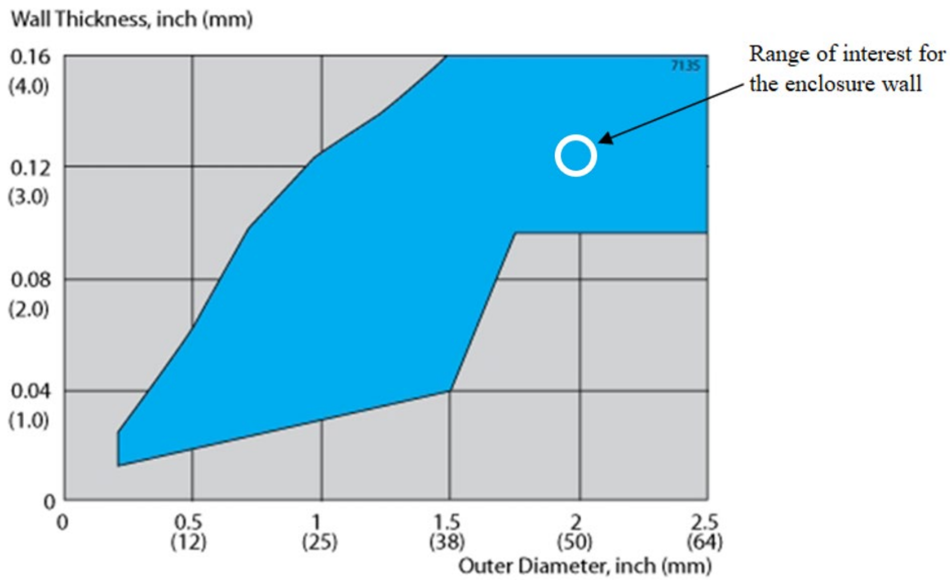


Figure 3-3. Principal Size Range for Seamless Tube and Pipe [40].

- Good stability at high temperature
- Reasonable pliancy and thickness
- Well-characterized thermal conductivity at high temperatures
- Usability in vacuum and inert atmospheres.

SIGRATHERM GFA soft graphite felt, produced by the SGL Group, was selected as the insulation. This material is in the form of flexible, soft felt and is manufactured in thicknesses between 3–11.5 mm. SIGRATHERM has an extremely low range of thermal conductivity (~0.13 W/m-K at 1,027°C) and has a usable range as an insulator up to about 2,200°C [41]. It can be used for vacuum and inert atmospheres, with comparable thermal conductivity performance over a wide temperature range, as seen in Figure 3-4. The literature does not state the inert gas or gas pressure used to perform the thermal conductivity measurements. Further, there is no mention in the manufacturer supplied

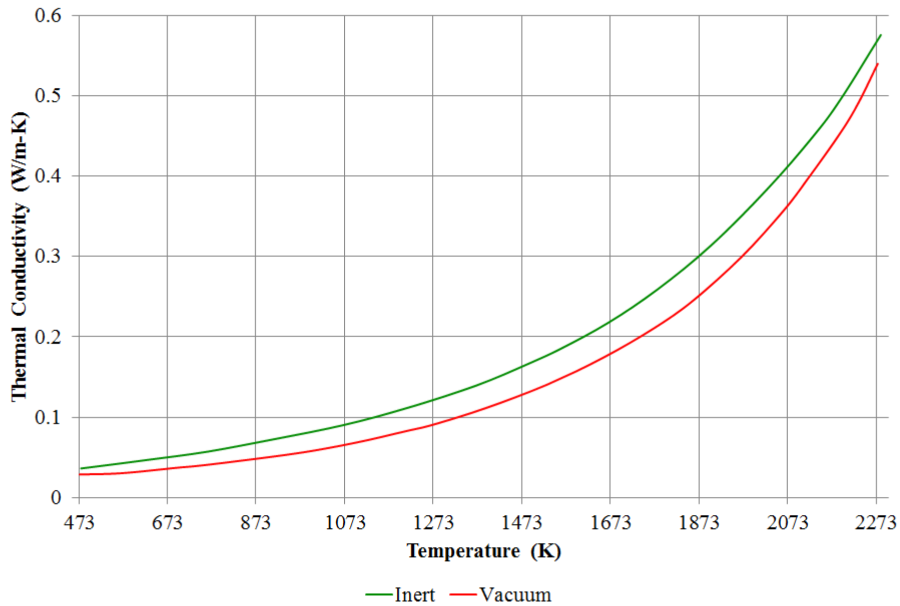


Figure 3-4. SIGRATHERM GFA Thermal Conductivity as a Function of Temperature [41].

literature about radiation heat transfer within the felt, so it is assumed that the manufacturer has lumped the thermal conductivity in with some effective radiative thermal conductivity. Another parameter is insulator performance in a neutron irradiation field. Graphite has a long history of application in nuclear environments and is predominantly known for its neutron moderation properties. Graphite tends to swell under irradiation due to neutron damage, leading to a sizeable increase of internal energy in the material. The stored energy can spontaneously release (referred to as *the Wigner effect*) at a threshold irradiation temperature of roughly 200 °C [42]. However, the density of the felt is roughly 4 percent of the density of solid graphite [35] [41], so any negative impacts on the insulator's thermal performance due to graphite swelling and release of Wigner energy are expected to be minimal.

3.2 Flexibility to Accept Various Instrumentation Techniques and Electrical Power Delivery

Thermocouples were selected as the primary direct measurement interface. However, an appropriate thermocouple electric feedthrough is needed to instrument OUTSET. A wide range of vacuum products that facilitate this function are commercially available. Vendors include Kurt J. Lesker Company and MDC Vacuum Products, LLC. The MDC 9392008 power and instrumentation feedthrough with a Conflat® 1.33 flange was selected for this purpose. The Conflat® fittings are the interface for this design and can be bolted to mating flanges that are installed onto the container and maintain hermetic seals capable of high vacuum conditions (pressure less than 1.3×10^{-13} Torr) over a temperature range that spans -200–450°C [43].

Aside from being vacuum tight and pressure resistant, these flanges can be configured or modified to contain feedthrough power connections, tubing fittings, and optical windows. This flexibility provides the capability to install the instruments, as well as the power to heat OUTSET and collect the benchmark data. These flanges may not be appropriate for in-pile experiments, as those enclosures may be required to be sealed through some more permanent method such as welding.

The MDC 9392008 feedthrough consists of two nickel leads that supply electrical power to the specimen for heating and two type-C thermocouple connection wires used to provide an instrumentation interface for thermocouples. The power feedthrough has a recommended maximum current limit of 15 A. Molybdenum is a refractory metal that has a 2,623°C melting point, excellent electrical conductance, low thermal expansion coefficient, and it is also very stable under inert/vacuum conditions and in neutron and gamma irradiation fields. Molybdenum wire with 0.51 mm diameter is selected to fabricate the electrical leads and will connect the experiment heater to the nickel leads of the power feedthrough.

Commercially available Omega™ model T5R-015-12 type-C thermocouples were selected for their ability to operate up to 2,760°C. type-C thermocouples are fabricated by making a junction between tungsten-5% rhenium and tungsten-26% rhenium wires. See Figure 3-5 for an image of a prototypic T5R-015-12 type-C junction with a wire diameter of 0.381 mm. These thermocouples conform to a measurement uncertainty of 1% at temperatures higher than 500°C. A specification sheet for this instrument can be found in Appendix I. Ungrounded, sheathed type-C thermocouples are available, but do not meet the current size constraints of OUTSET.

The vendor claims that this NIST traceable calibration is applicable up to 2,760°C in hydrogen, inert gas atmospheres, and in vacuum. These conditions are relevant for all

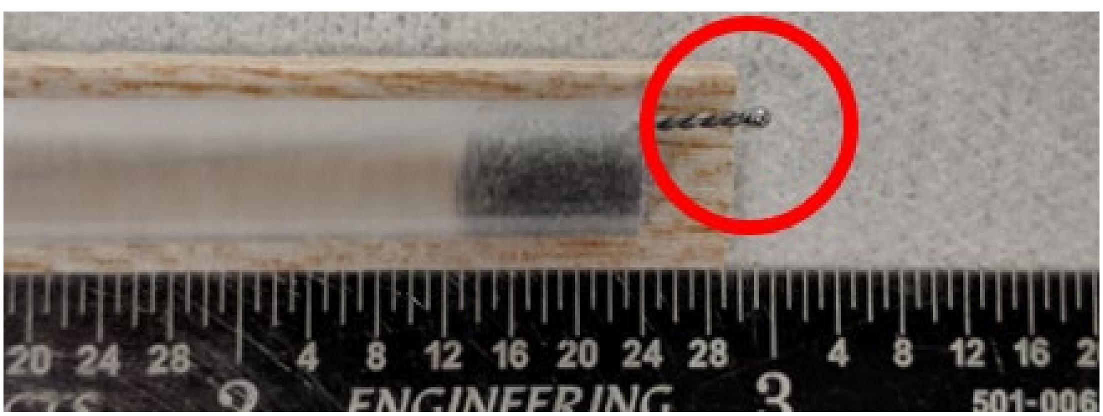


Figure 3-5. type-C thermocouple junction circled in red (scale in inches).

benchtop experiments, but the type-C thermocouples may be less useful in radiological tests due to the large neutron absorption cross sections of some tungsten and rhenium alloys; which may lead to excessive heating or transmutation of material in the instrument. Excessive heating may bias the thermocouple performance and, the Seebeck coefficient may change as the material composition changes due to nuclear transmutation [44]. Therefore, type-C thermocouples may only be useful in low neutron fluence tests.

As for thermocouple instrumentation support, an Omega™ HH1384 thermometer is used to display and log thermometry output from OUTSET trials. This digital unit has four input channels and a data logger that is compatible with type-C thermocouple temperature sensors. Temperature output follows the international scale of 1990 (ITS-90). The user guide for this instrument can be found in Appendix I.

Melt wires have a well-characterized melting point and allow researchers to place a wire in locations of interest to verify whether those locations reached the melting point temperature by observing a solid-to-liquid phase change in the wire. The use of melt wires as temperature monitors to verify peak operating temperatures, especially for nuclear applications, is widely accepted [45] [46]. Iridium-40% platinum melt wires that have a ~2,250°C melting point [47] are incorporated into the specimen region to provide confirmatory centerline temperature information for some OUTSET experiments. This noble metal alloy was also selected because it would not react with the specimen region components and change the wire melting characteristics.

Another method for measuring high-temperature experiments is to employ an optical measurement system such as pyrometry, or some infrared emission measurement device. The work produced by Matsumoto et al. demonstrated that the spectral emissivity of graphene at elevated temperatures (~2,200-2,300°C) peaks at wavelengths between 0.5μm -2.0 μm [48], which resides within the short-wave infrared spectrum. A FLIR A6261sc SWIR camera was obtained to measure specimen surface temperatures. These measurements can be made from observed light being emitted from an aperture/penetration through the containment wall, which provides a direct line of sight between the Conflat® viewport to the specimen surface.

The A6261sc SWIR camera was purchased with two notch filters; the ND1 filter that has an applicable minimum range of 400-1,200°C±6°C maximum and the ND3 of 1,100-2,200°C±24°C maximum. The camera was factory-calibrated to generate non-uniformity compensation (NUC) files appropriate to the specific filters, which are used to convert photon counts into temperature information. When loaded, the NUC calibration files and filters prohibit the camera from sensing SWIR light that resides out of the spectrum of interest; thereby reducing stray light reflections, noise, etc. that may produce measurement uncertainty. The camera is tested using the ND3 filter, supporting NUCs, and a stock SWIR compatible f/1.8 50mm lens for OUTSET temperature trials. The camera can be seen in Figure 3-6.

3.3 Ability to Provide and Maintain a Well Controlled Atmosphere

Given the need for achieving high operating temperatures, the enclosure was designed to be sealed to protect the specimen from chemical reaction effects. Titanium foil

Figure 3-6. FLIR A6261sc SWIR camera.

is preferred for use as a getter material due to its relatively high getter capacity (4.4 Pa-l/mg for O_2 at 20°C) in a vacuum/inert atmosphere [49] to eliminate any residual oxygen release during experiment operation.

The experiment enclosure is connected to an Adixen ASM340d leak detector, which was used to impart the vacuum atmosphere and to test the hermetic seal of the containment. The Adixen ASM340d contains an oil-free (turbo) pump vacuum system that can detect various helium isotopes (^{4}He and ^{3}He). It has a minimum detectable leak rate of $5 \cdot 10^{-12}$ cm^3/s under high vacuum and an operating temperature range of 0-35°C. A data specification sheet for this item can be found in Appendix I. Although the experiment can be evacuated through other pumping systems, the Adixen ASM340d is specifically chosen for this purpose because it is directly used to verify that OUTSET is hermetically sealed; which is crucial given the heavy reliance of the experiment on oxidation-sensitive refractory metals and carbon materials. Hermeticity is verified by evacuating OUTSET to $1\text{-}2\times10^{-2}$ mbar and imparting a gross stream of helium on each of the Conflat® flanges.

Helium that permeates the leaking joints will be swept into the detector ion chamber and the instrument will alarm. Perfect leak tightness is challenging to achieve, but the helium leak rate achieved by OUTSET is on the order of $1 \cdot 10^{-9}$ std. cm^3 (He)/s to $1 \cdot 10^{-7}$ std. cm^3 (He)/s, which is the common acceptance criteria used by the ORNL non-destructive examination group for irradiation capsules [50].

3.4 Provide Thermal Cycling

The vacuum and gas service connections are made with Swagelok® fittings and connect to a ¼ inch tube that is welded to the SWIR viewport. This interface allows OUTSET to be rapidly evacuated and backfilled with an inert gas to cool the experiment after a trial is completed. The work described in this dissertation utilizes the vacuum and gas service connections to evacuate the enclosure. It does not consider using inert gas to rapidly cool specimens and using backfill gases to facilitate NTP fuel power density experiments. Future work is needed to incorporate a system to explore these conditions.

3.5 Standardization of Specimen Geometry

Common diagnostic and testing techniques to quantify fuel material properties include mechanical testing, investigating microstructure morphology, and assessing fission gas retention. These properties are important for all phases of the fuel life, and a series of out-of-pile and in-pile material environmental exposure histories are required to attain these data. Developing a multipurpose specimen geometry that provides flexibility to gather the broadest set of these properties is critical to making the OUTSET experiment format suitable for fuel testing. The American Society for Testing and Materials (ASTM) provides guidelines for selecting standard sample sizes corresponding to most of these testing methods. Mechanical property test specimens are usually limited to grain size relative to the specimen test section size. Since NTP fuel and components are not fully developed, it is currently impossible to know grain size and structure.

The conventional transmission electron microscopy (TEM) sample geometry is independent of material grain size. The disk sample is 3.0 mm in diameter and 0.1 mm thick. Nuclear fuel interrogation with TEM is widely accepted as a leading assessment tool because it can provide information on material microstructure as a result of neutron damage, thermal effects, and fission [51] [52].

Thermophysical property data are also of interest for characterizing NTP materials. Laser flash diffusivity is a technique that measures thermal diffusivity, heat capacity, and thermal conductivity [53]. It has been demonstrated that this method can utilize 3 mm diameter by 3 mm thick cylindrical specimens to obtain accurate thermophysical property data [54].

The specimen geometry used by OUTSET is a right round cylinder that utilizes the TEM disk diameter of 3.0 mm, and a length that varies from 0.1–3.0 mm. Such a sample can yield a single laser flash diffusivity specimen, or from 1 to 30 slices to produce TEM disk samples. These particular specimens will provide thermophysical property data, mechanical data, and fission gas retention for fuel qualification. Subsequent versions of OUTSET may be dimensionally scaled to allow for longer specimen geometries, but it is recommended that the diameter of the cylindrical specimen remain at 3.0 mm to reduce post-irradiation sample machining and preparation in phase 2 tests until specimen material parameters like grain size can be quantified and used to fabricate specimens in accordance with ASTM standards.

3.6 Temperature Control and Thermal Management

A primary goal of OUTSET is to demonstrate feasibility and repeatability of the experiment's ability to expose specimens to prototypic conditions. This can be shown by thermally characterizing the enclosure and validating predictive thermal models. The NTP fuel operating temperature is 2,500°C. Successfully heating an NTP specimen and adequately managing the system's thermal loads is necessary for producing a successful out-of-pile experiment. Scoping calculations are useful to test preliminary design decisions and understand the feasibility of a design. For the OUTSET case a preliminary scoping calculation, detailed here, was developed to understand upper limit heat transfer magnitudes and heat input requirements needed to drive samples to NTP prototypic temperatures under out-of-pile boundary conditions. This information is needed to appropriately select power supplies and electrical power delivery components.

The conceptual CAD design of OUTSET seen in Figure 3-1, which was based on the experiment requirements, was used to support the scoping calculation. An (r-θ) finite element analysis model was generated from that initial model to represent the basic components of the experiment, which include:

- the specimen that is modeled as Pure Oil Company (Poco) grade AXF-5Q graphite,

- a generic insulating graphite felt, with a constant thermal conductivity of 0.9 W/m-K & Poco graphite thermophysical properties, and
- the containment that is modeled as commercial Ti-6Al-4V (i.e., grade 5 titanium).

The CAD geometry and subsequent finite element model can be seen in Figure 3-7. The radial geometry of the enclosure was set to be compatible with irradiation sites common to the HFIR at ORNL and the ATR at INL, and the internal components were sized to fit within the enclosure. The model enclosure and insulation materials were selected based on the decisions made in Section 3.1.

The heated specimen region, or carbon specimen, in this model does not represent the discrete specimen described in Section 3.5. Instead, the specimen region is defined to be a solid monolithic piece of Poco graphite and is larger than the intended specimen described in this section to establish a bounding input energy. Poco graphite was selected to represent the specimen in this scoping analysis because its thermophysical properties are well documented, it has near-blackbody emissivity, and it has a melting point greater than 3,000°C. Thermophysical properties used for these materials were obtained from the literature [35] [55]. As indicated earlier, the graphite specimen region is assumed to have a 1.2 cm diameter and is separated from the graphite insulative felt by a 5 mm radial gap. This gap is considered to be evacuated and the only heat transfer mechanism between the specimen and felt is thermal radiation. The felt outer face is in direct contact with the inner face of the titanium containment, which provides a heat conduction path at the boundary, as seen in Figure 3-8. Note that the carbon specimen

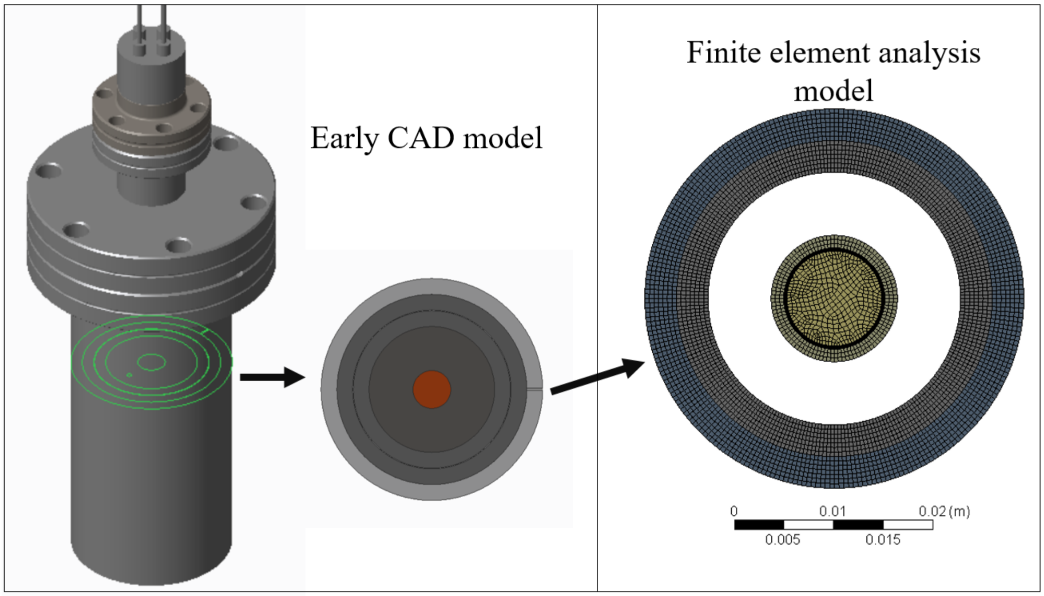


Figure 3-7. Bisecting the 3-D model about the specimen's axial centerline to produce an r-θ finite element analysis model.

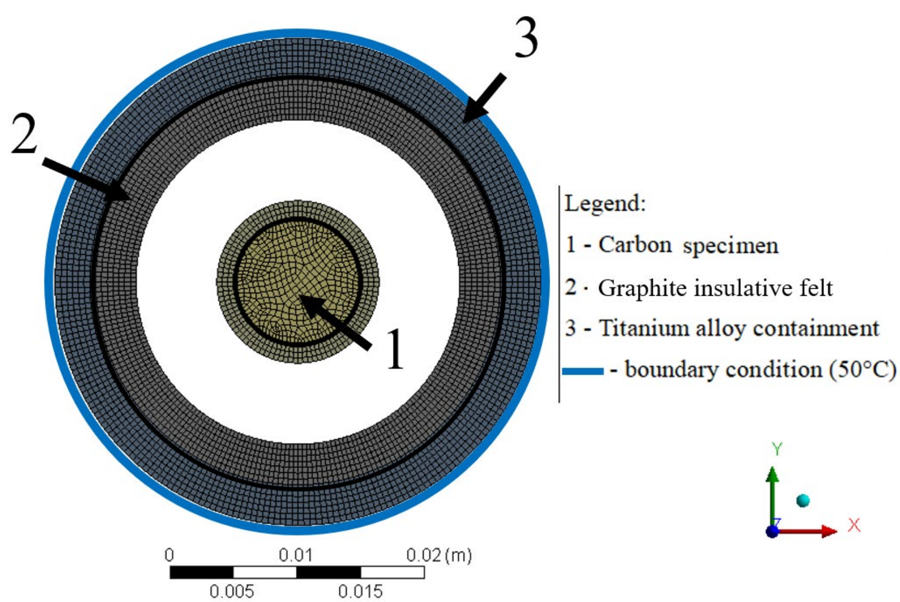


Figure 3-8. Meshed Finite Element Analysis Model Depicting the Materials and Boundary Condition.

region appears in Figure 3-8 appears to be a cylinder coaxially nested within an annulus. This feature was implemented to provide material selection flexibility within the model to designate different materials for a specimen outer containment. However, the specimen region is considered to be a single homogeneous part for the sake of the analysis detailed here.

ANSYS finite element analysis software includes a suite of verified heat transfer solution methods which are used to solve the thermal enclosure heat transport. However, custom contact conductance methods developed by researchers at ORNL were incorporated to simplify the modeling of the heat transfer between the insulation and the enclosure contact interface [56]. These methods were used specifically because they mesh the interstitial spaces between bodies within the model and treat them as being gas filled. For the 1-D model, the spaces were filled with a gas with a thermal conductivity of 1×10^{-6} W/m-K to simulate vacuum. These methods also perform a simplified radiation heat transfer calculation that assumes all radiated energy is transmitted in the direction normal to the emitting face. This method is appropriate for one-dimensional calculation but will be less accurate for higher dimension problems.

The model was meshed in ANSYS Workbench 16.2 using 2-dimensional (2D) thermal elements (PLANE77 2D 8-Node thermal solid element) [57], as seen in Figure 3-8. Note that a 2D element was used, while the model technically varies in one-dimension (r), it exploits a symmetry angle of 360° to create a two-dimensional (r-θ) analysis. Note that the model is assumed to extend infinitely in the z direction. The minimum element size for this model is 5×10^{-4} m. The enclosure outer surface was set to 50°C for these simulations, which corresponds to the coolant temperature of the HFIR and ATR. The convective heat transfer coefficient produced from reactor coolant flowing over the exterior of the enclosure is on the order of 30-40 kW/m^2-K for normal HFIR operations [58] [59]. Assuming the heat flux for this preliminary model is (1,000 $W/2\times10^{-3}m^2$) = 500 kW/m^2, the temperature difference between the bulk coolant temperature and the enclosure surface temperature is on the order of 10°C. Given the actual bulk coolant conditions range from reactor to reactor, and the temperature impact due to convection is small compared to NTP prototypic temperature, this effect is neglected and addressed later in the formal model validation section detailed in Chapter 5. The mass-specific heat generation rate {W/kg} is applied to graphite specimen material to simulate a heat input. There is a known density {kg/m^3} used to describe the specimen and the product of the heat generation rate and the density yield a volumetric heating quantity {W/ m^3}. Given that the geometry of the specimen diameter was fixed to 1.2 cm to produce a constant cross-sectional area {m^2}, the product of the volumetric heating rate and cross-sectional area revealed the linear heating rate {W/m}. Once a given linear heating rate was applied, a radial temperature distribution is established based on the system's heat transfer characteristics. For this scoping case, the heat generation rate used was 190 W/g. This value was converted to a linear heating rate by the method described above to produce a value of 42.9 kW/m.

Note that the structural degrees of freedom of the model were not considered for this preliminary analysis. The structural containment will not be exposed to high pressure or mechanical loading. The enclosure vessel will be fabricated from (1) off-the-shelf vacuum fittings which were rated for much higher loads, and (2) a metal tube section with a substantial wall thickness, which is assumed to be sufficient at this time.

Thermal expansion was also not considered in this scoping analysis. The surrogate fuel specimen is coaxially located within the graphite felt and the two bodies are separated by roughly a 5 mm gap, and the specimen diametrical change due to thermal expansion is on the order of 260μm at 2,500°C. Therefore, the specimen and felt will not come into contact when the specimen is at NTP prototypic temperatures. However, in later tests, inert gas is expected to be introduced and heat conductance through the gas gap will occur. Conductance lengths, which are a function of specimen size, will become sensitive to small changes, and thermal expansion of Poco graphite is on the order of one percent at 2,500°C [60]. Therefore, thermal expansion may become significant when testing prototypic fuel geometries in inert gas and should be estimated when analyzing these conditions.

Results from the thermal analysis can be found in Figure 3-9 and tabulated in Table 3-2. The derivation of these results may be found in Appendix II. The ANSYS output was verified against a 1-D closed form formulation of the model. Neither the specimen nor any other parts are near their respective reported melting points. However, it is important to show that a safety margin of at least 100°C is available. Also notice the peak specimen temperature is 2,549°C, which is just over the target temperature of 2,500°C. The surface temperature is 2,423°C, and there is a 126°C temperature drop across the specimen.

This preliminary finite element analysis demonstrated the feasibility of the preliminary OUTSET configuration to achieve steady-state target temperatures with reasonable boundary conditions. Another function of this analysis was to establish power

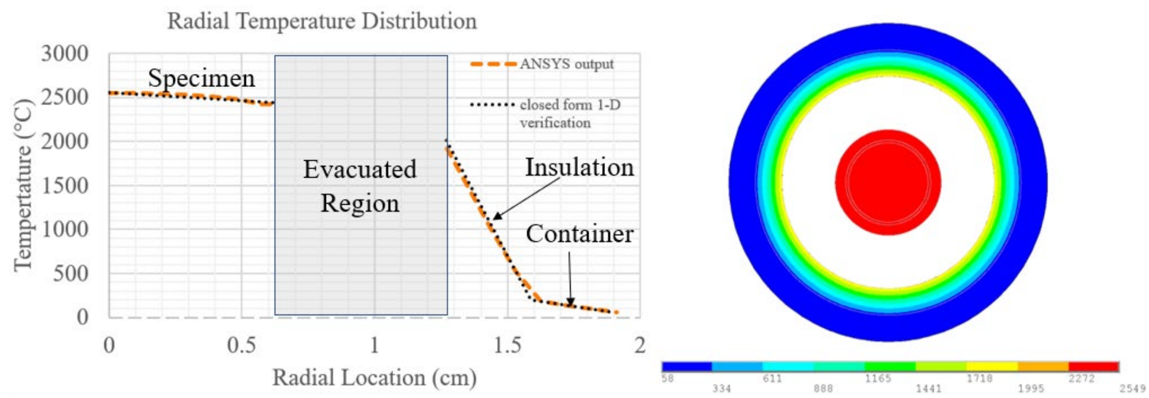


Figure 3-9. Radial temperature distribution (left) and temperature contour plot (right) for the cross-sectional analysis results (°C) of the preliminary OUTSET analysis results.

Table 3-2. Temperature results for the radial 1-D OUTSET finite element analysis with a 42.9 kW/m linear heating rate input.

Part	Material	Average Temp. (°C)	Minimum Temp. (°C)	Maximum Temp. (°C)	Melting Point (°C)
Specimen	POCO graphite	2,486	2,423	2,549	3,650
Insulator	SGL graphite	1,002	213	1,965	3,650
Containment	Ti-6AL-4V	125	58	194	1,604

requirements of the experiment by varying the heat generation rate of the specimen to achieve steady-state target temperatures around 2,500°C.

Assuming preliminary heated specimen geometry is 1.2 cm diameter × 2.0 cm in length, the power demand for the specimen is 860 W, or a power density of 0.4 MW/l. Note that volumetric heat generation rates are linked to mass-specific heat through material density and, as long as the material in question does not have a large density change over the temperature rage of interest, the two heat generation rate notations may be used interchangeably. Given the uncertainties of emissivity and temperature-dependent thermal conductivity of the constituent materials, it is necessary to acquire a power supply with a higher rating to ensure that peak temperatures could be achieved. This calculation provides an order of magnitude of the power requirement, implying that a 1 kW power source could provide adequate heating as opposed to a 10 kW source. The calculation also provides insight into the power density of the specimen. The hypothetical specimen has a power density roughly an order of magnitude less than NTP fuel requirements. Note that the specimen region geometry is much larger than the intended specimen geometry described in Section 3.5. Both geometries are a function of the diameter squared; where the specimen region has a diameter of 1.2 cm and the specimen has a diameter of 0.3 cm. Therefore, the volume of the specimen will be on the order of a magnitude less than the specimen region considered in this scoping analysis. Further, future in-pile experiments will rely on nuclear heating in the specimen region and the input power will be more closely aligned with prototypic NTP power densities.

3.6.1 Selecting an Energy Source for OUTSET

OUTSET must heat surrogate fuel samples to 2,500°C relying on an external energy source such as direct, alternating, or induced electrical current. The scoping analysis shows that power delivery on the order of a kilowatt is required to reach such temperatures. There are various options available to meet this need. Power sources such as lasers have been used to achieve extreme heat fluxes. Likewise, Linke et al. [61] successfully used an electron beam source to simulate high heat flux conditions for testing plasma facing material such as graphite and tungsten. Each heating method has its benefits and drawbacks. For example, the electron beam and laser sources are extremely effective but can be rather expensive. The electron beam source also generally must be operated under high vacuum; which will make it difficult to expose the specimen to gases simultaneously.

The CFEET and NTREES experiments use induction heating to achieve target temperatures. This heating is performed by placing a target inside an induction coil that uses alternating current tuned to an appropriate frequency to induce a current within the target, which creates heat via Ohmic heating. However, induction heating has limited penetration depth in electrically conductive materials and coupling to the material may change with material conductivity during the test. Induction effectiveness can also be sensitive to the absorption of the induced current by materials surrounding the target. The coils must also be actively cooled to ensure they do not melt or deform from thermal stresses. Adding these features to OUTSET increases the complexity of the enclosure and will change the thermal radiation paths of an out-of-pile experiment relative to in-pile performance, which will rely on fission as the heat source. Given that the purpose of this work is to design and demonstrate an experiment that directly translates to an in-pile reactor test, the internal configuration of the experiment should not be changed from one phase of the project to the next. The conclusion is that direct current (DC) electrical resistance heating is the most cost-effective and reliable option.

A Veeco model 2508 DC power module was selected to power OUTSET. This unit requires 240VAC/11.8A, 60 Hz AC power input and can deliver 2.5kW of DC power. The model 2508 has an output DC voltage range of 0-200V and output current range of 0-25A (10 mA resolution). It contains a proportional-integrator-differentiator (PID) controller that receives temperature information from a local type-K thermocouple. Since type-K thermocouples operate between -200° to 1,250°C and are not applicable for prototypic NTP temperatures the PID controller is not used for the OUTSET experiments. The power was manually controlled by adjusting the current to achieve the desired output power. A data specification sheet for this unit can be found in Appendix I.

3.6.2 Specimen Region Heating Development

The Veeco model 2508 DC power module is shown to provide the ~800W needed to energize OUTSET. However, further development of the specimen region is required to ensure it is capable of the Joule heating required to drive specimens to prototypic NTP temperatures. Electrical power is defined as the product of voltage and current $(P = VI)$. Through Ohm's law $(V = IR)$, power can be reformulated in terms of resistance and either voltage or current: $P = \frac{V^2}{R(T)}$ or $P = I^2R(T)$, respectively. Given that electrical systems are usually current limited, the second formulation reveals that a system with low resistance may require higher levels of electrical current to achieve high power values. The specimen region was initially planned to be fabricated from Poco graphite, which would be resistively heated with a DC power supply. Given that this material has an electrical resistivity of 400-1000 μΩ-in [60], and in the scoping analysis the specimen region was assumed sized to be on the order of 1.2 cm in diameter and 2.0 cm in length, then the specimen region resistance would be less than 1Ω. Using the formulation above, current demands would be $I = \sqrt{\frac{P}{R}} \geq \sqrt{\frac{800W}{1\Omega}} \geq 28\,A$. Under these conditions, the voltage requirements would also be on the order 28 V. A more resistive material would reduce the electrical current demands; reducing Joule heating and power losses in the electrical leads. A material with intermediate electrical resistivity (at least an order of magnitude less than Poco graphite) and the ability to withstand degradation at NTP prototypic temperatures was required. Other products in the SIGRATHERM line had suitable specific electrical resistivities and high temperature resistance, which indicated that the GFA felt may also be suitable for heating the OUTSET specimen region.

A combined heating element and specimen region was designed to consist of a ~2.5±0.1 cm long × ~0.5±0.1 cm inner diameter zirconia tube that contains compacted GFA felt for Joule heating. Solid Poco graphite plungers are pressed into the top and bottom of a zirconia tube to contain the GFA felt filament and provide a rigid interface for the electrical lead wires. This assembly set is surrounded by another annulus of Poco graphite. The zirconia tube is necessary to electrically isolate the thermocouple from the energized GFA felt filament. Zirconia ceramic is commonly used as an electrical resistor material and melts at 2,715°C, which makes the material applicable for use at NTP conditions. The graphite crucible was selected for its thermal radiation characteristics that are well-defined over a large temperature range. A prototype specimen region has a nominal electrical resistance of 4Ω, which lowered the current requirements from 28 A to roughly 14 A.

NTP specimens will be placed inside the zirconia annulus along with the GFA filament to ensure specimens reach maximum temperatures. Displacing some filament material has little effect on the heating effectiveness of the specimen region, given the NTP fuel surrogate candidates are made from high temperature resistant materials that have electrical resistivity values on the order of hundreds of μΩ-in. Figure 3-10 shows an annotated image of the specimen region and prototypic continuity measurement of a specimen region containing a melt wire within the specimen region.

3.6.3 Power Requirements Sensitivity Study

It is prudent to understand the performance sensitivity, as it relates to the insulation conductivity and emissivity, because these parameters will drive some of the decisions for OUTSET enclosure size and heat transfer reduction methods. Simple estimates for conductivity can be estimated using Fourier's law of cooling, formulated for cylindrical coordinates. This exercise assumes that outer surface heat flux (q") and thermal conductivity (k) are constant. Starting with the steady state heat conduction equation and internal heat generation:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0 \qquad 3\text{-}1$$

Integrating the equation, and assuming constant q" and k, yields Fourier's Law:

$$q'' = k\frac{dT}{dr} \qquad 3\text{-}2$$

Heat flux $q'' = \frac{q}{A}$, and for a cylinder, $A = 2\pi rL$. Separating variables yields:

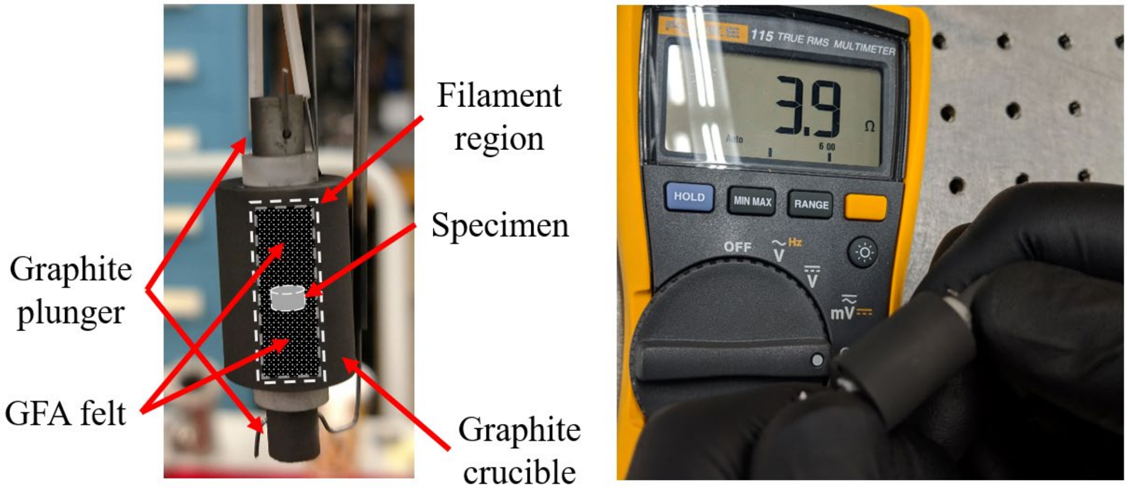


Figure 3-10. Annotated image of the specimen region (left), and continuity measurement of a prototypic specimen region (right).

$$\frac{q}{2\pi rL}dr = kdT \tag{3-3}$$

Integrating both sides of the equation yields:

$$\int_{r=r_i}^{r_o} \frac{q}{2\pi rL}dr = \int_{T=T_i}^{T_o} kdT \tag{3-4}$$

$$\frac{q}{2\pi L} ln\left|\frac{r_o}{r_i}\right| = k(T_i - T_o) \tag{3-5}$$

Rearranging equation 3-5 to isolate q produces:

$$q = \frac{2\pi kL(T_i - T_o)}{ln\left|\frac{r_o}{r_i}\right|} \tag{3-6}$$

where:

$$q \equiv constant\ power\ input$$

$$k \equiv constant\ thermal\ conductivity$$

$$L \equiv cylinder\ length$$

$$T_* \equiv cylinder\ inner(i) or\ outer\ (o)\ surface\ temperature$$

$$r_* \equiv cylinder\ inner(i) or\ outer\ (o)\ radius$$

In order to maintain the same specimen temperature (2,500°C), the temperature difference across the insulation must also remain constant, leaving the inner radius (r_i) as the only variable to perturb. Therefore, power input can be compared to insulation thickness as a function of the inner radius. For the finite element analysis, insulation thermal conductivity and cylinder lengths are assumed to be constant, thus following the relationship:

$$q_{initial} ln\left|\frac{r_o}{r_{initial}}\right| = q_{perturbed} ln\left|\frac{r_o}{r_{perturbed}}\right| = 2\pi k L(T_i - T_o) \qquad 3\text{-}7$$

$$q_{perturbed} = C_\delta q_{initial} \qquad 3\text{-}8$$

where:

$$C_\delta = \frac{ln\left|\frac{r_o}{r_{initial}}\right|}{ln\left|\frac{r_o}{r_{perturbed}}\right|} \qquad 3\text{-}9$$

A similar exercise can be performed to develop a proportionality constant for specimen emissivity, using the Stefan-Boltzmann law. The proportionality constant derivation assumes the specimen is in an enclosure. This model assumes the view factor of the specimen from the enclosure is small, such that the specimen emissivity dominates the radiation heat transport.

$$q'' = \varepsilon\sigma\left(T_{specimen}^4 - T_{enclosure}^4\right) \qquad 3\text{-}10$$

where $q = q''A(r)$

$$\frac{q''_{inital}}{\varepsilon_{initial}} = \frac{q''_{perturbed}}{\varepsilon_{perturbed}} = \sigma\left(T^4_{specimen} - T^4_{enclosure}\right) \tag{3-11}$$

$$q''_{perturbed} = C_\varepsilon q''_{inital} \tag{3-12}$$

$$C_\varepsilon = \frac{\varepsilon_{perturbed}}{\varepsilon_{initial}} \tag{3-13}$$

The current model assumes the containment inner radius (r_o) as 1.6 cm and the insulation inner radius ($r_{initial}$) as 1.3 cm and the insulation $\delta = r_o - r_{initial}$. The graphite emissivity ($\varepsilon_{initial}$) was assumed to be 0.8 for the reference finite element analysis case. Table 3-3 summarizes the results from perturbing both the insulation thickness and graphite emissivity; each of which were done independently. Notice, by doubling the thickness of the insulation, the power requirements to establish the specimen region temperature is reduced to 40% of the original power input. Perturbing emissivity has less of an effect.

The formulation seen in equation 3-14, is the classic expression to calculate heat transfer between two coaxial cylinders [62]. Equation 3-14 does not assume the view factor of the inner cylinder is small, as was done in equation 3-10. Equation 3-14 can be used to

$$q''_{inital} = \frac{\sigma\left({T_{specimen}}^4 - {T_2}^4\right)}{\frac{1}{\varepsilon_{specimen}} + \left(\frac{1}{\varepsilon_{insulation}} - 1\right)\frac{A_{specimen}}{A_{insulation}}} \tag{3-14}$$

$$\begin{aligned} q''_{inital}\left(\frac{1}{\varepsilon_{specimen\_i}} + \left(\frac{1}{\varepsilon_{insulation\_i}} - 1\right)\frac{A_{specimen}}{A_{insulation}}\right) \\ = q''_{perturbed}\left(\frac{1}{\varepsilon_{specimen\_p}} + \left(\frac{1}{\varepsilon_{insulation\_p}} - 1\right)\frac{A_{specimen}}{A_{insulation}}\right) \\ = \sigma\left({T_{specimen}}^4 - {T_{insulation}}^4\right) \end{aligned} \tag{3-15}$$

Table 3-3. Results from insulation thickness and emissivity perturbation study.

Parameter	Perturbation result				
Insulation δ (cm)	0.20	0.30	0.40	0.50	0.60
C_δ	1.55	1.00	0.72	0.55	0.44
$\varepsilon_{1'}$	0.88	0.84	0.8	0.76	0.72
C_ε	1.10	1.05	1.00	0.95	0.90

understand the effects of changing emissivity of the specimen ($\varepsilon_{specimen\_i}$) and insulation ($\varepsilon_{insulation}$). Note that if $A_1 \ll A_2$ then equation 3-14 reduces to equation 3-10. Assuming the temperature difference between the inner cylinder and the outer cylinder remains the same, a proportionality constant can be derived as:

$$q''_{perturbed} = C_{\varepsilon'} q''_{inital} \quad 3\text{-}16$$

where:

$$C_{\varepsilon'} = \frac{\left(\frac{1}{\varepsilon_{specimen\_i}} + \left(\frac{1}{\varepsilon_{insulation\_i}} - 1\right)\frac{A_{specimen}}{A_{insulation}}\right)}{\left(\frac{1}{\varepsilon_{specimen\_p}} + \left(\frac{1}{\varepsilon_{insulation\_p}} - 1\right)\frac{A_{specimen}}{A_{insulation}}\right)} \quad 3\text{-}17$$

Figure 3-11 shows plots of $C_{\varepsilon'}$ as a function of ε_2' (holding $\varepsilon_{specimen\_p} = \varepsilon_{specimen\_i}$); $C_{\varepsilon'}$ as a function $\varepsilon_{specimen\_p}$ (holding $\varepsilon_{insulation\_p} = \varepsilon_{insulation\_i}$); and C_ε. The models assumes $A_1 = 1.2 \cdot \pi L\ cm^2$, $A_{insulation} = 2A_{specimen}$, $\varepsilon_{insulation} = \varepsilon_{specimen} = 0.8$, which is consistent with the scoping model input parameters. Reducing the emissivity of either surface reduces the required input power. Reducing emissivity (ε_1) is more effective than reducing the insulation emissivity (ε_2), but it is more difficult to perform this in reality. It was decided to line the inner diameter of the outer cylinder with a low emissivity foil. Molybdenum metal was shown to be compatible with the OUTSET

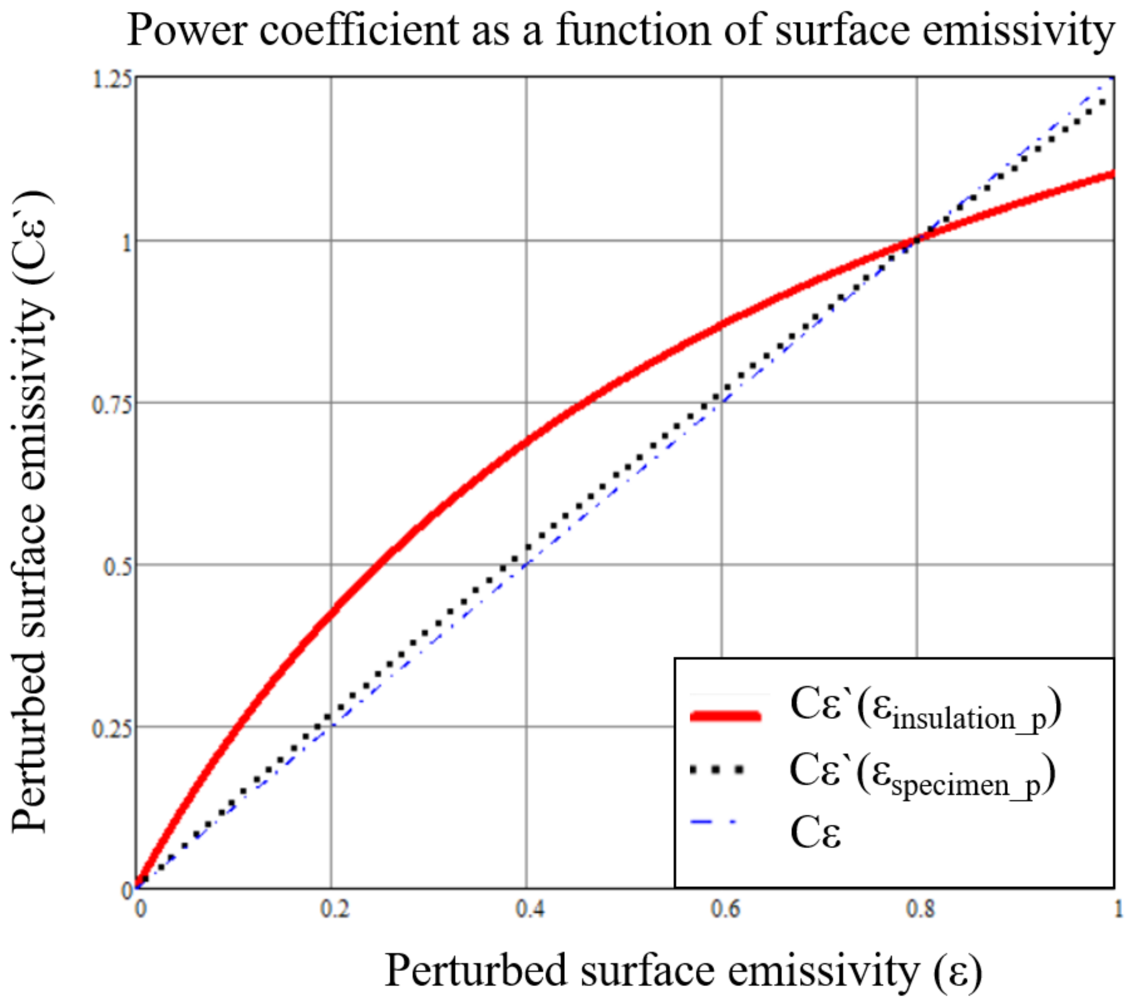


Figure 3-11. $C_{\varepsilon'}$ (proportionality constant) vs. of ε_2' (outer cylinder emissivity).

internal conditions. Therefore, a molybdenum foil radiation mirror with a theoretical emissivity between 0.2-0.4 is used for the experiments detailed in Chapter 4 to line the inner diameter on the innermost piece of wall insulation to reduce the input power to the specimen region. No molybdenum foils are used to line the felt located at the top and bottom felt pieces. Moreover, this feature was not considered in the preliminary scoping calculation, but it is included in the thermal performance model detailed in Chapter 5.

3.7 Design Summary

This chapter lays out a detailed approach to designing OUTSET such that the device meets prescribed requirements set forth by the testing strategy defined in Chapter 2. Research and preliminary heat transfer analysis produced a viable solution for thermal management of OUTSET. Specimen geometry and containment material protocols were identified to make the production of OUTSET flexible and cost-effective. The specimen region is designed to heat specimens to NTP prototypic temperatures. SIGRATHERM GFA felt on the order of 0.6 cm thick is used to insulate the specimen region. A low emissivity molybdenum foil lines the inner face of the insulation to reduce thermal radiation heat transfer from the specimen region to the insulation. The enclosure for OUTSET is selected to be made from 304L stainless steel, with the phase 2 in-pile test enclosure more likely using a titanium alloy. Specific Conflat® feedthrough ports and penetrations were chosen to provide instrumentation interfaces for OUTSET. A computer-aided drawing (CAD) model of OUTSET can be seen in Figure 3-12.

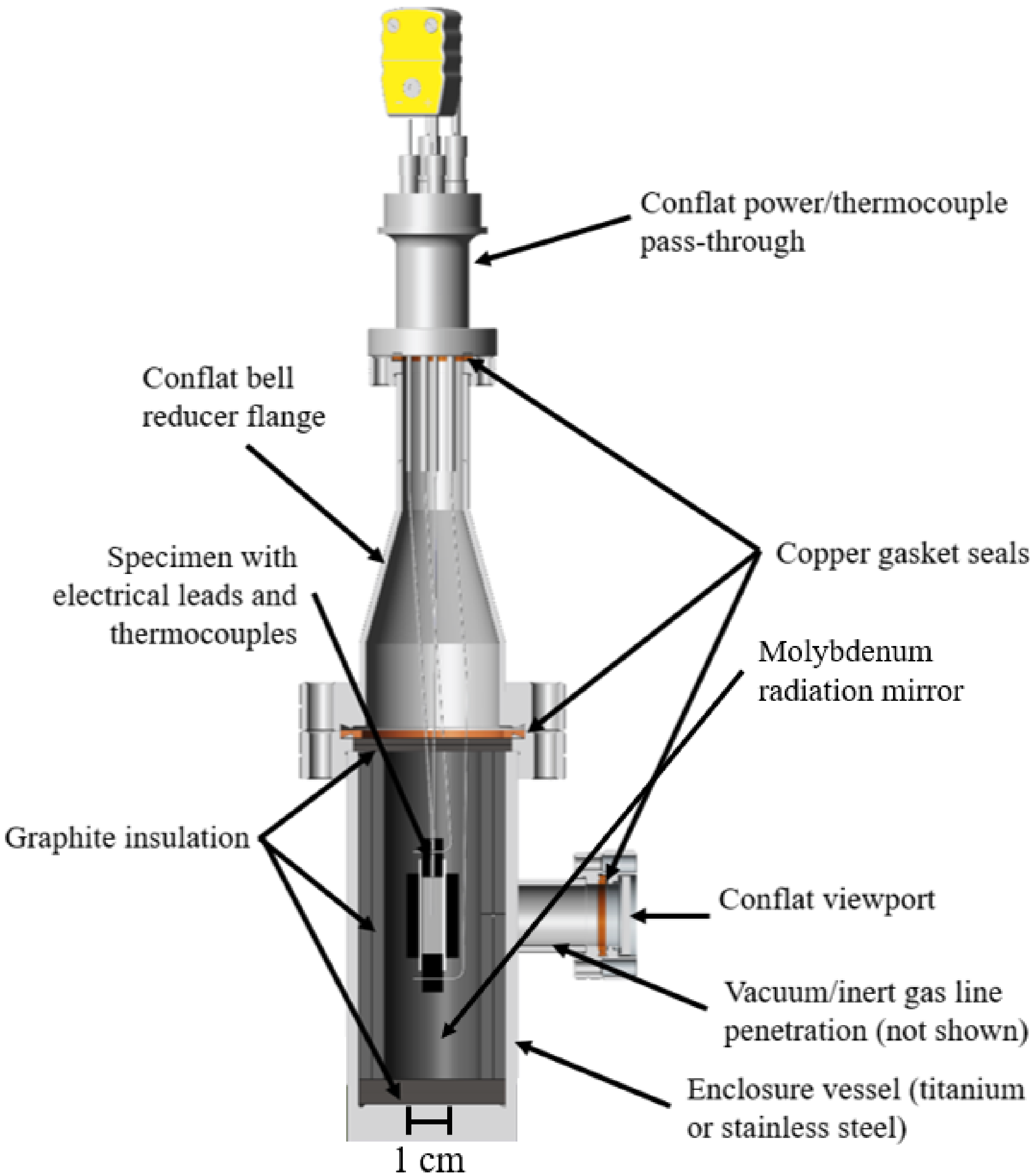


Figure 3-12. Computer aided drawing of OUTSET.

The figure illustrates the following features:

- DC power service inside the enclosure to directly energize the specimen holder,
- Thermocouples instrumentation located within a graphite crucible to test the various operating temperature regimes,
- Titanium alloy or stainless-steel alloy containment material,
- Molybdenum wire electrical leads,
- Molybdenum foil radiation mirror & titanium getter foil,
- Gas lines to impart various atmospheric conditions (vacuum, partial vacuum with an inert gas, etc.),
- An aperture for observing the experiment with optical measurement equipment, and

Chapter 4 documents the assembly of OUTSET and establishes experiment protocols for baseline performance tests. Thermal performance data are collected to demonstrate the OUTSET design.

CHAPTER 4.
EXPERIMENT TESTING AND RESULTS

OUTSET is fabricated in accordance with engineering drawings generated from CAD model described in Figure 3-12. These documents may be found in Appendix I. Figure 4-1 shows images of OUTSET in various stages of assembly. All components except for the insulation were cleaned with acetone and ethanol to reduce contaminants. The vessel plenum was lined with two layers of SIGRATHERM GFA soft graphite felt to produce an insulation thickness of 6.4 mm. A thin sheet of titanium getter foil, which cannot be seen in the figure, is placed between the outermost and innermost layers of the felt. A molybdenum foil, also not visible in the figure, is used to line the innermost felt piece to act as a radiation mirror. Zirconia tubes and beads are used to electrically isolate the electrical leads from each other and the thermocouple wires.

Figure 4-1.OUTSET attached to the Adixen ASM340d leak detector (left), component layout (top and bottom center), and view of the internal plenum (right).

4.1 Experiment Methods

This section defines the procedure, the order of operations, and logic used for performing a heating test with OUTSET.

- Form the SIGRATHERM GFA insulation and metal foil blanks to line the experiment plenum (example templates found in Appendix I).
- Trim thermocouple and electrical leads to the appropriate length.
- Clean all parts, aside from porous graphite felt, with pure acetone followed by 200 proof ethanol.
- Install the insulation & metal blanks, match drill an aperture hole to provide a line of sight from the plenum to the viewport window. Install a ceramic tube into the aperture hole.
- Install the power leads and thermocouples to the flanged feedthrough.
- Build the specimen region assembly by packing insulation into the specimen region and install graphite plugs. Place a specimen into the specimen region, if applicable.
- Attach the specimen region assembly to the electrical leads and instrument the specimen region graphite crucible with the thermocouple.
- Assemble the containment and bolt flanges to create vacuum seals at the non-welded junctions.
- Fix the experiment to a test stand, insulative base, or other fixturing to stabilize the assembly.

- Check the thermocouple and specimen region electrical circuits for continuity. Also, check for continuity between the enclosure and electrical leads to ensure there are no electrical short circuits.
- Attached a vacuum line/valve to the gas line penetration port on the viewport. Establish the desired internal atmosphere (vacuum, inert, etc.)
- Ensure the power supply is not energized while attaching the electrical leads. Attach external thermocouple and electrical leads to OUTSET. Attach the alternate ends of the thermocouple leads and electrical cables to the thermocouple reader instrument or power supply. Verify that the thermocouple reading.
- Set up a desired instrumentation logging scheme and energize the power supply/set the unit to the desired input power level.
- Water heat sink is installed for OUTSET tests

The inner plenum geometry was used to establish vector art template files that may be used to repeatably generate insulation and foil parts. For this version of OUTSET, an Epilog 50W FiberMark 24 laser engraver was used to “print” the templates onto the stock materials, and the machine power level was maximized to cut out individual metal foil parts as a function of the printing operation.

Cutting of the thermocouple and electrical leads must be carefully performed because these wires not only power and instrument the experiment, but they are also used to hang and locate the specimen region at the appropriate height to be visible from the viewport aperture. As determined in Chapter 3, wire diameters selected for the type-C thermocouples are 0.38 mm and the molybdenum power leads are 0.51 mm. While these materials are refractory metals known for being very hard and brittle, these wires sizes remain sufficiently flexible and may be bent or shaped to meet a rather wide range of configurations. The zirconia ceramic insulation should be installed onto the internal electrical components when performing this wiring work.

Establishing the connections between the power feedthrough electrical leads and the molybdenum leads was achieved by wrapping the molybdenum wire around the feedthrough lead and creating a compression joint with a ceramic bead (see Figure 4-2). This junction was sufficient to power the experiment, but more extensive development should be performed to create a more robust and user-friendly connection scheme.

Final assembly of the experiment involves mating a series of Conflat® flanges or connecting tube fittings. Guidance on bolt loading for metal gasket flanges is available from the flange manufacturer. However, assembling a hermetically sealed container may be challenging and is a crucial step in the process.

Using a helium leak detector to establish vacuum within OUTSET is the most straightforward hermeticity verification option because the instrument can provide very accurate containment leak rate measurements. However, one may glean hermeticity by employing sensitive high vacuum gauges to the system and observe vacuum degradation rates after sufficient vacuum levels are achieved, and the pump is isolated from the system. Note that oxygen must be removed from OUTSET, as it will react with refractory metals at the intended operating temperatures. Also, the presence of oxygen will cause hot graphite components to burn.

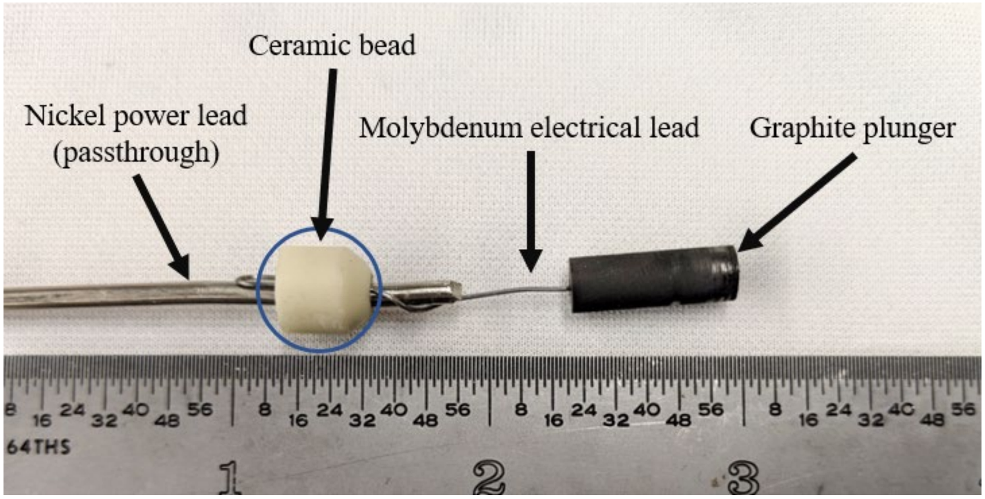


Figure 4-2. Electrical connector using a ceramic bead to create a compression joint between the nickel power feedthrough lead and the molybdenum electrical lead (junction circled in blue).

Verifying and establishing a suitable electrical circuit is the final phase of the experiment. Checking continuity of the various internal circuits is a useful practice, given some connections may be broken during assembly and handling. Also checking for short circuits between the thermocouple or electrical heating loop and the containment should be performed to ensure safe operation of the experiment. Resistance values can be obtained before OUTSET is assembled and then compared to post assembly reading. For this work, the specimen region electrical circuit generally exhibited resistance readings in the range of 3-5 Ω, and the thermocouple loop exhibited resistances between 0.6-0.9 Ω. Note that these measurements should be made while the experiment is not energized.

One final topic of discussion is the identifying of a reliable heat sink. A water bath was used to cool the OUTSET experiments described in this dissertation. This choice provides a stable boundary condition because the sink temperature cannot exceed the water saturation temperature. The sink temperature nominally kept between 20-100°C, and water levels are controlled to ensure the sink does not dry out and drive the enclosure surface temperature beyond the saturation temperature. Given the high design temperatures (≥2,500°C), a heat sink boundary condition fluctuation of roughly 80°C only contributes to 3-4% of the target specimen temperature.

4.2 Experiments

Experiments should be operated in accordance with the following general protocol:

- Verify the Veeco 2508 power supply current output limit is set to zero prior to making the OUTSET electrical connections.
- Verify electrical connections and thermocouple connections have been successfully made. Thermocouple connections are verified by checking Omega™ HH1384 thermometer output. Initiate thermocouple datalogging.
- Turn on the power supply and allow it to complete its start-up process.
- Increase the current limit setting from zero to the target limit over a 10-20 second interval. The target limit is determined by observing the power supply power output, which is displayed on the front of the unit.
- The power output may drift while the OUTSET specimen region is heating. Manually adjust the current output limit to correct for this drift. The goal is to maintain a constant power delivery to OUTSET over the course of the heating transient.

- Allow the thermocouple output to stabilize to a steady state condition. Record the corresponding steady state power output to relate power to steady state thermocouple temperature.
- Once the experiment trial is completed, reduce the current output limit back to zero and turn off the unit. This reduction cycle should be completed in less than 10 s.

A series of low-temperature tests were performed to verify the equipment/OUTSET performed acceptably and in a controlled manner. The low-temperature tests were performed to achieve steady state thermocouple temperatures in the range of 500–1,400°C, with a power input rage of 25-180W. Experiments were only instrumented with a thermocouple which was located in the annular graphite crucible portion of the specimen region. No direct measurements of specimen region centerline temperature were made because the energized specimen region corrupts the thermocouple voltage output signal. However, the scoping thermal analysis described in Chapter 3 suggests that the centerline temperature of the specimen region is on the order of 200°C higher than the peripheral areas in the heated section. Therefore, this temperature difference can be used to correlate thermocouple temperature to specimen region temperature until a more accurate model is produced and validated.

Some key observations from the low power tests include:

- Although a stringent cleaning and handling process is used, driving components to temperatures in excess of 1,200°C tend to volatilize compounds (likely oxygen, oxides, or moisture). This phenomenon was indicated from a spike in inlet pressure, roughly from 2×10^{-2} mbar to 5×10^{-1} mbar, to the helium leak detector during operation. These compounds may contaminate the refractory metal parts and cause embrittlement of the components. These compounds tend to plate out on other components and may volatilize again while performing future tests. It is recommended that all parts should be inspected after each experiment run to verify and minimize fouling of components in future tests. Furthermore, contaminants such as water become entrained in stainless steel containment components and ceramic insulation. Reducing the vacuum level of the experiment to sub-10^{-5} mbar prior to running an experiment trial will remove these contaminants from the system.

- An instantaneous power increase greater than 150 W generally leads to an experiment failure, which is accompanied by an observed order of magnitude increase in specimen region resistance. It is postulated that this effect was caused by rapid thermal expansion of the compressed felt filament within the specimen region that leads to the dislodging of one or both graphite plugs located at the top and bottom of the filament. This increases the specimen region electrical resistance and causes a reduction of current transmission through the specimen region. Reduced current decreases Joule heating in the specimen region and results in a lower filament temperature which reduced the filament thermal expansion. The negative feedback causes the circuit to rapidly degrade and ultimately the experiment fails to reach the target temperature. It is recommended that power is applied somewhat gradually during the initial moments of the experiment; i.e. 10-20 seconds to go from zero to full power. While this explanation was not fully verified, initiating power delivery to the specimen region in this fashion eliminated prematurely failed experiments.

4.2.1 Peak Power/Peak Temperature Experiment Discussion

Peak power/peak temperature (PPPT) experiments investigated power levels that ranged from 200-300W. The upper limit range was generally set by current limitations of OUTSET, which has a recommended 15 A limitation on the power feedthrough. Graphite electrical resistivity has been shown to decrease as a function of temperature [63] [64]. The prototypic NTP temperature experiments exhibited a minimum specimen region electrical resistance as low as 1-2 Ω while at peak temperature while initial room temperature resistances are on the order of 3-5 Ω. This reduction in electrical resistance at peak temperatures made it necessary to increase input current to maintain constant power input to the system. This power correction will be evident in some of the experiment results shown in the next section.

This phenomenon is also important to point out, given the electrically insulative ceramic components in the system also behave in a similar fashion. Degradation of electrical resistance in these insulators can be problematic from an instrumentation standpoint. Specifically, the OUTSET thermocouple provides temperature information for the Poco graphite carbon annulus which is electrically conductive and is located around the zirconia tube and electrically heated specimen region. The purpose of the tubular zirconia insulator is to isolate the thermocouple, which is placed in contact with the Poco graphite carbon annulus, from the energized felt filament. If the zirconia insulator's electrical resistance breaks down sufficiently to allow electrical current to transmit through the insulator, then signal noise that can corrupt the thermocouple output is increased. Coorstek yttria stabilized zirconia (datasheet found in Appendix I) shows that volumetric electrical resistivity can degrade 10 orders of magnitude over a temperature range of 25-1000°C. While this is not the exact grade zirconia used in OUTSET, this material's electrical performance indicates that zirconia electrical resistance is sensitive to temperature. At elevated temperatures, the thermocouple signal noise can occur due to power leakage through the zirconia insulating tube. In fact, the thermocouple output for some of the experiment results shown in the next section exhibit a noisier signal at temperatures above 1,500°C. Figure 4-3 shows a simplified circuit diagram of OUTSET, and demonstrates how the breakdown of electrical resistivity of the insulator affects the thermocouple electrical signal. For this case, it is assumed that system current (I_{total}) is less than 14 A. Under these example conditions, the excess electrical current leakage to the thermocouple instrument can be on the order of 20% of the current generated by the thermocouple from the thermoelectric effect. This phenomenon is not unique to OUTSET and is called electrical shunting [65]. The exponential degradation of electrical resistance associated with electrical shunting can have significant effects on OUTSET thermocouple measurements, which is quantified in Chapter 5.

4.2.2 Peak Power/Peak Temperature Experiment Results

The PPPT experiments demonstrated that OUTSET was thermally efficient, allowing the system to reach prototypic NTP temperatures without exceeding the power limits of the feedthrough. Early shakedown testing shows the thermocouple attained

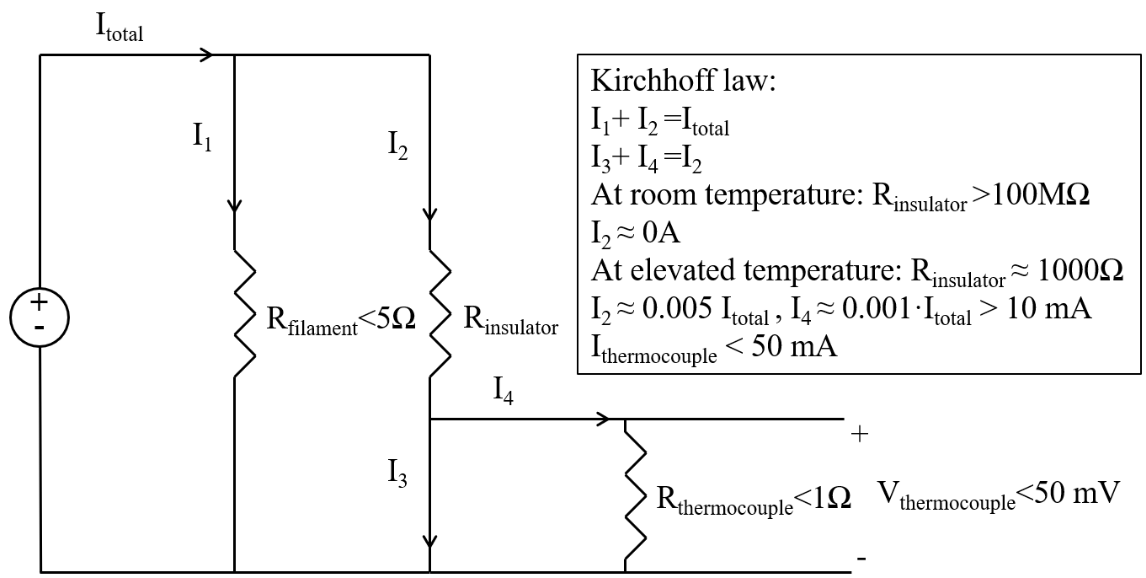


Figure 4-3. Circuit diagram illustrating current leakage as a function of insulator degradation.

temperatures of roughly 1,750°C with a power input of 253 W, as shown in Figure 4-4. The upper limit PPPT condition, which generally reaches thermocouple temperatures around 2,000°C and power input of roughly 300 W, has been demonstrated with various tests.

The thermocouple reader display output for a PPPT shakedown test, along with an image of light emission from the graphite specimen as seen through the viewport are shown in Figure 4-5. For the experiment represented in Figure 4-5, which is referred to as the PPPT1 case, the Omega™ HH1384 data logger was not recording data to a computer, but the output was video recorded and manually parsed to collect data as a function of time. The PPPT1 conditions were produced by setting the power to 300 W over a 10 s interval and allowing the specimen to approach steady state. Note that this case was not susceptible to specimen region resistance degradation, so no current adjustments were needed.

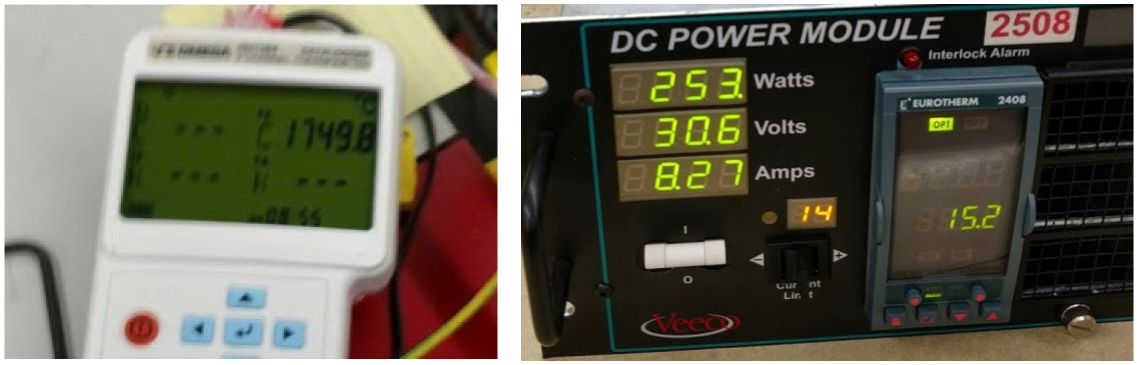


Figure 4-4. Thermocouple reading (left) and power supply settings (right) and for a 1,750°C Case.

Figure 4-5. Specimen region viewed through the viewport (left) and thermocouple reader display (right) for the PPPT1 experiment.

The PPPT1 data can be found plotted in Figure 4-6. Note that the thermocouple temperature follows an asymptotic trend and is consistent with the expected outcomes of such a thermal transient. Given the coarseness of the data, more experiments were conducted such that thermocouple data logging was controlled and recorded at a frequency of 1 Hz. This higher resolution data more clearly resolves the transient performance of OUTSET and shows repeatability under experiment conditions. A plot of select data sets can be found in Figure 4-7 and numerical derivatives of the data are found in Figure 4-8. These numerical derivatives are calculated as simple first-order divided differences. Figure 4-7 compares the PPPT1 experiment data to three other independent experiments performed on separate occasions. The three additional trials, named PPPT2-PPPT4, were performed by applying 300W of power to OUTSET specimen region. These experiments were also recording thermocouple output with the Omega™ HH1384 datalogger. Observed early-time (t = 0 - ~100s) adiabatic heat-up rates for experiments PPPT2 through PPPT4

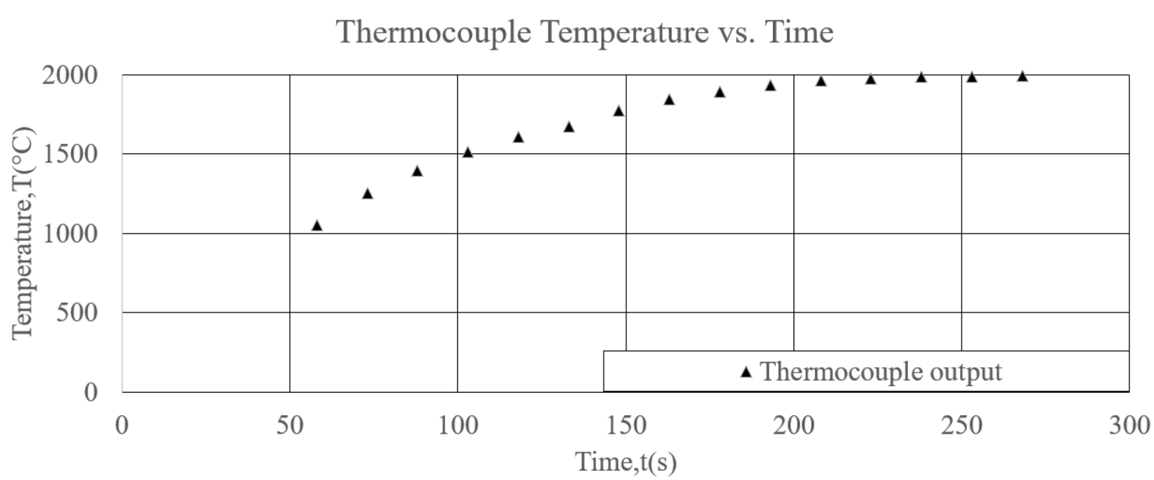


Figure 4-6. PPPT1 parsed thermocouple data plotted vs. time.

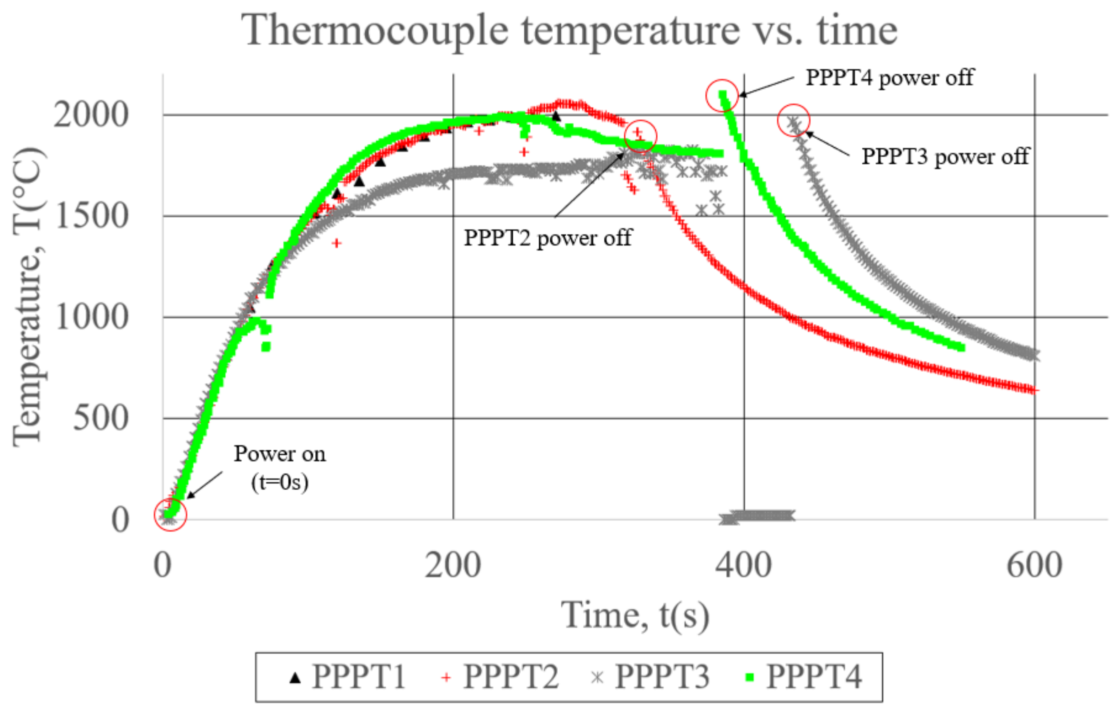


Figure 4-7. Thermocouple data plotted as a function of temperature for select PPPT experiments.

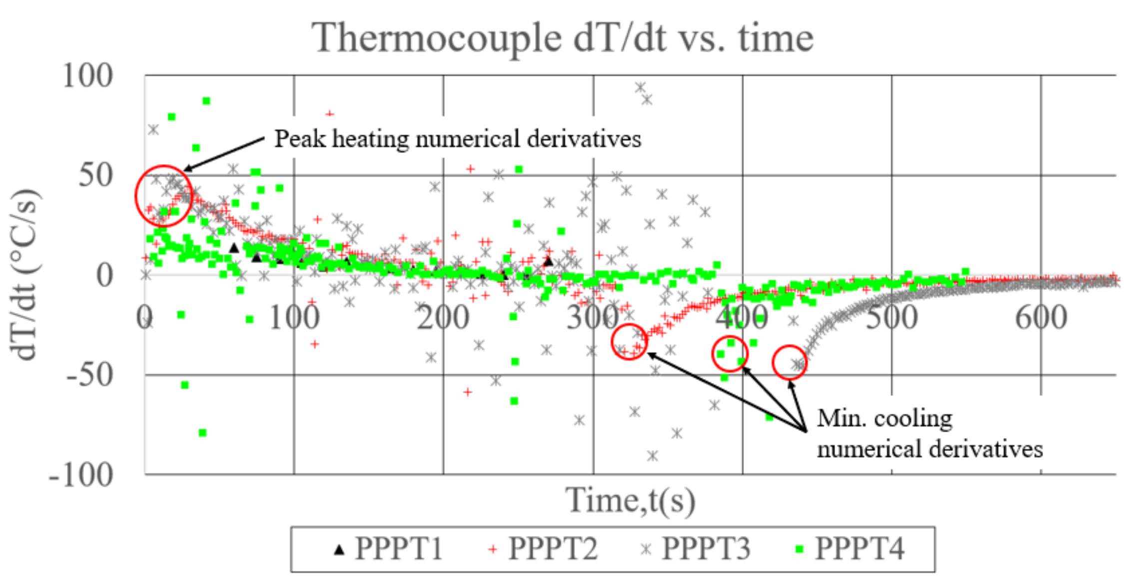


Figure 4-8. Numerical derivatives of the PPPT thermocouple data sets.

follow similar trends. Likewise, the available PPPT1 data follows the PPPT2 and PPPT4 data. Maximum temperature derivatives for heating periods of these trials are around 40°C/s, and minimum temperature derivatives of the cooling trends are around -40°C/s, as seen in the circled regions of Figure 4-8. Figure 4-9 shows the thermocouple output for the PPPT3 and PPPT4 experiments. Figure 4-7 and Figure 4-9 also show that PPPT3 thermocouple temperatures diverge from the other data sets around 100s, which indicates a reduction in power delivery to OUTSET for this trial. Electrical current adjustments were made for both PPPT3 and PPPT4 over the course of their transients to maintain the 300W input and drive the thermocouple to temperatures near 2,000°C, as indicated in Figure 4-9. Instability of the thermocouple data is seen in both cases between 200 and 400 seconds. Also, both thermocouple output signals show signs of increased noise during these adjustment periods.

The increased noise at high temperatures likely was the result of power leakage through the zirconia insulator into the graphite crucible, as described in the previous section. Power was disconnected to the PPPT3 and PPPT4 experiments, as indicated in the figure, and a discontinuous jump in temperature can be observed. This is followed by a temperature decay trend indicative of thermocouple cooling. This recovery of sensible thermocouple data, after the potential noise source is terminated, supports the source thermocouple noise stems from the energized specimen region. The cooldown periods for PPPT2 through PPPT4 were collected for comparison, and the “power off” times were all shifted to coincide with the initiation time (t = 0s); as seen in Figure 4-10. There is some

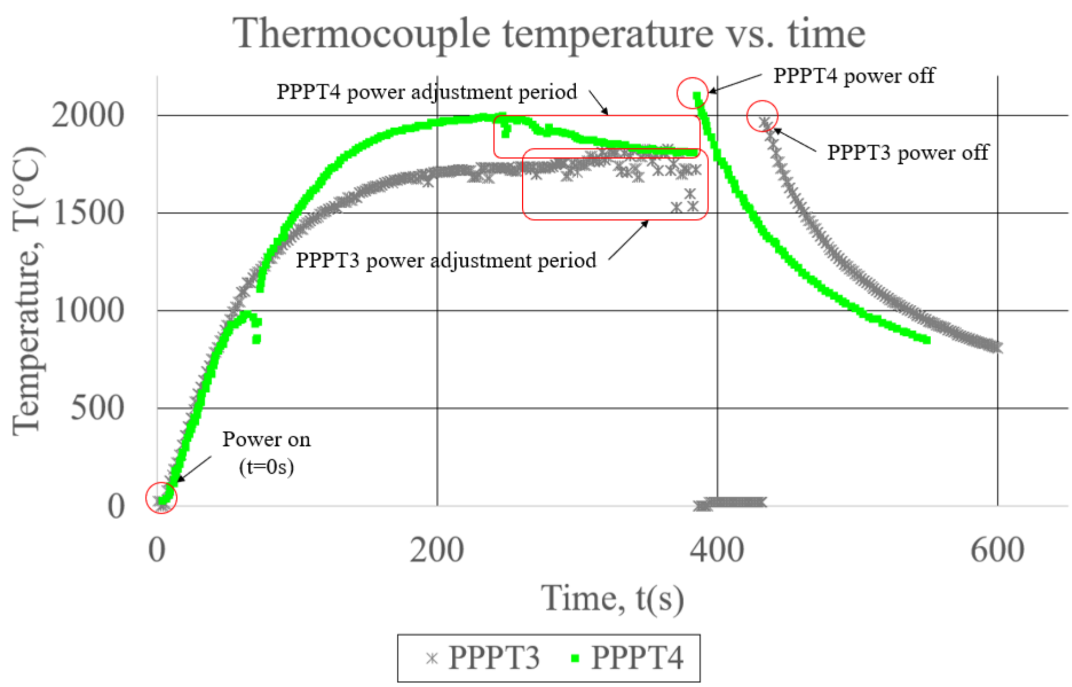


Figure 4-9. Thermocouple data plotted as a function of temperature for experiments PPPT 3 and PPPT4.

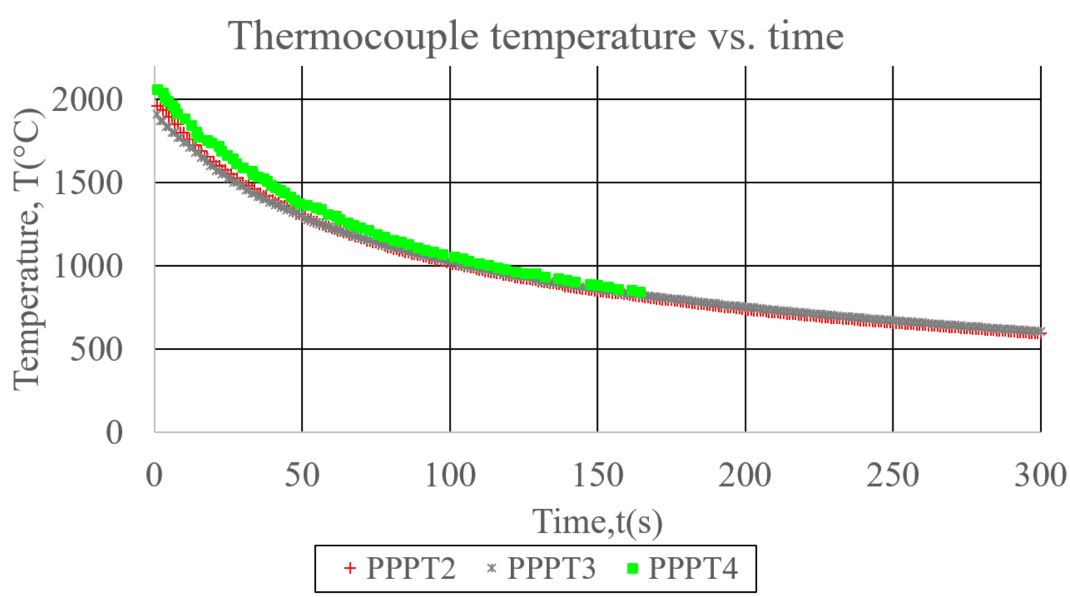


Figure 4-10. Thermocouple cooling data comparison between PPPT2 through PPPT4 (t = 0 seconds indicates power shutdown time).

discrepancy between initial cooldown temperatures for these cases, but this sample set has an average initial temperature of 1,978°C and standard deviation of 65°C.

4.3 SWIR Camera Discussion

It was previously discussed that the type-C thermocouples used for the OUTSET experiment have drawbacks such as signal noise insertion due to power leakage in the specimen region and uncertainty between the instrument temperature reading and the inferred component temperature of interest. This issue prompted an investigation into non-contact measurement systems that may perform reliable temperature measurements. Chapter 3 describes the FLIR A6261sc SWIR camera as an appropriate instrument for this purpose. This section describes the setup and implementation of the SWIR camera to measure OUTSET graphite crucible surface temperatures.

Care must be taken to ensure the optical imaging system is adequately set up to ensure the instrument accurately images the target of interest. The SWIR camera must be oriented with a direct line of sight view of the active region of the target. This was achieved by affixing the SWIR camera and OUTSET to a vibration isolation optical table. This special table is specifically designed for performing optical experiments and has a precise grid of threaded holes that are used to bolt down the optical and experiment equipment in a controlled fashion. Commercially available mounting equipment was used to clamp the equipment in place on the optical table. The SWIR camera has a stock 0.9-1.7μm, f/1.8 lens with a focal length 50mm, which establishes some orientation constraints for the experiment. Figure 4-11 shows the optical system, as seen from above.

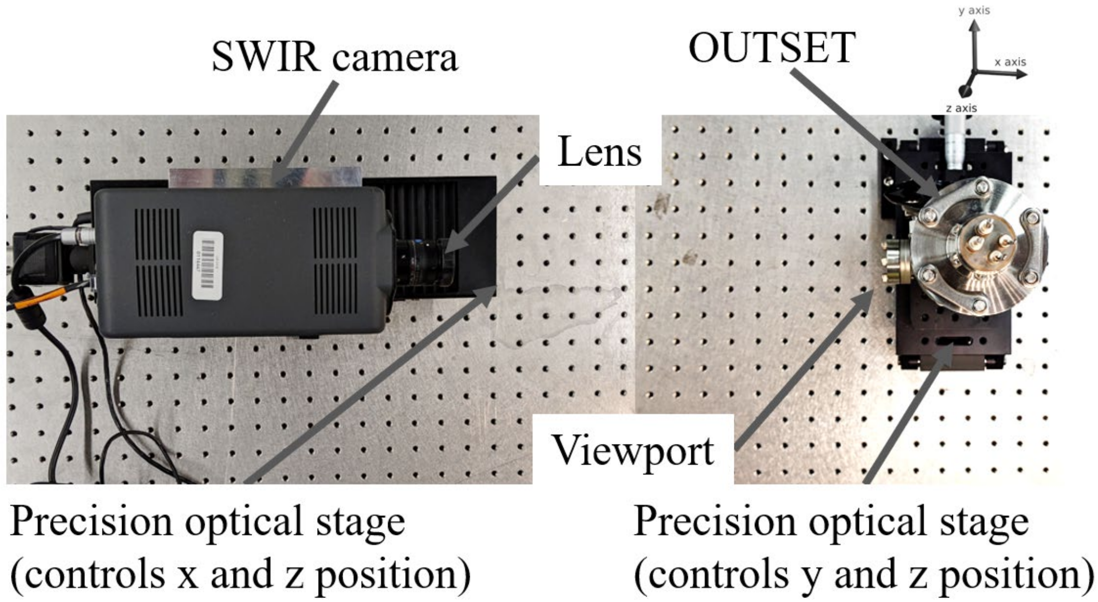


Figure 4-11. Optical system with SWIR camera on the left and OUTSET on the right.

The experiment layout constrains the equipment to the isolation table with optical stages so that fine adjustments can be made to guarantee the SWIR camera correctly observes the active region. The stages used have a movement resolution of 25µm. Figure 4-11 shows both the camera and OUTSET located on precision optical stages. These pieces of equipment are used to provide fine position control for the two pieces of equipment. The camera stage assembly has degrees of freedom in the x-direction (left to right in the figure) and z-direction (out of the page in the figure). The OUTSET stage assembly has degrees of freedom in the y-direction (up to down in the figure), and z-direction. Motion is achieved by adjusting screw drives on the stages to move an object into the desired position. The strategy for this experiment is to align the equipment in the y- and z-directions which locates the OUTSET viewport within the camera field of vision and then move the camera in the x-direction to adjust the focus.

FLIR issues proprietary ResearchIR software to interpret the SWIR camera output. This tool is intended to be used to interface with the camera, record of the camera output, and process & analyze the temperature information obtained from the recorded images. The software is also used to perform the fine adjustments for relative position between the camera and OUTSET viewport. ResearchIR processes the camera output and maps the light intensity observed by each of the pixels of the InGaAs detector to form an image. The SWIR camera is only sensitive light ranging from 0.9-1.7μm, which is just beyond the visible spectrum (maximum wavelength of 740 nm). Thermally hot objects produce a SWIR light source, making it straightforward to make out hot objects within ResearchIR and, conversely, difficult to observe room temperature objects within the software. Figure 4-12 compares what is observed by the SWIR camera to what is observed by a camera that is sensitive to the visible light spectrum at room temperature.

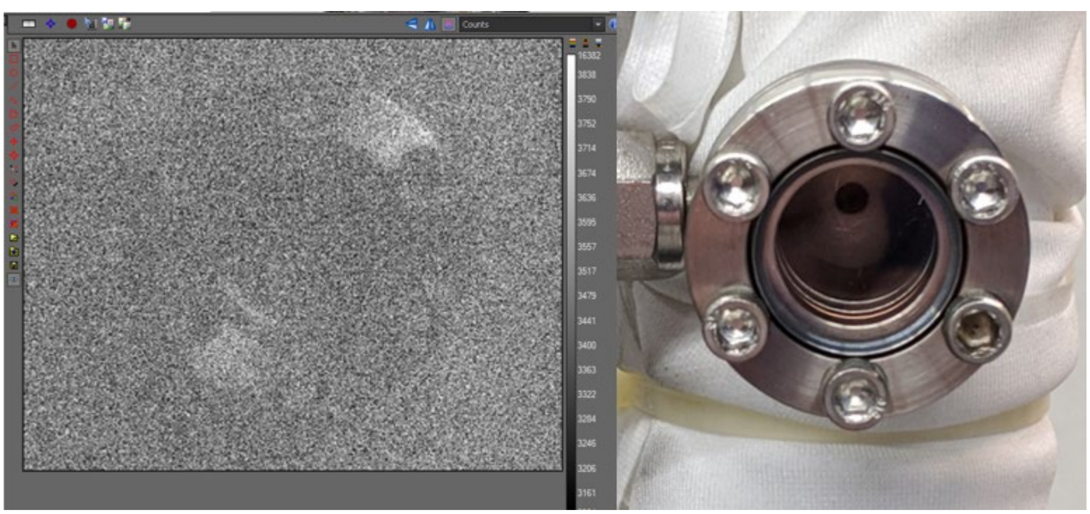


Figure 4-12. ResearchIR visualization of the SWIR output from the camera (left) and observed image of the OUTSET viewport (right).

Performing the fine adjustments between the camera and OUTSET was made impossible by the obscurity of the SWIR image. A soldering iron was used as an infrared light source to illuminate the OUTSET viewport and allow the ResearchIR software to resolve a usable image. This iron was heated to roughly 400°C and placed in close proximity to the viewport. The infrared light intensity emitted from the iron was sufficient to illuminate the viewport so that the viewport aperture could be oriented within the camera's field of vision. The optical stages were adjusted to focus the camera lens and locate the aperture within the center of the field. The focused SWIR camera image with the soldering iron illuminating the OUTSET viewport can be seen in Figure 4-13.

The soldering iron was also used to verify the rotational orientation of OUTSET with respect to the SWIR camera and verify it could resolve an image of a heat source within the OUTSET. This is performed by suspending the iron within the OUTSET specimen plenum and locating the heated tip in line with the aperture. OUTSET, which is placed in a tight-fitting metal base that is bolted to the optical stage, is slowly rotated within the base until the SWIR light signal being emitted from the iron is maximized. Note that all initial alignment adjustments are performed with no temperature interpretation made by the ResearchIR. Setting the software to interpret temperature requires installing notch filters and loading calibration NUC files. The software output observed under this configuration is difficult to interpret because the image only reports temperature data within the NUC calibration range. Figure 4-14 compares ResearchIR uncalibrated image output with calibrated temperature image output.

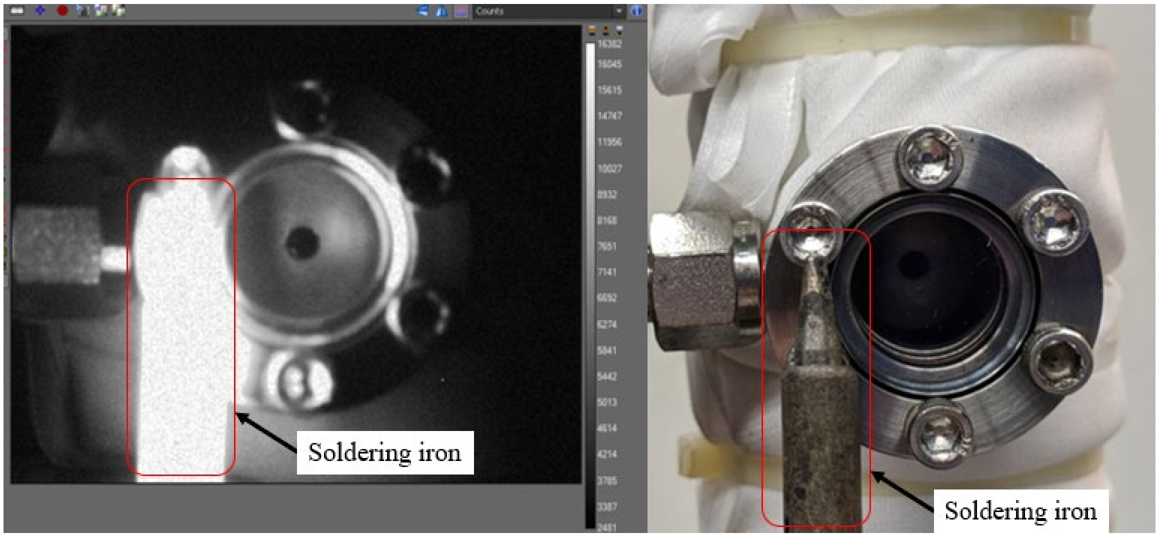


Figure 4-13. Comparison of the ResearchIR software (left) and visualization of OUTSET viewport being illuminated by a soldering iron.

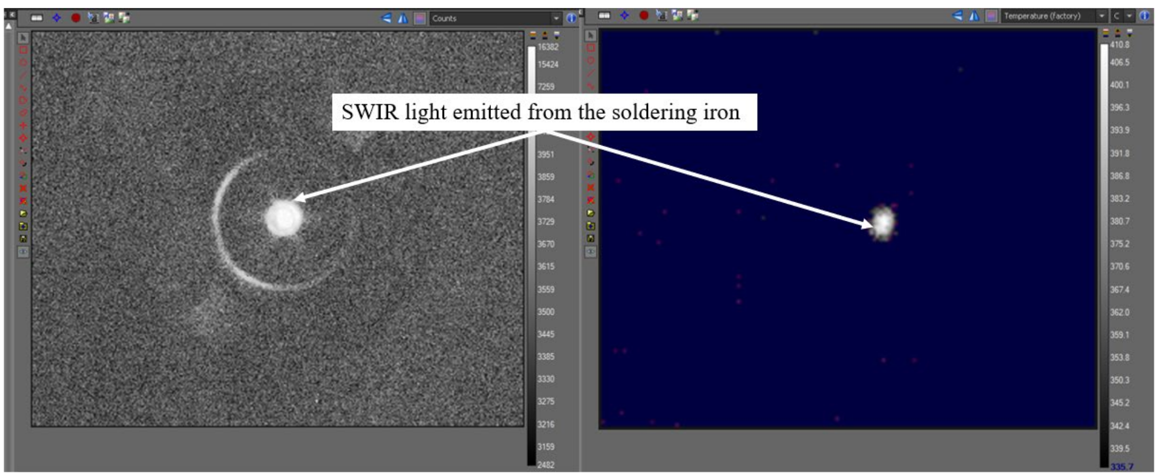


Figure 4-14. Comparison of ResearchIR uncalibrated image (left) with calibrated software output (right). Uncalibrated image output is in photon counts ranging from 2482-16382, and calibrated temperature data ranges from 335.7-410.8°C

The calibrated image in Figure 4-14 is interpreted as:

- The blue background indicates temperature information less than the minimum value reported on the scale at the right side of the image,
- The temperature scale located at the right side of the image indicated all temperatures observed in the field of view.

An experiment utilizing both the type-C thermocouple and the SWIR camera was performed to compare the two measurements. Note that this experiment does not correspond with any of the PPPT trials reported earlier in this chapter. Like the other PPPT experiments, OUTSET was energized with 300 W to impart a thermal transient that was recorded by these two independent temperature measurement instruments. The experiment is terminated around 120 s before the transient was allowed to stabilize because a discrepancy between the thermometry data and the SWIR camera output was observed. This discrepancy includes inconsistencies in both time and temperature scales. Synchronization between the SWIR camera and the thermocouple datalogger was attempted manually, but a delay of 30 seconds was observed between the two instrument responses. The thermocouple and SWIR data can be seen in Figure 4-15. The ResearchIR software doesn’t readily provide flexibility for adjustment once a NUC calibration file is loaded. This is particularly problematic when trying to adjust the software to consider the emissivity of the OUTSET active region. The camera is factory calibrated using a standard blackbody instrument with an emissivity of unity. The active region is graphite with expected emissivity of 0.7-0.8, which is 20-30% lower than that of the blackbody. As a

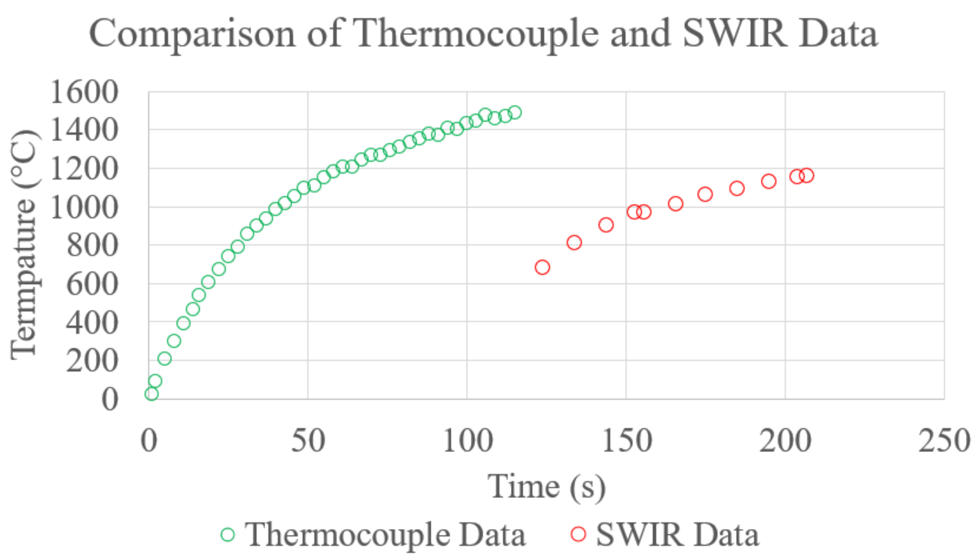


Figure 4-15. Comparison of the raw thermocouple and SWIR data.

result of these apparent biases, the thermocouple data and the SWIR camera data are linearly scaled for comparison purposes, and to ascertain if the two sets may be correlated. The original data sets are mapped to the scaled data sets using the following expression:

$$y = mx + b$$

where:

$$y \ \equiv scaled\ datum\ , x \equiv original\ datum\ , m\ \&\ b\ are\ scaling\ parameters$$

The scaling parameter m is the defined as the inverse maximum temperature for the respective data set. The scaling parameter b is the defined as the time difference between the observed power cutoff temperature of the thermocouple data set and the data set being scaled. For the thermocouple data, the scaling parameters are $m = \ 1/1487.8°C$ and $b = 0$. For the SWIR data, the scaling parameters are $m = \ 1/1158.1°C$ and $b = -90$; the time delay for the SWIR data is 90 seconds. The linearly transformed data sets are plotted in

Figure 4-16. The two sets show a similar trend and may be correlated to one another, i.e. not linearly independent. No uncertainty analysis was performed on these data sets, given they are inconclusive. At the time of this writing, the author is working with the camera manufacturer to troubleshoot the data discrepancies.

4.4 Melt Wire Usage Discussion

OUTSET peak power/temperature experiment trials PPPT3 and PPPT4 employed iridium-40% platinum melt wires with a ~2,250±40°C melting point [66]. The melt wires were placed in the specimen location at the center of the specimen region during the OUTSET assembly process. Both iridium and platinum are electrically conductive, and the wires had no effect on the specimen region resistance. Note that melt wires were not reused

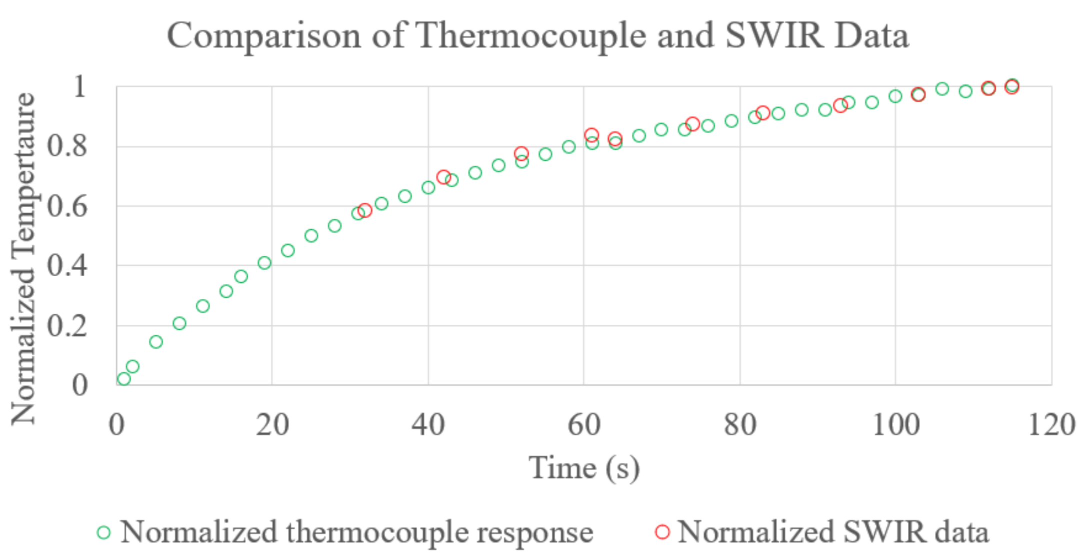


Figure 4-16. Comparison of thermocouple data and SWIR camera data

in multiple experiments. The wires were massed & photographed before and after experiment trials. Figure 4-17 and Figure 4-18 show before and after images of select melt wires. Shape and surface changes of each wire indicate melting and provide a positive indication that the associated experiment reached or exceeded 2,250°C during testing. Although the melt wire shape was subject to change during the experiment, there was no observed melt wire mass change. The PPPT3 and PPPT4 melt wires were 0.079g and 0.039 g, respectively, and there was no mass change due to melting. The latent heat of fusion for iridium and platinum are 41.3 g/mol and 21.3 g/mol, respectively [67]. The wires consist of two noble metals, so no reactions are expected to occur with the surrounding specimen region filament, nor is there any expected outgassing from the wires. This is consistent with the zero net mass change in the wires. The energy produced by melting the wires was 14 J for PPPT3 and 7 J for PPPT4, which is miniscule compared to the stored energy of the specimen region. The post-test wire images in the figures appear to be darker than their before-test counterparts. The wires' surfaces are not as dark as the pictures suggest and the outer surfaces appear shiny and amorphous. The surfaces no longer have the machine marks that were present prior to the experiment trials. The wires are smooth and rounded, which indicates the wires became molten and re-solidified.

The melt wires provide an indication of OUTSET minimum specimen region temperatures reached during the peak power/temperature tests. These direct temperature measurement instruments are easily deployed and have no noticeable impact on the OUTSET electrical performance. Melt wires also can be used for in-pile experiments and

Figure 4-17. Representative melt wires prior to the test (left) and after the test (right).

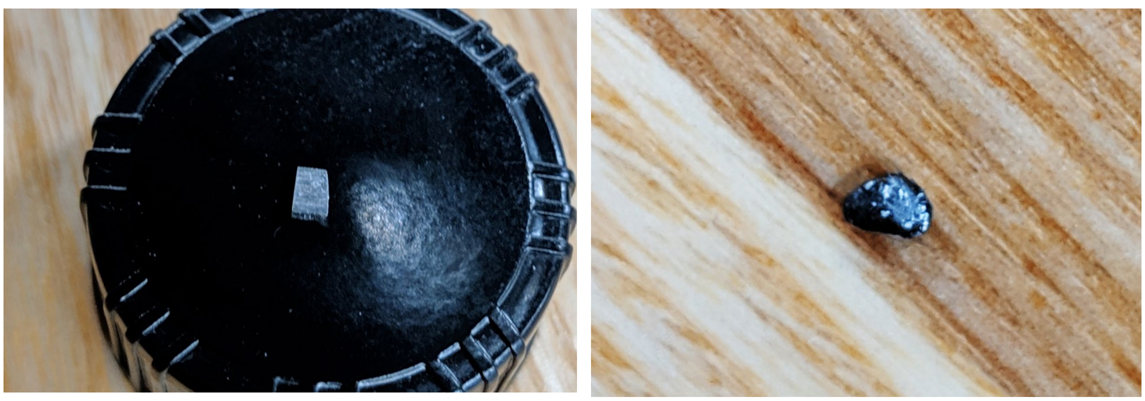


Figure 4-18. Melt wire prior to the test (left) and after the test (right).

are not subject to the same neutron irradiation-induced limitations as the type-C thermocouples. Therefore, they offer an alternate instrumentation scheme to provide specimen temperature data for phase 2 and phase 3 experiments. Also, the alloy composition of the Ir-Pt metal can be modified to produce wires with different melting temperatures that can bracket target temperatures for these future tests and verify achieved temperatures as opposed to only identifying minimum achieved temperatures.

CHAPTER 5.
COMPUTATIONAL ANALYSIS

This chapter focuses on the development of a finite element analysis (FEA) model that can accurately predict the performance of OUTSET; either with electrically heated surrogates or fission heated specimens. The chapter is separated into three basic sections: creating the base three-dimensional OUTSET finite element model, reporting the steady-state thermal model results, and reporting transient thermal model results. The first topic includes a very brief description for using Workbench graphical user interface within the ANSYS FEA software package, which allows the user to select specific physics analysis systems and establish the modeling conditions. This base model configuration provides fundamental constraints for both the steady-state and transient models such as boundary conditions, body-to-body contact conditions, and model mesh. The thermophysical properties and initial conditions are solution-method specific, and those conditions are described in their respective sections.

5.1 Setting up the Three-Dimensional Finite Element Model

The three-dimensional (3-D) model was created using ANSYS 19.1, while the scoping calculation r-θ model described in Chapter 3 was created in ANSYS 16.2. The latest version allows the user to increase the maximum number of computing cores dedicated to a solution from two to four cores, which reduces solution times. The ANSYS 19.1 program suite uses Workbench to establish the modeling inputs, including part geometry, material properties, body-to-body contact interfaces, FEA meshing data, symmetry & boundary conditions, load inputs, solution methods (i.e. transient vs. steady state), etc. Workbench provides a graphical user interface that utilizes drag-and-drop functionality to define analysis systems appropriate for a given simulation. A view of an unsaved project within the ANSYS Workbench interface can be seen in Figure 5-1.

Part geometries from CAD models are imported to Workbench or manually generated within the software to set the spatial and dimensional constraints of the simulation. The Workbench analysis systems each have a geometry module, but a standalone geometry module (found under the "Component Systems" tab) also may be used to supply the same geometry to multiple analysis systems. The OUTSET model used the standalone module for importing the part geometries. The strategy for establishing a working thermal model is to import the CAD geometries and port that information to a "Transient Thermal" analysis system. This system is used to create the model (model mesh, boundary conditions, body-to-body contact interface settings, etc.) and that model information is ported to a "Steady-State Thermal" analysis system. This modular approach allows the two analysis systems to share the base model and calculate either transient or steady state results. This setup strategy also provides a means to troubleshoot the base model using a steady-state model, which generally converges on solutions more quickly than the multiple time-step transient model. The Workbench "project schematic" for OUTSET, showing the geometry, transient, and steady-state modules is in Figure 5-2. The connection lines between the three modules indicate the base geometry configuration is supplied to the transient thermal module, and the model information (including geometry information) is supplied to the steady state thermal module.

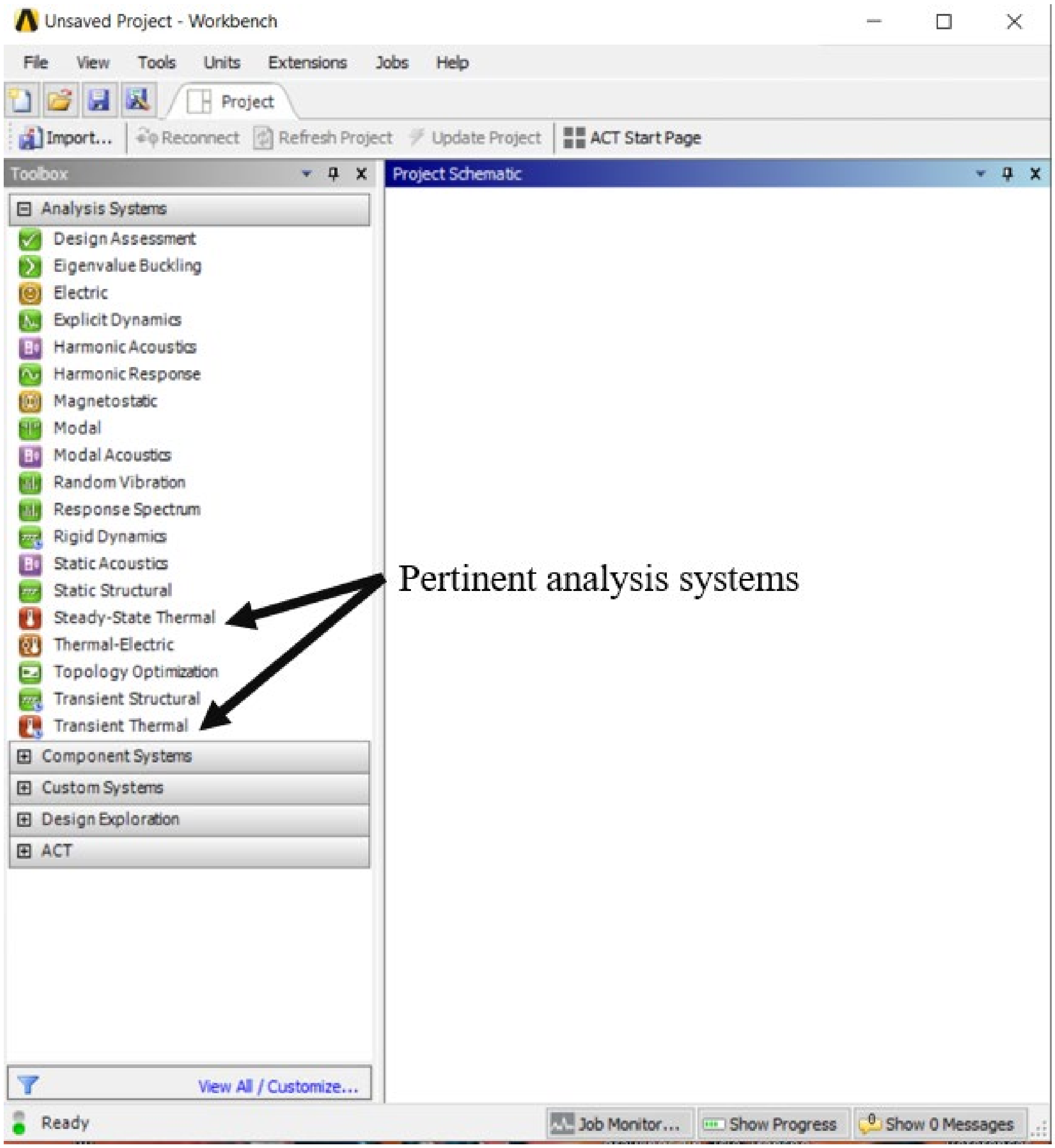


Figure 5-1. ANSYS Workbench interface showing the expanded "Analysis Systems" drop-down set.

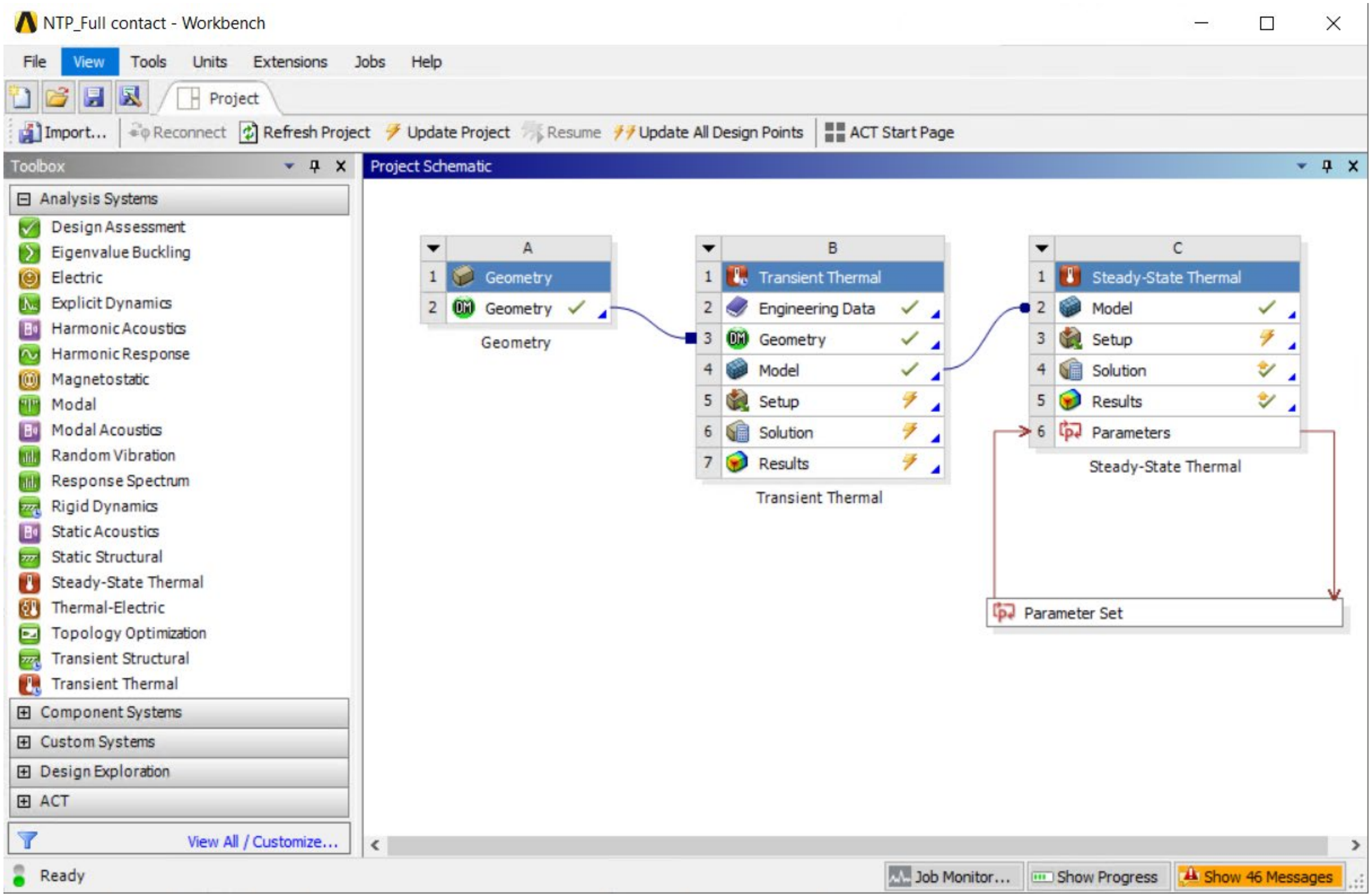


Figure 5-2. ANSYS Workbench project schematic for the OUTSET analysis.

5.1.1 *Model Geometry and Contacts Setup*

The ANSYS DesignModeler software within Workbench facilitates importing geometry files and provides some functionality for modifying or simplifying the model. In this way the viewport and power feedthrough were modified and/or suppressed to reduce the model complexity. Figure 5-3 shows the OUTSET geometry as seen in DesignModeler; the parts in yellow are all suppressed from the thermal analysis. Meshing and body-to-body contact selection are performed using the ANSYS Mechanical program, which uses the imported geometry to establish relationships between parts and other analysis parameters. A sectioned view of the final geometry state used for the OUTSET analysis, as seen from ANSYS Mechanical, is in Figure 5-4.

ANSYS Mechanical also allows a user to define contact interface designations between each part. Initially, the program automatically screens the newly input model and designates contacts based on the proximity of parts to one another. However, this process defines the contacts based on default program settings and the contact definitions should be manually checked for accuracy. Contact definitions are broken up in several categories that include bonded, no separation, frictionless, rough, and frictional. The first three contact types are the only definitions used in the OUTSET model because this model only considers thermal degrees of freedom. The bonded and no separation contacts are generally used for interfaces that are presumed to be fixed or welded together and assume that there are no spatial gaps at the contact interface(s). Frictionless contacts consider that the model represents accurate spatial gaps used to calculate a contact conductance. ANSYS has an option to leave contact conductance calculations as "program

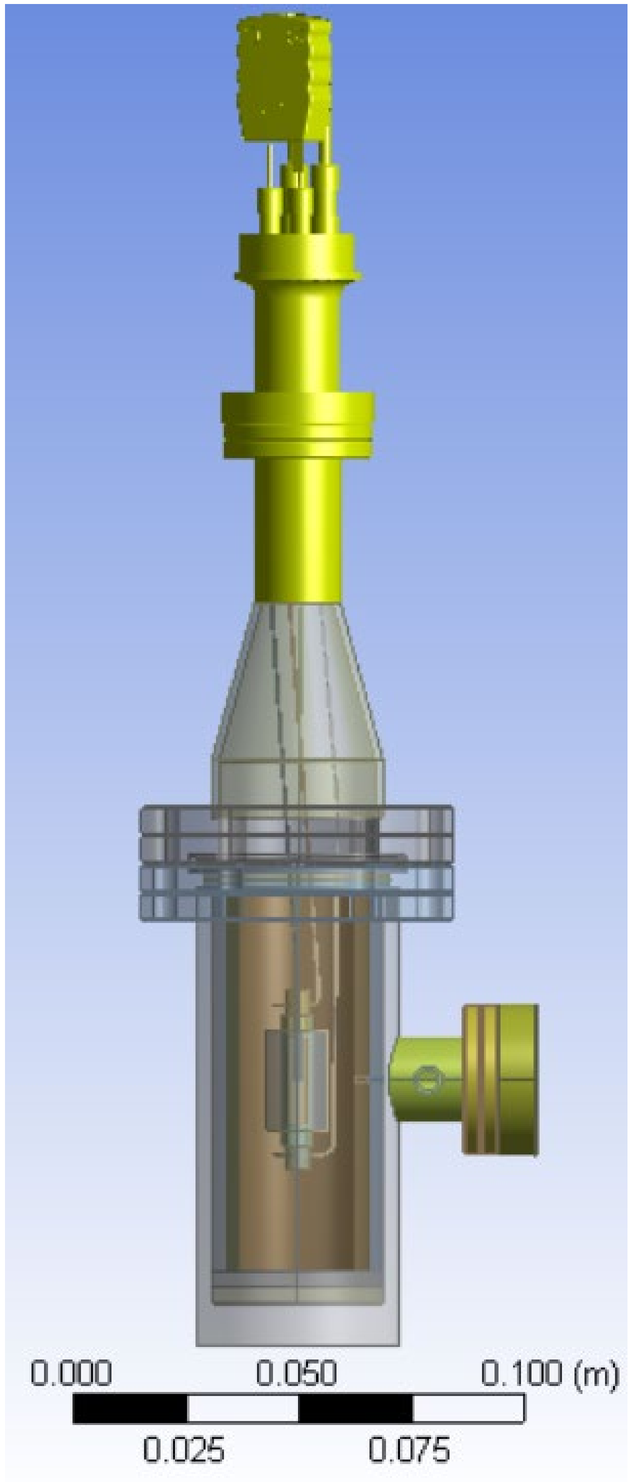


Figure 5-3. OUTSET model with suppressed parts in yellow.

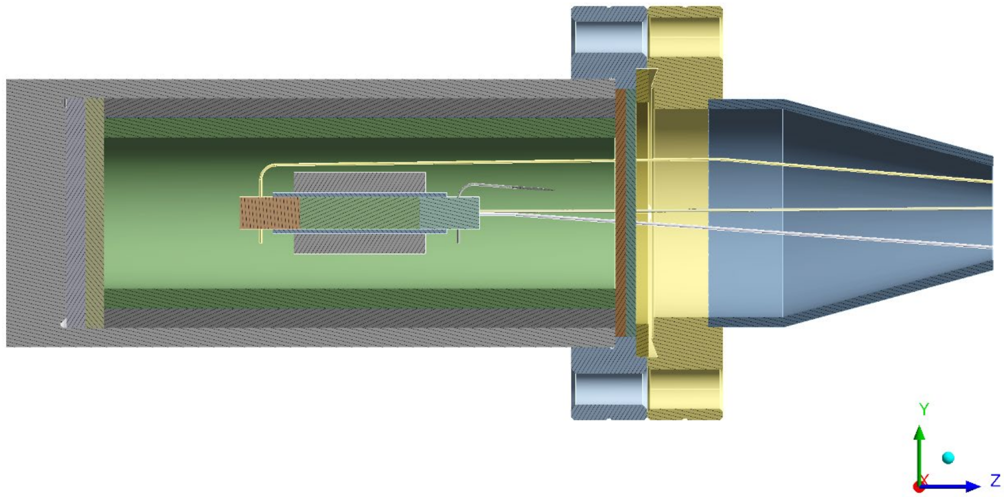


Figure 5-4. Final geometry state used for the OUTSET analysis.

conductance. controlled” or values may be user-defined.

The 3-D OUTSET model relies on program-controlled contact conductance, which is different from the approach used in the scoping calculation model described in Chapter 3. The scoping model was used to estimate power requirements for a lower power evacuated enclosure. The solution methods used for that model are intended for calculating contact resistance between two bodies with a gas occupying the interstitial spaces within the contact gap [56], and the vacuum was modeled as a gas with a thermal conductivity of 1×10^{-6} W/m-K. The 3-D OUTSET model is designed to represent the experiments detailed in Chapter 4, which were solely performed with an evacuated enclosure. There are numerous models available to estimate contact conductance under these conditions [68], but ANSYS solution methodologies are well demonstrated so this model relies on the software to calculate accurate contact conductance values.

Generally, all contacts were modelled as frictionless connections and used the ANSYS frictionless contact conductance models, except for interfaces that existed for parts that were bolted together (i.e. the copper gaskets between the flanges) and certain interfaces that existed in the specimen region (see Figure 5-5). These parts were fabricated to be size-on-size to reduce the chances of differential thermal expansion creating gaps in the specimen region at elevated temperatures. At these elevated temperatures, both the graphite and the zirconia experience thermal expansion on the order of 1.2-1.5% [55] [42]. Assuming the inner diameter of the graphite crucible and the outer diameter of the zirconia insulator are both 6mm, then the radial separation gap between these bodies are 3mm·(1.015-1.012) = 0.009mm or 9µm. These specific contacts were set to no separation. A full list of the contact setup can be found in the ANSYS summary report found in Appendix III

5.1.2 Input Conditions and Heat Transfer Discussion

The nominal input and boundary conditions for the model can be seen in Figure 5-6. All parts are initially set to 85°C. The primary boundary condition is placed on the containment outer wall and is a constant temperature condition set to 85°C; condition D in the figure. This is consistent with an experiment that is submerged in water or shrouded with a water-soaked jacket. Free convection heat transfer coefficients for water are on the order of 500 W/m^2-K [69]. OUTSET has a free convection water cooled surface area of 0.016 m^2 and, through Newton's law of cooling, the surface temperature 300W/(0.016 m^2·500 W/m^2-K) = 38°C higher than the ultimate heat sink. OUTSET experiment trials were performed at 22-25°C, making the wall temperature around 60°C. This demonstrates

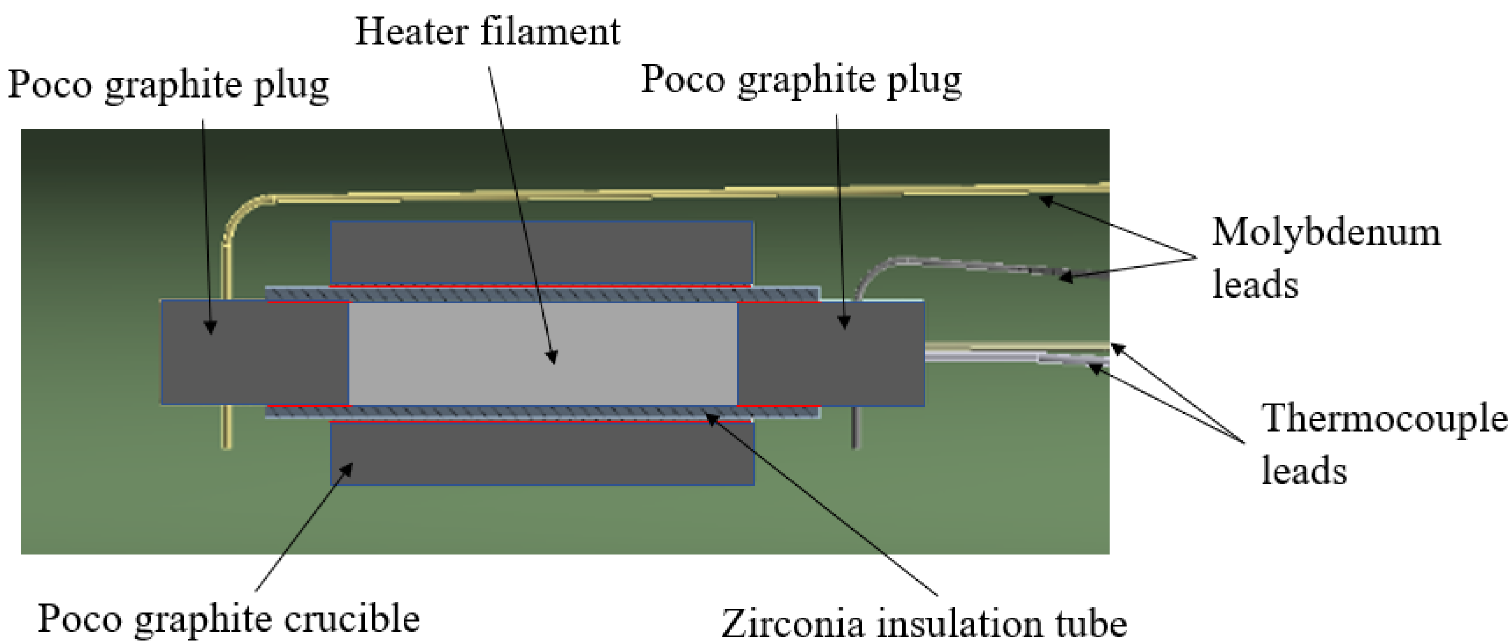


Figure 5-5. Specimen region no separation body-to-body contact points (in red).

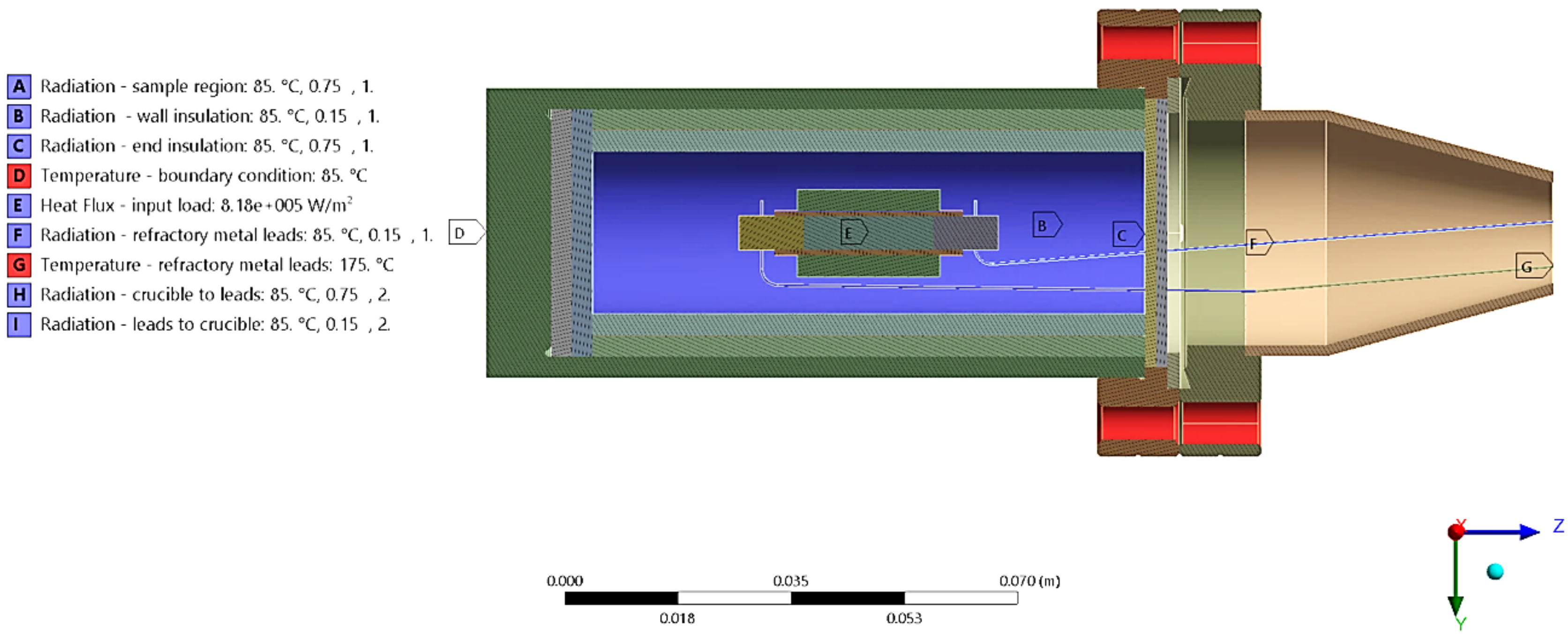


Figure 5-6. Input and boundary conditions for the OUTSET model.

the modeling uncertainty in the 85°C boundary condition is within 10s of °C from reality. Small changes in the heat sink boundary condition will impact the experiment centerline temperature on the same order, meaning with the boundary condition temperature is increased by 10°C, the centerline temperature will increase roughly the same amount and this change is generally less than 1% of the specimen region filament centerline temperature (>2,500°C).

The other boundary condition is also a prescribed constant temperature of 175°C set at the ends of the electrical and thermocouple leads located in the reducer portion of the top of the experiment (condition G in Figure 5-6). This condition forces an expected temperature difference of more than 1,200°C across the 7-10 cm long lead wires. This condition was imposed because the CAD model received from the manufacturer treated the power feedthrough as a solid single part, instead of breaking the part into its individual components. Recreating the power feedthrough with no knowledge or manufacturer drawings increases the model complexity and potential for modeling error, so the feedthrough was removed from the model. Providing an independent boundary condition for the thermocouple and power lead wires permits the capability of parameterizing this condition to understand its impact on the wire temperature distributions and thermocouple junction temperature.

The thermal input load is 300W, which coincides with the OUTSET experiments. The heat flux of the specimen region filament outer surface is evaluated using the nominal surface area of the cylindrical specimen region filament within the zirconia insulator, as indicated in Figure 5-5.

$$SA = \pi\left(\frac{D^2}{2} + DL\right) \qquad 5\text{-}1$$

$$SA = \pi\left(\frac{(5.17mm)^2}{2} + 5.17mm \cdot 20.0mm\right) = 366.8mm^2$$

$$q'' = \frac{P}{SA} \qquad 5\text{-}2$$

$$q'' = \frac{300W}{366.8mm^2} = 8.18 \times 10^5 \frac{W}{m^2}$$

Radiation heat transfer for a black body is defined by Stefan-Boltzmann law:

$$E(T) = \sigma T^4 \qquad 5\text{-}3$$

$$\sigma \equiv Stefan - Boltzmann\ constant = 5.670373 \times 10^{-8} \frac{W}{m^2 K^4}$$

$$T \equiv absolute\ temperature\ \{K\}$$

The Stefan-Boltzmann law considers perfect radiation, which is an idealized case. Black bodies are perfect transmitters and absorbers of thermal radiation. In reality, very few cases can be considered to operate under these conditions. In order to account for this, an additional emissivity (ε) term is introduced into the equation to account for the non-black radiative transfer characteristics of most cases involving real bodies. The modified Stefan-Boltzmann law which accounts for emitted heat in a gray body takes the following form:

$$E(T) = \varepsilon\sigma T^4 \qquad 5\text{-}4$$

$$0 < \varepsilon < 1$$

Gray bodies emit radiation at some spectral distribution, but the energy is less than that of the black body emitter. An average scalar emissivity term, which is defined as the integral spectral emissivity average of the applicable range of emission wavelength, is introduced to account for the reduction in emitted energy. Emissivity is generally a function of direction, wavelength, and temperature. The OUTSET internal components are made up from individual surfaces and areas that are combined to form an "enclosure." This term is formally defined as any surface that can be considered as completely surrounded by an envelope of other solid surfaces or open areas [62]. Siegel and Howell [62] state that heat transfer calculations involving enclosure geometries are usually assumed to contain diffuse-gray surfaces; the term denotes that emissivity is not dependent upon direction or wavelength [62]. Performing accurate measurements to account for all the various conditions is difficult and tabular values of emissivity are derived from averaged measurements to provide averaged quantities [62]. These quantities are formulated by averaging emissivity over all wavelengths and directions but remain dependent of temperatures. The OUTSET model is considered to operate under diffuse-gray body conditions where emissivity is spectrally and directionally independent, but emissivity remains dependent of temperature [70]. Equation 5-4 is expanded to the following form to account for the net radiation between gray two bodies [70]:

$$q_{net} = \frac{\sigma\left(T^4{}_i - T^4{}_j\right)}{\left(\frac{1-\varepsilon_i}{\varepsilon_i A_i} + \frac{1-\varepsilon_i}{A_i F_{ji}} + \frac{1-\varepsilon_j}{\varepsilon_j A_j}\right)} \qquad \text{5-5}$$

where:

ε_i = effective emissivity of surface i

F_{ji} = radiation view factor

The ANSYS Mechanical APDL Theory reference provides a detailed summary of how the software calculates radiation heat transfer [71] but the following portion of the dissertation summarizes the approach. Refer to Section 5.1.3 for the radiation view factor formulation. ANSYS uses the discretized form:

$$\sum_{i=1}^{N}\left(\frac{\delta_{ji}}{\varepsilon_i}-F_{ji}\frac{1-\varepsilon_i}{\varepsilon_i}\right)q''_i = \sum_{i=1}^{N}\left(\delta_{ji}-F_{ji}\right)\sigma T_i^4 \qquad \text{5-6}$$

where:

N = number of radiating surfaces

δ_{ji} = Kronecker delta

q''_i = heat flux of surface i

T_i = absolute temperature of surface i

A system of equations can be formulated from equation 5-6 that can be written as:

$$[A]\{q^o\} = \{B\} \qquad \text{5-7}$$

where:

element $A_{ij} = \delta_{ji} - (1-\varepsilon_i)F_{ji}, i = 1,2,\dots,N, j = 1,2,\dots,N$

$q^o \equiv heat\ flux\ vector$

$B_i = \varepsilon_i \sigma T_i^4, i = 1,2,\dots,N$

This system of equations is solved using the Newton-Raphson method to yield $\{q^o\}$. The values in the heat flux vector are then used to solve for the net radiation heat flux of the system for each iteration cycle; i.e.:

$$q_i^{net} = \varphi q_i^{k+1} + (1-\varphi)q_i^k, i = 1,2,\dots,N \qquad \text{5-8}$$

where:

φ = radiosity flux relaxation factor,

k = iteration number

The average radiation heat flux convergence value for this problem is set to be 0.1×10^{-3} W/m^2, meaning that when the difference between the kth +1 and the kth iterations is less than 0.1×10^{-3} W/m^2, the program considers the calculated radiation heat flux to be converged. Radiation transmittance is set between the specimen region and molybdenum foil irradiation mirror and between the annular graphite crucible and the thermocouple. Nominal emissivity values for each of the components are reported in Figure 5-7.

5.1.3 Mesh Optimization

The initial mesh scheme for OUTSET was generated by ANSYS Mechanical, which uses a tetrahedral element shape and "default" minimum element size. The Mechanical module within the transient analysis system receives a resolved part set from the Geometry module and Mechanical uses proprietary ANSYS algorithms to mesh all parts. Figure 5-8 shows the initial default mesh scheme produced by Mechanical. Notice the coarseness of the mesh in larger parts, especially the insulation and specimen region

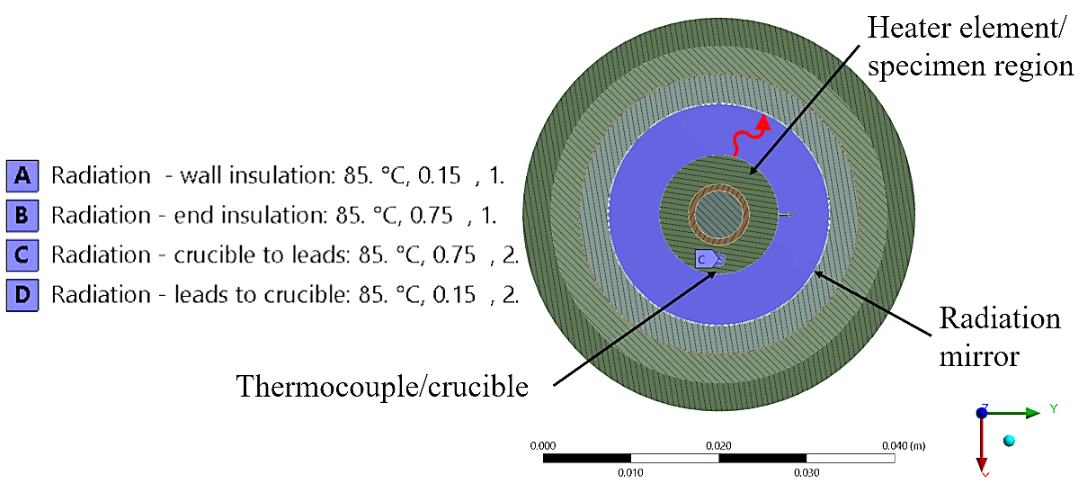


Figure 5-7. Radiation transport conditions for the OUTSET model with emissivity values [70].

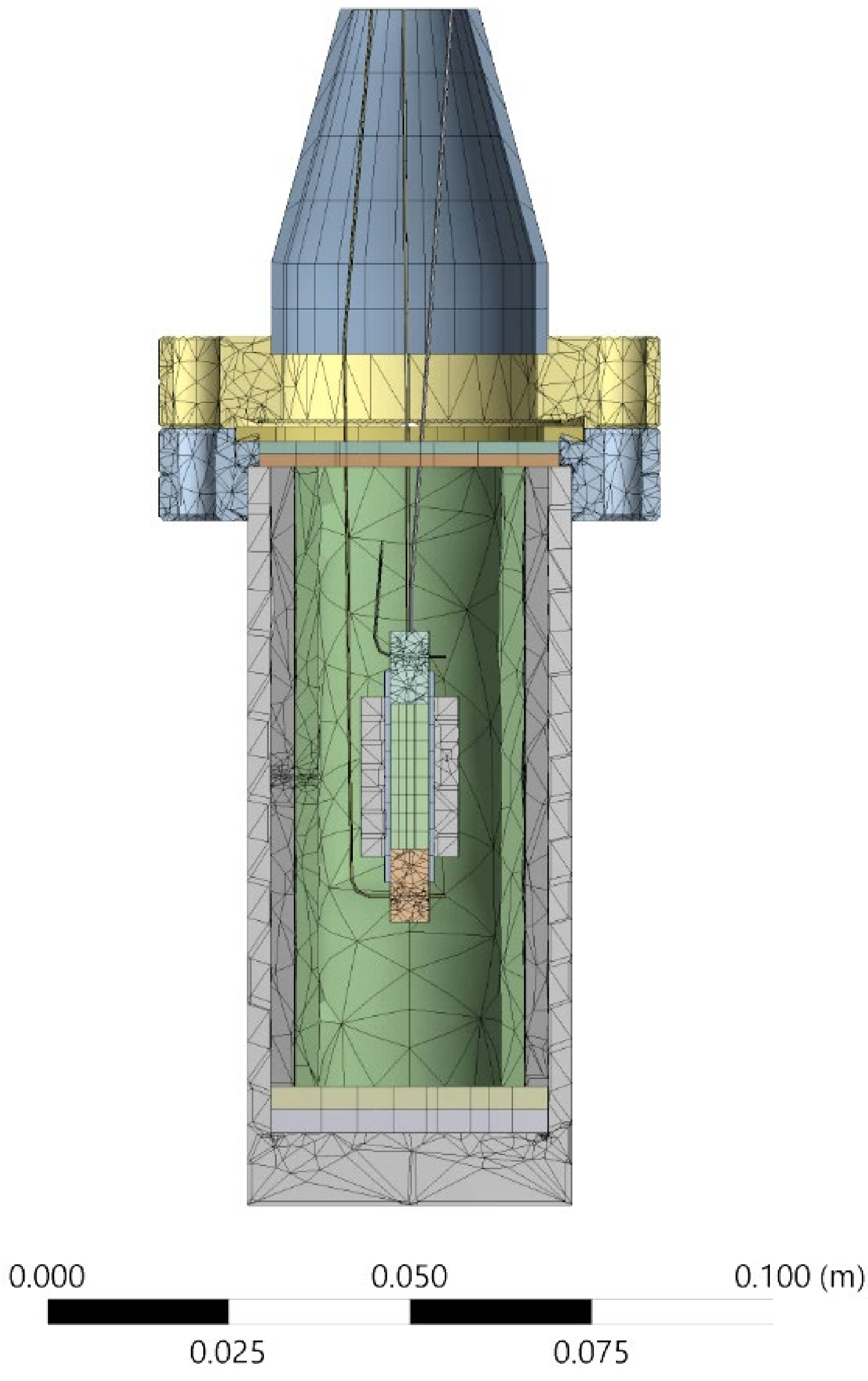


Figure 5-8. Initial OUTSET mesh scheme.

components. The 2-D simulation from Chapter 3 indicates that the temperature varies across these parts hundreds to thousands of degrees Celsius. Therefore, the mesh density in these parts required refinement to ensure the calculated steady state system temperature distributions are reliably predicted. This was achieved by gradually refining the mesh until the steady-state model temperatures stabilized. The following discussion describes how the mesh was optimized, and the final mesh will be presented at the end of this section.

Initially, the specimen region and insulation parts were meshed using a hex-dominant "brick" element shape and the lower order 2-D model was used to inform the refined element size for the parts. This approach turned out to be an ineffective approach because, as the element size decreased, the number of radiation heat transfer elements increased greatly. The outcome of this was a solution that took 50-70 hours to converge. Furthermore, the steady state converged specimen region temperature increased with every mesh refinement iteration.

ANSYS Mechanical uses the hemicube method to calculate 3-dimensional radiation view factors [71]. This approach is based on the Nusselt hemisphere, which demonstrates that any surface which covers identical areas on either a hemisphere or hemicube has the same view factor [72]. This method establishes an imaginary cube with 5 faces: one full face normally facing the Z direction, and 4 half faces oriented normal to the +X, -X, +Y, and -Y directions. These 5 faces are discretized into square pixels, set by the HEMIOPT APDL command that controls the hemicube resolution. For this analysis, the HEMIOPT was set to 10, which is the program default. See equation 5-9 for the discretized view factor equation for a surface, and Figure 5-9 for graphical representations of the hemicube method.

Equation 5-9, with N = 10, demonstrates that every surface (or in this case an element) has 10x5x5 hemicube surface with 300 pixels used to calculate view factors. These values are calculated and stored in a database to be used by the ANSYS heat transfer solution methods. The formulation of the discrete hemicube method sheds light on the potential for difficulty in solution convergence as a function of mesh density. The hemicube resolution is governed by the number of pixels on the surface of the hemicube shape [71].

$$F_{ji} = \sum_{n=1}^{N} \Delta F_n \frac{\cos\phi_i \cos\phi_j}{\pi r^2} \Delta A_j \qquad \text{5-9}$$

where:

N = number of pixels

ΔF_n= delta-view factor for each pixel

For geometries consisting of nested cylinders separated by a large gap, discrete view factors for a source element is proportional to $\frac{1}{r^2}$. For source and target elements that are separated by relatively large distances, the projection of the view factor is diminished. Cohen and Greenberg [72] state that view factor accuracy issues can arise "due to aliasing for small projections" and that "for very bright patches such as light sources, the effect of the inaccuracy can have a substantial deleterious effect", but the authors do not quantify the magnitude of the inaccuracy.

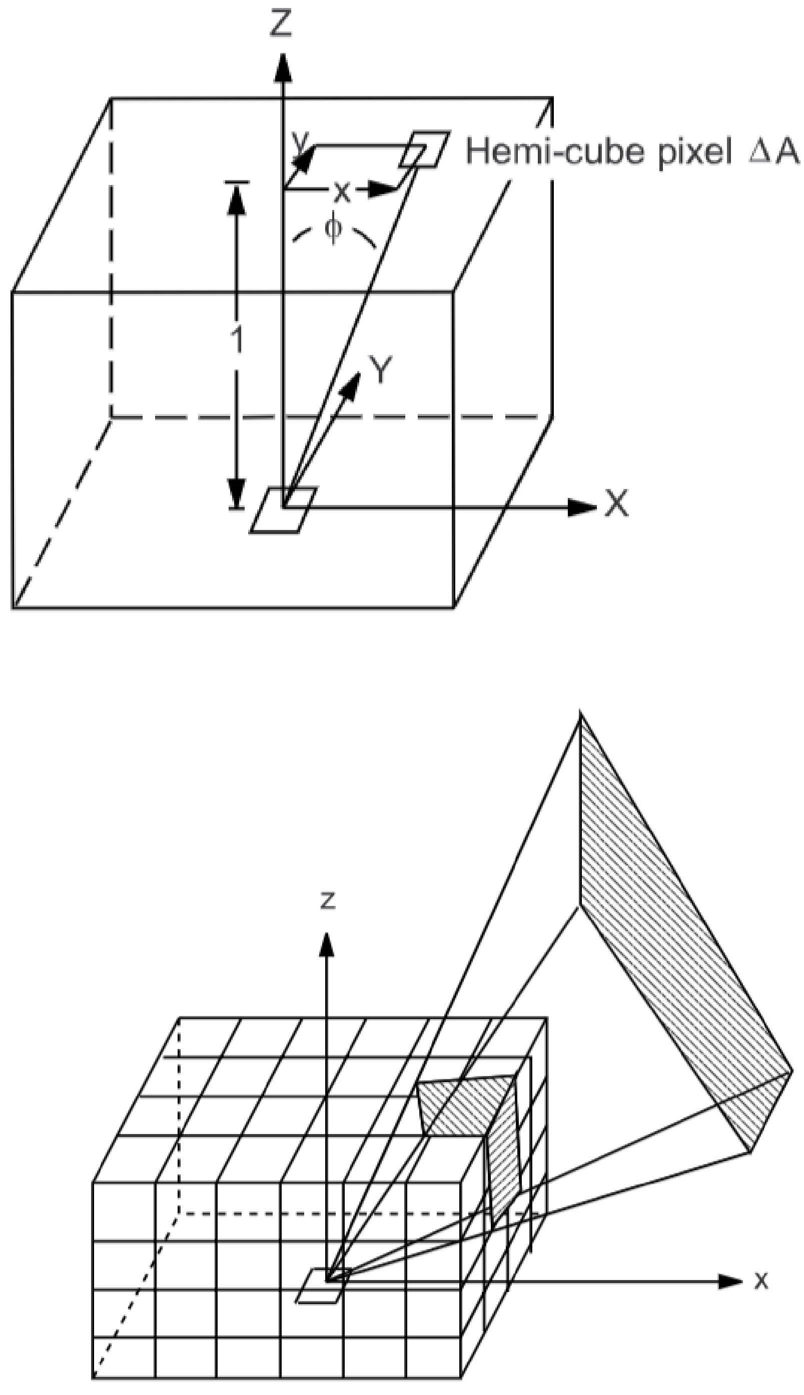


Figure 5-9. Graphical representation of the hemicube (top) and derivation of discrete view factors for the hemicube method (bottom) [71].

In order to counter these accuracy issues, a mesh scheme was developed that reduced small projection aliasing between specimen region and the inner wall of the molybdenum mirror, while also providing sufficient resolution in the radial direction. The two degrees of freedom for this scheme were the radial element thickness and the number of axial divisions for the insulation and mirror elements. The criteria for a converged mesh was to observe less than 0.1% change in average specimen region filament temperature while minimizing the product of the axial divisions and radial element size, N. Reducing the quantity N reduces the total number of radiation elements and improves solution times.

Figure 5-10 plots the filament temperature vs. N. The optimal parameters were found to be 6 axial divisions and 0.35 mm radial element thickness, N = 2.10. The element thickness constraint was also applied to the top and bottom insulation parts. The final mesh scheme for the model can be seen in Figure 5-11.

In order to verify the benefit of this meshing method, the heat flux error of the optimized mesh scheme was compared to the heat flux error from the earlier nonoptimized mesh scheme that employed cubic brick elements within the insulation region. These two insulation mesh schemes can be found in Figure 5-12. The heat flux error, which ANSYS reports to be unitless, was calculated using ANSYS provided numerical integration tools that sum the heat flux observed by a surface, and the optimal value is 0. The heat flux error of interest is associated with the specimen region surfaces; specifically, the crucible surface because it is susceptible to the most extreme aliasing for small projections. The average calculated steady state heat flux error for the optimized case is 1.886×10^{-4}, the average calculated steady state heat flux error for the nonoptimized mesh scheme was 1.223×10^{-3},

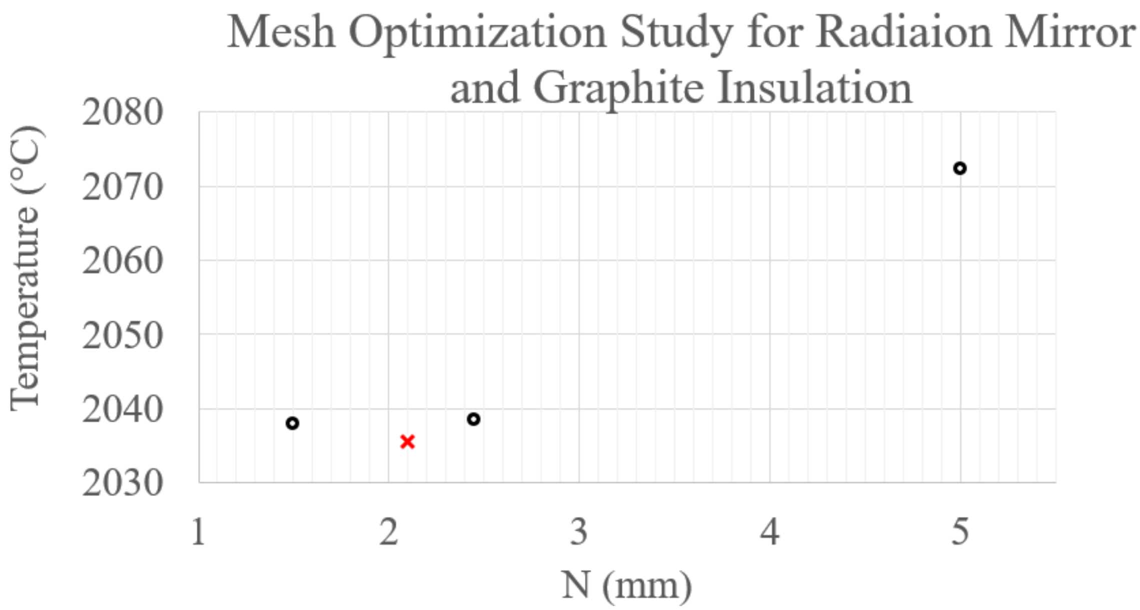


Figure 5-10. Mesh study output (final mesh parameter case N = 2.10 is denoted with red x).

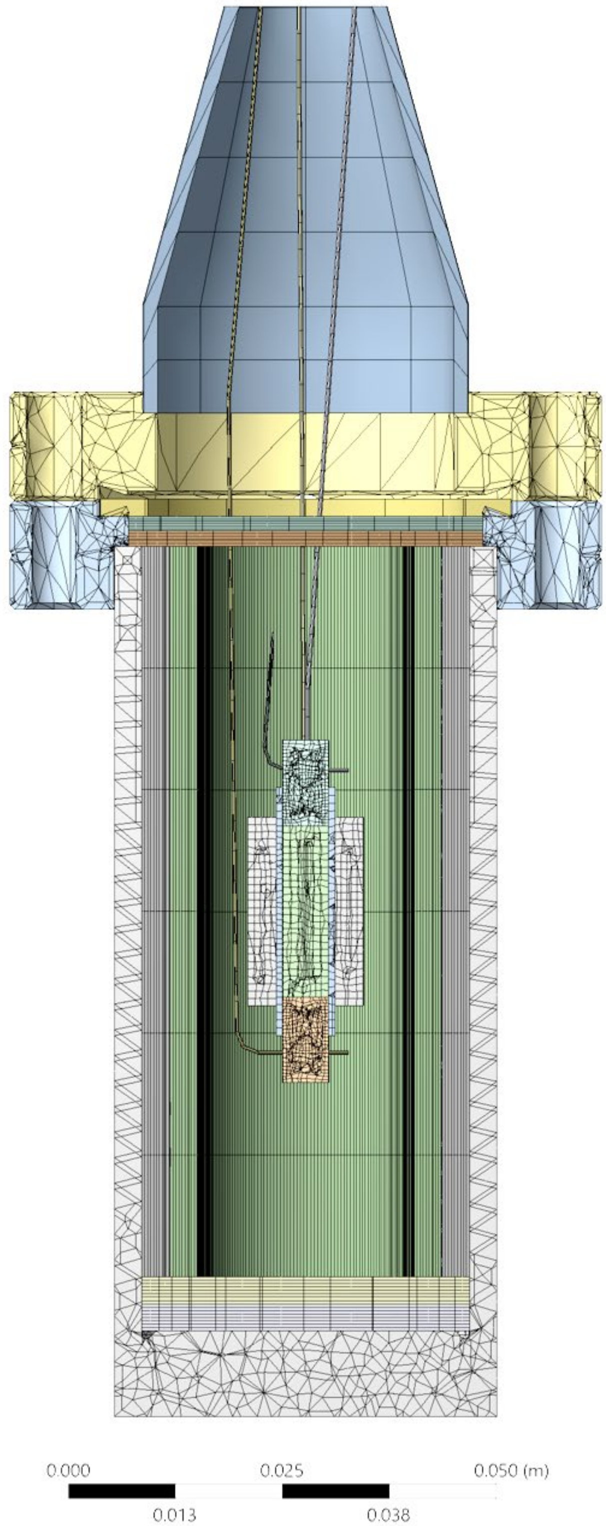


Figure 5-11. Final OUTSET mesh scheme.

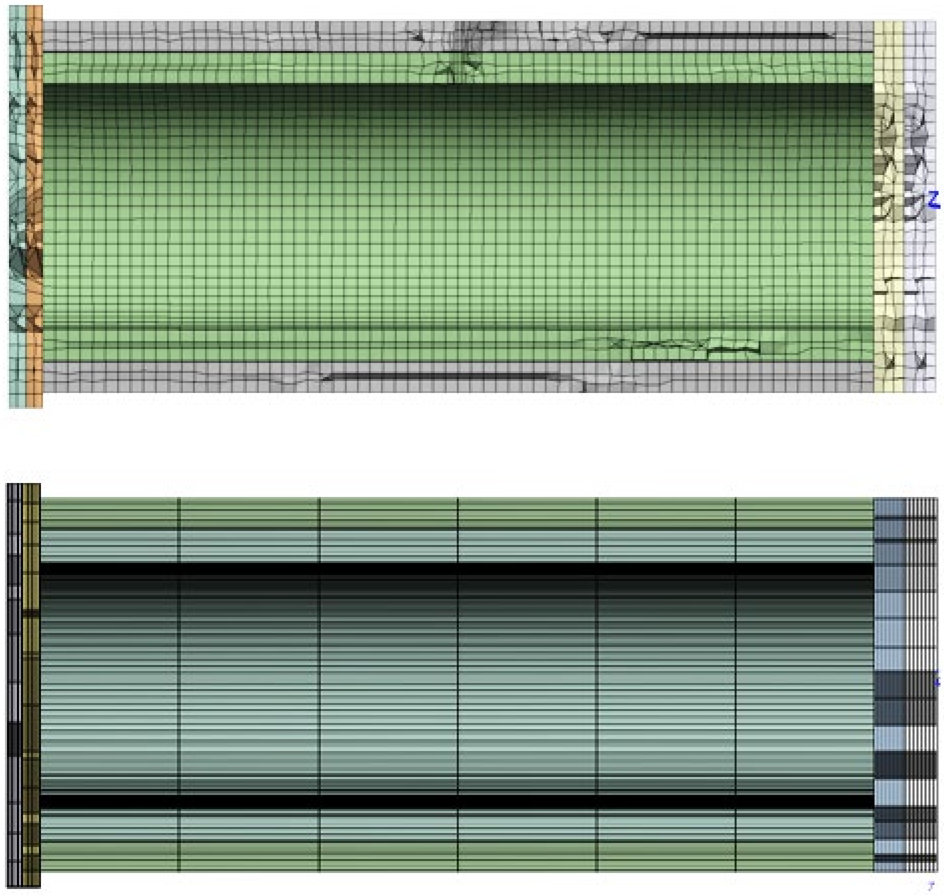


Figure 5-12. Comparison of the optimized insulation mesh (bottom) to the nonoptimized insulation mesh (top).

and the optimized mesh error is 15.3% of the nonoptimized case.

Further, the temperature drop between the filament surface to the crucible surface was calculated for both cases. The only heat transfer mechanism considered for these bodies in contact is conduction because ANSYS does not provide a mechanism to calculate intra-body radiation heat transfer. However, calculating the temperature drop across these bodies is useful because this quantity is proportional to heat flux. For the optimized mesh case, the temperature drop was calculated to be (2,345–1,970)°C = 375°C, and the temperature drop was calculated to be (2,425–2,101)°C = 324°C for the nonoptimized case. The relative difference between these two quantities is (375-324)/324 = 15.7%. The temperature drop for the nonoptimized case is also less than that of the optimized case, although both cases have the same power input and boundary conditions.

A final verification can be performed by comparing the temperature difference between the crucible surface and the inner surface of the molybdenum foil. For this case, thermal radiation is the dominant heat transfer mechanism and heat flux is proportional to ($T^4_{crucible}$ -T^4_{foil}). For the optimized and nonoptimized cases, these quantities are ($[1,970+273]^4$-$[1,932+273]^4$)K^4= 1.672×10^{12} K^4 and ($[2,101+273]^4$-$[2,061+273]^4$)K^4= 2.087×10^{12} K^4. The relative difference between these two quantities is 19.9%, which is on the order of the previous two calculated values. However, the radiation heat transfer case is highly nonlinear, and 0.5°C (~0.02%) changes in the temperatures of interest result in 1% changes in error.

5.2 Steady State Modeling Study

The OUTSET steady state model uses the geometry, meshing scheme, and input conditions described in previous sections. However, assigning material designations and thermophysical properties is required to complete the model. Material selection is for the steady state model is performed by associating user-defined material property data sets created in ANSYS Parametric Design Language (APDL). This association is performed by inserting a command snippet into each part instance, which allows the user to insert APDL commands within the Mechanical model, and manually set thermophysical properties for the instance. A set of technically reviewed APDL material property data sets, which are generated and used by the Nuclear Experiments and Irradiation Testing (NEIT) group at ORNL for creating thermally optimized experiments, were used for this purpose, and are referenced in Table 5-1. These property files are available upon request. Note, this approach is consistent with the lower dimensionality model.

The property data sets provide referenced, temperature dependent thermophysical property data for thermal conductivity and specific heat capacity, as well as single data points for density and molecular weight. This higher resolution data was chosen over the ANSYS supplied engineering data, which generally provides single data points for thermal conductivity and specific heat capacity, in order to establish potentially more accurate simulations. The material designations for all parts can be seen graphically in Figure 5-13, with each corresponding part set highlighted in green, and in the ANSYS summary report found in Appendix III.

Table 5-1. Thermophysical property assignments for OUTSET parts/components.

Material	Reference	OUTSET components
Stainless Steel	MAT_SS304.MAC [73]	Enclosure
Titanium	MAT_TI6AL4V.MAC [74]	Gettering foil
Molybdenum	MAT_MOLY.MAC [75]	Electrical lead wires and radiation mirror
Poco Graphite	MAT_POCO-GRAPHITE.MAC [76]	Specimen region crucible and graphite plugs
Tungsten	MAT_TUNGSTEN.MAC [77]	Thermocouple wires
Zirconia	MAT_ZRO2.MAC [78]	Specimen region electrical insulation tube
SIGRATHERM GFA Insulation	MAT_GFA-GRAPHITE.MAC*	Graphite insulation

*SIGRATHERM GFA Insulation uses the same graphite properties as Poco graphite except for thermal conductivity. This source data was digitized from Figure 3-4 [41].

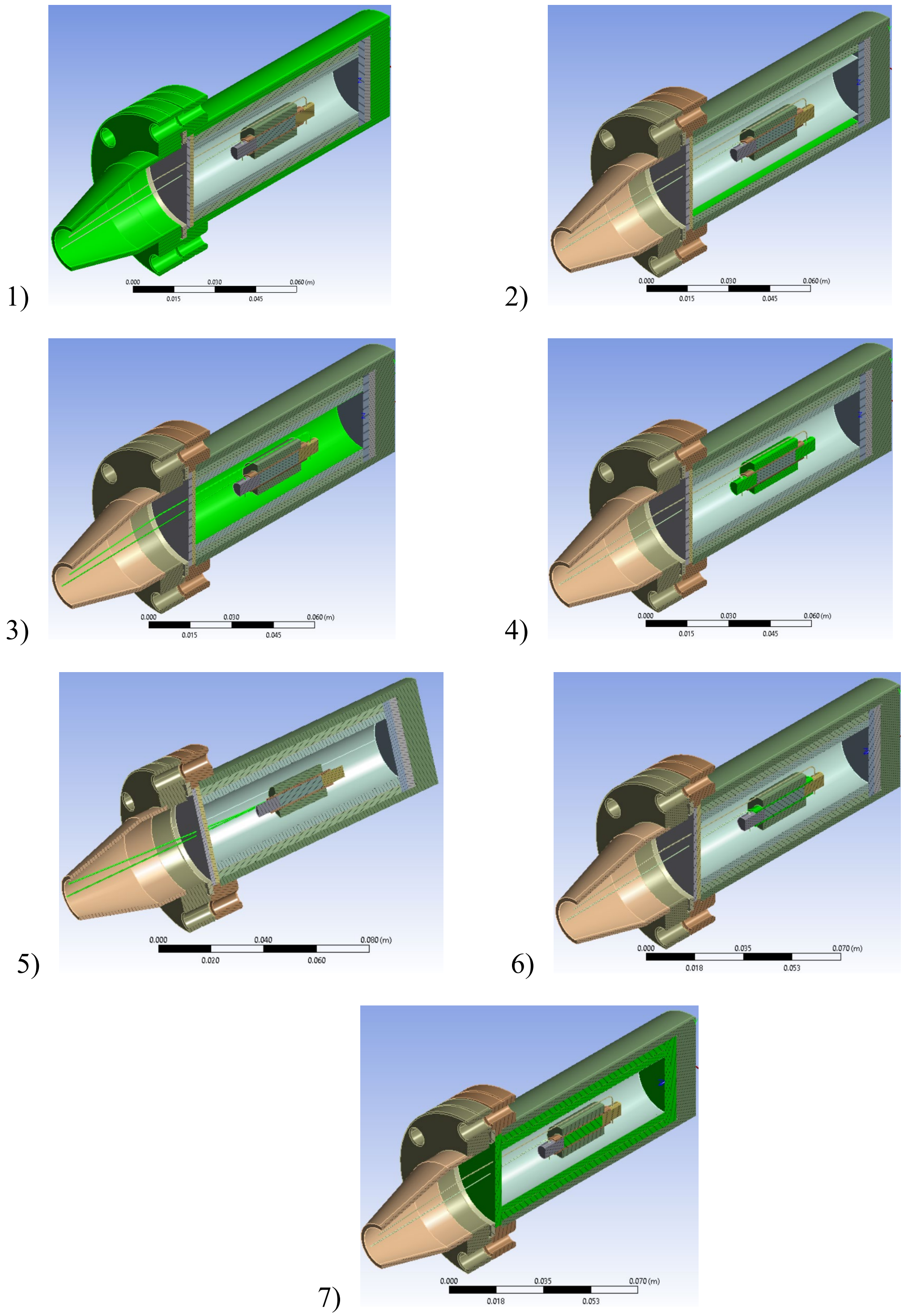


Figure 5-13. Material designations for OUTSET (highlighted in green): 1) stainless steel, 2) titanium, 3) molybdenum, 4) Poco graphite, 5) tungsten. 6) zirconia, 7) GFA insulation.

The OUTSET steady state model predicts temperatures for nominal conditions; i.e. 300W power input and conditions outlined in the previous section. However, the model was also set up to parameterize certain component conditions to perform basic sensitivity analysis discussed later in this dissertation.

The following components of the steady-state model were parameterized:

- Thermocouple and electrical lead boundary condition temperature (°C)
- Molybdenum mirror emissivity (unitless)
- Graphite felt insulation emissivity (unitless)
- Specimen region emissivity (unitless)
- Thermocouple and electrical lead emissivity
- Graphite insulation thermal conductivity perturbation (%)
- Thermocouple contact with the crucible (binary)

The nominal case parameters are defined in Table 5-2. Thermocouple and specimen region simulation outcomes using these nominal values are presented from Figure 5-14 through Figure 5-17. The thermocouple result of interest is located at the junction, which is circled in Figure 5-17, and corresponds to the thermocouple maximum temperature. The junction is inserted into a vertical hole located in the graphite crucible, as indicated in Figure 5-16. This part is electrically isolated from the from the specimen region filament by the zirconia insulator tube, as described in section 4.2.1. The minimum, maximum and average temperatures for these components are reported in Table 5-3. Note that the maximum thermocouple temperature is located at the instrument junction point, as indicated in Figure 5-17, and will be compared to OUTSET experiment thermocouple data.

Table 5-2. OUTSET analysis nominal case parameters.

Parameter	Value
Thermocouple and electrical lead boundary condition	175°C
Molybdenum mirror emissivity	0.15
Graphite felt insulation emissivity	0.75
Specimen region emissivity	0.75
Thermocouple and electrical lead Emissivity	0.15
Thermocouple contact with the crucible	on

Table 5-3. Temperature results for the higher dimensionality OUTSET finite element analysis.

Part	Material	Average Temp. (°C)	Minimum Temp. (°C)	Maximum Temp. (°C)	Melting Point (°C)
Specimen region filament	GFA graphite	2,297	2,040	2,360	3,650
Zirconia insulator	ZrO^2	2,141	1,932	2,358	2,700
Crucible	POCO graphite	1,978	1,924	1,997	3,650
Thermo-couple	W5%Re-W26% Re	N/A	N/A	1,988	3,422

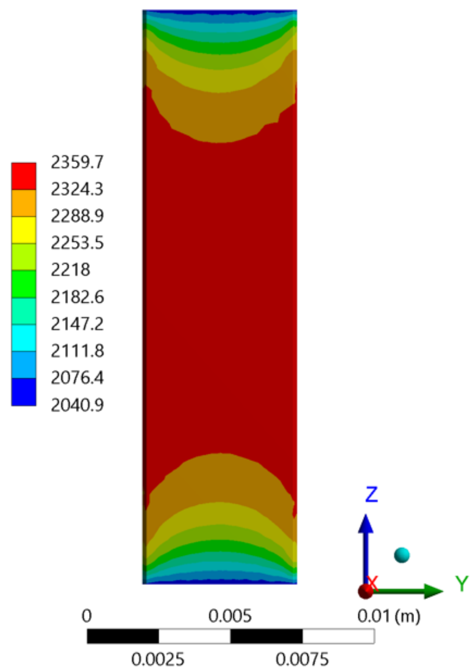


Figure 5-14. Specimen region filament temperature (°C)

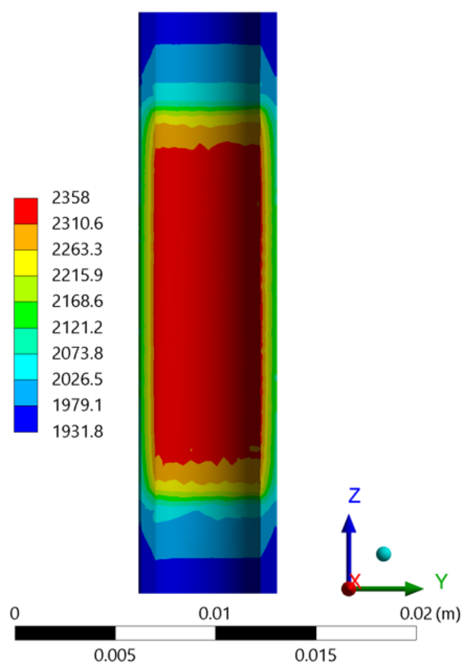


Figure 5-15. ZrO_2 insulator temperature (°C)

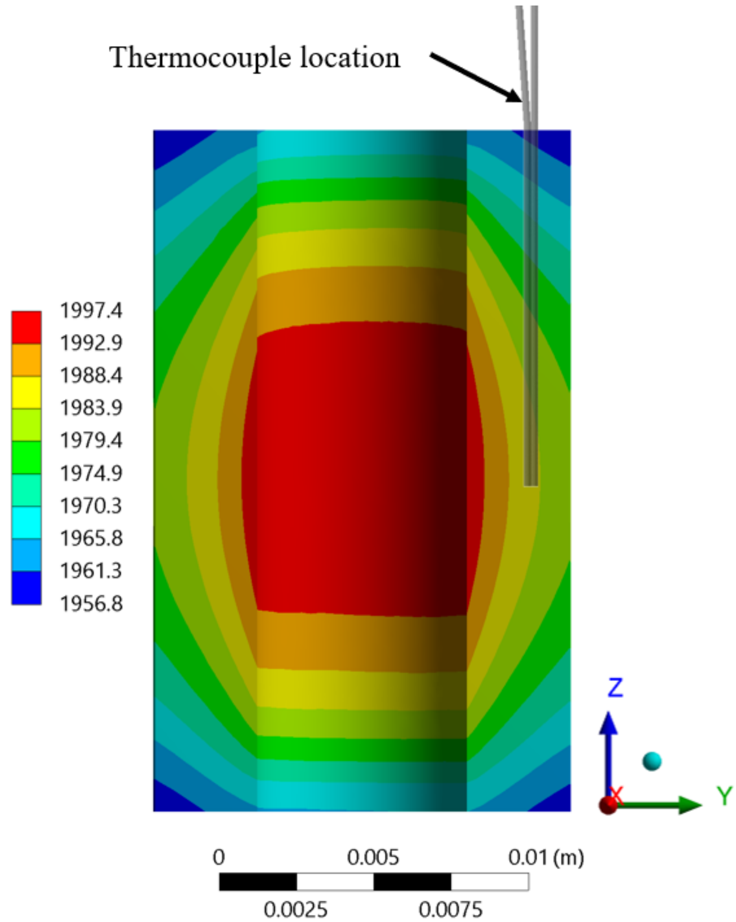


Figure 5-16. Graphite crucible temperature (°C)

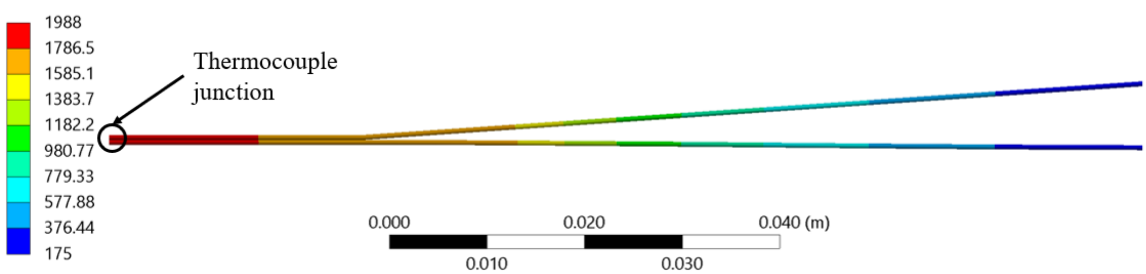


Figure 5-17. Thermocouple temperature (°C). Thermocouple junction coincides with the part maximum temperature and is indicated by the circled region (wire diameter is 0.381 mm).

Steady state heat flux maps of the OUTSET model are used to illustrate the direction and magnitude of the heat as it is transmitted from the specimen region. These maps also provide information about the heat transfer trends within the system which is used to identify model regions that may be sensitive to input parameters or boundary conditions. Figure 5-18 through Figure 5-22 show various vector heat flux maps of the OUTSET steady state model. Figure 5-18 shows peak heat fluxes are found in the molybdenum electrical lead wires, thermocouple wires (not shown in the cross-section view), and the specimen region. Figure 5-19 through Figure 5-21 focus on the specimen region and insulation. The specimen region is shown to emit heat asymmetrically within the thermocouple hole, as seen in Figure 5-21.

Demonstrating energy conservation within the model is important to demonstrate the accuracy of the calculation. This was practically achieved by multiplying the ANSYS calculated specimen region average heat flux by the outer surface area of the specimen region. This quantity is expected to be equivalent to the 300 W heat input. ANSYS reports the average specimen region heat flux as 1.885×10^{5} W/m^{2} and the specimen region outer surface area as 1.554×10^{-3} m^{2}. Therefore, the total heat being transferred from the specimen region is 293 W, which is 97.6 % of the total heat input. This 2.4% discrepancy will be addressed in Section 5.5

The same exercise was performed for the outer surfaces of the insulation to understand the distribution of heat between the outer surfaces of the insulation enclosure. The average heat flux total is 1.959×10^{4} W/m^{2} and the total outside surface area for the enclosure is 1.418×10^{-2} m^{2}, yielding a total heat load of 283 W. Note that the heat transmission in the molybdenum and tungsten wires were neglected for this calculation, which accounts for the heat load discrepancy. The top and bottom insulative surfaces account for roughly 30% of the total heat transfer, and the remaining heat transfers through the enclosure wall surface. This distribution points out a potential limitation in ANSYS, given that the program cannot account for spectral radiation heat transfer. Photons being emitted from the specimen region surface are expected to be scattered from the lower emissivity mirror to the higher emissivity top and bottom ends and be absorbed. The radiation heat transfer would be biased on those high emissivity surfaces. ANSYS cannot perform ray tracing calculations to accurately represent the photon transport physics. However, the program does accurately conserve energy sufficiently enough to produce converged solutions.

5.3 Transient Modeling Study

The transient model uses the nominal conditions also used by the steady-state model. All geometry, meshing, and input/boundary conditions are common between the transient and steady state models. However, there are differences between the property choices because the ANSYS transient solver clears the material property settings performed by the APDL scripting and replaces the user-defined data with default engineering data after the first time step calculation is completed. Therefore, all model parts were designated single point thermophysical properties for corresponding materials found in the ANSYS supplied engineering database except for the SIGRATHERM GFA insulation. A user-defined, temperature dependent property file was created and added to

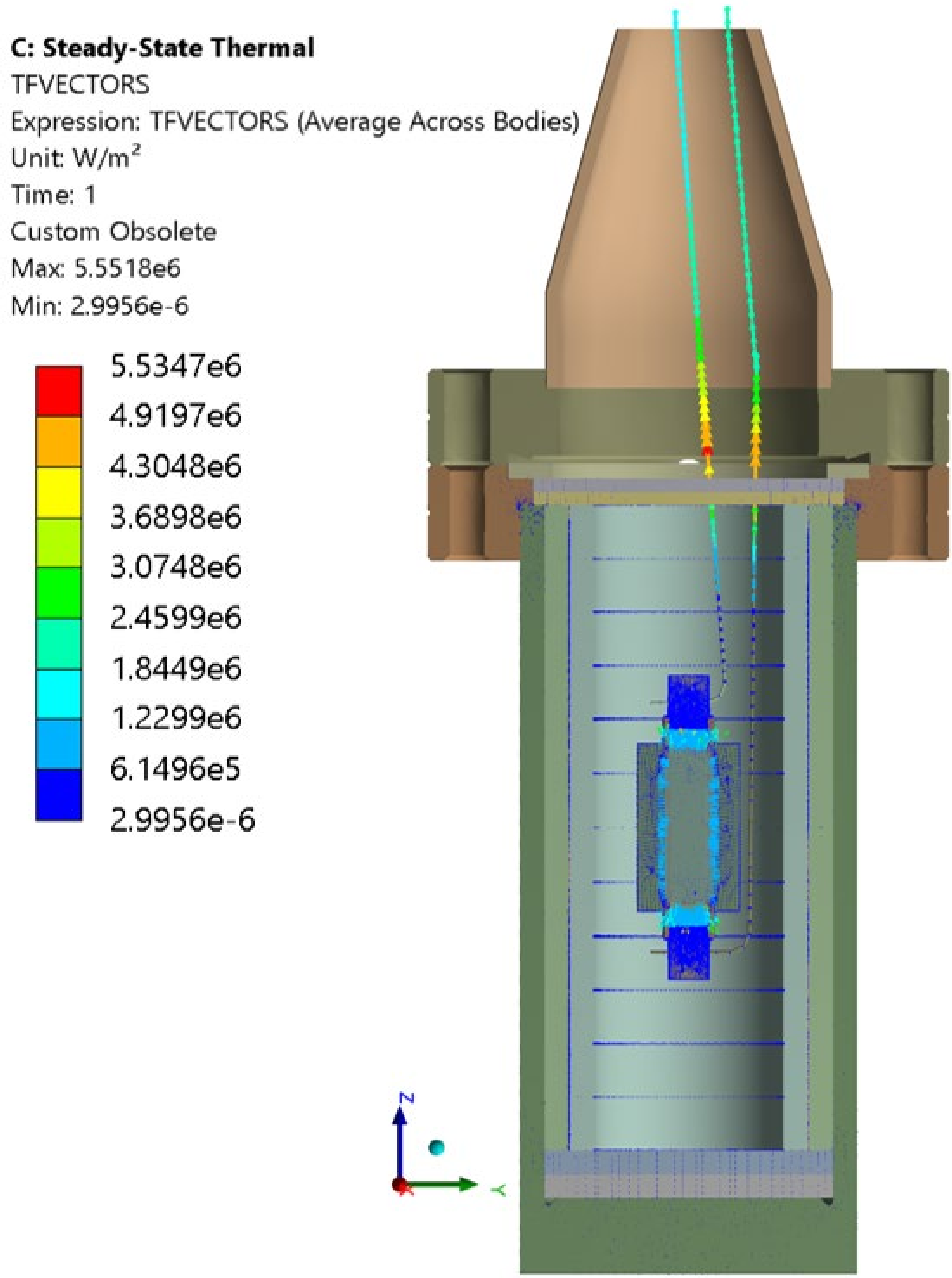


Figure 5-18. Vector heat flux of the OUTSET steady state model (cross-sectional view).

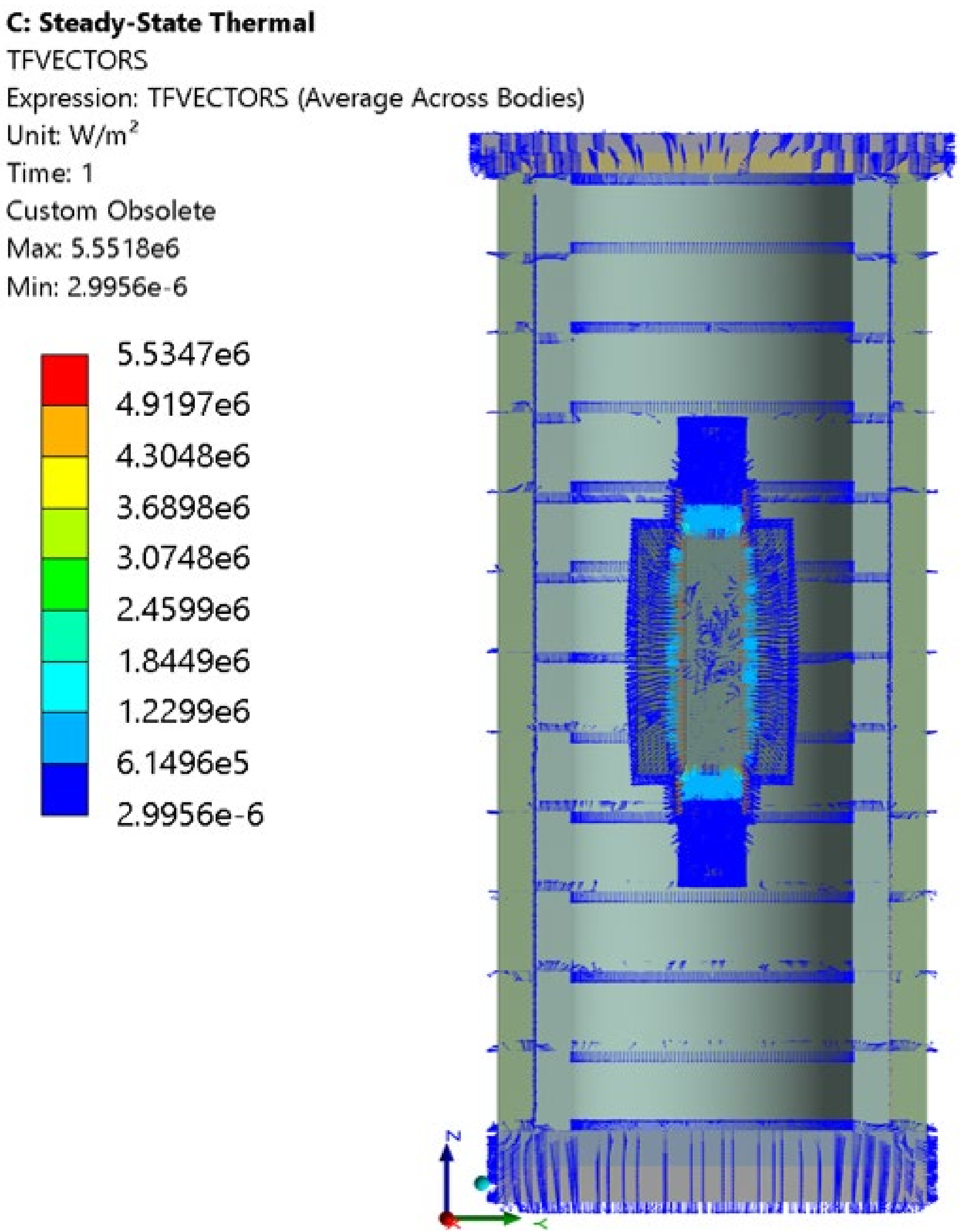


Figure 5-19. Vector heat flux of the OUTSET specimen region and GFA insulation (cross-sectional view).

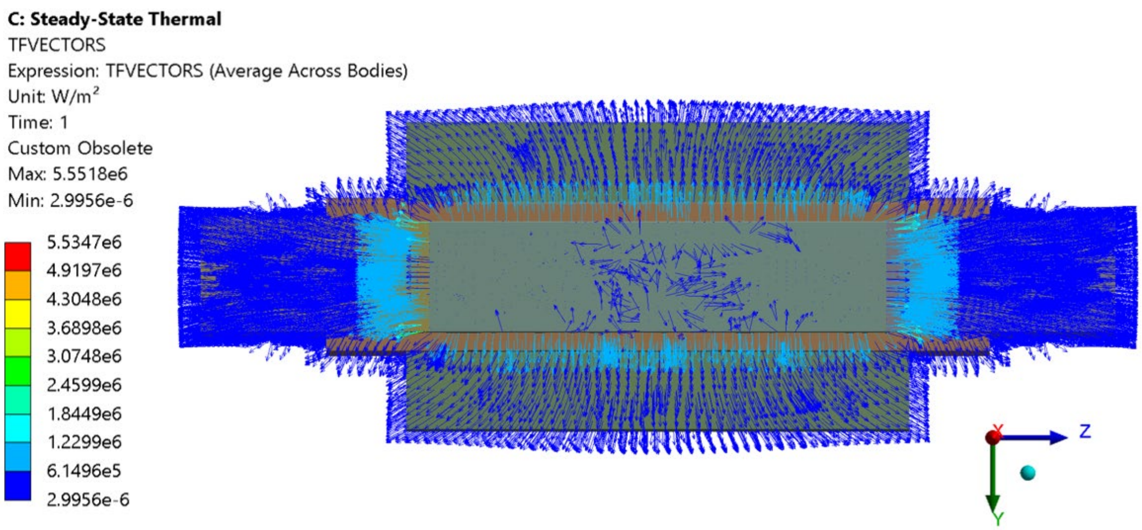


Figure 5-20. Vector heat flux of the OUTSET specimen region (cross-sectional view).

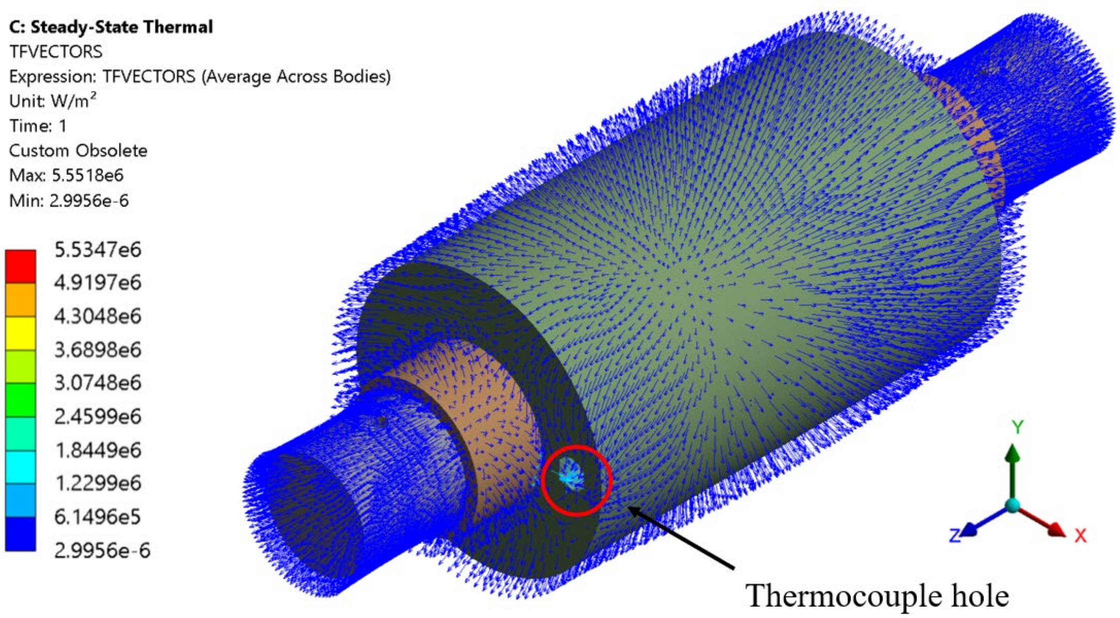


Figure 5-21. Vector heat flux of the OUTSET specimen region (isometric view).

the Engineering Database for this material because this material is expected to have such large temperature spans. A full list of the engineering data for the transient analysis can be found in the ANSYS summary report in Appendix IV.

Based on experience gained from OUTSET testing, the transient was set to run for a duration of 600 seconds. This timeframe was at least twice the length of time required for the thermocouple temperature to stabilize for OUTSET experiment heat-up transients. The transient analysis follows the same solution scheme as the steady state case, except for the fact that it is solving for multiple time steps. The minimum time step used for this simulation was 0.01s, and automatic time stepping was controlled within ANSYS. The output for the specimen region filament and thermocouple response calculated in the transient analysis can be seen in Figure 5-22. Note that the temperatures specimen region temperatures appear to reach constant values around 300 seconds.

5.4 Discussion of Results

The purpose of steady-state and transient models is to provide a design tool that accurately predicts future iterations of OUTSET. The steady state and transient analyses use a common set nominal parameters values, input conditions, and boundary conditions and produced results that matched performance trends of the OUTSET experiment thermocouple response data. The primary difference between the steady-state and transient simulations is that thermophysical properties used by the steady-state model provide temperature dependent data, whereas the transient model uses default single value thermophysical property data provided by ANSYS for all materials except the insulative graphite felt. The steady state case that uses higher resolution thermophysical property data yields an average specimen region filament temperature of 2,297°C and thermocouple response temperature of 1,988°C. The converged transient model yields an average specimen region filament temperature of 2,281°C and thermocouple response temperatures of 1,975°C. A comparison of these two cases shows less than a 1% difference between the converged transient and steady-state values. It seems that using lower resolution thermophysical property data provided by ANSYS, which yields faster solution times because it reduces convergence iterations, produces very good agreement with cases that use finer thermophysical property data. However, it is not recommended that this reduction in property resolution be applied to the GFA graphite insulation because of the large temperature spans observed in those parts. Both the transient analysis and steady state solutions took on the order of 8 hours to converge.

5.5 Model Validation

Model verification & validation (V&V) data are an important part of this work because it provides confidence that the model can accurately predict reality. The ASME Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer (V&V 20-2009) provides a recognized framework for performing V&V on the OUTSET model. Procedures within the V&V 20-2009 standard provide guidance on calculating both error (E) and validation uncertainty (u_{val}) quantities that are used to quantify "the degree of accuracy inferred from the comparison of solution and data for a specified variable at a specified validation point" [79]. V&V 20-2009 establishes that "in the validation process,

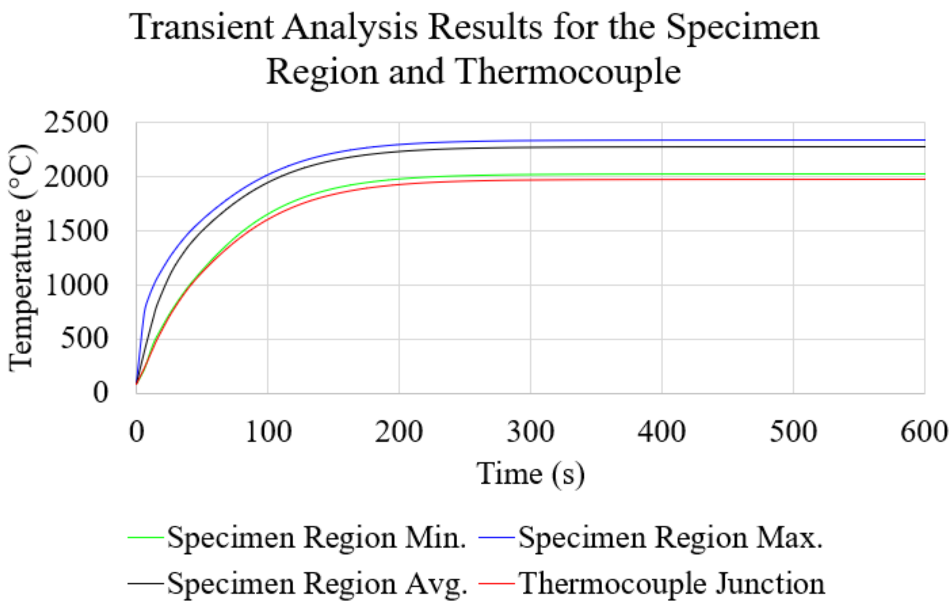


Figure 5-22. Transient analysis results for the specimen region filament and thermocouple response.

a simulation result (solution) is compared with an experiment result (data) for specified validation variables at a specified set of conditions (validation point)" [79]. Validation variables are gathered from three cases, and the OUTSET experiment falls into Case 1: the validation variable is directly measured. For the OUTSET experiment, the validation variable is thermocouple temperature ($T_{o,D}$). Specifically, the Sensitivity Coefficient Propagation Approach for Estimating u_{val} will be used for this work. The remainder of this section describes the calculation of error and uncertainty following the V&V 20-2009 Case 1 Sensitivity Coefficient Propagation Approach procedure. The PPPT2 experiment will be used as the specific validation variable data set, and the thermocouple response simulation results will be taken from the OUTSET analyses described earlier in this chapter. A schematic of the V&V 20-2009 Case 1 Sensitivity Coefficient Propagation Approach strategy can be found in Figure 5-23.

5.5.1 Calculating Error

The V&V 20-2009 standard defines the error as the difference between the nominal measured validation point (D) and the nominal tabulated simulation point (S). The error calculation for the OUTSET V&V work considers the experiment data set presented in Figure 5-24, in accordance with V&V 20-2009. The dataset, which corresponds to the PPPT1 experiment, only includes points where 12s ≤ t ≤ 252s. All data from 0 s ≤ t ≤ 11s are omitted from the set due to early time power ramping. Data after t = 252s is also omitted from the set and is considered to be nonrepresentative due to thermocouple response corruption from current leakage through the zirconia insulator. Refer to Section 4.2 for details on this phenomenon. Using sheathed, ungrounded thermocouples in future larger version of OUSET may alleviate the electrical shunting problem. The maximum calculated error is 62.8°C, minimum calculated error is -284.5°C, and the average error is 0.5°C. The minimum calculated error is clustered within a period of thermocouple instability and appears to be an outlier in the data set. This response was likely caused by the electrical shunt effect, as discussed earlier. The total error dataset is presented in Figure 5-24.

5.5.2 Evaluation of the Validation Uncertainty

Evaluating validation uncertainty is defined as [79]:

$$u_{val} = \sqrt{u_{T_{o,D}}^2 + u_{num}^2 + u_{input}^2}\ \{\%\} \qquad \text{5-10}$$

where:

$$u_{T_{o,D}} \equiv measurement\ uncertainty$$

$$u_{num} \equiv numerical\ uncertainty$$

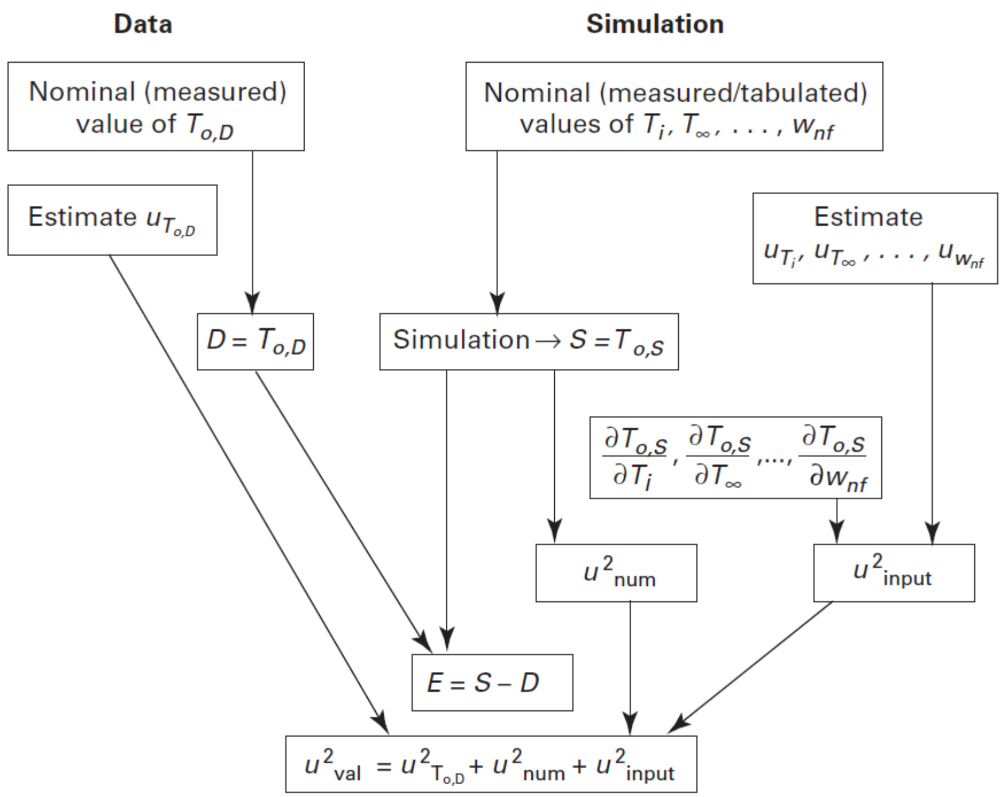


Figure 5-23. V&V 20-2009 Case 1 Sensitivity Coefficient Propagation Approach strategy [79].

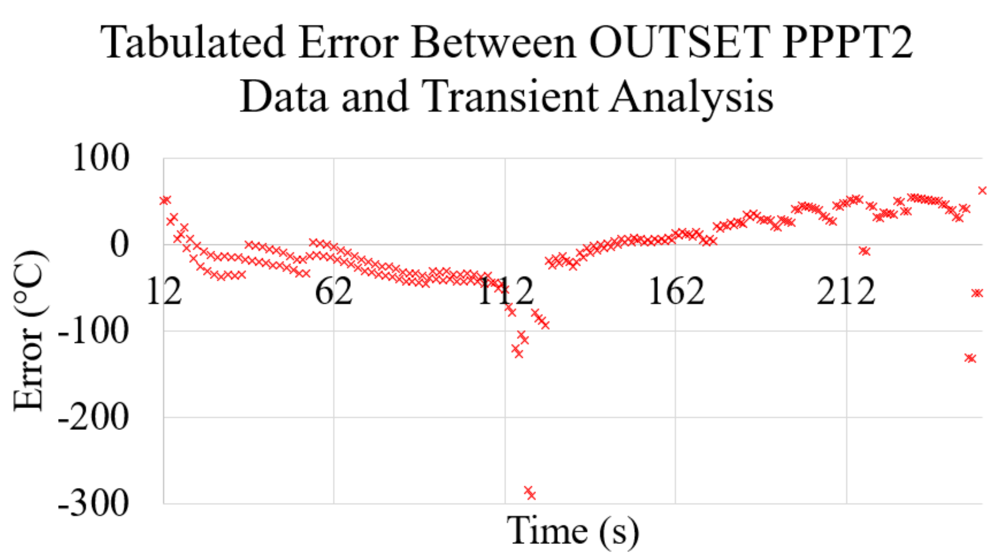


Figure 5-24. Tabulated error between the OUTSET PPPT1 data and the transient analysis.

$$u_{input} \equiv model\ input\ uncertainty$$

V&V 20-2009 formally defines the measurement uncertainty to be the square root of the sum of the squares of the systematic standard uncertainties for all independent error sources. For the OUTSET PPPT2 experiment, where the data are directly collected by a thermocouple, the systematic error is considered to be the fixed error of the type-C thermocouple and the calibration error of the Omega™ HH1384 thermometer. Omega™ reports the model T5R-015-12 type-C thermocouple has an accuracy of 1.0% over the temperature range from 0-2,330°C. The Omega™ HH1384 thermometer was calibrated at the ORNL metrology laboratory that organization reports a maximum error of 0.1%. Lastly, the error associated with thermocouple signal corruption at high temperatures is roughly 7.5 %. Therefore:

$$u_{T_{o,D}} = \sqrt{0.01^2 + 0.001^2 + 0.075^2} = 0.07567\ or\ 7.57\% \qquad \text{5-11}$$

V&V 20-2009 instructs that numerical uncertainty is quantified through code verification. ANSYS FEA software has been tested in detail and has a library of referenceable verification cases. Two verification cases that strongly relate the OUTSET analysis are "Radiation between Infinite Coaxial Cylinders" – case VM228 and "Thermocouple Radiation" – case VM107. Specific details for these cases are included in the ANSYS Mechanical APDL Verification Manual [80]. The VM107 case reports an agreement of 100% with benchmark data results and the VM228 case reports a minimum agreement of 95 % with benchmark data results. Therefore, the numerical uncertainty, u_{num} , is 5%. This quantity bounds the 2.4% discrepancy identified in Section 5.2

Model input uncertainty (u_{input}) for the OUTSET analyses are quantified by performing a sensitivity study on the steady state model thermocouple response to produce sensitivity coefficients by finite differences. These sensitivity coefficients are evaluated using independently perturbed input parameters that may affect the thermal performance of a model. This approach only takes the single parameters into account and no covariance of parameters were investigated. However, the ranges of perturbation were selected to account for temperature dependence, and correlation effects are not expected have a significant impact on the model performance beyond the cumulative effect of the individual parameters. For the OUTSET model, the input conditions include enclosure wall temperature, input power, material thermophysical properties, lead wire boundary temperature, power dissipation in lead wires, radiation heat transfer between bodies, and body-to-body contact resistance. This list is reduced to exclude specific heat capacity because this thermophysical property has no effect on a steady state model and thermal conductivity for all material excluding the GFA insulation.

The steady state model reports a 1,500°C temperature span across the insulation which is roughly an order of magnitude larger than any other parts. Therefore, it is decided that perturbing the insulation thermal conductivity outweighs all other thermal conductivity perturbations for the remaining materials. The only body-to-body contact considered is that between the thermocouple and the crucible. The model reflects the OUTSET experiment configuration; i.e. the model assumes that all parts that are intended to be in contact remain in contact for the duration of the analysis. However, it is difficult to verify that the thermocouple is in contact or remains in contact with the crucible over the duration of an experiment, so it must be assumed that the instrument either is in contact or it is not. Also, the specimen region flux map seen in Figure 5-21 shows that the model behaves asymmetrically as a consequence of inserting a thermocouple into the graphite annulus.

The enclosure wall temperature perturbed value is selected to be 40°C cooler than the nominal case based on the surface temperature uncertainty calculated in Chapter 5. The lead wire boundary condition was increased by roughly 45% to explore the effect that large boundary condition changes have on thermocouple response because of the high heat flux in the leads (see Figure 5-18) and the actual temperature is not well quantified. The material emissivity perturbations were selected in accordance with measured total and spectral emissivity bounds found in the literature [70] [81]. The GFA graphite insulation thermal conductivity was perturbed ±5% based on the standard deviation of thermal conductivity measurements made in vacuum by Chahine et al. [82].

The actual amount of electrical power being delivered to the specimen region is also not certain, due to the potential for Joule heating in the electrical circuit beyond the specimen region. Section 4.2.1 states that the specimen region has an electrical resistance of 1-2 Ω while at temperature. The 0.51mm diameter molybdenum electrical lead wire material has an electrical resistivity of roughly 2.5×10^{-3} Ω/cm. The length of wire used in each experiment is conservatively estimated at 25 cm, yielding a wire resistance of 0.06 Ω. Power is calculated as $P = I^2R$ and, assuming the maximum current of 15 A is being delivered to the experiment, the power being dissipated in the molybdenum wires is 14 W or 5% of 300W. Fourier's law of cooling states that heat input is proportional to temperature drop. Table 5-3 states the maximum temperature drop across the specimen region is 436°C. Therefore, perturbing the power input 5% to account for losses in the molybdenum lead wires produces a 22°C (-5.05%) reduction in temperature drop across the specimen region. This leads to a -1.11% reduction in the thermocouple temperature.

Radiation heat transfer between the molybdenum foil and the insulation is nominally neglected. This heat transfer mechanism is parameterized and is perturbed to either be off or on. Nominal emissivity values are used for this case.

Table 5-4 shows the nominal and perturbed values used for each case. The sensitivity study pertains to the steady state thermocouple response, so all input parameter perturbations are quantified by the change in thermocouple temperature. Table 5-5 summarizes the sensitivity study results, and the data are presented in Figure 5-25. The V&V 20-2009 standard defines model input uncertainty as:

$$u_{input} = \sqrt{\sum_{i=1}^{n} {\chi_i}^2 {u_{T_{o,D}}}^2} \tag{5-12}$$

where

$$\chi_i \equiv i^{th}\ sensitivity\ coefficient.$$

Therefore: 5-13

$$u_{input} = \sqrt{0.07567^2 \begin{bmatrix} (-.0201)^2 + (.0015)^2 + (.0026)^2 \\ +(-.0146)^2 + (-.0014)^2 + (.0015)^2 \\ +(.0468)^2 + (-.0111)^2 + (-.1217)^2 \end{bmatrix}}$$

$$u_{input} = 0.01008\ or\ 1.01\%$$

Table 5-4. Steady-state OUTSET model input parameter nominal vs. perturbed cases values.

Parameter	**Nominal Case**	**Perturbed Value**
Enclosure wall temperature	85°C	45°C
Lead wire boundary condition temperature	175°C	250°C
Molybdenum mirror\ Lead wire emissivity	0.15	0.19
Graphite\GFA felt insulation emissivity	0.75	0.80
Graphite insulation thermal conductivity perturbation	100%	105%/95%
Thermocouple contact with the crucible	on	off
Power reduction due to lead wire resistance	300 W	286 W
Molybdenum mirror transmission to insulation	off	on

Table 5-5. Summary of sensitivity study for model input uncertainty quantification.

Input Parameter	**Nominal case**	**Perturbed Case**	**Difference**	
	°C	**°C**	**°C**	**%**
Enclosure wall temperature	1,988	1,948	-40	-2.01
Lead wire boundary condition temperature		1,991	3	0.15
Molybdenum mirror\ Lead wire emissivity		1,983	-5	0.26
Graphite\GFA felt insulation emissivity		1,959	-29	-1.46
Graphite insulation thermal conductivity perturbation (105%)		1,985	-3	-0.14
Graphite insulation thermal conductivity perturbation (95%)		1,991	3	0.15
Thermocouple contact with the crucible (off)		1,895	-93	-4.68
Power reduction due to lead wire resistance		1,966	-22	-1.11
Molybdenum mirror transmission to insulation		1,746	-242	-12.17

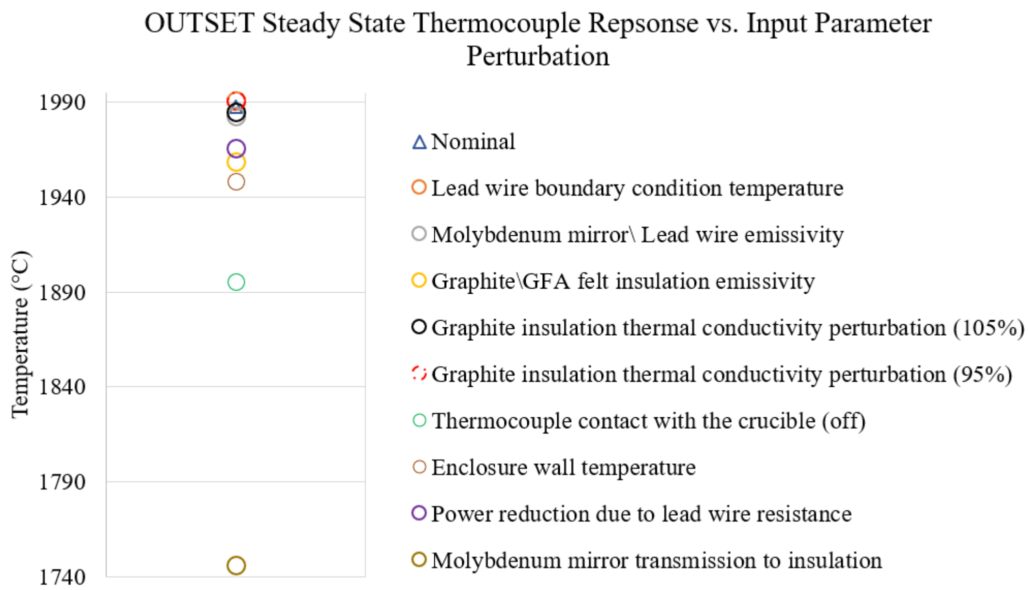


Figure 5-25. Predicted thermocouple response for various parameter perturbations.

From equation 5-10, the OUTSET modeling validation uncertainty is calculated in the following expression. The OUTSET transient model estimated uncertainty is plotted against OUTSET PPPT1 and PPPT2 experiment data in Figure 5-26.

$$u_{val} = \sqrt{u_{T_{o,D}}^2 + u_{num}^2 + u_{input}^2} = \sqrt{0.07567^{\,2} + 0.05^{\,2} + 0.01008^{\,2}}$$

$$u_{val} = 0.091 \; or \; 9.1\%$$

It should be noted that the sensitivity study remains incomplete. Specifically, the author acknowledges that the employed approach to calculating radiation heat transfer relies on the assumption that the values of emissivity for the various components are dependent only on temperature. This assumption is somewhat non-physical because it neglects the specular and angular dependence of the photon emissions within the enclosure. Given that the inner plenum of the experiment is not completely lined with reflective molybdenum foil and the top and bottom felt pieces are exposed to the specimen region, the radiation heat transfer has an inherent angular dependence. Moreover, the potential for oxidation of the reflective materials caused by moisture or oxygen that is volatilized during the experiment was not considered while modeling OUTSET. This phenomenon may occur and will have an impact on the spectral emissivity values of these materials. These impacts could not be explicitly modeled, given ANSYS can only accept an average temperature dependent emissivity. ANSYS also cannot perform ray tracing in a highly reflective photon rich environment. This limitation may lead to inaccurate handling of the radiation heat transfer at the top and bottom of the experiment plenum where surfaces have higher values than the plenum wall. Emissivity perturbation was included in the sensitivity

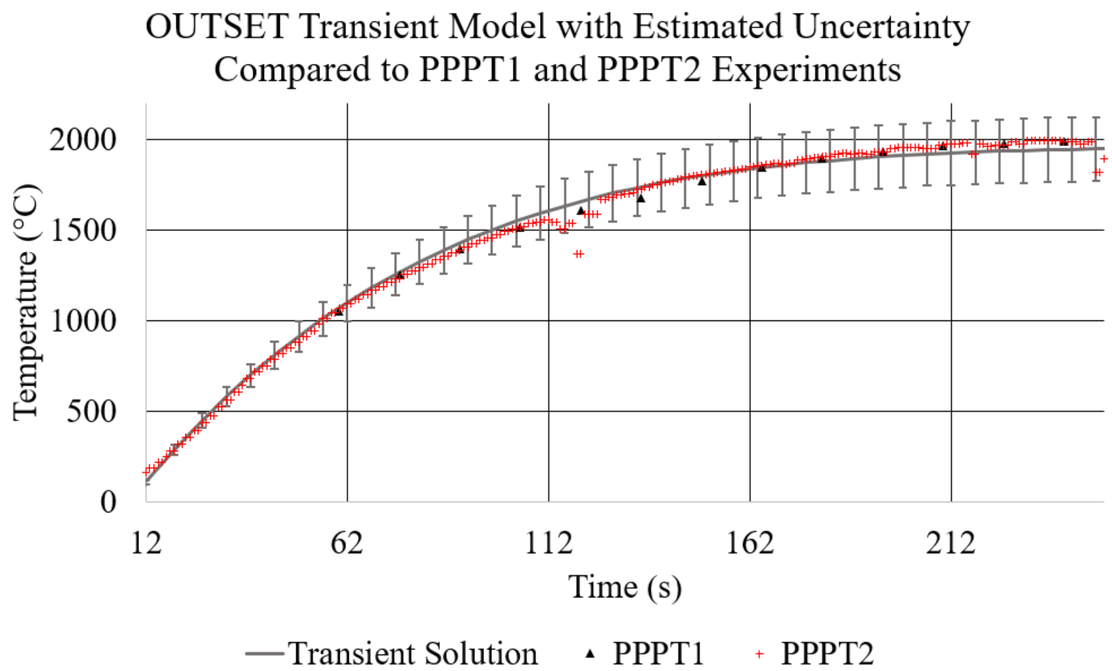


Figure 5-26. OUTSET transient model with estimated uncertainty compared to PPPT1 and PPPT2 experiment data.

study to attempt to account for these shortcomings, but explicit uncertainty for these physics were not fully explored in this study. It is recommended that a more in-depth study be performed to investigate the effects that specular and angular have on the thermal performance of OUTSET.

CHAPTER 6.
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This document describes a strategy for testing high-temperature fuels to support NTP fuel qualification. This strategy is comprised of three phases that include establishing an experiment design basis, called OUTSET, that can be thermally tested to validate models for designing and predicting the performance of experiments. The first phase is followed by designing and deploying in-pile reactor tests that will expose potential fuel candidates to prototypic NTP conditions and irradiate sub-scale fuel samples to obtain thermophysical property and mechanical testing data. The final phase transitions to full-scale reactor tests that expose full-scale prototypic fuel geometries to prototypic NTP conditions. Baseline design requirements for OUTSET are established as part of this dissertation. These requirements were used to fabricate and assemble the initial version of OUTSET. This apparatus was tested under various power conditions; and the Peak Power Peak Temperature series of these tests were used to generate benchmark thermal performance data. The data were predominantly generated by instrumenting the specimen region with a type-C thermocouple, but melt wires were incorporated into the specimen region to establish confirmatory minimum achieved temperatures, and a SWIR camera was unsuccessfully used to gather specimen region surface temperatures. An OUTSET finite element model capable of predicting steady-state and transient thermal performance was also developed and validated in accordance with ASME V&V 20-2009 as part of this work.

OUTSET is intended to be analogous to other non-radiological facilities, such as CFEET and NTREES, and will provide key capabilities for performing separate effects testing to rapidly down-select or qualify NTP fuels and components. However, the current version of OUTSET has only been demonstrated to operate under vacuum conditions. Future designs must incorporate the ability to deliver inert gas and hydrogen gas to the specimen region. As OUTSET transitions to an in-pile testing experiment, CFEET and NTREES will manage most of the out-of-pile testing portion of the strategy and stream optimized fuel forms to the in-pile iteration of OUTSET to fulfill the second phase of the testing strategy. Historically, this level of fuel/component qualification was performed by building prototypic reactors or nuclear furnaces. The testing strategy proposed in this dissertation can reduce project risk and lead to a more efficient fuel qualification process that are essential for the success of future NTP technology.

Almost nothing has been accomplished along the line of developing sub-scale in-pile irradiation experiments that can reach NTP conditions. The work detailed here intends to demonstrate such a platform to pioneer lower risk sub-scale experiments. Other contributions to the current state-of-the-art include:

- The development of an out-of-pile experiment that meets programmatic requirements.
- Low-cost DC electrical specimen region heating design that is able to heat specimens to NTP temperatures with 300 W of electrical power.
- A reliable set of preliminary thermal performance data that can be used to benchmark designs in support of future phases of the NTP fuel testing strategy.

The DC electrical specimen region heating design is particularly noteworthy. High-temperature resistant zirconia insulators, solid graphite, and graphite felt were used to devise a compact electrical specimen region that is capable of producing centerline temperatures in excess of 2,200°C. This approach to delivering power to OUTSET specimen is beneficial because the heat transfer characteristics are independent of specimen material which makes the OUTSET design versatile. Note that this work did not incorporate surrogate specimen material into OUTSET and that the development and testing of OUTSET was intended to demonstrate its feasibility and to generate data to validate design models for future in-pile tests. The heating concept has wide-ranging applications for other high-temperature experiment applications that include molten salt reactor component testing and commercial high-temperature furnace heater element design. Currently, this work has yielded two ORNL invention disclosure submissions and preliminary actions are being taken to patent some of the heating design technology.

Creating in-pile experiment facilities that are capable of subjecting fuel candidates to prototypic NTP conditions is of great interest to the NASA led domestic nuclear thermal propulsion program. National laboratories within the Department of Energy complex are working to develop experiment facilities that are compatible with the existing domestic research reactors. Operation of Transient Reactor Test (TREAT) Facility, located at the Idaho National Laboratory, was resumed 2018. At the time of this writing, engineers and researchers are working to design and qualify in-pile testing capabilities at a larger scale for the (TREAT) Facility in support of NTP fuel qualification.

6.1 Future Work

There are several areas of OUTSET development that deserve more attention, including:

- Establish a secondary loop within the specimen region to provide the crucial capability to impart hydrogen gas on the NTP specimen,
- Further improvement of prototypic NTP temperature resistant electrical connections for the specimen region,
- Troubleshooting and development of a more robust optical system for performing non-contact temperature measurements,
- Expanding the OUTSET design to allow for larger samples and different heat transfer mediums (i.e. inert fill gases),
- Perform preliminary radiological tests with fuel surrogates to verify in-pile OUTSET performance.

While the primary goal of phase 1 of the fuel testing strategy is to establish an in-pile experiment format which derives its power source from fission, OUTSET has many other out-of-pile applications that require reliable electrical heating. A more robust electrical connector that is capable of withstanding power impulses should be developed. Alternate materials and electrical lead configurations should also be investigated due to the embrittlement that was observed in the refractory metals as a result of a perceived reaction with volatilized oxygen and/ or moisture entrained in the experiment. Potential improvements include identifying more stable electrical resistor materials that do not volatilize or release entrained oxygen that will react with the refractory metals at elevated temperatures. This effect may also be alleviated by employing a better vacuum system that can remove entrained contaminants prior to starting experiment trials. Also, improving the electrical lead configuration to establish a positive connection with the heater filament will improve the reliability of the electrical heating circuit.

Chapter 4 described an optical temperature measurement system that uses a SWIR camera to perform no-contact surface temperature measurements of the OUTSET graphite crucible. However, there were some discrepancies between the SWIR measurements and the thermocouple data that must be reconciled. Troubleshooting of these discrepancies was halted after the initial tests were completed because the development of such an optical system was beyond the scope of this project. However, at the time of this writing, the author is working to obtain funding to further develop the SWIR camera system to make non-contact measurements. This work is required to instrument experiments supporting in-pile phases of the testing strategy, given the documented issues associated using type-C thermocouples in high neutron fluence applications [44], because they tend to decalibrate as a function of material transmutation in a neutron field.

The current version of OUTSET is only capable of handling samples on the order of 3.0 mm diameter x 3.0 mm, maximum. This form factor is selected to accommodate specimens designed for gathering mechanical and thermophysical property data. Other NTP technology development applications such as NTP instrumentation may require a more flexible sample region. Dimensionally up-scaling OUTSET to allow for larger specimen geometries will lead to increased power requirements to achieve prototypic NTP temperatures. Consequences of this change include an increased heat sink capacity and power delivery systems. While the heat transfer characteristics of a larger system are generally identical to the current OUTSET design, the current set assumptions made may not hold true for a larger water-cooled experiment.

OUTSET is intended to yield in-pile experiments to perform radiological tests on NTP fuels. The version of OUTSET described in this work was designed to be compatible with water-cooled research reactor environments. However, the radiation performance of the SIGRATHERM GFA insulation has yet to be demonstrated in-pile. At the time of this writing SGL Group, the graphite felt manufacturer, had no referenceable nuclear performance data for the insulation. Performing reactor tests to understand the potential degradation of thermal conductivity as a function of temperature and neutron fluence is necessary to ensure the reliability and predictability of in-pile versions of OUTSET.

BIBLIOGRAPHY

[1] S. K. Borowski, D. R. McCurdy and T. W. Packard, "Nuclear thermal rocket (NTR) propulsion: A proven game-changing technology for future human exploration missions," in GLEX-2012.09.4.6x12341, Washington, DC, 2012.

[2] The National Aeronautics and Space Administration, "NASA Technology Roadmaps TA 2: In-Space Propulsion Technologies," NASA, 2015.

[3] J. M. Napier, "NERVA FUEL ELEMENT DEVELOPMENT PROGRAM SUMMARY REPORT - JULY 1966 THROUGH JUNE 1972, Extrusion Studies," Oak Ridge Y-12 Plant, Oak Ridge, Tennessee 37830, 1973.

[4] S. K. Borowski, "Nuclear thermal rocket workshop reference system Rover/NERVA," Cleveland, OH, 1991.

[5] National Space Policy of the United States, 2010.

[6] K. M. Benensky and A. L. Qualls, "A Preliminary Nuclear Thermal Propulsion Fuel Qualification Plan," Oak Ridge National Laboratory, ORNL/LTR-2017/119, Oak Ridge, TN, 2017.

[7] M. E. Stewart and B. G. Schnitzler, "A Comparison of Materials Issues for Cermet and Graphite Based NTP Fuels," in AIAA Annual Joint Propulsion Conference, San Jose, CA, 2014.

[8] T. Knight and S. Anghaie, "Processing of pseudo-ternary carbide fuels for high temperature space nuclear reactors," in AIP Conference Proceedings, Albuquerque, New Mexico, 1999.

[9] H. Ludewig, M. Todosow, P. Montanez and P. Bezler, "Preliminary study of impact of fuel options on performance of Nuclear Thermal Propulsion (NTP) concepts," in AIP Conference Proceedings, Albuquerque, New Mexico, 2002.

[10] L. L. Lyons, "Performance of (U,Zr)C-Graphite (Composite) and of (U,Zr)C (Carbide) Fuel Elements in the Nuclear Furnace 1 Test Reactor," Los Alamos Scientific Laboratory, LA5398-MS, Los Alamos, NM, 1973.

[11] G. Krueger, "A cermet fuel reactor for nuclear thermal propulsion," NASA, 19920001878, 1995.

[12] W. Robbins and H. Finger, "An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program," NASA Contractor Report 187154, AIAA-91-3451, 1991.

[13] W. L. Kirk, "Nuclear Furnace-1 Test Report," Los Alamos Scientific Laboratory, Los Alamos, NM, 1973.

[14] Aerojet Nuclear Systems Company, "Induction Graphitizing Furnace Acceptance Test Report," Aerojet General, N73-24599, Azusa, CA, 1972.

[15] D. G. Pelaccio and M. S. El-Genk, "A Review of Nuclear Thermal Propulsion Carbide Fuel Corrosion and Key Issues.," New Mexico University Inst. for Space and Nuclear Power, Albuquerque, NM, 1994.

[16] R. Haslett, "Space Nuclear Thermal Propulsion Program Final Report," Grumman Aerospace Corporation, Bethpage, NY 11714, 1995.

[17] G. C. Allen, "Space Nuclear Thermal Propulsion Tests," in Nuclear Propulsion Technical Interchange Meeting, Cleveland, OH, 1992.

[18] W. J. Emrich, "Initial Operation and Shakedown of the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)," in AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, 2014.

[19] J. Busby and K. Leonard, "Space Fission Reactor Structural Materials: Choices Past, Present and Future," The Journal of The Minerals, Metals & Materials Society, vol. 59, no. 4, pp. 20-26, 2007.

[20] World Nuclear Association, "Research Reactors," October 2017. [Online]. Available: http://www.world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/research-reactors.aspx. [Accessed December 2017].

[21] D. Bedsun, D. Lee, M. Townsend, C. A. Cooper, J. Chapman, R. Samborsky, M. Bulman, D. Brasuell and S. K. Borowski, "Ground Testing a Nuclear Thermal Rocket: Design of a sub-scale demonstration experiment," in Joint Propulsion Conference, Atlanta, GA, 2012.

[22] R. H. Howard, T. J. Harrison and J. D. Rader, "Technology Implementation Plan: Irradiation Testing and Qualification for Nuclear Thermal Propulsion Fuel," Oak Ridge National Laboratory, ORNL/TM-2017/376, Oak Ridge, 2017.

[23] R. R. Asamoto and P. Novak, "Tungsten-Rhenium Thermocouples for Use at High Temperatures," The Review of Scientific Instruments, vol. 38, no. 8, pp. 1047-1052, 1967.

[24] Idaho National Laboratory, "FY 2009 Advanced Test Reactor National Scientific User Facility Users' Guide," Idaho Falls, ID, 2009.

[25] Oak Ridge National Laboratory, "High Flux Isotope Reactor (HFIR) USER GUIDE: A guide to in-vessel irradiations and experiments," Oak Ridge, TN, 2015.

[26] M. F. Ashby, Materials Selection in Mechanical Design, 3rd Ed., Burlington, MA: Butterworth-Heinemann, 2005.

[27] Granta, CES Granta Edupack, http://www.grantadesign.com/education/edupack/, 2017.

[28] B. A. Shaw, "Corrosion Resistance of Magnesium Alloys," in ASM Handbook, Volume 13A Corrosion: Fundamentals, Testing, and Protection, ASM International, 2003.

[29] A. Uzorh, "Corrosion Properties of Plain Carbon Steels," The International Journal Of Engineering And Science, vol. 2, no. 11, pp. 18-24, 2013.

[30] R. H. Howard, R. C. Gallagher and K. G. Field, "Mechanical performance of neutron-irradiated dissimilar transition joints of aluminum alloy 6061-T6 and 304L stainless steel.," vol. 508, no. C, 2018.

[31] R. Howard, J. McDuffee and Y. Katoh, "Graphite Compressive Creep Capsule Design for Irradiation in the HFIR," Atlanta, GA, 2013.

[32] G. Mathers, Welding of Aluminium and Its Alloys, Cambridge Woodhead Publishing Limited, 2002.

[33] P. Korinko and S. Malene, "Considerations for the weldability of types 304L and 316L stainless steel," Practical Failure Analysis, vol. 1, no. 4, 2001.

[34] S. Lampman, Weld integrity and performance: a source book adapted from ASM International handbooks, conference proceedings, and technical books, Materials Park, Ohio: ASM International, 1997.

[35] D. R. Lide, CRC Handbook of Chemistry and Physics, 86 Edition, 2005.

[36] L. Mansur, "Survey of Radiation Effects in Titanium Alloys," Oak Ridge National Laboratory, ORNL/TM-2008/137, Oak Ridge, TN, 2008.

[37] American Society of Mechanical Engineers, An International Code - ASME Boiler & Pressure Vessel Code Section IX: Welding and Brazing Qualifications, ASME, ISBN 9780791871003, 2017.

[38] D. Conner and D. Mobley, "Weld 350- Pipe welding procedure specification (WPS) ASME B31.3: GT53.TiGr5-1 (PP), Rev. 0," Oak Ridge National Laboratory, Oak Ridge, TN, 2017.

[39] ASTM International, "Standard Specification for Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers: ASTM B338 - 17," ASTM International, 2017.

[40] SANDVIK, "SANDVIK Ti GRADE 9 Tube and Pipe, Seamless Datasheet," SANDVIK, 2017.

[41] SGL Group, "Soft Felt for High Temperature Furnaces," [Online]. Available: https://www.sglgroup.com/cms/international/products/product-groups/cfrc_felt/speciality-graphites-for-high-temperature-furnaces/soft-felt.html. [Accessed July 2017].

[42] N. C. Gallego and T. D. Burchell, "A Review of Stored Energy Release of Irradiated Graphite," Oak Ridge National Laboratory, Oak Ridge, TN, 2011.

[43] Kurt J. Lesker Company, "CF Flanges Technical Notes," 2017. [Online]. Available: https://www.lesker.com/newweb/flanges/flanges_technicalnotes_conflat_1.cfm. [Accessed Dec. 2017].

[44] M. Scervini, C. Rae and B. Lindley, "Transmutation of thermocouples in thermal and fast nuclear reactors.," Marseille, France, 2013.

[45] ASTM, Standard Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance., West Conshohocken, PA: ASTM International, 2018.

[46] K. L. Davis, D. Knudson, J. Daw, J. Palmer and J. Rempe, "Melt wire sensors available to determine peak temperatures in ATR irradiation testing.," San Diego, CA, 2012.

[47] E. M. Savitsky, Handbook of Precious Metals, vol. 4, Moscow, Russia: Metallurgiya Publishers, 1984, pp. 18-29.

[48] T. Matsumoto, T. Koizumi, Y. Kawakami, K. Okamoto and M. Tomita, "Perfect blackbody radiation from a graphene nanostructure with application to high-temperature spectral emissivity measurements.," Optics Express, vol. 21, no. 25, pp. 30964-30974, 2013.

[49] K. Jousten, Handbook of Vacuum Technology, Weinheim, DE: Wiley-VCH, 2008.

[50] J. L. McDuffee, "Preparation of Sealed Unfinned Rabbit Capsules," Oak Ridge National Laboratory, Oak Ridge, TN, 2012.

[51] K. Terrani, J. Kiggans, Y. Katoh, K. Shimoda, F. Montgomery, B. Armstrong, C. Parish, T. Hinoki, J. Hunn and L. Snead, "Fabrication and characterization of fully ceramic microencapsulated fuels microencapsulated fuels.," vol. 426, no. 1-3, 2012.

[52] J. L. McDuffee, G. L. Bell, R. J. Ellis, R. W. Hobbs, L. L. Snead and M. Okuniewski, "Design, fabrication, and testing of gadolinium-shielded metal fuel samples in the hydraulic tube of the high flux isotope reactor.," Sendai, Japan, 2014.

[53] W. J. Parker, R. J. Jenkins, C. P. Butler and G. L. Abbott, "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity," vol. 32, no. 9, 1961.

[54] R. Tandon and A. Wereszczak, Mechanical Properties and Performance of Engineering Ceramics II, Hoboken, NJ: John Wiley & Sons., 2009.

[55] CINDAS LLC, 2017. [Online]. Available: https://www.cindasdata.com/.

[56] J. L. McDuffee, " Heat Transfer Through Small Moveable Gas Gaps in a Multi-Body System Using the ANSYS Finite Element Software," in Heat Transfer Summer Conference, Volume 1: Heat Transfer in Energy Systems, Minneapolis, MN, 2013.

[57] ANSYS, ANSYS finite element software, http://www.ansys.com/, 2017.

[58] J. McDuffee, "Temperature Verification, Transient Analysis, and Argon Activation for Materials Experiment MFE-RB-19J," Oak Ridge National Laboratory, C-HFIR-2016-007, Rev.0, Oak Ridge, TN, 2016.

[59] C. Petrie, "Thermal Safety Analysis for Irradiation of Miniature Fuel Specimens in the Inner Small Vertical Experiment Facility Positions," Oak Ridge National Laboratory, C-HFIR-2017-030, Rev.0, Oak Ridge, TN, 2017.

[60] Poco Graphite, Inc., "Properties and Characteristics of Graphite," Poco Graphite, Inc., IND-109441-0115, Decatur, TX 76234, 2015.

[61] J. Linke, H. Bolt, R. Duwe, W. Kühnlein, A. Lodato, M. Rödig, K. Schöpflin and B. Wiechers, "High heat flux simulation experiments with improved electron beam diagnostics," Journal of Nuclear Materials, Vols. 283-287, pp. 1152-1156, 2000.

[62] R. Siegel and J. R. Howell, Thermal Radiation Heat Transfer, New York, NY: McGraw-Hill Book Company, 1972.

[63] J. Moore, R. S. Graves and D. L. McElroy, " Thermal and Electrical Conductivities and Seebeck Coefficients of Unirradiated and Irradiated Graphites from 300 to 1000K.," vol. 22, no. 1, 1973.

[64] S. Rattanaweeranona, P. Limsuwan, V. Thongpoola, V. Piriyawonga and P. Asanithi, "Influence of Bulk Graphite Density on Electrical Conductivity," vol. 32, no. 2012, 2010.

[65] R. L. Anderson, "THERMOCOUPLE ERROR ANALYSIS IN THE DESIGN OF LARGE ENGINEERING EXPERIMENTS," Oak Ridge National Laboratory, Oak Ridge, TN, 1979.

[66] T. Massalski, H. Okamoto, P. Subramanian and L. Kacprzak, Binary alloy phase diagrams second edition plus updates, Materials Park, OH: ASM International, 1996.

[67] J. W. Arblaster, "Thermodynamic Properties of the Platinum Metals on ITS-90.," vol. 40, no. 2, 1996.

[68] C. V. Madhusudana, Thermal Contact Conductance, New York: Springer-Verlag New York Inc., 1996.

[69] J. Lienhard IV and J. Lienhard V, A Heat Transfer Textbook, Third Edition, Cambridge, MA: J.H. Lienhard V, 2000.

[70] Mikron Instrument Company, Inc., "Table of Emissivity of Various Surfaces," [Online]. Available: http://www-eng.lbl.gov/~dw/projects/DW4229_LHC_detector_analysis/calculations/emissivity2.pdf. [Accessed 15 10 2018].

[71] ANSYS, "Mechanical APDL 2019 R1 - Theory Reference," ANSYS, 2019. [Online]. Available: https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v193/ans_thry/ans_thry.html. [Accessed 21 1 2019].

[72] M. F. Cohen and D. P. Greenberg, "The Hemi-Cube: A Radiosity Solution of Complex Environments," San Francisco, CA, 1985.

[73] J. L. McDuffee, "Thermophysical Properties for 304 Stainless Steel," Oak Ridge National Laboratory, Oak Ridge, TN, 2010.

[74] J. L. McDuffee, "Thermophysical Properties for Titanium Alloy Ti-6Al4V," 2013.

[75] J. L. McDuffee, "Thermophysical Properties for Molybdenum," 2013.

[76] J. L. McDuffee, "Thermophysical Properties for POCO Graphite," 2013.

[77] N. O. Cetiner, "Thermophysical Properties for Tungsten," Oak Ridge National Laboratory, Oak Ridge, TN, 2014.

[78] J. L. McDuffee, "Thermophysical Properties for Zirconium Dioxide," 2011.

[79] ASME Performance Test Codes Committee, Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer., New York, NY: American Society of Mechanical Engineers, 2009.

[80] ANSYS, "ANSYS Mechanical APDL Verification Manual," [Online]. Available: https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v191/ans_vm/Hlp_V_VMTOC.html?q=ANSYS%20Mechanical%20APDL%20Verification%20Manual. [Accessed 4 March 2019].

[81] D. DeWitt, T. Riddle and R. Taylor, "Spectral and Total Emissivity and Reflectivity at High Temperatures.," Purdue University, West Lafayette, IN, 1978.

[82] K. Chahine, M. Ballico, J. Reizes and J. Madadnia, "Thermal Conductivity of Graphite Felt at High Temperatures," Perth, Western Australia, 2005.

APPENDICES

Appendix I
Select Attachments

Veeco 2508 Power Supply Datasheet

DC Power Supplies with PID Temperature Controllers

- **Achieve excellent flux stability using closed-loop temperature or power feedback**
- **Package consists of power supply, PID temperature controller, cables and adapters**
- **Provides optimal effusion cell control with integrated PID controller**
- **Increase available voltage envelope by stacking**
- **Certified for all major regulatory compliance standards**
- **All power supplies covered by a 4-year warranty**

Description

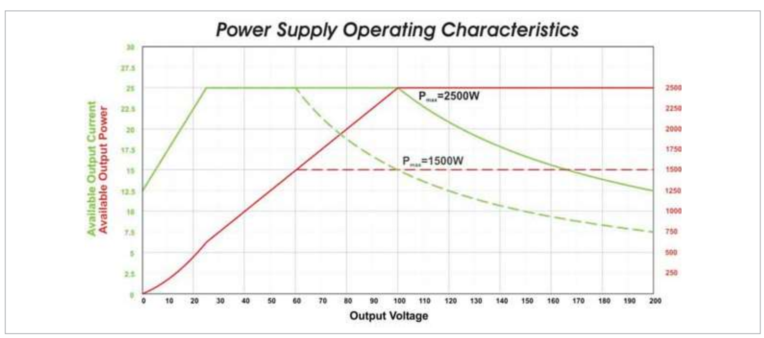
Veeco offers a complete line of power supplies that include PID temperature controllers for accurate, reliable operation of MBE sources and substrate heaters. Veeco's DC supplies are compatible with all Veeco effusion cells. The power supplies are offered in 1500 and 2500 wattages.

Product Model Options	
Wattage	Model Number
1500W	1508
2500W	2508
All models covered by a 4-year parts and labor warranty.	

Product Specifications

Mechanical Specifications—All Models	
Item	Specification
Form factor	½ rack width, 3U height (5-1/4")
Dimensions	9.5"Wx5.25"Hx20"D
Weight	24.2lbs (11Kg)

Environmental Specifications—All Models	
Item	Specification
Temperature	0-40°C (ambient)
Humidity	<90% (non-condensing)
Cooling	Internal DC fan with external user maintainable filter



Typical output current and output power of the 1508 & 2508 power supplies as a function of voltage.

Electrical Specifications—All Models		
Type	**Item**	**Specification**
Input	AC power	100-240VAC, 50-60Hz, single-phase
	Input current	1508—7.6A, 2508—11.8A (see "De-rating" below)
Output	Output voltage	0-200VDC, 10mV resolution (up to 400V for stack configurations)
	Output current	0-25A, 10mA resolution
	Output power	0-1500W, 1W resolution (1508), 0-2500W, 1W resolution (2508) (see "De-rating" below) (up to 10kW in stack configuration)
	Noise and ripple	<100mV (RMS)
Protection	Input Protection	Over current protection with double pole circuit, breaker, surge protected with varistor and gas discharge, limiter circuits
	De-rating	1500W from 180-240VAC (1508), 2500W from 180-240VAC (2508) 1000W from 100-179VAC (all models) For full rated power, connect to power mains rated >180VAC
	Thermal Protection	Heat sink is temperature monitored, output is disabled on over temperature condition
	Shutdown conditions	Over temperature, under temperature, over voltage under voltage, unstable AC

Interconnect Specifications—All Models	
Item	**Specification**
PID thermocouple	Type C, D, K, S available
PID communications	500VDC isolation, software selectable RS-232 or RS-485, D-9 connector
Communications	500VDC isolation, software selectable RS-232 or RS-485, D-9 connector
1508 to 1508 or 2508 to 2508 (stack) communications	500VDC isolation, intermodule link for series stack connection control, D-9 connector
Remote analog in	500VDC isolation, 4-20mA control input, BNC connector
Interlock inputs	500VDC isolation • Primary safety interlock (normally closed), pins 1(+), 4(-) • Force PID controller to 2nd setpoint (normally open), pins 2(+), 5(-) • Spare pins 3(+), 6(-) Interlocks are 12VDC, dry contact requiring 10mA external switch capability

Regulatory Compliance—All Models

All power supply models comply with the following international standards.	
Safety	UL 60950 (USA), EN 60950 (Europe), CSA C22.2 No. 60950-00 (Canada)
Conducted/radiated emissions	FCC Part 15 Subpart B Class A (North America), CISPR11/EN55011 Class A Group 1, ISM Equipment (Europe)
EMI Immunity/Electromagnetic Compatibility	IEC61000-6-2: 1999, EN61000-6-2: 1999
EC Compliance	"CE" marked

Veeco

Solutions for a nanoscale world.™

Compound Semiconductor • MBE Operations
4900 Constellation Drive, St. Paul, MN 55127 USA
Phone: (651) 482-0800, Fax: (651) 482-0600
www.veeco.com/mbe

Omega T5R-015-12 Thermocouple Datasheet

Tungsten-Rhenium Twisted Beaded Thermocouples

Tungsten-rhenium thermocouples were developed to meet the requirements for measuring ultra-high temperatures in the 2760°C (5000°F) range.

OMEGA sells 3 widely used tungsten-rhenium thermocouple calibrations: tungsten versus tungsten-26% rhenium, tungsten-5% rhenium versus tungsten-26% rhenium, and tungsten-3% rhenium versus tungsten-25% rhenium.

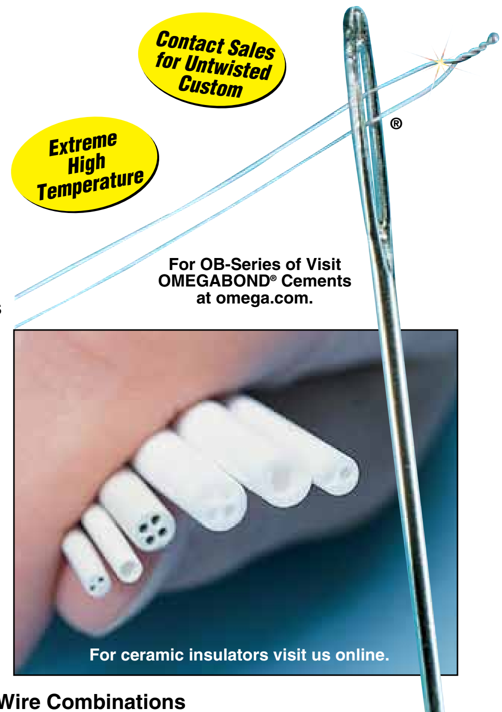
OMEGA® tungsten-rhenium thermocouples conform to the limits of error listed in the table below.

Because of the inherent brittleness of unalloyed tungsten, the tungsten versus tungsten-26% rhenium thermocouples are more difficult to handle than the tungsten-5% rhenium versus tungsten-26% rhenium combination.

The average emf of the W-3% Re/W-25% Re is slightly less than that of W/W-26% Re and slightly more than that of W-5% Re/W-26% Re. The ductility of W-3% Re is about equal to that of W-5% Re, but superior to that of unalloyed tungsten.

All 3 thermocouple calibrations can be used to 2760°C (5000°F) in hydrogen or inert gas atmospheres and in a vacuum. They deteriorate rapidly under oxidizing conditions and should not be used in air or atmospheres containing oxygen.

OMEGA tungsten-rhenium thermocouples come in 300 mm (12") lengths, which corresponds to each for a 600 mm (24") total length. Longer lead lengths are available; consult sales.



Limits of Error for Tungsten-Rhenium Thermocouple Wire Combinations

Wire Diameter mm (inch)	Temperature Range (†)	Maximum Error or Departure
0.075 (0.003)	0 to 425°C (32 to 800°F) 426 to 1750°C (800 to 3200°F)	±4.5°C (±8°F) ±1%
0.125 (0.005)	0 to 425°C (32 to 800°F) 426 to 1975°C (800 to 3600°F)	±4.5°C (±8°F) ±1%
0.25 to 0.50 (0.010 to 0.020)	0 to 425°C (32 to 800°F) 426 to 2325°C (800 to 4200°F)	±4.5°C (±8°F) ±1%

† Up to 2760°C (5000°F) for short-term exposure.

To Order

Materials	Wire Diameter mm (inch)	Unsheathed Model No.**
G Tungsten-Tungsten 26% Re	0.075 (0.003)	**TOR-003-12**
	0.125 (0.005)	**TOR-005-12**
	0.250 (0.010)	**TOR-010-12**
	0.381 (0.015)	**TOR-015-12**
	0.500 (0.020)	**TOR-020-12**
C* Tungsten 5% Re-Tungsten 26% Re	0.075 (0.003)	**T5R-003-12**
	0.125 (0.005)	**T5R-005-12**
	0.250 (0.010)	**T5R-010-12**
	0.381 (0.015)	**T5R-015-12**
	0.500 (0.020)	**T5R-020-12**
D Tungsten 3% Re-Tungsten 25% Re	0.127 (0.005)	**T3R-005-12**
	0.250 (0.010)	**T3R-010-12**
	0.381 (0.015)	**T3R-015-12**
	0.500 (0.020)	**T3R-020-12**

** Most popular of the 3 tungsten-rhenium thermocouples; a large selection of instrumentation is available.*

*** Tungsten-rhenium alloy thermocouples are supplied in standard 300 mm (12") lengths [600 mm (24") loops]. Change suffix **"-12"** in model number to indicate additional length (in inches) required. Consult Sales for other sizes.*

Ordering Example: T5R-005-12, *300 mm (12"), Type C thermocouple, 0.125 mm (0.005") diameter.*

Omega HH1384 Datalogger Datasheet

1 YEAR WARRANTY

CE

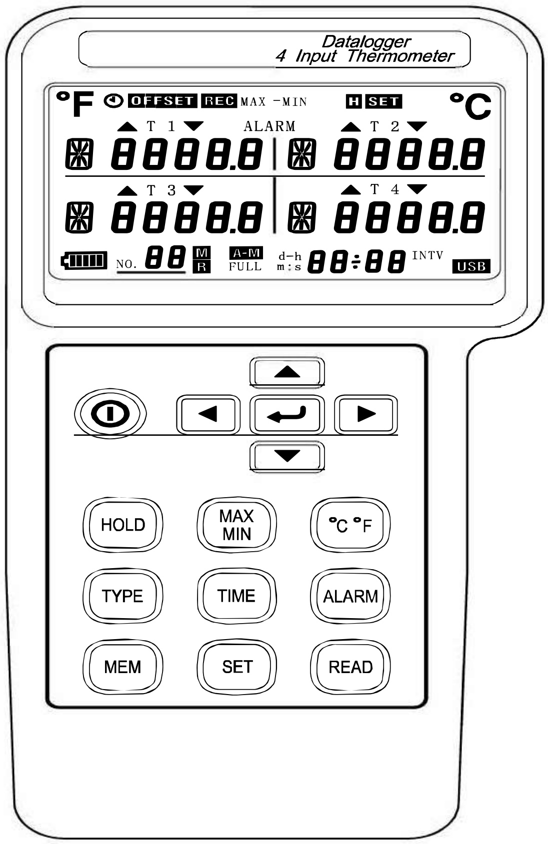
Made in Taiwan

User's Guide

DATALOGGER 4 INPUT THERMOMETER

HH1384

INSTRUCTION MANUAL



Shop online at

omega.com®

OMEGA®

omega.com

e-mail: info@omega.com

For latest product manuals:

omegamanual.info

ISO 9001 CERTIFIED CORPORATE QUALITY STAMFORD, CT

ISO 9001 CERTIFIED CORPORATE QUALITY MANCHESTER, UK

1. INTRODUCTION: FEATURES

This instrument is a digital 4 input thermometer and data logger that works with any K, J, E, T, R, S, N, L, U, B and C-type thermocouple temperature sensor.

Temperature indication follows the international temperature scale of 1990 (ITS-90).

- Read the following safety information carefully before attempting to operate the meter.
- Use the meter only as specified in this manual; otherwise, the protection provided by the meter may be impaired.

Environment conditions

① Altitude up to 2000 meters
② Relatively humidity 80% max.
③ Operation Ambient 0～50°C(32°F ~122°F)

Features

- Isolated Input Protection of 350Vp-p between any two inputs.
- Highly accurate thermometer with thermocouple K, J, E, T, R, S, N, L, U, B, C types.
- 4 input function T1/T2/T3/T4 temperature display.
- Programmable Hi – Lo alarm for 4 inputs.
- Display of MAX, MIN and MAX–MIN values of 4 inputs.
- Independent Input Setup (type of thermocouple, Hi – Lo alarm values).
- Memory and Read function (99 sets)
- 512KB auto datalogging capacity.
- USB interface.

Safety symbols

CE Comply with EMC

2. SPECIFICATIONS

2-1 Electronical Specifications

Type	°C		°F	
	Range	Accuracy	Range	Accuracy
K	-200 ~ -150 -150 ~ -100 -100 ~ 999.9 1000 ~ 1370	±3.0°C ±2.0°C ±0.05% ±1.0°C ±0.2% ±1.0°C	-328 ~ -238 -238 ~ -148 -148 ~ 999.9 1000 ~ 2498	±5.4°F ±3.6°F ±0.05% ±1.8°F ±0.2% ±1.8°F
J	-200 ~ -100 -100 ~ 100 100 ~ 999.9	±2.5°C ±1.5°C ±0.05% ±1.0°C	-328 ~ -148 -148 ~ 212 212 ~ 999.9 1000 ~ 1832	±4.5°F ±2.7°F ±0.05% ±1.8°F ±0.2% ±1°F
E	-150 ~ -100 -100 ~ 760	±3.0°C ±0.05% ±1.0°C	-238 ~ -148 -148 ~ 999.9 1000 ~ 1400	±5.4°F ±0.05% ±1.8°F ±0.2% ±1°F
T	-200 ~ -150 -150 ~ -100 -100 ~ 400	±3.0°C ±0.15% ±2.5°C ±0.1% ±1.0°C	-328 ~ -238 -238 ~ -148 -148 ~ 752	±5.4°F ±0.15% ±4.5°F ±0.1% ±1.8°F
R/S	0 ~ 100 100 ~ 300 300 ~ 999.9 1000 ~ 1600	±5.0°C ±3.0°C ±0.05% ±2.0°C ±0.25% ±2.0°C	32 ~ 212 212 ~ 572 572 ~ 999.9 1000 ~ 2912	±9.0°F ±5.4°F ±0.05% ±3.6°F ±0.25% ±3.6°F
N	0 ~ 999.9 1000 ~ 1300	±0.1% ±1.0°C ±0.2% ±1.0°C	32 ~ 999.9 1000 ~ 2372	±0.1% ±1.8°F ±0.2% ±1.8°F
L	-200 ~ 900	±0.1% ±1.0°C	-328 ~ 999.9 1000 ~ 1652	±0.1 % ±1.8°F ±0.2% ±1°F
U	0 ~ 600	±0.1% ±1.0°C	32 ~ 999.9 1000 ~ 1112	±0.1% ±1.8°F ±0.2% ±1°F
B	600 ~ 999.9 1000 ~ 1760	±0.05% ±2.0°C ±0.1% ±2.0°C	1112 ~ 1831 1832 ~ 3200	±0.05% ±3.6°F ±0.1% ±3.6°F
C	0 ~ 999.9 1000 ~ 1760	±0.1% ±1.5°C ±0.2% ±1.5°C	32 ~ 999.9 1000 ~ 3200	±0.1% ±2.7°F ±0.2% ±2.7°F

> **NOTE**
> This basic accuracy specification does not include the error of the temperature probe. Please refer to the temperature probe accuracy specification for additional details.

Temperature Coefficient:
0.01% of reading +0.1°C per °C (0.2°F per °F)
outside the specified +18°C to 28°C (+64°F to 82°F) range.
Isolated Input Protection between any Two Inputs : 350Vp-p
Manual Data Memory Capacity: 99 sets.
Continuity Data Logging Capacity: 36,000 sets.

2-2 General Specifications

Power Supply: 6 pcs size AA battery or DC 9V AC adaptor.

Battery Life: approx. 55 hours (Alkaline battery)

Auto Power Off: 5, 15 or 30 minutes (If no key is pressed).
Low Battery Indicator: The ( ) is displayed when the battery voltage drops below the operating voltage.

Measurement Rate : One time per 2 seconds.

Weight : 405g / 14.3oz (batteries included)

Dimension : 18.7(L) × 7.3(W) × 5.3(T) cm
7.3"(L) × 2.9"(W) × 2.1"(T)
Operating Temperature: 0 to 50℃ (32 to 122°F)

and Humidity: Below 80% RH.

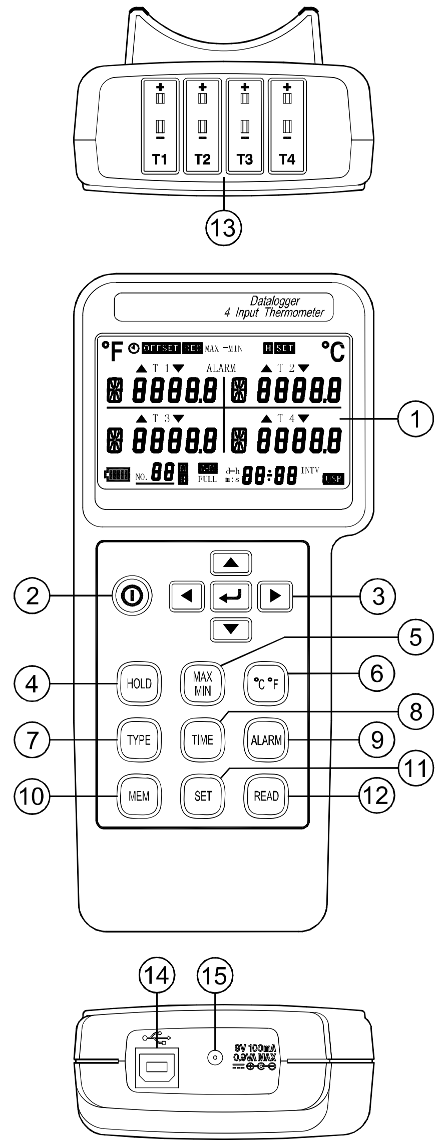
Storage Temperature: -10 to 60℃, 14 to 140°F

and Humidity: Below 70% RH.

Accessories: Instruction manual, alkaline batteries, USB cable, software CD, carrying case and K-type thermocouples (1 per channel).

3. PARTS & CONTROLS

3-1 Description of Parts & Control keys



(1). LCD Display

(2). ⏻ **Key :** Power on – off control key.

(3). ▲▼◀ ▶↲ Keys: Setting keys.

(4). HOLD Key:

① Data hold function key, press “**HOLD**” key to hold data, the “ $\boxed{H}$ ” symbol is displayed, press this key again to exit this function.

② Press and hold down “**HOLD**” key then press "⏻" key to turn on the meter, the “ ” symbol disappear, exit auto power off function.

(5). MAX MIN Key: Press “**MAX MIN**” key to circulate the reading of Maximum, Minimum, Maximum minus Minimum, and Current. Press this key for 2 seconds to exit this mode.

(6). °C / °F Key: Press “**°C / °F**” key to switch the units between Celsius (°C) and Fahrenheit (°F).

(7). TYPE Key: Press "**TYPE**" key to enter the thermocouple type select mode, press this key again to exit this mode.

(8). TIME Key: Press “**TIME**” key to circulate display data and time.

(9). ALARM Key: Press “**ALARM**” key to enable or disable Alarm function.

(10). MEM Key: Manual data memory control key.

(11). SET Key: Press “**SET**” key to start or exit setup.

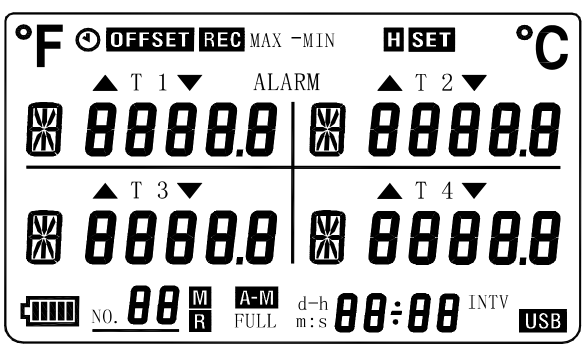
(12). READ Key: Manual memory data reading control key.

(13). T1, T2, T3, T4 : Thermocouple T1, T2, T3 and T4 inputs.

(14). USB Interface Jack.

(15). AC Adaptor Input Jack.

3-2 Description of Display



°F, °C : Temperature units.

: Auto power off indication.

OFFSET : The thermocouple measurement includes an offset indication.

REC : MAX MIN Recording mode and current reading indication.

REC MAX : Maximum reading indication.

REC MIN : Minimum reading indication.

REC MAX-MIN : Maximum minus Minimum value indication.

H : Data hold function indication.

SET : Setting mode indication.

: Thermocouple type indication.

ALARM : Alarm mode indication.

▲ALARM : Input temperature exceeds the high limit value indication.

▼ALARM : Input temperature is below the low limit value indication.

T1, T2, T3, T4 : Thermocouple T1, T2, T3, T4 input temperature measurement display.

: Battery capacity indication.

: Replace batteries indication.

NO. 88: Last manual data memory address number indication (01–99).

M : Manual data memory indication, **M** displays one time store one sets data into the memory.

NO. 88 **R** : Manual data memory read address number indication, the memory data displayed for read.

A-M : Auto data logging indication, **A-M** will disappear after storing the data.

INTV : Auto data log interval time setting indication.

Full : Auto data logged memory full indication, if exceeds 255 memory blocks, total maximum record capacity size is 36,000 sets of data for 4 input thermocouple temperature measurement (100,000 sets data for 1 input record).

d-h m:s 88:88 : Time display indication.

4. OPERATION INSTRUCTION

WARNING

- Before using the meter inspect the case. Do not use the meter if it appears damaged. Look for cracks or missing plastic. Pay particular attention to the insulation around the connectors.
- Disconnect thermocouples from the meter before opening the case.
- Replace the batteries as soon as the battery indicator " " appears. The possibility of false reading can lead to personal injury.
- Do not use the meter if it operates abnormally. Protection may be impaired.
- Do not operate the meter around explosive gas, vapor or dust.
- Do not use the meter with any part of the case or cover removed.

4-1 Setting the meter

1. Real – Time setting:

(a). Press "⏻" key to turn on the meter.

(b). Press "**SET**" key to enter the setting mode, the "Set clock" and " **SET** " symbols are displayed.

(c). Press "↵ " key to enter real time setting mode and the two flicking numbers of year.

(d). Press ▲ or ▼ key to set the year (real time).

(e). Press "↵ " key and move to the two flicking digits of month.
(f). Press ▲ or ▼ key to set month (real time).
(g). Press "↵ " key and move to the two flicking digits of day.
(h). Press ▲ or ▼ key to set day (real time).
(i). Press "↵ " key and move to the two flicking digits of hour.
(j). Press ▲ or ▼ key to set hour (real time).
(k). Press "↵ " key and move to the two flicking digits of minutes.
(l). Press ▲ or ▼ key to set minutes (real time).
(m). Press "↵ " key and move to the two flicking digits of second.
(n). Press ▲ or ▼ key to set seconds (real time).
(o). Press "↵ " key to store real time values.
(r). Press "**SET**" key to exit this mode.

2. Interval – Time setting :

The logging interval time determines how often the meter stores logged readings in memory.

(a). Press "⏻" key to turn on the meter.
(b). Press "**SET**" key to enter the setting mode, then press ▲ or ▼ key until the display shows "Set Intr".
(c). Press "↵" key to enter the interval time setting mode and the three flicking numbers of second.
(d). Press ▲ or ▼ key to set the desired second of interval time (1 to 255 seconds).
(e). Press "↵ " key to store the auto datalogging interval time.
(f). Press "**SET**" key to exit this mode.

3. Offset setting :

You can adjust the meter readings to compensate for the errors of a specific thermocouple. The allowable adjustment range is from +12.7 to -12.8 degree, regardless of the temperature units. You can store individual offsets for T1, T2, T3 and T4.

(a). Press "⏻" key to turn on the meter.
(b). Press "**SET**" key to enter the setting mode, then press ▲ or ▼ key until the display shows "**SEt OFSEt**".

(c). Press "↵ " key to enter the offset setting mode, the " **OFFSET** " symbol is displayed.

(d). Press ◀ or ▶ key to select the desired T1, T2, T3 or T4.

(e). Press ▲ or ▼ key to set the desired offset values.

(f).. Press "↵" key to store the offset value.

(g). Press "**SET**" key to exit this mode.

The temperature measurement plus the offset appears in the display. Remember to set the offset to 0.0 when it is no longer needed. The " **OFFSET** " symbol will disappear when the offset values all are 0.0.

4. Auto Power Off Time setting :

(a). Press "⏻" key to turn on the meter.

(b). Press "**SET**" key to enter the setting mode, then press ▲ or ▼ key until the display shows "**SEt SLEEP**".

(c). Press "↵ " key to enter the auto power off time setting mode, the "**SLEEP**" symbol is displayed.

(d). Press ▲ or ▼ key to choose the desired auto power off time. The choices are: 5, 15 and 30 minutes.

(e). Press "↵ " key to store the choice.

(f). Press "**SET**" key to exit this mode.

5. Alarm High / Low Limit setting :

(a). Press "⏻" key to turn on the meter.

(b). Press "**SET**" key to enter the setting mode, then press ▲ or ▼ key until the display shows "**SEt ALArn**".

(c). Press "↵ " key to enter the alarm high limit and low limit setting mode, the " ALARM " symbol is displayed.

(d). Press ◀ or ▶ key to select the desired T1, T2, T3 or T4.

(e). Press "↵ " key to enter the high limit value setting, the "▲" symbol is displayed.

(f). Press ▲ or ▼ key to set the desired alarm high limit value, the resolution of setting value is 0.1 degree, regardless of the temperature units.

(g). Press "↵ " key to store the alarm high limit value and to enter the alarm low limit value setting, the symbol “▼” is displayed.

(h). Press ▲ or ▼ key to set the desired alarm low limit value, the resolution of setting value is 0.1 degree, regardless of the temperature units.

(i). Press "↵ " key to store alarm low limit value. You can store individual alarm High / Low limit values for T1, T2, T3 and T4, by repeating (c) to (i) procedure.

(j). Press “**SET**” key to exit this mode.

(k). Press “**ALARM**” key to enter the alarm function, the “**ALARM**” symbol is displayed. When the measured temperature value exceeds the setting High temperature value (the “▲” symbol will flicker the display) or below the setting Low temperature value (the “▼” symbol will flicking display.) the beep will sound one time per 4 seconds.

(l). Press “**ALARM**” key again to exit the alarm function.

4-2 Setting the Thermocouple Type

1. Press "⏻" key to turn on the meter.
2. Press “**TYPE**” key to enter the thermocouple type choices. The currently selected thermocouple type blinks.
3. Press ◀ or ▶ key to select the desired T1, T2, T3 or T4.
4. Press ▲ or ▼ key until the thermocouple type you want appears on the display.
5. Press "↵ " key to store the thermocouple type. You can store individual thermocouple types for T1, T2, T3 and T4, by repeated (3) to (5) procedure.
6. Press “**TYPE**” key again to exit this choices.

4-3 Temperature Measurement

1. Press "⏻" key to turn on the thermometer.
2. Plug the thermocouple (s) into the thermocouple input. If no thermocouple is plugged into the selected input or the thermocouple is "open", the display will show "- - -".

3. Press "**°C / °F**" key to desired temperature scale.
4. Perform measurements by contacting the object being measured with the probe sensor.
5. Read the temperature on the display. The display shows "**OL**" (overload) or "**Un**" (under ranges) when the temperature being measured is outside the meter valid range.

4-4 Maximum (MAX), Minimum (MIN) Recording Measurement

1. Press "**MAX MIN**" key to enter the recording mode, the " REC " symbol is displayed.
2. Press "**MAX MIN**" key to circulate the display of the maximum (REC MAX), minimum (REC MIN), maximum minus minimum (REC MAX-MIN) and current REC) reading.
3. Press "**HOLD**" key to paused recording, the "**H**" symbol is displayed, press "**HOLD**" key again will resume recording.
4. Press "**MAX MIN**" key for 2 seconds to exit this mode.

4-5 Manual Data Memory and Read Function Operation

1. Clear the manual memorized data

(a). Press "⏻" key to turn off the meter.

(b). Press and hold down "**MEM**" key, then press "⏻" key again to turn on the meter, the "**CLr YES no** M" symbol is displayed.

(c). Press ◀ or ▶ key to select "**YES**" symbol is displayed flicking.

(d). Press "↵ " key to clear the manual memorized data.

(e). Press "↵ " key again to exit this mode.

2. Store manual data to memory

(a). Pressing "**MEM**" key one time will store one set of measured data to memory. The "**M**" symbol will disappear and the stored memory address will displayed.

(b). Maximum store memory capacity size is 99 sets.

3. Read the manual store data

(a). Press "**READ**" key to enter the read mode, the "$\boxed{\textbf{R}}$" symbol is displayed.

(b). Press ▲ or ▼ key to read the memories data, the memories data address will be displayed.

(c). Press "**READ**" key again to exit this mode.

4-6 Auto Datalogging Function Operation

1. Clear the Auto datalogged data :

Before entering into the clear memory data mode, users must down load the previous memory data to PC.

(a). Press "⏻" key to turn off the meter.

(b). Press and hold down "**MEM**" key, then press "⏻" key again to turn on the meter, the "**CLr YES no** $\boxed{\textbf{M}}$" symbol is displayed.

(c). Press "↵" key to enter the clear auto datalogged data mode, the "**CLr YES no** $\boxed{\textbf{AM}}$" symbol is displayed.

(d). Press ◀ or ▶ key to select "**YES**" symbol is displayed flickering

(e). Press "↵ " key to clear the auto datalogged data and exit this mode.

2. Store Auto datalogging data to memory :

(a). Press "**MEM**" key for 3 seconds to start auto datalogging, the "$\boxed{\textbf{A-M}}$" symbol is displayed, the "$\boxed{\textbf{A-M}}$" symbol according to the interval time will disappear after storing one set of data into the memory.

(b). Press "**MEM**" key for 3 seconds to stop data record, the current block number will be displayed for one second. Press "**MEM**" key for 3 seconds will resume data record, but maximum is divided to 255 memory blocks. Total maximum record capacity size is 36,000 sets data for 4 (b). input thermocouple temperature measurement (100,000 sets data for 1 input record).

(c). When maximum block or maximum capacity is full, the "**FULL**" symbol will be displayed, the data record is auto stopped.

3. Download data to PC :

Please refer to the software manual (CD-ROM) to download the data.

4-7 Disable Auto Power off Function

The meter will automatically enter sleep mode approx. 5, 15 or 30 minutes decided by user setting to save power consumption.

1. **Disable auto power off procedure :**

   (a). Press "⏻" key to turn off the meter.

   (b). Press and hold down "**HOLD**" key then press "⏻" key to turn on the meter, the auto power off function will be disabled, and the auto power off symbol "🕘" will disappear.

2. Auto power off mode is enabled each time you turn on the meter and is automatically disabled bt the follow modes :

   (a). MAX MIN record mode.

   (b). Auto datalogging function is active.

   (c). PC linked.

5. MAINTENANCE

5-1 General Maintenance

1. Clean the meter and accessories with a damp cloth and a mild soap. Do not use abrasives, solvent or alcohol.

5-2 Battery Replacement :

WARNING
To AVOID electrical shock, remove any inputs before replacing the batteries.

1. When operating the meter on batteries, periodically check the battery symbol to determine the remaining battery capacity. The number of black segments decreases as the batteries are used up. When the “ ” symbol display starts to flash, correct measurement is no longer possible. Replace the batteries with a fresh set.
2. Take care not to reverse the (+) and (-) polarity when inserting the batteries. Always replace all six batteries together. Do not mix old and new batteries or batteries of different type. Remove the batteries from the meter, if the meter is not to be used for a month or longer.

6. USB INTERFACE, SOFTWARE INSTALLATION AND OPERATION

- ❑ For the detailed instruction, please refer to the content of attached CD-ROM, which has the complete instruction of software operation and relevant information.
- ❑ Protocol : are enclosed within the content of CD-ROM, please open the CD-ROM for details.

OMEGAnet® Online Service omega.com	Internet e-mail info@omega.com

Servicing North America:

U.S.A.:
ISO 9001 Certified
Omega Engineering, Inc., One Omega Drive, P.O. Box 4047
Stamford, CT 06907-0047
Toll-Free: 1-800-826-6342 Tel: (203) 359-1660
FAX: (203) 359-7700 e-mail: info@omega.com

Canada:
976 Bergar
Laval (Quebec), Canada H7L 5A1
Toll-Free: 1-800-826-6342 TEL: (514) 856-6928
FAX: (514) 856-6886 e-mail: info@omega.ca

For immediate technical or application assistance:

U.S.A. and Canada:
Sales Service: 1-800-826-6342/1-800-TC-OMEGA®
Customer Service: 1-800-622-2378/1-800-622-BEST®
Engineering Service: 1-800-872-9436/1-800-USA-WHEN®

Mexico:
En Español: 001 (203) 359-7803 FAX: (001) 203-359-7807
info@omega.com.mx e-mail: espanol@omega.com

Servicing Europe:

Benelux:
Managed by the United Kingdom Office
Toll-Free: 0800 099 3344 TEL: +31 20 347 21 21
FAX: +31 20 643 46 43 e-mail: sales@omega.nl

Czech Republic:
Frystatska 184
733 01 Karviná, Czech Republic
Toll-Free: 0800-1-66342 TEL: +420-59-6311899
FAX: +420-59-6311114 e-mail: info@omegashop.cz

France:
Managed by the United Kingdom Office
Toll-Free: 0800 466 342 TEL: +33 (0) 161 37 29 00
FAX: +33 (0) 130 57 54 27 e-mail: sales@omega.fr

Germany/Austria:
Daimlerstrasse 26
D-75392 Deckenpfronn, Germany
Toll-Free: 0 800 6397678 TEL: +49 (0) 7059 9398-0
FAX: +49 (0) 7056 9398-29 e-mail: info@omega.de

United Kingdom:
ISO 9001 Certified
OMEGA Engineering Ltd.
One Omega Drive, River Bend Technology Centre, Northbank
Irlam, Manchester M44 5BD England
Toll-Free: 0800-488-488 TEL: +44 (0)161 777-6611
FAX: +44 (0)161 777-6622 e-mail: sales@omega.co.uk

It is the policy of OMEGA Engineering, Inc. to comply with all worldwide safety and EMC/EMI regulations that apply. OMEGA is constantly pursuing certification of its products to the European New Approach Directives. OMEGA will add the CE mark to every appropriate device upon certification.

The information contained in this document is believed to be correct, but OMEGA accepts no liability for any errors it contains, and reserves the right to alter specifications without notice.
WARNING: These products are not designed for use in, and should not be used for, human applications.

WARRANTY/DISCLAIMER

OMEGA ENGINEERING, INC. warrants this unit to be free of defects in materials and workmanship for a period of **13 months** from date of purchase. OMEGA's WARRANTY adds an additional one (1) month grace period to the normal **one (1) year product warranty** to cover handling and shipping time. This ensures that OMEGA's customers receive maximum coverage on each product.

If the unit malfunctions, it must be returned to the factory for evaluation. OMEGA's Customer Service Department will issue an Authorized Return (AR) number immediately upon phone or written request. Upon examination by OMEGA, if the unit is found to be defective, it will be repaired or replaced at no charge. OMEGA's WARRANTY does not apply to defects resulting from any action of the purchaser, including but not limited to mishandling, improper interfacing, operation outside of design limits, improper repair, or unauthorized modification. This WARRANTY is VOID if the unit shows evidence of having been tampered with or shows evidence of having been damaged as a result of excessive corrosion; or current, heat, moisture or vibration; improper specification; misapplication; misuse or other operating conditions outside of OMEGA's control. Components in which wear is not warranted, include but are not limited to contact points, fuses, and triacs.

OMEGA is pleased to offer suggestions on the use of its various products. However, OMEGA neither assumes responsibility for any omissions or errors nor assumes liability for any damages that result from the use of its products in accordance with information provided by OMEGA, either verbal or written. OMEGA warrants only that the parts manufactured by the company will be as specified and free of defects. OMEGA MAKES NO OTHER WARRANTIES OR REPRESENTATIONS OF ANY KIND WHATSOEVER, EXPRESSED OR IMPLIED, EXCEPT THAT OF TITLE, AND ALL IMPLIED WARRANTIES INCLUDING ANY WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE HEREBY DISCLAIMED. LIMITATION OF LIABILITY: The remedies of purchaser set forth herein are exclusive, and the total liability of OMEGA with respect to this order, whether based on contract, warranty, negligence, indemnification, strict liability or otherwise, shall not exceed the purchase price of the component upon which liability is based. In no event shall OMEGA be liable for consequential, incidental or special damages.

CONDITIONS: Equipment sold by OMEGA is not intended to be used, nor shall it be used: (1) as a "Basic Component" under 10 CFR 21 (NRC), used in or with any nuclear installation or activity; or (2) in medical applications or used on humans. Should any Product(s) be used in or with any nuclear installation or activity, medical application, used on humans, or misused in any way, OMEGA assumes no responsibility as set forth in our basic WARRANTY/DISCLAIMER language, and, additionally, purchaser will indemnify OMEGA and hold OMEGA harmless from any liability or damage whatsoever arising out of the use of the Product(s) in such a manner.

RETURN REQUESTS/INQUIRIES

Direct all warranty and repair requests/inquiries to the OMEGA Customer Service Department. BEFORE RETURNING ANY PRODUCT(S) TO OMEGA, PURCHASER MUST OBTAIN AN AUTHORIZED RETURN (AR) NUMBER FROM OMEGA'S CUSTOMER SERVICE DEPARTMENT (IN ORDER TO AVOID PROCESSING DELAYS). The assigned AR number should then be marked on the outside of the return package and on any correspondence.

The purchaser is responsible for shipping charges, freight, insurance and proper packaging to prevent breakage in transit.

FOR **WARRANTY** RETURNS, please have the following information available BEFORE contacting OMEGA:

1. Purchase Order number under which the product was PURCHASED,
2. Model and serial number of the product under warranty, and
3. Repair instructions and/or specific problems relative to the product.

FOR **NON-WARRANTY** REPAIRS, consult OMEGA for current repair charges. Have the following information available BEFORE contacting OMEGA:

1. Purchase Order number to cover the COST of the repair,
2. Model and serial number of theproduct, and
3. Repair instructions and/or specific problems relative to the product.

OMEGA's policy is to make running changes, not model changes, whenever an improvement is possible. This affords our customers the latest in technology and engineering.

ASM 340 helium Leak Detector Datasheet

ASM 340 Dry Version, Universal Voltage

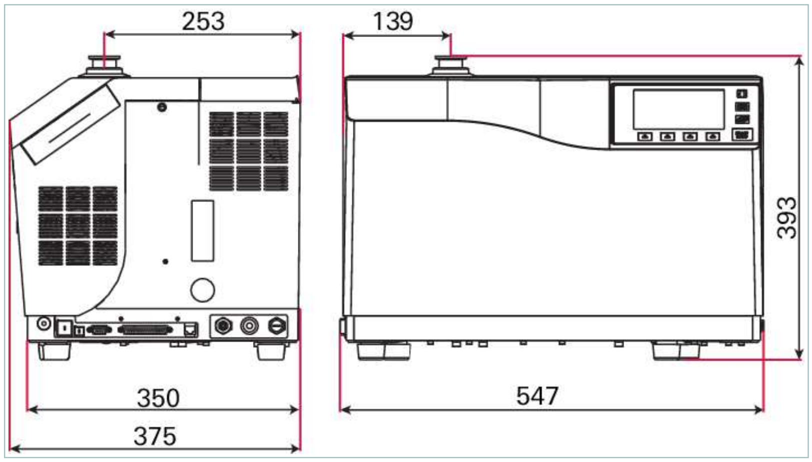
PFEIFFER VACUUM

Similar Image

ASM 340 Dry Version, Universal Voltage

- Oil free pumping system, backing pump capacity 3.4 m³/h
- 2.5 l/s helium pumping speed
- Customizable and detachable operator interface
- Integrated SD card for data processing
- Wired or wireless remote control and sniffer probes available as accessories

Dimensions



Technical Data	ASM 340 Dry Version, Universal Voltage
Backing pump capacity	3.4 m³/h
Detectable gases	^4He, ^3He, H_2
Dimensions (L x W x H)	547 x 375 x 393 mm | 21.54 x 14.76 x 15.47 inch
Flange (in)	DN 25 ISO-KF
I/O interfaces	Basic 15 pins I/O
Max. inlet test pressure	25 hPa
Minimum detectable leak rate for helium (sniffing leak detection)	$5 \cdot 10^{-10}$ Pa m³/s
Minimum detectable leak rate for helium (vacuum leak detection)	$5 \cdot 10^{-13}$ Pa m³/s
Noise level	52 dB(A)
Operating temperature (hard vacuum test)	0 – 35 °C
Operating temperature (sniffing test)	0 – 35 °C
Power consumption max.	600 W
Protection category	IP20
Pumping speed for He	2.5 l/s
Start-up time (20°C) without calibration	~ 3 min
Supply	90 – 240 V, 50/60 Hz
Test method	Vacuum and sniffing leak detection
Warranty: Year(s)	2
Weight	45 kg | 99.21 lb

Order number	
ASM 340 Dry Version	**KSBA00A0MM9A**

Accessories	
Cables|Mains cables / Power cords	
Mains Cable, 2.5 m, Switzerland	**103718**
Mains Cable, 2.5 m, U.K.	**104411**
Mains Cable, 2 m, Italy	**104758**
Connections|Bypass options	
Bypass option with Euro-style safety plug	**PT 445 411 -T**
Bypass Option with US Plug	**PT 445 413-T**
Control Devices|Remote controls	
Remote control, leak rate in mbar l/s, legend in English	**106688**
Remote control, leak rate in Pa m^3/s, legend in English	**108880**
Remote control RC 10, wired/wireless, for ASM and ASI leak detectors	**124193**
Protection|Inlet filters	
Inlet filter, 5 µm, DN 25/25 ISO-KF	**105844**
Sniffing|Helium pistols/ spray guns	
Helium spray gun "Elite-Kit", spray gun with additional accessories in a compact case	**109951**
Helium spray gun, standard	**112535**
Sniffing|Sniffer probes	
LP 503, sniffer probe with standard tip, 3 m	**BG 449 207 -T**
LP 505, sniffer probe with standard tip, 5 m	**BG 449 208 -T**
LP 510, sniffer probe with standard tip, 10 m	**BG 449 209 -T**
Sniffer probe, 5 m hose length, rigid 9 cm nozzle	**SNC1E1T1**
Sniffer probe, 10 m hose length, rigid 9 cm nozzle	**SNC2E1T1**
Transport|Transport carts	
Transport cart, 2 wheels, for ASM 340	**122570**

VACUUM SOLUTIONS FROM A SINGLE SOURCE

Pfeiffer Vacuum stands for innovative and custom vacuum solutions worldwide, technological perfection, competent advice and reliable service.

COMPLETE RANGE OF PRODUCTS

From a single component to complex systems:
We are the only supplier of vacuum technology that provides a complete product portfolio.

COMPETENCE IN THEORY AND PRACTICE

Benefit from our know-how and our portfolio of training opportunities!
We support you with your plant layout and provide first-class on-site service worldwide.

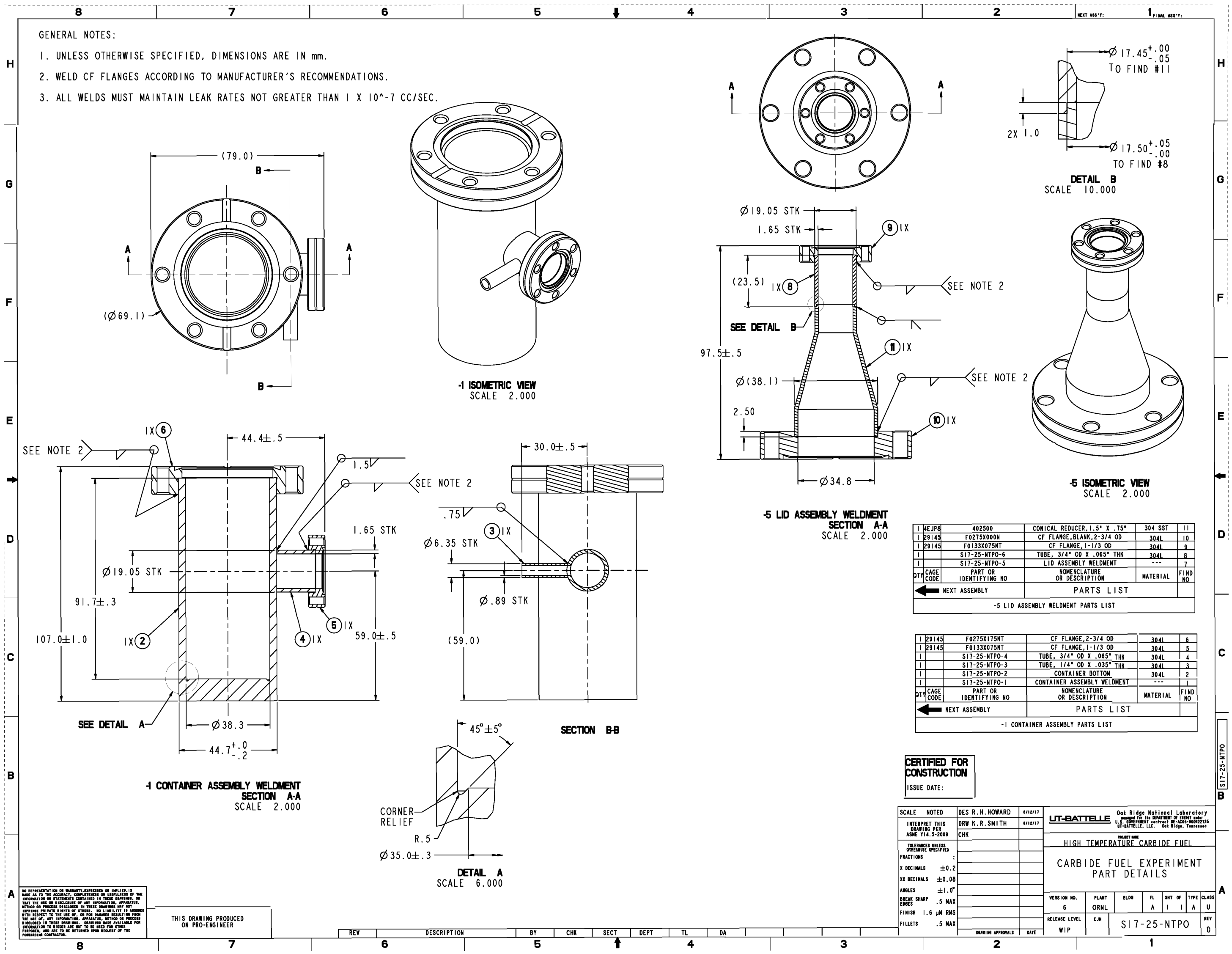
Are you looking for a perfect vacuum solution? Please contact us:

Pfeiffer Vacuum GmbH
Headquarters · Germany
T +49 6441 802-0
info@pfeiffer-vacuum.de

www.pfeiffer-vacuum.com

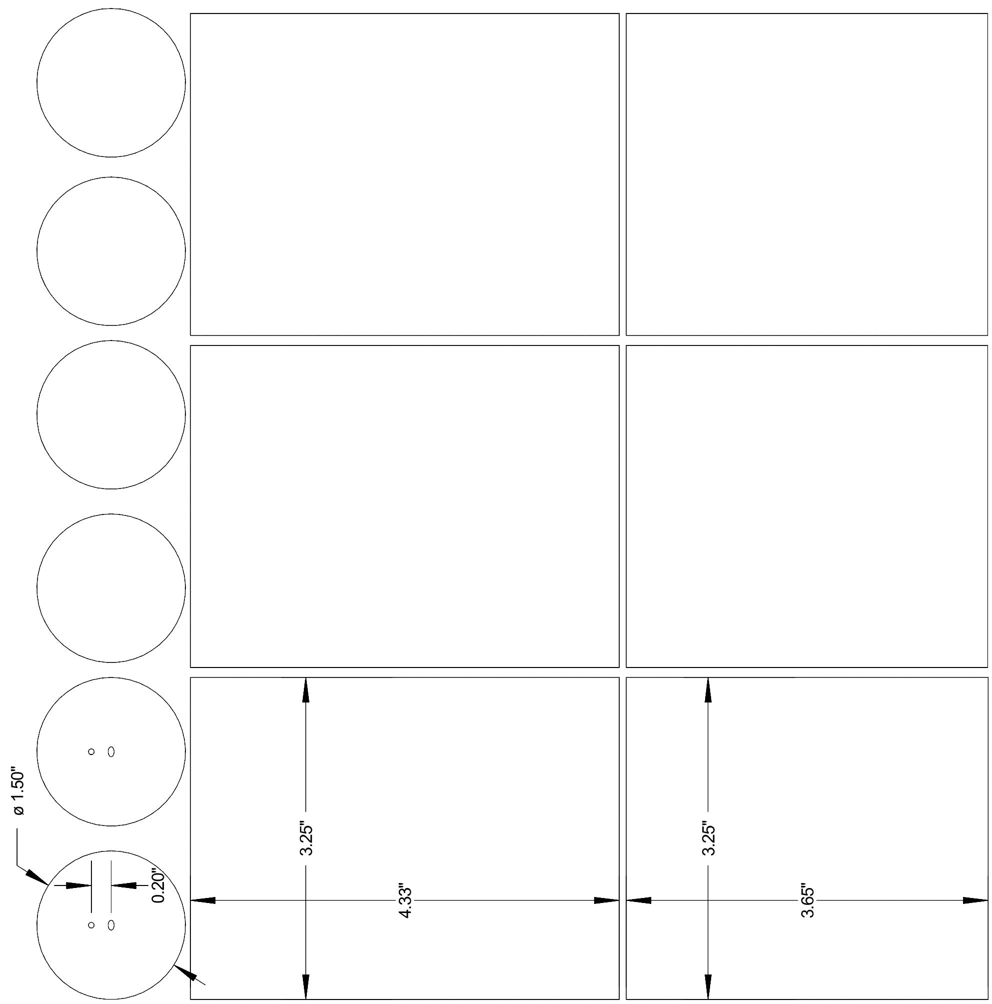
PFEIFFER VACUUM

OUTSET Engineering Drawing


GENERAL NOTES:
1. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN mm.
2. WELD CF FLANGES ACCORDING TO MANUFACTURER'S RECOMMENDATIONS.
3. ALL WELDS MUST MAINTAIN LEAK RATES NOT GREATER THAN 1 X 10^-7 CC/SEC.
-1 ISOMETRIC VIEW
SCALE 2.000
-1 CONTAINER ASSEMBLY WELDMENT
SECTION A-A
SCALE 2.000
SECTION B-B
DETAIL A
SCALE 6.000
CORNER RELIEF
-5 LID ASSEMBLY WELDMENT
SECTION A-A
SCALE 2.000
-5 ISOMETRIC VIEW
SCALE 2.000
DETAIL B
SCALE 10.000
SEE NOTE 2
SEE DETAIL A
SEE DETAIL B
1 4EJP8 402500 CONICAL REDUCER,1.5" X .75" 304 SST 11
1 29145 F0275X000N CF FLANGE,BLANK,2-3/4 OD 304L 10
1 29145 F0133X075NT CF FLANGE,1-1/3 OD 304L 9
1 S17-25-NTPO-6 TUBE, 3/4" OD X .065" THK 304L 8
1 S17-25-NTPO-5 LID ASSEMBLY WELDMENT --- 7
QTY CAGE CODE PART OR IDENTIFYING NO NOMENCLATURE OR DESCRIPTION MATERIAL FIND NO
NEXT ASSEMBLY PARTS LIST
-5 LID ASSEMBLY WELDMENT PARTS LIST
1 29145 F0275X175NT CF FLANGE,2-3/4 OD 304L 6
1 29145 F0133X075NT CF FLANGE,1-1/3 OD 304L 5
1 S17-25-NTPO-4 TUBE, 3/4" OD X .065" THK 304L 4
1 S17-25-NTPO-3 TUBE, 1/4" OD X .035" THK 304L 3
1 S17-25-NTPO-2 CONTAINER BOTTOM 304L 2
1 S17-25-NTPO-1 CONTAINER ASSEMBLY WELDMENT --- 1
QTY CAGE CODE PART OR IDENTIFYING NO NOMENCLATURE OR DESCRIPTION MATERIAL FIND NO
NEXT ASSEMBLY PARTS LIST
-1 CONTAINER ASSEMBLY PARTS LIST
CERTIFIED FOR CONSTRUCTION
ISSUE DATE:
SCALE NOTED
DES R.H.HOWARD
DRW K.R.SMITH
CHK
UT-BATTELLE
Oak Ridge National Laboratory
HIGH TEMPERATURE CARBIDE FUEL
CARBIDE FUEL EXPERIMENT
PART DETAILS
S17-25-NTPO
THIS DRAWING PRODUCED ON PRO-ENGINEER

GFA Insulation Template

GFA Insulation template (intended for 1/8 in. thick felt)



Coorstek Zirconia Datasheet

YTZP Zirconia

	Properties		Units	Performance
MECHANICAL	Density		g/cm^3	6.02
	Crystal Size	Average	µm	1
	Water Absorption		%	0
	Gas Permeability			0
	Color			IVORY
	Flexural Strength (MOR)	20 °C	MPa	1240
	Elastic Modulus	20 °C	GPa	210
	Poisson's Ratio	20 °C		0.30
	Compressive Strength	20 °C	MPa	2500
	Hardness	Knoop 1000 g	kg/mm^2	1300
		Knoop 100 g	kg/mm^2	-
		Rockwell 45 N	R45N	81
		Vickers 0.5 kg	kg/mm^2	-
	Tensile Strength	25 °C	MPa	-
	Fracture Toughness	K_{Ic}	MPa-m$^{1/2}$	13
THERMAL	Thermal Conductivity	20 °C	W/m-K	2.2
	Coefficient of Thermal Expansion	25-1000 °C	1 X 10^{-6}/°C	10.3
	Specific Heat	100 °C	J/kg-K	400
	Thermal Shock Resistance	Δ T	°C	350
	Maximum Use Temperature		°C	1500
ELECTRICAL	Dielectric Strength	6.35 mm	ac-kV/mm	9.0
	Dielectric Constant	1 MHz, 25 °C		29.0
	Dielectric Loss (tan δ)	1 MHz, 25 °C		0.0010
	Volume Resistivity	25 °C	Ω-cm	$> 10^{13}$
		500 °C	Ω-cm	2 X 10^4
		1000 °C	Ω-cm	$< 10^3$

The chart is intended to illustrate typical properties. Property values vary with method of manufacture, size, and configuration of part. Data contained herein is not to be construed as absolute and does not constitute a representation or warranty for which CoorsTek assumes legal responsibility. All properties are measured according to international standards (ASTM, DIN, JIS, etc.) applicable to country of origin. Contact CoorsTek for more information.

CoorsTek
+1 303 271 7100
info@coorstek.com

Appendix II

Derivation of Closed Form Solution of 1-Dimensional Scoping Model

$h_{film} := 35000 \cdot \frac{W}{m^2 \cdot K}$ heat transfer coefficient (W/m^2-C)

$T_{bulk} := (48 + 273) \cdot K$ bulk temperature (C)

$pf := 1$

$k_{Al} := 9.1 \cdot \frac{W}{m \cdot K}$

$\rho_{Al} := 2.7 \cdot \frac{gm}{cm^3}$

$Q_{Al} := 0 \frac{W}{gm}$

$Q_{v\_Al} := pf \cdot Q_{Al} \cdot \rho_{Al} = 0 \cdot \frac{W}{cm^3}$

$k_{C1} := 29.6 \cdot \frac{W}{m \cdot K}$

$\rho_{C1} := 1.8 \cdot \frac{gm}{cm^3}$

$Q_{v\_C1} := Q_{C1} \cdot \rho_{C1} = 342 \cdot \frac{W}{cm^3}$

$k_{C2} := 0.9 \cdot \frac{W}{m \cdot K}$

$\rho_{C2} := 1.8 \cdot \frac{gm}{cm^3}$

$Q_{C2} := 2.35 \frac{W}{gm}$

$Q_{v\_C2} := Q_{C2} \cdot \rho_{C2} = 4.23 \cdot \frac{W}{cm^3}$

$Q_{v\_hous} := Q_{v\_Al}$

$Q_{v\_sample} := Q_{v\_C1}$

$R_{sample} := \frac{12.7mm}{2} = 6.35 \cdot mm$

$R_{ins\_i} := \frac{25.4mm}{2} = 12.7 \cdot mm$

$R_{ins\_o} := \frac{2 \cdot R_{ins\_i} + 2 \cdot \frac{1}{8} in}{2} = 15.875 \cdot mm$

$R_{hous\_i} := R_{ins\_o} = 15.875 \cdot mm$

$R_{hous\_o} := \frac{3.81cm}{2} = 19.05 \cdot mm$

$Qgen_{sample} := Q_{v\_sample} \cdot \pi \cdot \left(R_{sample}{}^{2}\right) = 4.332 \times 10^{4} \cdot \frac{W}{m}$

$Qgen_{hous} := 0 \frac{W}{m}$

$q_{in\_hous} := Qgen_{sample} = 4.332 \times 10^{4} \cdot \frac{W}{m}$

$q_{in\_cool} := q_{in\_hous} + Qgen_{hous} = 4.332 \times 10^{4} \cdot \frac{W}{m}$

$T_{hous\_o} := T_{bulk} + \frac{q_{in\_cool}}{h_{film} \cdot 2 \cdot \pi \cdot R_{hous\_o}}$ $\qquad T_{hous\_o} / °C = 58$

$$T_{hous\_i} := \frac{Q_{v\_hous}}{4 \cdot k_{Al}} \cdot \left(R_{hous\_o}{}^{2} - R_{hous\_i}{}^{2}\right) \ldots \\ + \left(\frac{Q_{v\_hous} \cdot R_{hous\_i}{}^{2}}{2 \cdot k_{Al}} - \frac{q_{in\_hous}}{2 \cdot \pi \cdot k_{Al}}\right) \cdot \ln\left(\frac{R_{hous\_i}}{R_{hous\_o}}\right) + T_{hous\_o}$$ $T_{hous\_i} / °C = 196$

$T_{ins\_o} := T_{hous\_i}$ $\qquad T_{ins\_o} / °C = 196$

$$T_{ins\_i} := \frac{Q_{v\_C2}}{4\cdot k_{C2}}\cdot\left(R_{ins\_o}{}^{2} - R_{ins\_i}{}^{2}\right) \ldots$$

$$+\left(\frac{Q_{v\_hous}\cdot R_{ins\_i}{}^{2}}{2\cdot k_{C2}} - \frac{q_{in\_hous}}{2\cdot\pi\cdot k_{C2}}\right)\cdot\ln\left(\frac{R_{ins\_i}}{R_{ins\_o}}\right) + T_{ins\_o}$$

$$T_{ins\_i}/°C = 2013$$

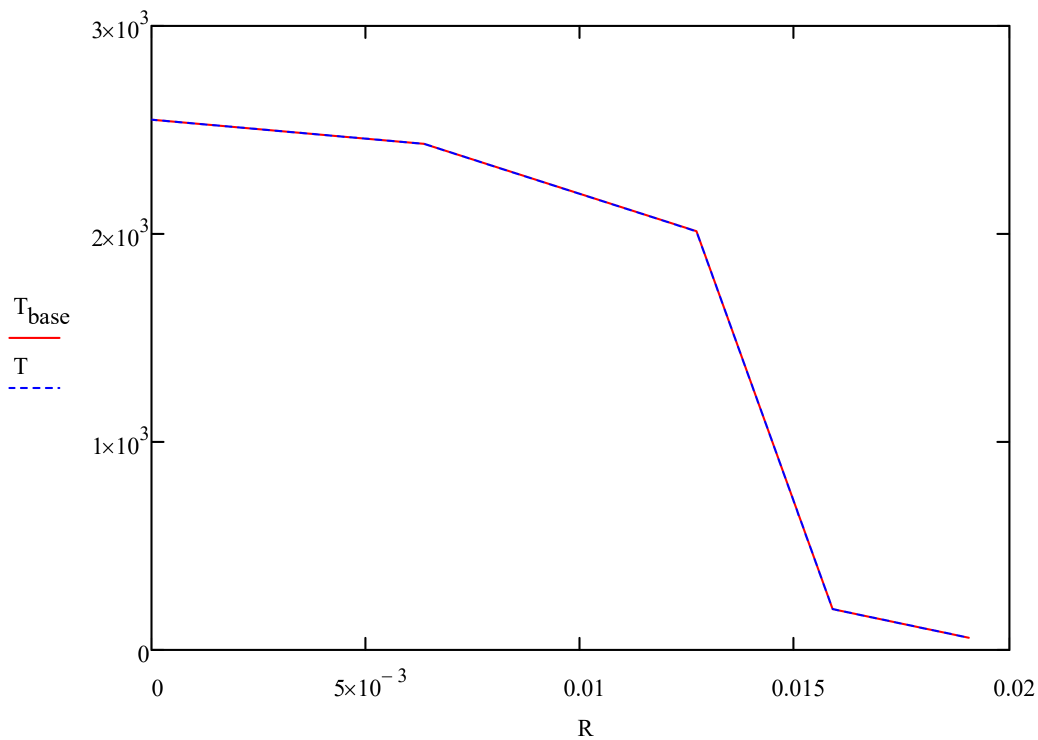
$$T_{sample\_o} := \left[\frac{Qgen_{sample}}{2\pi\cdot R_{sample}}\cdot\frac{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{R_{sample}}{R_{ins\_i}}}{\sigma} + T_{ins\_i}{}^{4}\right]^{\frac{1}{4}}$$

$$T_{sample\_o}/°C = 2433$$

$$T_{sample\_CL} := \left(\frac{Qgen_{sample}}{4\cdot\pi\cdot k_{C1}}\right) + T_{sample\_o}$$

$$T_{sample\_CL}/°C = 2549$$

$$R := \begin{pmatrix} 0 \\ \frac{R_{sample}}{m} \\ \frac{R_{ins\_i}}{m} \\ \frac{R_{ins\_o}}{m} \\ \frac{R_{hous\_o}}{m} \end{pmatrix} \qquad T_{base} := \begin{pmatrix} 2.549\times10^{3} \\ 2.433\times10^{3} \\ 2.013\times10^{3} \\ 196.338 \\ 58.191 \end{pmatrix} \qquad T := \begin{pmatrix} T_{sample\_CL}/°C \\ T_{sample\_o}/°C \\ T_{ins\_i}/°C \\ T_{ins\_o}/°C \\ T_{hous\_o}/°C \end{pmatrix} = \begin{pmatrix} 2.549\times10^{3} \\ 2.433\times10^{3} \\ 2.013\times10^{3} \\ 196.338 \\ 58.191 \end{pmatrix}$$

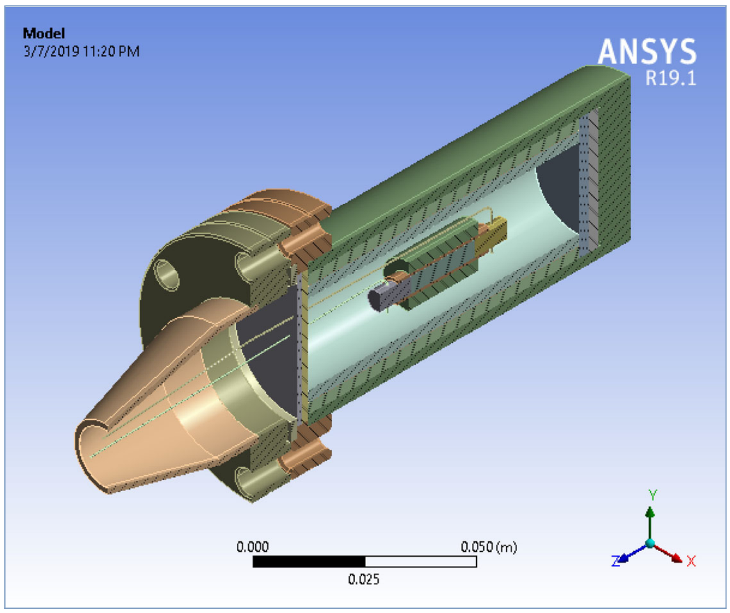


3×10^3
2×10^3
1×10^3
0
T_base
T
0
5×10^−3
0.01
0.015
0.02
R

Appendix III
Steady State Model ANSYS Summary Report

Project

First Saved	Sunday, October 28, 2018
Last Saved	Monday, March 4, 2019
Product Version	19.1 Release
Save Project Before Solution	No
Save Project After Solution	No



Contents

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (C2)

Geometry

TABLE 2
Model (C2) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	/home/urh/Desktop/WB/TIN_MAN_files/dp0/Geom/DM/Geom.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	6.9088e-002 m
Length Y	8.7854e-002 m
Length Z	0.16479 m
Properties	
Volume	1.9153e-004 m³
Mass	1.5035 kg
Statistics	
Bodies	27
Active Bodies	22
Nodes	413590
Elements	126848
Mesh Metric	None
Update Options	
Assign Default Material	No
Advanced Geometry Options	
Analysis Type	3-D

TABLE 3
Model (C2) > Geometry > Parts

Object Name	*SS_HOUSING (Transient Thermal)*	*SS_HOUSING_FLANGE (Transient Thermal)*	*SS_VIEWPORT_TUBE (Transient Thermal)*	*SS_VIEWPORT_FLANGE (Transient Thermal)*	*SS_EXHAUST_TUBE (Transient Thermal)*	*SS_REDUCER_LOWER_ (Transient Therma*
State	Meshed		Suppressed			
						Graphics Prop
Visible	Yes		No			

Transparency	1					
						Definitio
Suppressed	No		Yes			
Stiffness Behavior						I
Coordinate System						Global Coordinate S
Reference Temperature						By E
Behavior						
						Material
Assignment						Stru
Nonlinear Effects						
Thermal Strain Effects						
						Bounding E
Length X	4.4703e-002 m	6.9088e-002 m	1.905e-002 m	3.302e-002 m	2.102e-002 m	6.9088e-002 m
Length Y	4.4704e-002 m	6.9088e-002 m	1.9779e-002 m	7.62e-003 m	6.35e-003 m	6.9088e-002 m
Length Z	0.1017 m	1.27e-002 m	1.905e-002 m	3.302e-002 m	6.35e-003 m	1.27e-002 m
						Propertie
Volume	5.376e-005 m³	2.628e-005 m³	1.6435e-006 m³	4.0599e-006 m³	3.1508e-007 m³	3.1093e-005 m
Mass	0.42202 kg	0.2063 kg	1.2901e-002 kg	3.1871e-002 kg	2.4734e-003 kg	0.24408 kg
Centroid X	-2.6161e-018 m	9.1066e-008 m	-1.431e-004 m	1.0759e-013 m	1.9661e-002 m	7.6927e-008 m
Centroid Y	9.8474e-019 m	1.015e-007 m	3.0754e-002 m	4.0668e-002 m	2.9e-002 m	-8.5792e-008 m
Centroid Z	4.1127e-002 m	0.10069 m	5.9026e-002 m			0.11348 m
Moment of Inertia Ip1	5.1604e-004 kg·m²	8.8556e-005 kg·m²	8.6496e-007 kg·m²	2.9379e-006 kg·m²	9.7674e-008 kg·m²	9.4636e-005 kg·r
Moment of Inertia Ip2	1.6016e-004 kg·m²	8.8819e-005 kg·m²	8.734e-007 kg·m²	2.9378e-006 kg·m²	9.7577e-008 kg·m²	9.4899e-005 kg·r
Moment of Inertia Ip3	5.1604e-004 kg·m²	1.72e-004 kg·m²	9.8459e-007 kg·m²	5.591e-006 kg·m²	1.8915e-008 kg·m²	1.8344e-004 kg·r
						Statistic
Nodes	32278	25104	0			9556
Elements	18454	15668	0			5702
Mesh Metric						
						Transfer Prop
Source						B4::Tra
Read Only						

TABLE 4
Model (C2) > Geometry > SS_HOUSING(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_HOUSING(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.

MAT_SS304,matid
```

TABLE 5
Model (C2) > Geometry > SS_HOUSING_FLANGE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_HOUSING_FLANGE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 6
Model (C2) > Geometry > SS_VIEWPORT_TUBE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_VIEWPORT_TUBE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 7
Model (C2) > Geometry > SS_VIEWPORT_FLANGE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	

Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_VIEWPORT_FLANGE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 8
Model (C2) > Geometry > SS_EXHAUST_TUBE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_EXHAUST_TUBE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 9
Model (C2) > Geometry > SS_REDUCER_LOWER_FLANGE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	

ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_REDUCER_LOWER_FLANGE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 10
Model (C2) > Geometry > GFA_INSULATOR_BOTTOM_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	1.
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_BOTTOM_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.

GFA_K_pert  = ARG1
*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 11
Model (C2) > Geometry > GFA_INSULATOR_BOTTOM_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	

ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_BOTTOM_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 12
Model (C2) > Geometry > GFA_INSULATOR_WALL_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_WALL_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 13
Model (C2) > Geometry > TI_GETTER(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	

ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > TI_GETTER(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
MAT_TI6AL4V,matid
```

TABLE 14
Model (C2) > Geometry > GFA_INSULATOR_WALL_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_WALL_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 15
Model (C2) > Geometry > Parts

Object Name	*GFA_INSULATOR_TOP_2 (Transient Thermal)*	*GFA_INSULATOR_TOP_1 (Transient Thermal)*	*CU_HOUSLING_FLANGE_GASKET (Transient Thermal)*	*SS_VIEWPORT (Transient Thermal)*	*CU_VIEWPORT_FLANGE_GA: (Transient Thermal)*
State	Meshed			Suppressed	
					Graphics P
Visible	Yes			No	
Transparency	1				
					Defini
Suppressed	No			Yes	
Stiffness Behavior					
Coordinate System					Global Coordina
Reference Temperature					B
Behavior					
					Mate
Assignment					S
Nonlinear Effects					
Thermal Strain Effects					
					Boundir
Length X	4.1402e-002 m		4.8e-002 m	3.3782e-002 m	2.1e-002 m
Length Y	4.1402e-002 m		4.8e-002 m	8.8646e-003 m	2.e-003 m

Length Z	1.7463e-003 m		2.e-003 m	3.3782e-002 m	2.1e-002 m
					Prope
Volume	2.349e-006 m^3		1.4681e-006 m^3	5.1296e-006 m^3	2.9047e-007 m^3
Mass	1.8439e-002 kg		1.1525e-002 kg	4.0267e-002 kg	2.2802e-003 kg
Centroid X	3.7627e-021 m		3.3468e-008 m	1.5725e-009 m	7.5175e-007 m
Centroid Y	2.8028e-017 m	2.8348e-017 m	-1.7758e-006 m	4.8945e-002 m	4.4253e-002 m
Centroid Z	0.10258 m	0.10432 m	0.10619 m	5.9026e-002 m	
Moment of Inertia Ip1	1.9785e-006 kg·m^2		2.6475e-006 kg·m^2	3.6734e-006 kg·m^2	1.0002e-007 kg·m^2
Moment of Inertia Ip2	3.9475e-006 kg·m^2		5.2873e-006 kg·m^2	6.8816e-006 kg·m^2	1.9852e-007 kg·m^2
Moment of Inertia Ip3	1.9785e-006 kg·m^2		2.6475e-006 kg·m^2	3.6734e-006 kg·m^2	1.0002e-007 kg·m^2
					Statis
Nodes	9143	8907	172	0	
Elements	1872	1824	16	0	
Mesh Metric					
					Transfer P
Source					B4::
Read Only					

TABLE 16
Model (C2) > Geometry > GFA_INSULATOR_TOP_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_TOP_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 17
Model (C2) > Geometry > GFA_INSULATOR_TOP_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	

ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_INSULATOR_TOP_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 18
Model (C2) > Geometry > CU_HOUSLING_FLANGE_GASKET(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL)(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > CU_HOUSLING_FLANGE_GASKET(Transient Thermal) > Commands (APDL)(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_COPPER, matid
```

TABLE 19
Model (C2) > Geometry > SS_VIEWPORT(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	

ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_VIEWPORT(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 20
Model (C2) > Geometry > CU_VIEWPORT_FLANGE_GASKET(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > CU_VIEWPORT_FLANGE_GASKET(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_COPPER,matid
```

TABLE 21
Model (C2) > Geometry > GRAPHITE_CRUCIBLE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GRAPHITE_CRUCIBLE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.
```

```
!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 22
Model (C2) > Geometry > ZRO2_TUBE(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > ZRO2_TUBE(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_ZRO2,matid
```

TABLE 23
Model (C2) > Geometry > GFA_FILAMENT(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL)(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GFA_FILAMENT(Transient Thermal) > Commands (APDL)(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_GFA-GRAPHITE,matid
```

TABLE 24
Model (C2) > Geometry > GRAPHITE_FILAMENT_PLUG_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GRAPHITE_FILAMENT_PLUG_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 25
Model (C2) > Geometry > GRAPHITE_FILAMENT_PLUG_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > GRAPHITE_FILAMENT_PLUG_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 26
Model (C2) > Geometry > MO_ELECTRODE_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	

Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > MO_ELECTRODE_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_MOLY,matid
```

TABLE 27
Model (C2) > Geometry > Parts

Object Name	*TUNGSTEN_TC_1 (Transient Thermal)*	*TUNGSTEN_TC_2 (Transient Thermal)*	*MO_ELECTRODE_1 (Transient Thermal)*	*SS_REDUCER (Transient Thermal)*	*MO_WINDOW (Transient Thermal)*
State	Meshed				
Graphics Properties					
Visible	Yes				
Transparency	1				
Definition					
Suppressed	No				
Stiffness Behavior	Flexible				
Coordinate System	Global Coordinate System(Transient Thermal)				
Reference Temperature	By Environment				
Behavior	None				
Material					
Assignment	Structural Steel				
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				
Bounding Box					
Length X	2.8874e-003 m	1.9203e-003 m	4.5204e-003 m	3.81e-002 m	2.534e-002 m
Length Y	5.988e-003 m	1.044e-003 m	9.9958e-003 m	3.81e-002 m	2.534e-002 m
Length Z	0.10576 m		8.945e-002 m	4.7575e-002 m	8.53e-002 m
Properties					
Volume	2.0809e-008 m³	2.0764e-008 m³	1.121e-008 m³	7.4409e-006 m³	5.7526e-007 m³
Mass	1.6335e-004 kg	1.63e-004 kg	8.8e-005 kg	5.8411e-002 kg	4.5158e-003 kg
Centroid X	4.1991e-003 m	5.6401e-003 m	-1.8869e-003 m	3.822e-006 m	7.6808e-017 m
Centroid Y	-2.3207e-003 m	4.5811e-004 m	1.4298e-003 m	-2.0307e-010 m	1.6233e-017 m
Centroid Z	0.11194 m		0.11622 m	0.13828 m	5.9e-002 m
Moment of Inertia Ip1	1.5216e-007 kg·m²	1.5025e-007 kg·m²	6.7586e-008 kg·m²	1.7177e-005 kg·m²	3.0806e-006 kg·m²
Moment of Inertia Ip2	1.5214e-007 kg·m²	1.5025e-007 kg·m²	6.7362e-008 kg·m²	1.7177e-005 kg·m²	3.0806e-006 kg·m²
Moment of Inertia Ip3	2.6707e-011 kg·m²	6.0601e-012 kg·m²	2.2542e-010 kg·m²	1.4205e-005 kg·m²	7.1279e-007 kg·m²
Statistics					
Nodes	1956		2130	432	9626
Elements	363		396	56	1428
Mesh Metric	None				
Transfer Properties					
Source	B4::Transient Thermal				
Read Only	Yes				

TABLE 28
Model (C2) > Geometry > TUNGSTEN_TC_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	

Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > TUNGSTEN_TC_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_TUNGSTEN,matid
```

TABLE 29
Model (C2) > Geometry > TUNGSTEN_TC_2(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > TUNGSTEN_TC_2(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_TUNGSTEN,matid
```

TABLE 30
Model (C2) > Geometry > MO_ELECTRODE_1(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	

ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > MO_ELECTRODE_1(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_MOLY,matid
```

TABLE 31
Model (C2) > Geometry > SS_REDUCER(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL) 2(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > SS_REDUCER(Transient Thermal) > Commands (APDL) 2(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 32
Model (C2) > Geometry > MO_WINDOW(Transient Thermal) > Command Snippet

Object Name	*Commands (APDL)(Transient Thermal)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

Model (C2) > Geometry > MO_WINDOW(Transient Thermal) > Commands (APDL)(Transient Thermal)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.



MAT_MOLY,matid
```

Coordinate Systems

TABLE 33
Model (C2) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*	*Global Coordinate System(Transient Thermal)*
State	Fully Defined	
Definition		
Type	Cartesian	
Coordinate System ID	0.	
Coordinate System		Program Controlled
APDL Name		
Suppressed		No
Origin		
Origin X	0. m	
Origin Y	0. m	
Origin Z	0. m	
Define By		Global Coordinates
Location		Defined
Directional Vectors		
X Axis Data	[1. 0. 0.]	
Y Axis Data	[0. 1. 0.]	
Z Axis Data	[0. 0. 1.]	
Principal Axis		
Axis		X
Define By		Fixed Vector
Orientation About Principal Axis		
Axis		Y
Define By		Fixed Vector
Transformations		
Base Configuration		Absolute
Transformed Configuration		[0. 0. 0.]
Transfer Properties		
Source		B4::Transient Thermal
Read Only		Yes

Connections

TABLE 34
Model (C2) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 35
Model (C2) > Connections > Contacts(Transient Thermal)

Object Name	*Contacts(Transient Thermal)*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Source Assembly
Source Assembly	B4::Transient Thermal
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	4.9778e-004 m
Use Range	No
Face/Face	Yes
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies

Search Across	Bodies
Statistics	
Connections	41
Active Connections	35
Transfer Properties	
Source	B4::Transient Thermal
Read Only	Yes

TABLE 36
Model (C2) > Connections > Contacts(Transient Thermal) > Contact Regions

Object Name	*No Separation - SS_HOUSING To SS_HOUSING_FLANGE (Transient Thermal)*	*Bonded - SS_HOUSING To SS_VIEWPORT_TUBE (Transient Thermal)*	*Frictionless - SS_HOUSING To GFA_INSULATOR_BOTTOM_1 (Transient Thermal)*	*Frictionless - SS_HOUSING To GFA_INSULATOR_BOTTOM_2 (Transient Thermal)*	*Frictionless - SS_HOUSIN To GFA_INSULATOR_WALL_ (Transient Thermal)*
State	Fully Defined	Suppressed			
Scoping Method					
Contact	3 Faces	2 Faces	3 Faces	2 Faces	
Target	15 Faces	No Selection	3 Faces	2 Faces	
Contact Bodies	SS_HOUSING(Transient Thermal)				
Target Bodies	SS_HOUSING_FLANGE (Transient Thermal)	SS_VIEWPORT_TUBE (Transient Thermal)	GFA_INSULATOR_BOTTOM_1 (Transient Thermal)	GFA_INSULATOR_BOTTOM_2 (Transient Thermal)	GFA_INSULATOR_WALL_ (Transient Thermal)
Protected					
Type	No Separation	Bonded	Frictionless		
Scope Mode					
Behavior					
Trim Contact					
Trim Tolerance					
Suppressed					
Formulation					
Small Sliding					
Detection Method					
Thermal Conductance					
Pinball Region					
Elastic Slip Tolerance		Program Controlled			
Time Step Controls			None		
Contact Geometry Correction					
Target Geometry Correction					
Interface Treatment			Add Offset, No Ramping		
Offset			0. m		
Source					
Read Only					

TABLE 37
Model (C2) > Connections > Contacts(Transient Thermal) > Contact Regions

Object Name	*Bonded - SS_VIEWPORT_TUBE To SS_EXHAUST_TUBE (Transient Thermal)*	*No Separation - SS_VIEWPORT_FLANGE To SS_VIEWPORT (Transient Thermal)*	*No Separation - SS_VIEWPORT_FLANGE To CU_VIEWPORT_FLANGE_GASKET (Transient Thermal)*	*Frictionless - SS_REDUCER_LOWER_FLANGE To CU_HOUSLING_FLANGE_GASKET (Transient Thermal)*	*Bo SS_REDUCER To SS_RED Th*
State	Suppressed				
Scoping Method					
Contact	No Selection			2 Faces	3
Target	No Selection			2 Faces	3
Contact Bodies	SS_VIEWPORT_TUBE (Transient Thermal)	SS_VIEWPORT_FLANGE(Transient Thermal)		SS_REDUCER_LOWER_FLANGE(Transien	
Target Bodies	SS_EXHAUST_TUBE (Transient Thermal)	SS_VIEWPORT(Transient Thermal)	CU_VIEWPORT_FLANGE_GASKET (Transient Thermal)	CU_HOUSLING_FLANGE_GASKET (Transient Thermal)	SS_REDUCER
Protected					
Type	Bonded	No Separation		Frictionless	B
Scope Mode					
Behavior					

Trim Contact				
Trim Tolerance				
Suppressed				
Formulation				
Small Sliding				
Detection Method				
Elastic Slip Tolerance	Program Controlled			Prograr
Thermal Conductance				
Pinball Region				
Time Step Controls			None	
Contact Geometry Correction				
Target Geometry Correction				
Interface Treatment			Add Offset, No Ramping	
Offset			0. m	
Source				
Read Only				

TABLE 38
Model (C2) > Connections > Contacts(Transient Thermal) > Contact Regions

Object Name	*Frictionless - GFA_INSULATOR_WALL_1 To GFA_INSULATOR_TOP_2 (Transient Thermal)*	*Frictionless - TI_GETTER To GFA_INSULATOR_WALL_2 (Transient Thermal)*	*Frictionless - TI_GETTER To GFA_INSULATOR_TOP_2 (Transient Thermal)*	*Frictionless - GFA_INSULATOR_WALL_2 To GFA_INSULATOR_TOP_2 (Transient Thermal)*	*Frictionless - GFA_INSULATOR_TOP_ To GFA_INSULATOR_TOP_ (Transient Thermal)*
State	Fully Defined				
Scoping Method					
Contact	1 Face	2 Faces	1 Face		
Target	1 Face	2 Faces	1 Face		
Contact Bodies	GFA_INSULATOR_WALL_1 (Transient Thermal)	TI_GETTER(Transient Thermal)		GFA_INSULATOR_WALL_2 (Transient Thermal)	GFA_INSULATOR_TOP_ (Transient Thermal)
Target Bodies	GFA_INSULATOR_TOP_2 (Transient Thermal)	GFA_INSULATOR_WALL_2 (Transient Thermal)	GFA_INSULATOR_TOP_2(Transient Thermal)		GFA_INSULATOR_TOP_ (Transient Thermal)
Protected					
Type	Frictionless				
Scope Mode					
Behavior					
Trim Contact					
Trim Tolerance					
Suppressed					
Formulation					
Small Sliding					
Detection Method					
Thermal Conductance	Program Controlled				
Pinball Region	Program Controlled				
Time Step Controls	None				
Thermal Conductance Value					
Pinball Radius					
Geon					
Interface Treatment	Add Offset, No Ramping				
Offset	0. m				
Contact Geometry Correction					
Target Geometry					

Correction	
Tra	
Source	
Read Only	Yes

TABLE 39
Model (C2) > Connections > Contacts(Transient Thermal) > Contact Regions

Object Name	*No Separation - ZRO2_TUBE To GRAPHITE_FILAMENT_PLUG_1 (Transient Thermal)*	*No Separation - ZRO2_TUBE To GRAPHITE_FILAMENT_PLUG_2 (Transient Thermal)*	*No Separation - GFA_FILAMENT To GRAPHITE_FILAMENT_PLUG_1 (Transient Thermal)*	*No Separation - GFA_FILAMENT To GRAPHITE_FILAMENT_PLUG_2 (Transient Thermal)*	*GRA*
State	Fully Defined				
Scope					
Scoping Method	Geometry Selection				
Contact	2 Faces		1 Face		
Target	2 Faces		1 Face		
Contact Bodies	ZRO2_TUBE(Transient Thermal)		GFA_FILAMENT(Transient Thermal)		GRA
Target Bodies	GRAPHITE_FILAMENT_PLUG_1 (Transient Thermal)	GRAPHITE_FILAMENT_PLUG_2 (Transient Thermal)	GRAPHITE_FILAMENT_PLUG_1 (Transient Thermal)	GRAPHITE_FILAMENT_PLUG_2 (Transient Thermal)	MC
Protected	No				
Definition					
Type	No Separation				
Scope Mode	Automatic				
Behavior	Asymmetric				
Trim Contact	Program Controlled				
Trim Tolerance	4.9778e-004 m				
Suppressed	No				
Advanced					
Formulation	Augmented Lagrange				
Small Sliding	Program Controlled				
Detection Method	Program Controlled				
Thermal Conductance	Program Controlled				
Pinball Region	Program Controlled				
Pinball Radius					
Time Step Controls					
Elastic Slip Tolerance					
Geometric Modification					
Contact Geometry Correction	None				
Target Geometry Correction	None				
Interface Treatment					
Offset					
Transfer Properties					
Source	B4::Transient Thermal				
Read Only	Yes				

Mesh

TABLE 40
Model (C2) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Quality	
Mesh Metric	None
Statistics	
Nodes	413590
Elements	126848
Model Assembly	
Read Only	Yes

Steady-State Thermal (C3)

TABLE 41

Model (C2) > Analysis

Object Name	*Steady-State Thermal (C3)*
State	Solved
Definition	
Physics Type	Thermal
Analysis Type	Steady-State
Solver Target	Mechanical APDL
Options	
Generate Input Only	No

TABLE 42
Model (C2) > Steady-State Thermal (C3) > Initial Condition

Object Name	*Initial Temperature*
State	Fully Defined
Definition	
Initial Temperature	Uniform Temperature
Initial Temperature Value	85. °C

TABLE 43
Model (C2) > Steady-State Thermal (C3) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Direct
Solver Pivot Checking	Program Controlled
Radiosity Controls	
Radiosity Solver	Program Controlled
Flux Convergence	1.e-004
Maximum Iteration	1000.
Solver Tolerance	0.1 W/m²
Over Relaxation	0.1
Hemicube Resolution	10.
Nonlinear Controls	
Heat Convergence	Program Controlled
Temperature Convergence	Program Controlled
Line Search	Program Controlled
Output Controls	
Calculate Thermal Flux	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	D:\Documents\TARGET CAPSULES\2018\NTP\Model\LIBBY\FInal mesh testing\NTP_Full contact_files\dp7\SYS-1\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	Yes
Contact Summary	Program Controlled
Delete Unneeded Files	No
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

TABLE 44
Model (C2) > Steady-State Thermal (C3) > Loads

Object Name	*Radiation - sample region*	*Radiation - wall insulation*	*Radiation - end insulation*	*Temperature - boundary condition*	*Heat Flux - input load*	*Radiation - refractrory metal leads*	*Temperature - refractrory metal leads*	*Radiation - crucible to leads*	*Radiation - leads to crucible*
State	Fully Defined								
Scope									
Scoping Method	Geometry Selection								
Geometry	14 Faces	1 Face	2 Faces	96 Faces	4 Faces	18 Faces	4 Faces	3 Faces	6 Faces
Definition									
Type	Radiation			Temperature	Heat Flux	Radiation	Temperature	Radiation	
Correlation	Surface to Surface					Surface to Surface		Surface to Surface	
Emissivity	0.75 (step applied)	0.15 (step applied)	0.75 (step applied)			0.15 (step applied)		0.75 (step applied)	0.15 (step applied)
Ambient Temperature	85. °C (ramped)					85. °C (ramped)		85. °C (ramped)	
Enclosure	1.					1.		2.	
Enclosure Type	Open					Open		Open	
Suppressed	No								
					8.18e+005				

Magnitude		85. °C (ramped)	W/m² (ramped)		175. °C (ramped)	

FIGURE 1
Model (C2) > Steady-State Thermal (C3) > Radiation - sample region

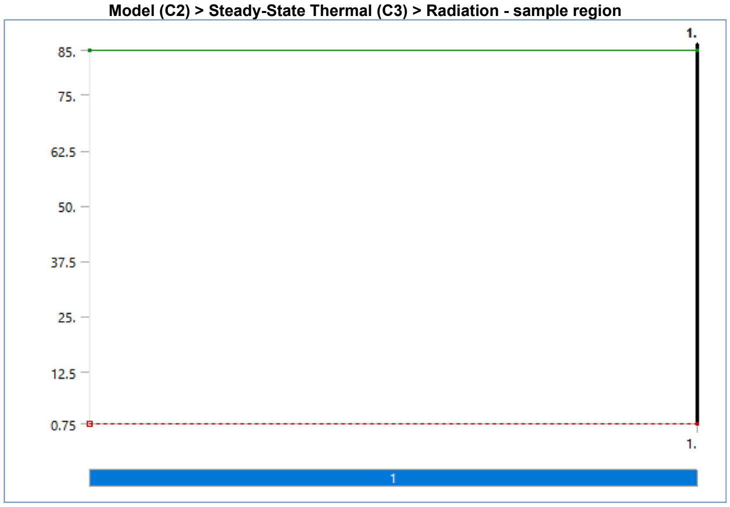


FIGURE 2
Model (C2) > Steady-State Thermal (C3) > Radiation - wall insulation

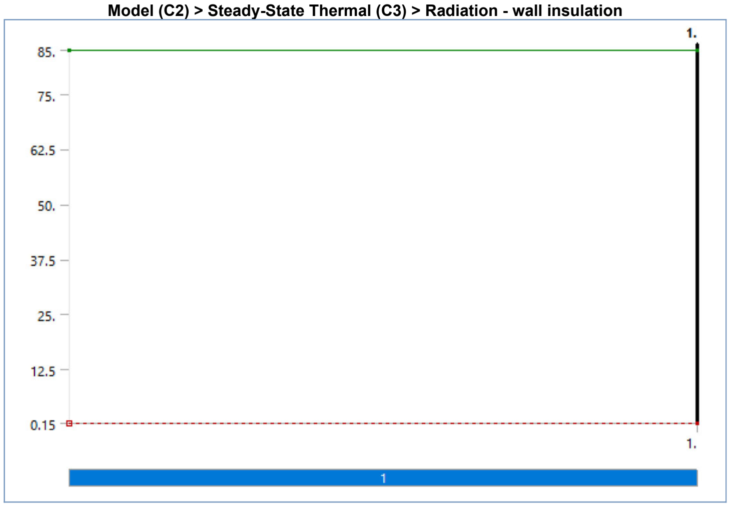


FIGURE 3
Model (C2) > Steady-State Thermal (C3) > Radiation - end insulation

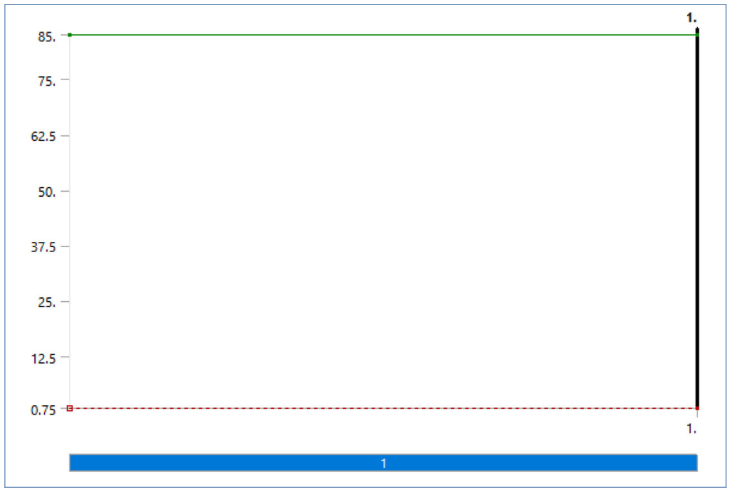


FIGURE 4
Model (C2) > Steady-State Thermal (C3) > Temperature - boundary condition

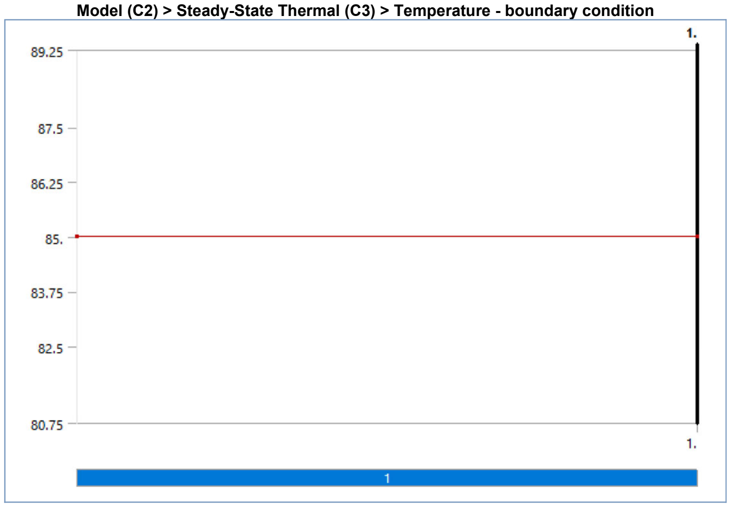


FIGURE 5
Model (C2) > Steady-State Thermal (C3) > Heat Flux - input load

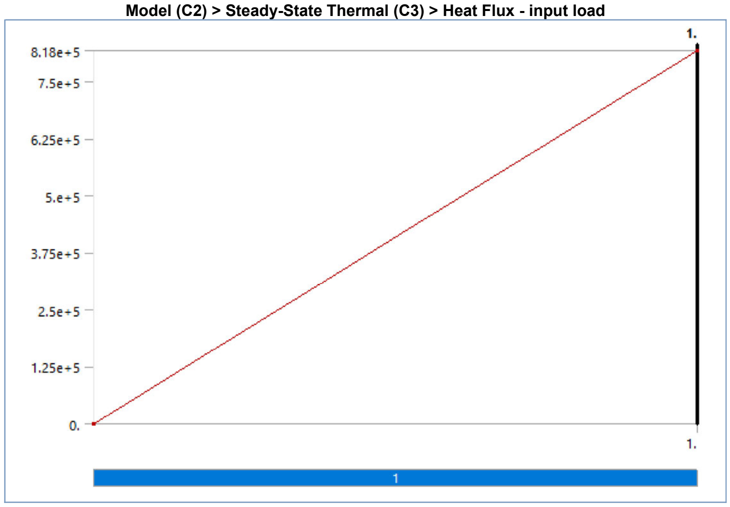


FIGURE 6
Model (C2) > Steady-State Thermal (C3) > Radiation - refractrory metal leads

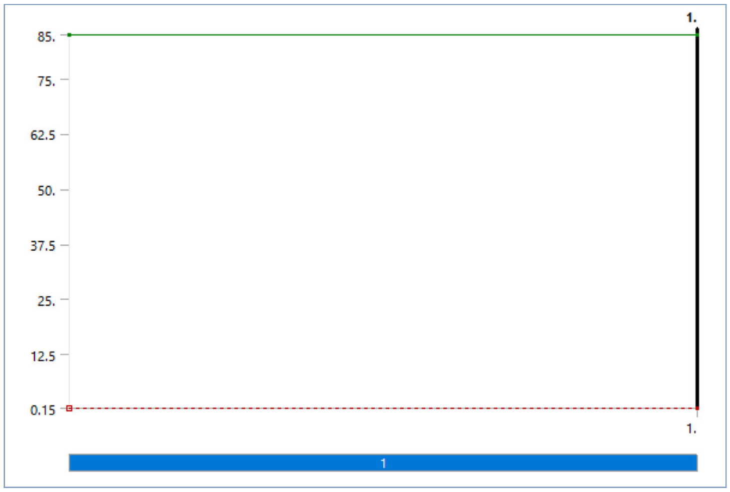


FIGURE 7
Model (C2) > Steady-State Thermal (C3) > Temperature - refractrory metal leads

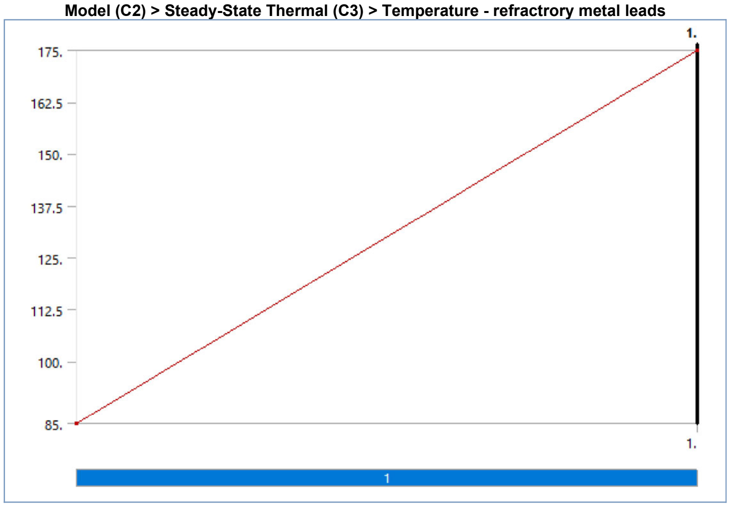


FIGURE 8
Model (C2) > Steady-State Thermal (C3) > Radiation - crucible to leads

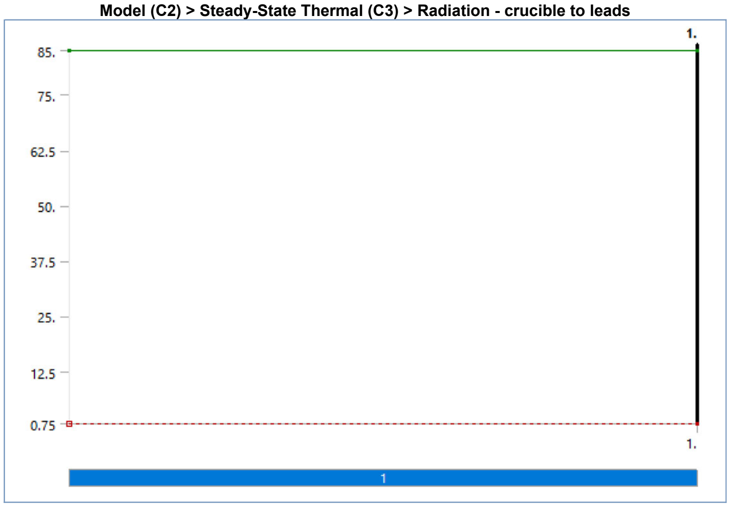
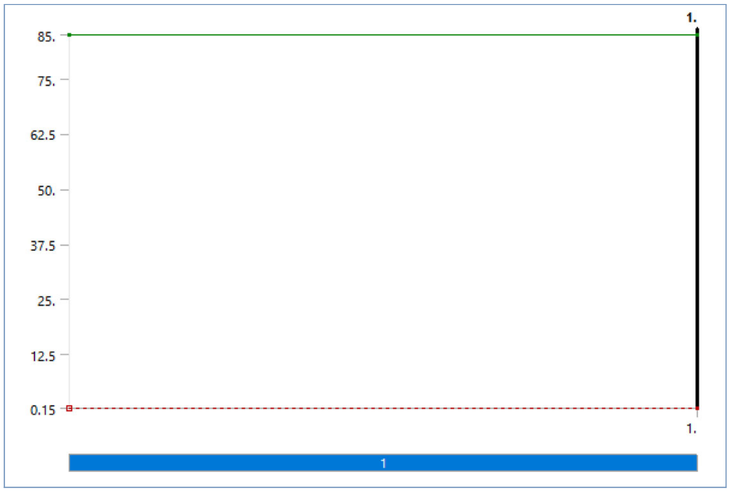


FIGURE 9
Model (C2) > Steady-State Thermal (C3) > Radiation - leads to crucible



Solution (C4)

TABLE 45
Model (C2) > Steady-State Thermal (C3) > Solution

Object Name	*Solution (C4)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
MAPDL Elapsed Time	8 h 50 m
MAPDL Memory Used	4.2695 GB
MAPDL Result File Size	202.44 MB
Post Processing	
Beam Section Results	No
On Demand Stress/Strain	No

TABLE 46
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 47
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Probes

Object Name	*T Probe - Thermocouple*
State	Solved
Definition	
Type	Temperature
Location Method	Geometry Selection
Geometry	2 Faces
Suppressed	No
Options	
Display Time	End Time
Spatial Resolution	Use Maximum
Results	
Temperature	1988. °C
Maximum Value Over Time	
Temperature	1988. °C
Minimum Value Over Time	
Temperature	1703.4 °C
Information	
Time	1. s
Load Step	1

Substep	2
Iteration Number	1615

FIGURE 10
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > T Probe - Thermocouple

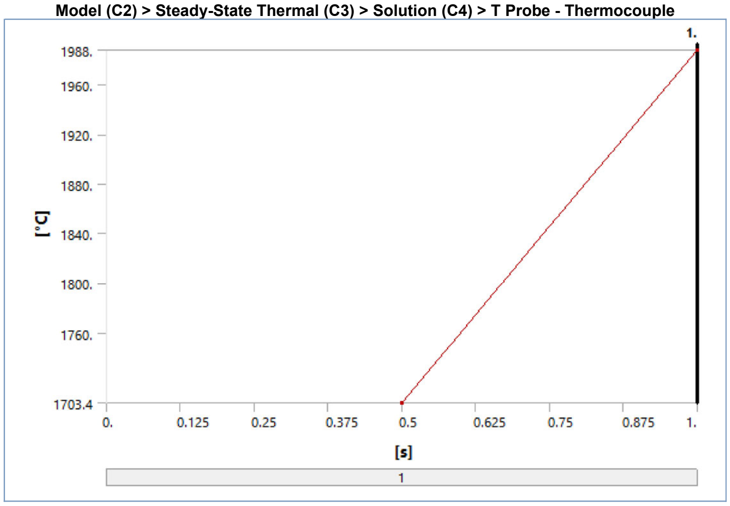


TABLE 48
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > T Probe - Thermocouple

Time [s]	T Probe - Thermocouple [°C]
0.5	1703.4
1.	1988.

Specimen Region

TABLE 49
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > Results

Object Name	*T - Crucible*	*T - Filament*	*T - Thermocouple*	*T - ZrO2 insulation*
State	Solved			
Scope				
Scoping Method	Geometry Selection			
Geometry	1 Body		2 Bodies	1 Body
Definition				
Type	Temperature			
By	Time			
Display Time	Last			
Calculate Time History	Yes			
Identifier				
Suppressed	No			
Results				
Minimum	1924.2 °C	2040.9 °C	175. °C	1931.5 °C
Maximum	1997.4 °C	2359.7 °C	1988. °C	2358. °C
Average	1977.6 °C	2296.8 °C	1140. °C	2140.5 °C
Minimum Occurs On	GRAPHITE_CRUCIBLE(Transient Thermal)	GFA_FILAMENT(Transient Thermal)	TUNGSTEN_TC_2(Transient Thermal)	ZRO2_TUBE(Transient Thermal)
Maximum Occurs On	GRAPHITE_CRUCIBLE(Transient Thermal)	GFA_FILAMENT(Transient Thermal)	TUNGSTEN_TC_2(Transient Thermal)	ZRO2_TUBE(Transient Thermal)
Minimum Value Over Time				
Minimum	1659.4 °C	1719.7 °C	130. °C	1658.9 °C
Maximum	1924.2 °C	2040.9 °C	175. °C	1931.5 °C
Maximum Value Over Time				
Minimum	1709.3 °C	1909.8 °C	1703.4 °C	1908. °C
Maximum	1997.4 °C	2359.7 °C	1988. °C	2358. °C
Information				
Time	1. s			
Load Step	1			
Substep	2			
Iteration Number	1615			

FIGURE 11
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Crucible

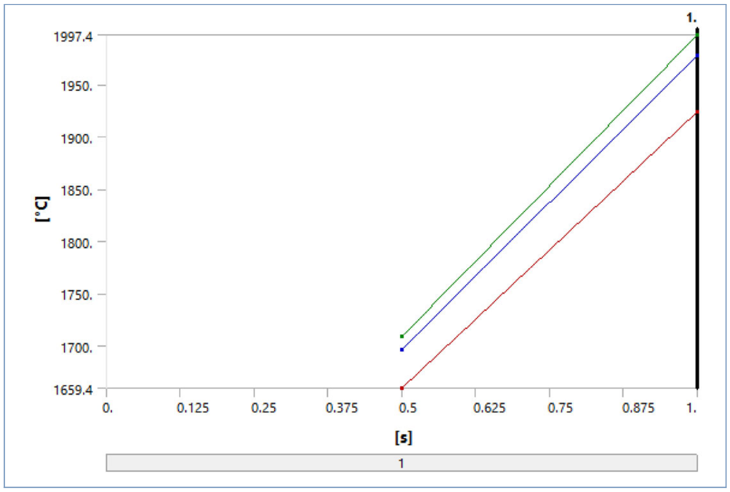


TABLE 50
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Crucible

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	1659.4	1709.3	1696.4
1.	1924.2	1997.4	1977.6

FIGURE 12
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Filament

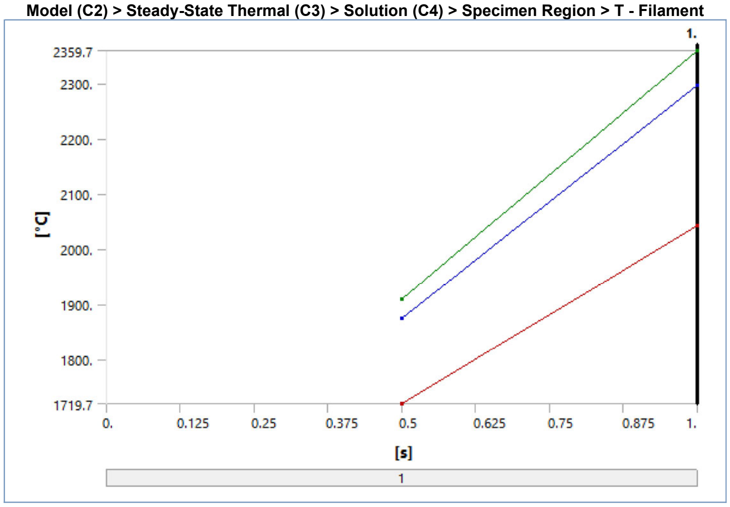


TABLE 51
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Filament

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	1719.7	1909.8	1873.3
1.	2040.9	2359.7	2296.8

FIGURE 13
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Thermocouple

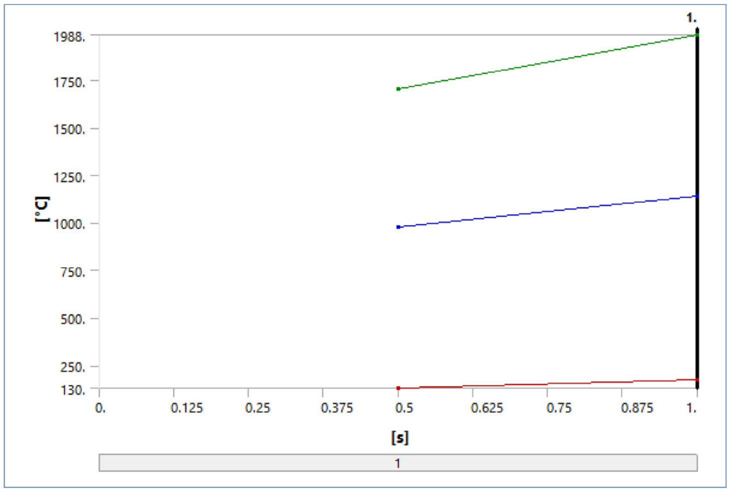


TABLE 52
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - Thermocouple

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	130.	1703.4	973.83
1.	175.	1988.	1140.

FIGURE 14
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - ZrO2 insulation

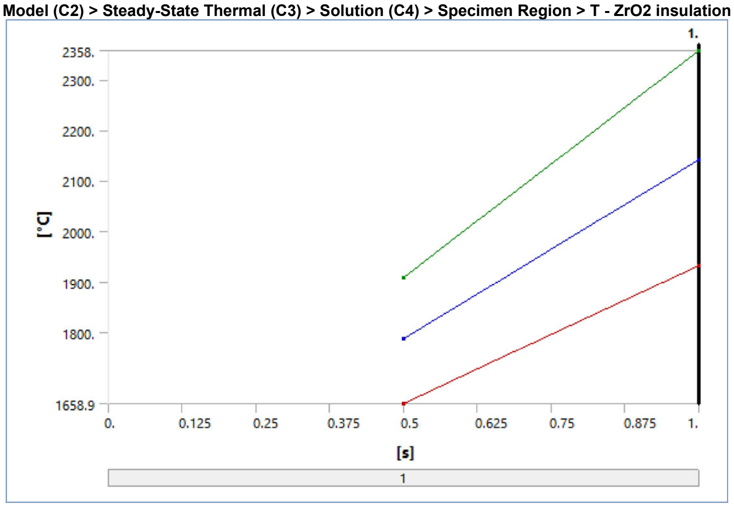


TABLE 53
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Specimen Region > T - ZrO2 insulation

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	1658.9	1908.	1786.9
1.	1931.5	2358.	2140.5

Metal Foils

TABLE 54
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Metal Foils > Results

Object Name	*T - Moly window*	*T - Ti getter*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Body	
Definition		
Type	Temperature	
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		

Minimum	1870.4 °C	548.66 °C
Maximum	1933.6 °C	1319.8 °C
Average	1899.4 °C	855.22 °C
Minimum Occurs On	MO_WINDOW(Transient Thermal)	TI_GETTER(Transient Thermal)
Maximum Occurs On	MO_WINDOW(Transient Thermal)	TI_GETTER(Transient Thermal)
Minimum Value Over Time		
Minimum	1604. °C	463.74 °C
Maximum	1870.4 °C	548.66 °C
Maximum Value Over Time		
Minimum	1658.2 °C	1110.8 °C
Maximum	1933.6 °C	1319.8 °C
Information		
Time	1. s	
Load Step	1	
Substep	2	
Iteration Number	1615	

FIGURE 15
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Metal Foils > T - Moly window

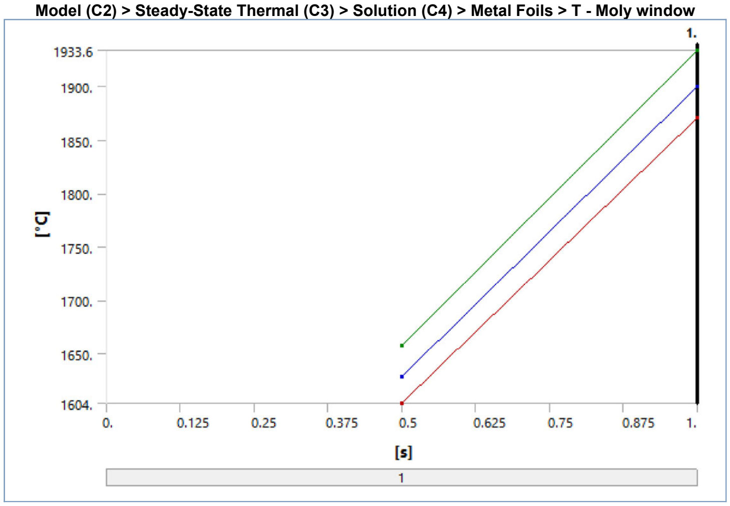


TABLE 55
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Metal Foils > T - Moly window

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	1604.	1658.2	1629.2
1.	1870.4	1933.6	1899.4

FIGURE 16
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Metal Foils > T - Ti getter

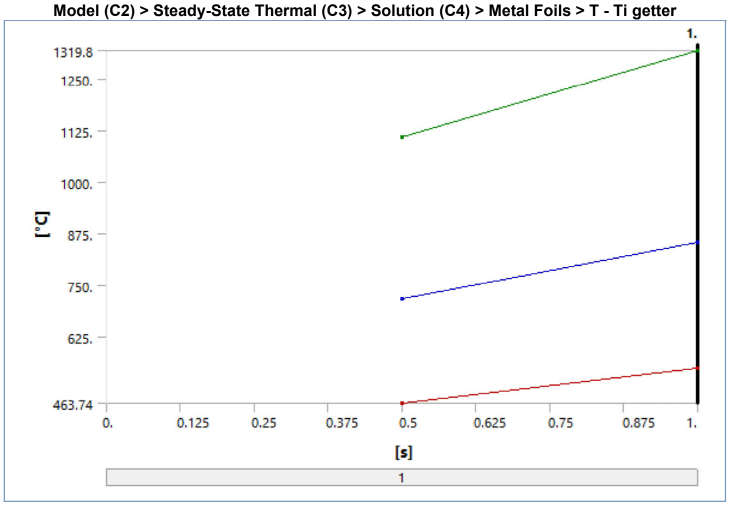


TABLE 56
Model (C2) > Steady-State Thermal (C3) > Solution (C4) > Metal Foils > T - Ti getter

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
0.5	463.74	1110.8	717.56
1.	548.66	1319.8	855.22

Material Data

Structural Steel

TABLE 57
Structural Steel > Constants

Density	7850 kg m^-3
Isotropic Secant Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat Constant Pressure	434 J kg^-1 C^-1
Isotropic Thermal Conductivity	60.5 W m^-1 C^-1
Isotropic Resistivity	1.7e-007 ohm m

TABLE 58
Structural Steel > Color

Red	Green	Blue
132	139	179

TABLE 59
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength Pa
0

TABLE 60
Structural Steel > Compressive Yield Strength

Compressive Yield Strength Pa
2.5e+008

TABLE 61
Structural Steel > Tensile Yield Strength

Tensile Yield Strength Pa
2.5e+008

TABLE 62
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4.6e+008

TABLE 63
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 64
Structural Steel > Alternating Stress Mean Stress

Alternating Stress Pa	Cycles	Mean Stress Pa
3.999e+009	10	0
2.827e+009	20	0
1.896e+009	50	0
1.413e+009	100	0
1.069e+009	200	0
4.41e+008	2000	0
2.62e+008	10000	0
2.14e+008	20000	0
1.38e+008	1.e+005	0
1.14e+008	2.e+005	0
8.62e+007	1.e+006	0

TABLE 65
Structural Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9.2e+008	-0.106	0.213	-0.47	1.e+009	0.2

TABLE 66
Structural Steel > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa	Temperature C
2.e+011	0.3	1.6667e+011	7.6923e+010	

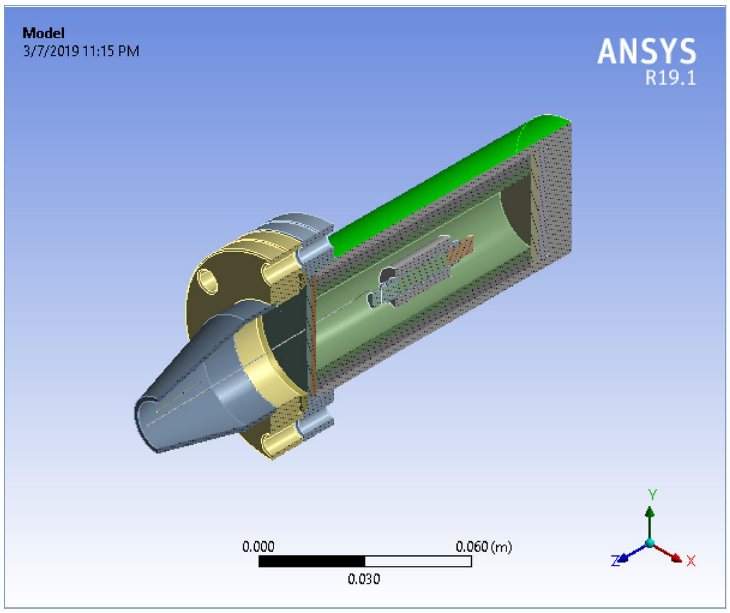
TABLE 67
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000

Appendix IV
Transient Model ANSYS Summary Report

Project

First Saved	Wednesday, October 24, 2018
Last Saved	Monday, March 4, 2019
Product Version	19.1 Release
Save Project Before Solution	No
Save Project After Solution	No



Contents

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (B4)

Geometry

TABLE 2
Model (B4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\Documents\TARGET CAPSULES\2018\NTP\Model\LIBBY\FInal mesh testing\NTP_Full contact_Transient_files\dp7 \Geom\DM\Geom.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	6.9088e-002 m
Length Y	8.7854e-002 m
Length Z	0.16479 m
Properties	
Volume	1.9153e-004 m³
Mass	0.96131 kg
Scale Factor Value	1.
Statistics	
Bodies	27
Active Bodies	22

Nodes	413590
Elements	126848
Mesh Metric	None
Update Options	
Assign Default Material	No
Basic Geometry Options	
Parameters	Independent
Parameter Key	
Attributes	Yes
Attribute Key	
Named Selections	Yes
Named Selection Key	
Material Properties	Yes
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	Yes
Coordinate System Key	
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (B4) > Geometry > Parts

Object Name	*SS_HOUSING*	*SS_HOUSING_FLANGE*	*SS_VIEWPORT_TUBE*	*SS_VIEWPORT_FLANGE*	*SS_EXHAUST_TUBE*	*SS_REDUCER_LOWER_*
State	Meshed		Suppressed			
						Graphics Prop
Visible	Yes		No			
Transparency	1					
						Definitio
Suppressed	No		Yes			
Stiffness Behavior						I
Coordinate System						Default Co
Reference Temperature						By E
Behavior						
						Material
Assignment	Stainless steel, martensitic		Structural Steel			Stainless steel, marte
Nonlinear Effects						
Thermal Strain Effects						
						Bounding I
Length X	4.4703e-002 m	6.9088e-002 m	1.905e-002 m	3.302e-002 m	2.102e-002 m	6.9088e-002 m
Length Y	4.4704e-002 m	6.9088e-002 m	1.9779e-002 m	7.62e-003 m	6.35e-003 m	6.9088e-002 m
Length Z	0.1017 m	1.27e-002 m	1.905e-002 m	3.302e-002 m	6.35e-003 m	1.27e-002 m
						Propertie
Volume	5.376e-005 m³	2.628e-005 m³	1.6435e-006 m³	4.0599e-006 m³	3.1508e-007 m³	3.1093e-005 m
Mass	0.41664 kg	0.20367 kg	1.2901e-002 kg	3.1871e-002 kg	2.4734e-003 kg	0.24097 kg
Centroid X	-2.6161e-018 m	9.1066e-008 m	-1.431e-004 m	1.0759e-013 m	1.9661e-002 m	7.6927e-008 m
Centroid Y	9.8474e-019 m	1.015e-007 m	3.0754e-002 m	4.0668e-002 m	2.9e-002 m	-8.5792e-008 m
Centroid Z	4.1127e-002 m	0.10069 m	5.9026e-002 m			0.11348 m
Moment of Inertia Ip1	5.0947e-004 kg·m²	8.7428e-005 kg·m²	8.6496e-007 kg·m²	2.9379e-006 kg·m²	9.7674e-008 kg·m²	9.3431e-005 kg·r
Moment of Inertia Ip2	1.5812e-004 kg·m²	8.7688e-005 kg·m²	8.734e-007 kg·m²	2.9378e-006 kg·m²	9.7577e-008 kg·m²	9.369e-005 kg·m
Moment of Inertia Ip3	5.0947e-004 kg·m²	1.6981e-004 kg·m²	9.8459e-007 kg·m²	5.591e-006 kg·m²	1.8915e-008 kg·m²	1.811e-004 kg·m
						Statistic
Nodes	32278	25104	0			9556
Elements	18454	15668	0			5702
Mesh Metric						

TABLE 4
Model (B4) > Geometry > SS_HOUSING > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	

File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_HOUSING > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.

MAT_SS304,matid
```

TABLE 5
Model (B4) > Geometry > SS_HOUSING_FLANGE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_HOUSING_FLANGE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 6
Model (B4) > Geometry > SS_VIEWPORT_TUBE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_VIEWPORT_TUBE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 7
Model (B4) > Geometry > SS_VIEWPORT_FLANGE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_VIEWPORT_FLANGE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 8
Model (B4) > Geometry > SS_EXHAUST_TUBE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_EXHAUST_TUBE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 9

Model (B4) > Geometry > SS_REDUCER_LOWER_FLANGE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_REDUCER_LOWER_FLANGE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                 See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 10
Model (B4) > Geometry > GFA_INSULATOR_BOTTOM_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_BOTTOM_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                 See Solving Units in the help system for more information.

GFA_K_pert  = ARG1
*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 11
Model (B4) > Geometry > GFA_INSULATOR_BOTTOM_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL

Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_BOTTOM_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 12
Model (B4) > Geometry > GFA_INSULATOR_WALL_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_WALL_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 13
Model (B4) > Geometry > TI_GETTER > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	

ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > TI_GETTER > Commands (APDL) 2

```
MAT_TI6AL4V,matid
```

TABLE 14
Model (B4) > Geometry > GFA_INSULATOR_WALL_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_WALL_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 15
Model (B4) > Geometry > Parts

Object Name	*GFA_INSULATOR_TOP_2*	*GFA_INSULATOR_TOP_1*	*CU_HOUSLING_FLANGE_GASKET*	*SS_VIEWPORT*	*CU_VIEWPORT_FLANGE_GA:*
State	Meshed			Suppressed	
					Graphics P
Visible	Yes			No	
Transparency	1				
					Defini
Suppressed	No			Yes	
Stiffness Behavior					
Coordinate System					Defaul
Reference Temperature					B
Behavior					
					Mate
Assignment	Graphite felt		Stainless steel, martensitic	Structural Steel	
Nonlinear Effects					
Thermal Strain Effects					
					Boundir
Length X	4.1402e-002 m		4.8e-002 m	3.3782e-002 m	2.1e-002 m
Length Y	4.1402e-002 m		4.8e-002 m	8.8646e-003 m	2.e-003 m
Length Z	1.7463e-003 m		2.e-003 m	3.3782e-002 m	2.1e-002 m
					Prope
Volume	2.349e-006 m³		1.4681e-006 m³	5.1296e-006 m³	2.9047e-007 m³
Mass	3.6996e-004 kg		1.1378e-002 kg	4.0267e-002 kg	2.2802e-003 kg

Centroid X	3.7627e-021 m		3.3468e-008 m	1.5725e-009 m	7.5175e-007 m
Centroid Y	2.8028e-017 m	2.8348e-017 m	-1.7758e-006 m	4.8945e-002 m	4.4253e-002 m
Centroid Z	0.10258 m	0.10432 m	0.10619 m	5.9026e-002 m	
Moment of Inertia Ip1	3.9695e-008 kg·m²		2.6138e-006 kg·m²	3.6734e-006 kg·m²	1.0002e-007 kg·m²
Moment of Inertia Ip2	7.9202e-008 kg·m²		5.2199e-006 kg·m²	6.8816e-006 kg·m²	1.9852e-007 kg·m²
Moment of Inertia Ip3	3.9695e-008 kg·m²		2.6137e-006 kg·m²	3.6734e-006 kg·m²	1.0002e-007 kg·m²
					Statis
Nodes	9143	8907	172	0	
Elements	1872	1824	16	0	
Mesh Metric					

TABLE 16
Model (B4) > Geometry > GFA_INSULATOR_TOP_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_TOP_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 17
Model (B4) > Geometry > GFA_INSULATOR_TOP_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_INSULATOR_TOP_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".
```

```
!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


*IF,GFA_K_pert,EQ,1,THEN
        MAT_GFA-GRAPHITE,matid
*ELSEIF,GFA_K_pert,EQ,2,THEN
        MAT_GFA-GRAPHITE105,matid
*ELSEIF,GFA_K_pert,EQ,3,THEN
        MAT_GFA-GRAPHITE95,matid
*ENDIF
```

TABLE 18
Model (B4) > Geometry > CU_HOUSLING_FLANGE_GASKET > Command Snippet

Object Name	*Commands (APDL)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > CU_HOUSLING_FLANGE_GASKET > Commands (APDL)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_COPPER, matid
```

TABLE 19
Model (B4) > Geometry > SS_VIEWPORT > Command Snippet

Object Name	*Commands (APDL) 2*
State	Suppressed
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_VIEWPORT > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 20
Model (B4) > Geometry > CU_VIEWPORT_FLANGE_GASKET > Command Snippet

Object Name	*Commands (APDL) 2*
State	Suppressed

File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > CU_VIEWPORT_FLANGE_GASKET > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_COPPER,matid
```

TABLE 21
Model (B4) > Geometry > GRAPHITE_CRUCIBLE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GRAPHITE_CRUCIBLE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 22
Model (B4) > Geometry > ZRO2_TUBE > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	

ARG8	
ARG9	

Model (B4) > Geometry > ZRO2_TUBE > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_ZRO2,matid
```

TABLE 23
Model (B4) > Geometry > GFA_FILAMENT > Command Snippet

Object Name	*Commands (APDL)*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GFA_FILAMENT > Commands (APDL)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_GFA-GRAPHITE,matid
```

TABLE 24
Model (B4) > Geometry > GRAPHITE_FILAMENT_PLUG_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GRAPHITE_FILAMENT_PLUG_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 25
Model (B4) > Geometry > GRAPHITE_FILAMENT_PLUG_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > GRAPHITE_FILAMENT_PLUG_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_POCO-GRAPHITE,matid
```

TABLE 26
Model (B4) > Geometry > MO_ELECTRODE_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > MO_ELECTRODE_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_MOLY,matid
```

TABLE 27
Model (B4) > Geometry > Parts

Object Name	*TUNGSTEN_TC_1*	*TUNGSTEN_TC_2*	*MO_ELECTRODE_1*	*SS_REDUCER*	*MO_WINDOW*
State	Meshed				
Graphics Properties					
Visible	Yes				
Transparency	1				
Definition					
Suppressed	No				
Stiffness Behavior	Flexible				
Coordinate System	Default Coordinate System				
Reference Temperature	By Environment				
Behavior	None				
Material					

Assignment	Tungsten		Molybdenum	Stainless steel, martensitic	Molybdenum
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				
Bounding Box					
Length X	2.8874e-003 m	1.9203e-003 m	4.5204e-003 m	3.81e-002 m	2.534e-002 m
Length Y	5.988e-003 m	1.044e-003 m	9.9958e-003 m	3.81e-002 m	2.534e-002 m
Length Z	0.10576 m		8.945e-002 m	4.7575e-002 m	8.53e-002 m
Properties					
Volume	2.0809e-008 m³	2.0764e-008 m³	1.121e-008 m³	7.4409e-006 m³	5.7526e-007 m³
Mass	4.0161e-004 kg	4.0075e-004 kg	1.1457e-004 kg	5.7667e-002 kg	5.8792e-003 kg
Centroid X	4.1991e-003 m	5.6401e-003 m	-1.8869e-003 m	3.822e-006 m	7.6808e-017 m
Centroid Y	-2.3207e-003 m	4.5811e-004 m	1.4298e-003 m	-2.0307e-010 m	1.6233e-017 m
Centroid Z	0.11194 m		0.11622 m	0.13828 m	5.9e-002 m
Moment of Inertia Ip1	3.741e-007 kg·m²	3.694e-007 kg·m²	8.7991e-008 kg·m²	1.6958e-005 kg·m²	4.0107e-006 kg·m²
Moment of Inertia Ip2	3.7405e-007 kg·m²	3.694e-007 kg·m²	8.77e-008 kg·m²	1.6958e-005 kg·m²	4.0107e-006 kg·m²
Moment of Inertia Ip3	6.5663e-011 kg·m²	1.4899e-011 kg·m²	2.9347e-010 kg·m²	1.4024e-005 kg·m²	9.2799e-007 kg·m²
Statistics					
Nodes	1956		2130	432	9626
Elements	363		396	56	1428
Mesh Metric	None				

TABLE 28
Model (B4) > Geometry > TUNGSTEN_TC_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > TUNGSTEN_TC_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_TUNGSTEN,matid
```

TABLE 29
Model (B4) > Geometry > TUNGSTEN_TC_2 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > TUNGSTEN_TC_2 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".
```

```
!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_TUNGSTEN,matid
```

TABLE 30
Model (B4) > Geometry > MO_ELECTRODE_1 > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > MO_ELECTRODE_1 > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_MOLY,matid
```

TABLE 31
Model (B4) > Geometry > SS_REDUCER > Command Snippet

Object Name	*Commands (APDL) 2*
State	Fully Defined
File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > SS_REDUCER > Commands (APDL) 2

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                See Solving Units in the help system for more information.


MAT_SS304,matid
```

TABLE 32
Model (B4) > Geometry > MO_WINDOW > Command Snippet

Object Name	*Commands (APDL)*
State	Fully Defined
File	
File Name	
File Status	File not found

Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments	
ARG1	
ARG2	
ARG3	
ARG4	
ARG5	
ARG6	
ARG7	
ARG8	
ARG9	

Model (B4) > Geometry > MO_WINDOW > Commands (APDL)

```
!   Commands inserted into this file will be executed just after material definitions in /PREP7.
!   The material number for this body is equal to the parameter "matid" unless a part of a Material Assignment.

!   The element type numbers for this body is equal to the parameter "typeids".

!   Active UNIT system in Workbench when this object was created:  Metric (m, kg, N, s, V, A)
!   NOTE:  Any data that requires units (such as mass) is assumed to be in the consistent solver unit system.
!                 See Solving Units in the help system for more information.



MAT_MOLY,matid
```

TABLE 33
Model (B4) > Materials > Stainless steel, martensitic Assignment

Object Name	*Stainless steel, martensitic Assignment*	*Graphite felt Assignment*	*Graphite felt Assignment 2*	*Graphite Assignment*	*Tungsten Assignment*	*Zirconia Assignment*	*Molybdenum Assignment*	*Stainless steel, martensitic Assignment 2*	*Titanium Assignment*
State	Fully Defined								
General									
Scoping Method	Geometry Selection								
Geometry	4 Bodies	5 Bodies	2 Bodies	3 Bodies	2 Bodies	1 Body	3 Bodies	1 Body	
Definition									
Material Name	Stainless steel, martensitic	Graphite felt		Graphite	Tungsten	Zirconia	Molybdenum	Stainless steel, martensitic	Titanium
Nonlinear Effects	Yes								
Thermal Strain Effects	Yes								
Reference Temperature	By Environment								
Suppressed	No								

Coordinate Systems

TABLE 34
Model (B4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. m
Origin Y	0. m
Origin Z	0. m
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Connections

TABLE 35
Model (B4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	No
Transparency	
Enabled	Yes

TABLE 36
Model (B4) > Connections > Contacts

Object Name	*Contacts*
State	Fully Defined

Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	4.9778e-004 m
Use Range	No
Face/Face	Yes
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
Statistics	
Connections	41
Active Connections	35

TABLE 37
Model (B4) > Connections > Contacts > Contact Regions

Object Name	*No Separation - SS_HOUSING To SS_HOUSING_FLANGE*	*Bonded - SS_HOUSING To SS_VIEWPORT_TUBE*	*Frictionless - SS_HOUSING To GFA_INSULATOR_BOTTOM_1*	*Frictionless - SS_HOUSING To GFA_INSULATOR_BOTTOM_2*	*Frictionless - SS_HOUSIN To GFA_INSULATOR_WALL_*
State	Fully Defined	Suppressed			
Scoping Method					
Contact	3 Faces	2 Faces	3 Faces	2 Faces	2 Faces
Target	15 Faces	No Selection	3 Faces	2 Faces	2 Faces
Contact Bodies	SS_HOUSING	SS_HOUSING	SS_HOUSING	SS_HOUSING	SS_HOUSING
Target Bodies	SS_HOUSING_FLANGE	SS_VIEWPORT_TUBE	GFA_INSULATOR_BOTTOM_1	GFA_INSULATOR_BOTTOM_2	GFA_INSULATOR_WALL_
Protected					
Type	No Separation	Bonded	Frictionless	Frictionless	Frictionless
Scope Mode					
Behavior					
Trim Contact					
Trim Tolerance					
Suppressed					
Formulation					
Small Sliding					
Detection Method					
Thermal Conductance					
Pinball Region					
Elastic Slip Tolerance		Program Controlled			
Time Step Controls			None	None	None
Contact Geometry Correction					
Target Geometry Correction					
Interface Treatment			Add Offset, No Ramping	Add Offset, No Ramping	Add Offset, No Ramping
Offset			0. m	0. m	0. m

TABLE 38
Model (B4) > Connections > Contacts > Contact Regions

Object Name	*Bonded - SS_VIEWPORT_TUBE To SS_EXHAUST_TUBE*	*No Separation - SS_VIEWPORT_FLANGE To SS_VIEWPORT*	*No Separation - SS_VIEWPORT_FLANGE To CU_VIEWPORT_FLANGE_GASKET*	*Frictionless - SS_REDUCER_LOWER_FLANGE To CU_HOUSLING_FLANGE_GASKET*	*Bo SS_REDUCER To SS_*
State	Suppressed	Suppressed	Suppressed		
Scoping Method					
Contact	No Selection	No Selection	No Selection	2 Faces	3
Target	No Selection	No Selection	No Selection	2 Faces	3

Contact Bodies	SS_VIEWPORT_TUBE	SS_VIEWPORT_FLANGE		SS_REDUCER_LOWER_FLANGE	
Target Bodies	SS_EXHAUST_TUBE	SS_VIEWPORT	CU_VIEWPORT_FLANGE_GASKET	CU_HOUSLING_FLANGE_GASKET	SS_R
Protected					
Type	Bonded	No Separation		Frictionless	B
Scope Mode					
Behavior					
Trim Contact					
Trim Tolerance					
Suppressed					
Formulation					
Small Sliding					
Detection Method					
Elastic Slip Tolerance	Program Controlled				Prograr
Thermal Conductance					
Pinball Region					
Time Step Controls				None	
Contact Geometry Correction					
Target Geometry Correction					
Interface Treatment				Add Offset, No Ramping	
Offset				0. m	

TABLE 39
Model (B4) > Connections > Contacts > Contact Regions

Object Name	*Frictionless - GFA_INSULATOR_WALL_1 To GFA_INSULATOR_TOP_2*	*Frictionless - TI_GETTER To GFA_INSULATOR_WALL_2*	*Frictionless - TI_GETTER To GFA_INSULATOR_TOP_2*	*Frictionless - GFA_INSULATOR_WALL_2 To GFA_INSULATOR_TOP_2*	*Frictionless - GFA_INSULATOR_TOP_2 To GFA_INSULATOR_TOP_*
State	Fully Defined				
Scoping Method					
Contact	1 Face	2 Faces	1 Face		
Target	1 Face	2 Faces	1 Face		
Contact Bodies	GFA_INSULATOR_WALL_1	TI_GETTER		GFA_INSULATOR_WALL_2	GFA_INSULATOR_TOP_
Target Bodies	GFA_INSULATOR_TOP_2	GFA_INSULATOR_WALL_2	GFA_INSULATOR_TOP_2		GFA_INSULATOR_TOP_
Protected					
Type	Frictionless				
Scope Mode					
Behavior					
Trim Contact					
Trim Tolerance					
Suppressed					
Formulation					
Small Sliding					
Detection Method					
Thermal Conductance	Program Controlled				
Pinball Region	Program Controlled				
Time Step Controls	None				
Thermal Conductance Value					
Pinball Radius					
					Geon
Interface Treatment	Add Offset, No Ramping				
Offset	0. m				
Contact Geometry					

Correction	
Target Geometry Correction	

TABLE 40
Model (B4) > Connections > Contacts > Contact Regions

Object Name	*No Separation - ZRO2_TUBE To GRAPHITE_FILAMENT_PLUG_1*	*No Separation - ZRO2_TUBE To GRAPHITE_FILAMENT_PLUG_2*	*No Separation - GFA_FILAMENT To GRAPHITE_FILAMENT_PLUG_1*	*No Separation - GFA_FILAMENT To GRAPHITE_FILAMENT_PLUG_2*	*GRA*
State				Fully Defined	
				Scope	
Scoping Method				Geometry Selection	
Contact	2 Faces		1 Face		
Target	2 Faces		1 Face		
Contact Bodies	ZRO2_TUBE		GFA_FILAMENT		GRA
Target Bodies	GRAPHITE_FILAMENT_PLUG_1	GRAPHITE_FILAMENT_PLUG_2	GRAPHITE_FILAMENT_PLUG_1	GRAPHITE_FILAMENT_PLUG_2	
Protected				No	
				Definition	
Type	No Separation				
Scope Mode				Automatic	
Behavior				Asymmetric	
Trim Contact				Program Controlled	
Trim Tolerance				4.9778e-004 m	
Suppressed				No	
				Advanced	
Formulation				Augmented Lagrange	
Small Sliding				Program Controlled	
Detection Method				Program Controlled	
Thermal Conductance				Program Controlled	
Pinball Region	Program Controlled				
Pinball Radius					
Time Step Controls					
Elastic Slip Tolerance					
				Geometric Modification	
Contact Geometry Correction				None	
Target Geometry Correction				None	
Interface Treatment					
Offset					

Mesh

TABLE 41
Model (B4) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	Default
Sizing	
Use Adaptive Sizing	Yes
Resolution	4
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	0.19911 m
Average Surface Area	3.33e-004 m²
Minimum Edge Length	4.0677e-005 m
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical

Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Statistics	
Nodes	413590
Elements	126848

TABLE 42
Model (B4) > Mesh > Mesh Controls

Object Name	*Body Sizing 2*	*Hex Dominant Method 2*	*Body Sizing 3*	*Contact Sizing*	*Face Sizing 3*	*Sweep Method*	*Face Sizing 4*	*Sweep Method 2*	*Sweep Method 3*	*Sweep Method 4*	*Sweep Method 5*
State	Fully Defined										
Scope											
Scoping Method	Geometry Selection				Geometry Selection						
Geometry	4 Bodies	5 Bodies	1 Body		1 Face	1 Body	1 Face	1 Body			
Contact Region				No Separation - GFA_FILAMENT To ZRO2_TUBE							
Definition											
Suppressed	No										
Type	Element Size		Element Size				Element Size				
Element Size	1.e-002 m		8.e-004 m		3.5e-004 m		3.5e-004 m				
Method		Hex Dominant				Sweep		Sweep			
Element Order		Use Global Setting				Use Global Setting		Use Global Setting			
Free Face Mesh Type		All Quad				Quad/Tri		Quad/Tri			
Control Messages		Yes, Click To Display...									
Src/Trg Selection						Manual Thin		Manual Thin			
Source						1 Face		1 Face			
Sweep Num Divs						6		6	8		
Element Option						Solid		Solid			
Advanced											
Defeature Size	Default		Default		Default		Default				
Behavior	Soft		Soft		Soft		Soft				

TABLE 43
Model (B4) > Mesh > Mesh Controls

Object Name	*Sweep Method 6*	*Body Sizing*	*Face Sizing*	*Sweep Method 7*	*Contact Sizing 2*	*Contact Sizing 3*	*Contact Sizing 4*
State	Fully Defined				Suppressed		
Scope							
Scoping Method	Geometry Selection						
Geometry	1 Body		1 Face	1 Body			
Contact Region					Frictionless - SS_HOUSING To GFA_INSULATOR_WALL_1	Frictionless - SS_HOUSING To GFA_INSULATOR_TOP_2	Frictionless - SS_HOUSING_FLANGE To GFA_INSULATOR_TOP_1
Definition							
Suppressed	No				Yes		
Method	Sweep			Sweep			
Element Order	Use Global Setting			Use Global Setting			
Src/Trg Selection	Manual Thin			Manual Source			

Source	1 Face			1 Face		
Free Face Mesh Type	Quad/Tri			Quad/Tri		
Sweep Num Divs	8			6		
Element Option	Solid			Solid		
Type		Element Size		Number of Divisions	Relevance	Element Size
Element Size		3.e-003 m	4.e-004 m			Default
Target				Program Controlled		
Active					No, Suppressed	
Relevance					0	
Advanced						
Defeature Size		Default				
Behavior		Soft				
Sweep Bias Type				No Bias		

Transient Thermal (B5)

TABLE 44
Model (B4) > Analysis

Object Name	*Transient Thermal (B5)*
State	Solved
Definition	
Physics Type	Thermal
Analysis Type	Transient
Solver Target	Mechanical APDL
Options	
Generate Input Only	No

TABLE 45
Model (B4) > Transient Thermal (B5) > Initial Condition

Object Name	*Initial Temperature*
State	Fully Defined
Definition	
Initial Temperature	Uniform Temperature
Initial Temperature Value	85. °C

TABLE 46
Model (B4) > Transient Thermal (B5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	50.
Current Step Number	1.
Step End Time	600. s
Auto Time Stepping	Program Controlled
Carry Over Time Step	Off
Initial Time Step	6. s
Minimum Time Step	0.6 s
Maximum Time Step	60. s
Time Step	1.e-002 s
Time Integration	On
Solver Controls	
Solver Type	Direct
Radiosity Controls	
Radiosity Solver	Program Controlled
Flux Convergence	1.e-004
Maximum Iteration	1000.
Solver Tolerance	0.1 W/m²
Over Relaxation	0.1
Hemicube Resolution	10.
Nonlinear Controls	
Heat Convergence	Program Controlled
Temperature Convergence	Program Controlled
Line Search	Program Controlled
Nonlinear Formulation	Program Controlled
Output Controls	
Calculate Thermal Flux	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	D:\Documents\TARGET CAPSULES\2018\NTP\Model\LIBBY\FInal mesh testing\NTP_Full contact_Transient_files\dp7 \SYS\MECH\

Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	Yes
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

TABLE 47
Model (B4) > Transient Thermal (B5) > Analysis Settings
Step-Specific "Step Controls"

Step	Step End Time	Initial Time Step	Minimum Time Step	Maximum Time Step
1	600. s	6. s	0.6 s	60. s
2	601. s	1.e-002 s	1.e-003 s	0.1 s
3	602. s			
4	603. s			
5	604. s			
6	605. s			
7	606. s			
8	607. s			
9	608. s			
10	609. s			
11	610. s			
12	611. s			
13	612. s			
14	613. s			
15	614. s			
16	615. s			
17	616. s			
18	617. s			
19	618. s			
20	619. s			
21	620. s			
22	621. s			
23	622. s			
24	623. s			
25	624. s			
26	625. s			
27	626. s			
28	627. s			
29	628. s			
30	629. s			
31	630. s			
32	631. s			
33	632. s			
34	633. s			
35	634. s			
36	635. s			
37	636. s			
38	637. s			
39	638. s			
40	639. s			
41	640. s			
42	641. s			
43	642. s			
44	643. s			
45	644. s			
46	645. s			
47	646. s			
48	647. s			
49	648. s			
50	649. s			

TABLE 48
Model (B4) > Transient Thermal (B5) > Loads

Object Name	*Temperature - boundary condition*	*Radiation - sample region*	*Radiation - wall insulation*	*Radiation - end insulation*	*Heat Flux - input load*	*Radiation - refractrory metal leads*	*Temperature - refractrory metal leads*	*Radiation - leads to crucible*	*Radiation - crucible to leads*
State	Fully Defined								
Scope									
Scoping Method	Geometry Selection								
Geometry	95 Faces	14 Faces	1 Face	2 Faces	4 Faces	18 Faces	4 Faces	6 Faces	3 Faces
Definition									
Type	Temperature	Radiation			Heat Flux	Radiation	Temperature	Radiation	
Magnitude	85. °C (step applied)				8.18e+005 W/m² (step applied)		175. °C (step applied)		
Suppressed	No								

Correlation		Surface to Surface				Surface to Surface		Surface to Surface	
Emissivity		0.8 (step applied)	0.15 (step applied)	0.75 (step applied)		0.15 (step applied)		0.15 (step applied)	0.75 (step applied)
Ambient Temperature		85. °C (step applied)				85. °C (step applied)		85. °C (step applied)	
Enclosure		1.				1.		2.	
Enclosure Type		Open				Open		Open	

FIGURE 1
Model (B4) > Transient Thermal (B5) > Temperature - boundary condition

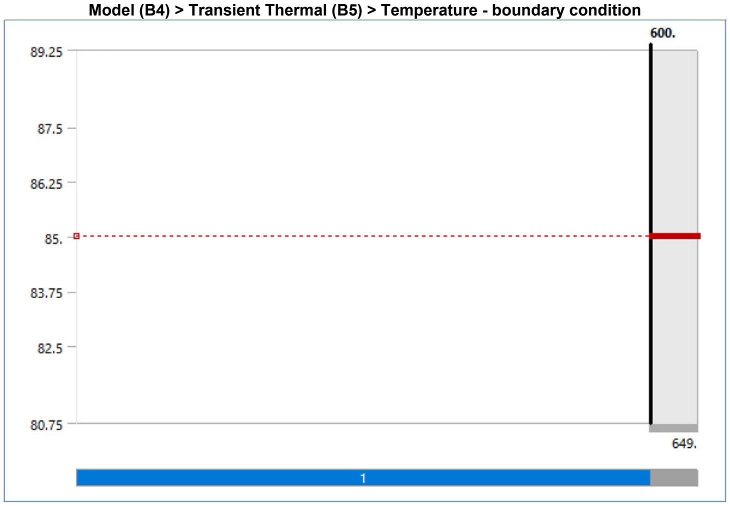


FIGURE 2
Model (B4) > Transient Thermal (B5) > Radiation - sample region

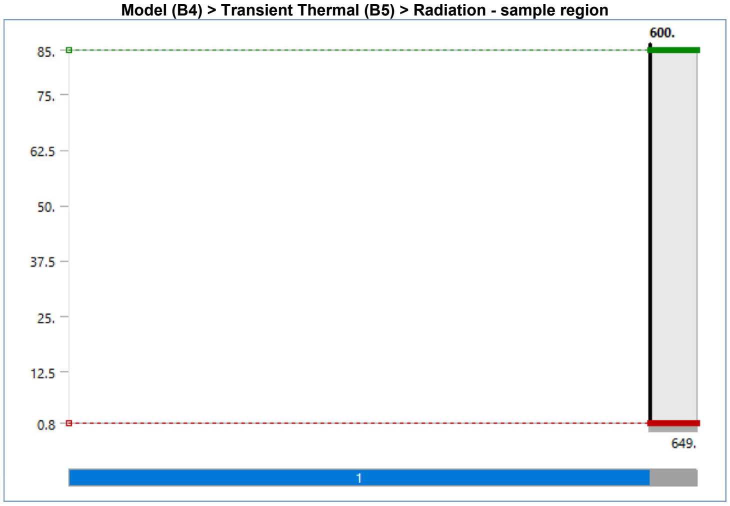


FIGURE 3
Model (B4) > Transient Thermal (B5) > Radiation - wall insulation

FIGURE 4
Model (B4) > Transient Thermal (B5) > Radiation - end insulation

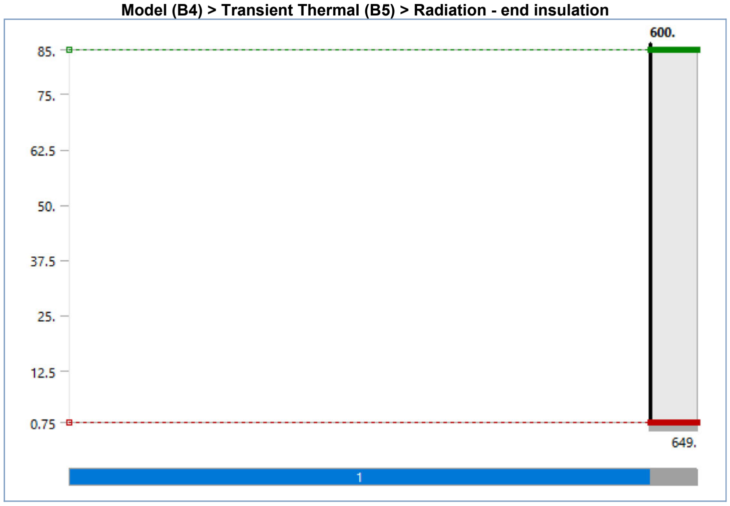


FIGURE 5
Model (B4) > Transient Thermal (B5) > Heat Flux - input load

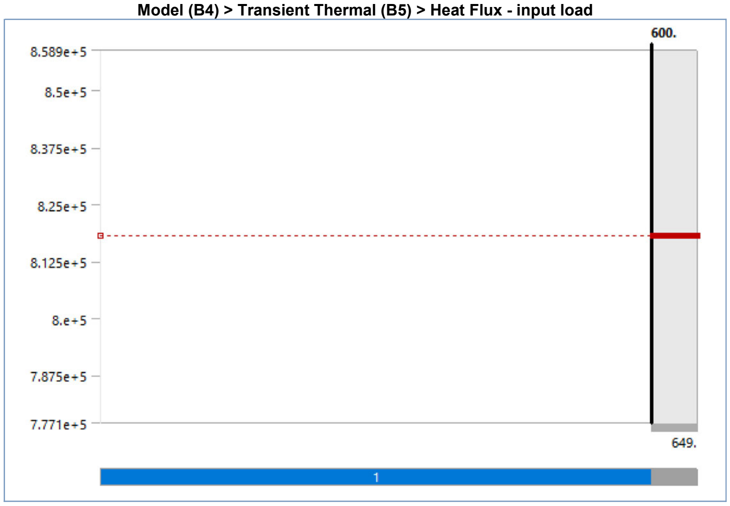


FIGURE 6
Model (B4) > Transient Thermal (B5) > Radiation - refractrory metal leads

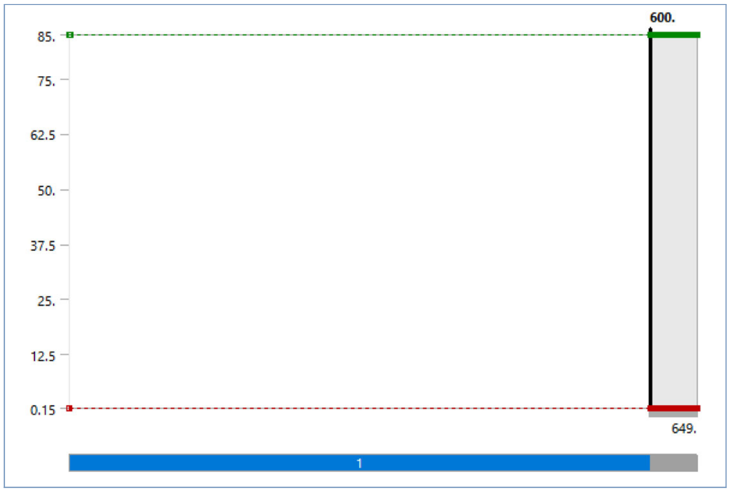


FIGURE 7
Model (B4) > Transient Thermal (B5) > Temperature - refractrory metal leads

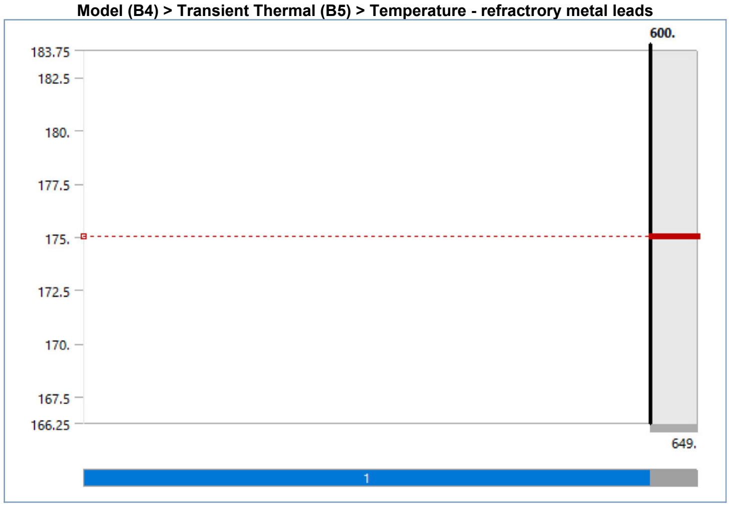


FIGURE 8
Model (B4) > Transient Thermal (B5) > Radiation - leads to crucible

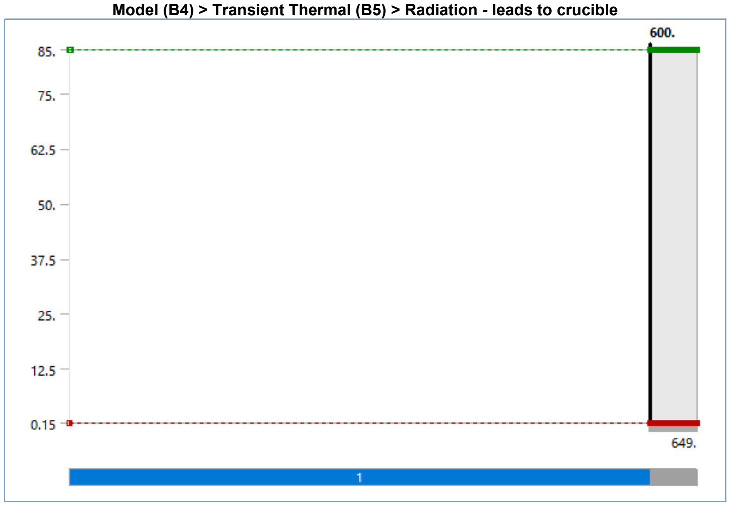
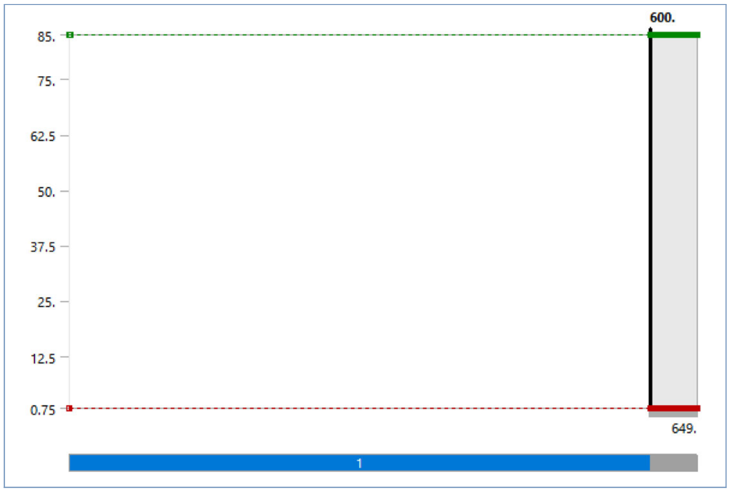


FIGURE 9
Model (B4) > Transient Thermal (B5) > Radiation - crucible to leads



Solution (B6)

TABLE 49
Model (B4) > Transient Thermal (B5) > Solution

Object Name	*Solution (B6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
MAPDL Elapsed Time	12 h 1 m
MAPDL Memory Used	4.2393 GB
MAPDL Result File Size	48.079 GB
Post Processing	
Beam Section Results	No

TABLE 50
Model (B4) > Transient Thermal (B5) > Solution (B6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 51
Model (B4) > Transient Thermal (B5) > Solution (B6) > Solution Information > Result Charts

Object Name	*Temperature - Global Maximum*	*Temperature - Global Minimum*
State	Solved	
Scope		
Scoping Method	Global Maximum	Global Minimum
Definition		
Type	Temperature	
Suppressed	No	
Results		
Minimum	741.34 °C	-517.29 °C
Maximum	2363.3 °C	84.163 °C

FIGURE 10
Model (B4) > Transient Thermal (B5) > Solution (B6) > Solution Information > Temperature - Global Maximum

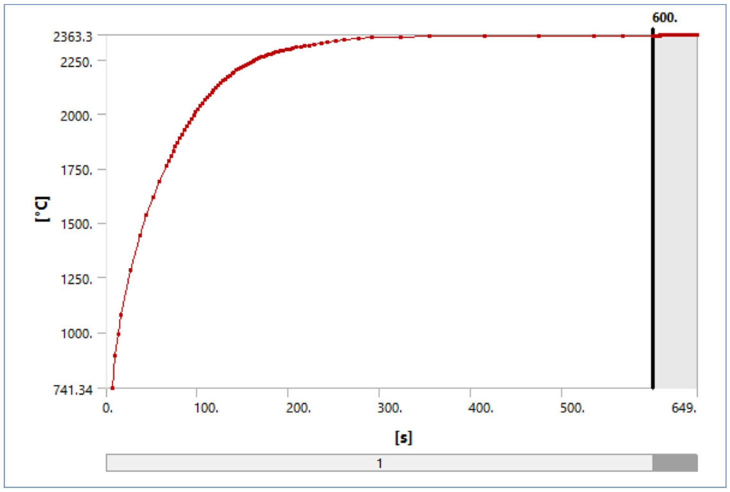


FIGURE 11
Model (B4) > Transient Thermal (B5) > Solution (B6) > Solution Information > Temperature - Global Minimum

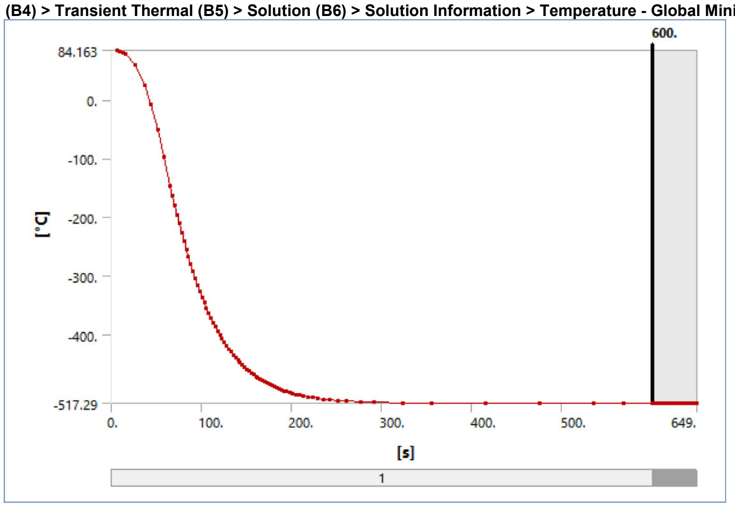


TABLE 52
Model (B4) > Transient Thermal (B5) > Solution (B6) > Results

Object Name	*T - Filament*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Type	Temperature
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	2028.3 °C
Maximum	2343.2 °C
Average	2281.2 °C
Minimum Occurs On	GFA_FILAMENT
Maximum Occurs On	GFA_FILAMENT
Minimum Value Over Time	
Minimum	218.8 °C
Maximum	2028.3 °C
Maximum Value Over Time	
Minimum	741.34 °C
Maximum	2343.2 °C
Information	
Time	649. s
Load Step	50

Substep	13
Iteration Number	1443

FIGURE 12
Model (B4) > Transient Thermal (B5) > Solution (B6) > T - Filament

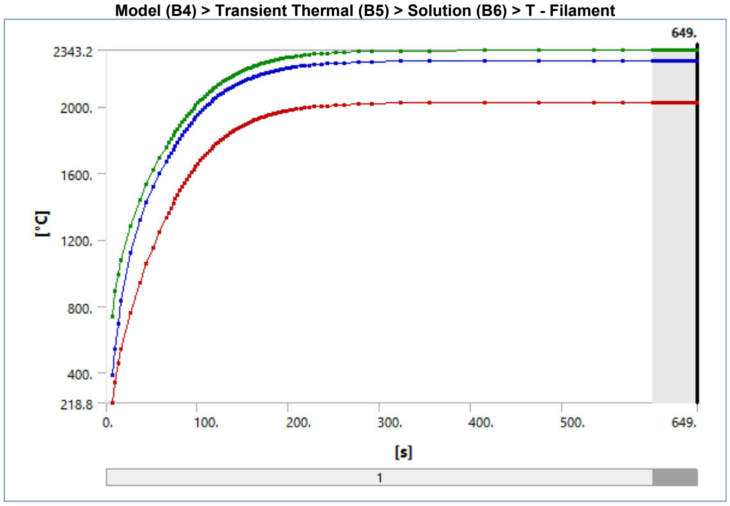


TABLE 53
Model (B4) > Transient Thermal (B5) > Solution (B6) > T - Filament

Time [s]	Minimum [°C]	Maximum [°C]	Average [°C]
6.	218.8	741.34	382.23
9.4341	340.73	887.82	542.84
12.868	457.55	989.97	696.45
16.302	540.89	1076.1	834.5
26.605	760.46	1280.9	1119.6
36.907	942.58	1442.1	1316.6
44.118	1053.7	1536.2	1425.4
51.328	1153.9	1618.1	1517.3
58.538	1247.2	1692.4	1599.
65.749	1333.9	1760.6	1673.1
68.277	1363.4	1784.	1698.3
70.765	1391.5	1806.3	1722.3
73.253	1418.6	1827.8	1745.5
75.741	1444.8	1848.8	1767.9
78.228	1470.1	1869.	1789.6
80.716	1494.4	1888.6	1810.5
83.204	1517.8	1907.5	1830.6
85.691	1540.4	1925.8	1850.
88.179	1562.1	1943.5	1868.7
90.667	1582.9	1960.4	1886.7
93.155	1603.	1976.8	1904.
95.642	1622.3	1992.6	1920.7
98.13	1640.8	2007.8	1936.8
100.62	1658.6	2022.5	1952.2
103.11	1675.7	2036.7	1967.
105.59	1692.1	2050.4	1981.2
108.08	1707.8	2063.6	1994.8
110.57	1722.9	2076.3	2007.8
113.06	1737.4	2088.5	2020.3
115.54	1751.3	2100.3	2032.3
118.03	1764.5	2111.5	2043.8
120.52	1777.2	2122.3	2054.8
123.01	1789.3	2132.7	2065.3
125.5	1800.9	2142.6	2075.4
127.98	1812.	2152.1	2085.1
130.47	1822.5	2161.2	2094.3
132.96	1832.6	2169.9	2103.1
135.45	1842.3	2178.2	2111.6
137.93	1851.5	2186.1	2119.7
140.42	1860.3	2193.7	2127.5
142.91	1868.6	2200.9	2134.8
145.4	1876.5	2207.8	2141.8
147.88	1884.1	2214.4	2148.5
150.37	1891.3	2220.7	2154.9
152.86	1898.2	2226.6	2161.1
155.35	1904.7	2232.4	2166.9
157.84	1910.8	2237.8	2172.5
160.32	1916.7	2243.	2177.8

162.81	1922.3	2248.	2182.9
165.3	1927.6	2252.7	2187.8
167.79	1932.6	2257.2	2192.4
170.27	1937.4	2261.5	2196.8
172.76	1941.9	2265.5	2200.9
175.25	1946.2	2269.4	2204.9
177.74	1950.3	2273.	2208.7
180.28	1954.3	2276.6	2212.3
182.91	1958.1	2280.1	2215.9
185.65	1962.	2283.5	2219.5
188.51	1965.7	2286.9	2223.
191.51	1969.5	2290.2	2226.5
194.5	1973.1	2293.5	2229.8
197.63	1976.5	2296.5	2233.
201.23	1980.2	2299.8	2236.4
204.83	1983.6	2302.9	2239.6
208.77	1987.	2306.	2242.8
213.11	1990.5	2309.1	2246.
217.91	1993.9	2312.2	2249.2
223.31	1997.4	2315.4	2252.4
228.71	2000.5	2318.1	2255.3
235.66	2003.9	2321.2	2258.5
242.61	2007.	2324.	2261.4
251.93	2010.3	2327.	2264.5
261.24	2013.1	2329.5	2267.1
276.4	2016.5	2332.6	2270.3
291.57	2018.9	2334.8	2272.5
323.42	2021.7	2337.3	2275.2
355.27	2023.4	2338.8	2276.7
415.27	2024.8	2340.1	2278.1
475.27	2025.2	2340.5	2278.4
535.27	2025.5	2340.8	2278.7
567.64	2025.8	2341.	2279.
600.	2026.1	2341.3	2279.3
600.01			
600.02			
600.05			
600.14			
600.24			
600.34			
600.44			
600.54			
600.64	2026.2		
600.74			
600.84			
600.94			
601.			
601.01			
601.02			
601.05			
601.14			
601.24		2341.4	
601.34			
601.44			
601.54			
601.64			
601.74			
601.84			
601.94	2026.3		
602.			
602.01			
602.02			
602.05			
602.14			2279.4
602.24			
602.34			
602.44			
602.54			
602.64			
602.74			
602.84			
602.94			
603.			
603.01			
603.02			
603.05			
603.14			
603.24			
603.34			
603.44			

603.54			
603.64			
603.74			
603.84			
603.94			
604.			
604.01			
604.02	2026.4	2341.5	
604.05			
604.14			
604.24			
604.34			
604.44			
604.54			
604.64			2279.5
604.74			
604.84			
604.94			
605.			
605.01			
605.02			
605.05			
605.14			
605.24			
605.34			
605.44	2026.5		
605.54			
605.64		2341.6	
605.74			
605.84			
605.94			
606.			
606.01			
606.02			
606.05			
606.14			
606.24			
606.34			2279.6
606.44			
606.54			
606.64			
606.74			
606.84			
606.94			
607.			
607.01	2026.6		
607.02			
607.05			
607.14			
607.24			
607.34			
607.44			
607.54		2341.7	
607.64			
607.74			
607.84			
607.94			
608.			
608.01			
608.02			
608.05			2279.7
608.14			
608.24			
608.34			
608.44			
608.54	2026.7		
608.64			
608.74			
608.84			
608.94			
609.			
609.01			
609.02		2341.8	
609.05			
609.14			
609.24			
609.34			
609.44			
609.54			
609.64			

609.74	2026.8		2279.8
609.84			
609.94			
610.			
610.01			
610.02			
610.05			
610.14			
610.24			
610.34			
610.44		2341.9	
610.54			
610.64			
610.74			
610.84			
610.94			2279.9
611.			
611.01			
611.02			
611.05			
611.14	2026.9		
611.24			
611.34			
611.44			
611.54			
611.64			
611.74			
611.84			
611.94			
612.			
612.01			
612.02			
612.05			
612.14			
612.24			
612.34			
612.44		2342.	
612.54			
612.64			
612.74			
612.84			2280.
612.94			
613.	2027.		
613.01			
613.02			
613.05			
613.14			
613.24			
613.34			
613.44			
613.54			
613.64			
613.74			
613.84			
613.94			
614.			
614.01			
614.02			
614.05			
614.14			
614.24			
614.34			
614.44			
614.54		2342.1	
614.64			
614.74			
614.84	2027.1		
614.94			
615.			
615.01			
615.02			
615.05			
615.14			
615.24			
615.34			
615.44			
615.54			
615.64			
615.74			
615.84			

615.94			
616.			
616.01			
616.02			
616.05			
616.14			
616.24			2280.1
616.34			
616.44			
616.54			
616.64			
616.74			
616.84			
616.94			
617.			
617.01			
617.02			
617.05			
617.14			
617.24			
617.34			
617.44			
617.54			
617.64			
617.74		2342.2	
617.84	2027.2		
617.94			
618.			
618.01			
618.02			2280.2
618.05			
618.14			
618.24			
618.34			
618.44			
618.54			
618.64			
618.74			
618.84			
618.94			
619.			
619.01			
619.02			
619.05			
619.14			
619.24			
619.34			
619.44			
619.54			
619.64			
619.74			
619.84			
619.94			
620.	2027.3		
620.01			
620.02		2342.3	
620.05			
620.14			
620.24			
620.34			2280.3
620.44			
620.54			
620.64			
620.74			
620.84			
620.94			
621.			
621.01			
621.02			
621.05			
621.14			
621.24			
621.34			
621.44			
621.54			
621.64			
621.74			
621.84			
621.94			
622.			

622.01			
622.02			
622.05			
622.14			
622.24			
622.34			
622.44			
622.54			
622.64	2027.4		
622.74			
622.84			
622.94			
623.		2342.4	
623.01			2280.4
623.02			
623.05			
623.14			
623.24			
623.34			
623.44			
623.54			
623.64			
623.74			
623.84			
623.94			
624.			
624.01			
624.02			
624.05			
624.14			
624.24			
624.34			
624.44			
624.54	2027.5		
624.64			
624.74			
624.84			
624.94			
625.			
625.01			
625.02			
625.03			
625.04		2342.5	
625.08			
625.18			2280.5
625.28			
625.38			
625.48			
625.58			
625.68			
625.78			
625.88			
625.94			
626.			
626.01			
626.02			
626.04			
626.12			
626.22			
626.32			
626.42			
626.52			
626.62			
626.72			
626.82			
626.92	2027.6		
627.			
627.01			
627.02			
627.05			
627.14			
627.24			
627.34			
627.44			
627.54			
627.64			
627.74			
627.84			
627.94			
628.			

628.01			
628.02			
628.05			
628.14			
628.24			
628.34			
628.44			
628.54			
628.64			
628.74		2342.6	2280.6
628.84			
628.94			
629.			
629.01			
629.02			
629.05			
629.14			
629.24			
629.34			
629.44			
629.54	2027.7		
629.64			
629.74			
629.82			
629.91			
630.			
630.01			
630.02			
630.05			
630.14			
630.24			
630.34			
630.44			
630.54			
630.64			
630.74			
630.84			
630.94			2280.7
631.		2342.7	
631.01			
631.02			
631.05			
631.14			
631.24			
631.34			
631.44			
631.54			
631.64			
631.74			
631.84			
631.94			
632.			
632.01			
632.02			
632.05	2027.8		
632.14			
632.24			
632.34			
632.44			
632.54			
632.64			
632.74			
632.84			
632.94			
633.			
633.01			
633.02			
633.05			
633.14			2280.8
633.24		2342.8	
633.34			
633.44			
633.54			
633.64			
633.74			
633.84			
633.94			
634.			
634.01			
634.02			

634.05			
634.14			
634.24			
634.34			
634.44			
634.54			
634.64			
634.74			
634.84			
634.94			
635.			
635.01			
635.02			
635.05			
635.14			
635.24			
635.34	2027.9		
635.44			
635.54			
635.64			
635.74			
635.84			
635.94			
636.			
636.01			
636.02			
636.05			
636.14			
636.24			
636.34			
636.44			
636.54			
636.64			
636.74			
636.84			
636.94			
637.			
637.01			2280.9
637.02			
637.05			
637.14			
637.24			
637.34		2342.9	
637.44			
637.54			
637.64			
637.74			
637.84			
637.94			
638.			
638.01			
638.02			
638.05	2028.		
638.14			
638.24			
638.34			
638.44			
638.54			
638.64			
638.74			
638.84			
638.94			
639.			
639.01			
639.02			
639.05			
639.14			
639.24			
639.34			
639.44			
639.54			
639.64			
639.74			
639.84			
639.94			
640.			
640.01			
640.02			
640.05			
640.14			

640.24			
640.34			
640.44			
640.54			
640.64			
640.74			
640.84			
640.94			
641.			
641.01			
641.02			
641.05			
641.14			
641.24			2281.
641.34			
641.44		2343.	
641.54			
641.64			
641.74			
641.84	2028.1		
641.94			
642.			
642.01			
642.02			
642.05			
642.14			
642.24			
642.34			
642.44			
642.54			
642.64			
642.74			
642.84			
642.94			
643.			
643.01			
643.02			
643.05			
643.14			
643.24			
643.34			
643.44			
643.54			
643.64			
643.74			
643.84			
643.94			
644.			
644.01			
644.02			
644.05			
644.14			
644.24			2281.1
644.34			
644.44			
644.54			
644.64		2343.1	
644.74			
644.84			
644.94	2028.2		
645.			
645.01			
645.02			
645.05			
645.14			
645.24			
645.34			
645.44			
645.54			
645.64			
645.74			
645.84			
645.94			
646.			
646.01			
646.02			
646.05			
646.14			
646.24			
646.34			

646.44			
646.54			
646.64			
646.74			
646.84			
646.94			
647.			
647.01			
647.02			
647.05			
647.14			
647.24			
647.34			
647.44			
647.54			
647.64			
647.74			2281.2
647.84			
647.94			
648.	2028.3	2343.2	
648.01			
648.02			
648.05			
648.14			
648.24			
648.34			
648.44			
648.54			
648.64			
648.74			
648.84			
648.94			
649.			

TABLE 54
Model (B4) > Transient Thermal (B5) > Solution (B6) > Probes

Object Name	*T Probe - Thermocouple*
State	Solved
Definition	
Type	Temperature
Location Method	Geometry Selection
Geometry	2 Faces
Suppressed	No
Options	
Display Time	End Time
Spatial Resolution	Use Maximum
Results	
Temperature	1974.8 °C
Maximum Value Over Time	
Temperature	1974.8 °C
Minimum Value Over Time	
Temperature	231.22 °C
Information	
Time	649. s
Load Step	50
Substep	13
Iteration Number	1443

FIGURE 13
Model (B4) > Transient Thermal (B5) > Solution (B6) > T Probe - Thermocouple

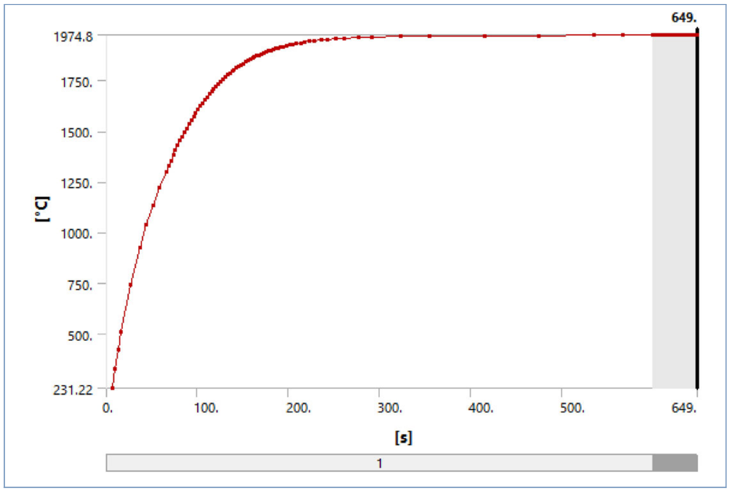


TABLE 55
Model (B4) > Transient Thermal (B5) > Solution (B6) > T Probe - Thermocouple

Time [s]	T Probe - Thermocouple [°C]
6.	231.22
9.4341	325.08
12.868	418.63
16.302	509.01
26.605	739.78
36.907	926.33
44.118	1036.6
51.328	1133.1
58.538	1220.4
65.749	1300.4
68.277	1327.6
70.765	1353.7
73.253	1379.
75.741	1403.6
78.228	1427.3
80.716	1450.3
83.204	1472.5
85.691	1493.9
88.179	1514.5
90.667	1534.4
93.155	1553.6
95.642	1572.1
98.13	1589.9
100.62	1607.
103.11	1623.5
105.59	1639.3
108.08	1654.6
110.57	1669.2
113.06	1683.3
115.54	1696.8
118.03	1709.7
120.52	1722.2
123.01	1734.1
125.5	1745.5
127.98	1756.4
130.47	1766.8
132.96	1776.8
135.45	1786.3
137.93	1795.4
140.42	1804.2
142.91	1812.4
145.4	1820.3
147.88	1827.8
150.37	1835.
152.86	1841.9
155.35	1848.4
157.84	1854.6
160.32	1860.6
162.81	1866.3
165.3	1871.7
167.79	1876.8
170.27	1881.7
172.76	1886.3

175.25	1890.7
177.74	1894.9
180.28	1899.
182.91	1902.9
185.65	1906.8
188.51	1910.7
191.51	1914.5
194.5	1918.2
197.63	1921.7
201.23	1925.5
204.83	1929.
208.77	1932.5
213.11	1936.
217.91	1939.6
223.31	1943.1
228.71	1946.3
235.66	1949.9
242.61	1953.
251.93	1956.4
261.24	1959.2
276.4	1962.8
291.57	1965.2
323.42	1968.2
355.27	1969.9
415.27	1971.3
475.27	1971.7
535.27	1972.1
567.64	1972.4
600.	
600.01	
600.02	
600.05	
600.14	
600.24	
600.34	
600.44	
600.54	
600.64	
600.74	
600.84	
600.94	1972.7
601.	
601.01	
601.02	
601.05	
601.14	
601.24	
601.34	
601.44	
601.54	
601.64	
601.74	
601.84	
601.94	
602.	
602.01	
602.02	
602.05	
602.14	
602.24	
602.34	
602.44	
602.54	
602.64	
602.74	1972.8
602.84	
602.94	
603.	
603.01	
603.02	
603.05	
603.14	
603.24	
603.34	
603.44	
603.54	
603.64	
603.74	
603.84	
603.94	

604.	1972.9
604.01	
604.02	
604.05	
604.14	
604.24	
604.34	
604.44	
604.54	
604.64	
604.74	
604.84	
604.94	
605.	
605.01	
605.02	
605.05	
605.14	
605.24	1973.
605.34	
605.44	
605.54	
605.64	
605.74	
605.84	
605.94	
606.	
606.01	
606.02	
606.05	
606.14	
606.24	
606.34	
606.44	
606.54	
606.64	
606.74	
606.84	1973.1
606.94	
607.	
607.01	
607.02	
607.05	
607.14	
607.24	
607.34	
607.44	
607.54	
607.64	
607.74	
607.84	
607.94	
608.	
608.01	
608.02	
608.05	
608.14	
608.24	
608.34	
608.44	
608.54	1973.2
608.64	
608.74	
608.84	
608.94	
609.	
609.01	
609.02	
609.05	
609.14	
609.24	
609.34	
609.44	
609.54	
609.64	
609.74	
609.84	
609.94	
610.	
610.01	

610.02	
610.05	
610.14	1973.3
610.24	
610.34	
610.44	
610.54	
610.64	
610.74	
610.84	
610.94	
611.	
611.01	
611.02	
611.05	
611.14	
611.24	
611.34	
611.44	
611.54	
611.64	
611.74	
611.84	
611.94	1973.4
612.	
612.01	
612.02	
612.05	
612.14	
612.24	
612.34	
612.44	
612.54	
612.64	
612.74	
612.84	
612.94	
613.	
613.01	
613.02	
613.05	
613.14	
613.24	
613.34	
613.44	
613.54	
613.64	
613.74	1973.5
613.84	
613.94	
614.	
614.01	
614.02	
614.05	
614.14	
614.24	
614.34	
614.44	
614.54	
614.64	
614.74	
614.84	
614.94	
615.	
615.01	
615.02	
615.05	
615.14	
615.24	
615.34	
615.44	
615.54	
615.64	
615.74	
615.84	
615.94	
616.	
616.01	
616.02	
616.05	

616.14	
616.24	
616.34	
616.44	
616.54	
616.64	
616.74	
616.84	
616.94	1973.6
617.	
617.01	
617.02	
617.05	
617.14	
617.24	
617.34	
617.44	
617.54	
617.64	
617.74	
617.84	
617.94	
618.	
618.01	
618.02	
618.05	
618.14	
618.24	
618.34	
618.44	
618.54	1973.7
618.64	
618.74	
618.84	
618.94	
619.	
619.01	
619.02	
619.05	
619.14	
619.24	
619.34	
619.44	
619.54	
619.64	
619.74	
619.84	
619.94	
620.	
620.01	
620.02	
620.05	
620.14	
620.24	
620.34	
620.44	
620.54	
620.64	1973.8
620.74	
620.84	
620.94	
621.	
621.01	
621.02	
621.05	
621.14	
621.24	
621.34	
621.44	
621.54	
621.64	
621.74	
621.84	
621.94	
622.	
622.01	
622.02	
622.05	
622.14	
622.24	

622.34	
622.44	
622.54	
622.64	
622.74	
622.84	
622.94	
623.	
623.01	
623.02	
623.05	1973.9
623.14	
623.24	
623.34	
623.44	
623.54	
623.64	
623.74	
623.84	
623.94	
624.	
624.01	
624.02	
624.05	
624.14	
624.24	
624.34	
624.44	
624.54	
624.64	
624.74	
624.84	
624.94	
625.	
625.01	
625.02	
625.03	
625.04	1974.
625.08	
625.18	
625.28	
625.38	
625.48	
625.58	
625.68	
625.78	
625.88	
625.94	
626.	
626.01	
626.02	
626.04	
626.12	
626.22	
626.32	
626.42	
626.52	
626.62	
626.72	
626.82	
626.92	
627.	
627.01	
627.02	
627.05	
627.14	
627.24	
627.34	1974.1
627.44	
627.54	
627.64	
627.74	
627.84	
627.94	
628.	
628.01	
628.02	
628.05	
628.14	
628.24	

628.34	
628.44	
628.54	
628.64	
628.74	
628.84	
628.94	
629.	
629.01	
629.02	
629.05	
629.14	
629.24	
629.34	
629.44	
629.54	
629.64	
629.74	
629.82	
629.91	
630.	
630.01	
630.02	1974.2
630.05	
630.14	
630.24	
630.34	
630.44	
630.54	
630.64	
630.74	
630.84	
630.94	
631.	
631.01	
631.02	
631.05	
631.14	
631.24	
631.34	
631.44	
631.54	
631.64	
631.74	
631.84	
631.94	
632.	
632.01	
632.02	
632.05	
632.14	
632.24	
632.34	
632.44	
632.54	
632.64	
632.74	
632.84	
632.94	1974.3
633.	
633.01	
633.02	
633.05	
633.14	
633.24	
633.34	
633.44	
633.54	
633.64	
633.74	
633.84	
633.94	
634.	
634.01	
634.02	
634.05	
634.14	
634.24	
634.34	
634.44	

634.54	
634.64	
634.74	
634.84	
634.94	
635.	
635.01	
635.02	
635.05	
635.14	
635.24	
635.34	
635.44	
635.54	
635.64	
635.74	
635.84	
635.94	1974.4
636.	
636.01	
636.02	
636.05	
636.14	
636.24	
636.34	
636.44	
636.54	
636.64	
636.74	
636.84	
636.94	
637.	
637.01	
637.02	
637.05	
637.14	
637.24	
637.34	
637.44	
637.54	
637.64	
637.74	
637.84	
637.94	
638.	
638.01	
638.02	
638.05	
638.14	
638.24	
638.34	
638.44	
638.54	
638.64	
638.74	1974.5
638.84	
638.94	
639.	
639.01	
639.02	
639.05	
639.14	
639.24	
639.34	
639.44	
639.54	
639.64	
639.74	
639.84	
639.94	
640.	
640.01	
640.02	
640.05	
640.14	
640.24	
640.34	
640.44	
640.54	
640.64	

640.74	
640.84	
640.94	
641.	
641.01	
641.02	
641.05	
641.14	
641.24	
641.34	
641.44	
641.54	
641.64	
641.74	
641.84	
641.94	
642.	
642.01	
642.02	1974.6
642.05	
642.14	
642.24	
642.34	
642.44	
642.54	
642.64	
642.74	
642.84	
642.94	
643.	
643.01	
643.02	
643.05	
643.14	
643.24	
643.34	
643.44	
643.54	
643.64	
643.74	
643.84	
643.94	
644.	
644.01	
644.02	
644.05	
644.14	
644.24	
644.34	
644.44	
644.54	
644.64	
644.74	
644.84	
644.94	
645.	
645.01	
645.02	
645.05	1974.7
645.14	
645.24	
645.34	
645.44	
645.54	
645.64	
645.74	
645.84	
645.94	
646.	
646.01	
646.02	
646.05	
646.14	
646.24	
646.34	
646.44	
646.54	
646.64	
646.74	
646.84	

646.94	
647.	
647.01	
647.02	
647.05	
647.14	
647.24	1974.8
647.34	
647.44	
647.54	
647.64	
647.74	
647.84	
647.94	
648.	
648.01	
648.02	
648.05	
648.14	
648.24	
648.34	
648.44	
648.54	
648.64	
648.74	
648.84	
648.94	
649.	

Material Data

Stainless steel, martensitic

TABLE 56
Stainless steel, martensitic > Constants

Isotropic Secant Coefficient of Thermal Expansion	9.95e-006 C^-1
Isotropic Resistivity	5.46e-007 ohm m

TABLE 57
Stainless steel, martensitic > Density

Density kg m^-3
7750

TABLE 58
Stainless steel, martensitic > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
2.e+011	0.28	1.5152e+011	7.8125e+010

TABLE 59
Stainless steel, martensitic > Isotropic Thermal Conductivity

Thermal Conductivity W m^-1 C^-1
24.9

TABLE 60
Stainless steel, martensitic > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 61
Stainless steel, martensitic > Specific Heat Constant Pressure

Specific Heat J kg^-1 C^-1
474

TABLE 62
Stainless steel, martensitic > Color

Red	Green	Blue
153	153	153

TABLE 63
Stainless steel, martensitic > Tensile Yield Strength

Tensile Yield Strength Pa
7.62e+008

TABLE 64
Stainless steel, martensitic > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
8.4e+008

Structural Steel

TABLE 65
Structural Steel > Constants

Density	7850 kg m^-3
Isotropic Secant Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat Constant Pressure	434 J kg^-1 C^-1
Isotropic Thermal Conductivity	60.5 W m^-1 C^-1
Isotropic Resistivity	1.7e-007 ohm m

TABLE 66
Structural Steel > Color

Red	Green	Blue
132	139	179

TABLE 67
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength Pa
0

TABLE 68
Structural Steel > Compressive Yield Strength

Compressive Yield Strength Pa
2.5e+008

TABLE 69
Structural Steel > Tensile Yield Strength

Tensile Yield Strength Pa
2.5e+008

TABLE 70
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4.6e+008

TABLE 71
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 72
Structural Steel > S-N Curve

Alternating Stress Pa	Cycles	Mean Stress Pa
3.999e+009	10	0
2.827e+009	20	0
1.896e+009	50	0
1.413e+009	100	0
1.069e+009	200	0
4.41e+008	2000	0
2.62e+008	10000	0
2.14e+008	20000	0
1.38e+008	1.e+005	0
1.14e+008	2.e+005	0
8.62e+007	1.e+006	0

TABLE 73
Structural Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9.2e+008	-0.106	0.213	-0.47	1.e+009	0.2

TABLE 74
Structural Steel > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa	Temperature C
2.e+011	0.3	1.6667e+011	7.6923e+010	

TABLE 75
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000

Graphite felt

TABLE 76
Graphite felt > Constants

Density	157.5 kg m^-3
Specific Heat Constant Pressure	2050 J kg^-1 C^-1

TABLE 77
Graphite felt > Color

Red	Green	Blue
235	222	222

TABLE 78
Graphite felt > Isotropic Thermal Conductivity

Thermal Conductivity W m^-1 C^-1	Temperature C
2.99e-002	0
2.99e-002	40
2.99e-002	88
3.24e-002	148
3.49e-002	204
3.73e-002	249
4.11e-002	312
4.48e-002	382
4.85e-002	445
5.48e-002	528
6.1e-002	611
6.6e-002	663
7.47e-002	746
8.71e-002	857
9.96e-002	942
0.1108	1013
0.122	1075
0.1357	1146
0.1506	1216
0.1668	1284
0.1867	1359
0.2017	1412
0.2166	1460
0.2365	1518
0.2564	1565
0.2851	1631
0.3087	1678
0.3324	1724
0.361	1774
0.4021	1834
0.4568	1912
0.5191	1982
0.5402	2000

Titanium

TABLE 79
Titanium > Constants

Isotropic Secant Coefficient of Thermal Expansion	8.89e-006 C^-1
Isotropic Resistivity	5.62e-007 ohm m

TABLE 80
Titanium > Density

Density kg m^-3
4510

TABLE 81
Titanium > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
1.02e+011	0.36	1.2143e+011	3.75e+010

TABLE 82
Titanium > Isotropic Thermal Conductivity

Thermal Conductivity W m^-1 C^-1
17.1

TABLE 83
Titanium > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 84
Titanium > Specific Heat Constant Pressure

Specific Heat J kg^-1 C^-1
540

TABLE 85
Titanium > Color

Red	Green	Blue
204	204	204

TABLE 86
Titanium > Tensile Yield Strength

Tensile Yield Strength Pa
3.15e+008

TABLE 87
Titanium > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4.11e+008

Graphite

TABLE 88
Graphite > Constants

Isotropic Thermal Conductivity	24 W m^-1 C^-1
Density	2250 kg m^-3
Specific Heat Constant Pressure	709 J kg^-1 C^-1

TABLE 89
Graphite > Color

Red	Green	Blue
155	244	255

Zirconia

TABLE 90
Zirconia > Constants

Isotropic Secant Coefficient of Thermal Expansion	7.27e-006 C^-1
Isotropic Resistivity	9.99e+006 ohm m

TABLE 91
Zirconia > Density

Density kg m^-3
6090

TABLE 92
Zirconia > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
1.38e+011	0.259	9.5436e+010	5.4805e+010

TABLE 93
Zirconia > Isotropic Thermal Conductivity

Thermal Conductivity W m^-1 C^-1
1.84

TABLE 94
Zirconia > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 95
Zirconia > Specific Heat Constant Pressure

Specific Heat J kg^-1 C^-1
427

TABLE 96
Zirconia > Color

Red	Green	Blue
255	255	204

TABLE 97
Zirconia > Tensile Yield Strength

Tensile Yield Strength Pa
1.32e+008

TABLE 98
Zirconia > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
1.32e+008

Molybdenum

TABLE 99
Molybdenum > Constants

Isotropic Thermal Conductivity	130 W m^-1 C^-1
Density	10220 kg m^-3
Specific Heat Constant Pressure	251 J kg^-1 C^-1

TABLE 100
Molybdenum > Color

Red	Green	Blue
234	247	209

Tungsten

TABLE 101
Tungsten > Constants

Isotropic Thermal Conductivity	174 W m^-1 C^-1
Density	19300 kg m^-3
Specific Heat Constant Pressure	132 J kg^-1 C^-1

TABLE 102
Tungsten > Color

Red	Green	Blue
170	170	170

VITA

Richard Harmon Howard was born to James Stanley Howard and Clarann Frazer Moore Howard in Montgomery, Alabama on July 18th, 1981. He received a bachelor's degree in Mechanical Engineering from Auburn University in 1999 and a master's degree in Nuclear Engineering in 2012. He joined the Oak Ridge National Laboratory in 2011 as a research engineer, where he designs experiments to support radioisotope production, nuclear fuels, and structural materials research. To date, Mr. Howard has made contributions to the resumption of domestic production of ^{238}Pu, developing Fe-Cr-Al cladding systems as an alternate to zirconium metal LWR cladding, resumption of domestic production of ^{60}Co and nuclear thermal propulsion.