

High Temperature Steady-State In-Pile Experiment Development for Nuclear Thermal Propulsion Testing and Computational Radiative Heat Transfer Validation

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Dedication

To Kailene.

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Abstract

A high temperature steady-state in-pile experiment was developed to simulate prototypical nuclear thermal propulsion conditions in addition to serve as a validation tool for radiative heat transfer computational methods. The experimental development of the test apparatus involved scaling the device to a larger heated region from a previous smaller out-of-pile prototype. A series of tests and investigations were conducted to replicate the smaller out-of-pile system's success of achieving 2500 K . However, limitations within the larger assembly were identified. The larger assembly can reliably generate usable temperature levels from room temperature up to those exceeding 1300 K . The larger system is achieving temperatures over 2500 K , but these are localized and unable to be monitored in the current design. Due to the limitations of the current heater, it is recommended that the apparatus be redesigned to utilize a heating element similar to that used during Project POODLE in the 1960s. However, the achieved temperature levels are still suitable for testing various components considered for a nuclear thermal rocket. Various in-pile experiments have been performed to test materials and instrumentation relevant to nuclear thermal rocket systems. This temperature level also provides sufficient thermal energy for radiative heat transfer studies. The experimental results were used to compare leading thermal modeling software packages and various solution methods. The experiment was compared against COMSOL and ANSYS. Within COMSOL the radiation view factors were calculated using the hemi-cube and the ray shooting solution methods. These were also compared against ANSYS, which utilized the hemi-cube view factor solution method.

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Nomenclature

AEC	Atomic Energy Committee
AES	Advanced Exploration Systems
CAD	Computer Aided Design
CF	ConFlat®
CFEET	Compact Fuel Element Environmental Test
DC	Direct Current
DOD	Department of Defense
EDXS	Energy Dispersive X-Ray Spectroscopy
EM	Electromagnetic
HEU	Highly Enriched Uranium
INL	Idaho National Laboratory
INSET	In-Pile Surrogate Testbed for Extreme Temperatures
IP	In-Pile
KF	Klein Flansche
LANL	Los Alamos National Laboratory
LEU	Low Enriched Uranium
LH2	Liquid Hydrogen
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCPS	Nuclear Cryogenic Propulsion Stage
NERVA	Nuclear Engine for Rocket Vehicle Applications
NRX	Nuclear Reactor Experiment
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
NTREES	Nuclear Thermal Rocket Element Environmental Simulator
OOP	Out-of-Pile
ORNL	Oak Ridge National Laboratory
OSURR	Ohio State University Research Reactor
OUTSET	Out-of-Pile Surrogate Testbed for Extreme Temperatures
PBR	Particle Bed Reactor
POODLE	Radioisotope Propulsion Technology Program
RF	Radio Frequency
RHT	Radiative Heat Transfer
RIFT	Reactor In-Flight Test
RTD	Resistance Temperature Detector
S2S	ANSYS Surface-to-Surface Radiation Transport Model
SNP	Space Nuclear Propulsion
SNTP	Space Nuclear Thermal Propulsion
SOP	Standard Operating Procedure
TC	Thermocouple
TIP	Technology Implementation Plan
TREAT	Transient Reactor Test
TRL	Technology Readiness Level
U.S.	United States of America
XE	Experimental Reactor
XRF	X-Ray Florescence

1 Nuclear Thermal Propulsion Introduction

A nuclear thermal rocket (NTR) produces thrust by heating, typically, hydrogen propellant through a nuclear reactor core at roughly 2500 K . This offers advantages over conventional chemical rockets by utilizing a less massive propellant and producing a larger specific impulse. These advantages will be discussed later.

1.1 Background

From 1955 until 1972, twenty-two rocket reactors were designed, constructed, and tested as a part of the Rover program [1]. The Nuclear Engine for Rocket Vehicle Applications (NERVA) project was the longest running project under the Rover program. The goal of the Rover program was to explore the capability of technologies that are needed for crewed planetary exploration missions [1]. The program, as stated by Borowski ([1]), demonstrated five core technologies: a range of thrust levels (25 to 250 klbf), high temperature carbide based (and cermet) nuclear fuels, sustained engine operation as long as a single burn of 62 minutes , accumulated lifetime at full power, and restart capability after 28 startup and shutdown cycles on the NRX-XE experimental engine. A technology readiness level of 5-6 was demonstrated during the Rover program, implying that nuclear thermal propulsion (NTP) is a "proven technology" [1]. Figure 1.1 shows a schematic of the NERVA-derived NTR engine.

To briefly touch on how an NTR generally works, propellant is heated by a nuclear reactor and thermally expanded and accelerated through a nozzle. This expansion and acceleration of fuel produces the rocket thrust. The propellant has low molecular weight, and is typically hydrogen. The use of control drums will manage the core criticality. Control drums surround the core and rotate to control reactivity. A portion of the circumference of the control drums is covered with a neutron absorber while the remainder of the circumference is a neutron reflector. The reactor will be operated in pulses of a short length dependent on the system's design, but will be on the order of minutes. The current proposed flight plan encompasses both the destination and return trips, and utilizes one pulse to reach cruising velocity and one pulse to slow down on approach. The rough order of magnitude maximum operating conditions of an NTP system are seen in Table 1.1. Note that some of these values are highly dependent on the chosen reactor design and represent maxima; for example, the hydrogen flow rate of a likely system will be more near 10 kg/s .

NTP has significant advantages over conventional chemical propulsion systems. NTP can reduce the Mars mission time from greater than 900 days for chemical rockets to less than 500 days for an NTR [1]. NTP has been recorded as being able to generate a specific impulse of 900 s . This is twice that of the best chemical rockets used today [5]. The specific impulse of a flight vehicle is a measure of the ratio of thrust to weight as shown in Equation 1.1 [6]. This reduction in mission time exposes the crew to significantly less space radiation, decreasing the risks associated with radiation exposure. Reduced travel time will also enable longer surface stays.

$$I_{sp} = \frac{F}{g_c \dot{m}} \quad (1.1)$$

where:

I_{sp} = specific impulse

F = total engine thrust

g_c = gravitational constant

$\dot{m}$ = propellant mass flow rate

In addition to shorter missions, NTP also offers the potential for less massive missions. NTP has been estimated to be able to reduce the launch mass by over 400 metric tons , depending on the mission scope. For perspective, that is the equivalent mass of the International Space Station [1]. This significant reduction in launch mass may potentially yield a less expensive mission.

Another facet of NTP is that it shows substantial “evolution and growth” capability [1]. For example, the bimodal system, generates its own electrical power to support spacecraft operational needs. Another adaptation is the addition of an oxygen afterburner nozzle to further increase the specific impulse while allowing for safer and more versatile fuel requirements. NASA has recognized the versatility of NTP in the Mars Design Reference Architecture 5.0 study by selecting NTP as the preferred propulsion option [1]. There are several design evolutions that can be implemented with NTP, enhancing its versatility, which is another benefit NTP offers over conventional chemical rockets. NTP is a proven technology that can lead to shorter, cheaper, and safer missions [1].

1.2 Rover Program (1950s - 1970s)

In the early 1950s the benefits of a nuclear rocket over a conventional chemical rocket were apparent to the United States government, which resulted in the pursuit of research and development of NTP. The Rover program launched in 1955 encompassed both the research and technology development of nuclear rockets, and expended around \$1.4B (1970s cost) [7]. A primary research focus of the Rover program, conducted by the Los Alamos National Laboratory (LANL), was the development of reactor systems and fuel for the NTR [8]. A total of twenty-two ground tests of nuclear rockets were conducted under this program [9]. The Rover program consisted of four projects: KIWI, NERVA, PHOEBUS, and RIFT [10]. Some of the records set throughout the Rover program are shown in Figure 1.2.

A diagram showing the Rover program structure is shown in Figure A.1 in Appendix A. This diagram is taken from the labeled reference that cites the original source, which is could not be found. Also provided in Appendix A is Figure A.2 showing the chronology of the Rover rocket reactor tests [4].

1.2.1 KIWI Project (1959 - 1964)

The KIWI project sought to design, build, and test nuclear rocket engine prototypes. The prototypes developed as a part of the KIWI project were never intended to be used directly in flight. The KIWI project concentrated on producing advanced hydrogen cooled reactors. The KIWI series of reactors were used to determine the feasibility of various high temperature concepts with hydrogen coolant/propellant. Following the conclusion of the KIWI experiments, efforts shifted from KIWI to the higher power graphite PHOEBUS reactor [10].

The first series of KIWI reactors is referred to as the KIWI-A series. These reactors were tested for years and proved that NTP could successfully generate the desired operational conditions. The final KIWI reactor was the B4E, which was the seventh reactor in the series. KIWI-B4E operated at 2000 K for 11 *minutes*. This design was used as the basis for subsequent reactors [8]. Following the KIWI series of reactors was the Nuclear Reactor Experimental (NRX) series. The NRX series continued to improve upon the KIWI series design by enhancing structural integrity, reducing fuel corrosion rates, and generating higher operating temperatures. The NRX reactor series was chosen as the design for the NERVA project [8]. Figure 1.3 shows a schematic of the NRX reactor that was chosen for use in the NERVA project.

1.2.2 NERVA Project (1961 - 1972)

The objective of the NERVA project that launched in 1961 was to, “establish a technology base for nuclear rocket engine systems to be utilized in the design and development of propulsion systems for space mission application [8].” The NERVA project is popularly incorrectly identified as a program equivalent to the Rover program. As Finseth ([10]) states, “The NERVA project is often mistakenly used in the context that it was America’s nuclear rocket program. In fact, the NERVA project was an advanced phase of the AEC-NASA Rover program [10].” Additional supporting references for this claim can be found in references [11] and [12].

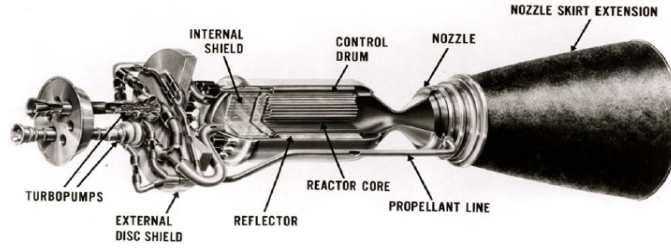


Figure 1.1: NERVA-derived NTR engine schematic [1].

Table 1.1: Approximate maximum NTP operating conditions.

Maximum Core Temperature (exit) [1]	3000 <i>K</i>
Core Heating Rate [2]	360 <i>K/s</i>
Total Neutron Fluence [3]	$\sim 10^{17} \text{ n/cm}^2$
Gas Chamber Pressure [1]	1000 <i>psi</i>
LH2 Flow Rate [4]	120 <i>kg/s</i>
Thrust [1]	250 <i>klbf</i>
Specific Impulse [1]	900 <i>s</i>

RECORD PERFORMANCES	
POWER (PHOEBUS-2A)	4100 MW
THRUST (PHOEBUS-2A)	930 kN
HYDROGEN FLOW RATE (PHOEBUS-2A)	120 kg/s
EQUIVALENT SPECIFIC IMPULSE (PEWEE)	845 s
MINIMUM REACTOR SPECIFIC MASS (PHOEBUS-2A)	2.3 kg/MW
AVERAGE COOLANT EXIT TEMPERATURE (PEWEE)	2550 K
PEAK FUEL TEMPERATURE (PEWEE)	2750 K
CORE AVERAGE POWER DENSITY (PEWEE)	2340 MW/m ³
PEAK FUEL POWER DENSITY (PEWEE)	5200 MW/m ³
ACCUMULATED TIME AT FULL POWER (NF-1)	109 MIN
GREATEST NUMBER OF RESTARTS (XE)	28

Figure 1.2: Experimental test records achieved during the Rover program [4].

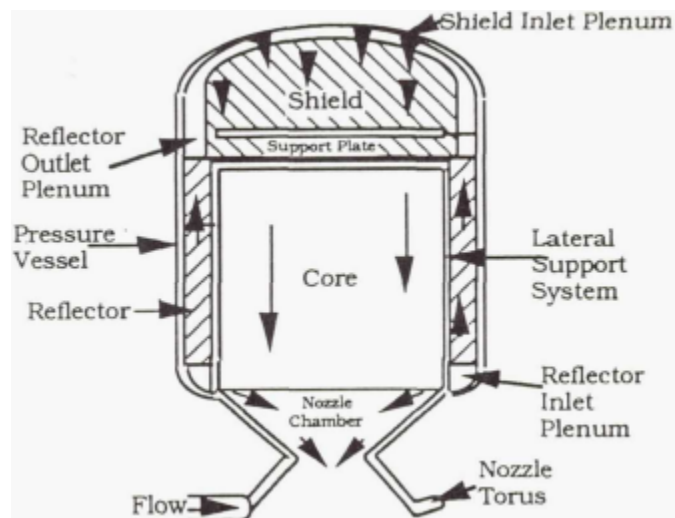


Figure 1.3: NRX reactor assembly and flow path [8].

The NERVA project employed the best of the KIWI reactor designs. This schematic can be seen in Figure 1.3. The reactor core was composed of graphite fuel elements impregnated with uranium carbide particles supported axially and laterally. The reflector was beryllium. There were twelve rotary control drums with a boron sheet in the reflector to control the reactivity of the system. This design was assembled so that, if incorporated into a flight engine system configuration, it could produce a specific impulse of roughly 825 s and a reactor operating temperature of 2300 K [8].

The NERVA propulsion system surface tests were conducted at the Nuclear Rocket Development Station in Nevada. The testing produced results that met all of the technology development goals that were set [8]. Additionally, the project culminated to the successful firing of a flight geometry engine called XE-Prime. The XE systems made incremental improvements to NRX systems. XE-Prime achieved about 55 *klbf* of thrust. Continuing the successful research, the goal of extending the life of fuel elements to 60 cycles was achieved in electrically heated fuel tests. Despite the successes of the NERVA project, the United States government ceased its funding in 1972 and eliminated the nuclear rocket program so the nation could focus on its involvement in the Vietnam War [10].

The flight configuration of the NERVA engine is shown in Figure 1.4.

1.2.3 RIFT Project (1961 - 1963)

Reactor In-Flight Test (RIFT) was developed to fly an NTR. The objectives recorded by Finseth ([10]) are, "to design, develop, fabricate, and flight test a NERVA-powered vehicle as an upper stage for the Saturn-class launch vehicle." This project's goal was essentially using a flight version of a propulsion system from NERVA on a Saturn vehicle [10].

The plan was to build RIFT at Sunnyvale, California, test RIFT at Jackass Flats, Nevada, and launch RIFT at Cape Canaveral, Florida. However, the United States government became concerned with the ejection of fuel elements from the reactor during testing. This fuel ejection is known to also have previously occurred during the KIWI surface tests. Resulting from their concerns, the United States government canceled the RIFT project in 1963 [10].

1.2.4 PHOEBUS Project (1963 - 1968)

The PHOEBUS project used three new test reactors to achieve higher power levels and longer duration operations than what was seen in KIWI [10]. Building upon the KIWI B4E fuel elements, the PHOEBUS project consisted of additional reactors to test and improve the nuclear fuel performance. Figure 1.5 shows a diagram of the fuel elements used in KIWI B4E [13].

The PHOEBUS project yielded successful tests. The second (of three) PHOEBUS reactor tests is regarded as a significant NTP milestone. PHOEBUS 1B was successfully operated at 73 *klbf* of thrust for 30 *minutes*. These values are representative of the practical power demand and thrust required for planetary exploration [1]. The final PHOEBUS reactor test, 2A, produced 210 *klbf* of thrust for 12 *minutes*. During the PHOEBUS 2A test, the reactor control systems operated successfully in a full radiation environment. The PHOEBUS 2A test also used regeneratively cooled counter-flow tie tubes to provide turbine-driven energy. This is attractive for future NTP engines that will operate on an expander cycle. The PHOEBUS project improved upon a successful KIWI project and reaffirmed the promise of NTP as a viable space exploration tool [13].

1.3 SNTP Program (1980s - 1990s)

The Space Nuclear Thermal Propulsion (SNTP) program started its first of three planned phases in 1987. This program was initially referred to by the U.S. Department of Defense (DOD) as the classified program,

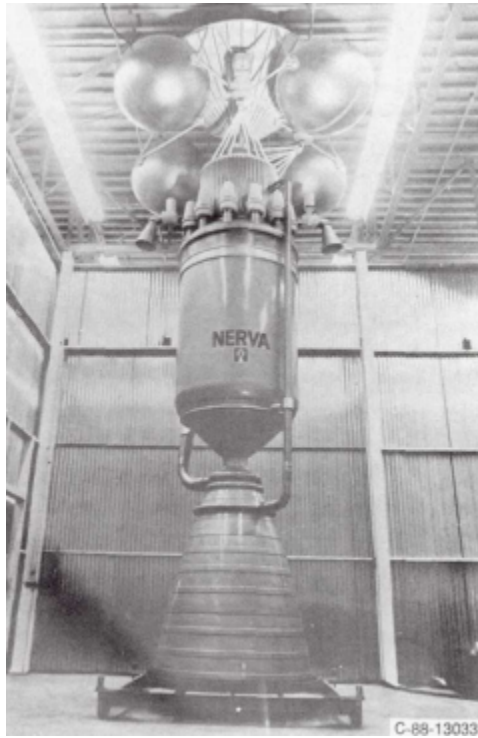


Figure 1.4: NERVA flight engine configuration [8].

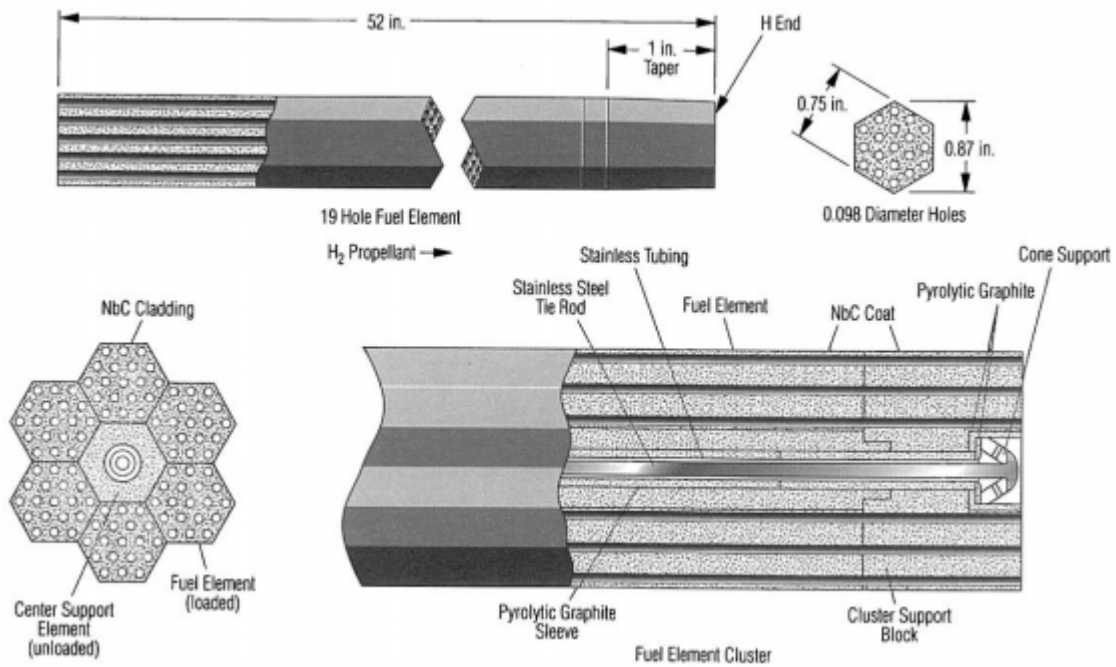


Figure 1.5: KIWI B4E fuel element cluster [13].

Timberwind. Timberwind was originally conceived to develop a method to rapidly intercept ballistic missiles [12]. The SNTP program would go on to develop nuclear engine technology for over five years and expend almost \$200M. The program had seen some substantial successes, but its funding was terminated in 1992 when the United States government’s priorities shifted following the end of the Cold War [7].

The goal of the SNTP program was to produce a nuclear engine system that could generate a specific impulse of 1000 s and a fuel particle temperature of 3500 K. This goal was planned to be pursued across three phases. Phase I of the SNTP program sought to verify the feasibility of the particle bed reactor (PBR) as a propulsion source. Phase II started in 1991 and had an objective of performing a ground demonstration of a prototypical PBR engine. Phase III, which was never reached, was planned to demonstrate the SNTP system in-flight. A PBR uses nuclear fuel particles that are each roughly the size of a grain of sand. These fuel particles are packed in two cylindrical porous frits to form a fuel element. A working cold fluid, in the case of NTP this is usually hydrogen, passes through the fuel elements. This cools the fuel and heats the working fluid. This heating of the working fluid causes expansion, which is where the desired thrust comes from. The surface area to volume ratio of a sphere optimizes the heat transfer from the fuel particles to the coolant [7].

The SNTP program offered a baseline fuel particle design for use in the PBR engine. This baseline PBR fuel particle was made up of a uranium carbide (UC_{2-x}) kernel with surrounding graphite layers and an outer coating of zirconium carbide (ZrC) or niobium carbide (NbC). For scale the particle is about 0.5 mm in diameter [7].

According to Haslett ([7]), the studies conducted under the SNTP program proved that a PBR upper stage engine offered double the payload capabilities of the Delta, Atlas, and Titan boosters, and NASA’s ”heavy lifters”. However, around 1991 NASA reviewed the PBR engine as viable, albeit higher risk, and concluded that the ”higher thrust-to-weight ratio of the PBR engine was not required for the Space Exploration Initiative mission [7].” As a result, the program was transferred to the Air Force. Not long after this, in 1993, the Air Force chose to terminate the funding for the program bringing all of its successful work to a halt [7].

1.4 State of NTP Testing Capabilities

To re-continue the pursuit of human interplanetary exploration, NASA has recently dedicated funds for NTP research. The precursor to the current NASA Space Nuclear Propulsion (SNP) project were the Advanced Exploration Systems (AES) NTP project and the Nuclear Cryogenic Propulsion Stage (NCPS) project, which began in 2011. The NCPS project sought to evaluate the affordability of NTP [14]. The project had 5 key components (as listed in [14]):

1. Pre-conceptual design of NCPS and architecture integration
2. Development of a High Power (1 MW input) Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
3. NCPS Fuel Design and Testing
4. NCPS Fuels Testing in NTREES and the Compact Fuel Element Environmental Test (CFEET) system
5. Affordable NCPS Development and Qualification Strategy

There were three classes of fuel elements under consideration during the NCPS project: coated graphite composites, cermets (ceramic/metallic composites), and advanced ceramics. Oak Ridge National Laboratory (ORNL) led the coated graphite composite work, which obtained the highest technology readiness level (TRL) of the three considered classes. Cermets were researched by NASA with considerable support from ORNL and Idaho National Laboratory (INL). Cermets were shown to be of an intermediate TRL. NASA also led research into advanced ceramics. Advanced ceramics yielded the lowest TRL. Regarding fuel type, an independent review panel recommended highly enriched uranium (HEU) for use in flight demonstrations.

The AES NTP project was planned to focus on a HEU graphite composite fuel [14].

Two test facilities have been developed, neither with nuclear reactor capabilities, to investigate potential fuels, materials, and components pertaining to NTP systems. These NTREES and CFEET, which will be discussed later. Both of these test facilities are located at NASA MSFC.

In addition to NASA's testing capabilities, ORNL has also been developing NTP testing experiments. ORNL's experimental plan will also be discussed later and offers the potential for in-pile (IP) reactor testing.

1.4.1 Compact Fuel Element Environmental Test

The Compact Fuel Element Environmental Test (CFEET) offers sub-scale testing of possible NTP fuel elements at prototypical NTP temperatures. CFEET is "an ambient pressure induction furnace capable of high temperature operation and hydrogen flow [15]." CFEET is able to simulate NTP temperature, up to 3000 K , and heating rates by using a 50 kW power supply [15]. The chamber of CFEET is approximately 46 cm in height and 25 cm in diameter. CFEET uses radio frequency (RF) induction coils to volumetrically heat the sample [16]. The temperature of the sample is measured using pyrometry through an opening in the sample region seen in Figure 1.6. Pyrometry assumes a surface emissivity and uses the Stefan-Boltzmann law for gray bodies (discussed later in section 5.1) to calculate the measured temperature. Although CFEET cannot simulate the radiation environment of NTP or utilize fission heating, future adjustments to the system are under development to support radioactive samples [15].

In addition to the experimental testing of CFEET, a thermal model has also been developed. The thermal model incorporates thermal radiation, thermal conduction, convection heat loss, and radio frequency heating [16].

1.4.2 Nuclear Thermal Reactor Element Environmental Simulator

The Nuclear Thermal Reactor Element Environmental Simulator (NTREES) is designed to conduct non-nuclear testing of NTP full-scale fuel elements by simulating the prototypical thermal hydraulic environment. The NTREES vessel has a diameter of 91 cm and a length of 305 cm [17]. NTREES uses an RF induction heater and 1.2 MW of power to arrive at expected NTP temperatures. NTREES also uses flowing hydrogen at pressures up to 1000 psi and temperatures up to 3000 K . Pyrometry is used to measure the specimen temperature. Although NTREES is a non-nuclear testing facility, it is licensed to test depleted uranium [18]. A diagram of the 2009 NTREES facility can be seen in Figure 1.7.

1.4.3 SIRIUS-1 Transient Test Series

The SIRIUS-1 experiment is designed by INL for use in the Transient Reactor Test (TREAT) reactor located at INL. The work "is focused on the development of a static capsule design, validation and verification of capsule and in-pile instrumentation for the transient testing of concept NTP fuels [20]." SIRIUS-1 utilizes nuclear heating, opposed to electrical heating, to reach capsule temperatures exceeding 2600 K . The capsule is tested under an inert atmosphere of 3% hydrogen and 97% argon to limit any chemical effects on the reactor environment. SIRIUS-1 can exercise heating rates of 90 K/s , and cannot reach prototypical volumetric power densities. The experiment can also only reach prototypical temperature levels for a few seconds to minutes [20]. A schematic of the SIRIUS-1 capsule design can be seen in Figure 1.8.

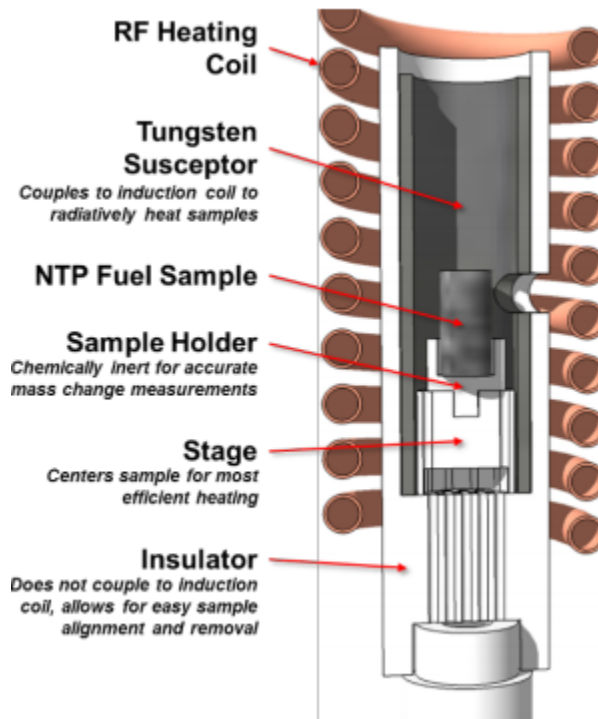


Figure 1.6: CFEET sample holder and heating assembly [15].

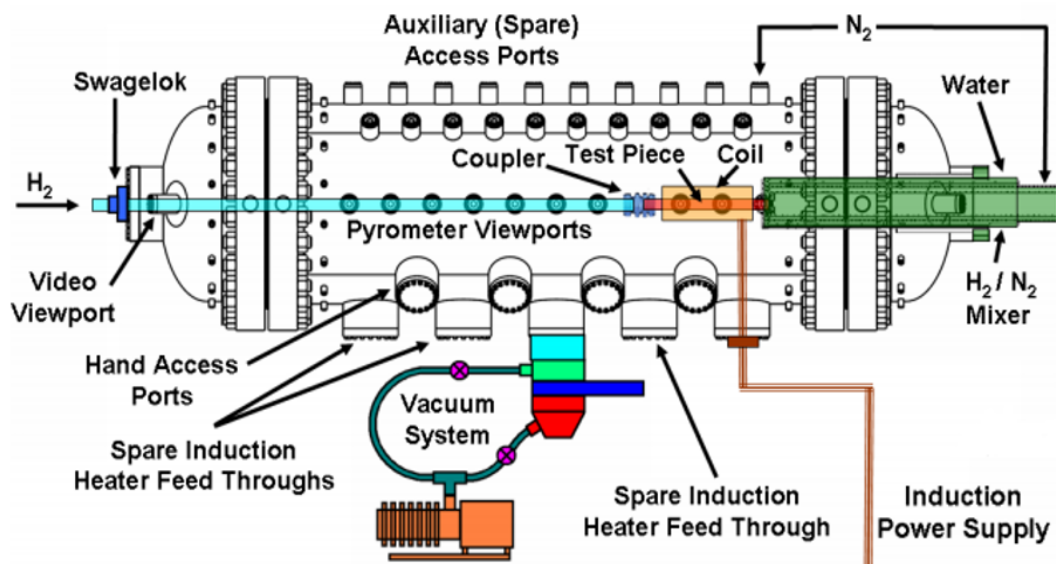


Figure 1.7: NTREES diagram [19].

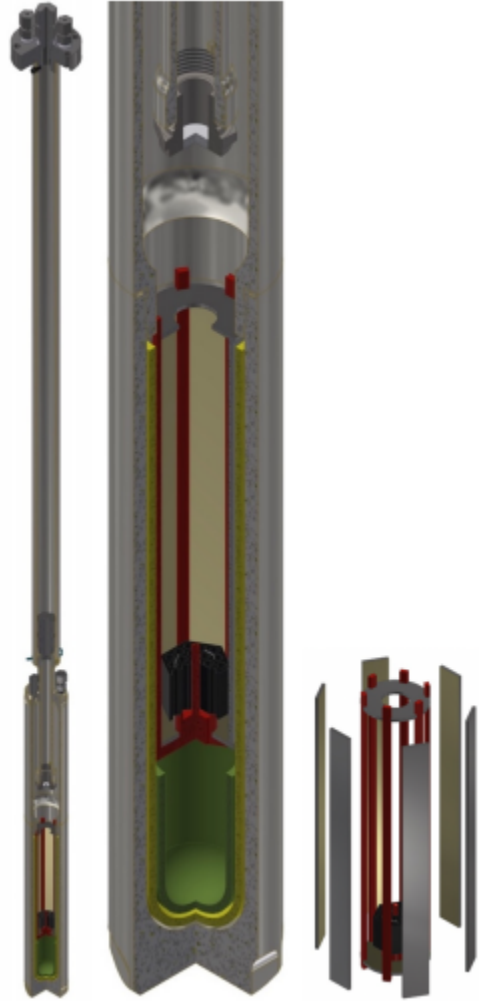


Figure 1.8: SIRIUS-1 capsule design [20].

2 NTP Testing Strategy for Fuels, Instrumentation, and Materials

A technology implementation plan (TIP) was produced by ORNL that describes the development, testing, and qualification of surrogate and prototypical NTP fuel elements. In addition to probing various potential fuel types and geometries, the experimental testing can accommodate instrumentation components that fit within the testing apparatus's specimen region. The TIP presents a natural progression of out-of-pile (OOP) surrogate testing to IP surrogate testing to prototypical fuel testing [21]. The OOP testing has been and will be conducted using the Out-of-Pile Surrogate testbed for Extreme Temperatures (OUTSET) - formerly known as the out-of-pile experiment set apparatus (also OUTSET), which will be discussed later. The TIP flow-chart can be seen in Figure 2.1.

The TIP generalizes the testing of small-scale surrogate and enriched fuel samples. These samples are exposed to prototypical NTP conditions to determine the optimal fuel geometries as well as identify the limiting operating conditions. This information will be used to influence the fuel design. This surrogate testing is part of the OOP and IP steps of the TIP. The third phase of the TIP is the prototypical fuel testing phase. This is a series of full-scale fuel element irradiation experiments that will expose the fuel to the expected limiting cases [21].

2.1 OUTSET-1

The first phase of the TIP is the OOP testing. This is conducted using OUTSET. A preliminary schematic of OUTSET, which will be referred to as OUTSET-1 can be seen in Figure 2.2. OUTSET-1 was designed and constructed to perform three functions:

- Provide electrical heating to allow the specimen to achieve target temperatures [21].
- Design flexibility to accept various direct and indirect instrumentation techniques [21].
- Provide and maintain a controlled vacuum or inert atmosphere [21].

The materials, geometry, etc. of OUTSET-1 were considered carefully and the rationale driving the design decisions can be seen in reference [22]. SIGRATHERM GFA felt was used to insulate the specimen region. Hafnia insulators were used to isolate the thermocouple to prevent signal noise. A low emissivity molybdenum foil was used to line the inner surface of the felt to reduce thermal radiation heat transfer from the sample to the insulation. The structural components were made from 304L stainless steel. Stainless steel cannot be used for the IP testing as stainless steel is susceptible to neutron activation. These design conclusions greatly influenced the IP experiment apparatus design. In addition to the construction of the experiment, a thermal analysis model was used to verify and validate the experimental results and influence the experiment's design. Following the conclusion of OUTSET-1's testing, it has been determined that the heat transfer analysis produced an acceptable solution for the thermal performance of OUTSET-1. OUTSET-1 has been proven to reach specimen temperatures of 2400 K using 300 W of electrical power under its initial design [22].

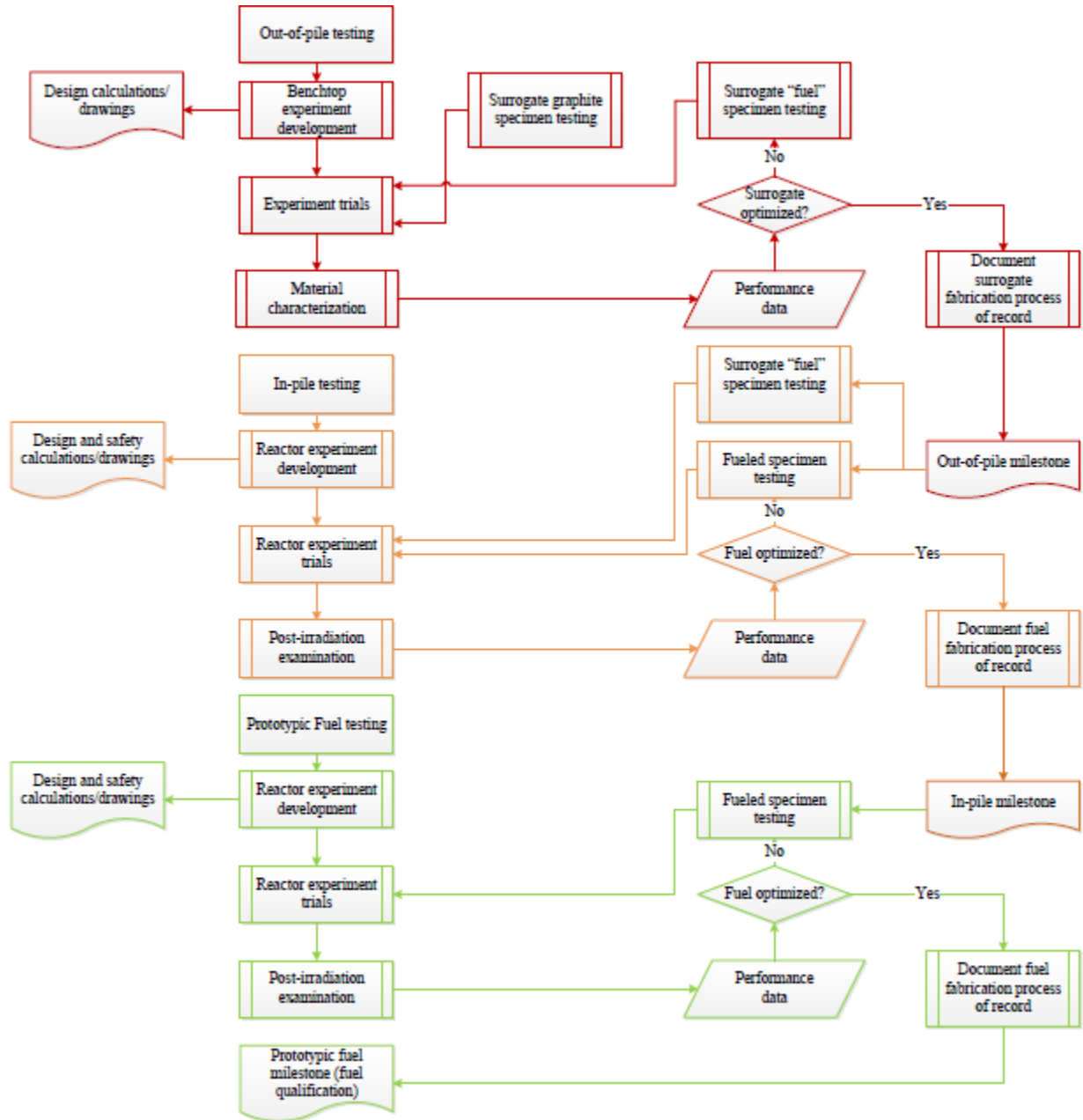


Figure 2.1: Technology implementation plan flow-chart [21].

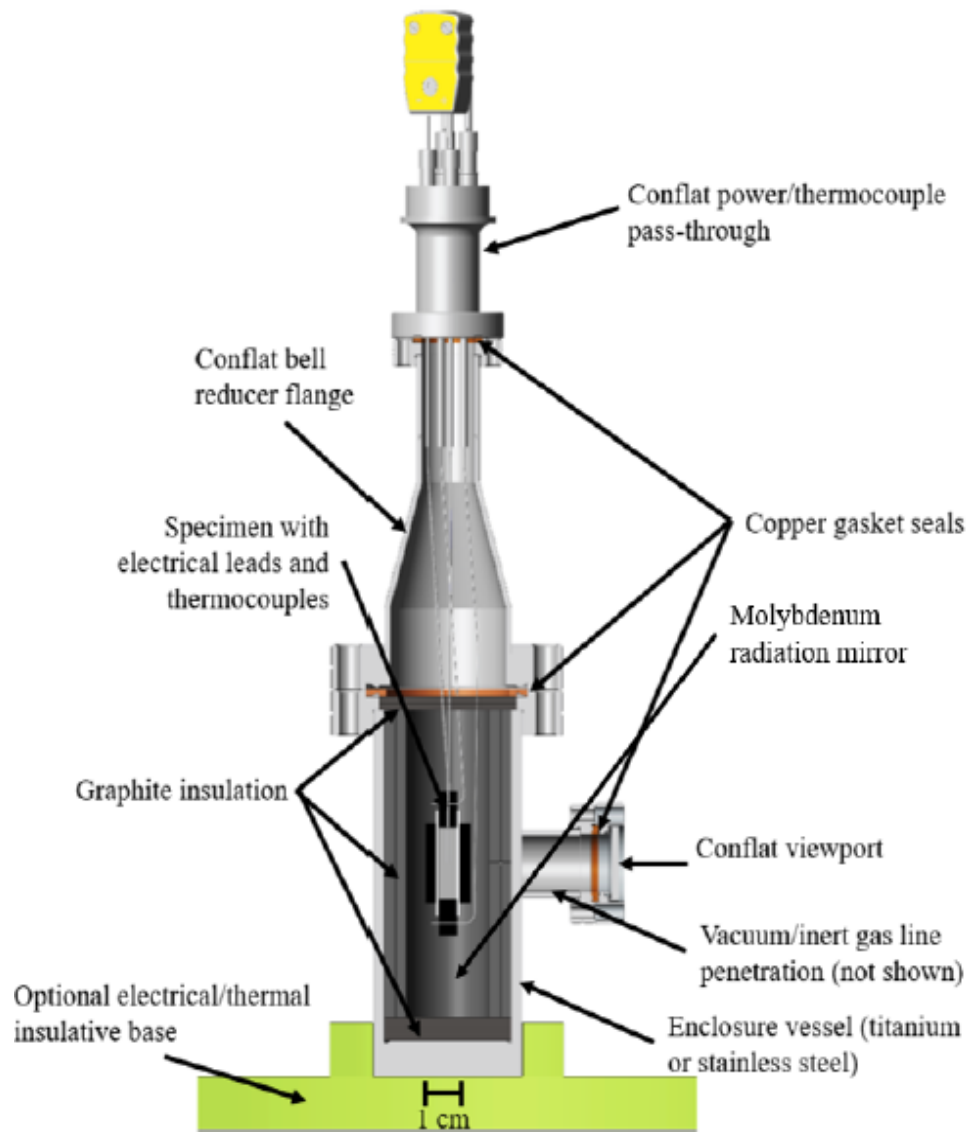


Figure 2.2: Initial schematic of OUTSET-1 [22].

3 INSET

The second phase of the TIP is the IP testing. This is conducted using the In-Pile Surrogate testbed for Extreme Temperatures (INSET). This was previously known as the In-Pile Experiment Set Apparatus (also INSET). A schematic of the original INSET design can be found in Figure 3.1. The original design assembly was roughly 33 cm axially. INSET shares the same thermal performance goals as OUTSET, but adds the capability of IP testing. INSET seeks to serve as an in-pile steady-state high temperature testbed. The IP testing was conducted at the Ohio State University Research Reactor (OSURR). The OSURR produces a neutron flux of about $10^{12} \text{ n/cm}^2/\text{s}$, where 74% of this flux consists of thermal neutrons while at maximum operating power of 450 kW at the testing location [23]. Prototypical NTP fluences of roughly 10^{17} n/cm^2 can be achieved with an irradiation time of only a few hours [3]. The updated OUTSET and INSET are identical, except for structural material. OUTSET generically refers to the apparatus set that will not be irradiated while INSET refers to the apparatus that will be irradiated. This work seeks to develop INSET to advance NTP testing capabilities, and to develop OUTSET to validate thermal radiation models. Again, the INSET and OUTSET referred to here are identical in every way except for the implemented structural material.

The 304L stainless steel body used for OUTSET produces high-energy gamma radiation when activated by neutron field. This challenge is what inspired the body of INSET to be made using 6061 aluminum. The design of INSET needs to facilitate high temperatures in the presence of a neutron field. The early design of OUTSET was developed with the intention to be easily developed and scaled to realize the current OUT/INSET design. Dr. Richard Howard is responsible for designing the entirety of the OUTSET-1 apparatus [22]. The current OUT/INSET apparatus will be used as an experimental tool to validate thermal radiation models.

OUTSET-1 was conceived to establish a successful heater design that was capable of heating material samples. Compatible material samples were of the dimensions typical for transmission electron microscopy - 3 mm cylindrical disks. This small-scale and out-of-pile apparatus demonstrated successful heating up to 2300 K [22]. This apparatus was scaled-up to a larger body. The larger apparatus became the current design for INSET. INSET was larger than OUTSET-1 to accommodate more thermal insulation as well as enable the possibility for larger sample testing. An image depicting the size difference between the heater demonstrator OUTSET-1 and the in-pile larger scale INSET can be seen in Figure 3.2.

The larger heated region of INSET over OUTSET-1 introduced some thermal obstacles that will be discussed later in Section 3.3.

3.1 INSET Definitions, Components, and Design

The initial INSET design, shown in Figure 3.1, presented experimental challenges. As such, the design was continually revisited and adjusted; the experimental challenges are presented in Section 3.3.

This document captures the progression and evolution of the experimental design. As such, there are differences in the models presented. The incremental designs and investigations will be quarantined¹ to Appendix A, where appropriate. Some steps may be relevant to the primary discussion of this document and will be included in the main text.

¹The linear progression of the model as well as the dependency between the model and the experiment was disrupted by the COVID-19 pandemic, resulting in computational progression and experimental stagnation.

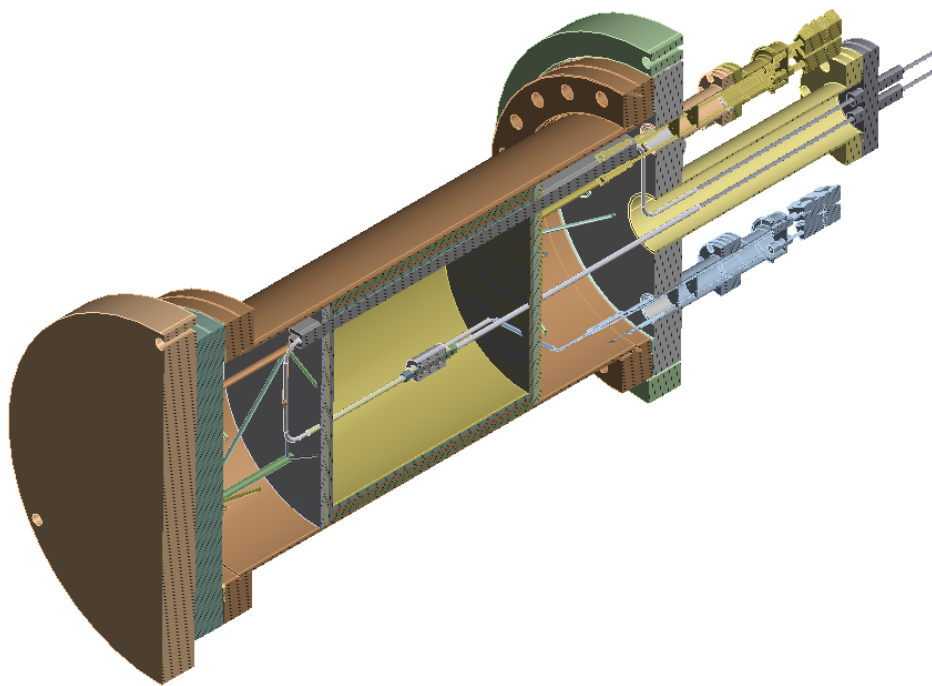


Figure 3.1: Computer aided design schematic of the initial INSET design.

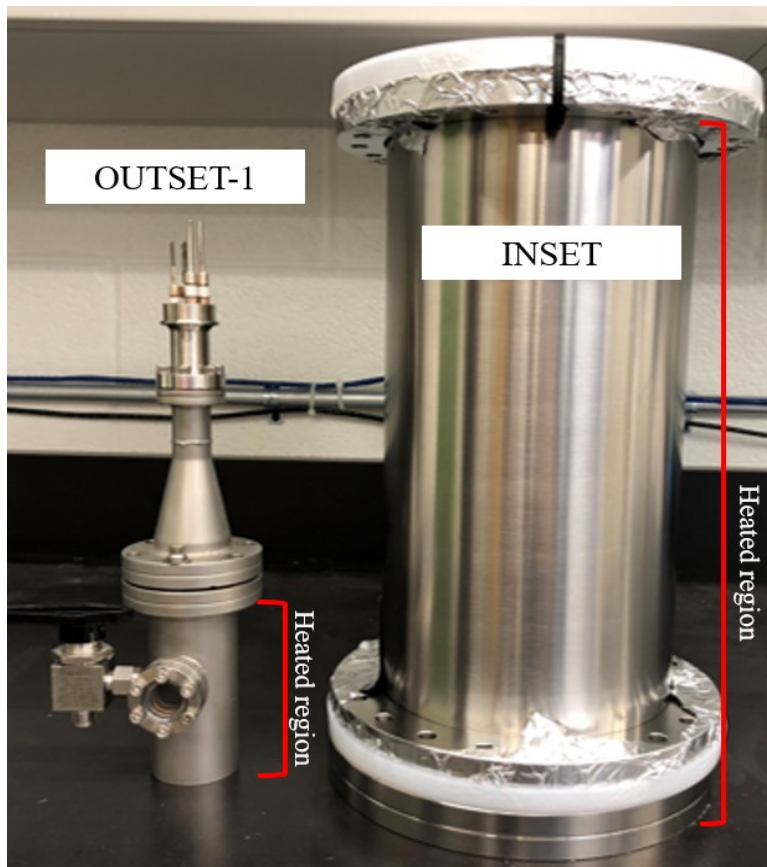


Figure 3.2: Spatial comparison showing OUTSET-1 heated region next to current INSET scale.

3.1.1 INSET Components

Prior to the discussion on the design progression, some context and definitions are necessary. INSET serves as a direct current (DC) heated system. The current is delivered to the resistive heater through copper leads in a 2.75 *in.* vacuum passthrough. The vacuum vessel is comprised of an 8 *in.* ConFlat® (CF) blank connected to an 8 *in.* by 13 *in.* CF pipe nipple. The pipe nipple is topped by a multi-purpose flange (shown in Figure 3.3) that has four 1.33 *in.* CF flanges as well as one 2.75 *in.* CF flange. The flanges on the multi-purpose flange are used for power delivery, thermocouple passthroughs, and gas removal. The heater is in a vacated plenum of pressures below 10^{-1} *mTorr*. The temperature of various locations within the apparatus is monitored by thermocouples in conjunction with a thermocouple data logger.

The power supply used for the bulk of the testing was an Elektro-Automatik PSI 9200-50 2U (shown in Figure 3.4). This unit is capable of supplying 3 *kW*, 200 *V*, and 50 *A* [24]. The power supply was connected to INSET via 8 AWG SEOOW cables from McMaster-Carr (part id: 7080K41). The electrical connection between the power cables and INSET was secured by threading the copper vacuum passthrough on the multi-purpose flange and fastening a ring terminal between two nuts on the leads. The unit can be operated in constant current, voltage, or power mode. Tests were conducted utilizing the constant current or constant power modes depending on the goals of the test. As shown on the right in Figure 3.4, the supply generates logs than can be stored on a flash drive. These logs record the set and actual power, voltage, and current. These logs will be shown later along with the thermal results of testing.

The next system to be discussed will be that of the thermocouples (TC). The multi-purpose flange has the capacity for three CF thermocouple passthroughs. Each TC passthrough consists of two thermocouple connections, which defines INSET's TC capacity at six internal TCs. The TCs used were either type C or type K. The type C TCs were Omega T5R-015-12 26 AWG tungsten-rhenium twisted unsheathed. These type C TCs are usable from 273 *K* to 2598 *K* [25]. A hafnia sheath was applied to each type C TC in the heated region. The type K TCs were Omega CHAL-020-BW 24 AWG Chromega Alomega butt-welded unsheathed. These type K TCs are usable from 273 *K* to 1143 *K* [26]. The type K TCs were used during lower temperature experiments in addition to monitoring the external surface temperature of INSET. The measurements from the TCs were processed and recorded by a Grant SQ2020-2F8. This logger can accept up to eight differential TC connections [27].

The gas removal system consisted of a 1.33 *in.* CF Swagelok® to gas tube connection. The gas line connected INSET to the vacuum pump with a pressure gauge in-line. The vacuum pump used is an Edwards NXDS6i dry scroll pump. This pump can achieve a peak pumping speed of $6.2\text{ m}^3\text{h}^{-1}$ and a reported ultimate vacuum of 0.015 *Torr* [28]. The pressure was monitored by an analog Granville-Phillips 275 Convector Gauge. This gauge was placed in-line between INSET and the scroll pump. A continuous vacuum was being pulled during every test using INSET. A complete setup of OUTSET showing the gas line connections as well as the aforementioned systems can be seen in Figure 3.5.

Now that the peripheral components of the experiment have been presented, the core heater components and regions will be introduced. Since copper melts around 1400 *K*, the current must be delivered to the heater by a different conductor. The conductor chosen is molybdenum tubing. Molybdenum has favorable thermal, electric, and neutronic properties [22]. This molybdenum tubing slip fits over the copper from the 2.75 *in.* power passthrough and carries current to the heater. There have been two design iterations to identify the best molybdenum circuit geometry. The computer aided design (CAD) image of the selected design is shown in Figure 3.6 along with the other components mentioned in this section.

The vacated plenum space shown in Figure 3.6 is the empty space between the internal components. This region is a vacuum and simply refers to the vacated space that everything internal lives in. The size of the vacated plenum region has an impact on heat transfer, which will be discussed in Section 6. The size of the plenum region is dictated by the innermost layers of insulation.

The insulation is used to contain the thermal energy in the plenum region. The insulation helps prevent the

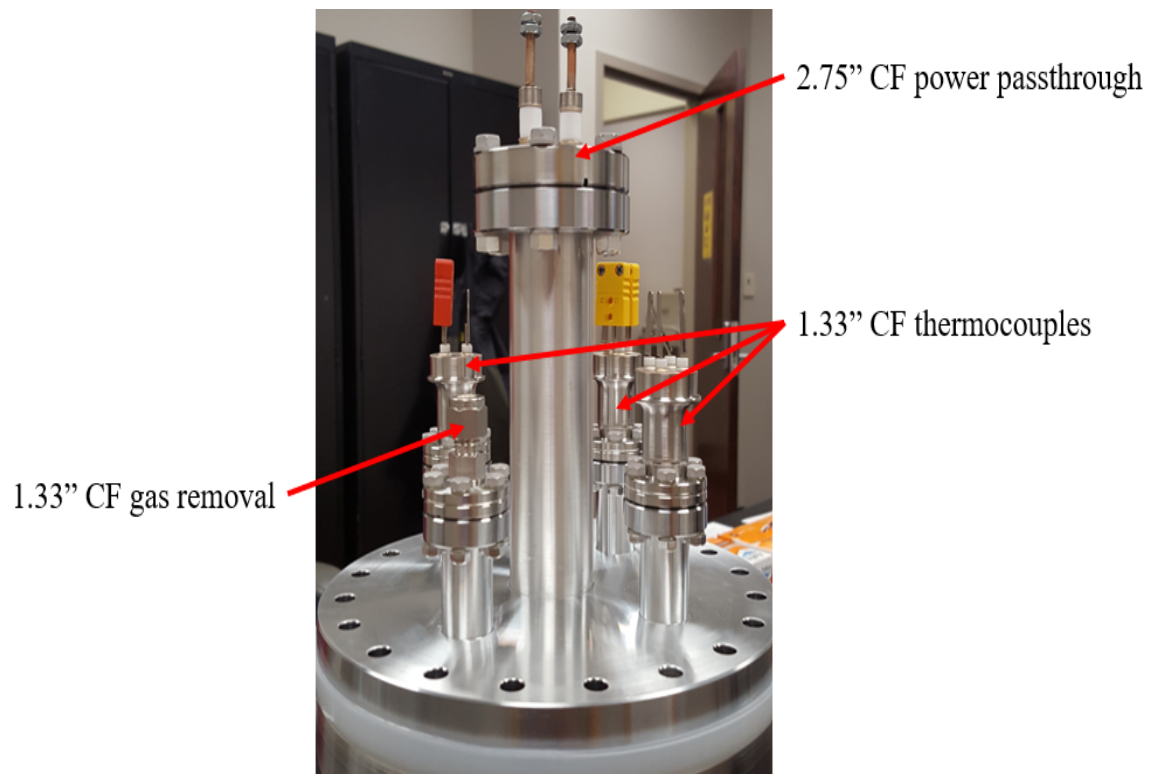


Figure 3.3: Custom multi-purpose flange.

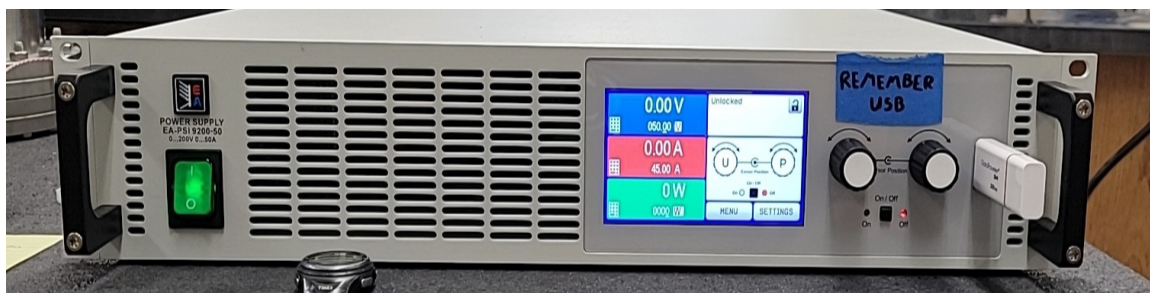


Figure 3.4: Elektro-Automatik PSI 9200-50 2U power supply.

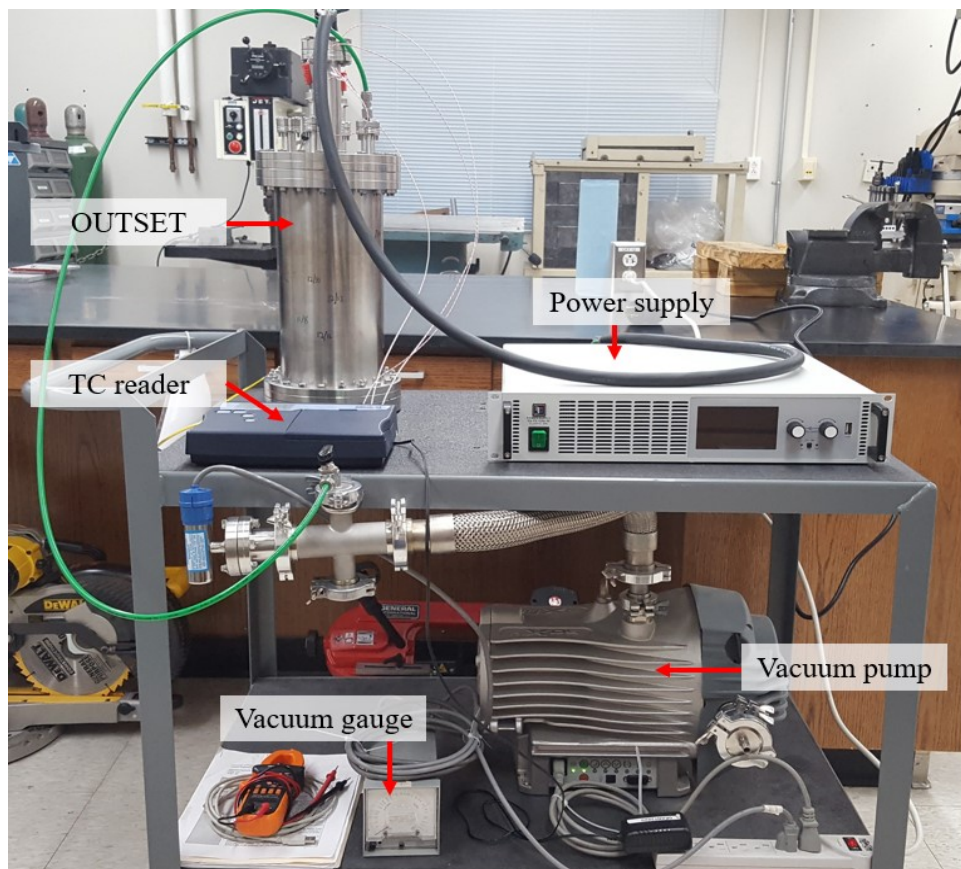


Figure 3.5: Standard complete setup of OUTSET.

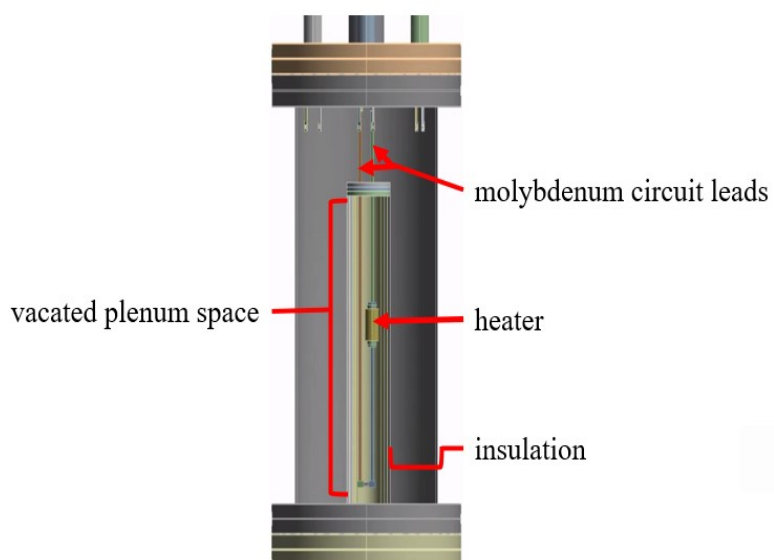


Figure 3.6: INSET internal CAD.

external surface of the apparatus from reaching undesirable temperature levels as well as returning thermal energy back towards the heater for higher internal temperature levels. The amount of insulation is dependent on the goal of the experiment. As insulation is removed, the necessary power to reach a given temperature level will increase. Additionally, the external surface will also be subject to increased temperature levels if the insulation is reduced (while all else is held constant). Insulation may need to be removed to accommodate a larger test sample or test geometry. This was the case for the experiment presented in Section 3.4.3. The insulation used is a combination of graphite felt and molybdenum foil. The molybdenum foil is the innermost layer of insulation when it is used. This low emissivity material helps reflect the thermal photons back into the plenum region. This 0.003 *in.* molybdenum foil from Elmet Technologies is 99.95% molybdenum (part id: 053599061075). The graphite felt is placed between the molybdenum foil and the internal wall of INSET. The graphite felt is produced by SGL Carbon and is SGRATHERM® GFA5. This felt has a thickness of 0.25 *in.* and a thermal conductivity shown in Figure 3.7. Graphite has long been used in nuclear reactor environments. The nuclear and thermal properties of this material make it attractive for in-pile high temperature testing [22].

The final component to discuss is the heater. The heater utilizes a filament to generate resistive heating. The filament is held within a ceramic crucible. The ceramic crucible is encompassed by a shell that is used to house TCs and other instrumentation. The ends of the ceramic crucible are capped with high temperature and electrically conductive plugs to keep the filament in place while enabling the current delivery. The plugs and shell are made from POCO graphite. The crucible has been a challenging piece to push to higher temperatures - zirconia, alumina, hafnia, high density magnesia, and high purity magnesia have all been used. The filament has historically been cut from a piece of SGRATHERM® GFA5 (shown in Figure 3.8). GFA5 does work, however, tests have shown that a related material, SGRATHERM® MFA5, may provide better electrical stability at elevated temperatures and currents. An image labeling the various aforementioned parts of the heater is shown in Figure 3.8. This figure contains a CAD image along with a real photograph of the heater assembly.

The resistance of the heater varies from run to run. The resistance is determined by the length of filament packed into the heater. This follows theory (Equation 3.1) [30].

$$R = \frac{\rho L}{A} \quad (3.1)$$

where:

R = resistance

ρ = conductor resistivity

L = conductor length

A = cross-section area of conductor

Equation 3.1 considers a rigid conductor, but if the heater is packed more densely with filament material and the filament becomes crumpled within the crucible, the resistance will be lower than if there is less material. This is due to the compression of the filament. As the filament is compressed, the electrons within the material are forced closer together - creating an path of less resistance. The compliance of the filament allows for the heater to be more densely packed and thus, allows for an adjustable resistance. As will be discussed later, this compliance, or lack of rigidity, may present challenges that would not be associated with a solid rigid heater. The resistance of the heater is measured using a digital multimeter after packing the filament and can be seen in Figure 3.9 for a 10.5 Ω case. This was the heater used for the in-pile experiment presented in Section 3.4.2.

3.1.2 Design Evolution

The first larger design of INSET that followed the successful demonstration of OUTSET-1 used a combination of copper and molybdenum to complete the electrical circuit to the heater. This copper was used in the

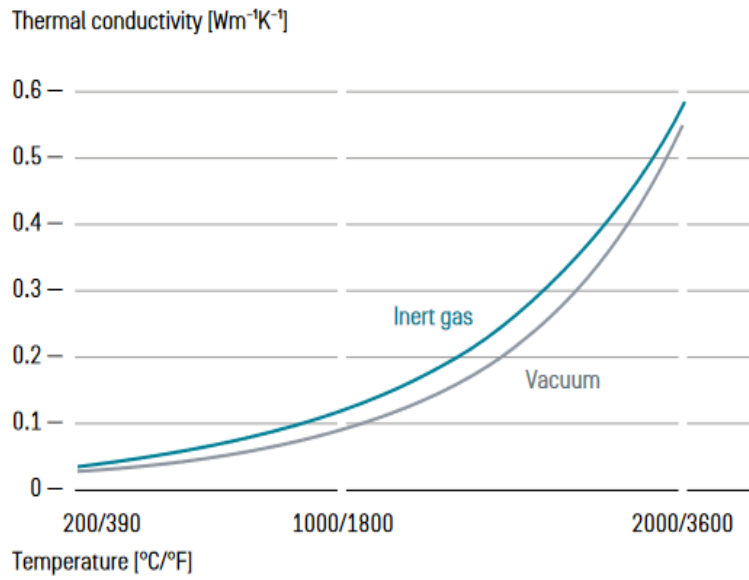


Figure 3.7: The thermal conductivity of Sigratherm® GFA5 [29].

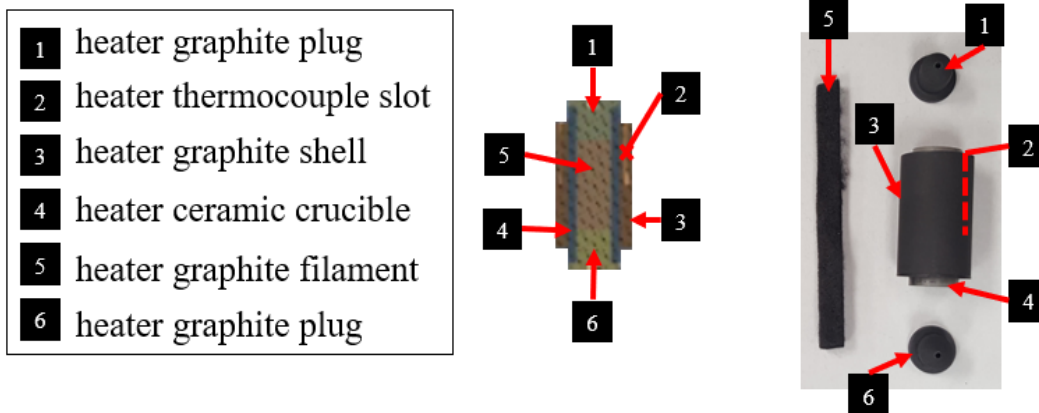


Figure 3.8: Components of INSET heater. CAD image in the center. Real image on the right.

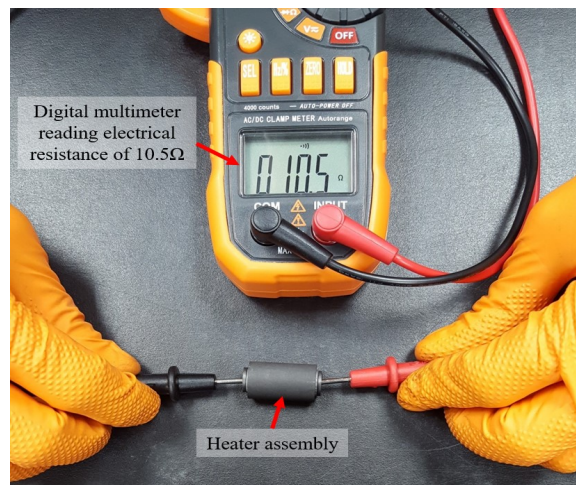


Figure 3.9: Example of heater resistance measurement.

lower temperature areas of the internal region of INSET and was coupled to molybdenum tubing prior to the higher temperature locations. The copper rod was bent in such a way that the rod went from the power passthrough, behind (relative to heater) the insulation, under the bottom insulation, and back up before transitioning to molybdenum. This was a cumbersome design that presented assembly difficulties as well as circuit integrity failures. The copper needed to be perfectly electrically insulated using polyimide tape throughout its entire length. If any amount of the copper was exposed to the internal wall of INSET, a short to the body of the apparatus would occur. This is a substantial safety risk and warranted the re-taping of the copper many times. To alleviate the difficulties associated with assembly, the circuit design was altered to be solely molybdenum tubing below the power passthrough. The thermal models suggested that this pivot away from copper would not significantly impact the heat transfer within the heated region. A side-by-side comparison of the respective CAD drawings is shown in Figure 3.10 where the copper design is shown in 3.10 (a) and the molybdenum circuit is shown in 3.10 (b).

Although the molybdenum made assembly easier, it required additional consideration on how to practically machine the circuit. Molybdenum tubing is fragile under compression. Bob Sitterson and David Bryant at ORNL helped devise a clever solution to this move away from copper. Figure 3.11 shows a comparison of the copper design against the molybdenum assembly. In this figure the copper design is shown in 3.11 (a) and the molybdenum circuit is shown in 3.11 (b).

The molybdenum circuit proved easier to assemble and more reliable at maintaining the desired electrical continuity path. It also required less polyimide tape and ceramic support structures. As seen in Figure 3.10 (a), the copper snaked beneath the bottom layers of insulation. This required the bottom insulation layers to be elevated by electrically non-conducting materials that can withstand around 1000 K . Structures akin to scaffolding were constructed using alumina to serve this purpose. The copper design was harder to assemble, more time consuming, and presented more safety concerns than the molybdenum circuit. The additional material cost of molybdenum is offset by the expedience of assembly and surety of safety. The circuit design change also presented only minor thermal impacts - the additional material within the plenum region serves as a minor heat sink. As such, the molybdenum circuit shown in Figure 3.10 (b) and Figure 3.11 (b) was selected to be the circuit design moving forward.

3.1.3 Standard INSET TC Placement

The placement of the thermocouples utilized in INSET can vary from test to test depending on the experiment and experimenter. For a large majority of tests, or the "standard", the following TC placement was implemented. One type C TC was slotted into the vacancy in the heater shell. This will often, but not always be referred to as "TC2". Another type C TC was positioned just inside the top layer of insulation on the heater side. This is often labeled as "TC4". Finally, a type K TC was taped to the external surface of the experiment apparatus to monitor the surface temperature for safety. This will often be referred to as "TC3". This convention is not for every test, but for most. When this convention is broken, it will be stated. When this convention holds, that will also be stated. A schematic of the TCs within the testing apparatus can be seen in Figure 3.12. Each red "X" denotes the position of one of the type C thermocouples. There are no thermocouples in the heater filament, or centerline, due to the electrical dependence of thermocouples on a temperature measurement. Thermal models suggest that there is up to around a 100 K difference between the centerline and the thermocouple through the crucible and partial shell.

3.2 INSET Assembly and Operating Procedure

Inserted here is a sample of a generic standard operating procedure (SOP) for the assembly and operation of INSET. This serves as a basis for experimenters to build upon.

University of Tennessee, Knoxville
Nuclear Engineering Department

Oak Ridge National Laboratory
Nuclear and Extreme Environment Measurements Group

Standard Operating Procedure: In-Pile Surrogate Testbed for Extreme Temperatures

Primary Task	In-Pile Surrogate Testbed for Extreme Temperatures (INSET) operation.
Sub-Tasks	Conduct experiments for Nuclear Thermal Propulsion (NTP) candidate fuel surrogates and/or instrumentation.
SOP Revision Date	January 14, 2021 Tyler Steiner
Statement of Work	INSET will be developed to achieve localized centerline temperatures up to 2500 K. These temperature levels will be obtained under a vacuum (approximately 10^{-3} mTorr). The power required to generate the maximum temperature levels will not exceed 1 kW. The manufactured high-temperature environment will be used as a testing environment for NTP materials and instrumentation. INSET is designed to be compatible with a reactor environment to simulate the fluence of an NTP system. INSET can test NTP materials and instruments at prototypical temperature and neutron fluence levels.
Potential Hazards	• Hot surface – During operation, the experiment apparatus may reach surface temperatures around 375 K. It must be ensured the hot apparatus will not interfere with the surrounding moderator. • Electrical – Operation requires the use of a high voltage power source, which presents a shock hazard to the user and bystanders. Continuity checks, monitoring, robust electrical connections, and general caution will be used to prevent shock induced harm. • Pinch and drop – During assembly, the top multi-purpose flange must be lowered onto the pipe nipple body of the apparatus; this presents a potential pinch point. The weight of the apparatus is upwards of 20 lbs, which may cause harm if it is dropped. • Cut – Sharp metal foils and fine gauge metal wire will be used in INSET. • Inhalation – Graphite felt is used as insulation in INSET and produces easily-liberated airborne graphite particles. These graphite particles may irritate the sinus cavities. Respirators, distance, or limited use of the graphite felt will mitigate any potential irritation.
Process Steps	<u>INSET Assembly:</u> 1. Attach and secure bottom flange to pipe nipple with copper gasket. 2. Insert bottom insulation (listed in the order of bottom to top). a. Graphite felt b. Graphite felt c. Graphite felt

- d. Molybdenum foil (optional)
- 3. Insert side insulation (listed in the order of outside to inside).
 - a. Graphite felt
 - b. Graphite felt
 - c. Graphite felt
 - d. Molybdenum foil (optional)
- 4. Attach power passthrough to multi-purpose flange with copper gasket.
 - a. Include passthrough extensions.
 - i. These internal extensions may be molybdenum or copper depending on the desired temperature environment. For anticipated centerline temperature levels exceeding 1200 K, molybdenum should be used as the extension and circuit material.
- 5. Instrument multi-purpose flange as desired.
 - a. Type K thermocouples
 - b. Type C thermocouples
 - c. Vacuum line passthroughs
 - d. Gas line passthroughs
- 6. Insert top insulation (listed in the order of top to bottom) via slip fit through passthrough extensions and circuit mentioned in step 4.a.
 - a. Graphite felt
 - b. Graphite felt
 - c. Graphite felt
 - d. Molybdenum foil (optional)
- 7. Construct heater to desired resistance.
 - a. It is recommended to pulverize and tear the graphite felt prior to insertion into the heater crucible. This will decrease the filament density and increase the resistance, yielding higher powers at lower current levels.
- 8. Secure heater to power passthrough (or extensions).
 - a. Using molybdenum tubing
- 9. Ensure instrumentation is in desired location(s).
- 10. Continuity check
 - a. For this and future continuity checks: if circuit continuity is not established, do not proceed until it is.
 - i. Verify primary heating circuit is isolated.
 - ii. Verify thermocouples and additional instrumentation are isolated.
 - iii. Verify INSET structural components are isolated.
- 11. Attach and secure multi-purpose flange, primary heating circuit, relevant felts and foils, and heater assembly to top of pipe nipple using a copper gasket.
- 12. Continuity check
- 13. Attach vacuum hose.
- 14. Secure Type K thermocouple to external surface of INSET.
 - a. To monitor surface for safety

15. Load INSET into handling basket.

Basket and INSET Assembly:

1. Place solid flat round G10 piece with three holes down.
2. Slide in aluminum all-thread rod through the three holes in G10.
3. Tighten a nut to each aluminum all-thread rod under G10.
4. Place the assembled and sealed INSET onto the solid G10 piece.
5. Slide a nut onto each of the standing aluminum all-thread rods until each nut is below the location of largest diameter on INSET.
6. Slide additional G10 ring through the aluminum all-thread until it wraps around the largest diameter of INSET.
7. Slide a nut onto each of the standing aluminum all-thread rods until each nut contacts the G10 ring.
8. Slide a nut onto each of the standing aluminum all-thread rods until each nut is roughly 5 inches above the highest point of INSET.
9. Slide eyebolt plate through the aluminum all-thread until it contacts highest nuts.
10. Slide a nut onto each of the standing aluminum all-thread rods until each nut contacts the eyebolt plate.

Operation:

1. Begin pumping down to desired pressure.
2. Continuity check
3. Reach desired pressure.
4. Continuity check
5. Verify HV power supply is off.
6. Connect HV supply to power outlet.
7. Connect HV supply to INSET.
8. Continuity check.

The following steps are for generic operation. User should consult specific experiment procedure for specific operation instructions.

9. Turn HV supply on, but driving no current.
 - a. In the event of an unintended or problematic electrical incident, power should be ceased immediately. Removing the power cable from the rear of the HV supply and the outlet will de-energize the apparatus.
10. Commence desired experimental heating conditions.
 - a. Monitor all thermocouple information.
 - b. Monitor HV supply stability.
11. Conclude experiment.
12. Turn off HV supply.
13. Disconnect HV supply from outlet.
14. Disconnect HV supply from INSET.
15. Monitor cooling.

16. Commence post-experimentation handling following safety guidelines after a timeframe dictated by activation analysis.

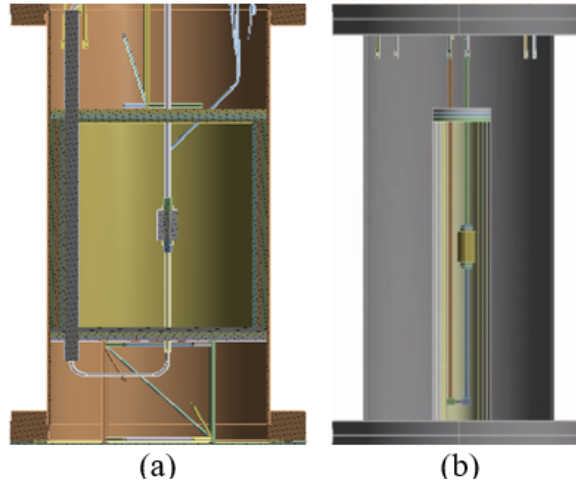


Figure 3.10: Early INSET circuit alteration CAD. (a) copper. (b) molybdenum.

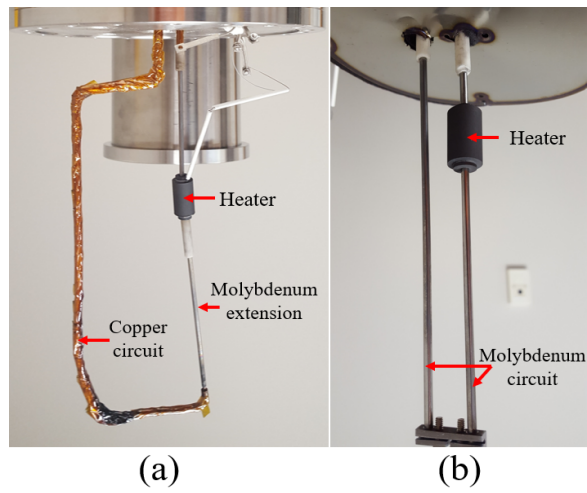


Figure 3.11: Early INSET circuit alteration images. (a) copper. (b) molybdenum.

3.3 Experimental Challenges

The scaling up of OUT/INSET to the size shown in Figure 3.2 generated considerable complications when striving to reach NTP prototypical temperatures. This subsection will provide a discussion on these experimental challenges.

The parameters adjusted were the heater ceramic crucible, heater plugs, heater shell, heater filament, and thermal ramp rate. Melt wires were implemented to verify TC data.

3.3.1 Heater Ceramic

A potential challenge that prevented reaching prototypical temperatures was the possible breakdown of the ceramic used in the heater. The initial ceramic used was zirconia that was manufactured by McDanel Advanced Ceramic Technologies. Using this ceramic, the experiment failed to exceed heater thermocouple temperatures of 1300 K . The failure would present itself in the instability of the circuit, seen in rapid fluctuations in the high voltage power supply's voltage, current, and supplied power. These fluctuations are thought to be caused by electrical shorts in the heater. One suspicion is that the ceramic was breaking down and current was shorting through or around the ceramic. Post-test examination showed that the white zirconia had become infused throughout with a gray substance (shown in Figure 3.13) - thought to be liberated graphite, either from the shell or the filament. The grayed ceramic was brittle, and often removed in several pieces. The zirconia lost its electrically insulative properties.

The McDanel Advanced Ceramic Technologies zirconia was suspected to contribute to the electrical shorts. To test this, a new batch of zirconia was obtained from Randy Parten at ORNL's High Temperature Material Laboratory. The McDanel zirconia along with Parten's zirconia were examined using x-ray fluorescence (XRF) to qualify the material composition of each. The results of the XRF test are shown in Appendix A in Figure A.6 and Figure A.7. The XRF only showed slight differences in the material being used. To confirm this, an experimental run was performed using the new zirconia (Parten's) and it also failed around the same temperature as the previous material and exhibited similar traits of the failure. This repeated failure using zirconia prompted an investigation into the success of the ceramic in the heater of reference [22] as well as an inquiry into zirconia-carbon interactions. This pursuit revealed that zirconia may not have been the ceramic used by reference [22], but alumina may have been used instead. It was also learned that zirconia can react with carbon at high temperatures producing zirconium carbide and free oxygen. This was seen by the appearance of the ceramic transitioning from white to gray in addition to the suspected formation of various oxides. Upon further investigation, zirconia was not the ceramic in the preliminary heater design; I was later informed it was alumina.

The experiment was then run using alumina as the ceramic in the heater. These tests showed much more stability in the thermocouple temperature readings and power supplied. However, the experiment was still unable to reach prototypical NTP temperatures, and would saturate around 1500 K . After several runs where the thermocouple-reported temperatures did not exceed 1500 K , melt wires were introduced to challenge the readings of the thermocouples. The inspiration to doubt the thermocouple readings came from the observation of melted alumina, oxygen diffusion, and scorching in and around the heater region. These observations occur at temperatures above the recorded 1500 K ; for context the alumina used melts around 2000 K [31]. The melt wires used can be seen in Figure 3.14. One of the melt wires used was pure platinum and the other was 60% platinum and 40% iridium. The pure platinum melt wire melts around 2050 K and the platinum-iridium around 2550 K [22]. The first melt wire test was run on January 23, 2020. During the test using the melt wires, the thermocouple did not report a temperature above 1500 K . However, there were such high temperatures reached that the alumina crucible melted, the graphite filament combusted, and the melt wires were unrecoverable. An image of the aftermath of this run is shown in Figure 3.15. This figure shows the view inside the broken alumina crucible.

A possible, and difficult to test, explanation for the localized heating and melting of the ceramic is electrical arcing. The experiment was electrically heated using up to 1 kW and 25 A . Poor initial electrical connec-

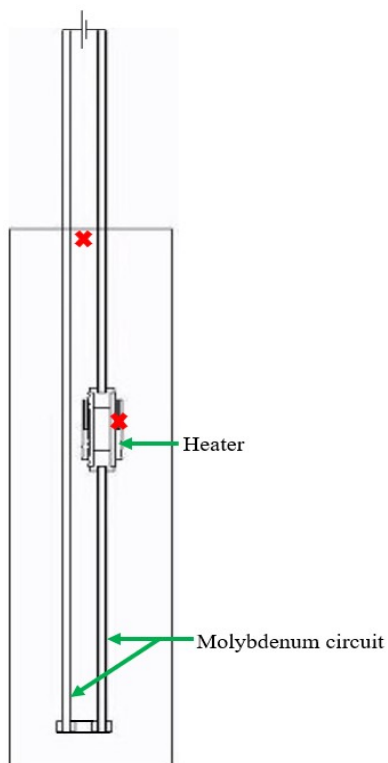


Figure 3.12: Common standard TC positions.



Figure 3.13: ZrO_2 that is no longer white following 1300 K test.

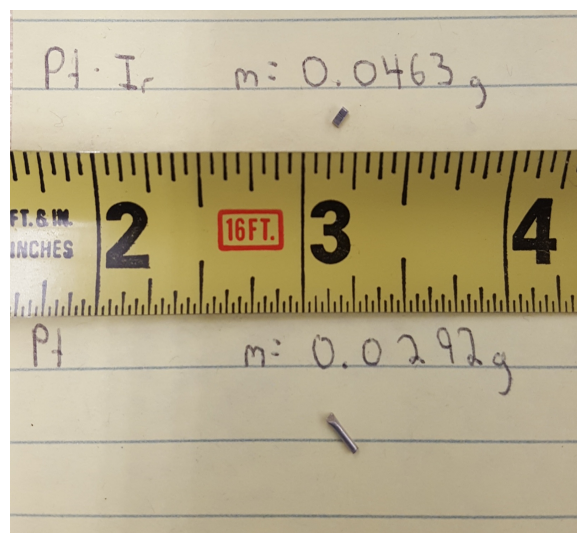


Figure 3.14: Melt wires before January 23, 2020 test.



Figure 3.15: Heater (possible melt wires shown near bottom-center of crucible) after January 23, 2020 test.

tions and loss of circuit continuity through thermal expansion can induce arcing in the mentioned electrical environment.

Additional tests were conducted to investigate the failure of alumina. A test was performed at a maximum DC power around 600 W, a current of 25 A, and an approximate voltage of 25 V. The thermocouple data is plotted for this run in Figure 3.16. This test was instrumented with two type C thermocouples and one type K. One type C TC was placed in the slot within the graphite shell. This is the black curve in Figure 3.16. The other type C was placed near the heater. This is the pink curve in Figure 3.16. Both of the type C TCs can be seen in Figure 3.17. The type K TC was placed behind (relative to the heater) the top layer of insulation in the upper empty space between the top insulation and the multi-purpose flange. This corresponds to the brown curve in Figure 3.16.

The power supply used for this run was not the Elektro-Automatik that was mentioned in Section 3.1.1. A Veeco DC power supply was used for this run instead. The Veeco power supply offers a maximum current of 25 A, which was the power generation limit for this test. At this 25 A level, the Ohm's Law relationship between current, resistance, and power yielded a power of 600 W (Equation 3.2) [30].

$$Power[W] = (Current[A])^2(Resistance[\Omega]) \quad (3.2)$$

This power level induced a maximum TC temperature around 1775 K. Again, this stock of alumina melts around 2000 K. An observation that suggests that the filament may be substantially locally heated is that this alumina appeared to melt at TC measurements below its melting point. Compared with the data in Figure 3.16, Figure 3.17 shows the melted alumina after this test. This discrepancy between TC data and physical observations will be continually explored and considered throughout this section.

Despite the discrepancy between the TC and the post-test examination, alumina shows reliability and stability in a high current environment up to temperatures near its melting point. This implies that the dielectric properties of alumina remain in high current and high temperature environments - with the material changing matter state prior to its electrical breakdown. However, the melting point of this alumina is below the goal temperature associated with an NTP testbed that can test any temperature level that may be seen in an NTR. As such, other high melting point ceramic crucibles have been investigated.

The next ceramic chosen to test for its high melting point was hafnia. Hafnia is reported to thermally fail around 2800 K [32]. A total of four tests were conducted using a hafnia crucible in the heater. Each test resulted in similar power supply observations and post-test observations. However, the suspected electrical faults that will be discussed occurred at various times, temperatures, and power supply settings. The effects seen occur within the temperature range from 1150 K to about 1300 K recorded by the TC in the shell. Only four tests were conducted with hafnia due to material availability and observations that this would not address the challenges by this heater. To enable the discussion surrounding the hafnia test results, the experiment performed on June 22, 2021 will be presented as an example case. This was the final test using hafnia. This test adheres to the standard TC placement presented in Section 3.1.3. Figure 3.18 shows the temperature levels during the final hafnia test. The power supply was turned off around 2100 s.

This temperature data was obtained by continuously increasing the power supplied by the power supply in constant power mode. This mode of operation allows the user to alter the power output and the power supply will adjust voltage and current output accordingly to meet the set power level. The goal of this final hafnia test was to explore the failure mechanism observed in previous runs. As such, the failure was allowed to develop to better understand the causes. The power supply data can be found in Figure 3.19. Note that the temperature begins to quickly cool down once the power supply is turned off around 2100 s in Figure 3.18. The power supply log and the TC log do not align perfectly since each machine was started at different times. This temporal separation can be seen in the minutes before any temperature increase shown on the bottom left in Figure 3.18.

As can be seen in Figure 3.19, the current and voltage begin to fluctuate wildly around 2800 *half-seconds* (or 1400 s). The maximum power level obtained in this test was just over 300 W, but the current and voltage

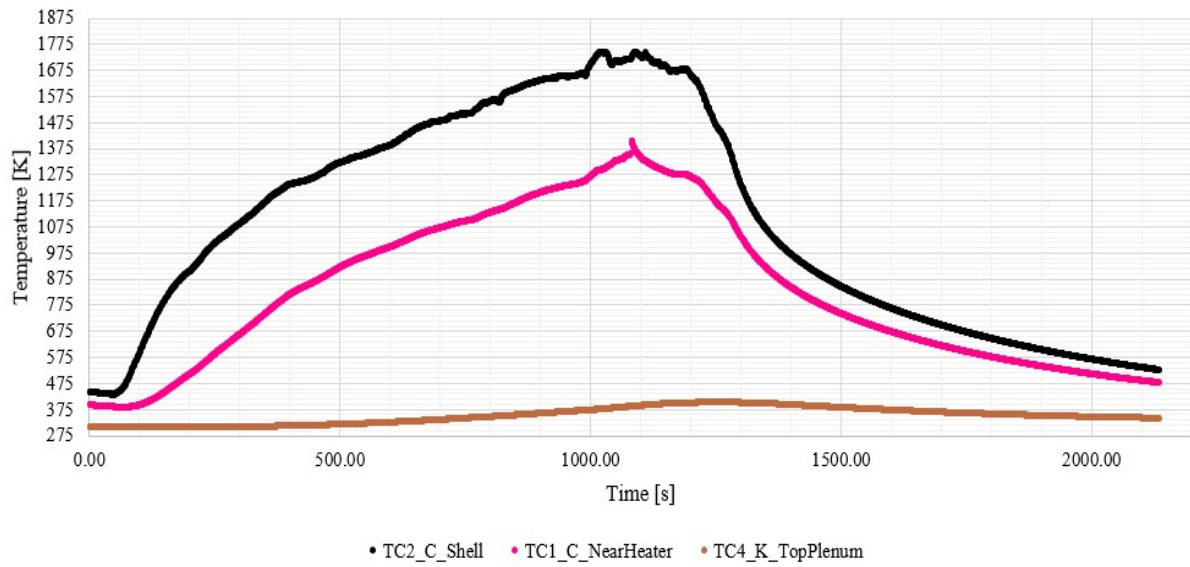


Figure 3.16: March 4, 2021 Al_2O_3 TC data.

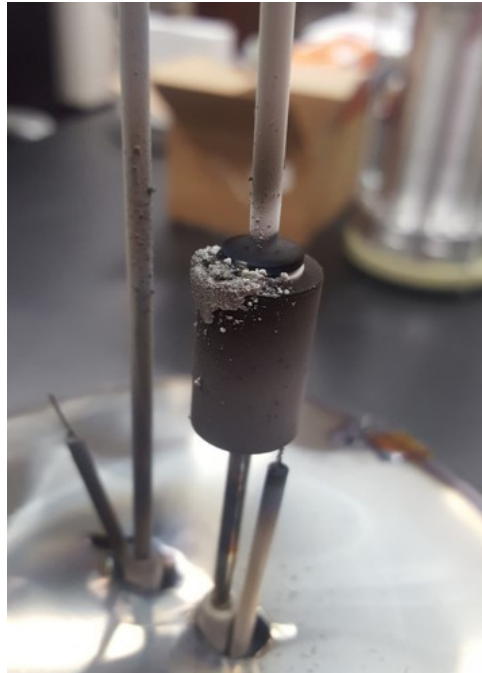


Figure 3.17: March 4, 2021 post-test observation of melted Al_2O_3 .

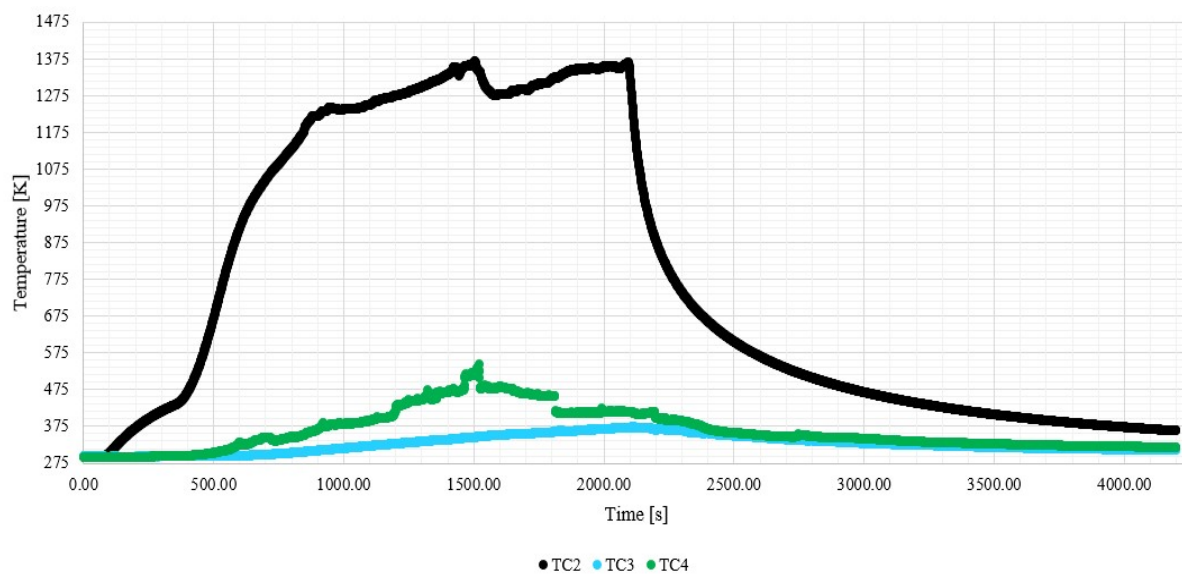


Figure 3.18: June 22, 2021 HfO_2 TC data.

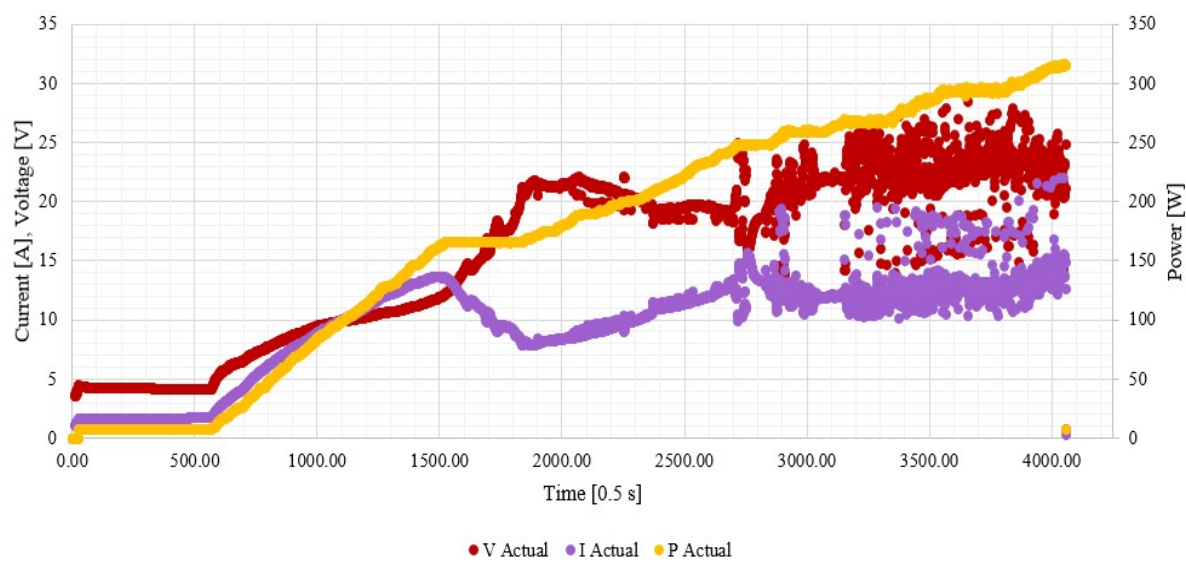


Figure 3.19: June 22, 2021 HfO_2 power supply data.

fluctuations remove the significance of this setting. To obtain a more clear picture of the fluctuations, the last 70 s of the test are shown in Figure 3.20. The onset of the fluctuations coincide with a brief temperature drop. This drop, and the fluctuations, may be caused by a loss of continuity of the electrical circuit. The continuity can be disrupted by a loss of contact between segments of the electrical circuit, such as between the plugs and the filament. It is challenging to further interpret the temperature data given the behavior of the circuit, and subsequently, the power supply.

During the observed failure in the electrical continuity of the heater circuit, the current periodically spikes and the voltage periodically plummets. These sudden changes occur at the same time. The sudden discharge of increased current is indicative of electrical arcing within the circuit. The voltage drops when the current arcs due to a decrease in the electrical potential between the arcing surfaces. Further evidence of arcing is observed by local scorching and apparent sputtering within the inner wall of the crucible. This material deformation from suspected electrical arcing can be found in Figure 3.21. The inner wall of the crucible appears locally melted. This local heating may be due to arcing. It is nearly impossible to identify the path of the arc. The path may be from the higher electrical potential plug to the filament, damaging the crucible wall in its travel. One family of paths that has been eliminated is any path involving the shell. As will be discussed in Section 3.3.3, arcing was still observed in tests where the graphite shell was removed prior to testing. To identify the source of the arcing, additional ceramics were tested. Additionally, other heater component variables were adjusted to systematically isolate the root cause of the arcing. These will be presented in later sections. To offer some conclusions here, after manipulating all of the variables within the heater assembly, it can be inferred that the source of the electrical difficulties is the compliant graphite filament.

A minor, but continuous, investigation into where the arcing may be occurring was conducted. During assembly, it was recorded which side of the heater the higher electrical potential would be introduced to. This potential would dictate the direction of the flow of current. This was recorded for dozens of runs. The end of the crucible that was situated near a higher electrical potential (the positive end) during heating would see more damage than the end at the lower potential. This supports the claim that arcing is occurring since arcing is the sudden movement of charges from higher potential to lower potential. This investigation was qualitative and should not be used as anything more than such. It was simply a minor investigation into a curiosity that produced results that do not disagree with the leading suspicions.

To be confident that the electrical failure was not a result of hafnia's dielectric properties at elevated temperatures and currents, magnesia was the next, and final, ceramic crucible tested. While acquiring magnesia, a technical expert and founder at Tateho-Ozark offered input regarding the dielectric stability of hafnia. This expert advised that, at 30 V, the hafnia should not be the cause of the electrical continuity breakdown. He also mentioned that alumina is much more stable up to melting point than other oxides, which agrees with the aforementioned results [33]. To be thorough, two blends of magnesia were tested. One will be referred to as "high purity magnesia", and the other will be referred to as "high density magnesia." These classifications were dictated by the vendor: Tateho-Ozark. The vendor's technical support and advice was invaluable in addition to the samples they provided for this testing. The chemical composition of both of these blends can be found in the Appendix. The composition of high purity magnesia can be found in Figure A.9. The composition of high density magnesia can be found in Figure A.8. The primary difference between the chemical composition of the blends is the presence of yttria. The high density blend has 2% yttria added, while the high purity blend does not. Magnesia was selected due to its high melting point around 2800 K [35].

The preliminary magnesia tests followed an incremental stepping up of power. A power level was held for some time, before it would be increased to the next level. This process was repeated during the tests. This procedure produced a power function that resembles a staircase. The tests were performed this way to investigate the dependence of the failure on time and temperature. By following a staircase-esque profile and maintaining a given power level for minutes before increasing the power, the failure mechanism may become known. If the electrical issues started between steps while power was being actively increased, then the ramping electrical environment or the increasing temperature may be the failure inducer. The other mode of failure would be if the electrical fluctuations occurred while the power was constant for minutes.

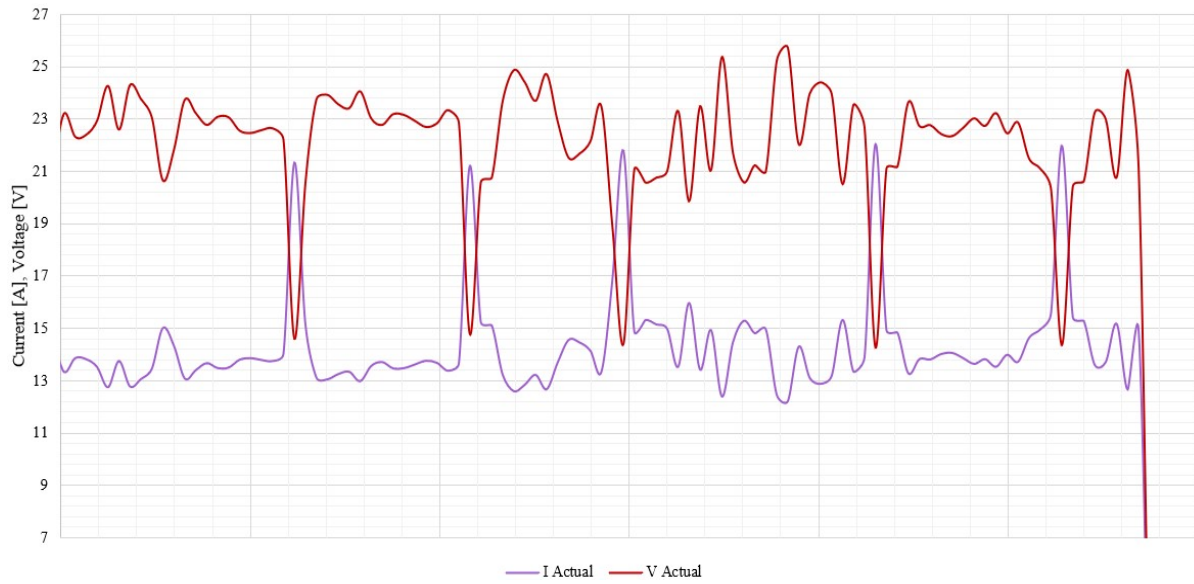


Figure 3.20: June 22, 2021 HfO_2 power supply data of last 70 s.



Figure 3.21: June 22, 2021 HfO_2 post-test observation of arcing effects within crucible.

This would imply that the negative effects were more time dependent. It is worth noting that if the failure depends neither directly on time or temperature, it would not be a physical property limit of any materials chosen. The failure would be related to a more random phenomenon, such as the spatial compression, movement, or thermal expansion. This test profile was retroactively applied to alumina as well. The results of the staircase-esque profile series of tests were valuable. Each test that used a different high temperature ceramic failed in a similarly observed way: electrical fluctuations inferred from power supply data and localized scorching and material removal from post-test examinations within the crucible. However, each failure occurred at different times and temperature levels. The alumina staircase test failed at a much lower temperature (1502 K) and much longer time (5200 s) than the previous alumina run shown in Figure 3.16. This inconsistency in the observed failure implies that the failure is independent of the ceramic crucible used. The same stock of ceramic fails at different temperatures, times, and power levels. Different materials also fail at different temperatures, times, and power levels.

Both magnesia temperature plots adhere to the standard TC placement presented in Section 3.1.3. The first blend of magnesia tested was the high density blend. The TC data for this run is plotted in Figure 3.22. The elevated temperature levels were obtained by the power supply levels shown in Figure 3.23. Note that for the high density and high purity magnesia tests, the TC at the top of the inner plenum region (TC4) was broken. It was replaced after these runs. The data is included for completeness.

Evident in Figure 3.22 and Figure 3.23 is the incremental increase in power. This is what was referred to earlier as the "staircase-esque profile." The temperature follows the power supply output and displays an obvious step profile. During a ramp, the power supply was shut off between steps and during the ramp due to the current and voltage fluctuations seen near the end of the test. These fluctuations seen in Figure 3.23 are similar to those seen with hafnia in Figure 3.20. The high density magnesia resulted in a nearly identical failure mechanism to that of hafnia, but at different power levels, time, and temperature. The tangible observations from this run are captured in the post-test examination image shown in Figure 3.24.

Again, the effects observed in the post-test examination of the high density magnesia are reminiscent of those following the hafnia run, albeit it to a lesser extent since the fluctuations were not allowed to persist to protect the power supply. The next ceramic used to investigate the crucible's impact on the observed failure mechanism is the high purity magnesia. This material is soft and easily crushed. Without much effort, it can be crushed by squeezing it between two fingers. This is relevant because the post-test examination showed that the crucible cracked through its full thickness at two locations. It was held together by the graphite shell until the shell was removed for thorough examining. This cracking is most likely due to thermal expansion conflicts and not electrical effects. The temperature profile for the step test of high purity magnesia is shown in Figure 3.25. The brief drop in temperature around 4450 s is also seen in the power supply behavior. The power supply log for this run is shown in Figure 3.26.

The power supply log for the high purity magnesia test has some unique characteristics. It also has some familiar traits. The step profile leads the TC data as expected. The experiment was ended when the power supply began to fluctuate. These current and voltage fluctuations can be seen at the end of the test in Figure 3.26 and are similar to those seen in the high density magnesia run and the hafnia run. One important note is that the fluctuations begin here while the power level is held constant, unlike the high density magnesia run. The unique facet of this plot is the sudden drop in current accompanied by a sudden spike in voltage before the curves eventually resume their previous trends. This occurs around 7700 *half-seconds* (or 3850 s). This brief interruption of the trends must be induced by a sudden large increase of resistance. As predicted by Ohm's Law relationship between current, resistance, and voltage - if the voltage increases and the current decreases, the resistance must increase by more than the current decreases. (Equation 3.3) [30].

$$Voltage[V] = (Current[A])(Resistance[\Omega]) \quad (3.3)$$

In addition to the series of sudden resistance increases, the crucible cracked. This paragraph will present conjecture surrounding the sudden resistance increase. One possible explanation is the introduction of an impurity into the heater filament. At some point during the heating, the fragile crucible cracked. This may

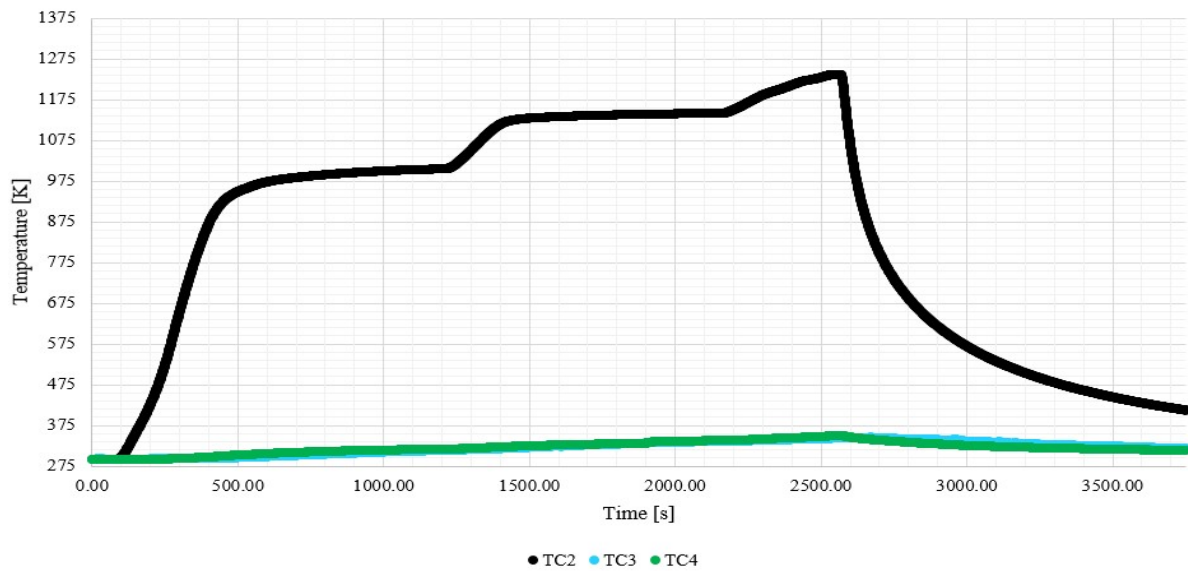


Figure 3.22: July 19, 2021 high density MgO TC data.

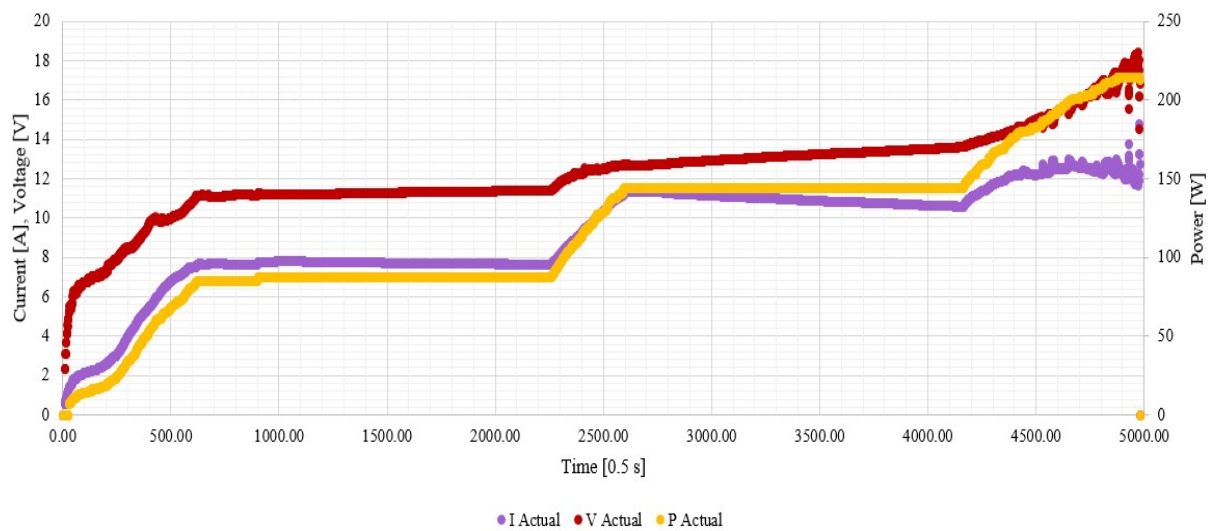


Figure 3.23: July 19, 2021 high density MgO power supply data.

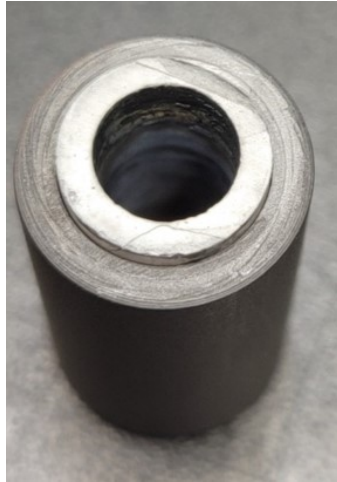


Figure 3.24: July 19, 2021 high density MgO post-test observation.

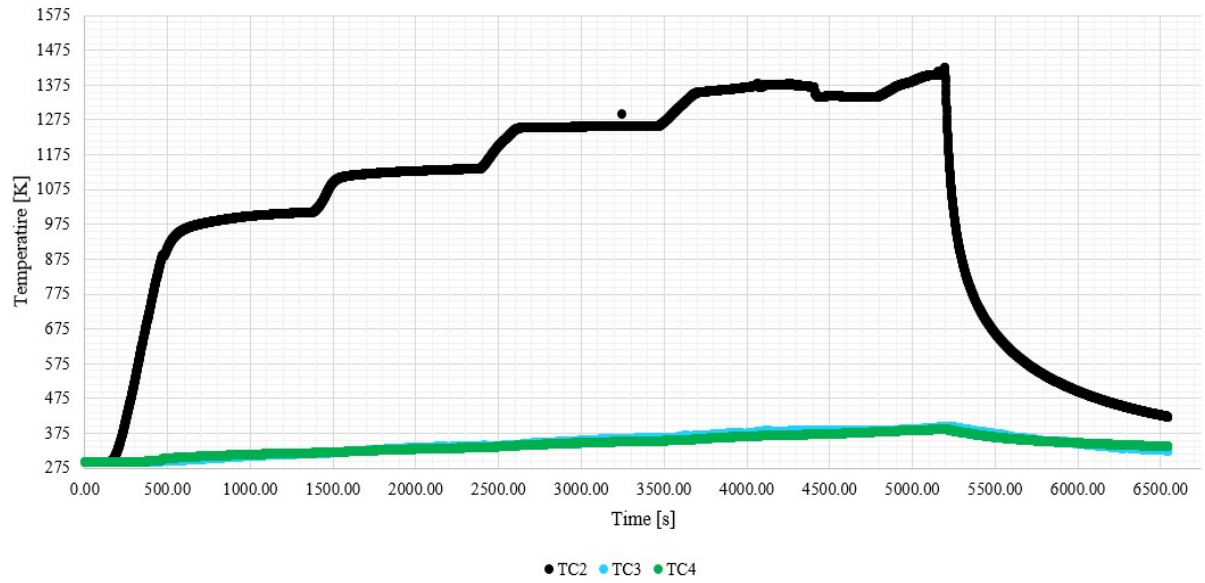


Figure 3.25: July 20, 2021 high purity MgO TC data.

have released oxides or introduced other impurities into the filament. The cracking may have also opened the seal for other sources of impurities to enter the filament space. During heating when the resistance suddenly increased, the analog pressure gauge displayed a 7 mTorr increase before dropping back down. These impurities must have then been removed since the trends resume. They could have been removed either by the exposure to high temperature or the continually pulling vacuum pump. Due to the fragility of the high purity magnesia, not many samples survived the coupling with the graphite shell prior to testing. This step test was not reattempted as a result of the low supply of high purity magnesia heater assemblies. The incentive to attempt to repeat the temporary resistance increase is overshadowed by the end result of power supply fluctuations reminiscent of the previous runs. Further investigations would need to be performed to identify the principal failure.

The post-test examination sample can be found in Figure 3.27. The scorching is evident in this image. The area near the ends of the crucible, or near the plugs, is deformed and has minor ridges due to localized melting.

To isolate the ceramic used for the crucible and its role in the inability to achieve NTP prototypical temperatures, various materials were tested. Zirconia, alumina, hafnia, high density magnesia, and high purity magnesia were all used. The results while changing the ceramic used are all similar: the power supply begins to fluctuate and the post-test examinations reveal localized melting and scorching, which are signs of potential electrical arcing. This arcing may be brought upon by the disjointed nature between components of the electrical circuit. The compliant filament is not rigidly fixed to any other component of the circuit. In a high current and high temperature environment, the compliance and unreliable contact of the filament may be the source of failure - not the ceramic crucible. This possibility will be discussed in the following sections.

3.3.2 Heater Plugs

To systematically troubleshoot each component of the heater, the next discussion will focus on the testing performed to investigate the heater plugs and their role in the failure of the electrical circuit.

The early OUTSET tests utilized a "flat" heater plug. The power supply fluctuations were observed early on and it was proposed that changing the plug may enable better contact between the plug and the filament. Opposed to a squared flat plug, a tapered plug was conceived, machined, and implemented. This tapered plug penetrates the filament by burrowing into the material. The flat plug offered less depth into the filament and a more surface-level contact between the plug and filament interface. A comparison of a flat plug and a tapered plug can be found in Figure 3.28. Each plug variation was tested using an alumina crucible.

The power supply log is unavailable for any test performed prior to June 22, 2021. This includes the heater plug investigation runs. The storage of power supply logs was not practiced by the experimenters simply because they were unaware of this capability. Despite this conundrum, written logs of the power, current, and voltage levels were recorded periodically during testing. During the flat plug test performed on June 16, 2021, the power was increased steadily until around 150 W over about 8 minutes . At 8 minutes , the shell TC recorded temperatures around 1050 K . The power was then increased to 300 W over the course of about a minute. This level was held for a few minutes near 1370 K . After these few minutes, the power supply levels began to fluctuate and the test was concluded. The temperature data for the flat plug run is shown in Figure 3.29. Again, this utilized an alumina crucible.

Following the flat plug form factor, the tapered shape was tested. This test was performed on June 17, 2021 and utilized the same components as the flat plug run, except for the plugs. During this run the power was raised to 200 W after about 18 minutes . This level was held for 11 minutes and produced a shell TC temperature of 1200 K . This temperature was unable to be maintained beyond this 11 minutes due to the onset of electrical fluctuations. Despite the various plug geometries and the various test conditions, the experiment displayed its familiar failure mechanism via electrical fluctuations seen in the power supply. The shape of the heater plugs has no effect on the prevention of the electrical fluctuations.

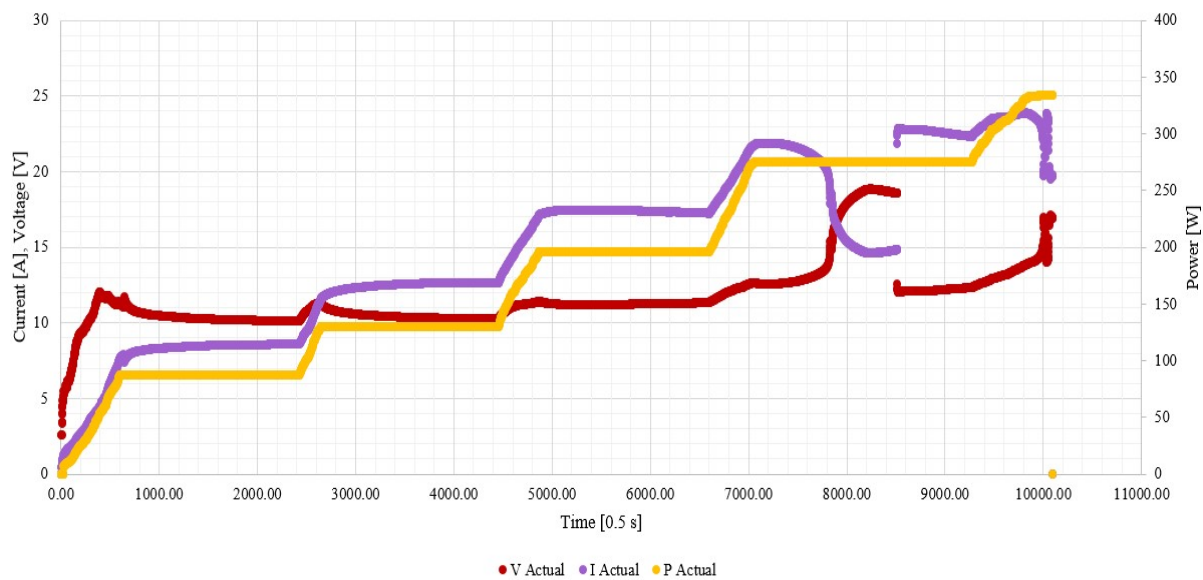


Figure 3.26: July 20, 2021 high purity MgO power supply data.



Figure 3.27: July 20, 2021 high purity MgO post-test observation of scorching within crucible.



Figure 3.28: Comparison between tapered (left) and flat (right) heater plugs.

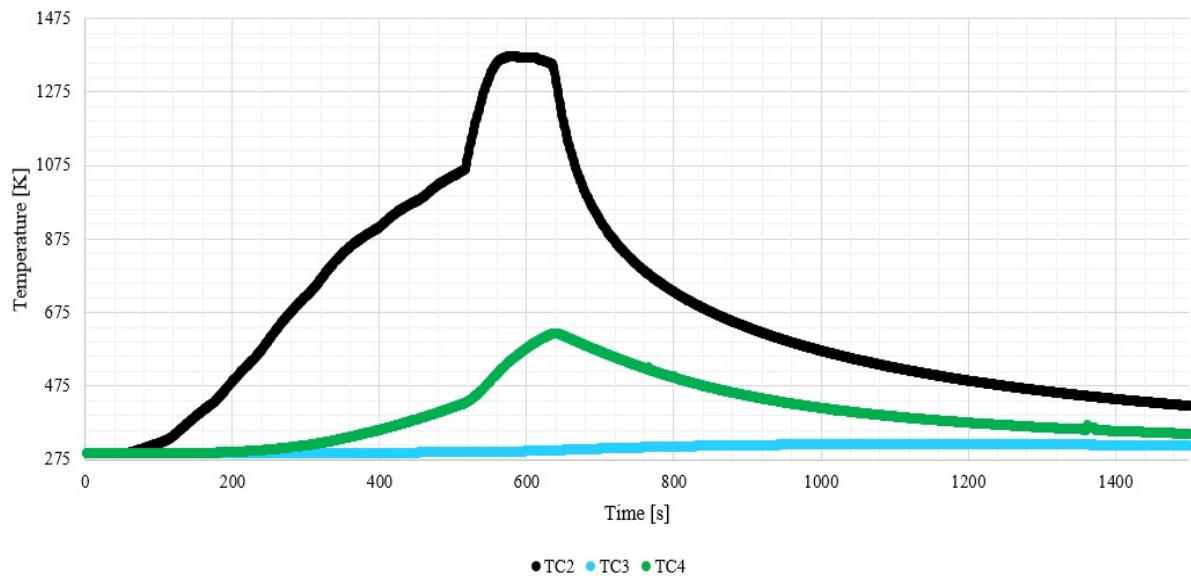


Figure 3.29: June 16, 2021 flat plug TC data.

Once the shape of the plugs was eliminated as a potential source of the failure, various plug-related investigations were performed. The first relates to the contact between the plugs and molybdenum circuit. The molybdenum tubing that makes up the electrical circuit up to the heater, is slip fitted into a slot in the plugs. This slip fit is a sturdy connection. If the molybdenum tubing begins to axially thermally expand, it may pull the plug out of the crucible, breaking the integrity of the electrical circuit. This would have deleterious effects, possibly leading to arcing and power supply fluctuations. A diagram of this potential failure cause is shown in Figure 3.31. The red circle is an artistic effect to show that the region of the molybdenum tubing nearest the heater would experience the highest temperatures. This local heating would cause the molybdenum to expand along the direction shown by the red vertical arrows. Through the mechanical linkage forming the 90° corners near the bottom of the molybdenum tubing, this expansion may pull the plug from the crucible. This is shown by the downward blue arrow. It may also be removing the tubing from the plug, if the plug is more secured to the crucible - also resulting in circuit demise.

To quantify the likelihood of this movement, the thermal expansion of molybdenum was considered. The length of the molybdenum tubing in question is 0.273 m . At temperature levels near 1500 K , the linear thermal expansion of molybdenum has been recorded as 0.752% [36]. This implies an extension of the tubing around 2 mm . The plug penetrates 9 mm into the crucible. The 2 mm expansion of the tubing would not be enough to remove the plug from the crucible and would not substantially remove the plug from contact with the filament. Molybdenum is often touted as having a low thermal expansion.

To further ensure the molybdenum tubing was not removing the plug from the crucible, carbon paste and a flexible graphite gasket were implemented. High temperature carbon paste was used to adhere the plug to the inner wall of the crucible. The graphite gasket material, Grafoil, was used to add material between the plug and crucible as well as between the plug and molybdenum tubing. This additional material created a tighter and more secure slip fit between the surfaces. Several tests were conducted to investigate the impact of the carbon paste and the Grafoil. The carbon paste is a much stronger connection than the Grafoil. The carbon paste makes it challenging to separate the pasted surfaces - often requiring vice grips or the destruction of the heater assembly to liberate the plug. The Grafoil also has a similar impact, but can often be removed with standard pliers and not an immense amount of effort. Combinations of both materials were used in multiple tests that were performed to accomplish tasks other than observing the impact of paste and Grafoil. As such, TC plots will not be shown here. The impact of the carbon paste and Grafoil was negligible. It was indiscernible as to which combination of the paste and Grafoil were used. Both materials increased the security of the tubing to the plugs and the plugs to the crucible, but they appeared to have no effect on the electrical fluctuations. The bond between the circuit components was secure and the thermal expansion of the tubing is small. These observations imply that the culprit of the electrical fluctuations is not a mechanical separation between the molybdenum tubing and the plugs or between the plugs and the crucible.

To eliminate the plugs as a potential source for the failures observed, two form factors of plugs were implemented: flat and tapered. To ensure the plugs maintained continuity with the molybdenum circuit and the crucible, carbon paste and Grafoil were added to the heater. None of these alterations remedied the electrical fluctuations or enabled INSET to reach maximum prototypical NTP temperature levels.

3.3.3 Heater Shell

The heater shell was made from rigid POCO graphite. Graphite is electrically conductive. To explore the impact that the electrically conductive shell could have on the electrical fluctuations, a test was completed without the graphite shell. The graphite shell was electrically insulated from the heater's current path through the use of the ceramic crucible. However, if the ceramic crucible's dielectric properties breakdown at elevated temperature or current levels, the current may have been passing through the ceramic - resulting in electrical fluctuations. The no-shell test was performed using high density magnesia as the crucible. The TCs used adhere to the standard set in Section 3.1.3. With the removal of the shell, the TC cannot be placed in the shell. Instead, that TC was placed near the crucible. This can be seen in Figure 3.32. It is

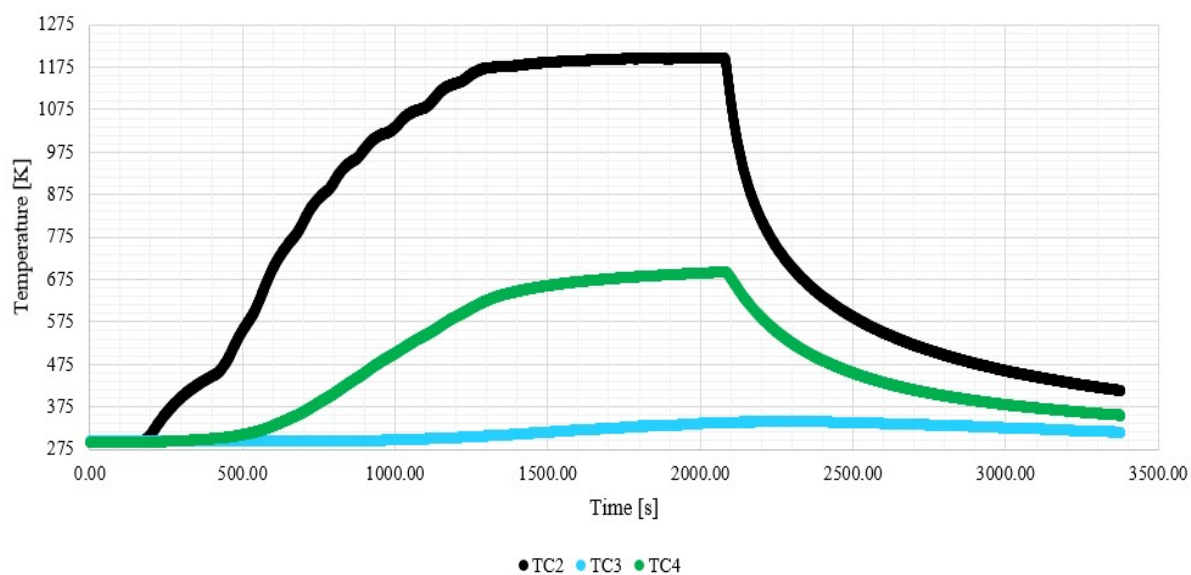


Figure 3.30: June 17, 2021 tapered plug TC data.

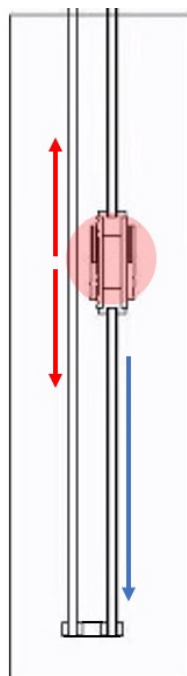


Figure 3.31: Diagram of potential molybdenum tubing thermal expansion removing plug from circuit.

important to note that the thermal conduction path to the shell and, subsequently, the shell TC has been removed. Without the shell, the thermal energy is transferred via radiative heat transfer through the vacuum to the TC. This will result in lower recorded temperatures, for a given power input, than with the shell since conduction is a more effective heat transfer mechanism than radiation.

Power delivery to the experiment was increased at a rate similar to that seen in the OUTSET-1 ([22]) tests in order to replicate that work. This rate is about 150 W/minute . The temperature data for the no-shell run is shown in Figure 3.33 and the power supply log is shown in Figure 3.34.

The brief fluctuations in Figure 3.34 around 700 half-seconds are reflected in the temperature data in Figure 3.33 around 500 seconds . This sudden voltage increase and abrupt current drop must correspond to a substantial resistance increase. The trends resume after a few minutes. The typical electrical fluctuations are not seen in this run, but electrical reliability has not been demonstrated. This is a similar result to the related run that incorporated the shell. The post-test examination of the no-shell run (as well as the shell run) has yielded interesting observations. The post-test heater can be seen in Figure 3.35 along with a close-up of the crucible.

Prior to the comments regarding the observations made from the post-test examination, it must be stated that I am a nuclear engineer by training. Some general advice about the following phenomena has been provided by a material scientist [37]. Conclusive and critical statements regarding the observations will be withheld. Information will be presented to enable a more informed reader to reach substantive conclusions. From Figure 3.35, it can be seen that the TC is covered in oxides (white) from the magnesia crucible. The crucible is also much more white than the pre-test sample. The pre-test sample was darker and more off-white. There was also a dark flaky substance on the molybdenum tubing as well as the thermocouple's hafnia sheath. This may be burnt liberated oxides or impurities from the magnesia. The magnesia crucible has also cracked around its radius. Additionally, as seen in the close-up, small icicle-esque structures formed on the surface of the crucible. There are thicker protrusions as well. To speculate, these may be related to the vapor pressure of the ceramic. The material may be vaporizing from the surface before cooling and resolidifying in the cooler vacuum. Regardless of the underlying material science driving these phenomena, it would require an extreme thermal environment to witness these results. Such a thermal environment would be one that exists at temperature levels well above those recorded by the TC - shell or no shell. Further high temperature tests would be needed to investigate this phenomena.

In an attempt to isolate and to repeat the material and TC observations, a similar run to the one performed without a graphite shell was performed, but with a graphite shell. The temperature data for the run that used a shell is shown in Figure 3.36. This test was conducted using the constant power mode on the power supply to ramp power at a rate roughly around 150 W/minute . The TCs were in the same locations as they were for the no-shell run, except the standard TC placement (Section 3.1.3) was reinstated with the TC slotted in the now-present shell. Although the recorded temperature for the no-shell run is lower than that of the run with a shell, it is suspected that the filament temperatures were similar. The recorded temperature is less for the no-shell run because the effective thermal conductivity of a vacuum is less than that of a graphite shell - thus the no-shell test would conduct less thermal energy to the TC.

As shown in Figure 3.36, this run yielded the highest temperature levels seen since the OUTSET-1 tests. The temperature also appears to be rather stable. At first, this was a promising result. However, the post-test examination in combination with the inconsistencies against previous similar runs still raises concerns about the reliability of the current INSET design. Additionally, the surface temperature of the apparatus exceeded 400 K without any active cooling. If this design and temperature were to be implemented in an in-pile experiment, active cooling would be required to prevent thermally interacting with the moderator in the reactor system. The power supply log associated with this run is shown in Figure 3.37.

The power supply utilized has a current limit of 50 A . This run maintained a maximum current of 43 A . The remaining 7 A of the supply's capability were not utilized out of an abundance of caution to prevent damaging the power supply. Prior to the successful use of the power supply mentioned in Section 3.1.1, two



Figure 3.32: Pre-test image of the no-shell run.

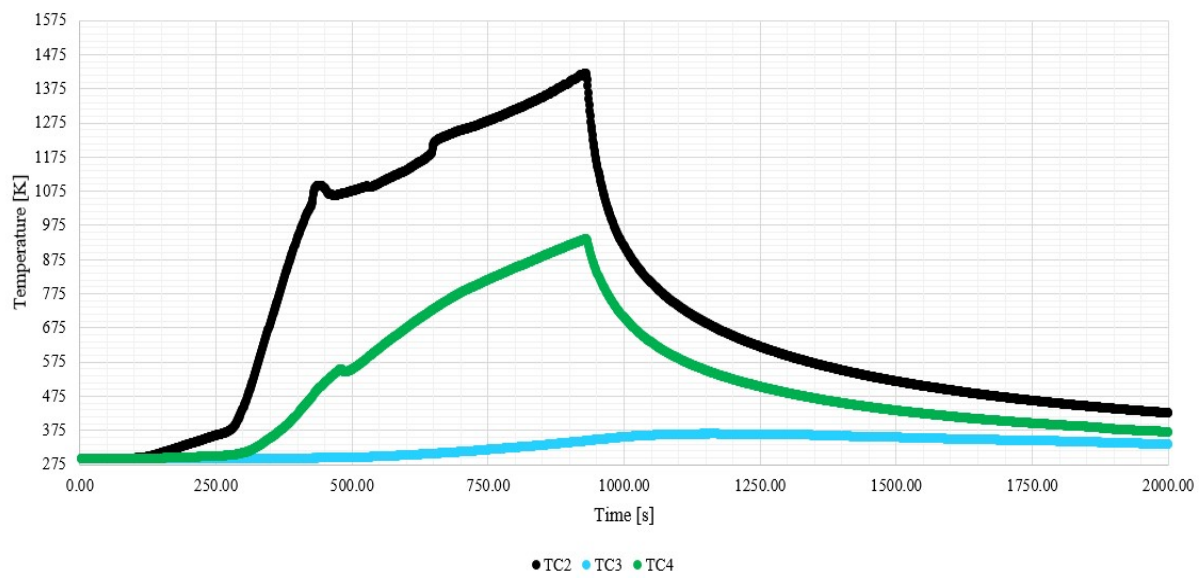


Figure 3.33: July 27, 2021 no-shell TC data.

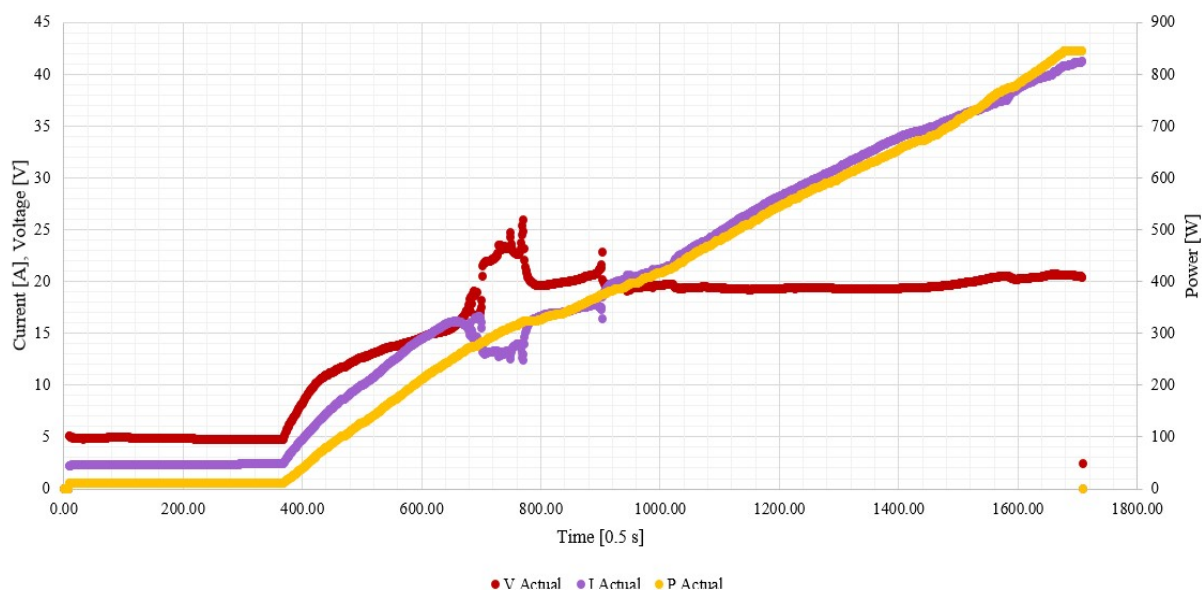


Figure 3.34: July 27, 2021 no-shell power supply data.

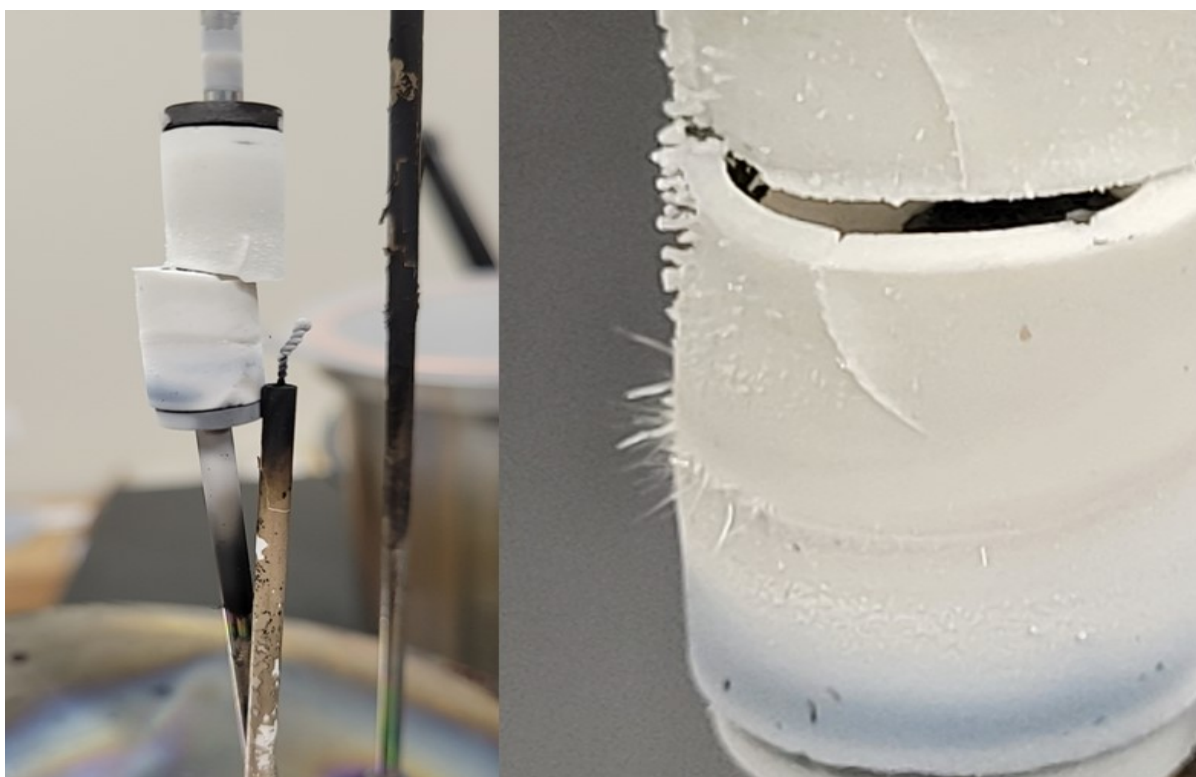


Figure 3.35: July 27, 2021 no-shell post-test observation.

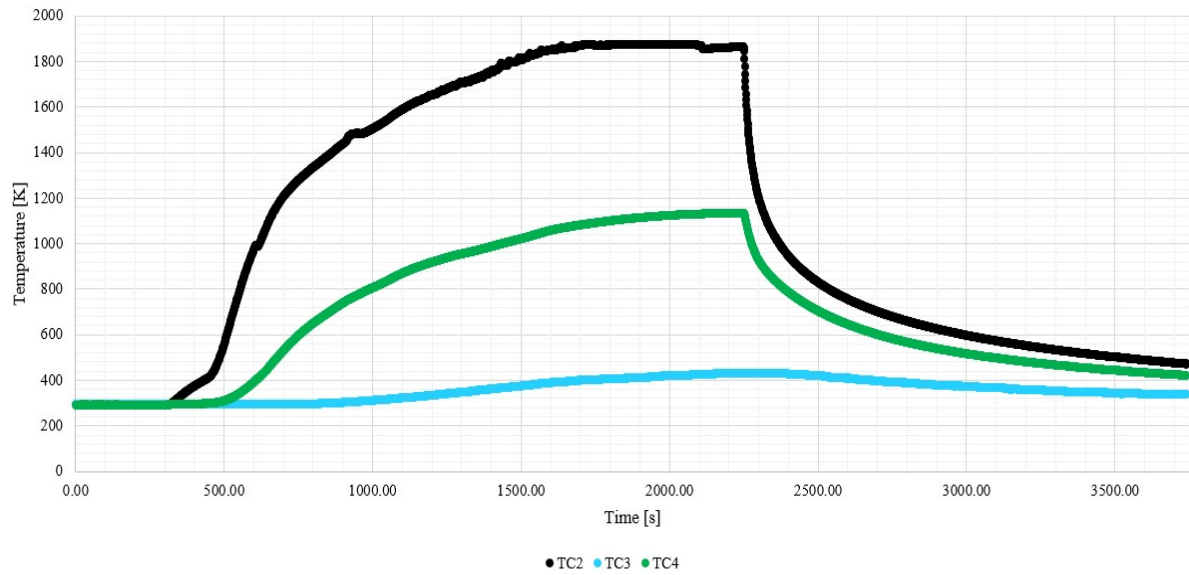


Figure 3.36: July 28, 2021 shell-present TC data.

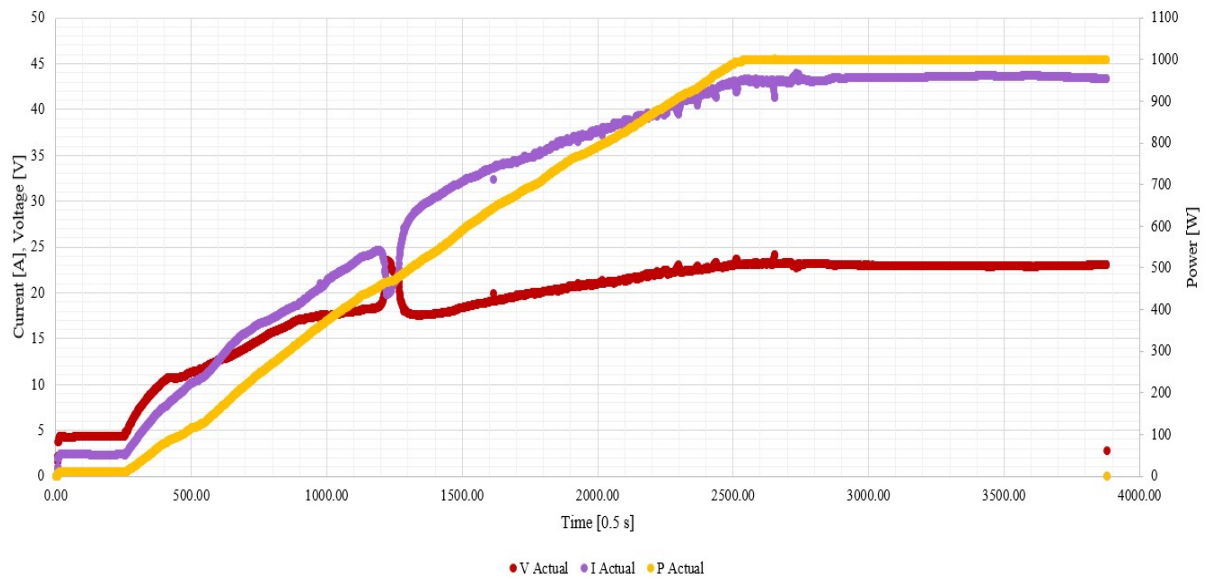


Figure 3.37: July 28, 2021 shell-present power supply data.

separate power supplies were damaged beyond use during testing. Regardless, this 43 A current equated to a power level of 1 kW. This is the highest level of DC power ever supplied to the experiment.

The post-test examination of the run with the shell led to interesting observations. The crucible was cracked in a nearly identical manner to the no-shell run. The graphite shell was cracked as well. However, the TC slot on this particular shell was not machined in the center of the thickness of the shell. The shifted TC slot was milled in a position where the material removed was on the inner surface of the shell. This edge milling lead to a stress concentration in a state of thermal expansion. An observation that calls back to the plug discussion in Section 3.3.2 was also made. The molybdenum tubing fused to its slot in the plugs. The plugs had to be separated from the tubing and the only way to do so was to break the plug or break the tubing - both were done. The fusion of molybdenum to graphite can only occur at extremely high temperatures or at currents that mimic that of tungsten inert gas welding. These observations can be seen in Figure 3.38 and Figure 3.39. Figure 3.38 shows the circuit assembly following the test. Similar outcomes to the no-shell run can be seen here. Figure 3.39 shows the heater assembly following the test. The molybdenum fusion to the plugs can be seen on the right. The cracked crucible can be seen in the middle. The cracked shell is shown on the left. The inner wall of the shell also displays oxide deposition.

Despite the apparent success shown exclusively by the temperature records of the shell-present run, the damage to the heater made it unusable in any subsequent tests. Not only does this destruction make each run more financially expensive, it also eliminates the potential for any tests that would require thermal cycling. Figure 3.39 does not show the filament. The filament was never recovered or found following this test. The material data sheet for the filament reports a maximum application temperature of 2300 K [38]. There is evidence that this temperature level was exceeded by at least 250 K. A platinum-iridium melt wire was inserted into the filament prior to this trial, and post-test observations indicated the instrument melted. This indicates that the filament operated at or beyond the wire melting point of 2550 K ([22]). The melt wire result indicates that filament temperatures exceeded the recorded TC data. A more comprehensive discussion of the melt wire usage is presented together in Section 3.3.7.

The presence of a shell did not have a significant impact on the behavior of the experiment. The temperatures recorded with a shell present, do not imply higher temperatures were obtained, the shell simply enables more effective heat transfer to the TC. Both the no-shell and the shell-present run yielded material failures. In the presence of such extreme material phenomena, it is evident that the TC data is not an accurate representation of the thermal environment within the filament. This concept will be explored more in Section 3.3.7. Although the temperature data appeared stable for the shell-present run, when compared against similar tests, the stability occurrence is inconsistent. This is further evidence that the current heater design may not be the most successful at a scale larger than that of OUTSET-1. This also supports the need for non-electrical based measurements, such as optical pyrometry.

3.3.4 Heater Filament

The OUTSET-1 heater filament was SGL SIGRATHERM® GFA5 graphite felt ([29]). This felt was cut into a strand and inserted into the crucible. It was contained in the crucible with the heater plugs. The role that the filament has on the high temperature success of the experiment will be discussed here. A strand of GFA can be seen in Figure 3.8. The length of this strand was cut to adjust the resistance. Due to the natural porosity, varying internal density, and heterogeneity of the GFA strand, a more homogeneous graphite filament was conceived. Also from SGL SIGRATHERM®, MFA ([38]) graphite composite was used. A piece of this carbon composite block was broken off and ground into a powder or sand-like consistency. This graphite powder will be referred to as the "sand" filament. This sand would then be poured into the crucible, serving the role of a filament. A pile of this sand can be seen in Figure 3.40.

The various filament tests were conducted using the standard TC setup, a 50 W/minute power ramp rate up to 200 W, and an alumina crucible. Using the GFA strand at the aforementioned conditions, the temperature data in Figure A.26 was obtained.



Figure 3.38: July 28, 2021 shell-present post-test observation.

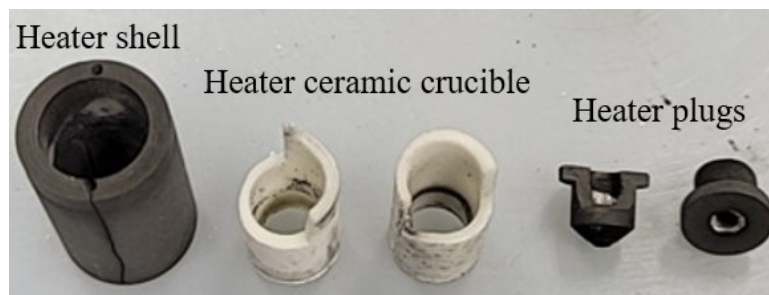


Figure 3.39: July 28, 2021 shell-present post-test observation - heater.

The power supply data is unavailable for this run, but according to written logs, there was an electrical fluctuation around the time of the disruption to the temperature trend (1400 s). The run was also concluded as soon as the current began to undesirably vary. Repeating this test, but with MFA sand, the temperature data in Figure 7.9 was obtained.

The thermal records between the strand test and the sand test show similar results. The sand has been demonstrated to lead to more stability and less electrical fluctuations per run. There were still electrical fluctuations in various runs that used the sand MFA filament, but they were less common than when using the strand GFA. Post-test observations have shown that the strand returns to its pre-test state. The elasticity of the strand of felt returns the filament to its pre-test resistance and size when it comes back to room temperature. This shape memory is not seen in the sand. The sand behaves like a sintered powder. It compresses during heating, but does not resume its original shape or resistance after the apparatus has cooled to pre-test room temperature conditions. This compression of the sand may hint at what is happening when arcing is occurring. If the filament is compressing under the elevated thermal and electrical environment, it will fall out of contact with the plugs.

In addition to the strand GFA and sand MFA filaments, two other forms of filament were tested. The first of which is the "pulverized strand." The pulverized strand filament was a strand of GFA that had been torn apart into small tufts of GFA. This was done to increase the resistance of the heater by manufacturing a lower density filament. A higher resistance allows for a given power level to be reached with less current. This lower density pulverized strand behaved nearly exactly as the GFA strand. It simply required less current to reach a given power level, but still displayed the same failure mechanisms. The other form factor was only tested once because it did not produce desirable results. The other form factor will be referred to as graphite "rebar." The rebar filament was a strand of GFA placed vertically in the crucible and not squished into the space at all. Then, around the standing felt, MFA sand was poured. The rebar filament was conceived as a way to combine the stability of the sand with the memory of the strand. This was not the case. The rebar filament behaved similarly to the strand and was difficult to assemble. As such, the rebar was not used in any other tests.

Four filament form factors using two different graphite stocks were tested to investigate the filament's impact on the observed electrical fluctuations and the inability of INSET to reach maximum prototypical NTP temperature levels. No filament was able to demonstrate indefinite stability or reach temperatures of 2500 K. The compliance and lack of rigidity exuded by the filaments is a cause for concern. The lack of fixed mechanical linkages between the plugs and the filament enable the system to become dynamic due to the filament's compliance. This dynamic system cannot be monitored by TCs and melt wires alone. It also cannot be controlled well, as seen by undesired power supply fluctuations. The challenges and unknowables associated with this heater design can be circumvented by using a solid resistive heating element instead of the compliant filament design in use. The concept of a solid heater will be discussed later in Section 4.1.

3.3.5 Thermal Ramp Rate

To investigate the effect of the thermal ramp rate on the success of INSET, three primary heating rates were implemented across experiments. These rates can be approximated as 50 W/minute, 150 W/minute, and 350 W/minute. These values correspond to the manual manipulation of the constant power mode power supply. The slower thermal and electrical ramp rates were much more stable than the higher rates. OUTSET-1 reported a ramp rate around 100 W/min.

The 50 W/minute rate demonstrated the most stability and, as such, was used in the later radiative heat transfer studies. An example case of the 50 W/minute power ramp rate utilized an alumina crucible, an MFA sand filament, and the standard TC loadout. The TC data for this run can be seen in Figure A.27 and the power supply log is shown in Figure 3.44. The power supply log was focused in on the early ramp. The duration of the test (79 minutes) obscures the ramp data; by condensing the plot, more fine details can



Figure 3.40: Pile of MFA sand filament material.

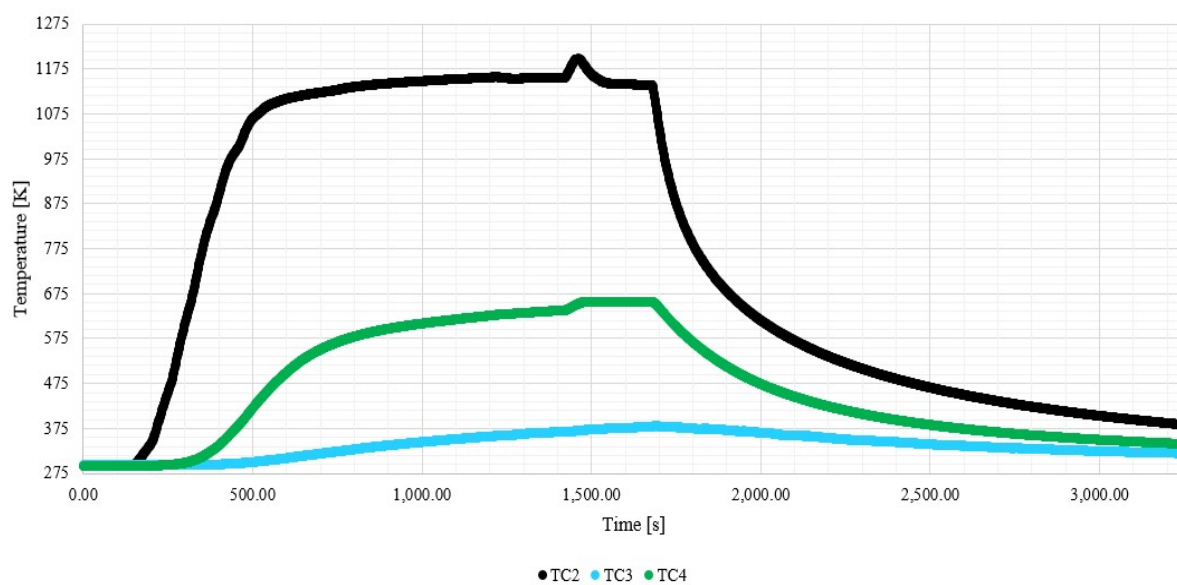


Figure 3.41: June 10, 2021 GFA strand TC data.

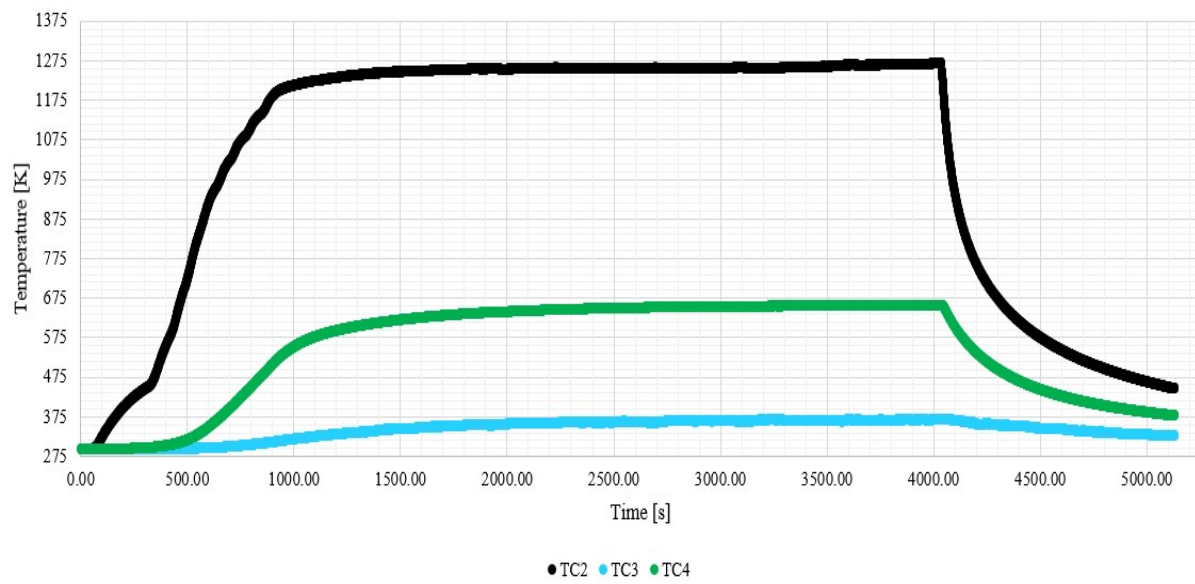


Figure 3.42: June 18, 2021 MFA sand TC data.

be seen during the ramp period. Once 200 W was reached, the supply did not fluctuate and maintained this current and voltage level until the test concluded. More on the 50 W/minute cases will be shown in the latter portion of this document. The stability of the system exposed to 50 W/minute can be seen in these figures.

The 150 W/minute DC power ramp rate displayed less stability than the lower rate. This increased ramp rate is accompanied by a higher temperature and power level by necessity. Due to the inescapable higher temperature levels associated with a faster ramp rate, high purity magnesia was used for the heater in the example case presented here. MFA sand was used for the filament and the standard TC placement was practiced. The TC data for the 150 W/minute case can be found in Figure 3.45 and the power supply log is shown in Figure 3.46. The instability and the frequent electrical fluctuations can be seen here. The test was ended when the power supply approached the current limit (50 A). The varying power supply output was much more prominent here than in the 50 W/minute tests.

The 350 W/minute ramp case was only tested once. This was only tested once because the results were nearly unusable. The heater shattered during the test after only about 30 s. Again, with the elevated ramp rates, higher temperatures are inevitable. As such, high density magnesia was used for the crucible, sand MFA for the filament, and the TCs were in the standard positions. This ramp rate has demonstrated itself as the least stable and least controllable. The data is highly unsatisfactory, but will be shown here for completion and since the sheer nearly nonsensical nature of the data is evidence on its own that portrays the instability at this ramp rate. The TC data for the 350 W/minute case can be found in Figure 3.47 and the power supply log is shown in Figure 3.48.

The 350 W/minute ramp rate test incorporated a melt wire in the filament. This melt wire melts around 2550 K [22]. After the test, the melt wire was recovered and melting was observed. This will be discussed more in Section 3.3.7. Additionally, after the test, it was observed that the entire assembly cracked and fell apart. Every piece of the assembly was broken during the short test and was found at the bottom of the heated plenum region. The heater was introduced to so much current and thermal energy so quickly, that it physically shattered. A post-image of every component of the heater assembly can be found in Figure 3.49.

The ramp rate has an effect on the stability of the circuit. Slower ramp rates yield a more stable and controllable experiment. However, the slower ramp rates are associated with lower temperatures and power levels. The ramp rate affects the stability, but it is not the sole influencer. The maximum temperature and DC power introduced to an experiment have a significant impact on the system as well. At the scale of INSET, the heater does not perform well at substantially fast ramp rates or elevated temperature and power levels.

3.3.6 OUTSET-1 Equivalent Heat Flux

The heated surface area is larger in the current OUTSET design when compared to OUTSET-1. For a fixed power level, the heat flux will be less in the larger system. In an attempt to replicate the success of OUTSET-1, an attempt to supply an equivalent heat flux was made. The heated surface area of OUTSET-1 was formed by a hollow cylinder with a diameter of 28 mm and a height of 74 mm. This equates to a surface area of $7.74 \times 10^{-3} m^2$. The plenum region of OUTSET has a diameter of 63 mm and a height of 210 mm. This equates to a surface area of $4.78 \times 10^{-2} m^2$. OUTSET-1 reached 2200 K using 300 W of DC supplied power. Dividing the 300 W of power by the $7.74 \times 10^{-3} m^2$ surface area of OUTSET-1 yields a heat flux of $3.88 \times 10^4 W/m^2$. To match this heat flux with a the larger surface area of OUTSET, additional power is needed. To quantify the necessary power level, the calculated heat flux of $3.88 \times 10^4 W/m^2$ is multiplied by OUTSET's heated surface area of $4.78 \times 10^{-2} m^2$. This calculates to a necessary power of 1852.71 W. This relationship is shown in Equation 3.4.

$$\dot{q} = \frac{P_{OUTSET-1}}{A_{OUTSET-1}} = \frac{P_{OUTSET}}{A_{OUTSET}} \quad (3.4)$$

where:

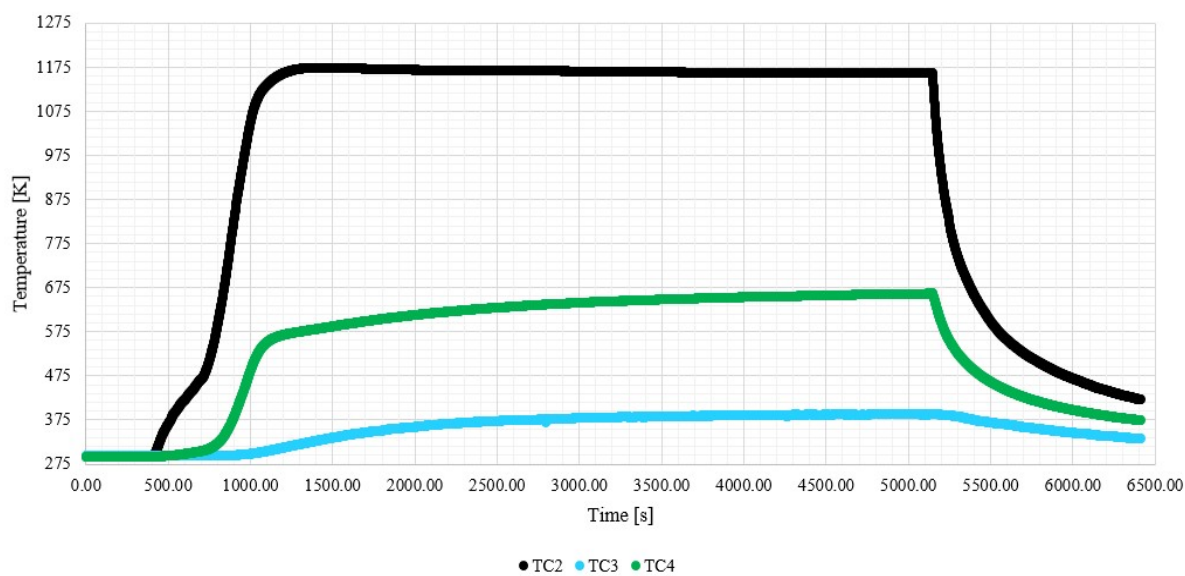


Figure 3.43: August 2, 2021 50 W/minute TC data.

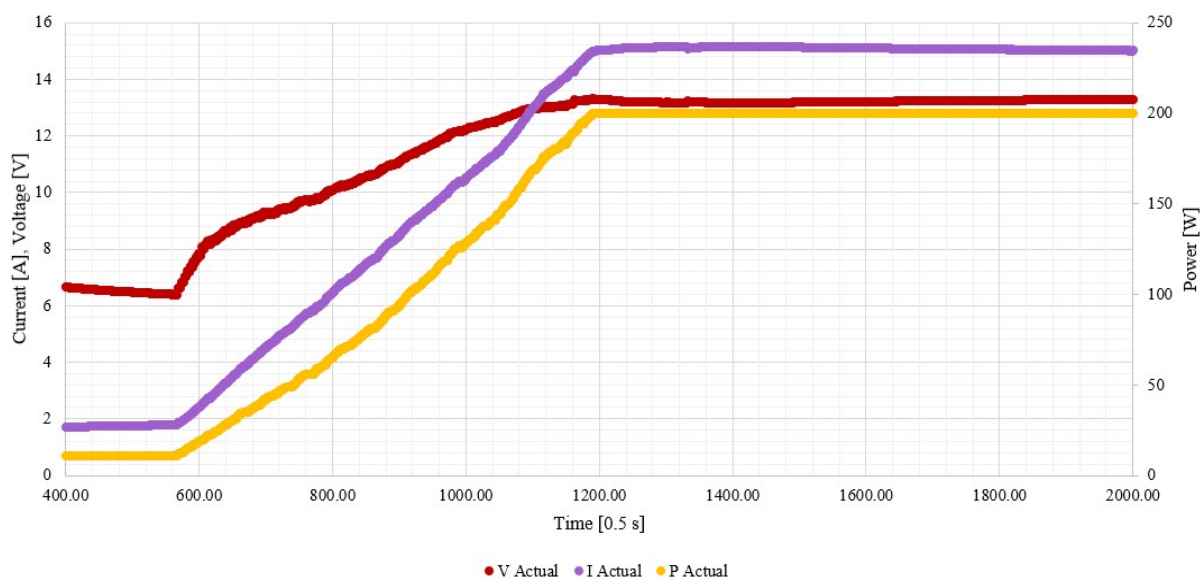


Figure 3.44: August 2, 2021 50 W/minute condensed power supply data.

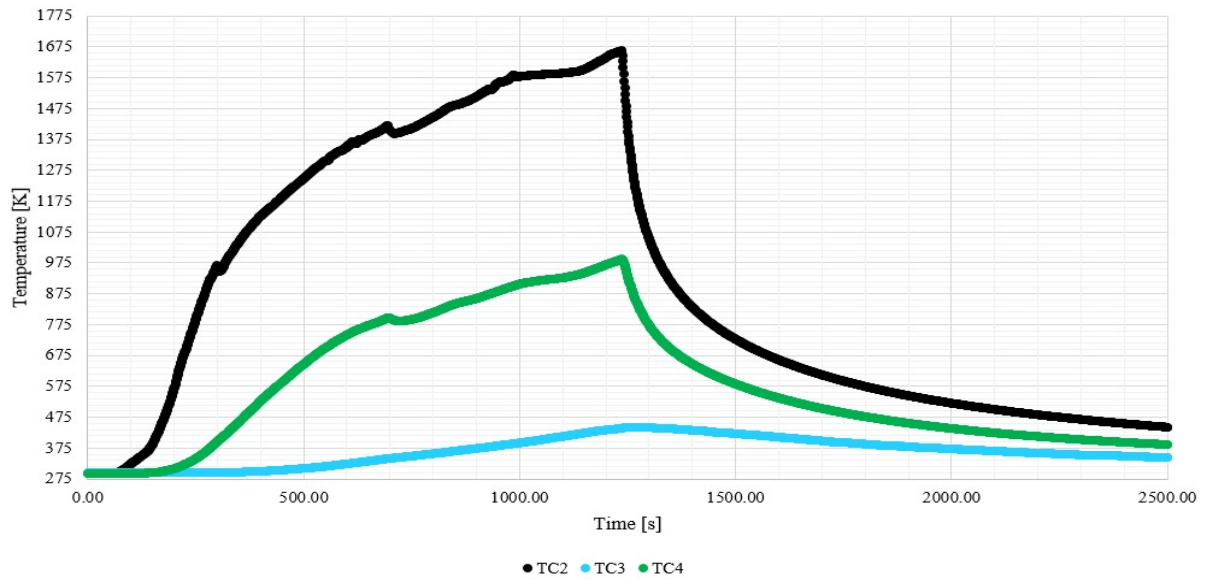


Figure 3.45: July 26, 2021 150 W/minute TC data.

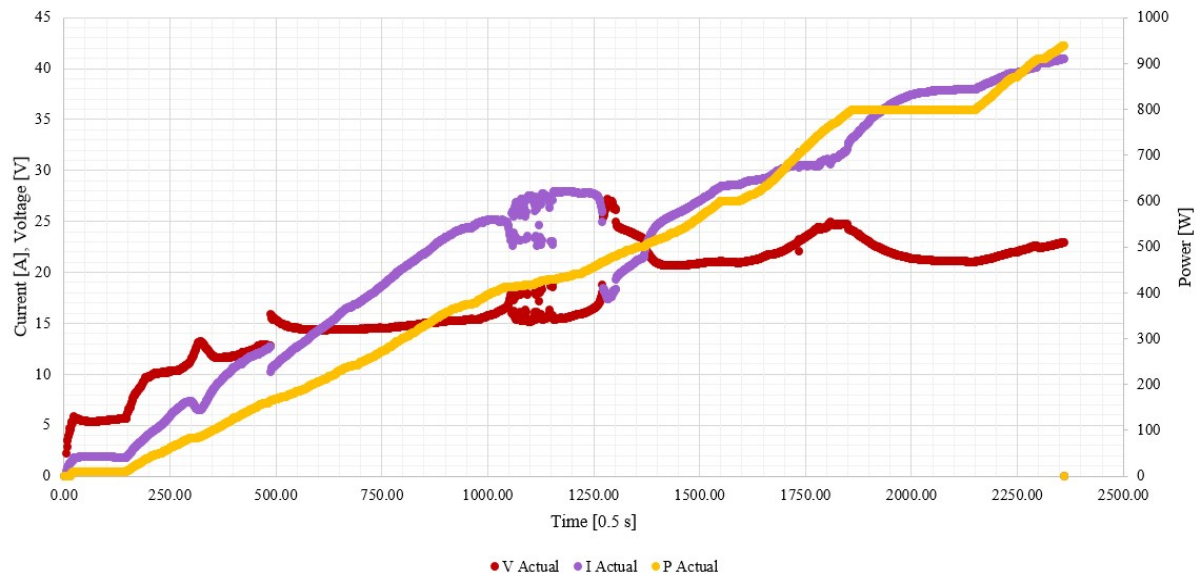


Figure 3.46: July 26, 2021 150 W/minute power supply data.

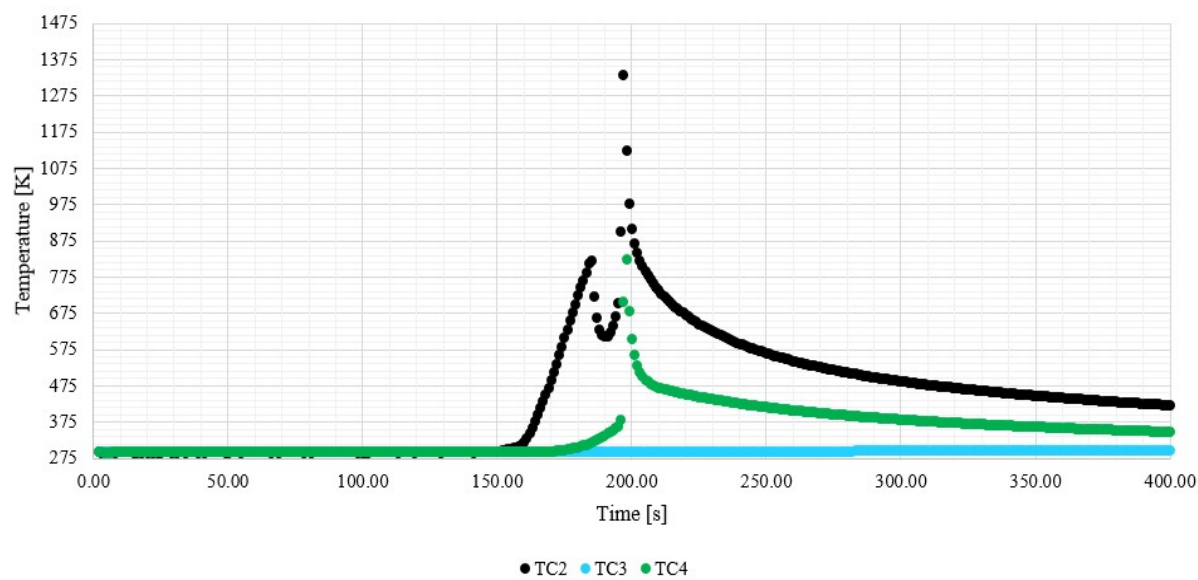


Figure 3.47: August 17, 2021 350 W/minute TC data.

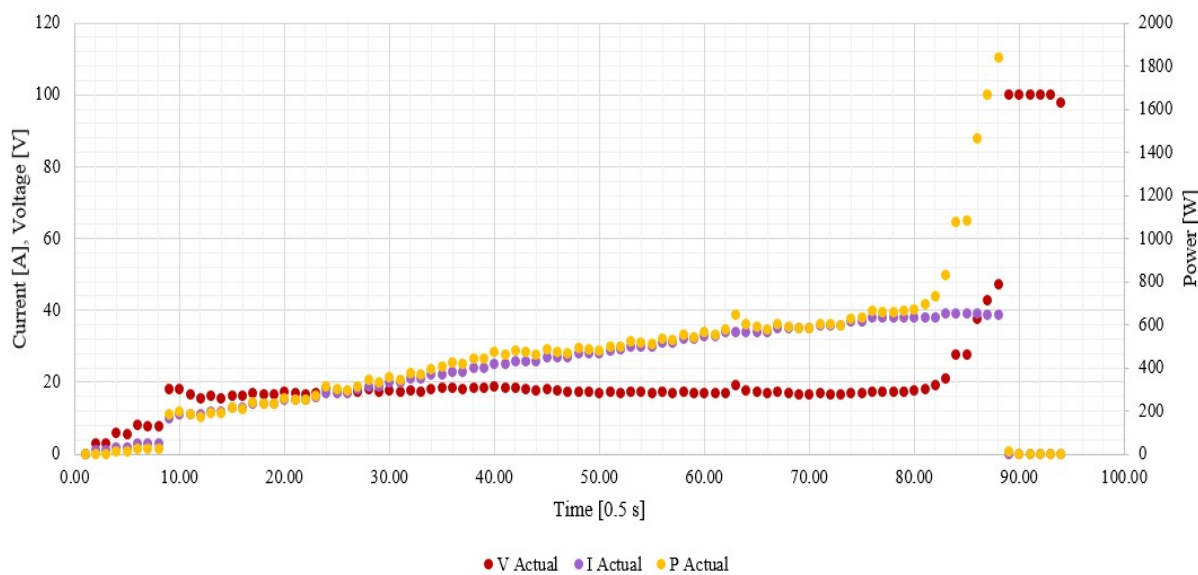


Figure 3.48: August 17, 2021 350 W/minute power supply data.

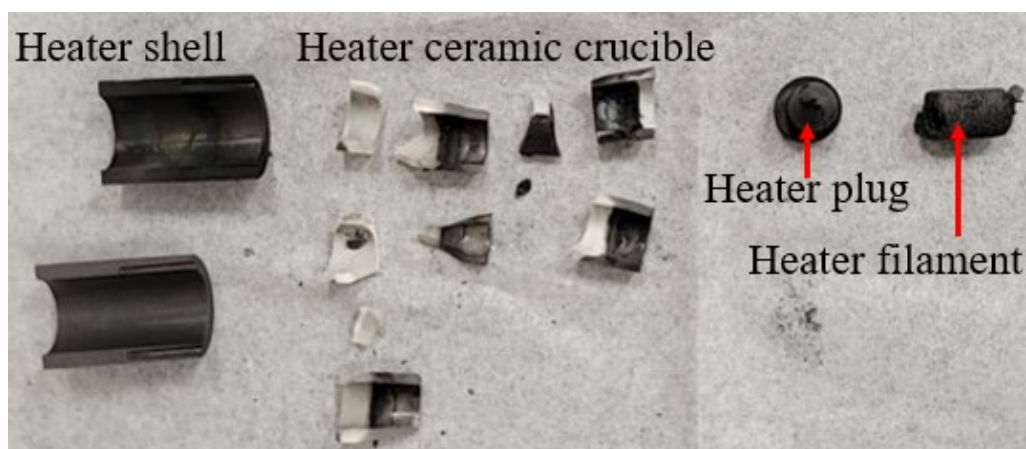


Figure 3.49: August 17, 2021 350 W/*minute* post-test observation.

$\dot{q}$ = heat flux
 P = power supplied
 A = surface area

Previous tests have shown that the resistance of the heater filament decreases as temperature increases. This observation is supported by literature [39]. This decreasing resistance requires additional current to be supplied to maintain constant power (Equation 3.2). To prevent the power supply from becoming current limited before 1852 W could be reached, the test would have to be conducted quickly to combat the effects of decreasing resistance. The results of this test have been shown in Figure 3.47, Figure 3.48, and Figure 3.49. A power level of 1838 W was reached, but only momentarily, prior to catastrophic heater failure.

3.3.7 Melt Wire Discussion

Melt wires were used to verify the TC data. Each melt wire discussed in this section was the same platinum-iridium alloy. Energy dispersive x-ray spectroscopy (EDXS) was performed on a melt wire after it had melted to investigate the presence of any impurities. This work was performed by Dr. Gerald Egeland at the University of Tennessee, Knoxville. The spectrum from the EDXS test is shown in the Appendix in Figure A.10. The melt wire composition is shown in Table 3.1. This melt wire has a reported melting point around 2550 K [22]. An unused melt wire can be seen in Figure 3.50 for context.

Melt wires were incorporated into four tests: one 1 kW , two 200 W , and one 1800 W . The melt wires were placed in various locations during the tests. Figure 3.51 shows a schematic of the location of the melt wires and the TCs. A red "X" shows where a TC was. Both TC locations were utilized for every test. A yellow "X" shows the potential location for a melt wire. These yellow "X"s correspond to a location within the filament as well as in the unoccupied TC slot in the graphite shell. An image of the melt wires loaded into the heater can be seen in Figure 3.52. Figure 3.52 (a) shows the melt wire in the filament while Figure 3.52 (b) shows the melt wire in the unoccupied TC slot.

The 1 kW test was performed on July 28, 2021 and has been presented by Figure 3.36, Figure 3.37, Figure 3.38, and Figure 3.39. The melt wire was in the filament position for this test (Figure 3.52 (a)). The maximum temperature recorded by the shell TC during this run was 1875 K . This 1875 K is below the melt wire's melting point 2550 K . However, post-test examination shows that the melt wire did melt. The melt wire must have undergone a phase change to reach the deformed state shown in Figure 3.53.

A thermal model was used to further investigate the observed temperature discrepancy. When considering the 1 kW case, the model reported a shell TC temperature of 1895 K . This is about 1% different than the actual TC reading of 1875 K . The model reported a maximum filament temperature of 2049 K . This is still below the melting point of the melt wire in the filament. This implies that there is substantial localized heating and complex phenomena occurring within the filament that neither the TC or models can record. Figure 3.54 shows the COMSOL (Section 6.1) results for the model simulating this test.

A lower temperature test was conducted and a melt wire was incorporated to investigate the temperature difference between the TC location in the shell versus the centerline of the filament. This test was performed on August 10, 2021. Like the previously presented melt wire test, this test utilized a melt wire in the filament (Figure 3.52 (a)). Unlike the previous melt wire test, the maximum temperature recorded by the TC in the shell was 1276 K . This is approximately half of the melting point of the melt wire. The melt wire in the filament melted at this recorded temperature level. The temperature data for this run is shown in Figure 3.55 and adheres to the standard TC placement. Figure 3.56 shows the power supply data for this run. Finally, Figure 3.57 shows the post-test melted melt wire. This run used an alumina crucible and a MFA sand filament. Note the stability of the filament heater at lower temperature levels.

The melted melt wire at the lower recorded temperature level calls into question the accuracy of the TC reading. At this point in testing, there were two competing ideas: the TC reading was inaccurate or there



Figure 3.50: Unused and not melted Pt-Ir melt wire.

Table 3.1: Composition of melt wire using EDXS.

Element Number	Element Symbol	Element Name	Atomic Conc. [%]	Weight Conc. [%]
78	Pt	Platinum	45.07	49.69
77	Ir	Iridium	36.77	39.94
44	Ru	Ruthenium	18.16	10.37

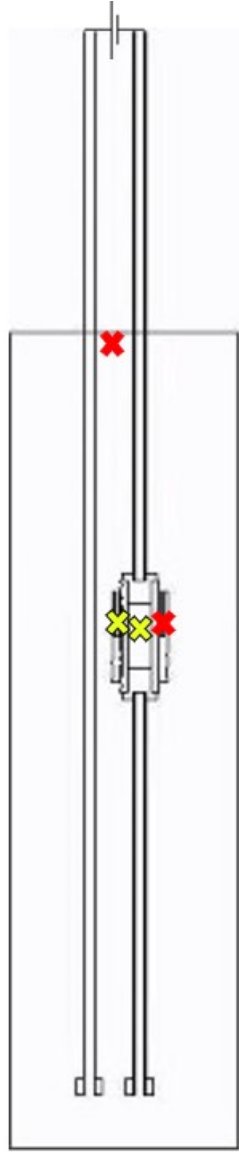


Figure 3.51: Schematic of potential melt wire and TC placements.

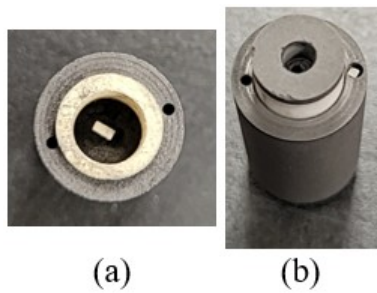


Figure 3.52: Image of potential melt wire and TC placements. (a) in filament. (b) in TC slot.



Figure 3.53: July 28, 2021 melted Pt-Ir melt wire.

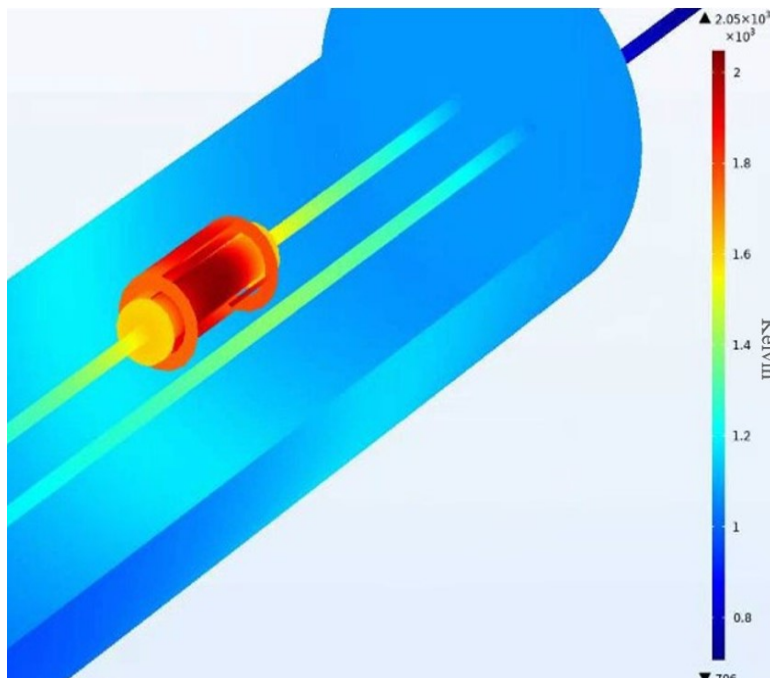


Figure 3.54: 1 kW model results for melt wire test.

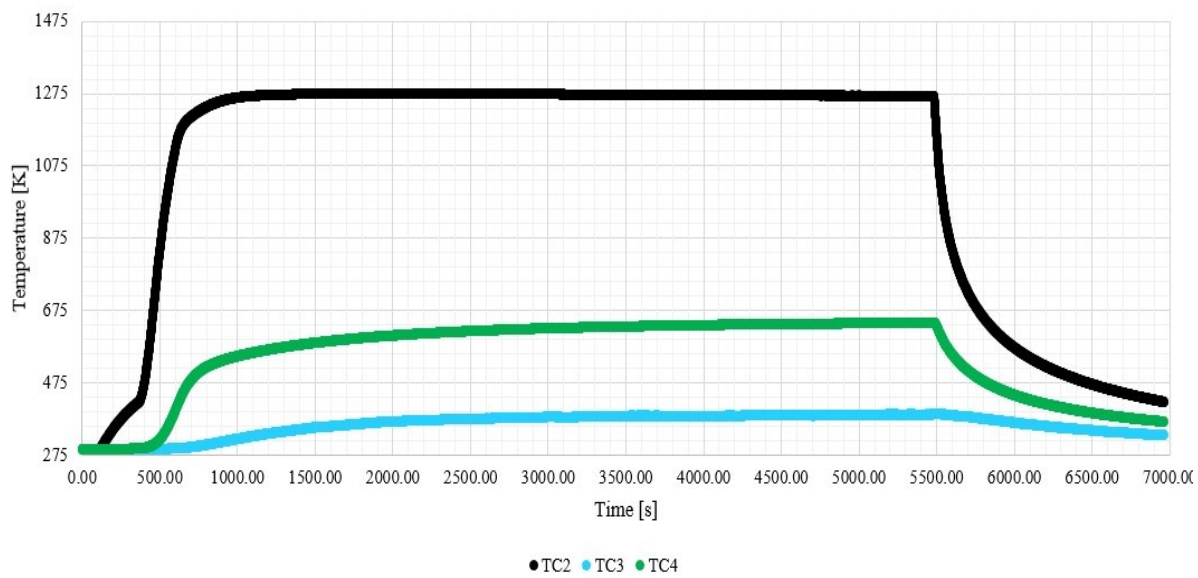


Figure 3.55: August 10, 2021 TC data.

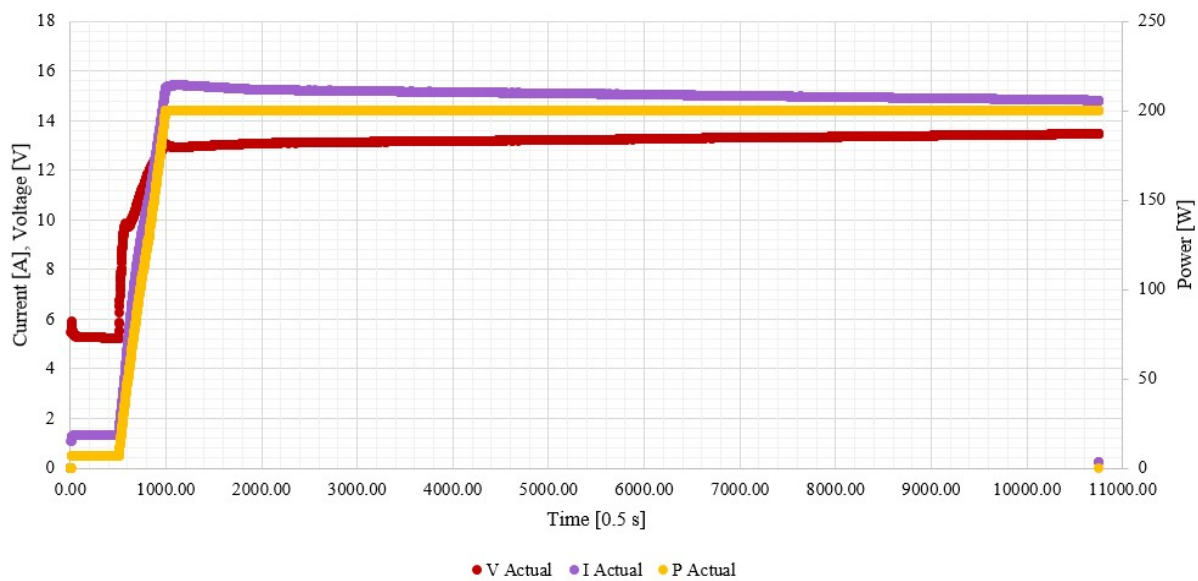


Figure 3.56: August 10, 2021 power supply data.



Figure 3.57: August 10, 2021 melted Pt-Ir melt wire.

was substantial localized heating in the filament. To investigate the validity of the TC readings, a nearly identical test to the August 10, 2021 test was conducted. On August 13, 2021 a similar 200 W run was conducted. This run produced a maximum TC reading of 1254 K. This test also used an alumina crucible, standard TC placements, and an MFA sand filament. However, the melt wire for this run was placed in the unused TC slot (Figure 3.52 (b)). The melt wire did not melt in this location. The temperature data for this run is shown in Figure 3.58 and adheres to the standard TC placement. Figure 3.59 shows the power supply data for this run. Finally, Figure 3.60 shows the post-test not melted melt wire.

The final test that used a melt wire was the aforementioned 350 W/minute 1838 W test on August 17, 2021. This melt wire was placed in the filament and melted. The temperature data for this run was shown in Figure 3.47 and the power supply log was shown in Figure 3.48. The melted melt wire can be seen in Figure 3.61.

The melt wires that were used melted at a reported 2550 K [22]. The wires were seen to melt whenever the melt wire was placed in the filament, regardless of what the shell TC recorded. The melt wire did not melt when it was equidistant from the centerline with the TC in the shell while the recorded temperature was below the wire's melting point.

3.4 In-Pile INSET Deployment for NTP Experiments

INSET was designed to be used for in-pile testing. The in-pile testing that has been completed at the time of writing this document has been performed at the OSURR. The following sections will present the in-pile deployment of INSET.

Prior to the discussion of the in-pile research conducted, it is necessary to present the interfacing methods between INSET and the OSURR. A "basket" was fabricated to lower INSET via overhead crane into the 9.5 in. vertical dry tube. Once lowered into the dry tube, the dry tube with INSET inside, would be moved into position next to the reactor core. The basket was made from flame-retardant garolite G-10/FR4 from McMaster-Carr. This G-10 material is suitable for high temperature and nuclear environments while being easily machined and structurally strong. An image showing uncut sheets and the machined pieces is in Figure 3.62.

The basket was formed by using 6061 aluminum to hold the G-10 together. Aluminum all-thread rod was used in conjunction with aluminum nuts to link the G-10 and help restrain INSET. The nuts offer enough strength to support the weight of the aluminum body of INSET when lifting the experiment into the dry tube. An image of the aluminum rod and G-10 coupling can be seen in Figure 3.63. INSET was then lowered into the basket. An image of INSET in the basket frame is shown in Figure 3.64.

To couple the basket to the overhead crane, a stainless steel eyebolt was used. This eyebolt was bolted to an aluminum plate. The aluminum plate served to tie the all-thread rod together, house the eyebolt, and offer a source for strain relief on cables connected to INSET. The plate was machined from aluminum stock using a mill press and band saw. The aluminum plate was bolted to the all-thread rods via aluminum nuts at the top of the basket. Figure 3.65 shows the coupling plate between INSET's basket and the overhead crane. The three small holes are for the all-thread rods. The larger holes are for cables to the experiment including the power cable, TC extensions, and the vacuum line. Figure 3.66 shows the assembly of INSET and the basket at OSURR. This basket used a different, but similar, aluminum plate to later assemblies. Thus image was taken from the November 2019 experiment at the OSURR.

TC extension wires were necessary to connect the TC data logger to the TCs in the experiment while INSET was lowered into the dry tube. The data logger was a significant distance away from the top of the reactor pool to enable the safe use and monitoring during reactor operation. The same applies to the power cable and vacuum line. The power cable must be long enough to deliver current from the supply, down into the dry tube, and to INSET. The vacuum tubing also must be sufficiently long to traverse this distance from the pump to INSET. In-line with the exhaust of the vacuum was an ICAMTM Alpha Beta Air Monitor.

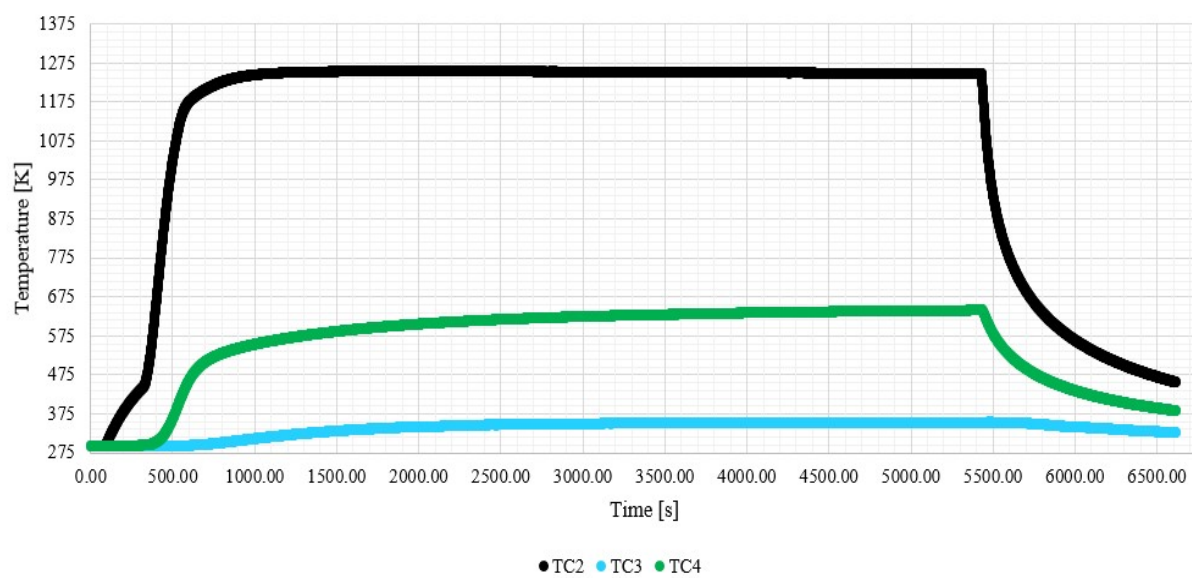


Figure 3.58: August 13, 2021 TC data.

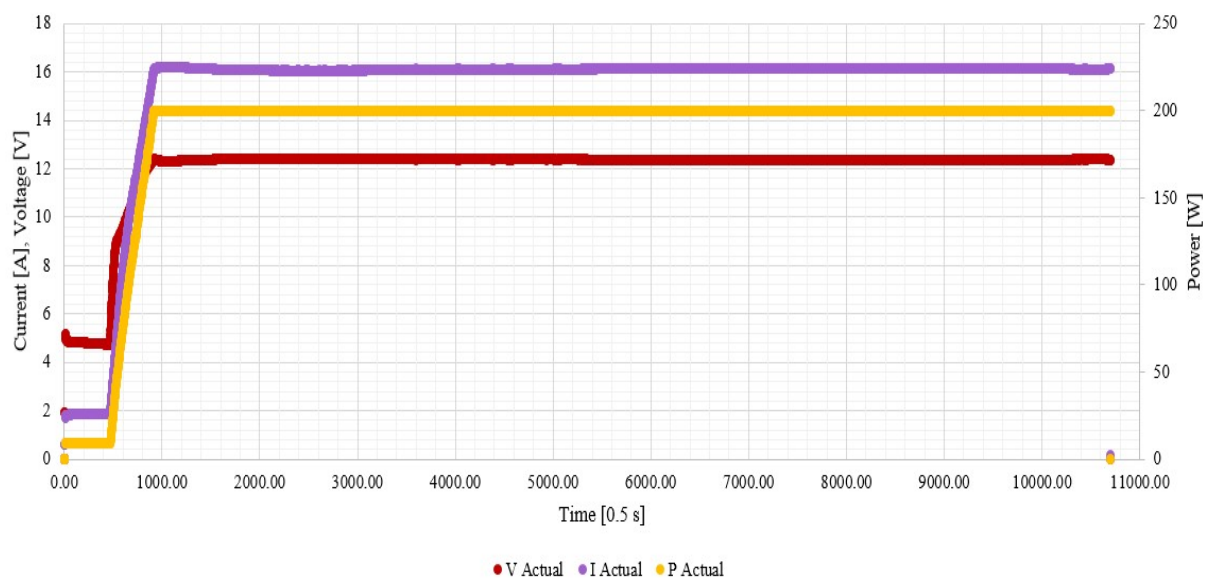


Figure 3.59: August 13, 2021 power supply data.



Figure 3.60: August 13, 2021 not melted Pt-Ir melt wire.



Figure 3.61: August 17, 2021 melted Pt-Ir melt wire.



Figure 3.62: G-10 used for in-pile basket.



Figure 3.63: Frame of in-pile basket.

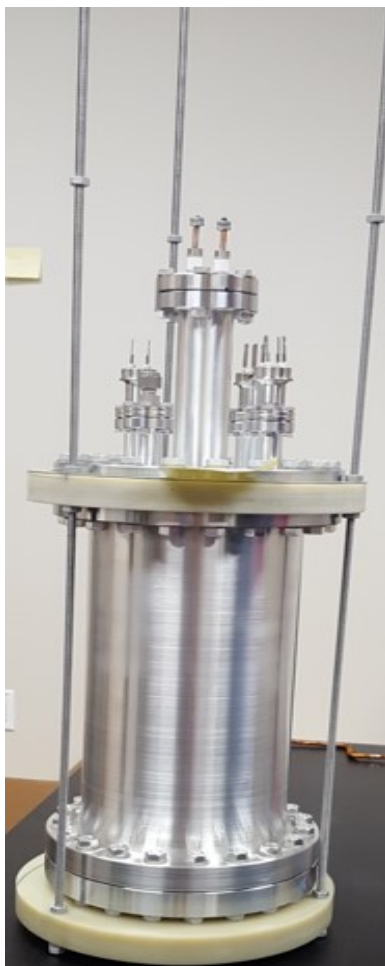


Figure 3.64: Frame of in-pile basket with INSET.



Figure 3.65: Aluminum coupling plate for in-pile basket.

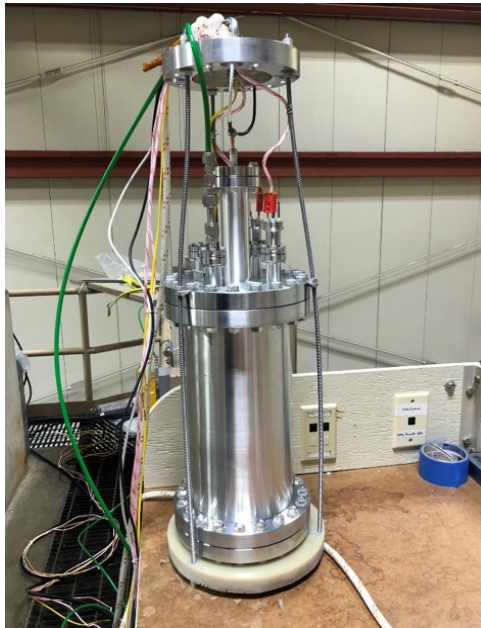


Figure 3.66: INSET and basket at OSURR in November 2019.

The ICAMTM was placed after the pump in the gas flow sequence. This monitor checks that the vacuum pump was not pulling radioactive particles from the reactor space and into the reactor bay. Prior to use, the ICAMTM was verified to be properly calibrated. A measurement of the background activity was recorded for baseline. The tubing connecting the vacuum pump to the ICAMTM was the same material used to connect INSET to the vacuum pump - nylon 11 tubing with an inner diameter of 0.180 in.. A Klein Flansche (KF) flange to CF Swagelok® was used to couple the pump to the tubing that fed into the ICAMTM.

3.4.1 November 2019

INSET was conceived to advance the capabilities of the field of experimental tests simulating NTP prototypical conditions. The first in-pile test using INSET was conducted in November of 2019 at the OSURR. The November 2019 run has been documented in reference [40]. To enable this document to serve as a complete piece of work describing INSET and the author’s contributions, text from reference [40] is included here. The quoted text has been extracted from an internal working version of reference [40] and has been adapted for formatting and readability, such as merging figure numbers with this document. Reference [40] has been published in *Nuclear Technology*. The author of this document is the primary author of the extracted text from reference [40]. The plot shown in Figure 3.67 was constructed by Dr. Richard Howard: a co-author of reference [40]. The acknowledgments stated in reference [40] include essential contributors to the INSET experiment.

As stated in reference [40], "The first specimens that were tested using INSET and OSURR were developed by graduate researchers with the University of Tennessee, Knoxville. The material specimens consisted of molybdenum formed by three different production methods in addition to a molybdenum-zirconium cermet. The specimens were cylindrical with a diameter of 3 mm and a thickness of 1 mm. This work specifically intends to investigate irradiation damage of cermet fuel candidates for use in NTP systems. To minimize the annealing in the specimens, the experiment maintained a temperature below 1070 K [41]."

"The first irradiation using INSET and the OSURR implemented two type C thermocouples and one type K thermocouple. The two type C thermocouples were both placed within the heater to redundantly measure the generated temperature. The type K thermocouple was used to monitor the external surface temperature of INSET to ensure the heat generated would not influence reactor operation (i.e. moderator boiling). INSET offers the freedom to be instrumented with up to six thermocouples. Each of the three passthroughs may be alternately instrumented if thermocouples are not the desired instrumentation." [40]

"At 450 kW the OSURR can generate a total neutron flux up to roughly $1.3 \times 10^{12} \text{ n/cm}^2/\text{s}$ at the ex-core 9.5 in. vertical dry tube. At this location, the maximum thermal neutron flux is $8.7 \times 10^{11} \text{ n/cm}^2/\text{s}$. This is the dry tube that was used in the experiment to house INSET. During the experiment, the reactor was operated at roughly 250 kW [23]. The reactor was operated for 5 hours to achieve a prototypical NTP fluence of roughly 10^{17} n/cm^2 ." [40]

"The performed experiment sought to test NTP candidate materials at relevant NTP temperature and fluence levels. The results from the experiment, as produced from data using two redundant type C thermocouples in the heater and one external type K thermocouple can be seen in Figure 3.67. The OSURR is a well understood and instrumented facility, enabling high confidence that prototypical fluence levels were achieved.

Figure 3.67 shows the temperature of three thermocouples during the irradiation of INSET. The blue curve ("Surface TC" or top curve) corresponds to the vertical axis on the right and the external type K thermocouple. The red curve ("Crucible TC2") corresponds to left vertical axis and one of the type C thermocouples in the heater. The black curve ("Crucible TC1") also corresponds to left vertical axis and the other type C thermocouple in the heater. The horizontal axis shows the time formatted as "hour:minute:second." The shaded region around 12:14 shows the electrical heating of INSET (12:02 – 12:18). For this experiment, the supplied electrical power was increased to around 40 W over roughly 5 minutes and held at 40 W for about 10 minutes. This generated the temperature values shown in Figure 3.67. The reactor was powered on at

8:07 and powered off at 13:07, resulting in a 5 *hour* irradiation.

The redundant thermocouples show a maximum temperature achieved around 730 *K*. These thermocouples are located a few millimeters from the centerline. The thermal model and benchtop testing show that there is a roughly 250 *K* difference between the centerline and the thermocouple location. Accounting for this difference, the peak temperature achieved by INSET during this experiment is around 980 *K*, which is safely below the noted annealing limit of 1070 *K*.

The type K thermocouple was implemented to ensure minimal temperature-related impacts on the reactor. The maximum temperature recorded by the external type K thermocouple was around 330 *K*, which is well below the boiling point of the moderator.

It is suspected that the thermocouple-recorded temperatures began to rise with the reactor's startup because of radiation induced heating effects. The neutron and gamma heating of the thermocouples will need to be further explored to be well-quantified. Benchtop testing, thermal models, and the distinct change in the shape of the curves when the electrical heating is applied offer evidence that the electrical heating is still generating heater temperatures around 980 *K*.

It is also suspected that the discontinuity seen in Crucible TC2 around 12:28 is the result of thermal expansion effects. This jump discontinuity is an immediate 70 *K* spike followed by 4 *minutes* of continually declining temperature readings until the trend is resumed at 419 *K*. During this cooling period, it is likely that components shift under thermally induced stresses and deformations. It is possible that the thermocouple came into contact with the internal wall of the crucible during the cooling period. This discontinuity does not warrant substantial concern as it is not seen in Crucible TC1 and since the cooling trend resumes after a short time." [40]

This iteration of INSET utilized the copper circuit and larger plenum size as shown in Figure 3.10 (a). The power supply used for this test was a Veeco power supply, not the Elektro-Automatik power machine.

The results of this test were evaluated prior to the discoveries presented in Section 3.3.7. As such, the observed temperature discrepancy between the TC and the centerline was not considered for this run. The 250 *K* difference claimed between the centerline and TC is now known to not be accurate. This number was obtained from an attempt to force the thermal models to reflect the experimental results. The models were adjusted so that the temperature difference between the TC and filament reflected observations from early and preliminary melt wire tests. Such melt wire tests were later expanded upon and further investigated by the work in Section 3.3.7. Once it was determined that there was substantial localized heating in the filament via physical effects that standard thermal models did not predict, the models were compared to the observed temperature levels at locations other than the filament. These models agree well with the TC readings and will be discussed more later. The current thermal models suggest that there is roughly a 10 *K* difference at a 40 *W* power level. However, following the tests shown in Section 3.3.7, this difference is not accurate either. The thermal models fail to capture the intense localized heating discussed in the *Melt Wire Discussion* section (3.3.7).

The irradiated and heated samples anneal any induced damage around 1070 *K* [41]. Given that these samples were placed in the filament region and that the shell TCs recorded a maximum temperature around 730 *K*, it is likely that the samples were heated beyond their annealing temperature. The researcher who developed the samples was unable to detect any damage to the samples following post-irradiation examination. This is now thought to be caused by the elevated localized temperatures in the filament that were unable to be observed via TCs. The recently uncovered and unknown, but large, discrepancy between the TC and centerline resulted in a null result when testing the samples. One success from this experiment is that INSET has been successfully demonstrated to reach elevated temperatures in a reactor environment. The filament may not serve as a viable test location for samples since its temperature cannot be accurately monitored at this point.

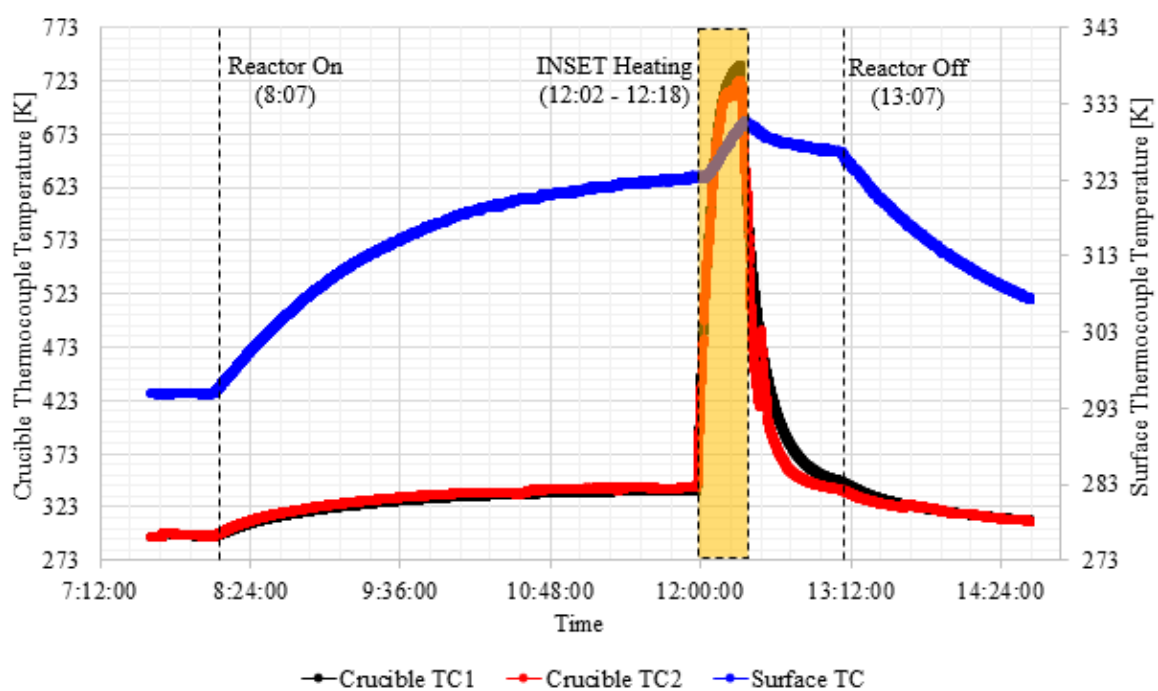


Figure 3.67: INSET November 2019 thermocouple data [40].

3.4.2 March 2021

The next in-pile deployment of INSET took place on March 10, 2021. The significant delay between in-pile tests was caused by the COVID-19 pandemic. INSET was tested using the molybdenum circuit design with the smaller plenum shown in Figure 3.10 (b). This test was intended to demonstrate the performance of INSET at power levels above 40 W in-pile. The power supply used for this test was a Veeco power supply, not the Elektro-Automatik supply. During the test, the power supply offered fluctuating levels of power, current, and voltage. This behavior was not intended, and is further discussed in Section 3.3. The maximum observed power level was around 850 W, which occurred for a brief moment while the current was being manually decreased. During the test, the power was increased to 400 W and held for around 7 minutes. The power was then stepped up to roughly 600 W for about 8 minutes. The supply began to fluctuate erratically after this point and current, and thus power, was decreased. This lowering of current immediately produced a brief spike in power. It is suspected that this spike is a result of internal power supply logic. When the device was current limited at 25 A, it is speculated that the supply restricts voltage and power to not exceed the 25 A maximum. However, once the current is no longer at its limit (i.e. while decreasing the current), this restriction may be removed from the power and voltage. This is speculation in an attempt to explain what caused the sudden power spike immediately following lowering the current level.

The step up to 400 W and subsequently to 600 W produced the temperature data shown in Figure 3.68. This figure shows the TC data for the duration of the reactor operation following the restart, which will be discussed later. The surface type K TC data is unavailable for this test. During the installation of INSET into the dry tube, the type K extension wire was pinched and damaged. This produced nonsensical surface temperature data ranging from 256 K to 303 K. Three type C TCs were used internally. Two of these type C TCs were each slotted into the TC slots in the heater shell. The other type C TC was located between the top layers of insulation and the multi-purpose flange. The TCs in the shell are represented by the red and blue curves in Figure 3.68. These curves correspond to the right axis. The difference in observed temperature values between the shell TCs comes from the asymmetry of the design. The axial centerline of the heater does not coincide with the axial centerline of INSET. The heater is more near one internal wall of molybdenum foil insulation, rather than being centered. This results in a more efficient exchange of thermal energy on one side of the plenum. The wall near the heater can reflect thermal energy back to the heater more effectively. The TC in the shell near this wall shows higher recorded temperatures (blue curve). The green curve is the data from the type C in the upper plenum region and corresponds to the right axis. The black curve shows the reactor power and is associated with the left axis. This test demonstrated that INSET operates and behaves the same in-pile and out-of-pile. Benchtop tests are less expensive, easier to perform, and are not associated with an activation risk.

INSET was exposed to a fluence of 1.42×10^{16} neutrons/cm² during its time in the dry tube test position. This fluence was achieved from the reactor power profile shown in Figure 3.69. The reactor power was intended to be held at 450 kW for the duration of the day. However, around 10:20 a.m., the reactor power was reduced to 50 kW for 30 minutes before the reactor was shut down. The power was reduced as a result of the ICAMTM measuring an increased count in β particles. The ICAMTM monitoring system measured a steady increase of β particles, eventually tripping the default alarm on the monitor. The alarm was set to 100 cps, where cps is "counts per second." The reactor was shut down for 2 hours so the reactor staff had time to assess the situation and evaluate the risk of proceeding with restarting the test. It was concluded that the elevated presence of effluent β particles were coming from a known modification to the reactor. This modification led to an increased amount of argon in a peripheral system to the reactor. The argon was activating and decaying via β particle emission. The apparent increased level of β particles was deemed to be safe. The reactor staff restarted the reactor around 12:20 p.m. and brought the reactor up to 450 kW to continue the irradiation. During the restarted portion, INSET was heated using DC power as shown in Figure 3.68.

The March 10, 2021 in-pile experiment utilized an alumina crucible. This material melts around 2000 K. Alumina has been observed to melt at TC temperatures nearly identical to those observed by the TCs used in this irradiation experiment (Figure 3.17). Prior to any post-irradiation examination, it is suspected that

the power supply fluctuations and the absence of steady-state in the TC data may be caused by the material deterioration of the ceramic crucible. This has been observed in both out-of-pile and in-pile tests.

In addition to the March 10, 2021 irradiation serving as a test to evaluate the in-pile performance of INSET at elevated power levels, INSET also served as the vessel to irradiate flow sensors. A pair of flow meters were mounted to the external surface of the multi-purpose flange. This configuration is shown in Figure 3.70. This CAD image was made by Dan Floyd, who also designed and built the flow meter irradiation test.

The flow meter test was unable to be conducted due to a failure in an instrument. Following the removal of INSET from the reactor after about one week, it was observed that a flow meter broke. It is unclear if the strength of the plastic failed due to the irradiation or mechanical stress during loading.

3.4.3 May 2021

The next irradiation occurred on May 19, 2021. It was another instrumentation irradiation, but incorporated INSET heating. This test sought to investigate the degradation of pressure sensors and a resistance temperature detector (RTD) at elevated temperatures in a radiation field. INSET was configured with an alumina crucible and a strand GFA filament. To evaluate the performance of instrumentation, helium was passed through INSET via aluminum tubing, heated, and routed up to the RTD followed by the pressure sensors. To accommodate the aluminum tubing, the inner diameter of the heated plenum region needed to be increased. The inner diameter for this test was increased to 4.5 *in.*. Four layers of GFA felt insulation and one molybdenum foil was used to contain the thermal energy in each direction. The researcher testing the instrumentation set the testing parameters of 100°C (373 K) for 15 *minutes* at the RTD. A CAD image of the internal INSET plenum is shown in Figure 3.72. This experiment utilized three type K thermocouples. One TC was used to monitor the external surface of INSET. One TC was slotted into the heater in the standard TC slot. The last TC was placed near the gas loop to monitor gas tubing temperature. The red "X"s in Figure 3.72 show the locations of the two internal type K TCs. The aluminum tubing to carry the helium gas is shown in blue. The temperature of the aluminum tubing was monitored to ensure the experiment did not generate temperature levels that would compromise the structural integrity of the tubing. This was necessary to prevent pressurizing the plenum region with helium in the event of a leak due to compromised tubing. Upstream flow meters were also used, but redundancy was practiced to ensure safety. A thermal model using COMSOL was built around this CAD file. The model suggests that a power level around 100 W is necessary to satisfy the desired testing conditions of 373 K at the RTD with helium flow rates of 13 *ft*³/*hour*.

The location of the RTD can be seen in Figure 3.73 (a) inside the red box at the top of the apparatus. The pressure transducers can also be seen mounted to the top of the multi-purpose flange. Figure 3.73 (b) shows the internal gas tubing, real TC placements, and the heater system.

The Veeco DC power supply was used for this irradiation experiment. The electrical power was increased to 100 W over 5 *minutes*. 100 W was held for 50 *minutes*. This generated satisfactory temperature levels at the RTD. The OSURR was operated at 450 *kW* for 7 *hours* continuously to produce a fluence of 10¹⁷ *neutrons/cm*². There were no β particle alarms tripped during this irradiation. The TC and RTD data for this run is shown in Figure 3.74. The black curve (TC2) represents the TC in the heater shell. The green curve (TC1) corresponds to the TC reading at the gas tubing. The blue curve (TC4) recorded the surface temperature of INSET to prevent influencing the reactor moderator. The red curve is the temperature recorded by the RTD that was being investigated. As shown by the red curve, the RTD was held around 373 K for 15 *minutes*, successfully accomplishing the testing goals. The influence of the gas flow on the temperature can be seen by the dip around 500 s (13:03). The gas flow introduced convection through the tubing and removed thermal energy from the heated plenum region. A similar effect is seen after INSET has ceased heating, but before the system cooled to ambient conditions. Here, the temperature slightly increases as the gas flow stops. The convection is no longer present to remove the residual thermal energy in the system in addition to the gamma heating generated by the reactor. This deployment of INSET demonstrated the flexibility of the system to accept gas flow with a larger plenum region at lower temperature levels. Dan

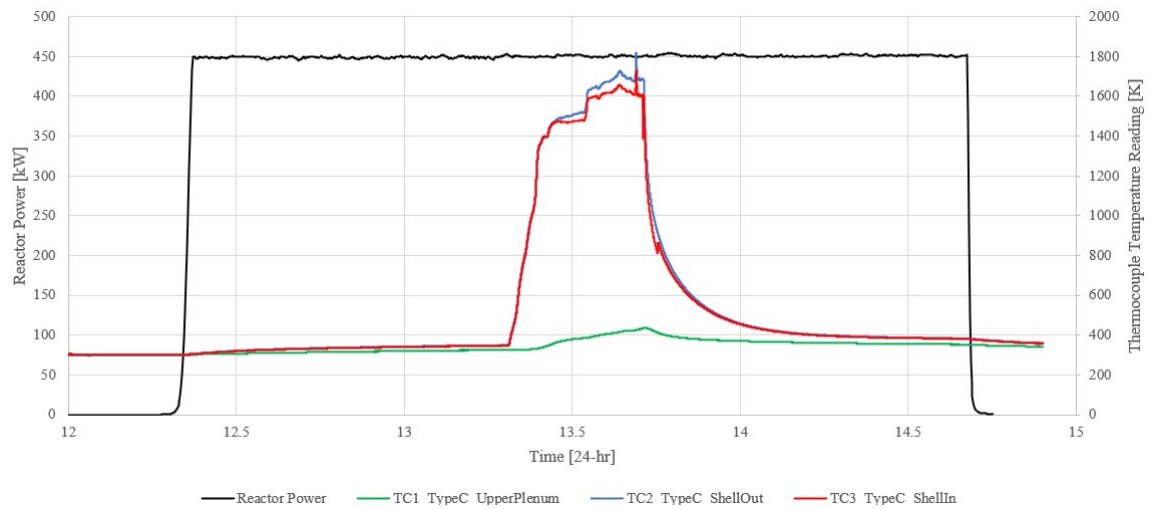


Figure 3.68: INSET March 2021 thermocouple and reactor power data.

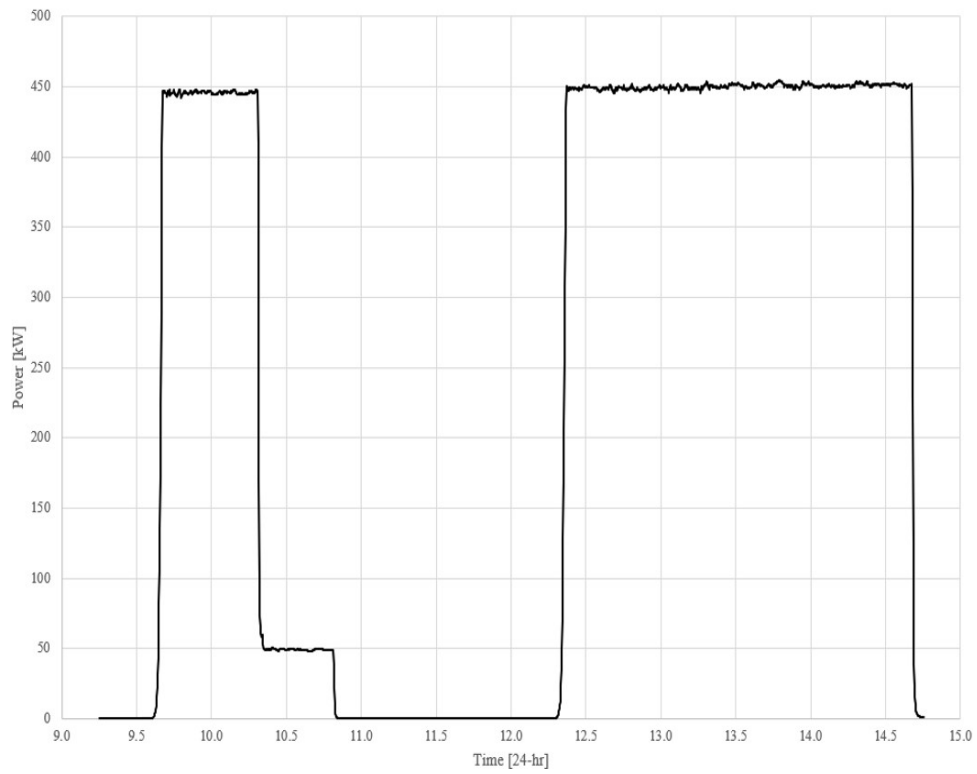


Figure 3.69: INSET March 2021 reactor power profile.

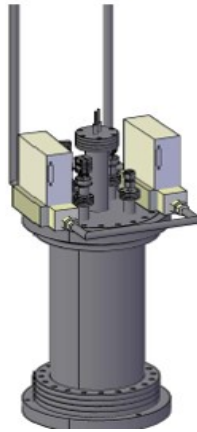


Figure 3.70: CAD of flow meters mounted on INSET.



Figure 3.71: Broken flow meter.

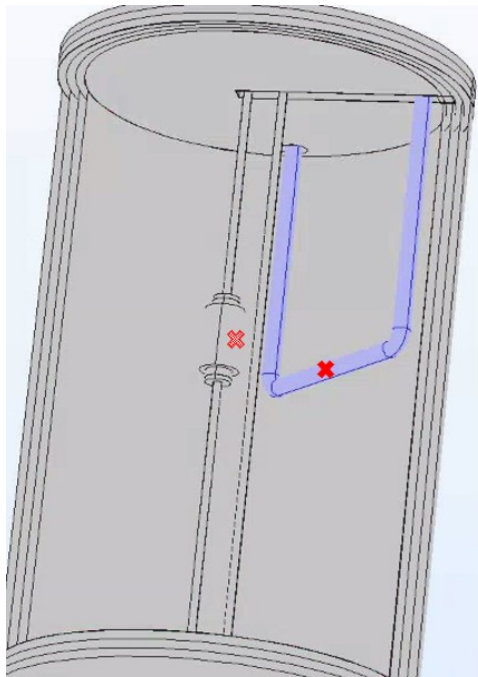


Figure 3.72: May 2021 CAD and TC placement.



Figure 3.73: May 2021 INSET image. (a) external. (b) internal.

Floyd was the researcher who sought to test the RTD and pressure sensor. Additional information pertaining to the instrumentation results of the experiment will be published by Dan Floyd.

3.5 Experimental Uncertainty Quantification

The experimental data consists of thermocouple readings. The thermocouple itself, and the TC reader, each have values of uncertainty associated with them. The TCs used were manufactured by Omega. The TC data logger was manufactured by Grant Instruments. The individual errors associated with each source of error is shown in Table 3.2. These are the reported maximum error values provided by the manufacturers for the temperature ranges seen in the experiments.

Since the error sources are independent quantities, the errors will add in quadrature. Summing in quadrature to quantify the error associated with a reading from two sources is described in Equation 3.5 [42].

$$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (3.5)$$

where:

σ = uncertainty

u = derived quantity

x = error source #1

y = error source #2

Translating the general form of Equation 3.5 into terms relevant to temperature measurements yields Equation 3.6.

$$\sigma_{total} = \sqrt{\sigma_{TC}^2 + \sigma_{SQ}^2} \quad (3.6)$$

where:

$total$ = net reading

TC = from thermocouple

SQ = from SQ2020 data logger

The error associated with a reading using a type C TC is quantified in Equation 3.7.

$$\sigma_{typeC} = \sqrt{1\%^2 + 0.1\%^2} = 1.005\% \quad (3.7)$$

The error associated with a reading using a type K TC is quantified in Equation 3.8.

$$\sigma_{typeK} = \sqrt{0.75\%^2 + 0.05\%^2} = 0.7517\% \quad (3.8)$$

Every TC temperature plot presented in this document abides by the error values calculated in either Equation 3.7 or Equation 3.8. Error bars have not been included in the plots simply due to scale. For a measurement around 1175 K, the error bar would be about ± 12 K. This size error bar is invisible in plots containing temperature information ranging from 275 K to 1175 K. To demonstrate this omission, Figure 3.75 is shown. Note the scale of the axes. The TC data is shown by the black line. The density of data points forces the error bars to blend together, but are shown in gray.

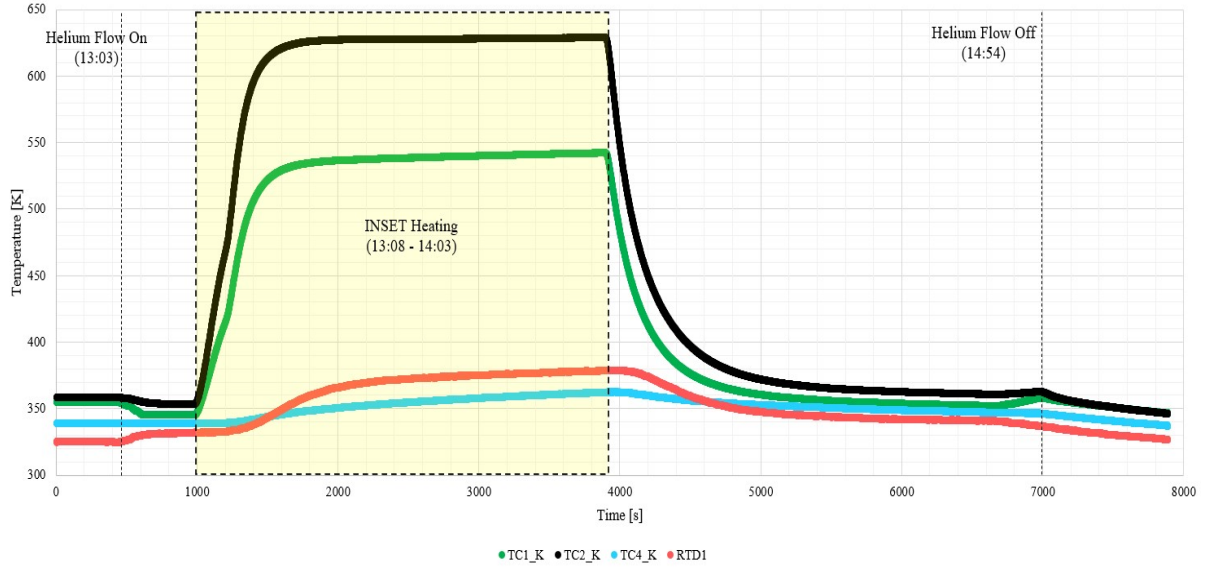


Figure 3.74: May 19, 2021 TC and RTD data.

Table 3.2: Experimental error values.

Source	Reported Error [%]	Reference
Type C TC	± 1	[25]
Type K TC	± 0.75	[26]
SQ2020 Logger - Type C	± 0.1	[27]
SQ2020 Logger - Type K	± 0.05	[27]

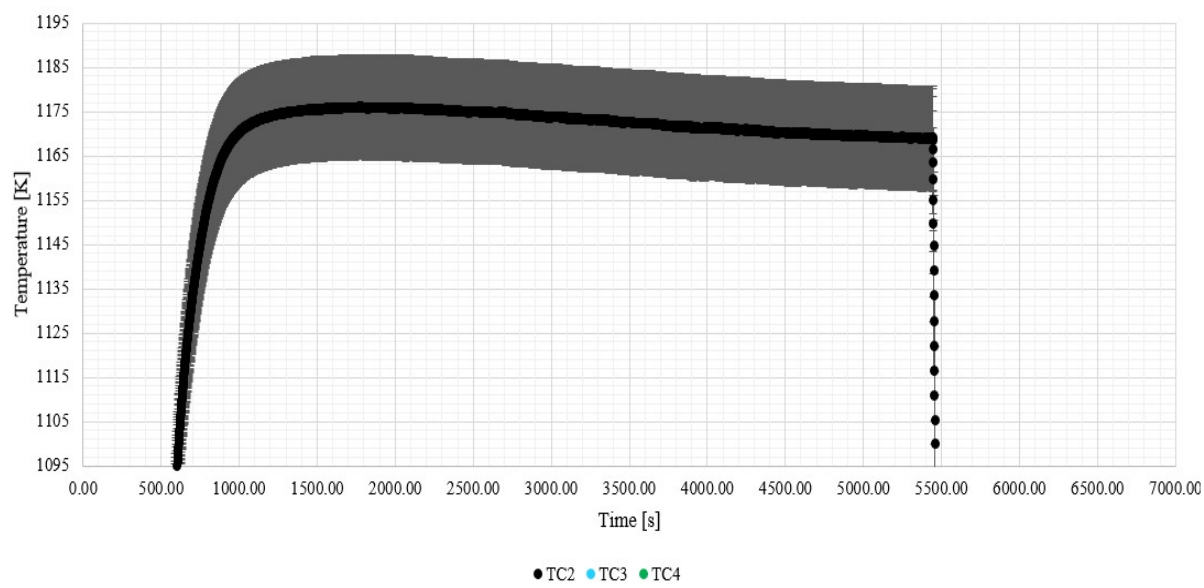


Figure 3.75: Demonstration of error bars on TC plot.

4 INSET Discussion

The goal of replicating the 2300 K reported from the OUTSET-1 tests proved to be a significant challenge. INSET was not able to reach these temperatures. The only difference between the current INSET design and the OUTSET-1 tests is the scale. INSET's heated plenum surface area is roughly six times larger than OUTSET-1's. The success of using a compliant, not mechanically fixed, filament heater appears to scale poorly. To reach this conclusion a number of variables were systematically isolated and tested.

The ceramic that makes up the crucible was investigated. Zirconia, alumina, hafnia, high purity magnesia, and high density magnesia were all tested. None of the tested ceramics were successful. The ceramics that did not interact with the carbon in the filament or did not melt all failed in the same manner. Electrical fluctuations observed through the power supply behavior were the fault that appeared in every high temperature ceramic test.

It was suspected that the filament that cannot be fixed to the heater plugs may have been falling out of contact with the plugs - resulting in rapid circuit degradation. Two form factors of heater plugs were tested. Again, the electrical fluctuations were observed in tests using both forms. The mechanical interactions between these plugs and the rest of the circuit was also investigated. Carbon paste and Grafoil - a carbon foil gasket - were used to secure the plugs to the circuit. This did not impact the outcome.

The presence of the instrumented graphite shell was also evaluated. The electrical fluctuations were observed in the case with the shell as well as without the shell. The presence of the shell does not influence the occurrence of electrical fluctuations.

The consistency and type of graphite filament was tested. A strand of GFA felt resulted in similar results as the MFA sand and the combination rebar. These variations in the filament did not prevent the electrical fluctuations and failure to reach recorded temperatures of 2300 K .

Melt wires were introduced to challenge or verify the temperature levels observed by the TCs. These melt wires melt around 2550 K . Whenever a melt wire was placed in the filament, it melted. It did not matter if the TC recorded a maximum temperature of 1875 K or 1276 K , the filament melt wire melted. If a melt wire was placed in a position mimicked by the shell TC, it did not melt at a TC recorded temperature level of 1254 K . This implies that there is a substantial and unknown temperature difference between the filament and the shell - a difference of, at least about, 1300 K . The melt wire in the shell with the TC agrees with the TC data. These also agree with the thermal models. The models predict a maximum temperature difference between the TC and filament of 150 K , for a case using 1000 W of power. The models, TC data, and shell melt wire are in agreement. The filament melt wire is the dissenting observation. Such complications were not reported in the OUTSET-1 tests.

The electrical fluctuations observed in every iteration of testing are preventing higher temperatures from being obtained. The electrical breakdown of the circuit driving the resistive heating prevents additional thermal energy from being generated in the heater. These fluctuations also remove the controllability of the testbed. The fluctuations have appeared at various temperature, voltage, current, and power settings and at different times into the heating. Lower temperature levels tend to produce fluctuations less often, but it still can occur. The substantial localized heating in the filament in addition to the unsecured and compliant filament may be inducing the fluctuations at this scale.

INSET has demonstrated moderate repeatable success at temperature levels below 1100 K outside of the filament. This temperature level can still serve as a viable and useful testbed for NTP interests. This temperature will be useful to test a significant amount of instrumentation and materials that are not located within the NTR reactor core. INSET can also generate this level of temperature in-pile. It has been reported that a proposed NTP flight demonstration spacecraft was modeled to evaluate the thermal profile of the system. This work is presented in Reference [43]. The high power NTP demonstration modeled for deep-space missions produced a maximum spacecraft temperature of 1546 K at engine shutdown. The majority of the

spacecraft maintains a temperature level below 1100 K . Locations of interest on the periphery of the engine also maintain temperatures below 1100 K [43]. According to Johnson et al. ([43]), a significant amount of an NTP flight demonstration spacecraft will experience temperature levels that are within the temperature range of INSET's capabilities.

However, the inability to perfectly monitor, control, model, characterize, or consistently repeat the temperatures seen within INSET from test to test warrants a redesign. It has been shown that a compliant filament heater design is not successful at the scale of INSET. It is recommended that a solid, rigid, fixed heating element be pursued. NASA has seen success with a DC resistively heated, high temperature, hydrogen compatible heating element in the past. Section 4.1 will present this design.

4.1 Project POODLE

A DC resistively heated, high temperature, hydrogen compatible heating element was developed from 1965 to 1967 as a part of the Atomic Energy Commission and NASA joint Radioisotope Propulsion Technology Program (POODLE) [44]. Task V under this program called for the experimental simulation of a radioisotope heat source. As stated by reference [44], "This task was concerned with techniques for simulating radioisotope heat source characteristics using electrical resistance heaters." Although this project was motivated by radioisotope propulsion, the heating element that was developed can accomplish goals similar to those of INSET.

The project saw early success with a graphite heater. Reference [44] states, "The test thruster utilized a graphite heater which was operated at 2000°C for *72 hours* with hydrogen flow." Flowing hydrogen for an extended period over a graphite heater at 2273 K is reminiscent of the NTP environment. The primary difference between this environment and an NTP environment is the rate of heating. NTP requires more rapid transients. Following the success of the hydrogen flow tests using a graphite heater, a new heater design was considered. For the new design, the POODLE team considered four materials: graphite, molybdenum, tantalum, and tungsten. Reference [44] offers additional insight into the material selection process. The material selected out of the aforementioned four was tungsten. "Tungsten was chosen as the heater material because of its high melting point (3395°C), favorable electrical and mechanical properties, low evaporation rate, and strength at high temperature. [44]" The previous graphite test was run for *72 hours*. The new heater was to be tested for *720 hours*. Graphite was not selected for this longer test due to its evaporation rate and affinity for hydrogen. For NTP experiments, *72 hours* of testing should be sufficient, but *720 hours* exceeds the necessary operation time. Again, POODLE was not concerned with NTP, the connection is made in this document due to testbed goal similarities.

Two tungsten heater designs were developed: cylindrical and helical. Each heater element design was approximately *2 in.* in diameter and *14 in.* in length. Either of these heating elements would spatially fit in the current INSET body. The POODLE Final Report provides extensive detail on material composition, fabrication, insulation, and instrumentation. Both the cylindrical and helical heaters demonstrated 2473 K for a continuous operation time of *720 hours* [44]. To monitor temperature, thermocouples and optical pyrometers were used. Analytical models were also used for validation. The models, TCs, and pyrometers were all in agreement. Schematics of the implemented heaters are shown in Figure 4.1. Figure 4.1 (a) shows the cylindrical heater. This heater element utilized two half-cylinders to generate resistive heating. Figure 4.1 (b) shows the helical heater.

Table 4.1 shows the experimental ("Exp.") and analytical ("Comp.") testing results from both the cylindrical and helical heater elements during the *720 hour* test.

To achieve the maximum prototypical temperatures in an NTP system, it is recommended that INSET be adapted to follow the success of POODLE. POODLE has demonstrated a well-instrumented, reliable, large-scale heater. The current iteration of INSET has not been able to generate high temperatures around 2500 K . Implementing a heater element similar to that used in POODLE may address the issues seen in INSET. It

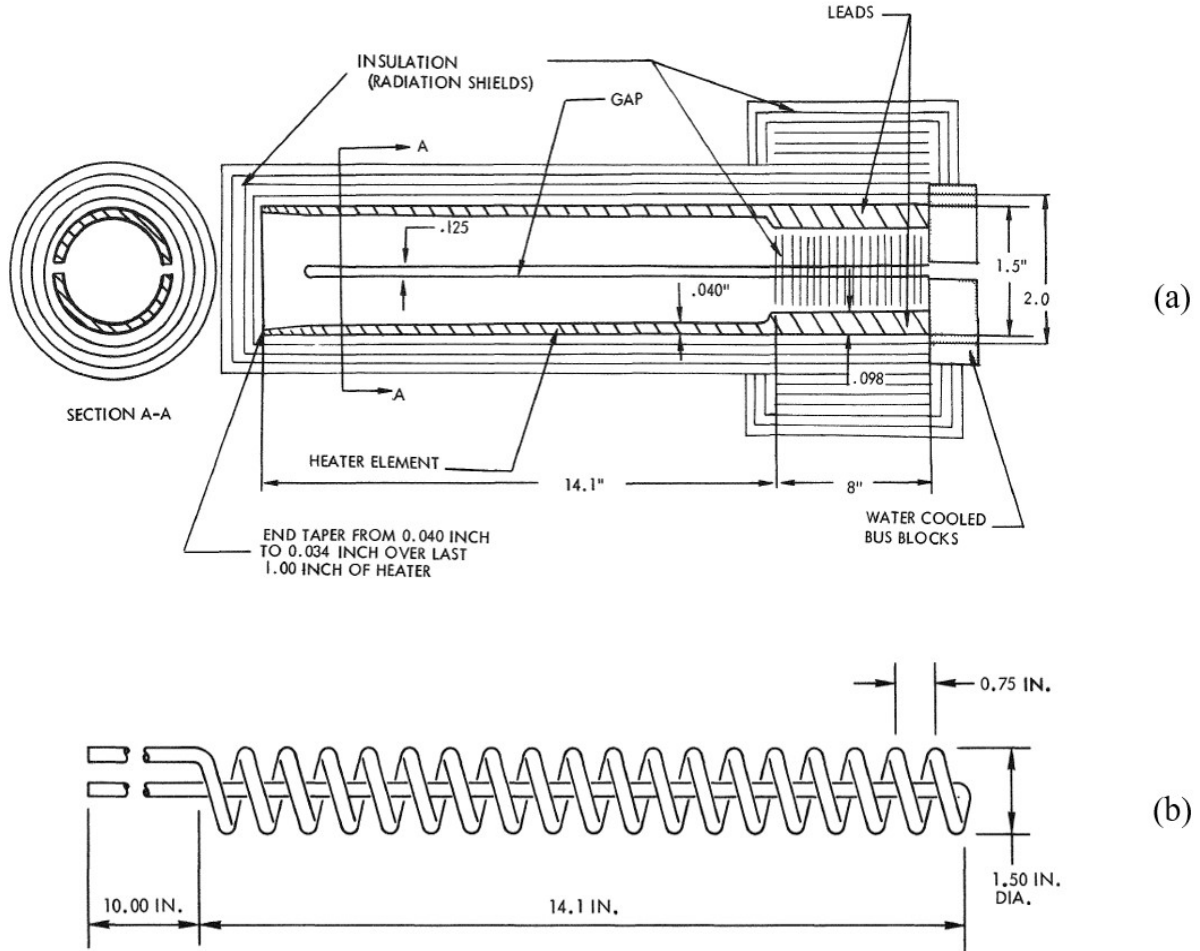


Figure 4.1: POODLE heater schematics. (a) cylindrical. (b) helical. [44]

Table 4.1: POODLE heater test result parameters [44].

Parameter	Cylindrical-Exp.	Cylindrical-Comp.	Helical-Exp.	Helical-Comp.
Voltage [V]	5.94	6.67	17.22	16.00
Current [A]	800	718	315	300
Resistance [Ω]	0.0074	0.0093	0.054	0.053
Power [W]	4750	4790	5424	4800
Max Temperature [K]	2473	2473	2473	2473

will also remove the substantial thermal gradient seen within INSET. In-pile testing of the POODLE designs have not been conducted. This is a logical next step towards an in-pile, high temperature, steady-state, hydrogen compatible testbed. To couple INSET with a POODLE heater element, a higher current vacuum power passthrough, a higher current and voltage limited DC power supply, and the actual heating element are needed. The vacuum power passthrough and DC power supply can be obtained and implemented easily. These components are available off-the-shelf. The most intensive stage of mating POODLE to INSET comes from the heater fabrication. Although, the fabrication methods are detailed in the POODLE final report, they are not trivial and may require some iterative work prior to success. If INSET is to simulate the full range of NTP temperature levels, in-pile, and in the presence of hydrogen flow, it is recommended that a POODLE heater element be replicated and coupled to INSET.

Despite, the inability to simulate the full range of NTP temperature levels, INSET has demonstrated moderate success at lower temperature levels. INSET has served as a successful testbed for modest temperature experiments as well as a successful validation tool for radiative heat transfer investigations.

5 Radiative Heat Transfer Introduction

All real objects above absolute zero (0 K) radiate energy under any condition at all times. This radiation is emitted from vibrations and electronic and molecular oscillations and transitions in the material. Net energy is transferred between bodies of different temperatures via electromagnetic (EM) waves. The emitted EM waves can transfer energy to another body; this is called absorption. This exchange of energy between bodies is called radiative energy transfer. When radiative energy transfer is driven by thermal effects, it is called radiative heat transfer (RHT) or thermal radiation heat transfer - the focus of the work presented in this document. A blackbody is an ideal object that emits the maximum amount of energy uniformly in all directions at every wavelength. A blackbody also perfectly absorbs all incident energy at all wavelengths. [45].

5.1 Background

In 1901 Max Planck developed the law describing the distribution of hemispherical emissive power, $E_{\lambda b}$. Hemispherical emissive power is the energy emitted by a black surface per unit time, per unit area, and per unit wavelength interval. The expression that was developed to describe this was verified experimentally and is shown in Equation 5.1 (Planck Law) [45].

$$E_{\lambda b} = \frac{2\pi hc_o^2}{n^2 \lambda^5 [e^{\frac{hc_o}{n k_B \lambda T}} - 1]} \quad (5.1)$$

where:

$E_{\lambda b}$ = hemispherical emissive power

h = Planck constant = $6.626 \times 10^{-34}\text{ Js}$ [45]

c_o = speed of light in vacuum = $2.998 \times 10^8 \frac{\text{m}}{\text{s}}$ [45]

n = refractive index

λ = wavelength

k_B = Boltzmann constant = $1.381 \times 10^{-23} \frac{\text{J}}{\text{K}}$ [45]

T = temperature

Prior to Planck's work, in the late 1880s, Joseph Stefan experimentally observed that emissive power was related to the fourth power of the absolute temperature of a radiating body. His student Eduard Boltzmann was able to derive the same relation by analyzing a Carnot cycle. Planck provided the energy per unit wavelength interval emitted by a blackbody. Stefan and Boltzmann developed the hemispherical *total* emissive power, E_b . The Stefan-Boltzmann law shown in Equation 5.2 describes the radiation for all wavelengths emitted into a vacuum (emitted blackbody energy flux) [45].

$$E_b = \int_0^\infty E_{\lambda b} d\lambda = \sigma T^4 \quad (5.2)$$

where:

E_b = blackbody hemispherical total emissive power

σ = Stefan-Boltzmann constant = $5.670 \times 10^{-8} \frac{W}{m^2 K^4}$ [45]

T = temperature

A common assumption in radiation heat transfer calculations is that surfaces are *diffuse-gray* [45]. *Diffuse* denotes that directional emissivity and absorptivity are independent of direction. This implies the emitted intensity is uniform over all directions, as it is for a blackbody. *Gray* signifies that spectral emissivity and absorptivity are independent of wavelength (but not necessarily temperature). Each surface temperature will yield emitted spectral radiation that is a fixed fraction of blackbody spectral radiation for any wavelength. As described by Siegel and Howell, "The diffuse-gray surface therefore absorbs a fixed fraction of incident radiation from any direction and at any wavelength. It emits radiation that is a fixed fraction of blackbody radiation for all directions and all wavelengths [45]." This assumption is common because it significantly simplifies the analysis, however, it may sacrifice accuracy. The directional-spectral and the hemispherical-total values of emissivity and absorptivity are all equal for a diffuse-gray surface since the directional and spectral dependencies are removed under the diffuse-gray assumption [45]. Removing the wavelength and directional dependence yields an expression with less variables, making it easier (and typically faster) to solve.

5.2 The Radiation View Factor

In a non-participating medium, (i.e. a medium that does not absorb, emit, or scatter thermal radiation) radiative heat transfer between surfaces is a function of the surface characteristics and the optical view exchanged between the surfaces [46]. The proportional quantity of thermal radiation that can be transmitted from an emitting surface to a target surface is called the view factor (also referred to as the configuration factor, shape factor, or form factor). The net radiative heat transferred in a given wavelength range between two diffuse surfaces with constant surface emissive powers is given by Equation 5.3 [46].

$$Q_{IJ} = \frac{(E_{I\lambda b} - E_{J\lambda b})d\lambda}{\frac{1-\epsilon_I}{\epsilon_I A_I} + \frac{1}{A_I F_{IJ}} + \frac{1-\epsilon_J}{\epsilon_J A_J}} \quad (5.3)$$

where:

Q_{IJ} = net heat exchanged

$E_{I\lambda b}$ = hemispherical emissive power of surface I

ϵ_I = surface emissivity of surface I

A_I = geometric area of surface I

F_{IJ} = view factor from surface I to surface J

The view factor, F_{IJ} , is defined as the fraction of energy leaving Surface I that is incident on Surface J. Equation 5.4 defines the view factor mathematically and its symbols are defined by Figure 5.1. [46].

$$A_I F_{IJ} = \int_{A_I} \int_{A_J} \frac{\cos(\theta_I) \cos(\theta_J)}{\pi r_{IJ}^2} dA_I dA_J \quad (5.4)$$

The thermal radiative energy exchanged between surfaces utilizes view factors through radiosity calculations. Radiosity is simply the energy fluence leaving a surface. The total energy fluence leaving a surface used in combination with how much of a surface is visible yields the energy transferred to the surface of interest. Radiosity is described by Equation 5.5 and visualized in Figure 5.2.

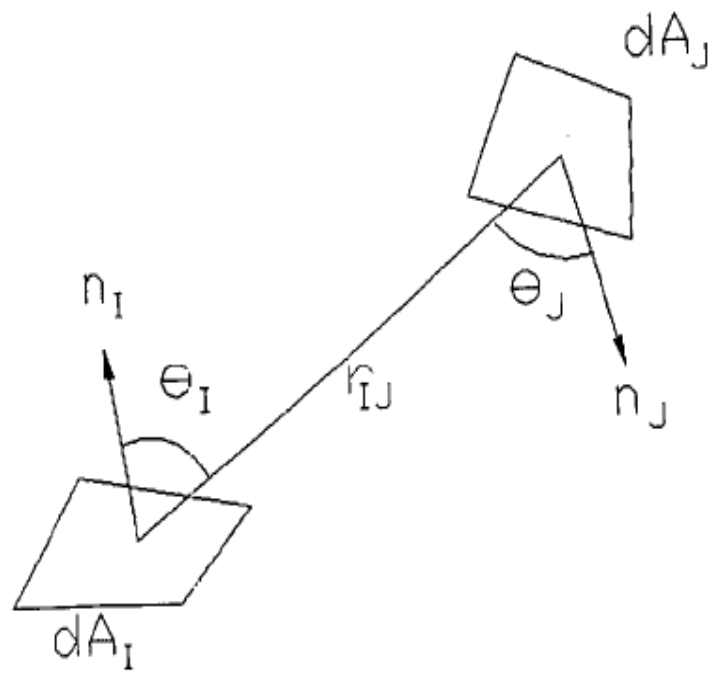


Figure 5.1: View factor nomenclature for Equation 5.4 [46].

$$J = \rho_d G + \epsilon E_b(T) \quad (5.5)$$

where:

J = radiosity

ρ_d = diffuse reflectivity

G = incoming radiative flux

ϵ = emissivity

E_b = blackbody hemispherical total emissive power

T = temperature

For some simple geometries, such as concentric cylinders, the view factor values have been analytically calculated and tabulated. However, for complex geometries, analytical solutions are not available [46]. This applies to most real applications. As such, there are a number of numerical techniques available to calculate the view factor values for more complicated geometries. The three presented here are: ray tracing, unit sphere projection, and hemi-cube projection.

5.2.1 Ray Tracing

Ray tracing traces the spatial path of a particle in a given environment. In the case of thermal radiation, the photon is the particle of interest. Each ray is traced to record which surface it strikes. If a ray leaves surface I and strikes surface J, that ray will contribute to F_{IJ} . Practical uses of ray tracing typically employ many particles, resulting in many paths. The rays may be absorbed, reflected, or transmitted along their paths.

5.2.2 Projection - Unit Sphere

All projection methods are based on work originally performed by Nusselt. The unit sphere method was developed for the field of photography to achieve improved lighting effects. As Cohen states, "For a finite area, the form-factor [or view factor] is equivalent to the fraction of the circle (which is the base of the hemisphere) covered by projecting the area onto the hemisphere and then orthographically down onto the circle [48]." This is the basis of the unit sphere method for determining view factors. A pictorial description of the unit sphere approach is shown in Figure 5.3 [48].

To practically compute the view factors, the unit sphere needs to be segmented into pixels along the surface of the sphere. Each pixel is projected down onto the base of the unit sphere such that each pixel has its own view factor. The area projected from the distant surface onto the unit sphere surface is approximated by the number of pixels encompassed by that projection. The view factor of the distant object can be determined from the encompassed pixels' view factors [48] [46].

An advantage of the unit sphere method is that for a fixed number of pixels, the view factor values can be pre-calculated from the center of the unit sphere to each pixel. This saves computational effort. However, the unit sphere has three fundamental disadvantages:

1. The natural curved lines of a sphere can lead to inaccuracies in the view factor of a surface of interest [46].
2. Aliasing is common since the partial covering of a pixel is not traditionally distinguished from a complete coverage, which can lead to errors [46]. See Figure 5.4 for a pictorial description of these errors [49].
3. There is no way to identify if a surface is being obstructed, which will result in an inaccurately lower view factor [46].

A different projection method was then developed to mitigate these disadvantages.

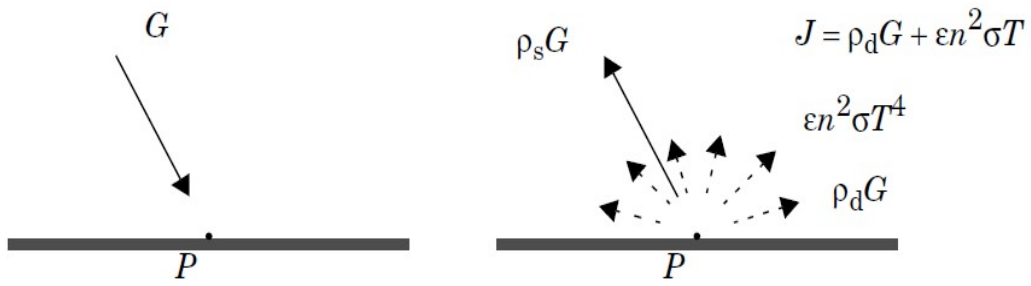


Figure 5.2: Radiosity diagram [47].

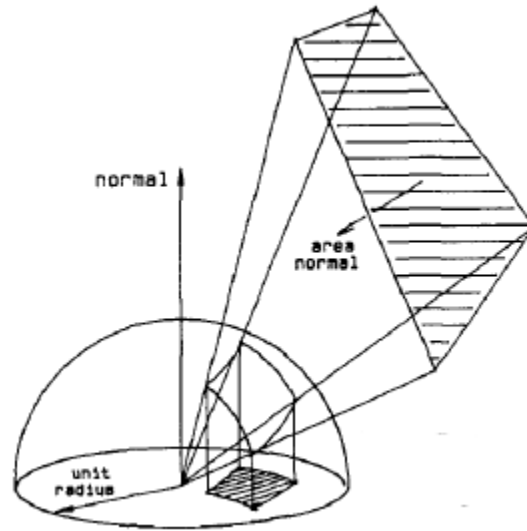


Figure 5.3: Unit sphere projection diagram [48].

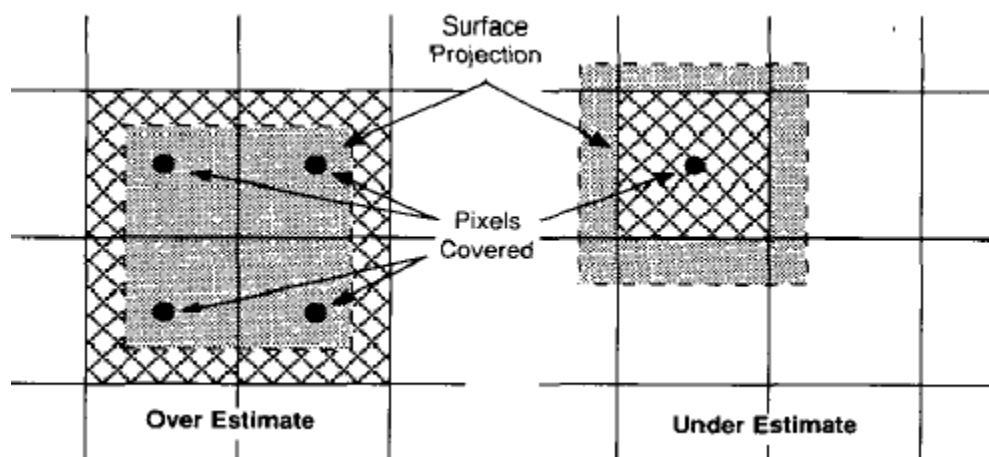


Figure 5.4: View factor aliasing over/under prediction [49].

5.2.3 Projection - Hemi-Cube

Cohen et al. ([48]) developed the hemispherical cube method in 1985 to avoid the curved lines of a unit sphere [46]. This is the first disadvantage listed in the Unit Sphere section (5.2.2). The hemi-cube method uses a similar approach to the unit sphere method, but uses a cube. Instead of a sphere, the element is encompassed by one half of a cube, shown in Figure 5.5 [46].

The hemi-cube circumvents the first disadvantage of the unit sphere (5.2.2), but the second and third disadvantage still apply. The evaluation of the radiation view factors is otherwise identical to that of the unit sphere method [46]. The hemi-cube method is more accurate than the unit sphere, but less accurate than the ray tracing method. However, the projection methods are typically less computationally expensive than the ray tracing approach [46].

5.3 State of Computational Thermal Radiation

Calculations of view factors for complex geometries remains a challenge for accurately solving computational radiative heat transfer problems. According to Emery, the ray tracing method probably represents the best numerical method for computing the view factor to the level of computational effort required [46]. Despite this, some of the leading heat transfer programs, such as ANSYS, have not been able to optimize the ray tracing method for usable software. ANSYS uses the hemi-cube method to solve view factors. The following statements, which are provided by the ANSYS online documentation, expand on the radiation heat transfer solution methods: "The energy exchange between two surfaces depends in part on their size, separation distance, and orientation. These parameters are accounted for by a geometric function called a view factor. The main assumption of the S2S [surface-to-surface] model is that any absorption, emission, or scattering of radiation can be ignored; therefore, only surface-to-surface radiation need be considered for analysis [50]." This S2S model assumes that all surfaces are gray and diffuse. This means that reflectivity is independent of the outgoing and incoming direction of the radiation. The emissivity and absorptivity of a gray surface are also independent on the wavelength of the radiation [50]. These assumptions have the potential to impact the results of the thermal analysis in a non-trivial way, especially when implementing highly scattering foils, such as molybdenum.

In 2018, COMSOL - a multiphysics program, released an update that incorporated the option to use ray tracing for radiation heat transfer in addition to its pre-existing projection method capabilities. COMSOL uses a z-buffering algorithm to address the obstruction disadvantage when using the hemi-cube method. COMSOL also allows the user to set wavelength dependent surface emissivity values [47]. Using the ray tracing view factor method and the spectral dependence of emissivity, the diffuse-gray body assumptions can be tested using COMSOL.

There has been similar non-thermal radiation work to use the ray tracing method to calculate view factors in fields such as computer graphics ([51]) and computational fluid dynamics ([52]).

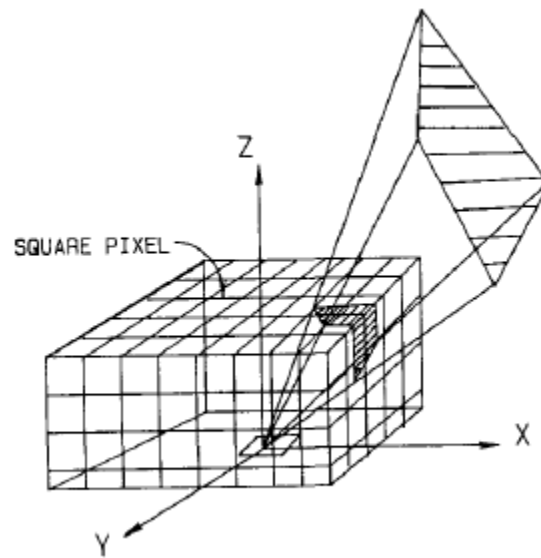


Figure 5.5: The hemi-cube [48].

6 RHT Analysis

The concepts discussed in Section 5.1 offer the foundation for which the purpose of this work was built upon. The comparison between thermal radiation computational solutions and experimental observations first requires an understanding of the information provided in Section 5.1. The objective of this work is to qualify the capability of computational tools against experimental results as it pertains to radiative heat transfer.

The scope of this work encompasses qualifying leading thermal radiation modeling software packages. The two tools analyzed during this study were ANSYS and COMSOL. As alluded to earlier, ANSYS offers thermal radiation view factor solutions through the hemi-cube method [50]. COMSOL also calculates view factors following a hemi-cube approach. However, COMSOL additionally offers the capability of calculating view factors through the Ray Shooting method [47]. It can be inferred that the Ray Shooting method emulates a random walk ray tracing solution. I have been informed by a COMSOL representative that details of the Ray Shooting method are proprietary and information beyond that presented in the user manual is inaccessible to the public.

Both COMSOL and ANSYS use a radiosity (Equation 5.5) solution method when evaluating thermal radiation environments. A radiosity solution method tallies the outgoing energy fluence from one surface and uses the view factor results to determine how much of that energy reaches other surfaces as well as open space. All thermal radiation solution methods presented here use radiosity to evaluate thermal radiation heat transfer [50], [47].

ANSYS and COMSOL both default to the Gauss-Seidel iterative solution method to solve the systems of radiosity equations. The Gauss-Seidel method starts with an approximation of the actual solution and attempts to improve upon the approximation following each iteration. The premise of the Gauss-Seidel method is introduced here [53].

The Gauss-Seidel method begins with a system of equations in the form of

$$Ax = b \quad (6.1)$$

where:

$A = m \times n$ matrix

x = unknown column vector with n elements

b = column vector with m elements

The A matrix can be rewritten as

$$A = I + L + U \quad (6.2)$$

where:

I = identity matrix

L = lower triangular matrix with zero main diagonal

U = upper triangular matrix with zero main diagonal

Substituting Equation 6.2 into Equation 6.1

$$Ax = (I + L + U)x = b \quad (6.3)$$

Moving Lx and Ux to the right hand side of Equation 6.3

$$x = b - Lx - Ux \quad (6.4)$$

Following Equation 6.4, a guess is made as to what x is. For the i th iteration

$$x(i+1) = b - Lx(i+1) - U(i) \quad (6.5)$$

Equation 6.5 is solved for and iteratively refreshed until a solution for x converges within a predetermined convergence criteria.

If the Gauss-Seidel solution fails to converge, a direct solution method may be attempted. Direct solution methods seek to compute the system of equations directly, not simultaneously. One common direct solution technique, used by ANSYS and COMSOL, is the LU decomposition method. The LU decomposition approach is introduced here [53].

The LU decomposition method begins with a system in the form of

$$Ax = b \quad (6.6)$$

where:

$A = m \times n$ matrix

$x =$ unknown column vector with n elements

$b =$ column vector with m elements

A is then decomposed into

$$A = LU \quad (6.7)$$

where:

$L =$ lower triangular matrix with zero main diagonal

$U =$ upper triangular matrix with zero main diagonal

The premise of the LU decomposition method is that now L and U can be computed directly. Substituting Equation 6.7 into Equation 6.6

$$Ax = LUx = b \quad (6.8)$$

Equation 6.8 can be rewritten as

$$Ly = b \quad (6.9)$$

$$Ux = y \quad (6.10)$$

Now y can be solved for directly, followed by x .

The default convergence criteria for the solutions are as follows. ANSYS will complete a solution once the relative tolerance is less than 10^{-4} , or 0.01% [50]. COMSOL will finish solving once the relative tolerance is less than 10^{-3} , or 0.1% [47]. The solver will continue to iterate until the calculated solution error is below the relative tolerance.

OUTSET has been used to challenge the results of the thermal radiation models. OUTSET offers a heater with a high-emissivity in a vacuum (below 1 *mTorr*) environment at high temperature levels. This high-temperature heat source in a vacuum is an effective thermal radiation emitter; this enables OUTSET to serve as an experimental tool to validate the produced models.

OUTSET utilizes several thermocouples of various types to measure temperature at designated locations within the apparatus. Type K thermocouples are usable in temperature regions ranging from room temperature up to around 1500 *K*. Type C thermocouples are viable in the higher temperature regions up to approximately 2800 *K*. The TCs are placed in locations presented in Section 3.1.3.

It is valuable to present the defined list of requirements for the IN/OUTSET design. IN/OUTSET was designed to fulfill the following:

- Same as OUTSET-1: Provide electrical heating to allow the specimen to achieve target temperatures [21].
- Same as OUTSET-1: Design flexibility to accept various direct and indirect instrumentation techniques [21].
- Same as OUTSET-1: Provide and maintain a controlled vacuum or inert atmosphere [21].
- Provide a testbed for high-temperature in-pile testing relevant to NTP.
- Serve as a validation tool for thermal radiation computational models.

6.1 Base Case and Definitions

A series of computational sensitivity studies was conducted to investigate various RHT parameters and to compare against experimental data. The base properties for each investigation are presented in Table 6.1. These properties will remain unchanged for every configuration tested unless otherwise specified. Every thermal model developed for RHT computational investigations utilized an alumina crucible and the standard TC placements presented in Section 3.1.3 unless otherwise specified.

The view factor resolution affects the accuracy of the solution. For the hemi-cube method in COMSOL, "The number of z-buffer pixels on each side of the 3D hemi-cube equals the specified resolution squared. Thus the time required to evaluate the irradiation increases quadratically with resolution. [47]" The resolution setting while using the Ray Shooting method in COMSOL controls the number of rays emitted. For a 3D case there are n^2 rays, where n is the designated value for resolution [47].

All of the thermal models developed were steady-state, not transient, models. To enable the comparison with experimental data, the corresponding experiments were run for a length of time such that the system would achieve a constant state. The steady-state condition for the experiments was defined by the rate of temperature change recorded by the TC in the shell. The experiment was deemed steady-state if the recorded temperature was changing by less than $1\text{ K}/\text{minute}$. This definition fits every 200 W RHT experiment, except for two where electrical fluctuations were observed. A total of fifteen 200 W RHT experiments were conducted to compare against the computational results. This equates to three experimental runs per emissivity configuration (Section 7.2).

Table 6.1: Base properties of RHT computational investigations.

Parameter	Value
POCO graphite emissivity	0.77 [54]
POCO graphite thermal conductivity	30 W/mK [54]
Molybdenum emissivity	0.15 [22]
Molybdenum thermal conductivity	130 W/mK [55]
Alumina emissivity	0.75 [56]
Alumina thermal conductivity	28 W/mK [57]
GFA emissivity	0.75 [22]
GFA thermal conductivity	Figure 3.7 [29]
Power input	200 W
Wall temperature boundary condition	Radiation to ambient at 373 K
View factor solution resolution	256
Meshed elements	31990

7 RHT Investigations

The following sections will detail various cases and present discussions on the agreement between the computational results and experimental observations. Each discussion will provide relevant information such as assumptions, boundary conditions, and utilized instrumentation if any are different from the information provided in Section 6.1.

7.1 Mesh Sensitivity and Aliasing

To eliminate mesh induced variations in the models, a mesh that was usable in both COMSOL and ANSYS had to be developed. This was done by creating a free tetrahedral mesh in COMSOL and exporting it to ANSYS via a .nas file. It required substantial effort to find a mesh method and sizing that was compatible with ANSYS from COMSOL. The requirement for identical meshes across software restricted the type and sizing of the meshes used.

Twelve unique free tetrahedral meshes were made and applied to COMSOL Ray Shooting, COMSOL hemi-cube, and ANSYS hemi-cube when possible. The variations in the sizing in each mesh were established by COMSOL predefined settings (i.e. "finer", "fine", "normal", "coarse", etc.). A standard mesh was chosen following the mesh sensitivity study that was used for subsequent investigations. This mesh was selected due to its favorable thermal results and computational cost.

A summary of the mesh sensitivity results versus shell TC temperature can be found in Figure 7.1. In Figure 7.1 and Figure 7.2, "C" denotes a COMSOL model, "A" refers to an ANSYS model, "HC" stands for hemi-cube, and "RS" corresponds to Ray Shooting. Every model used for this plot had identical settings except for the mesh. The colors within these plots will be mentioned where appropriate. There were twelve meshes applied in each of the three view factor solution methods (COMSOL hemi-cube, COMSOL Ray Shooting, and ANSYS hemi-cube). Since the meshes were native to COMSOL, not all were compatible with ANSYS - there are only six ANSYS cases shown.

The twelve meshes shown in Figure 7.1 expectedly yielded different computational times and number of elements per solution method. Each solution method also drove the solution time. Figure 7.2 shows the combined effects of solution method, software used, and mesh size on the computational time.

Using the implications of the data shown in Figure 7.1 and Figure 7.2, the mesh with 31990 *elements* was chosen as the mesh to be used in future investigations. In the referenced figures, the points associated with this mesh are shown in red. This mesh utilized the COMSOL sizing as follows: "finer" on the heater, "fine" on the circuit tubing, and "normal" on the internal walls. This mesh was compatible with both ANSYS and COMSOL. It computed a TC temperature that did not fall on the extremities for any solution method - the results were within 2% of the mean per solution method. This mesh also offered a reasonable solution time. It was the finest COMSOL-generated free tetrahedral mesh compatible with ANSYS. The maximum element size in the chosen mesh was 0.055 *mm* and the minimum element size was 0.004 *mm*. The final mesh is shown in Figure 7.3. All other meshes considered are shown in Appendix A.

Combinations of meshes with uniform and variable sizing across geometric entities were employed to isolate any RHT aliasing hindrances. Computational RHT models rely heavily on the radiation view factor. Each mesh element will have a unique radiation view factor associated with it. Aliasing can occur when an element has an obstructed, partial, or skewed view of another mesh element. The concept of aliasing is discussed in Section 5.2. Varying the size of elements across geometric entities dilutes the impacts of aliasing. Small elements with view factors to small elements will compute differently than small elements to large elements. Of the twelve meshes developed, only three had a uniform mesh size across the entire model geometry. The remaining nine had some combination of large to small, small to large, etc. The results from the varying mesh size did not noticeably differ from the uniform mesh cases when considering temperature or solution time. The results from the uniform mesh cases are shown by the blue points in Figure 7.1 and Figure 7.2.

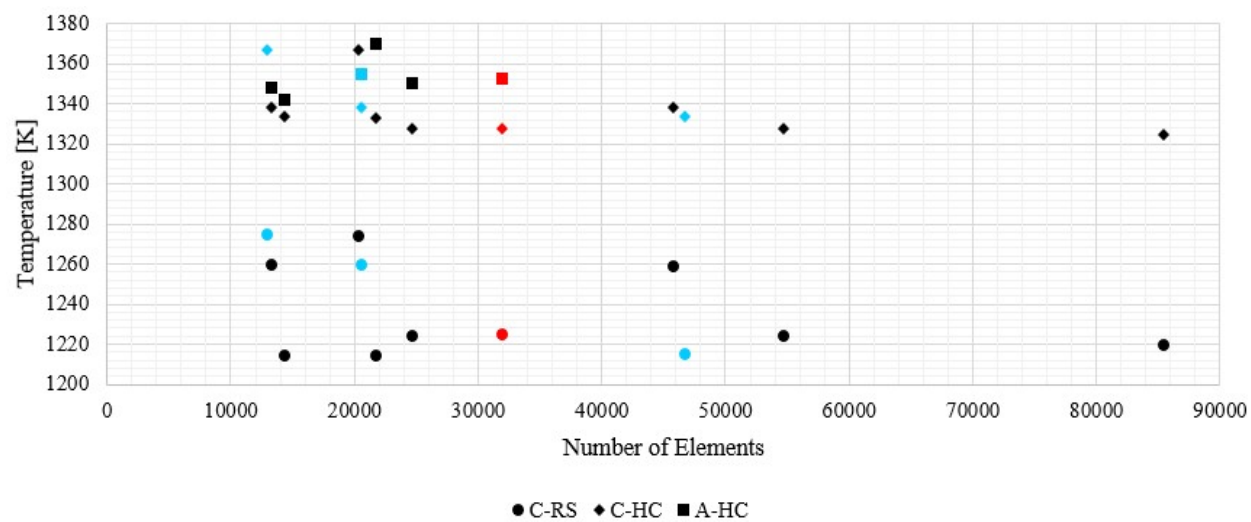


Figure 7.1: Thermal summary of mesh sensitivity study.

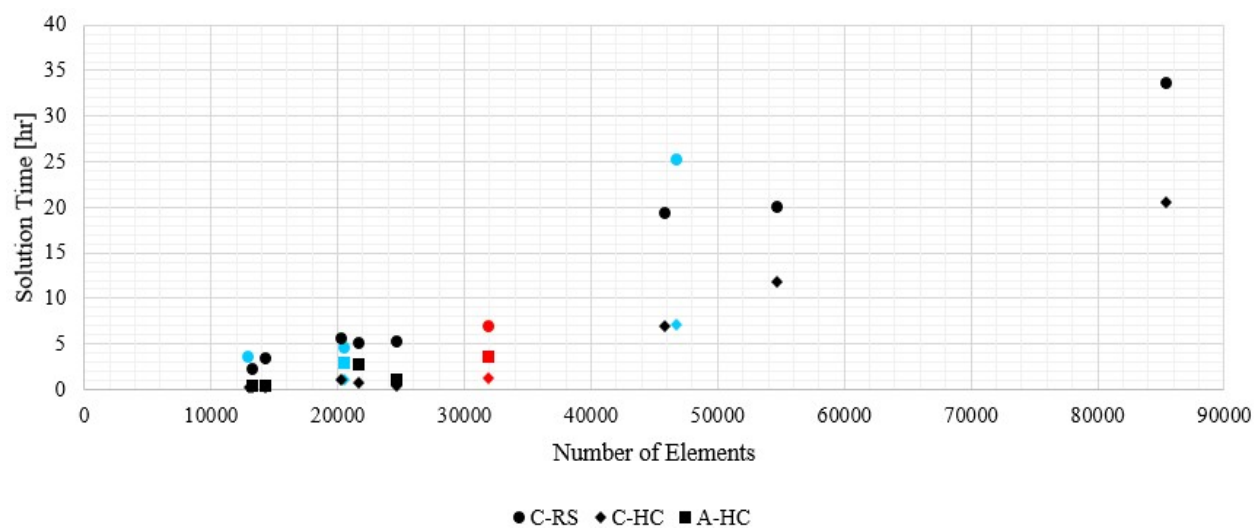


Figure 7.2: Temporal summary of mesh sensitivity study.

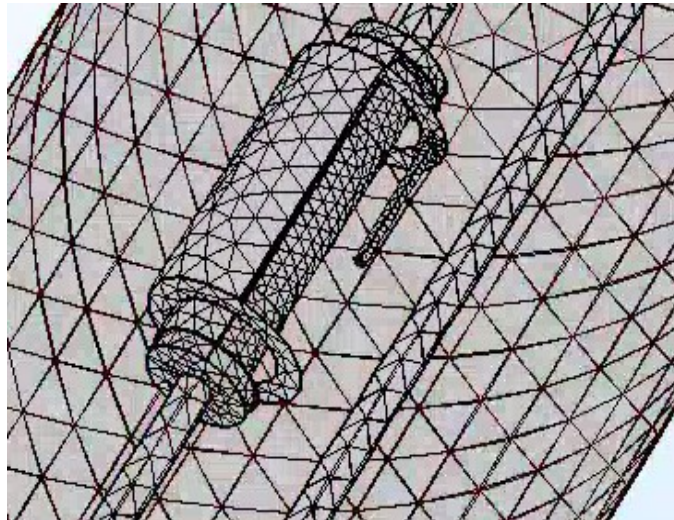


Figure 7.3: Free tetrahedral mesh for RHT investigations with 31990 *elements*.

7.2 Emissivity Sensitivity

The Stefan-Boltzmann law for a blackbody is described in Equation 5.2. A blackbody represents an ideal surface, not a real surface; a blackbody has an emissivity of one. A real surface has an emissivity between zero and one. The hemispherical total emissive power for a real body is shown here in Equation 7.1 [45].

$$E = \sigma T^4 \epsilon \quad (7.1)$$

where:

E = real body hemispherical total emissive power

σ = Stefan-Boltzmann constant = $5.670 \times 10^{-8} \frac{W}{m^2 K^4}$ [45]

T = temperature

ϵ = emissivity

As shown in Equation 7.1, emitted thermal radiation is a function of emissivity. To identify how dependent the thermal radiation heat transfer within OUTSET is on emissivity, an emissivity sensitivity investigation was conducted. The Ray Shooting method and the hemi-cube method for view factor calculations were used and the results are presented here.

Prior to the discussion presenting the emissivity study, a naming convention must be conveyed. For brevity and ease of communication, a simplified way to reference the various emissivity runs was established. When molybdenum foil was used for an inner-most wall insulation, it will be denoted via "Mo". When GFA5 graphite felt was used as an inner-most insulation wall, "G" will be referenced. There are three primary inner-most wall locations: "top", "side", and "bottom". Figure 7.4 shows where these locations are within the experiment. "Top" refers to the lid of the vacated plenum cylinder. "Side" refers to the mid-section of the vacated plenum cylinder. The side is shown by the dotted pattern in Figure 7.4. "Bottom" refers to the base of the cylinder. The naming convention will be used in the following manner: Top-Side-Bottom. For example, if every inner-most layer of insulation of molybdenum the case would be referenced as "Mo-Mo-Mo". If the side wall was replaced with graphite felt it would be named "Mo-G-Mo". If the bottom was then also replaced with graphite, "Mo-G-G" would be used.

The emissivity sensitivity study will be presented in the following order:

1. Mo-Mo-Mo (base case)
2. Mo-G-Mo
3. G-Mo-Mo
4. G-G-Mo
5. G-G-G

The base case adheres to the parameters shown in Table 6.1. Each non-base case was implemented by only changing the mentioned value for the mentioned variable one at a time. The other parameters were set to that of the base case. To isolate the impact of the view factor solution method on the computational results, the cases presented using the Ray Shooting method were identically rerun using the hemi-cube method in COMSOL and ANSYS. In addition to the base case parameters conveyed via Table 6.1, the material properties for the GFA5 graphite felt insulation are shown. These were applied to the relevant models.

Along with each computational result, the experimental data will also be presented. Each computational iteration of the emissivity study encompasses a thermal model generated by COMSOL Ray Shooting, COMSOL hemi-cube, and ANSYS hemi-cube. The experimental validation was achieved by conducting three identical experimental setups mimicking the configuration seen in the models. Each experimental case was performed three times to ensure the results were statistically significant and to rectify any sources of random

error.

Each experiment utilized eight layers of GFA5 graphite felt wrapped along the internal wall of OUTSET to form the cylinder of the inner plenum region. Some cases also included molybdenum foil as the inner-most insulation material. There were four layers of graphite felt insulation on the top of the vacated plenum region. Again, some runs included molybdenum foil as the inner-most layer here as well. The bottom of the plenum region was also contained by four layers of graphite felt and the occasional molybdenum foil. All of this insulation was in place to prevent the external surface of the experimental apparatus from reaching unsafe levels of temperature. It also helped shrink the plenum region, which enables higher heater temperatures according to surface area heat flux. Figure A.22 in Appendix A shows the minimum amount of insulation in OUTSET for the tests conducted (top not shown).

7.2.1 Emissivity: Mo-Mo-Mo

The first emissivity environment considered was the Mo-Mo-Mo case. This environment utilized only molybdenum foil as the inner-most layers of insulation in the plenum region. Molybdenum has a low emissivity (0.15) and tends to scatter thermal energy. Applying the parameters in Table 6.1, the models produced the results seen in Figure 7.5. Figure 7.5 (a) shows the temperature distribution when using COMSOL and the Ray Shooting view factor solution method. The axis maximum is $1.29 \times 10^3 K$. Figure 7.5 (b) corresponds to COMSOL hemi-cube. The axis maximum is $1.36 \times 10^3 K$. Figure 7.5 (c) is the ANSYS hemi-cube result. Note that this distribution is in degrees Celsius. To convert degrees Celsius to Kelvin, add 273.15 to the value. The units are not consistent across modeling software due to early decisions - the difference is an artifact of older models. The maximum on the axis in Figure 7.5 (c) is $1098.6^\circ C$ or $1371.75 K$.

To verify the model results, a series of three experiments was performed. The experiment also used molybdenum as the only inner-most layer of insulation. The experiment was configured to replicate the setup in the thermal models. The shell TC results from one of the three experiments is shown in Figure 7.6. The temperature records for the remaining tests are shown in Figure A.23 and Figure A.24 in Appendix A. This test adheres to the standard TC placement presented in Section 3.1.3. The raw power supply data was not recorded for this series of experiments. However, the power was gradually increased to $200 W$ over $4 minutes$ and held for the duration implied in Figure 7.6.

The steady-state shell TC (TC2) temperature was averaged across the redundant experiments. Here steady-state is defined by an observed temperature change of less than $1 K/minute$. The experimental uncertainty discussed in Section 3.5 was applied to these steady-state values. Figure 7.7 shows the comparison between the computational and experimental results for the Mo-Mo-Mo case. The steady-state values in this figure were observed by the shell TC. This figure shows the spread of computed results against the observed experimental result. The computational error bars have been produced using the results of Equation 7.5, Equation 7.6, and Equation 7.7 presented in Section 7.5. The experimental error bar was calculated using Equation 3.7.

The COMSOL Ray Shooting result varies from the experimental value by 2.72% and took $6.51 hours$ to solve. The COMSOL hemi-cube result varies from the experimental value by 2.18% and took $1.07 hours$ to solve. The ANSYS hemi-cube result varies from the experimental value by 3.32% and took $3.43 hours$ to solve. The temperature percent error is visualized by Figure 7.7.

7.2.2 Emissivity: Mo-G-Mo

The next emissivity case that will be presented is that where the side (Figure 7.4) molybdenum foil was removed. This exposed a layer of GFA5 graphite felt insulation in its place. The setup for this series of experiments and models used a molybdenum foil top and bottom with a graphite felt side. Graphite has a higher emissivity than molybdenum (0.75) and will scatter thermal energy less than molybdenum. This series of computational and experimental tests followed the standard TC placement (Section 3.1.3) and virtual material parameters (Table 6.1). These settings produced the computational results seen in Figure 7.8.

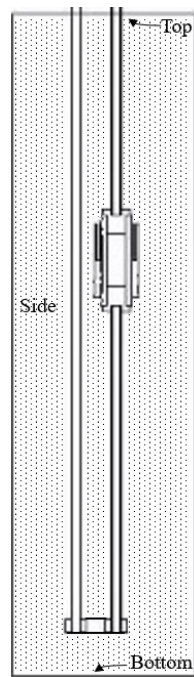


Figure 7.4: OUTSET schematic with wall naming convention labeled.

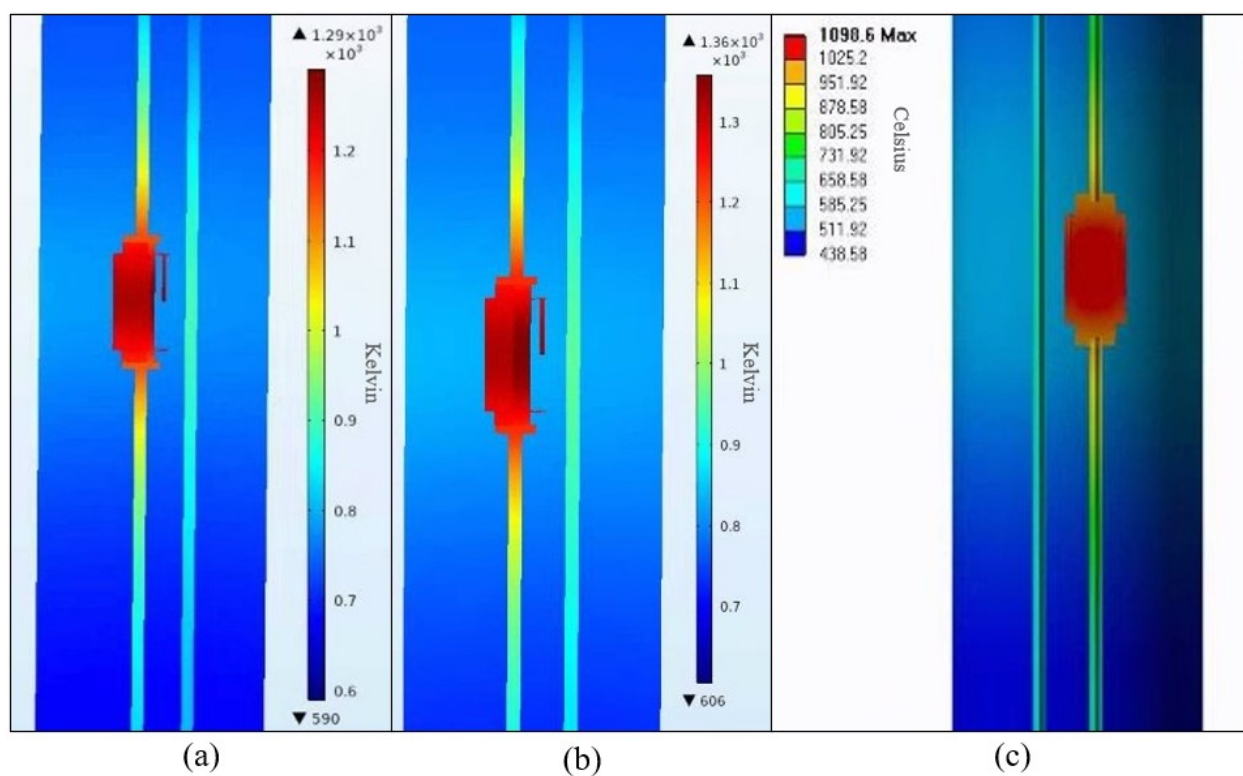


Figure 7.5: Temperature distribution for computational Mo-Mo-Mo case.
(a) COMSOL Ray Shooting [K]. (b) COMSOL hemi-cube [K]. (c) ANSYS hemi-cube [$^{\circ}\text{C}$].

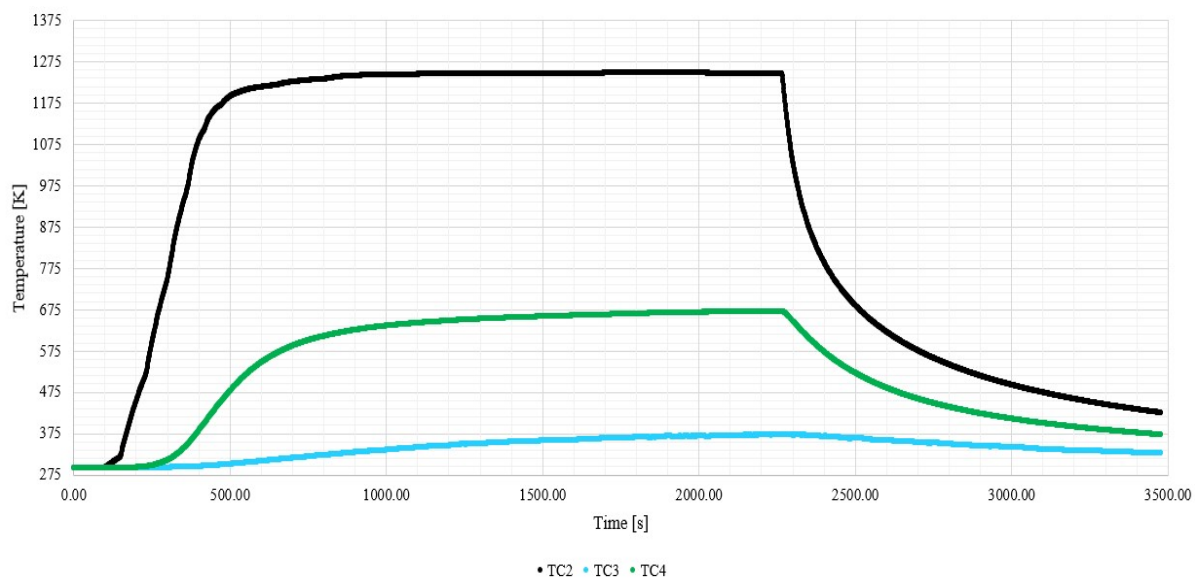


Figure 7.6: June 7, 2021 Mo-Mo-Mo TC data.

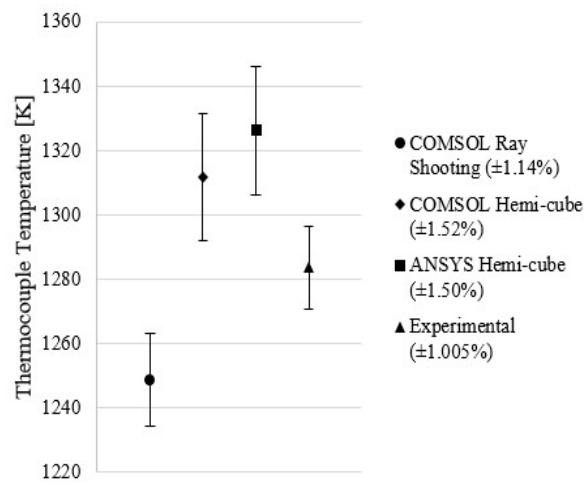


Figure 7.7: Mo-Mo-Mo computational and experimental shell TC temperature comparison.

As with the Mo-Mo-Mo discussion, the side-by-side figure showing the comparison is as follows: Figure 7.8 (a) used COMSOL Ray Shooting, (b) used COMSOL hemi-cube, and (c) used ANSYS hemi-cube. This will be the format for later discussions as well. The maximum axis value in Figure 7.8 (a) is $1.25 \times 10^3 K$, (b) is $1.28 \times 10^3 K$, and (c) is 1333.65 K (shown as 1060.5°C).

The validation experiment was conducted three times. The experiment set adhered to the same configuration as the model. This experiment used the standard TC placement. The raw power supply data is not available for this series. The power was increased to 200 W over 4 minutes and held for the duration implied in Figure 7.9. Figure 7.9 shows the temperature distribution for this experiment. The two partner runs for this series can be seen in Figure A.25 and Figure A.26 in Appendix A.

Again, the steady-state shell TC (TC2) temperature was averaged across the redundant experiments. When the temperature was changing less than 1 K/minute, the system was deemed to be steady-state. This average is shown in Figure 7.10 where it is compared against the model results. The experimental uncertainty is defined in Section 3.5. The computational error bars have been produced using the results of Equation 7.5, Equation 7.6, and Equation 7.7 presented in Section 7.5.

The COMSOL Ray Shooting result varies from the experimental averaged value by 0.15% and took 6.51 hours to solve. The COMSOL hemi-cube result varies from the experimental value by 2.18% and took 0.98 hours to solve. The ANSYS hemi-cube result varies from the experimental value by 7.19% and took 0.32 hours to solve. The temperature percent error is visualized by Figure 7.10.

7.2.3 Emissivity: G-Mo-Mo

This case was established by removing the molybdenum foil from the top to expose the GFA5 graphite felt. Molybdenum foil was placed along the side and on the bottom here. Asymmetrical distributions of varying emissivity were tested to evaluate the dependence on scattering directionality and heater temperature. This series of computational and experimental tests followed the standard TC placement (Section 3.1.3) and virtual material parameters (Table 6.1). These settings produced the computational results seen in Figure 7.11. Figure 7.11 (a) used COMSOL Ray Shooting, (b) used COMSOL hemi-cube, and (c) used ANSYS hemi-cube. The maximum axis value in Figure 7.11 (a) is $1.28 \times 10^3 K$, (b) is $1.35 \times 10^3 K$, and (c) is 1367.95 K (shown as 1094.8°C).

Again, the validation experiment was conducted three times. The experiment set followed the same configuration as the model. This experiment used the standard TC placement. The raw power supply data is available for this series. The power was increased to 200 W over 4 minutes and held for the duration shown in Figure 7.12. The temperature profile for this run is shown in Figure 7.13. The TC data for the two partner runs for this series can be seen in Figure A.27 and Figure A.28 in Appendix A. Note the TC temperature recorded against the other emissivity cases.

To compare the model to the experiment series, the steady-state shell TC (TC2) temperature was averaged across the redundant experiments. Steady-state is anytime the temperature was changing less than 1 K/minute above room temperature. This average is shown in Figure 7.14 where it is compared against the model results. The experimental uncertainty is defined in Section 3.5. The computational error bars have been produced using the results of Equation 7.5, Equation 7.6, and Equation 7.7 presented in Section 7.5.

The COMSOL Ray Shooting result varies from the experimental averaged value by 6.32% and took 8.37 hours to solve. The COMSOL hemi-cube result varies from the experimental value by 11.28% and took 1.07 hours to solve. The ANSYS hemi-cube result varies from the experimental value by 13.39% and took 4.75 hours to solve. The temperature percent error is visualized by Figure 7.14. Note the spread in the analytical results against other cases.

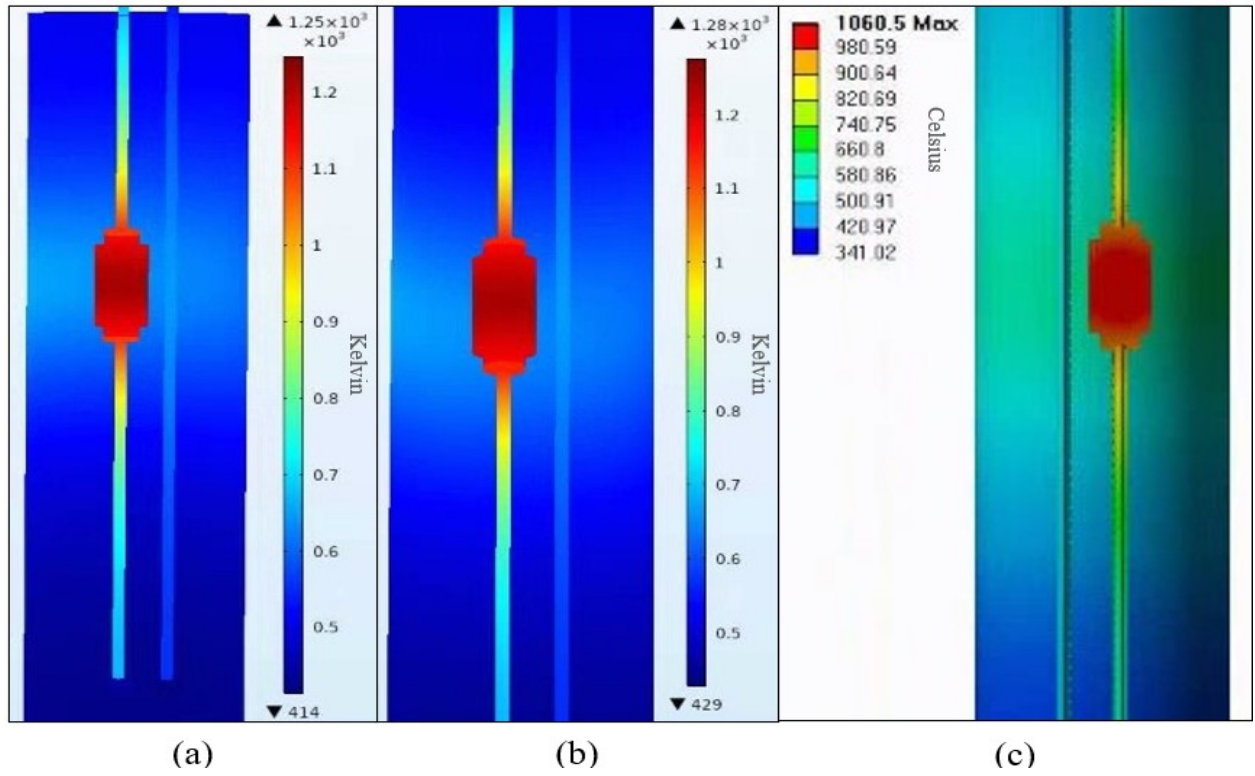


Figure 7.8: Temperature distribution for computational Mo-G-Mo case.
(a) COMSOL Ray Shooting [K]. (b) COMSOL hemi-cube [K]. (c) ANSYS hemi-cube [°C].

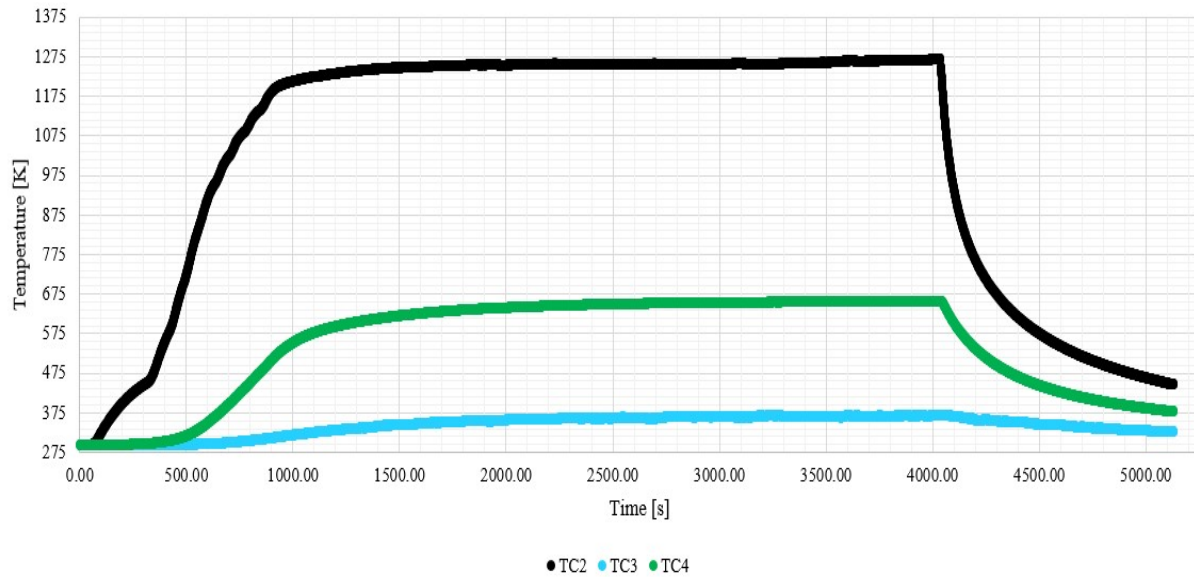


Figure 7.9: June 18, 2021 Mo-G-Mo TC data.

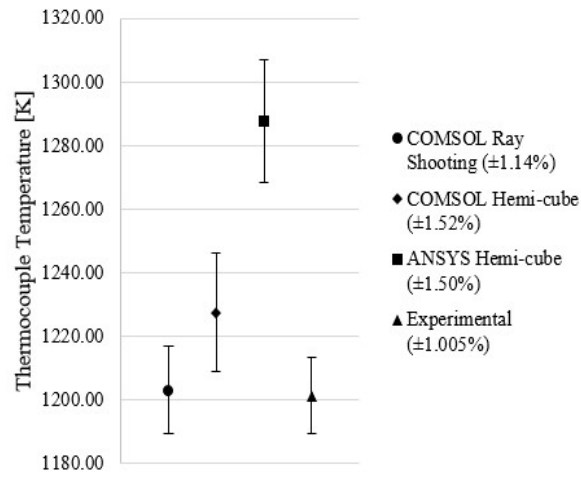


Figure 7.10: Mo-G-Mo computational and experimental shell TC temperature comparison.

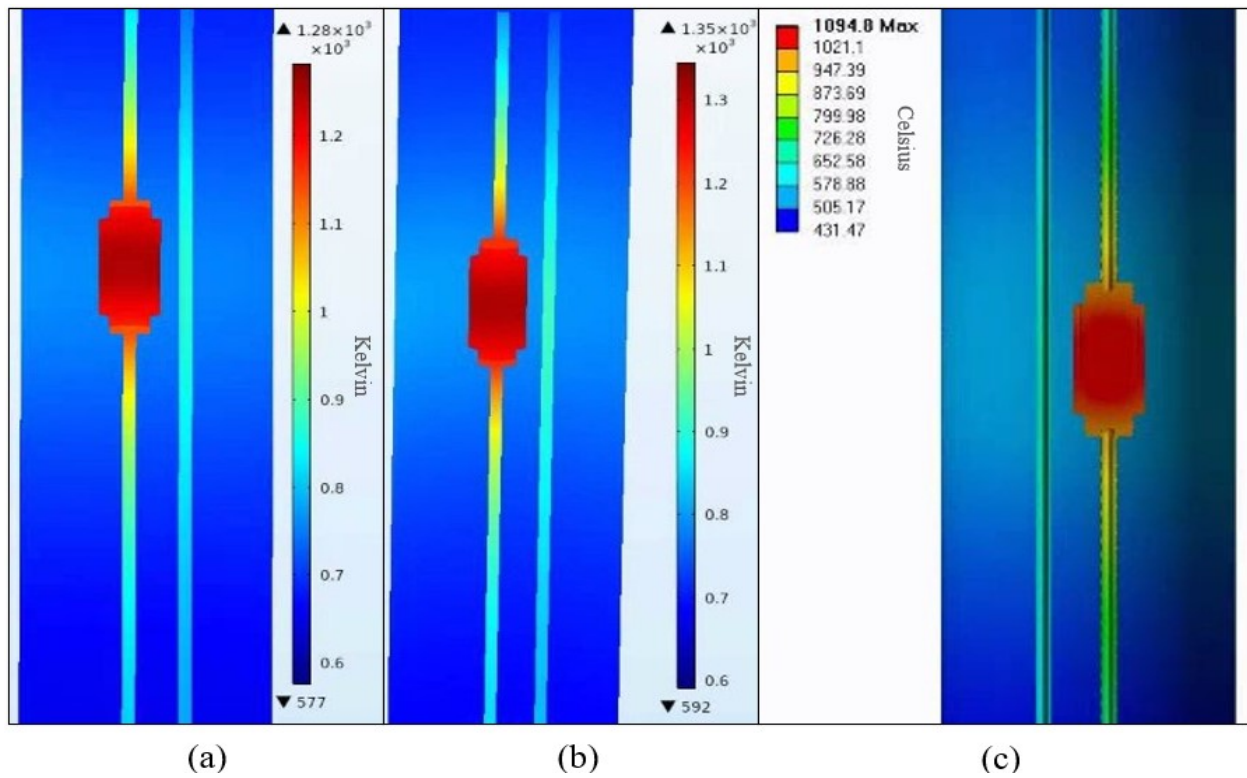


Figure 7.11: Temperature distribution for computational G-Mo-Mo case.
(a) COMSOL Ray Shooting [K]. (b) COMSOL hemi-cube [K]. (c) ANSYS hemi-cube [°C].

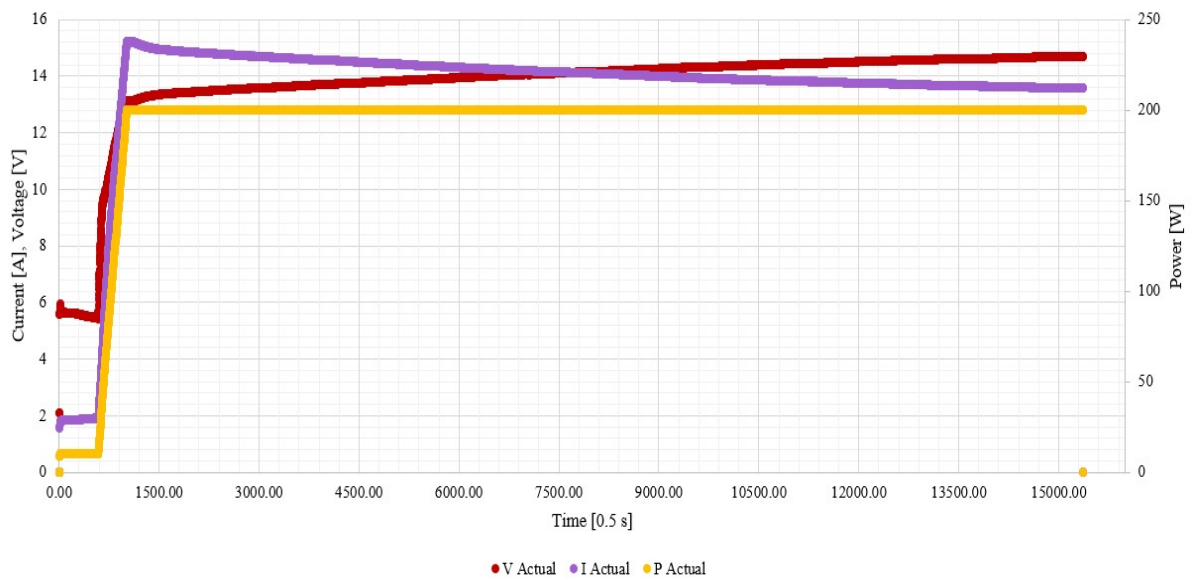


Figure 7.12: August 4, 2021 G-Mo-Mo power supply data.

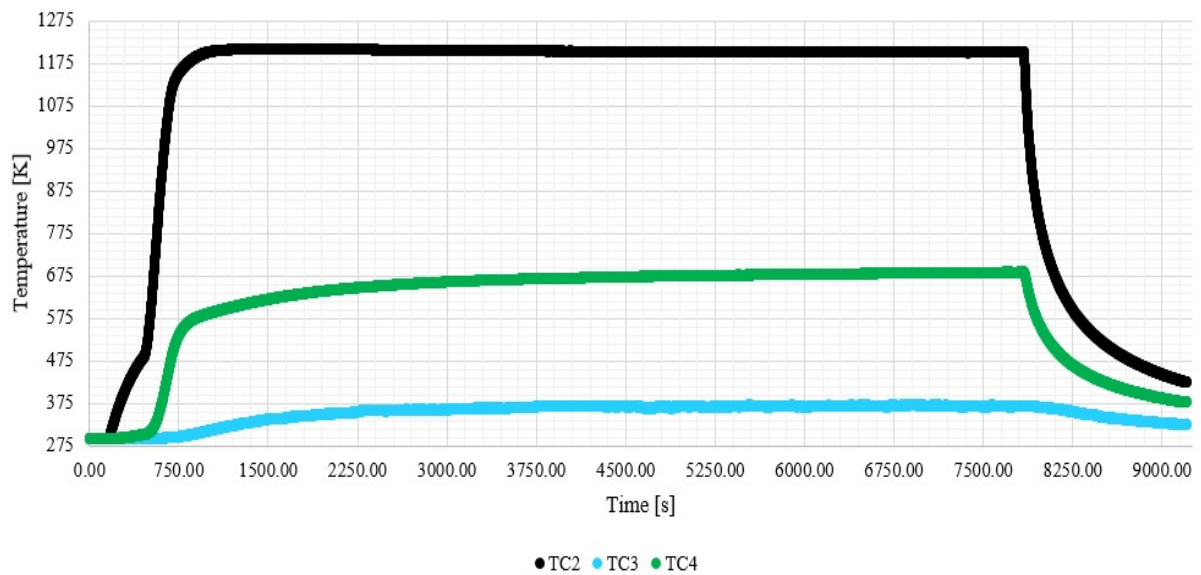


Figure 7.13: August 4, 2021 G-Mo-Mo TC data.

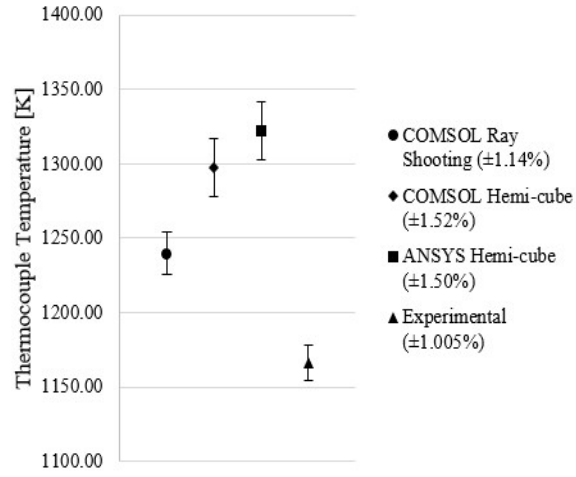


Figure 7.14: G-Mo-Mo computational and experimental shell TC temperature comparison.

7.2.4 Emissivity: G-G-Mo

For the G-G-Mo case, the only molybdenum foil on the inside served as the bottom inner-most layer of insulation. The thermal radiation interacted with graphite felt on the top and side within the plenum. This series of computational and experimental tests followed the standard TC placement (Section 3.1.3) and virtual material parameters (Table 6.1). These settings produced the computational results seen in Figure 7.15. Figure 7.15 (a) used COMSOL Ray Shooting, (b) used COMSOL hemi-cube, and (c) used ANSYS hemi-cube. The maximum axis value in Figure 7.15 (a) is $1.25 \times 10^3 K$, (b) is $1.28 \times 10^3 K$, and (c) is $1332.65 K$ (shown as $1059.5^\circ C$).

The validation experiment was conducted three times. The experiment set followed the same configuration as the model. This experiment used the standard TC placement. The power supply data is shown in Figure 3.56. The TC data is shown Figure 3.55. The experiment presented by Figure 3.55 served two purposes: to investigate the melt wire behavior in the heater (Section 3.3.7) and for this radiative heat transfer study. The partner runs for the G-G-Mo series are shown in Figure A.29 and Figure A.30 in Appendix A.

The steady-state shell TC (TC2) recorded temperature was averaged across the redundant experiments. Steady-state was established when the temperature was changing less than $1 K/minute$, during power supply operation. This average is shown in Figure 7.16 where it is compared against the model results. The experimental uncertainty is defined in Section 3.5. The computational error bars have been produced using the results of Equation 7.5, Equation 7.6, and Equation 7.7 presented in Section 7.5.

The COMSOL Ray Shooting result varies from the experimental averaged value by 0.03% and took 6.13 *hours* to solve. The COMSOL hemi-cube result varies from the experimental value by 2.10% and took 0.98 *hours* to solve. The ANSYS hemi-cube result varies from the experimental value by 7.07% and took 0.31 *hours* to solve. The temperature percent error is visualized by Figure 7.16.

7.2.5 Emissivity: G-G-G

The G-G-G case had no reflective molybdenum foil insulation present. The top, side, and bottom inner-most layers of insulation were all GFA5 graphite felt. An image of the inside of OUTSET under these conditions is shown in Figure A.22 in Appendix A. This series of computational and experimental tests followed the standard TC placement (Section 3.1.3) and virtual material parameters (Table 6.1). These settings produced the computational results seen in Figure 7.17. Figure 7.17 (a) used COMSOL Ray Shooting, (b) used COMSOL hemi-cube, and (c) used ANSYS hemi-cube. The maximum axis value in Figure 7.17 (a) is $1.25 \times 10^3 K$, (b) is $1.28 \times 10^3 K$, and (c) is $1286.95 K$ (shown as $1013.8^\circ C$). Note the similarities between the G-G-Mo case and this G-G-G case in COMSOL along with the differences between the respective ANSYS results.

The validation experiment was conducted three times. The experiment set followed the same configuration as the model. This experiment used the standard TC placement. The power supply data is shown in Figure 3.59. The TC data is shown Figure 3.58. The experiment presented by Figure 3.58 served two purposes: to investigate the melt wire behavior in the TC slot (Section 3.3.7) and for this radiative heat transfer study. The partner runs for the G-G-G series are shown in Figure A.31 and Figure A.32 in Appendix A.

The steady-state shell TC (TC2) recorded temperature was averaged across the redundant experiments. Steady-state was established when the observed temperature was changing less than $1 K/minute$, during power supply operation. This average is shown in Figure 7.18 where it is compared against the model results. The experimental uncertainty is defined in Section 3.5. The computational error bars have been produced using the results of Equation 7.5, Equation 7.6, and Equation 7.7 presented in Section 7.5.

The COMSOL Ray Shooting result varies from the experimental averaged value by 0.69% and took 6.82 *hours* to solve. The COMSOL hemi-cube result varies from the experimental value by 1.31% and took 0.97 *hours* to solve. The ANSYS hemi-cube result varies from the experimental value by 2.43% and took 0.14 *hours* to solve.

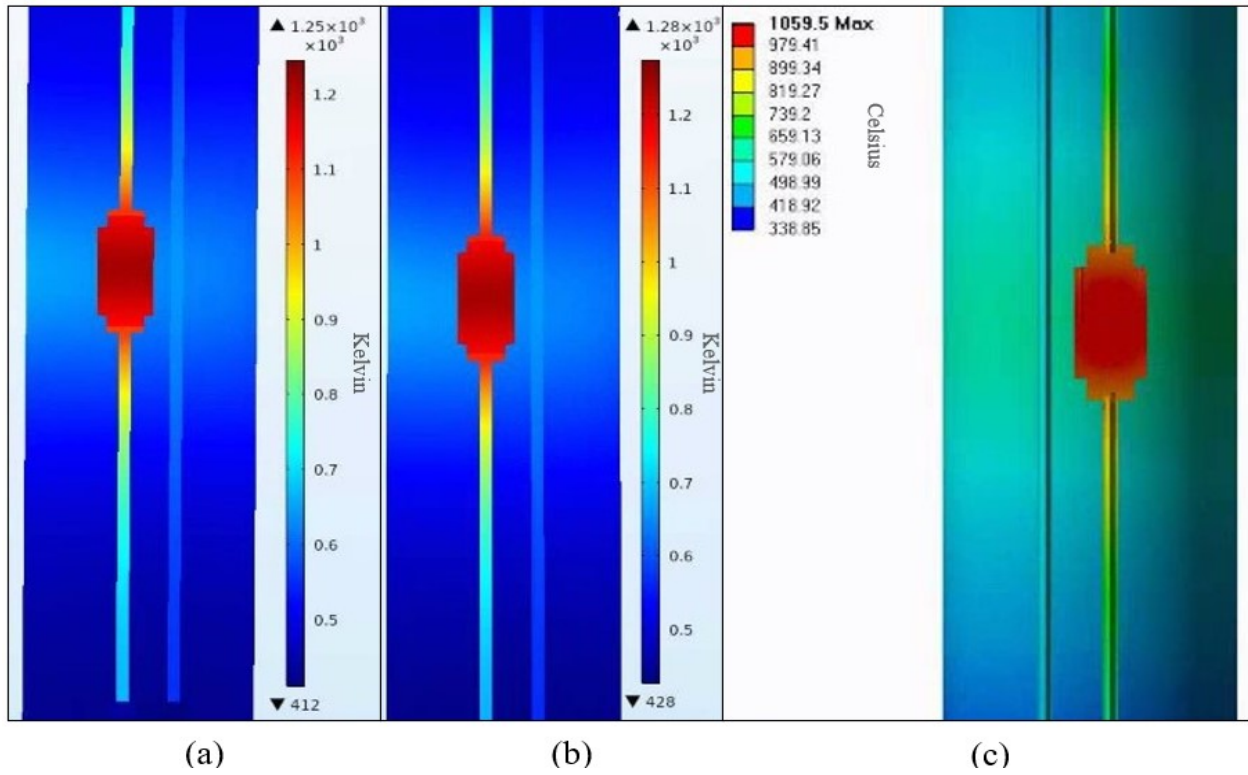


Figure 7.15: Temperature distribution for computational G-G-Mo case.
(a) COMSOL Ray Shooting [K]. (b) COMSOL hemi-cube [K]. (c) ANSYS hemi-cube [°C].

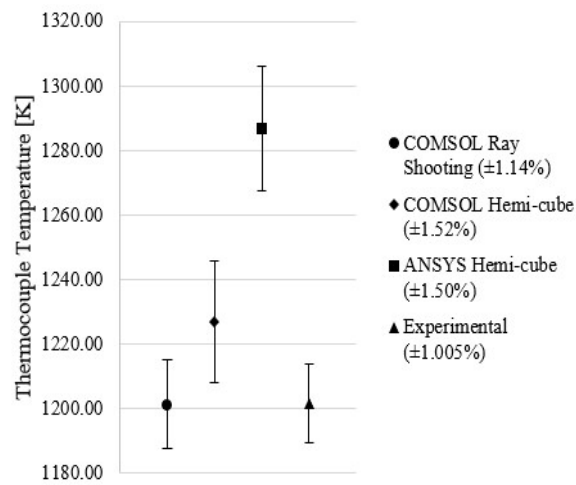


Figure 7.16: G-G-Mo computational and experimental shell TC temperature comparison.

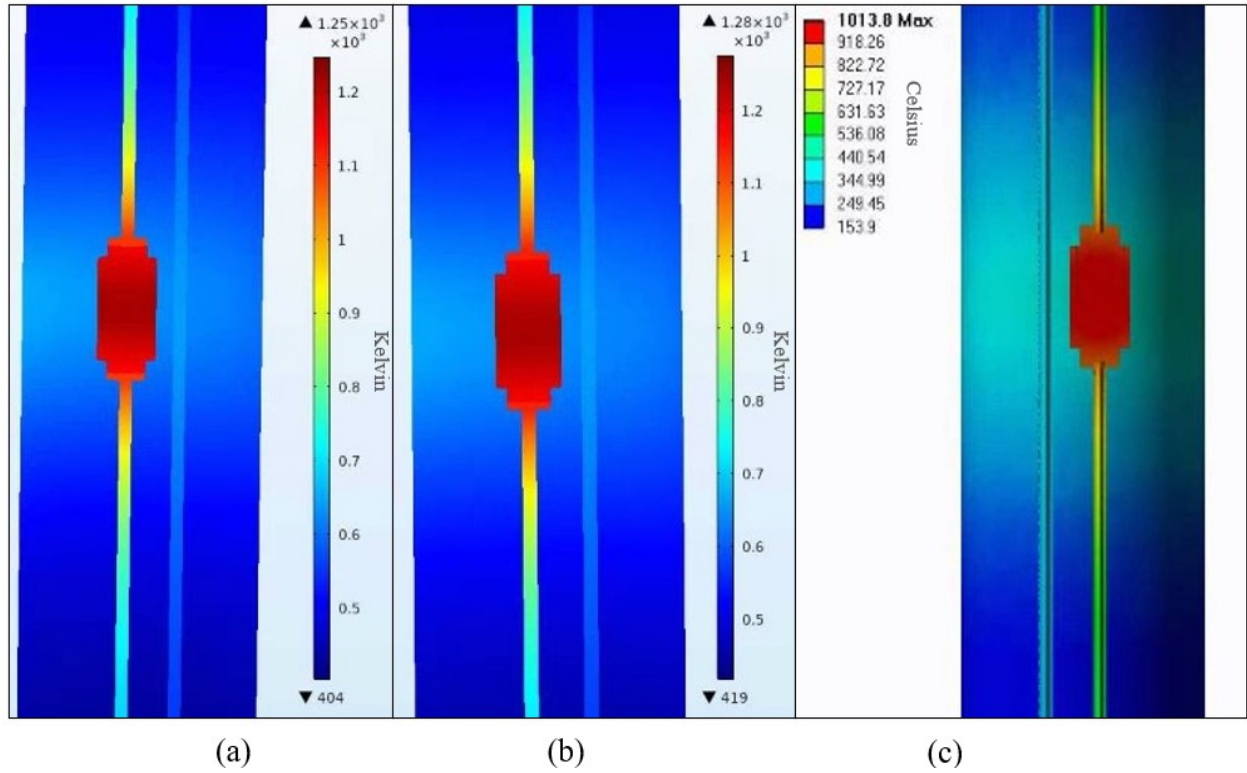


Figure 7.17: Temperature distribution for computational G-G-G case.
(a) COMSOL Ray Shooting [K]. (b) COMSOL hemi-cube [K]. (c) ANSYS hemi-cube [°C].

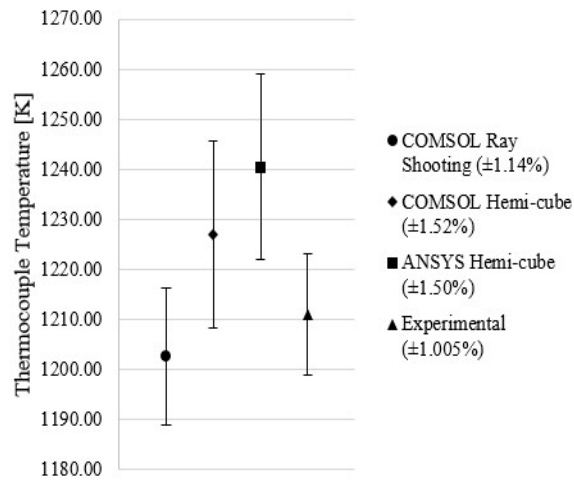


Figure 7.18: G-G-G computational and experimental shell TC temperature comparison.

solve. The temperature percent error is visualized by Figure 7.18.

7.2.6 Emissivity Discussion

A summary of the aforementioned results of the emissivity study is shown in Table 7.1. Here "C-RS" is shorthand for COMSOL Ray Shooting, "C-HC" stands for COMSOL hemi-cube, and "A-HC" represents ANSYS hemi-cube. T_{comp} is the temperature reported at the shell TC by the computational model. T_{exp} is the average of the steady-state shell TC recorded temperature from the three redundant experimental runs. The percent difference value was calculated according to the process shown in Equation 7.2. "Soln. Time" is the computational solution time. A visualization of the relative difference recorded in Table 7.1 is shown in Figure 7.19.

$$C = \left| \frac{T_{exp} - T_{comp}}{T_{exp}} \right| \times 100\% \quad (7.2)$$

where:

C = percent difference

T_{exp} = experimental temperature

T_{comp} = computational temperature

A high emissivity relates to a high absorptivity due to energy conservation. The low emissivity foil primarily scatters the radiation, opposed to absorbing it. It is impossible to say with certainty what is driving the discrepancy between solution methods without accessing the driving software in COMSOL. Details of COMSOL's Ray Shooting view factor solution method are proprietary and information beyond that presented in the user manuals is inaccessible to the public. It is of the speculation of the author of this document that the differences between radiative heat transfer solution methods are due to the longevity of the transported photons. The hemi-cube method may only monitor the photon to its first interaction. The view factor may be calculated and the heat may be transferred once per photon. The title of "Ray Shooting" allows for the logical connection to "ray tracing" which typically follows photons beyond the first interaction. This is computationally expensive and may be the reason for the Ray Shooting method's long solution times. If the photons are only tracked to the first interaction in the hemi-cube method, each photon would deposit all of its energy at the site of its first interaction. This would lead to a less flat temperature distribution with peaks. This would result in higher localized temperatures, which is seen in the results. The information presented in this paragraph is pure speculation by the author, who has no information on COMSOL and ANSYS solution methods, besides what is publicly available.

It is also possible that the hemi-cube method is underestimating the view factor between the heater region and the plenum walls. Calculating smaller view factors would result in less thermal radiation being exchanged, producing higher heater temperatures. This may be the reason for the higher heater temperatures.

To expand on the emissivity dependence, additional computational cases were tested. These tests utilized emissivity values of 1 and 1×10^{-10} , which are both nonphysical, so experimental validation is not possible. The following computational tests were conducted. This shorthand adheres to the "Top-Side-Bottom" notation previously used. However, instead of the material being presented in this notation, the emissivity of the virtual surface will be. Each of the listed cases here was solved using COMSOL Ray Shooting, COMSOL hemi-cube, and ANSYS hemi-cube.

1. 1 - 0.15 - 0.15
2. 1×10^{-10} - 0.15 - 0.15
3. 0.15 - 1 - 0.15
4. 0.15 - 1×10^{-10} - 0.15

Table 7.1: Summary of emissivity study results.

Case	Method	$T_{comp}[K]$	$T_{exp}[K]$	Difference [%]	Soln. Time [hr]	$[\% \times hr]$
Mo-Mo-Mo	C-RS	1248.70	1283.68	2.72	6.51	17.71
	C-HC	1311.70	1283.68	2.18	1.07	2.33
	A-HC	1326.25	1283.68	3.32	3.43	11.39
Mo-G-Mo	C-RS	1203.10	1201.35	0.15	6.51	0.98
	C-HC	1227.50	1201.35	2.18	0.98	2.14
	A-HC	1287.75	1201.35	7.19	0.32	2.30
G-Mo-Mo	C-RS	1239.80	1166.07	6.32	8.37	52.90
	C-HC	1297.60	1166.07	11.28	1.07	12.07
	A-HC	1322.25	1166.07	13.39	4.75	63.60
G-G-Mo	C-RS	1201.30	1201.64	0.03	6.13	0.18
	C-HC	1226.90	1201.64	2.10	0.98	2.06
	A-HC	1286.65	1201.64	7.07	0.31	2.19
G-G-G	C-RS	1202.70	1211.07	0.69	6.82	4.71
	C-HC	1226.90	1211.07	1.31	0.97	1.27
	A-HC	1240.50	1211.07	2.43	0.14	0.34

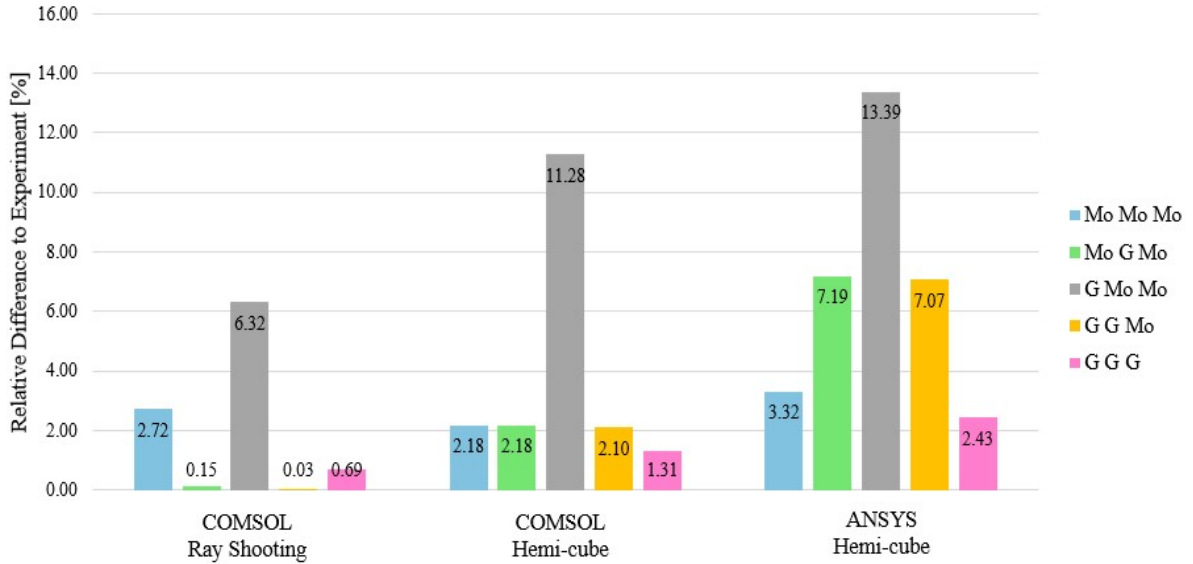


Figure 7.19: Visualization of relative difference for each solution method and emissivity case.

5. 1 - 1 - 0.15

6. 1×10^{-10} - 1×10^{-10} - 0.15

This series of computational tests produced eighteen (six per three solution methods) temperature profiles. Only a few figures will be included here for brevity. These investigations utilizing the extremes of possible emissivity values were conducted to emphasize the differences between highly scattering and highly absorbing material. Additionally, the extremes offer insight into the largest divergence possible from the standard solutions. The temperature cannot change more due to emissivity than when emissivity is at its fundamental limits.

The first limiting case presented here is shown in Figure 7.20. The results in this figure were obtained using COMSOL Ray Shooting. The emissivity of the top inner-most layer of insulation was set to 1 and to 1×10^{-10} (ϵ_{top}). Figure 7.20 (a) has the emissivity of the top surface set to 1. Figure 7.20 (b) has the emissivity of the top surface set to 1×10^{-10} . The legend units are Kelvin. The maximum temperature in Figure 7.20 (a) is $1.29 \times 10^{-3} K$ and the minimum is 588 K. The maximum temperature in Figure 7.20 (b) is $1.29 \times 10^{-3} K$ and the minimum is 393 K. Note that the color scale is not the same in (a) and (b). The solution time for (a) and (b) was 7.75 hours and 6.75 hours respectively. To keep this discussion independent of the view factor solution method to focus on the emissivity impacts, the COMSOL hemi-cube and the ANSYS hemi-cube results will be stored in Appendix A. The limiting emissivity cases produced similar trends across view factor solution methods as the earlier discussion pertaining to varying emissivity.

The second of two limiting cases presented here is shown in Figure 7.21. The results in this figure were obtained using COMSOL Ray Shooting. The emissivity of the side inner-most layer of insulation was set to 1 and to 1×10^{-10} (ϵ_{side}). Figure 7.21 (a) has the emissivity of the side surface set to 1. Figure 7.21 (b) has the emissivity of the side surface set to 1×10^{-10} . The legend units are Kelvin. The maximum temperature in Figure 7.21 (a) is $1.28 \times 10^{-3} K$ and the minimum is 569 K. The maximum temperature in Figure 7.21 (b) is $1.31 \times 10^{-3} K$ and the minimum is 569 K. The solution time for (a) and (b) was 8.09 hours and 9.00 hours respectively. The limiting emissivity cases produced similar trends across view factor solution methods as the earlier discussion pertaining to varying emissivity. The remaining fourteen results for various solution methods and emissivity settings can be found in Appendix A starting with Figure A.33.

From the computational results it can be seen that emissivity is inversely proportional to scattering. As emissivity decreases, scattering increases, and biases the energy deposition away from the low emissivity surface. Considering the case where the side emissivity is set to zero, the thermal radiation is scattered elsewhere in the plenum region. Wielding the dependence of directional heating on emissivity has practical benefits. If the goal is to generate localized heating, it is beneficial to lower the emissivity of the side walls to scatter the thermal radiation toward other regions. The spatial variations of emissivity influence the spatial variations of radiation heat transfer.

7.3 Geometry Dependence

To investigate the role that the view factor solution methods play in radiative heat transfer independent of geometry, two simple geometries were established. The modeled systems were a sphere in a sphere and a cylinder in a cylinder. Both of these geometries were studied in COMSOL using each the Ray Shooting and hemi-cube methods. The bodies were set to be molybdenum (Table 6.1) to weakly mimic the thermal radiation environment in OUTSET.

For the sphere in a sphere geometry, the inner sphere was solid with an outer diameter of 15 mm. The outer sphere was hollow with an outer diameter of 30.15 mm and an inner diameter of 30 mm. This thickness is equal to the molybdenum foil thickness used in OUTSET. This geometry is shown in Figure 7.22. For heat generation, 300 W was applied to the inner sphere. The space is vacuum between the inner and outer spheres - enabling radiative heat transfer.

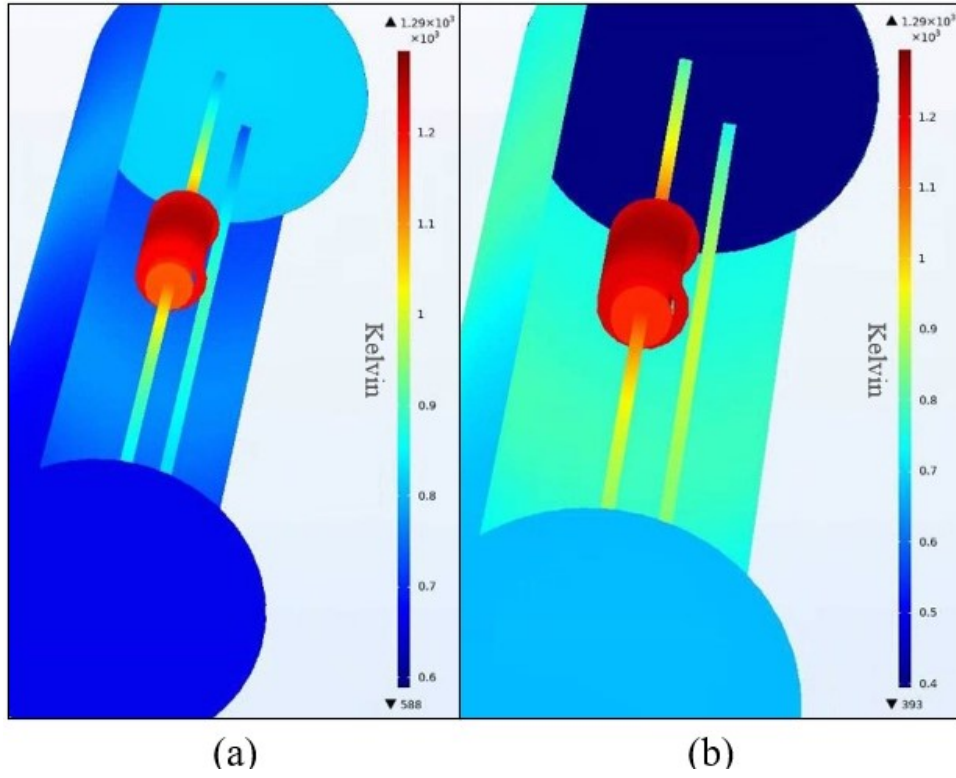


Figure 7.20: Temperature distribution of top emissivity limiting cases $[K]$.
 (a) $\epsilon_{top} = 1$. (b) $\epsilon_{top} = 1 \times 10^{-10}$. Using COMSOL Ray Shooting.

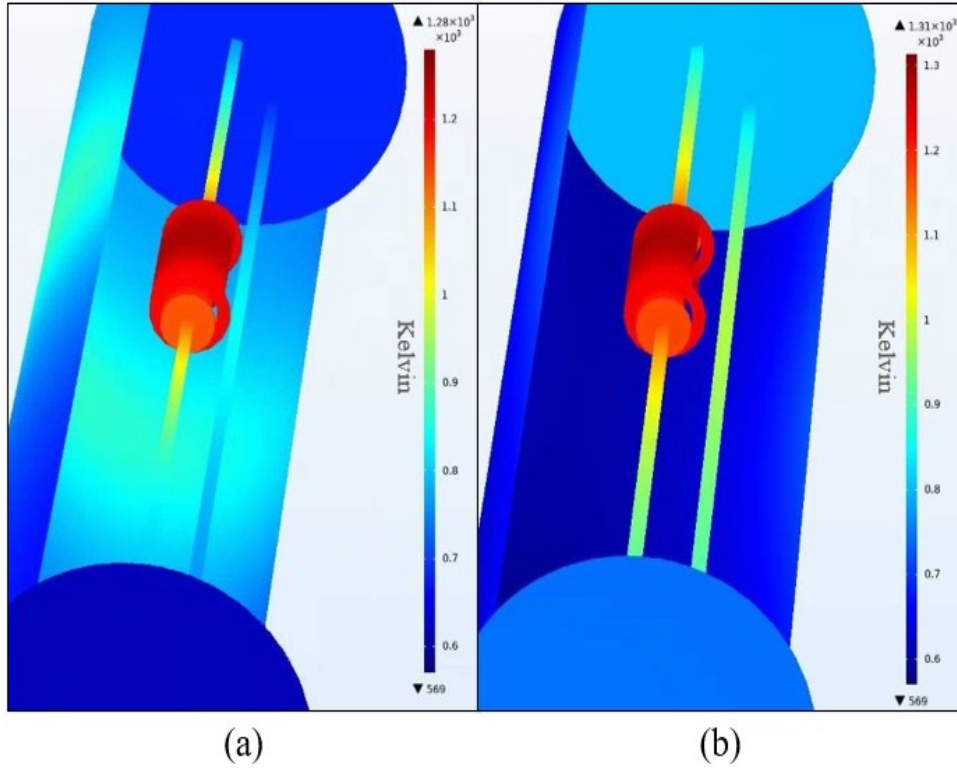


Figure 7.21: Temperature distribution of side emissivity limiting cases [K].
 (a) $\epsilon_{side} = 1$. (b) $\epsilon_{side} = 1 \times 10^{-10}$. Using COMSOL Ray Shooting.

The sphere in sphere Ray Shooting case took 1.12 *hours* to solve. The solution produced an inner sphere surface temperature of 2266.1 *K* and a maximum outer sphere surface temperature of 1747.6 *K*. The sphere in sphere hemi-cube case took 0.03 *hours* to solve. The solution produced an inner sphere surface temperature of 2265.2 *K* and a maximum outer sphere surface temperature of 1746.5 *K*. The two cases varied by 0.04% at the inner sphere and by 0.97% at the outer sphere. The hemi-cube solution solved 37 times faster than the Ray Shooting solution.

For the cylinder in cylinder geometry, the inner cylinder was solid with an outer diameter of 15 *mm* and a height of 30 *mm*. The outer cylinder was hollow with an outer diameter of 30.15 *mm*, an inner diameter of 30 *mm*, and a height of 200 *mm*. This geometry is shown in Figure 7.23. For heat generation, 300 *W* was applied to the inner cylinder. The space is vacuum between the inner and outer cylinders.

The cylinder in cylinder Ray Shooting case took 1.77 *hours* to solve. The solution produced an inner cylinder surface temperature of 2059.3 *K* and a maximum outer cylinder surface temperature of 1598.6 *K*. The cylinder in cylinder hemi-cube case took 0.11 *hours* to solve. The solution produced an inner cylinder surface temperature of 2058.5 *K* and a maximum outer cylinder surface temperature of 1571.0 *K*. The two cases varied by 0.04% at the inner cylinder and by 1.76% at the outer cylinder. The hemi-cube solution solved 16 times faster than the Ray Shooting solution. The cylinder in cylinder geometry is more similar to the OUTSET geometry than the sphere in sphere geometry.

The simple geometries presented here are intended to contrast the more complex OUTSET radiative heat transfer solutions. The OUTSET model offers information regarding solutions using a geometry of a fixed complexity. To investigate how thermal radiation solution methods perform in cases with varying complexity, simple cases were also investigated.

7.4 Boundary Condition Sensitivity

The computational models require a thermal boundary condition be provided to converge to a solution. The full model of OUTSET including every component from the external body, every layer of felt, and every passthrough was originally considered. This model was incredibly computationally expensive to solve - requiring greater than 5 *days* to solve. For the full model, a boundary condition is easy to define. The external surface temperature of OUTSET is controllable during experimental runs. However, with the reduced model presented in this document, a boundary condition setting is less trivial. The reduced model removed the external structural components, all but the inner-most layers of insulation, and the passthroughs to reduce computational cost. The boundary condition setting determination was further complicated by the inability to access the experiment due to the COVID-19 pandemic. This situation forced the models to be developed and run without any experimental insight. If this work were to be performed again, it is recommended that the experiments and models are conducted in parallel - taking advantage of experimental insights and applying them to the models. In an attempt to combat the lack of experimental feedback, a boundary condition sensitivity study was performed. This work used OUTSET-1 as a weak basis for decision making.

The boundary condition applied to the models was on the not-heater-facing side of the inner-most layer of insulation. This surface is the external surface of the reduced (schematic in Figure 3.12) model of OUTSET. Due to the physical nature of the graphite felt, the contact between the felt and molybdenum in addition to the felt with other layers of felt was poor. The woolly texture of the felt prevented close spatial and thermal contact between layers of insulation. As such, a radiative boundary condition was applied to the aforementioned confining surface. At such low contact pressure between the layers of insulation, a radiative boundary condition is suspected to be more representative of the physical system than a conductive or convective setting. Later, during experimental runs using molybdenum foil as the inner-most layer of insulation, the side foil was not in contact with the next layer of insulation in some places - making the only thermal exchange through radiation. The boundary condition setting also had to be compatible with both COMSOL and ANSYS.



Figure 7.22: Sphere in sphere geometry.

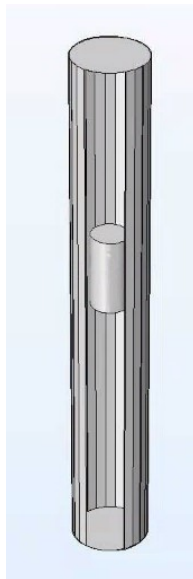


Figure 7.23: Cylinder in cylinder geometry.

The radiation boundary condition implemented in this sensitivity study varied from 303 K to 2273 K. These temperature settings were applied to the ambient environment that the external model surface was radiating to. For example, when considering the 303 K case, the external model surface radiated to an ambient environment of 303 K. This study was conducted in ANSYS using 500 W of power delivered to the heater of OUTSET. The value of 500 W was the early expected value to enable OUTSET to reach 2000 K at the shell TC. Each model in this study took around 3.14 hours to solve. The results of the study are plotted in Figure 7.24. The shell TC temperatures are labeled on the plot so it is easier to identify minor changes.

Note that from Figure 7.24 some boundary condition settings are heating the heater. When the boundary condition is set to a higher temperature than the heater would naturally reach, the walls will transfer thermal energy to the heater - producing a higher temperature. This is shown by the rapid growth of the trend. To offset this impact of boundary condition induced heating, which is not physical, the chosen boundary condition for the already presented 200 W models was 373 K. The 500 W boundary condition results imply that a boundary condition of a radiative thermal exchange to an ambient environment at 373 K will not substantially drive the results of the 200 W cases.

7.5 Computational Uncertainty Quantification

The estimated error calculated within COMSOL provides a quantification of the error in the reported temperature levels. This error was calculated using the L^2 norm function within the steady-state solution. The L^2 norm function is shown in Equation 7.3 taken from reference [58]. The implementation of the L^2 norm in COMSOL is thoroughly described in reference [58]. ANSYS also reports error using the L^2 norm function.

$$\|\nu\| = \sqrt{\int \nu^2(x) dx} \quad (7.3)$$

where:

ν = function space compared to mean that can be integrated over all locations

x = generic position variable

The L^2 norm error associated with each base case at the shell TC location will be presented here. Each base case uses 200 W of power, molybdenum foil along every inner-most surface, the standard TC setup, and a different view factor solution method. The L^2 norm at the shell TC for the base COMSOL Ray Shooting case was 1.85×10^{-5} K. The L^2 norm at the shell TC for the base COMSOL hemi-cube case was 2.38×10^{-5} K. The L^2 norm at the shell TC for the base ANSYS hemi-cube case was 6.21×10^{-3} K. The L^2 norm error is indicative of the uncertainty produced within the model as a result of the model's computation. This error is representative of the quality of the iterative solver's approximate solution.

For other emissivity cases, the L^2 norm values are of similar magnitudes as the aforementioned values. The maximum and minimum L^2 norm values at the shell TC are as follows. The maximum L^2 norm for COMSOL Ray Shooting came from the G-G-G case with a value of 2.15×10^{-5} K. The minimum L^2 norm for COMSOL Ray Shooting came from the 1×10^{-10} - 1×10^{-10} - 0.15 case with a value of 1.71×10^{-5} K. The maximum L^2 norm for COMSOL hemi-cube came from the 1×10^{-10} - 1×10^{-10} - 0.15 case with a value of 2.41×10^{-5} K. The minimum L^2 norm for COMSOL hemi-cube came from the G-Mo-Mo case with a value of 2.37×10^{-5} K. The maximum L^2 norm for ANSYS hemi-cube came from the 0.15 - 1×10^{-10} - 0.15 case with a value of 6.29×10^{-3} K. The minimum L^2 norm for ANSYS hemi-cube came from the G-G-G case with a value of 6.20×10^{-3} K. As stated in Section 7.2, the naming convention used is as follows: Top-Side-Bottom. For example, if every inner-most layer of insulation of molybdenum the case would be referenced as "Mo-Mo-Mo". If the side wall was replaced with graphite felt it would be named "Mo-G-Mo". If the bottom was then also replaced with graphite, "Mo-G-G" would be used. In the limiting emissivity cases, the value of emissivity is listed (i.e. 1×10^{-10}).

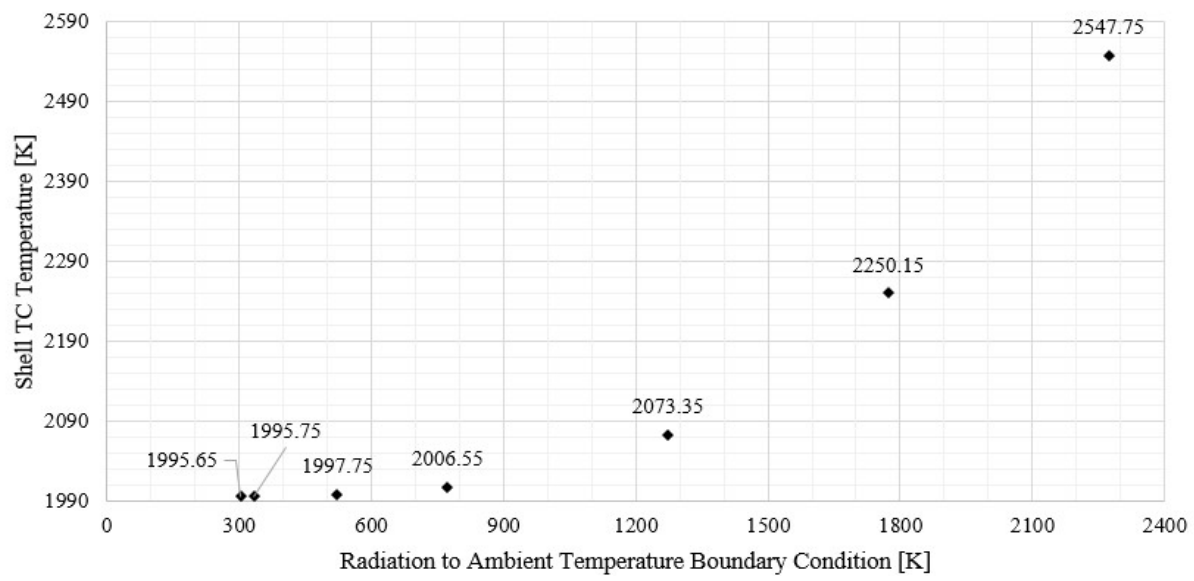


Figure 7.24: Computational boundary sensitivity shell TC results.

The L^2 norm also varied per mesh. The above values are at the shell TC for the chosen mesh with 31990 *elements*, maximum element size of 0.055 *mm*, and a minimum element size of 0.004 *mm*. The largest base case L^2 norm at the shell TC was $2.40 \times 10^{-2} K$. This maximum occurred using ANSYS hemi-cube and a mesh with 21690 *elements*. The smallest base case L^2 norm at the shell TC was $5.14 \times 10^{-8} K$. This minimum occurred using COMSOL Ray Shooting and a mesh with 85445 *elements*. This mesh took about 33 *hours* to solve and was not compatible with ANSYS.

An example of the spatial L^2 norm error distribution in the model is shown in Figure 7.25. The slightly lighter colors correspond to areas of larger error. There were spikes in the error at the interface of the heater shell and heater plugs, which is why the scale in Figure 7.25 shows a high maximum. These spikes are due to inconsistent meshing across boundaries. Figure 7.25 is difficult to interpret due to the isotropic error, but the model is oriented in the same manner as Figure 7.17, for example.

The L^2 norm error is the inherent model solution uncertainty. The other source of computational uncertainty pertains to the model inputs.

The impact of the model inputs on the final thermal results was evaluated through a perturbation study. Values for emissivity and thermal conductivity were perturbed for each software and view factor solution method. The size of these perturbations were defined through uncertainties in the properties reported in literature. Similar work was performed using OUTSET-1. The OUTSET-1 perturbation study used ANSYS hemi-cube. This work will reference the results from the OUTSET-1 perturbation study. This work will also present the results when using COMSOL Ray Shooting and COMSOL hemi-cube. Table 7.2 shows the nominal and adjusted values for each parameter perturbed. The reference that was used to set the perturbation range is also provided in Table 7.2. All perturbations were applied to the base case (Table 6.1).

The total computational uncertainty will result from the L^2 norm error and the model input uncertainty. The error sources are independent quantities so the errors will add in quadrature. This process has been demonstrated in Section 3.5 by Equation 3.5 [42]. Translating the general form of Equation 3.5 into terms relevant to the computational uncertainty yields Equation 7.4. The L^2 norm uncertainty was obtained by converting the reported L^2 norm value to a percentage of the nominal temperature value via division.

$$\sigma_{total} = \sqrt{\sigma_{L^2}^2 + \sigma_{G-emis}^2 + \sigma_{G-k-plus}^2 + \sigma_{G-k-minus}^2 + \sigma_{Mo-emis}^2 + \sigma_{Al_2O_3-k}^2} \quad (7.4)$$

where:

$total$ = net computational uncertainty

L^2 = from L^2 norm

$G - emis$ = from graphite emissivity perturbation

$G - k - plus$ = from graphite thermal conductivity +5% perturbation

$G - k - minus$ = from graphite thermal conductivity -5% perturbation

$Mo - emis$ = from molybdenum emissivity perturbation

$Al_2O_3 - k$ = from alumina thermal conductivity perturbation

The results of the perturbation study using the COMSOL Ray Shooting solution method are shown in Table 7.3. The reported temperatures correspond to the computed values at the shell TC. The perturbed temperature (Perturbed Temp.) was generated by adjusting the specified input only.

Using Equation 7.4, the error associated with the COMSOL Ray Shooting model inputs is quantified in Equation 7.5. The terms are presented in the order listed in Equation 7.4. The values are taken from Table 7.3.

$$\sigma_{CRS} = \sqrt{(1.48 \times 10^{-6}\%)^2 + (-0.72\%)^2 + (-0.05\%)^2 + (0.05\%)^2 + (-0.78\%)^2 + (-0.42\%)^2} = 1.14\% \quad (7.5)$$

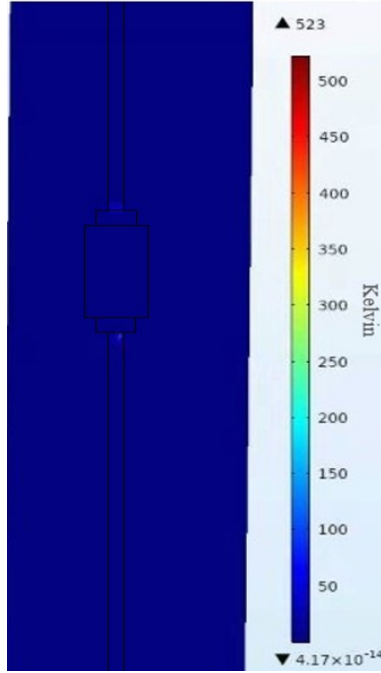


Figure 7.25: L^2 norm error distribution for Mo-Mo-Mo 200 W case.

Table 7.2: Perturbation settings for computational systematic uncertainty quantification.

Parameter	Nominal Value	Perturbed Value	Reference
Graphite emissivity	0.75	0.80	[22]
Graphite thermal conductivity	100%	$\pm 5\%$	[22], [59]
Molybdenum emissivity	0.15	0.19	[22]
Alumina thermal conductivity	28 W/mK	6.3 W/mK	[60]

Table 7.3: Perturbation results for COMSOL Ray Shooting computational systematic uncertainty quantification.

Parameter	Difference [%]	Nominal Temp. [K]	Perturbed Temp. [K]
Graphite emissivity	-0.72	1248.70	1239.70
Graphite thermal conductivity +5%	-0.05	1248.70	1248.10
Graphite thermal conductivity -5%	0.05	1248.70	1249.30
Molybdenum emissivity	-0.78	1248.70	1239.00
Alumina thermal conductivity	-0.42	1248.70	1243.50

The results of the perturbation study using the COMSOL hemi-cube solution method are shown in Table 7.4. The reported temperatures correspond to the computed values at the shell TC.

Using Equation 7.4, the error associated with the COMSOL hemi-cube model inputs is quantified in Equation 7.6. The terms are presented in the order listed in Equation 7.4. The values are taken from Table 7.4.

$$\sigma_{CHC} = \sqrt{(1.81 \times 10^{-6}\%)^2 + (-0.48\%)^2 + (-0.05\%)^2 + (0.02\%)^2 + (-1.44\%)^2 + (0.08\%)^2} = 1.52\% \quad (7.6)$$

Using the results from Reference [22] and OUTSET-1, the ANSYS hemi-cube perturbation study produces the variations seen in Table 7.5. Table 7.5 has been adapted from Reference [22]. The percent differences listed by Reference [22] were applied to the results of the OUTSET model to generate the temperature values shown in Table 7.5. The alumina thermal conductivity adjustment is unique to this work. These temperature values are the steady-state temperature reported by the shell TC.

Using Equation 7.4, the error associated with the ANSYS hemi-cube model inputs is quantified in Equation 7.7. The terms are presented in the order listed in Equation 7.4. The values are taken from Table 7.5.

$$\sigma_{AHC} = \sqrt{(4.68 \times 10^{-4}\%)^2 + (-1.46\%)^2 + (-0.14\%)^2 + (0.15\%)^2 + (0.26\%)^2 + (0.15\%)^2} = 1.50\% \quad (7.7)$$

The differences between the calculated computational uncertainty and the experimentally obtained values (Table 7.1) can be attributed to the view factor solution method. The RHT view factors were computed via proprietary means. It is not possible to directly calculate the uncertainty associated with the view factors. The error associated with user input was quantified through a perturbation study. The intrinsic error associated with computational solver was quantified through the L^2 norm. The remaining differences between the computational uncertainty and the experimental error must come from the view factor solution method.

Table 7.4: Perturbation results for COMSOL hemi-cube computational systematic uncertainty quantification.

Parameter	Difference [%]	Nominal Temp. [K]	Perturbed Temp. [K]
Graphite emissivity	−0.48	1311.70	1305.40
Graphite thermal conductivity +5%	−0.05	1311.70	1311.10
Graphite thermal conductivity −5%	0.02	1311.70	1312.00
Molybdenum emissivity	−1.44	1311.70	1292.80
Alumina thermal conductivity	0.08	1311.70	1312.80

Table 7.5: Perturbation results for ANSYS hemi-cube computational systematic uncertainty quantification.

Parameter	Difference [%]	Nominal Temp. [K]	Perturbed Temp. [K]
Graphite emissivity	−1.46	1326.25	1306.89
Graphite thermal conductivity +5%	−0.14	1326.25	1324.39
Graphite thermal conductivity −5%	0.15	1326.25	1328.24
Molybdenum emissivity	0.26	1326.25	1329.70
Alumina thermal conductivity	0.15	1326.25	1328.27

8 RHT Discussion

Series of experiments were conducted with varying radiative heat transfer environments. These tests were conducted to evaluate the accuracy of popular modern thermal modeling software and view factor solution methods. These experiments were performed using OUTSET heated by 200 W of power (DC) and an internal pressure below 10 *mTorr*. The computational models that were investigated were the COMSOL Ray Shooting, COMSOL hemi-cube, and the ANSYS hemi-cube radiation view factor solution methods.

The experiments used various combinations of highly scattering molybdenum foils and highly absorbing graphite felt to manipulate the radiative heat transfer environment. Each experimental thermocouple reading was averaged over three runs to mitigate sources systematic error. The varying emissivity configurations were replicated by the thermal models. The computational cost and accuracy to the experiment were used to evaluate the various models' success.

Table 7.1 shows the relative success and computational solution time associated with each emissivity configuration. The COMSOL Ray Shooting method resulted in a calculated thermocouple temperature closer to the experimental reading four out of five times. COMSOL Ray Shooting also had the longest solution times five out of five times. The hemi-cube results overpredict the TC temperature levels in five out of five cases.

Each solution method produced its largest disagreement with the experimental data in an emissivity environment with high directional scattering. The G-Mo-Mo case presents an environment where the thermal radiation was scattered away from the bottom and side of the heated plenum region and towards the top. The solution methods show agreement with the experimental data in a uniform highly absorbing environment (G-G-G). The hemi-cube results from ANSYS and COMSOL produced their smallest deviations from the experiential results in the G-G-G case.

The computational uncertainty was quantified by considering the error associated from user input and material properties through a perturbation study. The inherent solver L^2 norm error was also used in this evaluation. The remaining separation between the predicted computational uncertainty and the experimental results was from the RHT view factor solution method and computation.

9 Conclusions

INSET can moderately reliably generate thermocouple temperatures from 293 K to around 1300 K at the heater shell for multiple hours. It can yield 1800 K at this location for a brief period, but cannot sustain this level. These temperature levels has been applied to in-pile instrument testing for nuclear thermal propulsion systems. INSET can simulate the thermal environment of most locations in a proposed nuclear thermal propulsion flight demonstration while maintaining reactor compatibility.

Scaling OUTSET/INSET to a larger design than the preliminary OUTSET-1 configuration proved to be challenging. The larger system cannot replicate the 2300 K temperature levels reported from OUTSET-1 ([22]). Isolating and changing the heater ceramic material, the heater plug configuration, the presence of a heater shell, the form factor of the heater filament, and the thermal ramp rate has not produced the experimental success seen in the smaller OUTSET-1.

The temperature range producible by INSET also serves as a viable testing environment for radiative heat transfer experiments. The out-of-pile twin of INSET, OUTSET, was utilized to validate computational radiative heat transfer view factor solution methods. OUTSET was used to validate COMSOL and ANSYS radiative heat transfer models. Both hemi-cube and Ray Shooting radiation view factor solution methods were compared against experimental data. Models and experiments with various emissivity configurations were executed. OUTSET served as a validation tool to identify the accuracy of the models in these highly scattering and highly absorbing radiation environments. The accuracy and computational time of the various modeling approaches have been quantified and compared against redundant OUTSET experiments that

were heated using 200 W. COMSOL Ray Shooting yielded thermal results closest to the experimental results in four out of five emissivity cases. COMSOL Ray Shooting also had the longest solution times in five out of five emissivity cases. COMSOL Ray Shooting, COMSOL hemi-cube, and ANSYS hemi-cube each yielded the largest disagreement with the experimental results in a high directional scattering environment. This study has shown the significance of the view factor solution method. Different view factor approaches produced different errors and solution times. A figure of merit was considered using the five emissivity cases. This figure of merit was quantified by multiplying the solution time and the percent difference against the experiment. A larger number implies a less attractive method - either due to a large error and/or a long solution time. The results from this attempt did not offer decisive and clear insight into the relative success of the models.

The concept of a rapidly deployable and relatively inexpensive steady-state, high temperature, in-pile testbed has usages for NTP demonstration. This value has been demonstrated by INSET, despite the inability to achieve controllable temperature levels of 2500 K with the current heater design. The continuation of development of INSET will further enhance the demonstrated ability of the experiment apparatus.

10 Future Work

The work presented in this document identified some challenges with the current iteration of INSET - namely the ability to control and monitor temperature levels up to 2500 K. To reach these temperature levels, the heater should be redesigned. Project POODLE presents a reasonable starting point for such a redesign. Integrating one of the Project POODLE heaters into INSET may enable the system to reach maximum NTP prototypical conditions. To verify the goal temperatures are being generated, instrumentation beyond thermocouples is recommended. The high current electrical environment of the experiment prevents thermocouples from recording at every location of interest. A combination of thermocouples, optical pyrometry, and melt wires should be implemented. This is also reminiscent of the POODLE design. Once INSET can properly achieve 2500 K, possibly through the use of a Project POODLE heater, it will be able to simulate (in a reactor) the temperature and radiation environment of a nuclear thermal rocket.

Following the successful demonstration of a high temperature in-pile system, the apparatus should be developed to accept heated hydrogen flow. Hydrogen is the identified propellant for nuclear thermal rockets. Fortunately, Project POODLE considered the compatibility with hydrogen when selecting materials for the heater and the insulation. Project POODLE also reports a successful heating of 2300 K for 72 hours in the presence of hydrogen flow. Integrating the work demonstrated in Project POODLE into INSET may alleviate some of the challenges with elevated temperature levels as well as with the introduction of hydrogen.

Heating the experiment through a nuclear source eliminates some of the challenges observed with electrical heating and is more akin to the nuclear thermal propulsion environment. The heater design presented in this document is such that a nuclear source can simply replace the electrical heater. OUTSET/INSET remains compatible with nuclear heated specimens. Additional instrumentation is still recommended for a nuclear source.

Active cooling will be required on the external surface of the apparatus if elevated power levels are applied to and sustained within INSET to yield 2500 K. During 1 kW tests, the surface of the apparatus reached temperatures up to 430 K. This temperature exceeds the boiling point of the moderator used in most reactors. To prevent boiling the moderator, active cooling is necessary on the surface of INSET.

The radiative heat transfer investigations utilized two different materials to dictate the emissivity environment - molybdenum foil and graphite felt. Expanding on these investigations by incorporating materials with emissivity values above 0.75, below 0.15, and between these values may identify further shortcomings and strengths in the modeling software. Software packages beyond COMSOL and ANSYS should also be considered. A figure of merit could be developed to quantify the success of the various modeling approaches.

Expanding on the work shown here would present the opportunity to develop a robust figure of merit. Such a figure of merit could be used to drive decisions when choosing software packages as well as radiative heat transfer view factor solution methods.

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Appendices

Herein contains auxiliary information that is supplemental to the main body of this document.

Appendix A Additional Figures

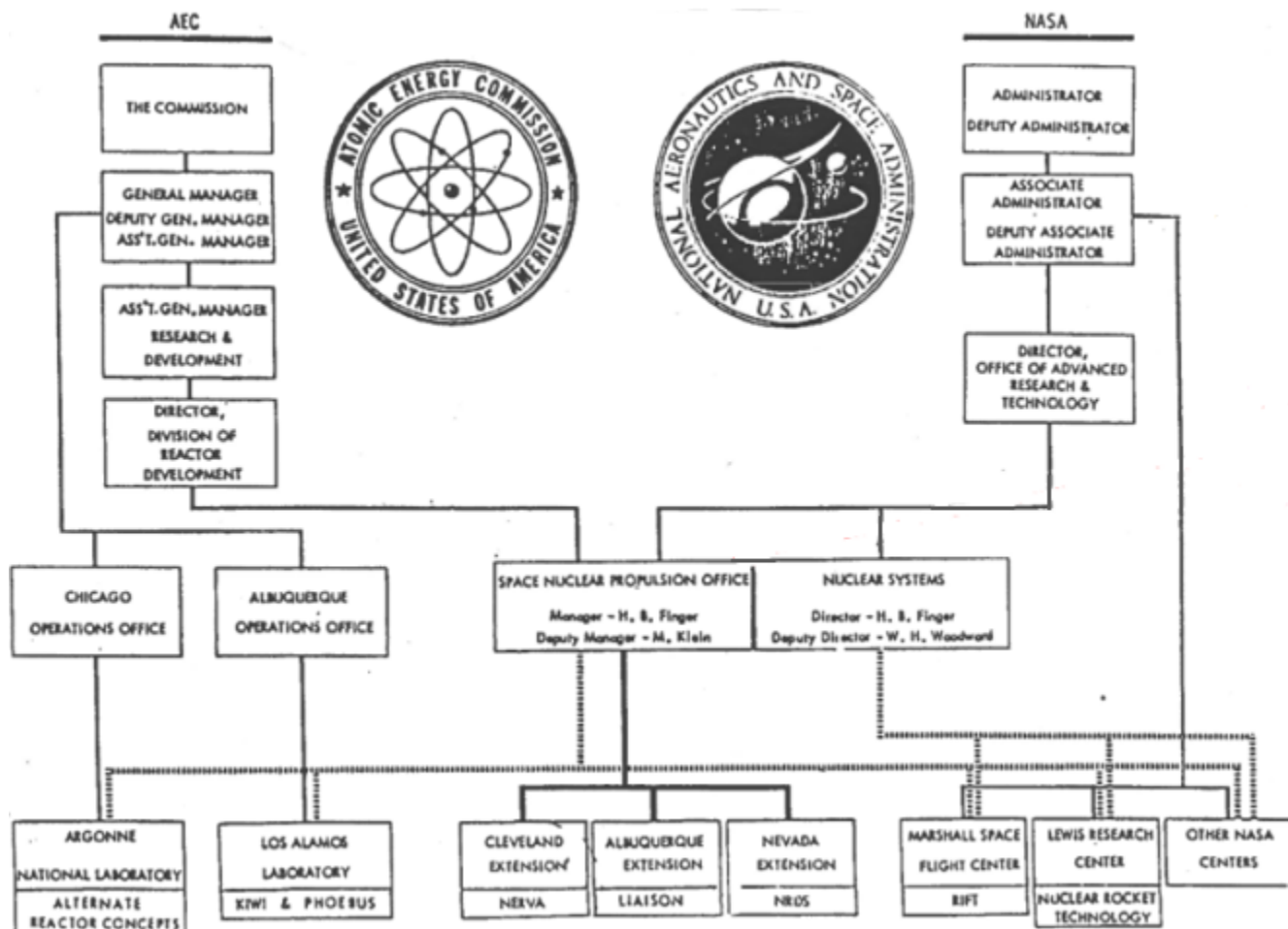


Figure A.1: Rover program organizational structure [11].

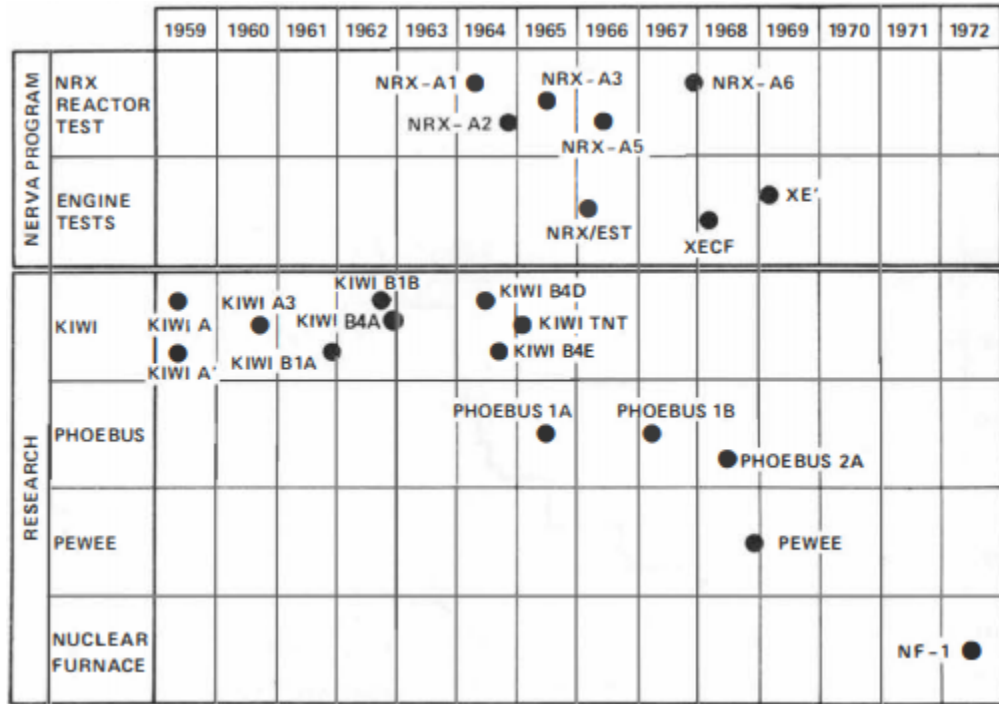


Figure A.2: Chronology of rocket reactor tests during the Rover program [4].

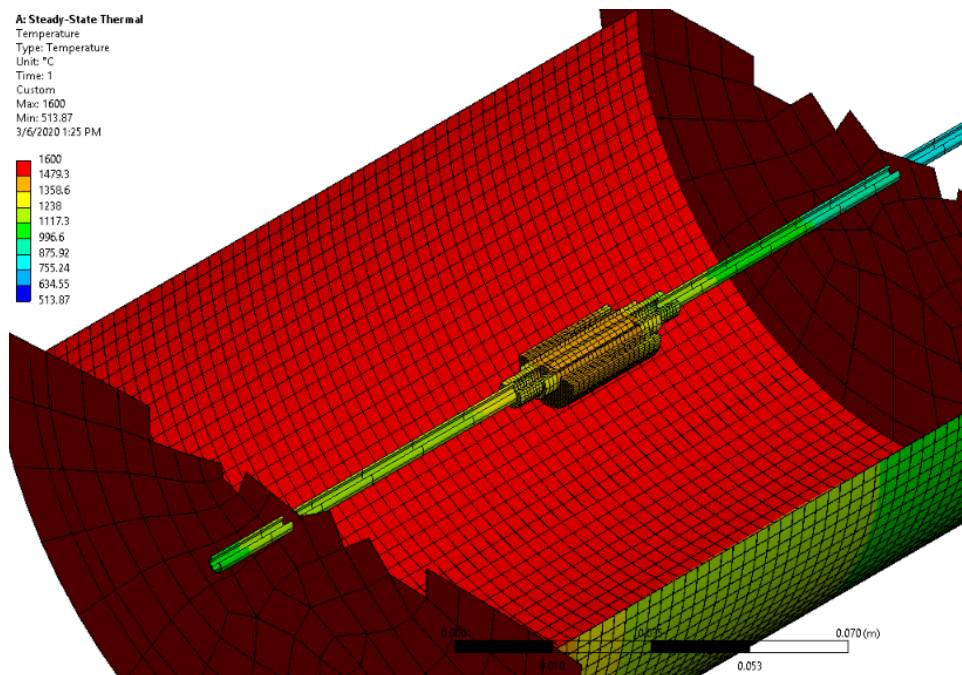


Figure A.3: Heat loss investigation: Large with tubes.

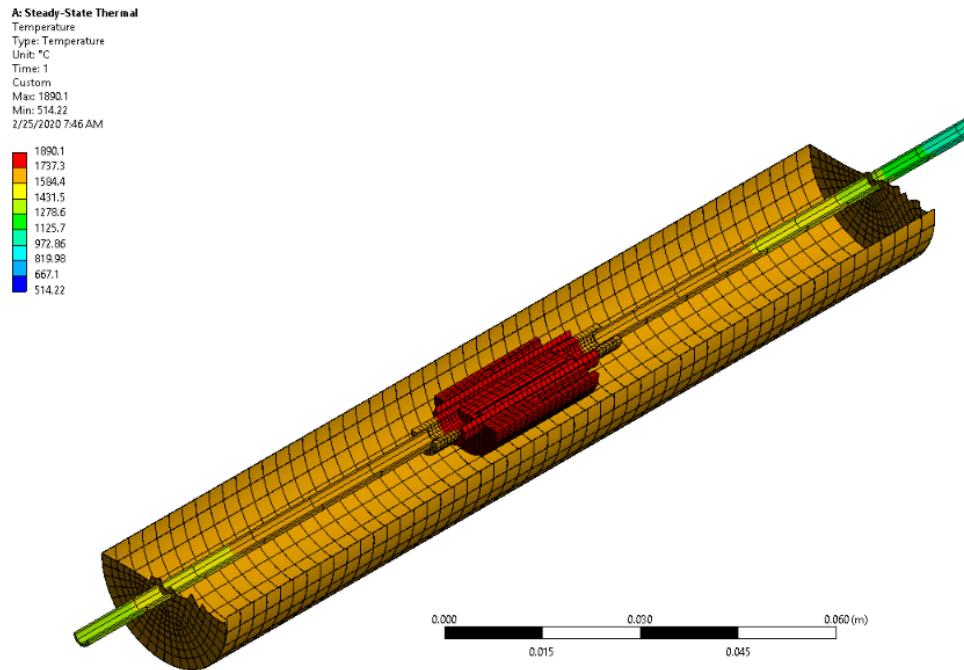


Figure A.4: Heat loss investigation: Small with tubes.

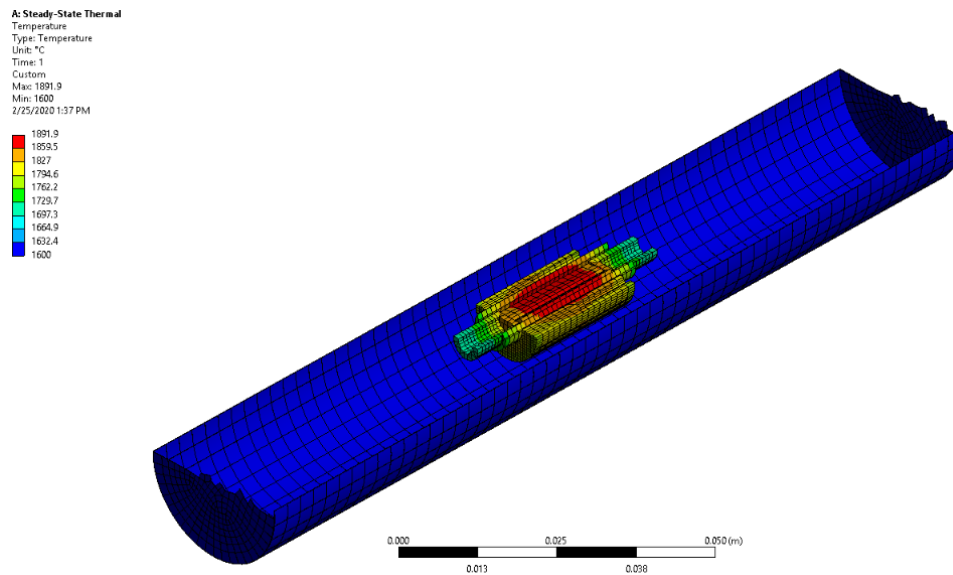


Figure A.5: Heat loss investigation: Small without tubes.

Quality Management
RRD Quality Team

Certificate of Verification

XL3-85241

Reading No	2
Mode	General Metals
Time	2019-11-19 03:48
Duration	6.89
Units	%
Sigma Value	2
Sequence	Final
Alloy1	Zr 705 : 0.69
Alloy2	No Match : *3.76
Flags	
Requisition #	RH111919
Item #	na
Description	material sample
Heat #	na
Supplier	na
Inspector	Hendricks



	%	±	Error
Sb	< LOD	:	0.148
Sn	< LOD	:	0.130
Cd	< LOD	:	0.126
Pd	< LOD	:	0.127
Ag	< LOD	:	0.186
Ru	< LOD	:	0.063
Mo	< LOD	:	0.193
Nb	2.229	±	0.061
Zr	94.049	±	1.536
Bi	< LOD	:	0.045
Se	< LOD	:	0.014
Au	< LOD	:	0.053
W	< LOD	:	0.002
Re	< LOD	:	0.160
Ta	< LOD	:	0.164
Hf	1.960	±	0.132
Ni	0.211	±	0.059
Co	< LOD	:	0.072
Fe	< LOD	:	0.114
Mn	< LOD	:	0.176
Cr	< LOD	:	2.112
V	< LOD	:	0.876
Ti	< LOD	:	1.951
Al	< LOD	:	80.000

Supervised By: BSH

Figure A.6: XRF results of McDanel ceramic.

XL3-85241			
Reading No	1		
Mode	General Metals		
Time	2019-11-19 03:48		
Duration	5.85		
Units	%		
Sigma Value	2		
Sequence	Final		
Alloy1	Zr 702 : 0.67		
Alloy2	No Match : *3.30		
Flags			
Requisition #	RH111919		
Item #	na		
Description	material sample 37		
Heat #	na		
Supplier	na		
Inspector	Hendricks		

	%	±	Error
Sb	< LOD	:	0.100
Sn	< LOD	:	0.087
Cd	< LOD	:	0.079
Pd	< LOD	:	0.077
Ag	< LOD	:	0.122
Ru	< LOD	:	0.030
Mo	0.335	±	0.097
Nb	< LOD	:	0.045
Zr	96.735	±	0.605
Bi	< LOD	:	0.026
Se	< LOD	:	0.011
Au	< LOD	:	0.047
W	< LOD	:	0.002
Re	< LOD	:	0.085
Ta	< LOD	:	0.142
Hf	1.974	±	0.113
Ni	< LOD	:	0.133
Co	< LOD	:	0.072
Fe	< LOD	:	0.098
Mn	< LOD	:	0.121
Cr	< LOD	:	0.608
V	< LOD	:	0.556
Ti	< LOD	:	0.729
Al	< LOD	:	80.000

Supervised By: ACH

Figure A.7: XRF results of ORNL's (Parten) ceramic.

Chemical Analysis:	
MgO +Y2O3	99.38%
CaO	0.38%
SiO2	0.04%
Al2O3	0.03%
Fe2O3	0.16%
C	<50 ppm
S	<10 ppm
B	<10 ppm
Cd	<10 ppm
B+Cd	<20 ppm
Y2O3	2%

Figure A.8: Tateho-Ozark high density magnesia composition [34].

Chemical Analysis:	
MgO	99.40%
CaO	0.32%
SiO₂	0.07%
Al₂O₃	0.03%
Fe₂O₃	0.06%
C	<50 ppm
S	<10 ppm
B	<10 ppm
Cd	<10 ppm
B+Cd	<20 ppm

Figure A.9: Tateho-Ozark high purity magnesia composition [34].

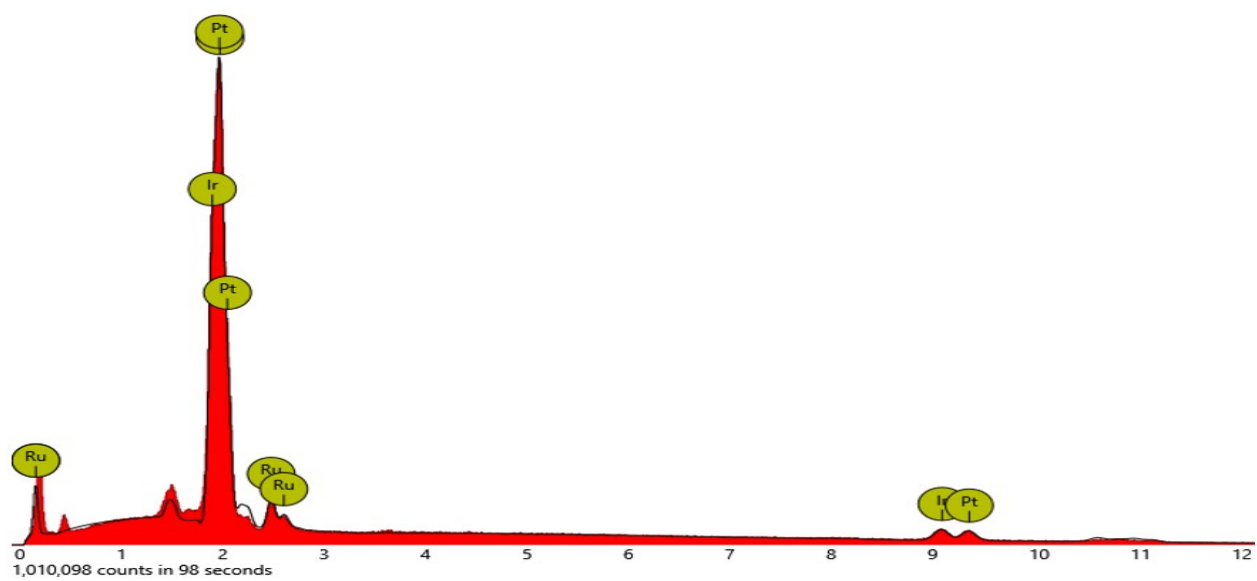


Figure A.10: EDXS spectrum of platinum-iridium melt wire.

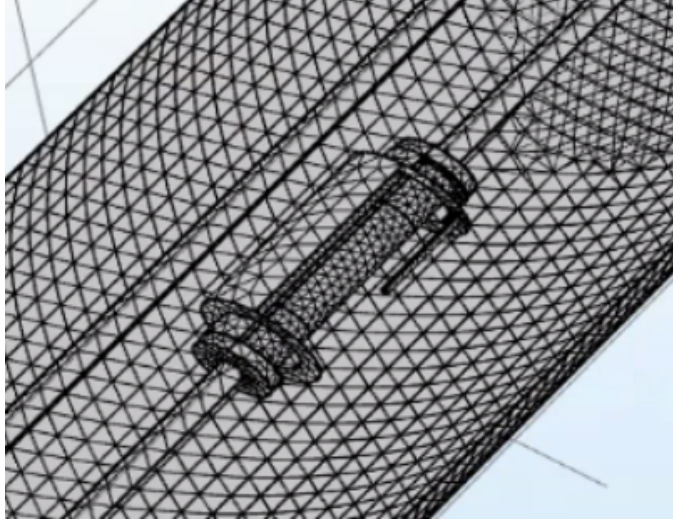


Figure A.11: Free tetrahedral mesh for RHT investigations with 54737 *elements*.

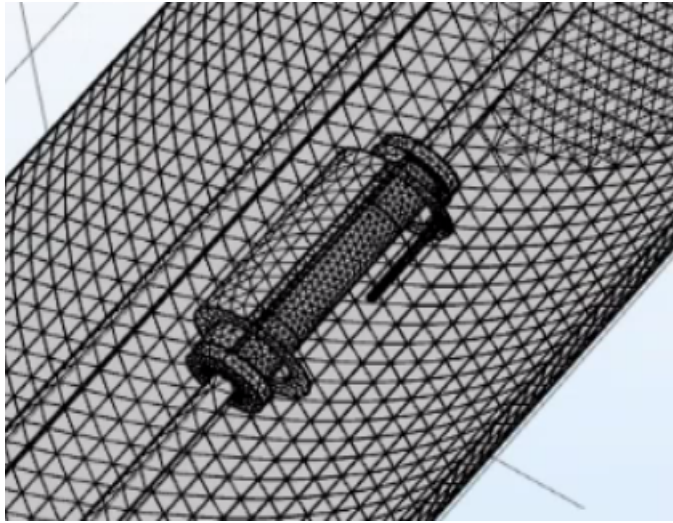


Figure A.12: Free tetrahedral mesh for RHT investigations with 85445 *elements*.

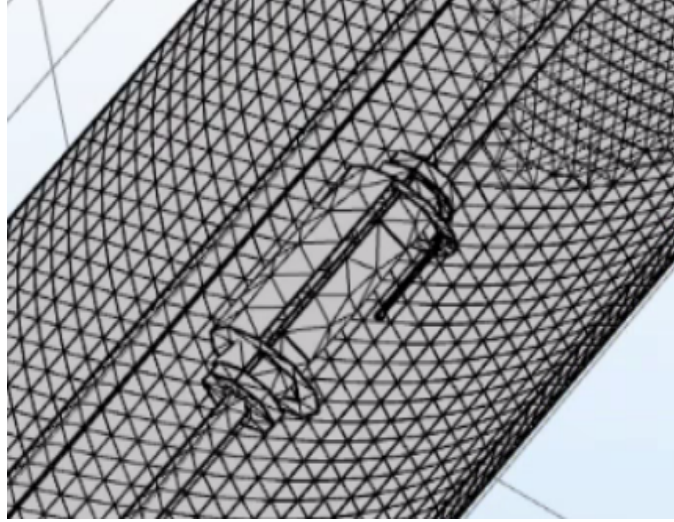


Figure A.13: Free tetrahedral mesh for RHT investigations with 45802 *elements*.

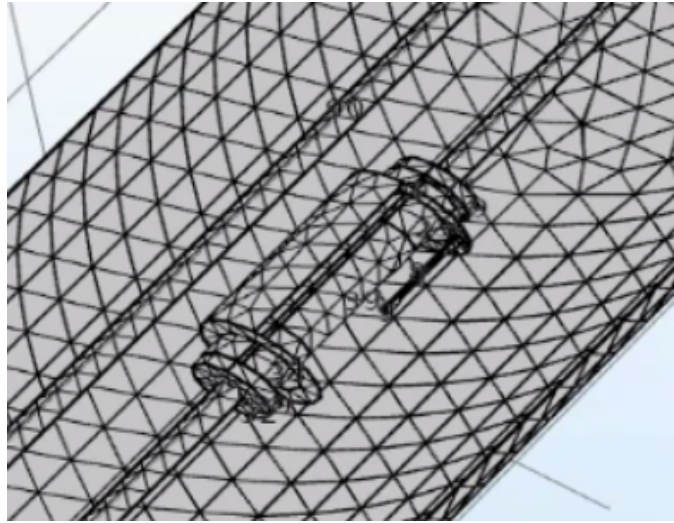


Figure A.14: Free tetrahedral mesh for RHT investigations with 21690 *elements*.

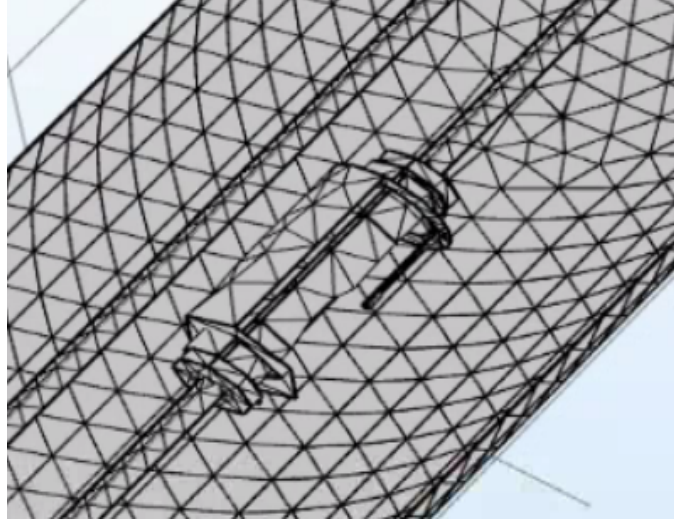


Figure A.15: Free tetrahedral mesh for RHT investigations with 20335 *elements*.

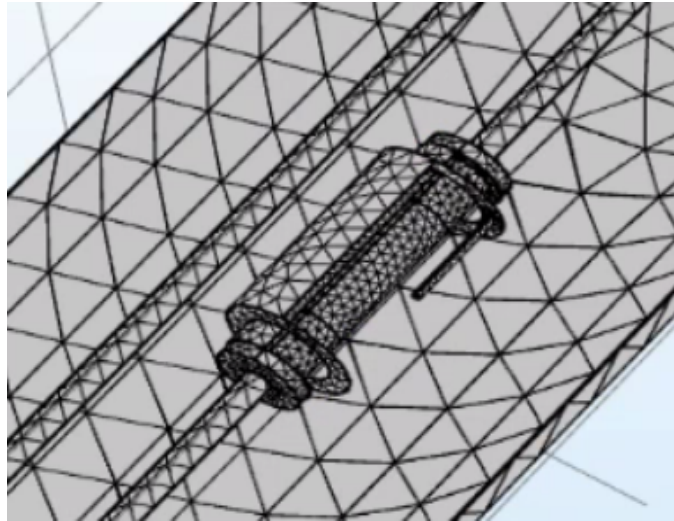


Figure A.16: Free tetrahedral mesh for RHT investigations with 24634 *elements*.

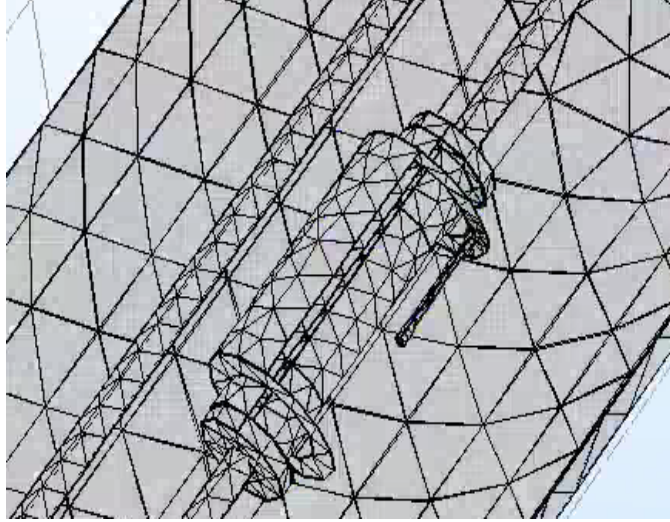


Figure A.17: Free tetrahedral mesh for RHT investigations with 14334 *elements*.

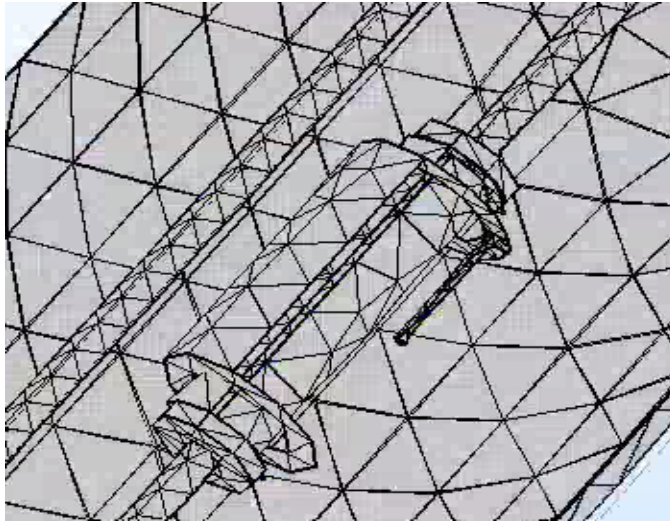


Figure A.18: Free tetrahedral mesh for RHT investigations with 13248 *elements*.

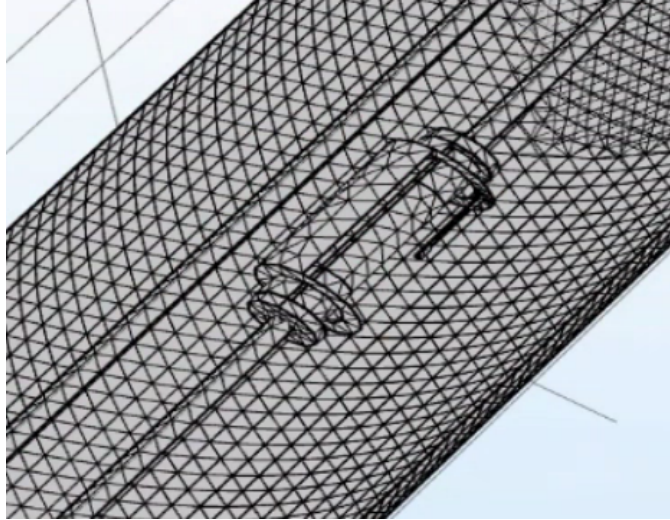


Figure A.19: Free tetrahedral mesh for RHT investigations with 46777 *elements*.

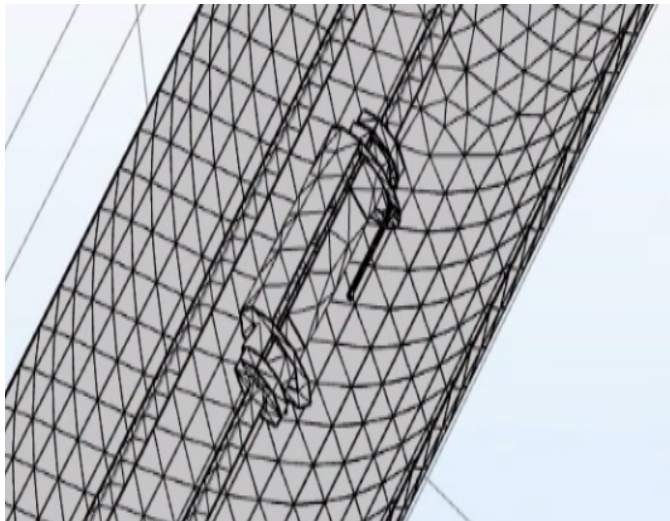


Figure A.20: Free tetrahedral mesh for RHT investigations with 20604 *elements*.



Figure A.21: Free tetrahedral mesh for RHT investigations with 12979 *elements*.

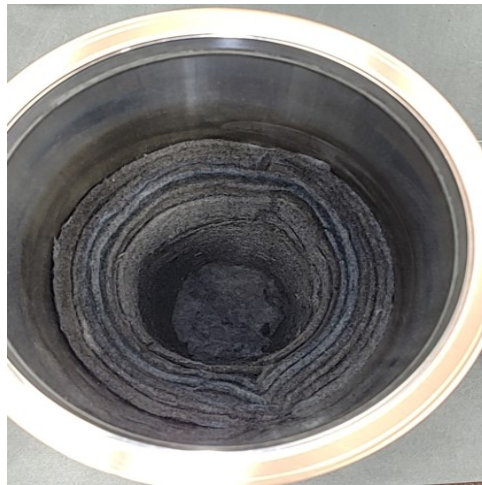


Figure A.22: Minimum insulation used in OUTSET - GFA graphite felt layers (top not shown).

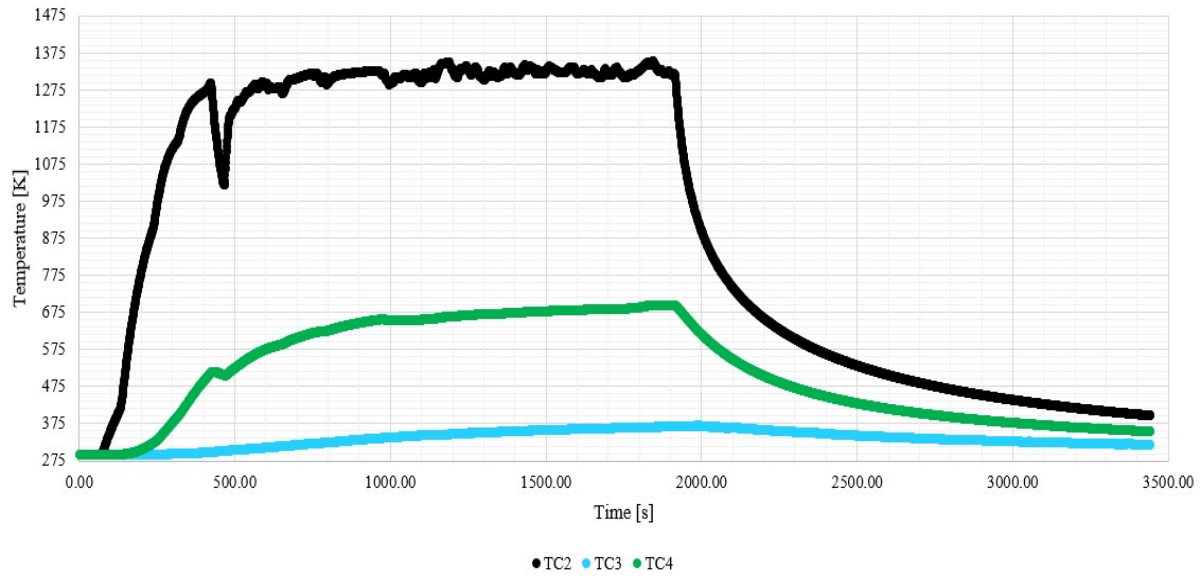


Figure A.23: June 8, 2021 Mo-Mo-Mo TC data.

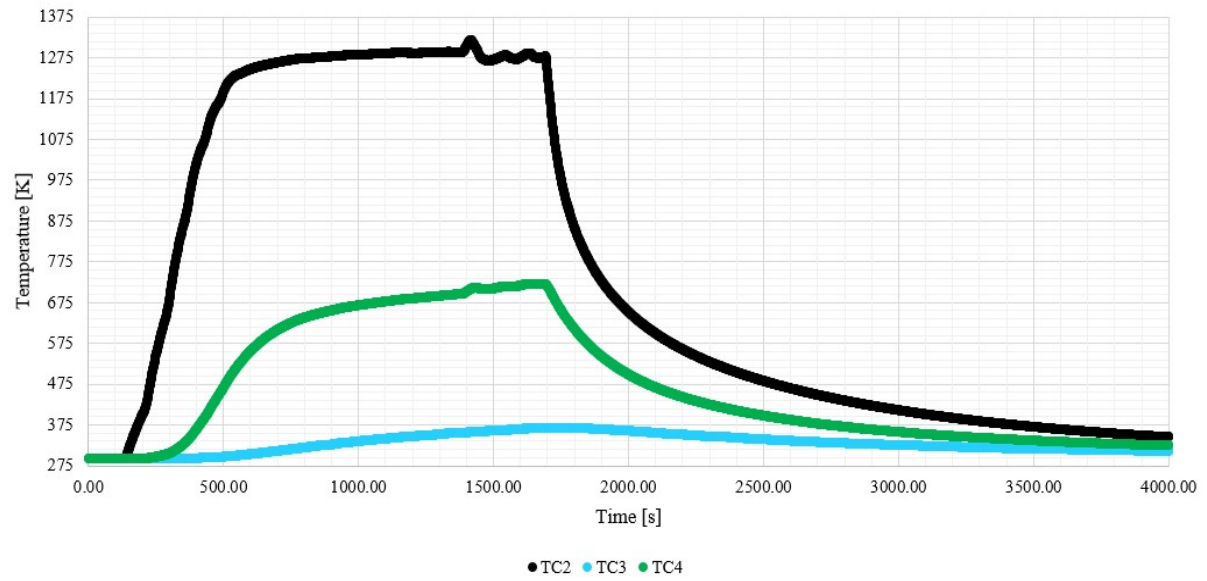


Figure A.24: June 9, 2021 Mo-Mo-Mo TC data.

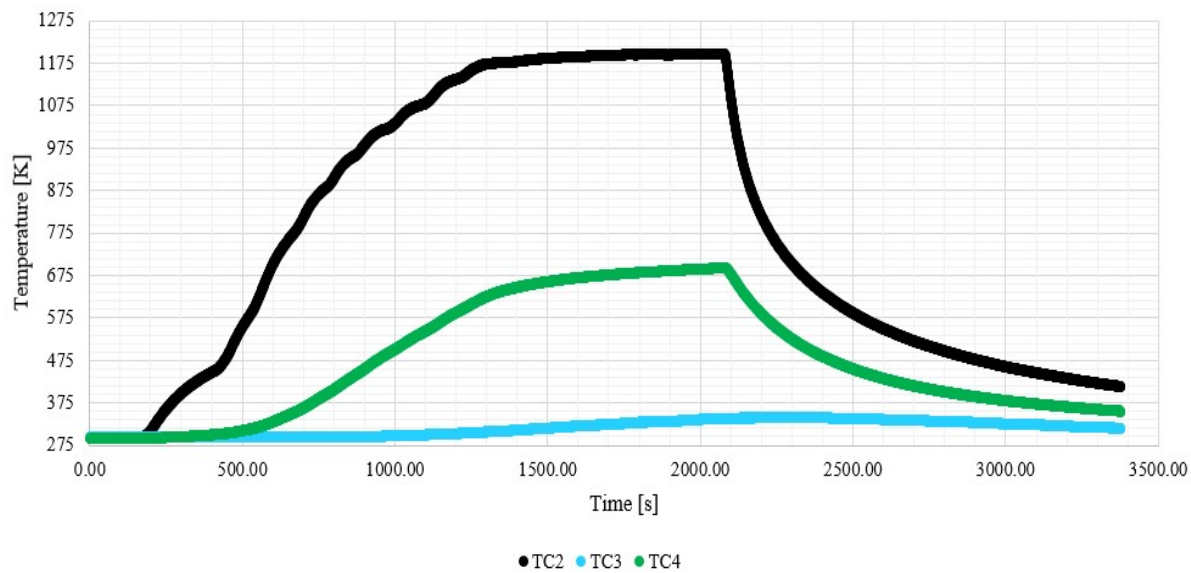


Figure A.25: June 17, 2021 Mo-G-Mo TC data.

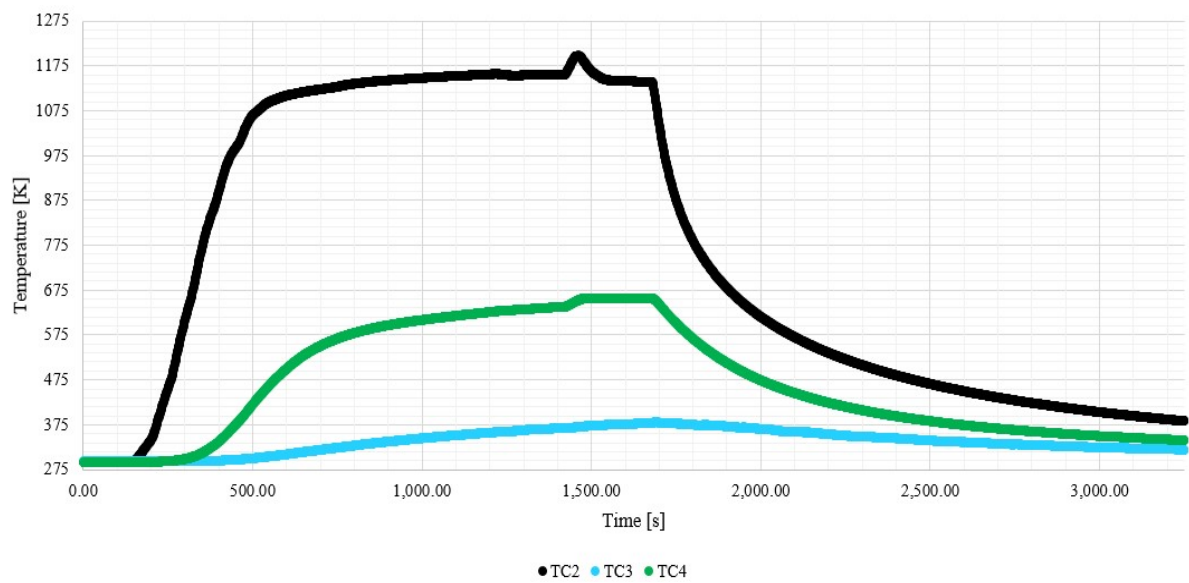


Figure A.26: June 10, 2021 Mo-G-Mo TC data.

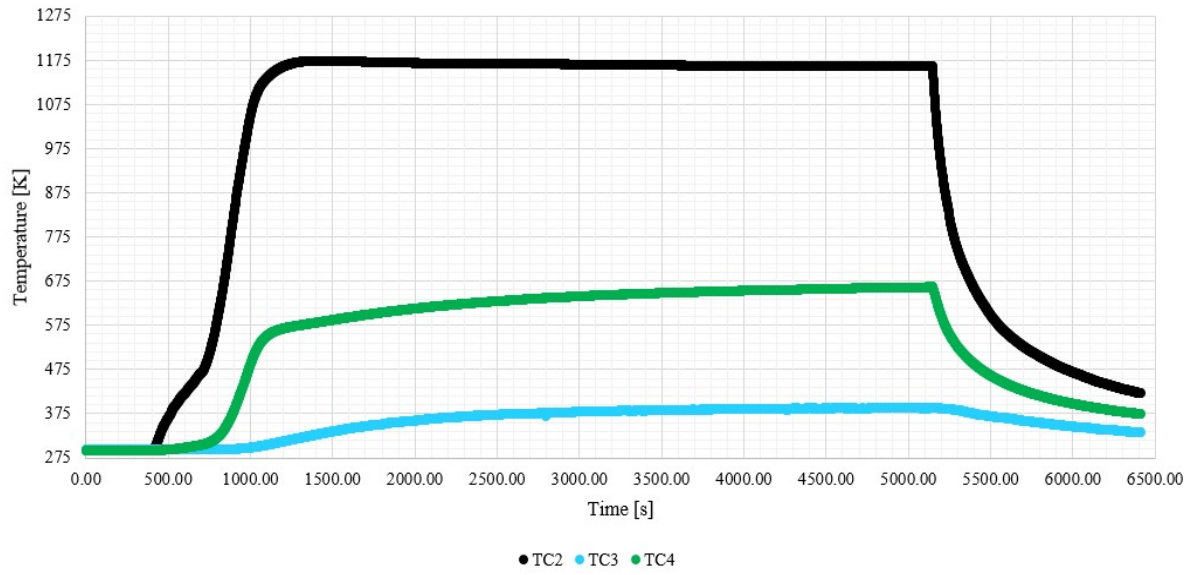


Figure A.27: August 2, 2021 G-Mo-Mo TC data.

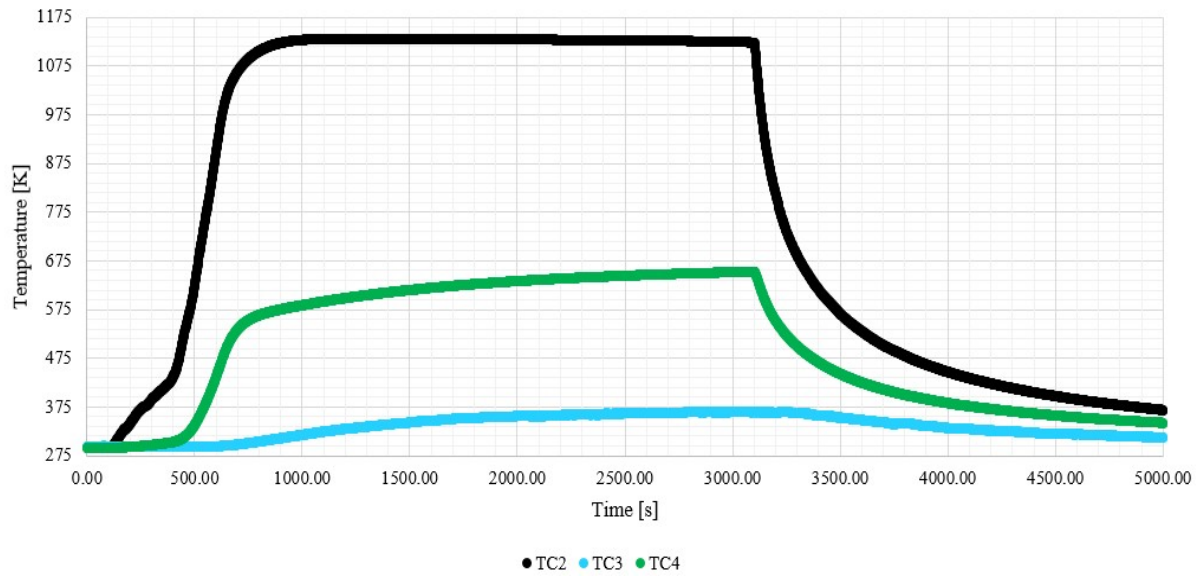


Figure A.28: August 3, 2021 G-Mo-Mo TC data.

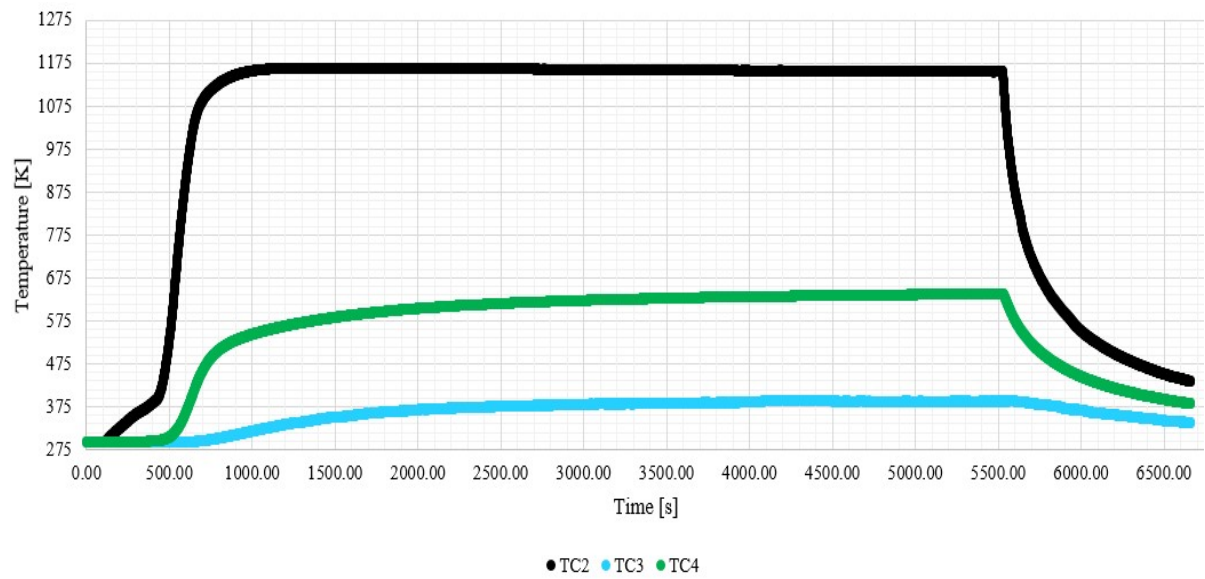


Figure A.29: August 5, 2021 G-G-Mo TC data.

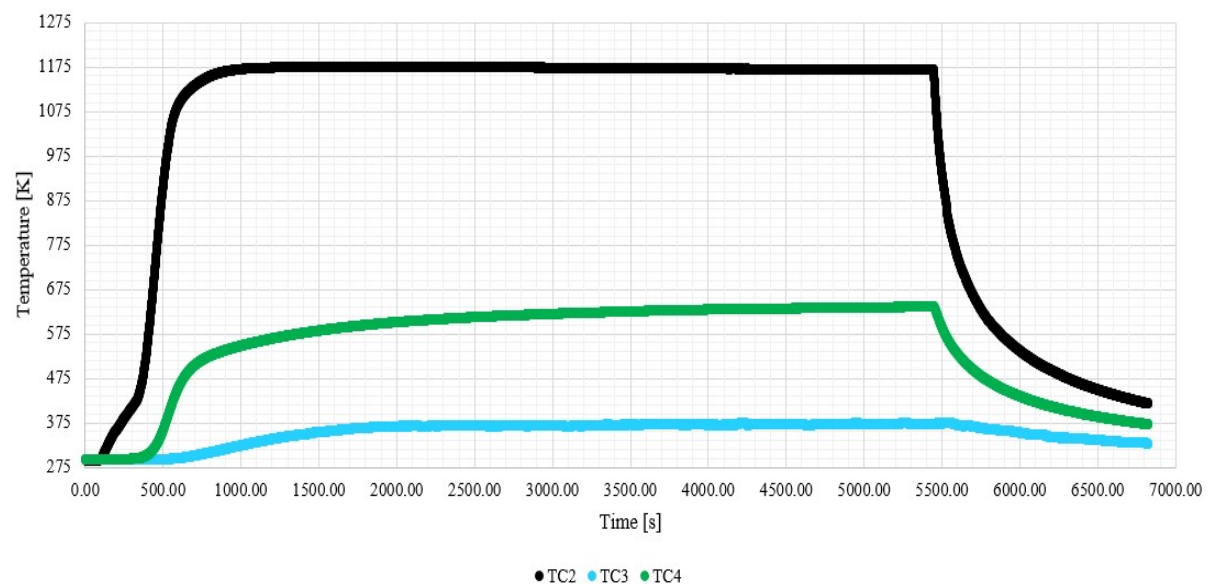


Figure A.30: August 9, 2021 G-G-Mo TC data.

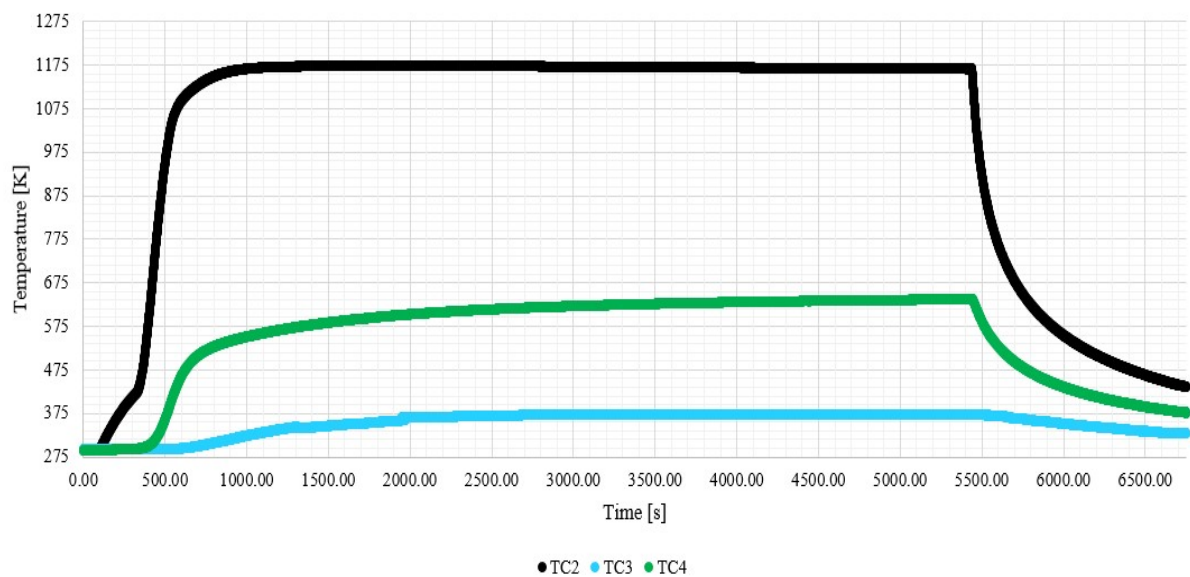


Figure A.31: August 11, 2021 G-G-G TC data.

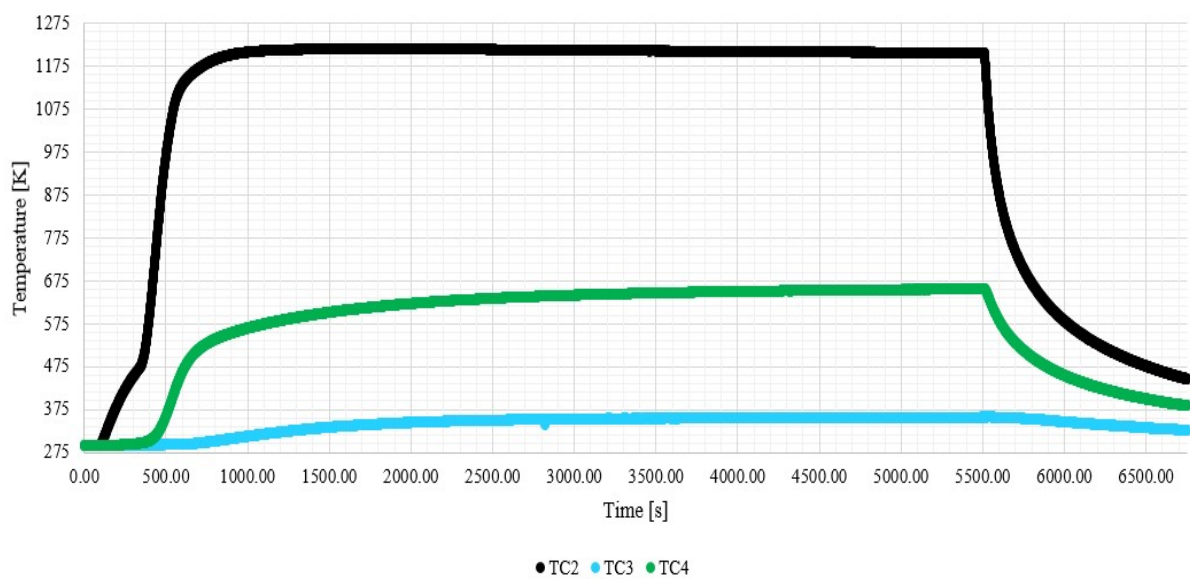


Figure A.32: August 12, 2021 G-G-G TC data.

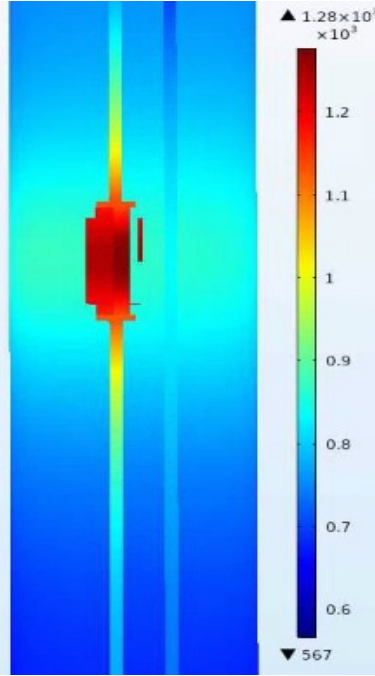


Figure A.33: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1$ and $\epsilon_{side} = 1$.
Using COMSOL Ray Shooting.

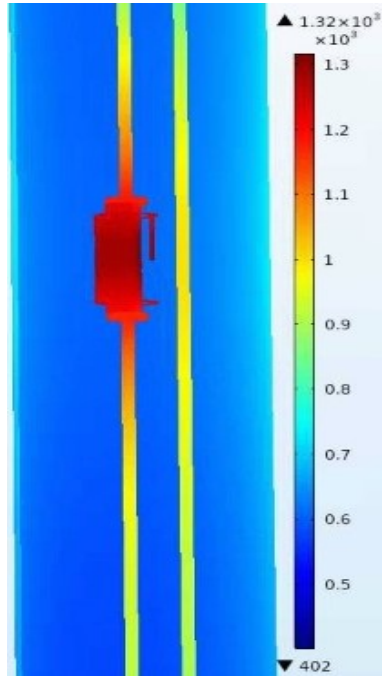


Figure A.34: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1 \times 10^{-10}$ and $\epsilon_{side} = 1 \times 10^{-10}$.
Using COMSOL Ray Shooting.

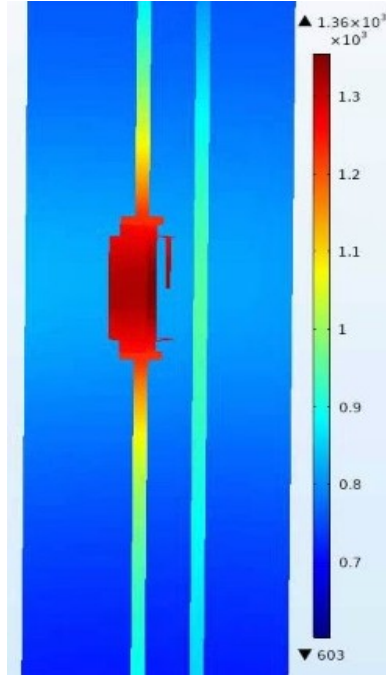


Figure A.35: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1$.
Using COMSOL hemi-cube.

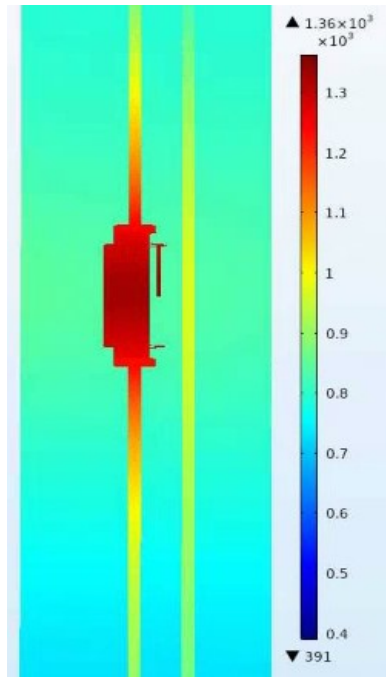


Figure A.36: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1 \times 10^{-10}$.
Using COMSOL hemi-cube.

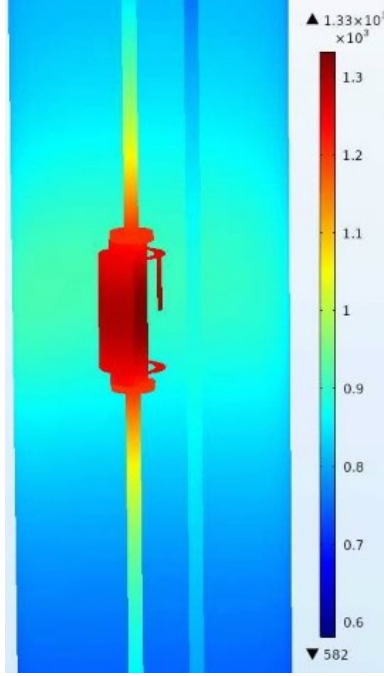


Figure A.37: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{side} = 1$.
Using COMSOL hemi-cube.

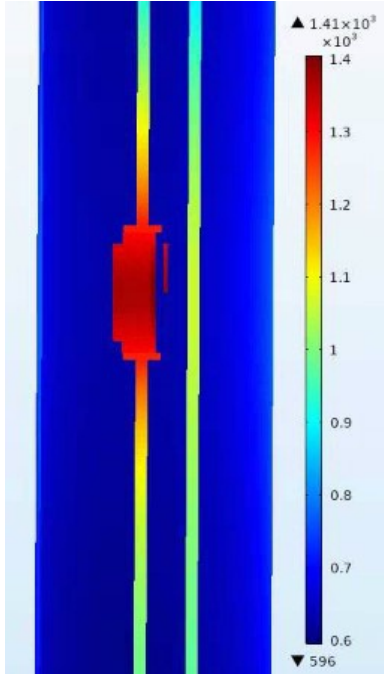


Figure A.38: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{side} = 1 \times 10^{-10}$.
Using COMSOL hemi-cube.

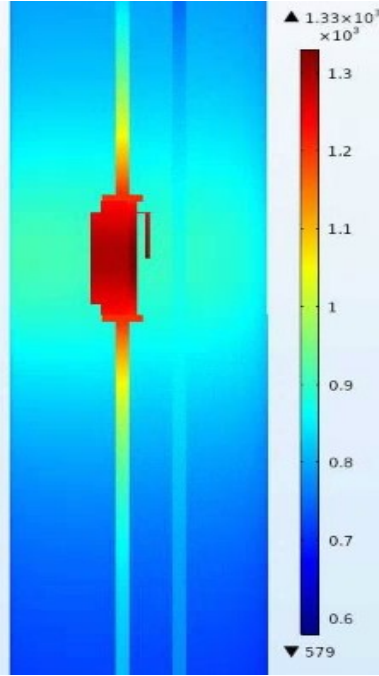


Figure A.39: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1$ and $\epsilon_{side} = 1$.
Using COMSOL hemi-cube.

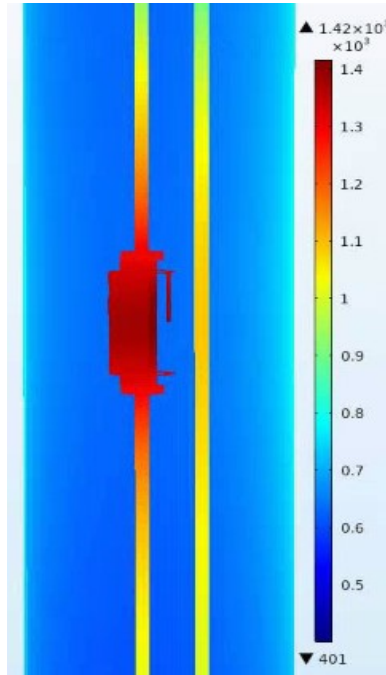


Figure A.40: Temperature distribution ($[K]$) of emissivity limiting case with $\epsilon_{top} = 1 \times 10^{-10}$ and $\epsilon_{side} = 1 \times 10^{-10}$.
Using COMSOL hemi-cube.

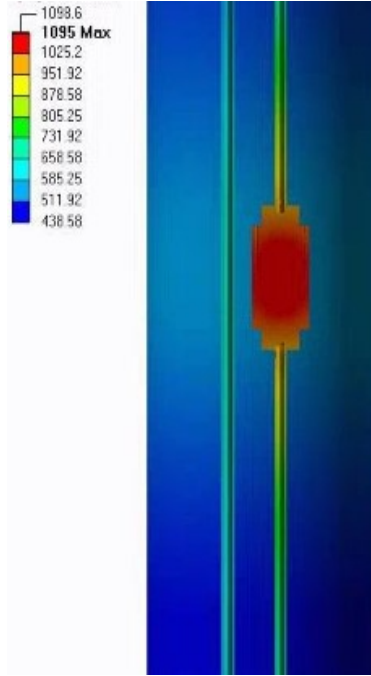


Figure A.41: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{top} = 1$.
Using ANSYS hemi-cube.

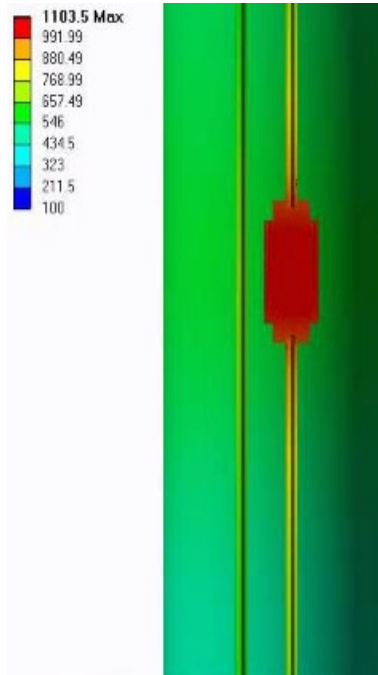


Figure A.42: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{top} = 1 \times 10^{-10}$.
Using ANSYS hemi-cube.

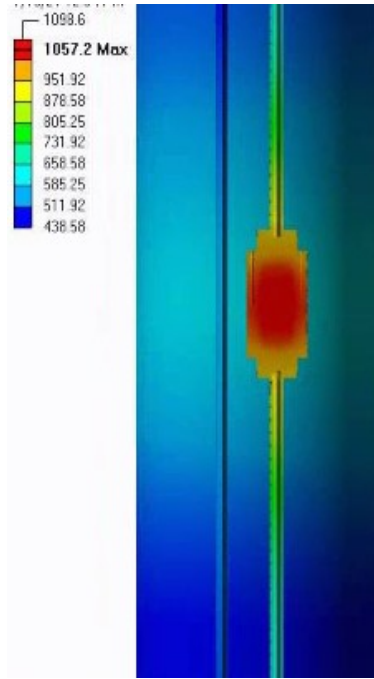


Figure A.43: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{side} = 1$.
Using ANSYS hemi-cube.

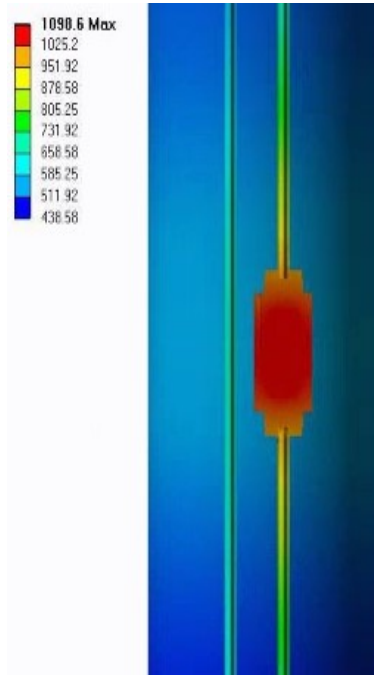


Figure A.44: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{side} = 1 \times 10^{-10}$.
Using ANSYS hemi-cube.

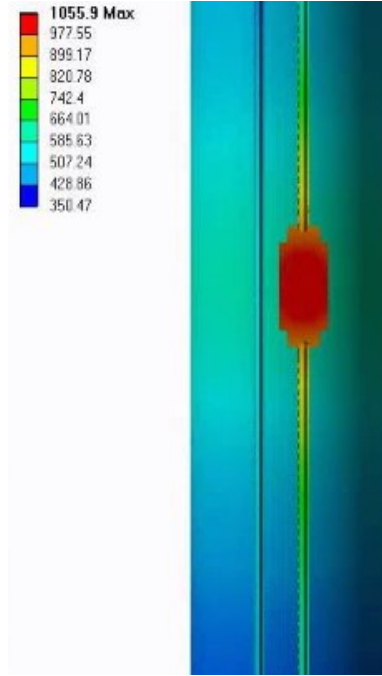


Figure A.45: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{top} = 1$ and $\epsilon_{side} = 1$. Using ANSYS hemi-cube.

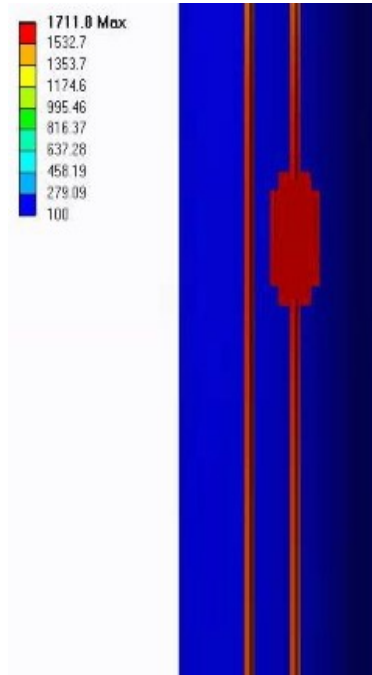


Figure A.46: Temperature distribution ($[^{\circ}C]$) of emissivity limiting case with $\epsilon_{top} = 1 \times 10^{-10}$ and $\epsilon_{side} = 1 \times 10^{-10}$. Using ANSYS hemi-cube.

Appendix B User Manuals and Data Sheets



Operating Guide

PSI 9000 2U

DC Laboratory Power Supply



Attention! This document is only valid for devices with firmware "KE: 2.31" (standard version) or "KE: 2.14" (GPIB, 3W), "HMI: 2.20" and "DR: 1.6.6" or higher. For availability of updates for your device check our website or contact us.



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1. General

1.1 About this document

1.1.1 Retention and use

This document is to be kept in the vicinity of the equipment for future reference and explanation of the operation of the device. This document is to be delivered and kept with the equipment in case of change of location and/or user.

1.1.2 Copyright

Reprinting, copying, also partially, usage for other purposes as foreseen of this manual are forbidden and breach may lead to legal process.

1.1.3 Validity

This manual is valid for the following equipment with **TFT display** panel, including derived variants.

Model	Article nr.	Model	Article nr.
PSI 9080-40 2U	06230304	PSI 9750-06 2U	06230313
PSI 9200-15 2U	06230305	PSI 9080-120 2U	06230314
PSI 9360-10 2U	06230306	PSI 9200-50 2U	06230315
PSI 9500-06 2U	06230307	PSI 9360-30 2U	06230316
PSI 9750-04 2U	06230308	PSI 9500-20 2U	06230317
PSI 9080-60 2U	06230309	PSI 9750-12 2U	06230318
PSI 9200-25 2U	06230310	PSI 9040-40 2U	06230319
PSI 9360-15 2U	06230311	PSI 9040-60 2U	06230320
PSI 9500-10 2U	06230312	PSI 9040-120 2U	06230321

1.1.4 Symbols and warnings

Warning and safety notices as well as general notices in this document are shown in a box with a symbol as follows:

	Symbol for a life threatening danger
	Symbol for general safety notices (instructions and damage protection bans) or important information for operation
	<i>Symbol for general notices</i>

1.2 Warranty

EA Elektro-Automatik guarantees the functional competence of the applied technology and the stated performance parameters. The warranty period begins with the delivery of free from defects equipment.

Terms of guarantee are included in the general terms and conditions (TOS) of EA Elektro-Automatik.

1.3 Limitation of liability

All statements and instructions in this manual are based on current norms and regulations, up-to-date technology and our long term knowledge and experience. The manufacturer accepts no liability for losses due to:

- Usage for purposes other than designed
- Use by untrained personnel
- Rebuilding by the customer
- Technical changes
- Use of not authorized spare parts

The actual delivered device(s) may differ from the explanations and diagrams given here due to latest technical changes or due to customized models with the inclusion of additionally ordered options.

1.4 Disposal of equipment

A piece of equipment which is intended for disposal must, according to European laws and regulations (ElektroG, WEEE) be returned to the manufacturer for scrapping, unless the person operating the piece of equipment or another, delegated person is conducting the disposal. Our equipment falls under these regulations and is accordingly marked with the following symbol:



1.5 Product key

Decoding of the product description on the label, using an example:

PSI 9 080 - 40 2U zzz

					Field for identification of installed options and/or special models
					S01...S0x = Special version
					3W = Option 3W installed (GPIB port instead of interface slot)
					Construction (not always given)
					2U = 19" rack enclosure with 2U of height
					Maximum current of the device in Ampere
					Maximum voltage of the device in Volt
					Series : 8 = Series 8000 or 800, 9 = Series 9000
					Type identification: PSI = Power Supply Intelligent

1.6 Intended usage

The equipment is intended to be used, if a power supply or battery charger, only as a variable voltage and current source, or, if an electronic load, only as a variable current sink.

Typical application for a power supply is DC supply to any relevant user, for a battery charger the charging of various battery types and for electronic loads the replacement of an ohmic resistor by an adjustable DC current sink in order to load relevant voltage and current sources of any type.



- Claims of any sort due to damage caused by non-intended usage won't be accepted.
- All damage caused by non-intended usage is solely the responsibility of the operator.

1.7 Safety

1.7.1 Safety notices

Mortal danger - Hazardous voltage



- Electrical equipment operation means that some parts can be under dangerous voltage. Therefore all parts under voltage must be covered! This basically applies to all models, though 40 V models according to SELV can't generate hazardous DC voltage.
- All work on connections must be carried out under zero voltage (output not connected to load) and may only be performed by qualified and informed persons. Improper actions can cause fatal injury as well as serious material damage.
- Never touch cables or connectors directly after unplugging from mains supply as the danger of electric shock remains.
- Never touch the contacts on DC output terminal directly after switching off the DC output, because there still can dangerous voltage present, sinking more or less slowly depending on the load! There also can be dangerous potential between negative DC output to PE or positive DC output to PE due to charged X capacitors.
- Always follow 5 safety rules when working with electric devices:
 - Disconnect completely
 - Secure against reconnection
 - Verify that the system is dead
 - Carry out earthing and short-circuiting
 - Provide protection from adjacent live parts



- The equipment must only be used as intended
- The equipment is only approved for use within the connection limits stated on the product label.
- Do not insert any object, particularly metallic, through the ventilator slots
- Avoid any use of liquids near the equipment. Protect the device from wet, damp and condensation.
- For power supplies and battery chargers: don't connect load, particularly such with low resistance, to devices under power; sparking may occur which can cause burns as well as damage to the equipment and to the load.
- For electronic loads: don't connect power sources to equipment under power, sparking may occur which can cause burns as well as damage to the equipment and to the source.
- ESD regulations must be applied when plugging interface cards or modules into the relative slot
- Interface cards or modules may only be attached or removed after the device is switched off. It's not necessary to open the device.
- Do not connect external power sources with reversed polarity to DC input or outputs! The equipment will be damaged.
- For power supply devices: avoid where possible connecting external power sources to the DC output, and never those that can generate a higher voltage than the nominal voltage of the device.
- For electronic loads: don't connect a power source to the DC input which can generate a voltage more than 120% of the nominal input voltage of the load. The equipment isn't protected against over voltage and may be irreparably damaged.
- Never insert a network cable which is connected to Ethernet or its components into the master-slave socket on the back side of the device!
- Always configure the various protecting features against overvoltage etc. for sensitive loads to what the target application requires!

1.7.2 Responsibility of the user

The equipment is in industrial operation. Therefore the operators are governed by the legal safety regulations. Alongside the warning and safety notices in this manual the relevant safety, accident prevention and environmental regulations must also be applied. In particular the users of the equipment:

- must be informed of the relevant job safety requirements
- must work to the defined responsibilities for operation, maintenance and cleaning of the equipment
- before starting work must have read and understood the operating manual
- must use the designated and recommended safety equipment.

Furthermore, anyone working with the equipment is responsible for ensuring that the device is at all times technically fit for use.

1.7.3 Responsibility of the operator

Operator is any natural or legal person who uses the equipment or delegates the usage to a third party, and is responsible during its usage for the safety of the user, other personnel or third parties.

The equipment is in industrial operation. Therefore the operators are governed by the legal safety regulations. Alongside the warning and safety notices in this manual the relevant safety, accident prevention and environmental regulations must also be applied. In particular the operator has to

- be acquainted with the relevant job safety requirements
- identify other possible dangers arising from the specific usage conditions at the work station via a risk assessment
- introduce the necessary steps in the operating procedures for the local conditions
- regularly control that the operating procedures are current
- update the operating procedures where necessary to reflect changes in regulation, standards or operating conditions.
- define clearly and unambiguously the responsibilities for operation, maintenance and cleaning of the equipment.
- ensure that all employees who use the equipment have read and understood the manual. Furthermore the users are to be regularly schooled in working with the equipment and the possible dangers.
- provide all personnel who work with the equipment with the designated and recommended safety equipment

Furthermore, the operator is responsible for ensuring that the device is at all times technically fit for use.

1.7.4 User requirements

Any activity with equipment of this type may only be performed by persons who are able to work correctly and reliably and satisfy the requirements of the job.

- Persons whose reaction capability is negatively influenced by e. g. drugs, alcohol or medication may not operate the equipment.
- Age or job related regulations valid at the operating site must always be applied.



Danger for unqualified users

Improper operation can cause person or object damage. Only persons who have the necessary training, knowledge and experience may use the equipment.

Delegated persons are those who have been properly and demonstrably instructed in their tasks and the attendant dangers.

Qualified persons are those who are able through training, knowledge and experience as well as knowledge of the specific details to carry out all the required tasks, identify dangers and avoid personal and other risks.

1.7.5 Alarm signals

The equipment offers various possibilities for signaling alarm conditions, however, not for danger situations. The signals may be optical (on the display as text) acoustic (piezo buzzer) or electronic (pin/status output of an analog interface). All alarms will cause the device to switch off the DC output.

The meaning of the signals is as follows:

Signal OT (OverTemperature)	• Overheating of the device • DC output will be switched off • Non-critical
Signal OVP (OverVoltage)	• Overvoltage shutdown of the DC output due to high voltage entering the device or generated by the device itself due to a defect • Critical! The device and/or the load could be damaged
Signal OCP (OverCurrent)	• Shutdown of the DC output due to excess of the preset limit • Non-critical, protects the load from excessive current consumption
Signal OPP (OverPower)	• Shutdown of the DC output due to excess of the preset limit • Non-critical, protects the load from excessive power consumption
Signal PF (Power Fail)	• DC output shutdown due to AC undervoltage or defect in the AC input • Critical on overvoltage! AC input circuit could be damaged

1.8 Technical Data

1.8.1 Approved operating conditions

- Use only inside dry buildings
- Ambient temperature 0-50 °C (32-122 °F)
- Operational altitude: max. 2000 m (1.242 mi) above sea level
- Max. 80% relative humidity, non-condensing

1.8.2 General technical data

Display: Color TFT touch screen with gorilla glass, 4.3", 480pt x 272pt, capacitive

Controls: 2 rotary knobs with pushbutton functions, 2 pushbutton

The nominal values for the device determine the maximum adjustable ranges.

PSI 9000 2U Series

1.8.3 Specific technical data

1000 W	Model 2U		
	PSI 9040-40	PSI 9080-40	PSI 9200-15
AC input			
Voltage range	90...264 V AC		
Connection	1ph (L,N,PE)		
Frequency	45-65 Hz		
Fusing	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 23 A		
Power factor	≈ 0.99		
DC output			
Max. output voltage U _{Max}	40 V	80 V	200 V
Max. output current I _{Max}	40 A	40 A	15 A
Max. output power P _{Max}	1000 W	1000 W	1000 W
Overvoltage protection range	0...44 V	0...88 V	0...220 V
Overcurrent protection range	0...44 A	0...44 A	0...16.5 A
Overpower protection range	0...1100 W	0...1100 W	0...1100 W
Output capacitance	5440 µF	5440 µF	800 µF
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0...40.8 V	0...81.6 V	0...204 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U _{Nom}	< 0.1% U _{Nom}	< 0.1% U _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.02% U _{Nom}	< 0.02% U _{Nom}	< 0.02% U _{Nom}
Load regulation at 0...100% load	< 0.05% U _{Nom}	< 0.05% U _{Nom}	< 0.05% U _{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}
Ripple ⁽²⁾	< 114 mV _{PP} < 8 mV _{RMS}	< 114 mV _{PP} < 8 mV _{RMS}	< 164 mV _{PP} < 34 mV _{RMS}
Remote sensing compensation	Max. 5% U _{Nom}	Max. 5% U _{Nom}	Max. 5% U _{Nom}
Output voltage fall time (at no load) after switching DC output off	-	-	Down from 100% to <60 V: less than 10 s
Current regulation			
Adjustment range	0...40.8 A	0...40.8 A	0...15.3 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I _{Nom}	< 0.2% I _{Nom}	< 0.2% I _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% I _{Nom}	< 0.05% I _{Nom}	< 0.05% I _{Nom}
Load regulation at 0...100% ΔU _{OUT}	< 0.15% I _{Nom}	< 0.15% I _{Nom}	< 0.15% I _{Nom}
Ripple ⁽²⁾	< 3.7 mA _{RMS}	< 3.7 mA _{RMS}	< 2.2 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}
Power regulation			
Adjustment range	0...1020 W	0...1020 W	0...1020 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P _{Nom}	< 1% P _{Nom}	< 1% P _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% P _{Nom}	< 0.05% P _{Nom}	< 0.05% P _{Nom}
Load reg. at 10-90% ΔU _{OUT} * ΔI _{OUT}	< 0.75% P _{Nom}	< 0.75% P _{Nom}	< 0.75% P _{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

1000 W	Model 2U		
	PSI 9040-40	PSI 9080-40	PSI 9200-15
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}
Efficiency ⁽⁴⁾	≤ 92%	≤ 92%	≤ 93%
Internal resistance regulation			
Adjustment range	0...30.6 Ω	0...61.2 Ω	0...408 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽³⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950: 2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)
Article number	06230319	06230304	06230305

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

PSI 9000 2U Series

1000 W	Model 2U		
	PSI 9360-10	PSI 9500-06	PSI 9750-04
AC input			
Voltage range	90...264 V AC		
Connection	1ph (L,N,PE)		
Frequency	45-65 Hz		
Fusing	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 23 A		
Power factor	≈ 0.99		
DC output			
Max. output voltage U_{Max}	360 V	500 V	750 V
Max. output current I_{Max}	10 A	6 A	4 A
Max. output power P_{Max}	1000 W	1000 W	1000 W
Overvoltage protection range	0...396 V	0...550 V	0...825 V
Overcurrent protection range	0...11 A	0...6.6 A	0...4.4 A
Overpower protection range	0...1100 W	0...1100 W	0...1100 W
Output capacitance	330 µF	120 µF	40 µF
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0...367.2 V	0...510 V	0...765 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U_{Nom}	< 0.1% U_{Nom}	< 0.1% U_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.02% U_{Nom}	< 0.02% U_{Nom}	< 0.02% U_{Nom}
Load regulation at 0...100% load	< 0.05% U_{Nom}	< 0.05% U_{Nom}	< 0.05% U_{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U_{Nom}	≤ 0.2% U_{Nom}	≤ 0.2% U_{Nom}
Ripple ⁽²⁾	< 210 mV _{PP} < 59 mV _{RMS}	< 190 mV _{PP} < 48 mV _{RMS}	< 212 mV _{PP} < 60 mV _{RMS}
Remote sensing compensation	Max. 5% U_{Nom}	Max. 5% U_{Nom}	Max. 5% U_{Nom}
Output voltage fall time (at no load) after switching DC output off	Down from 100% to <60 V: less than 10 s		
Current regulation			
Adjustment range	0...10.2 A	0...6.12 A	0...4.08 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I_{Nom}	< 0.2% I_{Nom}	< 0.2% I_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.05% I_{Nom}	< 0.05% I_{Nom}	< 0.05% I_{Nom}
Load regulation at 0...100% ΔU_{OUT}	< 0.15% I_{Nom}	< 0.15% I_{Nom}	< 0.15% I_{Nom}
Ripple ⁽²⁾	< 1.6 mA _{RMS}	< 0.5 mA _{RMS}	< 0.3 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I_{Nom}	≤ 0.2% I_{Nom}	≤ 0.2% I_{Nom}
Power regulation			
Adjustment range	0...1020 W	0...1020 W	0...1020 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P_{Nom}	< 1% P_{Nom}	< 1% P_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.05% P_{Nom}	< 0.05% P_{Nom}	< 0.05% P_{Nom}
Load reg. at 10-90% ΔU_{OUT} * ΔI_{OUT}	< 0.75% P_{Nom}	< 0.75% P_{Nom}	< 0.75% P_{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

1000 W	Model 2U		
	PSI 9360-10	PSI 9500-06	PSI 9750-04
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}
Efficiency ⁽⁴⁾	≤ 93%	≤ 93%	≤ 93%
Internal resistance regulation			
Adjustment range	0...1101.6 Ω	0...2550 Ω	0...5737.5 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽³⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950:2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)
Article number	06230306	06230307	06230308

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

PSI 9000 2U Series

1500 W	Model 2U		
	PSI 9040-60	PSI 9080-60	PSI 9200-25
AC input			
Voltage range	90...264 V AC		
- with additional derating	90...150 V AC		
Connection	1ph (L,N,PE)		
Frequency	45-65 Hz		
Fusing	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 23 A		
Power factor	≈ 0.99		
DC output			
Max. output voltage U _{Max}	40 V	80 V	200 V
Max. output current I _{Max}	60 A	60 A	25 A
Max. output power P _{Max}	1500 W	1500 W	1500 W
Max. output power P _{Max} with derating	1000 W	1000 W	1000 W
Overvoltage protection range	0...44 V	0...88 V	0...220 V
Overcurrent protection range	0...66 A	0...66 A	0...27.5 A
Overpower protection range	0...1650 W	0...1650 W	0...1650 W
Output capacitance	5440 µF	5440 µF	800 µF
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0..40.8 V	0...81.6 V	0...204 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U _{Nom}	< 0.1% U _{Nom}	< 0.1% U _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.02% U _{Nom}	< 0.02% U _{Nom}	< 0.02% U _{Nom}
Load regulation at 0...100% load	< 0.05% U _{Nom}	< 0.05% U _{Nom}	< 0.05% U _{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}
Ripple ⁽²⁾	< 114 mV _{PP} < 8 mV _{RMS}	< 114 mV _{PP} < 8 mV _{RMS}	< 164 mV _{PP} < 34 mV _{RMS}
Remote sensing compensation	Max. 5% U _{Nom}	Max. 5% U _{Nom}	Max. 5% U _{Nom}
Output voltage fall time (at no load) after switching DC output off	-	-	Down from 100% to <60 V: less than 10 s
Current regulation			
Adjustment range	0...61.2 A	0...61.2 A	0...25.5 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I _{Nom}	< 0.2% I _{Nom}	< 0.2% I _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% I _{Nom}	< 0.05% I _{Nom}	< 0.05% I _{Nom}
Load regulation at 0...100% ΔU _{OUT}	< 0.15% I _{Nom}	< 0.15% I _{Nom}	< 0.15% I _{Nom}
Ripple ⁽²⁾	< 5.6 mA _{RMS}	< 5.6 mA _{RMS}	< 1.3 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}
Power regulation			
Adjustment range	0...1530 W	0...1530 W	0...1530 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P _{Nom}	< 1% P _{Nom}	< 1% P _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% P _{Nom}	< 0.05% P _{Nom}	< 0.05% P _{Nom}
Load reg. at 10-90% ΔU _{OUT} * ΔI _{OUT}	< 0.75% P _{Nom}	< 0.75% P _{Nom}	< 0.75% P _{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

1500 W	Model 2U		
	PSI 9040-60	PSI 9080-60	PSI 9200-25
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}	≤ 0.7% P _{Nom}
Efficiency ⁽⁴⁾	≤ 92%	≤ 92%	≤ 93%
Internal resistance regulation			
Adjustment range	0...20.4 Ω	0...40.8 Ω	0...244.8 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽⁴⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950:2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)
Article number	06230320	06230309	06230310

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

PSI 9000 2U Series

1500 W	Model 2U		
	PSI 9360-15	PSI 9500-10	PSI 9750-06
AC input			
Voltage range	90...264 V AC		
- with additional derating	90...150 V AC		
Connection	1ph (L,N,PE)		
Frequency	45-65 Hz		
Fusing	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 23 A		
Power factor	≈ 0.99		
DC output			
Max. output voltage U _{Max}	360 V	500 V	750 V
Max. output current I _{Max}	15 A	10 A	6 A
Max. output power P _{Max}	1500 W	1500 W	1500 W
Max. output power P _{Max} with derating	1000 W	1000 W	1000 W
Overvoltage protection range	0...396 V	0...550 V	0...825 V
Overcurrent protection range	0...16.5 A	0...11 A	0...6.6 A
Overpower protection range	0...1650 W	0...1650 W	0...1650 W
Output capacitance	330 µF	120 µF	40 µF
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0...367.2 V	0...510 V	0...765 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U _{Nom}	< 0.1% U _{Nom}	< 0.1% U _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.02% U _{Nom}	< 0.02% U _{Nom}	< 0.02% U _{Nom}
Load regulation at 0...100% load	< 0.05% U _{Nom}	< 0.05% U _{Nom}	< 0.05% U _{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}
Ripple ⁽²⁾	< 210 mV _{PP} < 59 mV _{RMS}	< 190 mV _{PP} < 48 mV _{RMS}	< 212 mV _{PP} < 60 mV _{RMS}
Remote sensing compensation	Max. 5% U _{Nom}	Max. 5% U _{Nom}	Max. 5% U _{Nom}
Output voltage fall time (at no load) after switching DC output off	Down from 100% to <60 V: less than 10 s		
Current regulation			
Adjustment range	0...15.3 A	0...10.2 A	0...6.12 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I _{Nom}	< 0.2% I _{Nom}	< 0.2% I _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% I _{Nom}	< 0.05% I _{Nom}	< 0.05% I _{Nom}
Load regulation at 0...100% ΔU _{OUT}	< 0.15% I _{Nom}	< 0.15% I _{Nom}	< 0.15% I _{Nom}
Ripple ⁽²⁾	< 2.4 mA _{RMS}	< 0.7 mA _{RMS}	< 0.5 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}
Power regulation			
Adjustment range	0...1530 W	0...1530 W	0...1530 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P _{Nom}	< 1% P _{Nom}	< 1% P _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% P _{Nom}	< 0.05% P _{Nom}	< 0.05% P _{Nom}
Load req. at 10-90% ΔU _{OUT} * ΔI _{OUT}	< 0.75% P _{Nom}	< 0.75% P _{Nom}	< 0.75% P _{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

1500 W	Model 2U		
	PSI 9360-15	PSI 9500-10	PSI 9750-06
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.7% P _{Nom}	≤ 0.8% P _{Nom}	≤ 0.85% P _{Nom}
Efficiency ⁽⁴⁾	≤ 93%	≤ 93%	≤ 93%
Internal resistance regulation			
Adjustment range	0...734.4 Ω	0...1530 Ω	0...3825 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽⁴⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950:2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)	≈ 12 kg (26.5 lb)
Article number	06230311	06230312	06230313

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

PSI 9000 2U Series

3000 W	Model 2U		
	PSI 9040-120	PSI 9080-120	PSI 9200-50
AC input			
Input voltage	180...264 V AC		
- with additional derating	180...207 V AC		
Input connection	1ph (L,N,PE)		
Input frequency	45-65 Hz		
Input fuse (internal)	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 46 A		
Power factor	> 0.99		
DC output			
Max. output voltage U_{Max}	40 V	80 V	200 V
Max. output current I_{Max}	120 A	120 A	50 A
Max. output power P_{Max}	3000 W	3000 W	3000 W
Max. output power P_{Max} with derating	2500 W	2500 W	2500 W
Overvoltage protection range	0...44 V	0...88 V	0...220 V
Overcurrent protection range	0...132 A	0...132 A	0...55 A
Overpower protection range	0...3300 W	0...3300 W	0...3300 W
Output capacitance	10880 μ F	10880 μ F	1600 μ F
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0...40.8 V	0...81.6 V	0...204 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U_{Nom}	< 0.1% U_{Nom}	< 0.1% U_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.02% U_{Nom}	< 0.02% U_{Nom}	< 0.02% U_{Nom}
Load regulation at 0...100% load	< 0.05% U_{Nom}	< 0.05% U_{Nom}	< 0.05% U_{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U_{Nom}	≤ 0.2% U_{Nom}	≤ 0.2% U_{Nom}
Ripple ⁽²⁾	< 114 mV _{PP} < 8 mV _{RMS}	< 114 mV _{PP} < 8 mV _{RMS}	< 164 mV _{PP} < 34 mV _{RMS}
Remote sensing compensation	Max. 5% U_{Nom}	Max. 5% U_{Nom}	Max. 5% U_{Nom}
Output voltage fall time (at no load) after switching DC output off	-	-	Down from 100% to <60 V: less than 10 s
Current regulation			
Adjustment range	0...122.4 A	0...122.4 A	0...51 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I_{Nom}	< 0.2% I_{Nom}	< 0.2% I_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.05% I_{Nom}	< 0.05% I_{Nom}	< 0.05% I_{Nom}
Load regulation at 0...100% ΔU_{OUT}	< 0.15% I_{Nom}	< 0.15% I_{Nom}	< 0.15% I_{Nom}
Ripple ⁽²⁾	< 11 mA _{RMS}	< 11 mA _{RMS}	< 6.5 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I_{Nom}	≤ 0.2% I_{Nom}	≤ 0.2% I_{Nom}
Power regulation			
Adjustment range	0...3060 W	0...3060 W	0...3060 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P_{Nom}	< 1% P_{Nom}	< 1% P_{Nom}
Line regulation at ±10% ΔU_{AC}	< 0.05% P_{Nom}	< 0.05% P_{Nom}	< 0.05% P_{Nom}
Load reg. at 10-90% ΔU_{OUT} * ΔI_{OUT}	< 0.75% P_{Nom}	< 0.75% P_{Nom}	< 0.75% P_{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

3000 W	Model 2U		
	PSI 9040-120	PSI 9080-120	PSI 9200-50
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.8% P _{Nom}	≤ 0.8% P _{Nom}	≤ 0.85% P _{Nom}
Efficiency ⁽⁴⁾	≤ 92%	≤ 92%	≤ 93%
Internal resistance regulation			
Adjustment range	0...10.2 Ω	0...20.4 Ω	0...122.4 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽³⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950:2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 15 kg (33 lb)	≈ 15 kg (33 lb)	≈ 15 kg (33 lb)
Article number	06230321	06230314	06230315

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

PSI 9000 2U Series

3000 W	Model 2U		
	PSI 9360-30	PSI 9500-20	PSI 9750-12
AC input			
Input voltage	180...264 V AC		
- with additional derating	180...207 V AC		
Input connection	1ph (L,N,PE)		
Input frequency	45-65 Hz		
Input fuse (internal)	T16 A		
Leak current	< 3.5 mA		
Inrush current @230 V	≈ 46 A		
Power factor	> 0.99		
DC output			
Max. output voltage U _{Max}	360 V	500 V	750 V
Max. output current I _{Max}	30 A	20 A	12 A
Max. output power P _{Max}	3000 W	3000 W	3000 W
Max. output power P _{Max} with derating	2500 W	2500 W	2500 W
Overvoltage protection range	0...396 V	0...550 V	0...825 V
Overcurrent protection range	0...33 A	0...22 A	0...13.2 A
Overpower protection range	0...3300 W	0...3300 W	0...3300 W
Output capacitance	660 µF	240 µF	80 µF
Temperature coefficient for set values Δ/K	Voltage / current: 100 ppm		
Voltage regulation			
Adjustment range	0...367.2 V	0...510 V	0...765 V
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.1% U _{Nom}	< 0.1% U _{Nom}	< 0.1% U _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.02% U _{Nom}	< 0.02% U _{Nom}	< 0.02% U _{Nom}
Load regulation at 0...100% load	< 0.05% U _{Nom}	< 0.05% U _{Nom}	< 0.05% U _{Nom}
Rise time 10...90%	Max. 30 ms	Max. 30 ms	Max. 30 ms
Settling time after load step	< 1.5 ms	< 1.5 ms	< 1.5 ms
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}	≤ 0.2% U _{Nom}
Ripple ⁽²⁾	< 210 mV _{PP} < 59 mV _{RMS}	< 190 mV _{PP} < 48 mV _{RMS}	< 212 mV _{PP} < 60 mV _{RMS}
Remote sensing compensation	Max. 5% U _{Nom}	Max. 5% U _{Nom}	Max. 5% U _{Nom}
Output voltage fall time (at no load) after switching DC output off	Down from 100% to <60 V: less than 10 s		
Current regulation			
Adjustment range	0...30.6 A	0...20.4 A	0...12.24 A
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 0.2% I _{Nom}	< 0.2% I _{Nom}	< 0.2% I _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% I _{Nom}	< 0.05% I _{Nom}	< 0.05% I _{Nom}
Load regulation at 0...100% ΔU _{OUT}	< 0.15% I _{Nom}	< 0.15% I _{Nom}	< 0.15% I _{Nom}
Ripple ⁽²⁾	< 5 mA _{RMS}	< 1.5 mA _{RMS}	< 0.9 mA _{RMS}
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽³⁾	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}	≤ 0.2% I _{Nom}
Power regulation			
Adjustment range	0...3060 W	0...3060 W	0...3060 W
Accuracy ⁽¹⁾ (at 23±5 °C / 73±9 °F)	< 1% P _{Nom}	< 1% P _{Nom}	< 1% P _{Nom}
Line regulation at ±10% ΔU _{AC}	< 0.05% P _{Nom}	< 0.05% P _{Nom}	< 0.05% P _{Nom}
Load reg. at 10-90% ΔU _{OUT} * ΔI _{OUT}	< 0.75% P _{Nom}	< 0.75% P _{Nom}	< 0.75% P _{Nom}

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) RMS value: LF 0...300 kHz, PP value: HF 0...20MHz

(3) The display error adds to the error of the related actual value on the DC output

PSI 9000 2U Series

3000 W	Model 2U		
	PSI 9360-30	PSI 9500-20	PSI 9750-12
Power regulation			
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Display: Accuracy ⁽²⁾	≤ 0.85% P _{Nom}	≤ 0.85% P _{Nom}	≤ 0.8% P _{Nom}
Efficiency ⁽⁴⁾	≤ 93%	≤ 93%	≤ 93%
Internal resistance regulation			
Adjustment range	0...367.2 Ω	0...765 Ω	0...1912.5 Ω
Accuracy ⁽¹⁾	≤ 1% of max. resistance ± 0.3% of maximum current		
Display: Resolution	See section „1.9.6.4. Resolution of the displayed values“		
Analog interface ⁽³⁾			
Set value inputs	U, I, P, R		
Actual value output	U, I		
Control signals	DC on/off, remote control on/off, resistance mode on/off		
Status signals	CV, OVP, OCP, OPP, PF, OT, DC on/off		
Galvanic isolation from device	Max. 400 V DC		
Insulation			
Output (DC) to enclosure (PE)	DC minus: permanent max. ±400 V DC plus: permanent max. ±400V + output voltage		
Input (AC) to output (DC)	Max. 2500 V, short-term		
Miscellaneous			
Cooling	Temperature controlled fans, front inlet, rear exhaust		
Ambient temperature	0...50 °C (32...122 °F)		
Storage temperature	-20...70°C (-4...158 °F)		
Humidity	< 80%, not condensing		
Standards	EN 60950:2006 + A11: 2009 + A1:2010 + A12:2011 + AC:2011 + A2:2013 EN 61326-1:2013-07		
Overvoltage category	2		
Protection class	1		
Pollution degree	2		
Operational altitude	< 2000 m (6500 ft)		
Digital interfaces			
Featured	1x USB-B for communication, 1x USB-A for functions, 1x GPIB (only with option 3W)		
Slot (standard version)	Optional: CAN, CANopen, Profibus, Profinet, RS232, Ethernet, EtherCAT, ModBus TCP		
Galvanic isolation from device	Max. 400 V DC		
Terminals			
Rear side	Share Bus, DC output, AC input, remote sensing, analog interface, USB-B, master-slave bus, Interface module slot		
Front side	USB-A		
Dimensions			
Enclosure (WxHxD)	19" x 2U x 463 mm (18.2")		
Total (WxHxD)	483 x 88 x min. 535 mm (19" x 3.5" x 21.1") (depending on DC terminal type)		
Weight	≈ 15 kg (33 lb)	≈ 15 kg (33 lb)	≈ 15 kg (33 lb)
Article number	06230316	06230317	06230318

(1) Related to the nominal values, the accuracy defines the maximum deviation between an adjusted values and the true (actual) value.

(2) The display error adds to the error of the related actual value on the DC output

(3) For technical specifications of the analog interface see „3.5.4.4 Analog interface specification“ on page 58

(4) Typical value at 100% output voltage and 100% power

1.8.4 Views

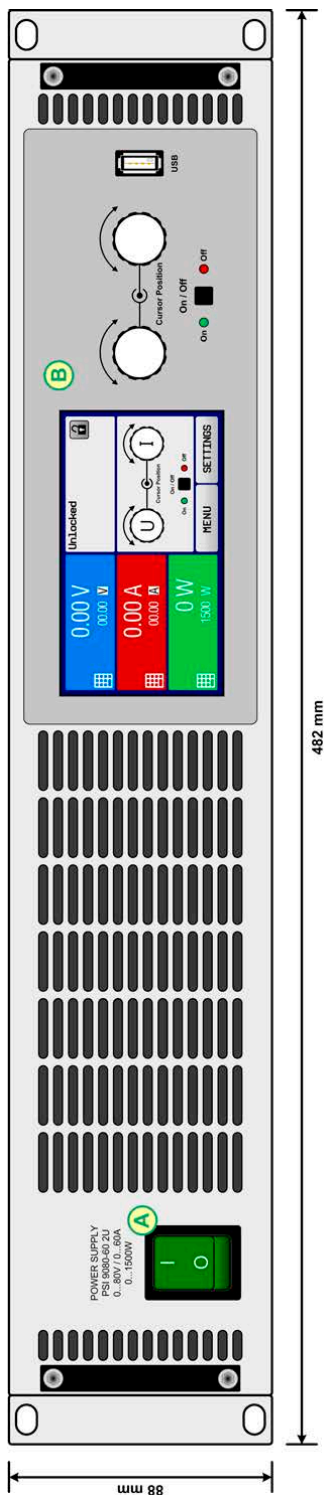


Figure 1 - Front side

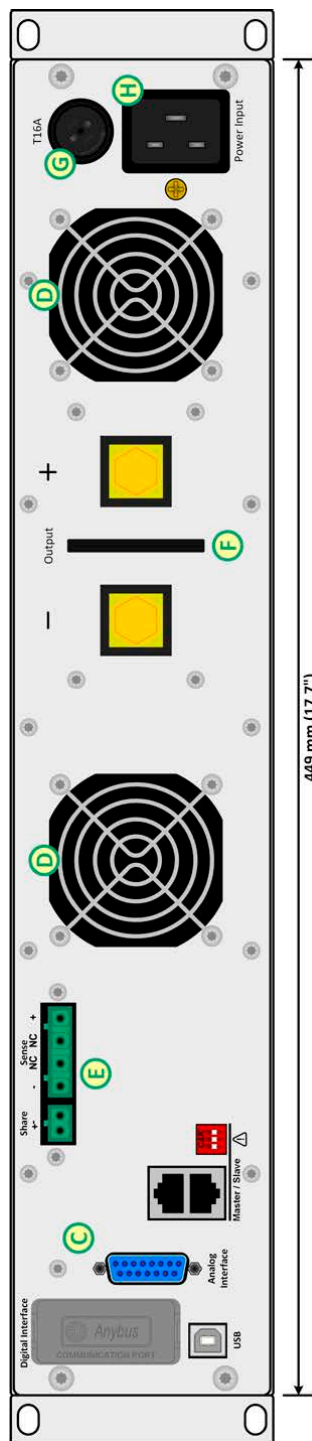
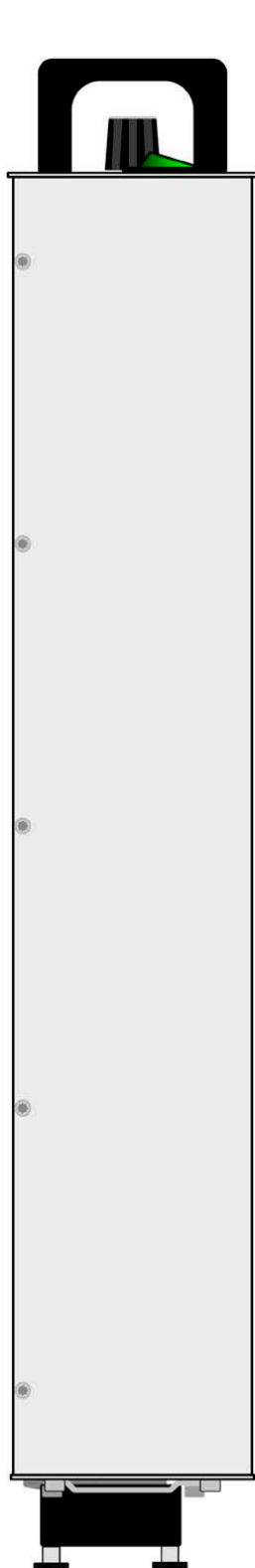


Figure 2 - Rear side (standard version)

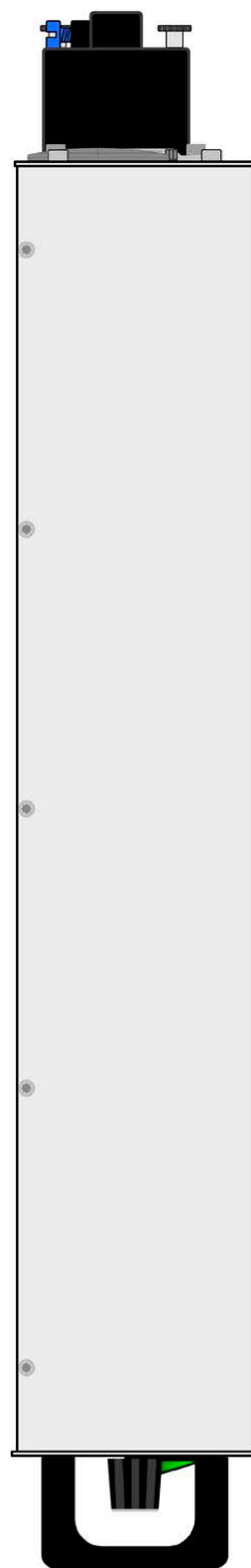
 Do not loosen the grounding point (brass screw next to AC inlet) in order to connect PE cables! The device is supposed to be grounded via the AC cord, while the grounding point is used to connect the enclosure to PE.

- A - Power switch
- B - Control panel
- C - Control interfaces (digital, analog)
- D - Exhausts
- E - Share Bus and remote sensing connectors
- F - DC output (terminal type 1)
- G - AC input fuse
- H - AC input connector



32 mm
(1,3")

Figure 3 - Left hand side with DC terminal type 1



53 mm (2,1")
463 mm (18,2")
40 mm
(1,6")

Figure 4 - Right hand side with DC terminal type 2

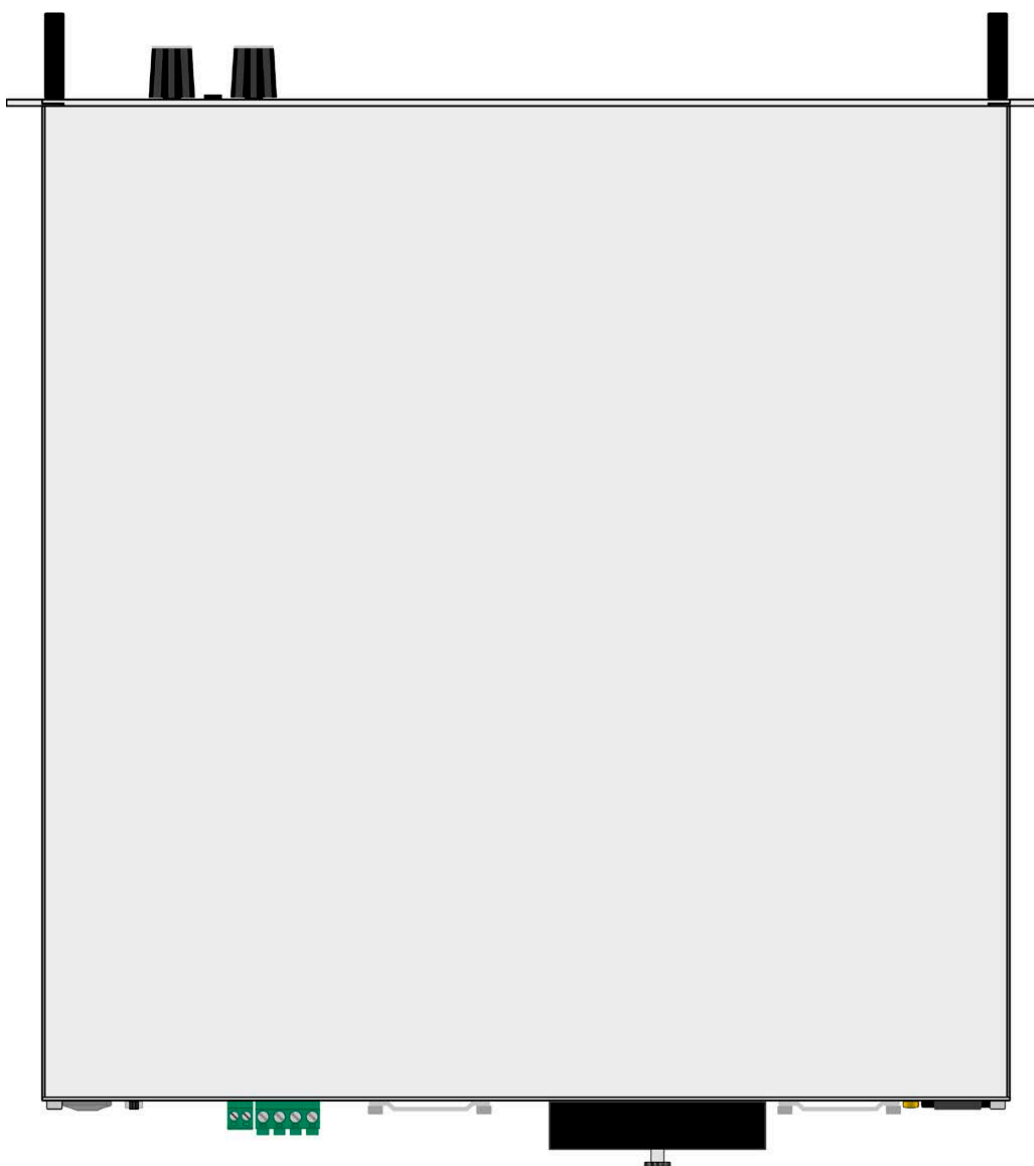


Figure 5 - View from above, with DC cover (terminal type 1)

1.8.5 Control elements

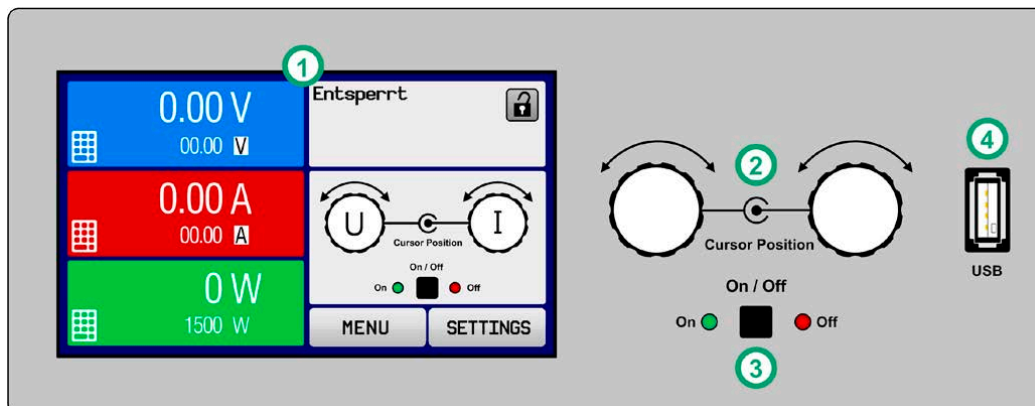


Figure 6 - Control Panel

Overview of the elements on the control panel

For a detailed description see section „1.9.6. The control panel (HMI)“.

(1)	Touchscreen display Used for selection of set values, menus, status and display of actual values and status. The touchscreen can be operated with the fingers or with a stylus.
(2)	Rotary knob with push button function Left knob (turn): adjusting the voltage set value, or setting the parameter values in the menu. Left knob (push): selection of the decimal position to be changed (cursor) for the assigned value. Right knob (turn): adjusting the current, power or resistance set value, or setting parameter values in the menu. Right knob (push): selection of the decimal position to be changed (cursor) for the assigned value.
(3)	On/Off Button for DC output Used to toggle the DC output between on and off, also used to start a function run. The LEDs “On” and “Off” indicate the state of the DC output, no matter if the device is manually controlled or remotely
(4)	USB-A port For the connection of standard USB sticks. See section „1.9.6.5. USB port (front side)“ for more details.

1.9 Construction and function

1.9.1 General description

The DC laboratory power supplies of the PSI 9000 2U series are especially suitable for test systems and industrial applications due to their compact construction in a 19" enclosure with 2 height units. Apart from basic functions of power supplies, set point curves can be generated in the integrated function generator (sine, rectangular, triangular and other curve types). Arbitrary generator curves (99 points) can be saved to and loaded from an USB stick.

For remote control the devices are provided as standard with an USB port on the back side as well as a galvanically isolated analog interface.

Via optional plug-in interface modules, other digital interfaces such as Ethernet, Profibus, ProfiNet, ModBus TCP, CAN, CANopen, EtherCAT or RS232 can be added. These enable the devices to be connected to standard industrial buses simply by replacing or adding a small module. The configuration, if necessary at all, is simple. Thus the power supplies may, for example, be operated with other power supplies or even other types of equipment or controlled by a PC or PLC, all using the digital interfaces.

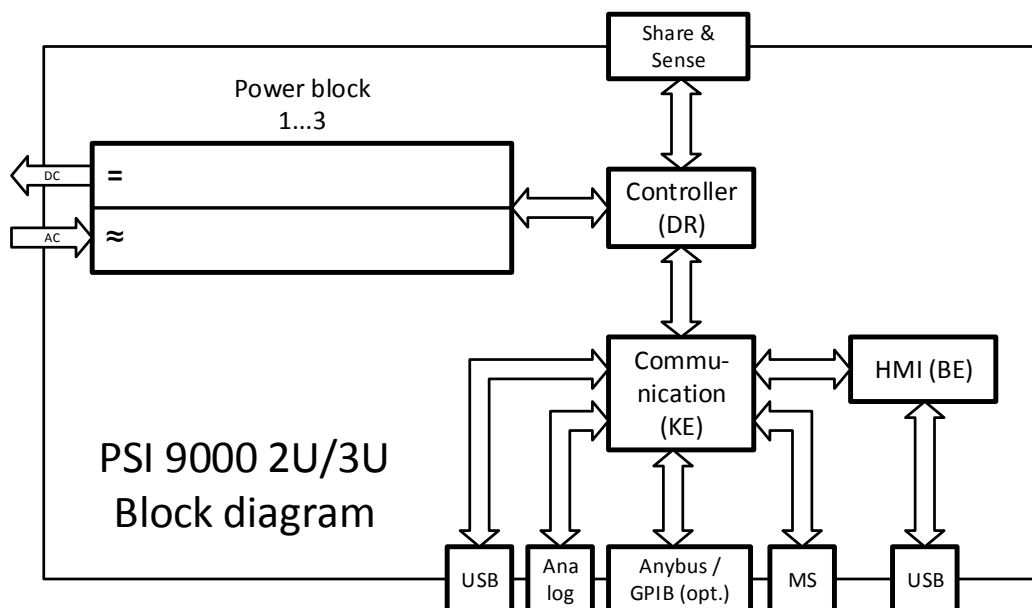
In addition, the devices offer as standard the possibility for parallel connection in Share bus operation for constant current sharing plus a genuine master-slave connection with totaling of the slave units is also provided as standard. Operating in this way allows up to 16 units to be combined to a single system with a total power of up to 48 kW.

All models are controlled by microprocessors for fast and exact measurement and display of actual values.

1.9.2 Block diagram

The block diagram illustrates the main components inside the device and their relationships.

There are digital, microprocessor controlled components (KE, DR, BE), which can be target of firmware updates.



1.9.3 Scope of delivery

- 1 x Power supply device PSI 9000 2U
- 1 x Mains cord, 2 m (6.5 ft) with Euro plug (Schuko) or US plug or UK 13 A or UK command plug, depending on shipping destination and rated power
- 1 x Share Bus plug (separately or plugged)
- 1 x Remote sensing plug (separately or plugged)
- 1 x USB cable, 1.8 m (5.9 ft)
- 1 x Set of mounting brackets (for conversion between 19" <-> desktop)
- 1 x USB stick with software and documentation

1.9.4 Accessories

For these devices the following accessories are available:

IF-AB Digital interface modules	Pluggable and retrofittable digital interface modules for RS232, CANopen, Ethernet, Profibus, ProfiNet, ModBus TCP, EtherCAT or CAN are available. Details about the interface modules and the programming of the device using those interfaces can be found in separate documentation. It's usually available on the USB stick which is included with the device or as PDF download on our website.
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1.9.5 Options

These options are usually ordered along with the device, as they are permanently built in or preconfigured during the manufacturing process. Retrofitting upon request.

POWER RACKS 19"-rack	Racks in various configurations up to 42U as parallel systems are available, or mixed with electronic load devices to create test systems. Further information in our product catalogue, on our website or upon request
3W GPIB interface	Replaces the standard slot for pluggable interface modules by a rigidly installed GPIB port. This option can be retrofitted upon request. The device will keep the USB and analog interfaces. Via the GPIB port only SCPI commands are supported.

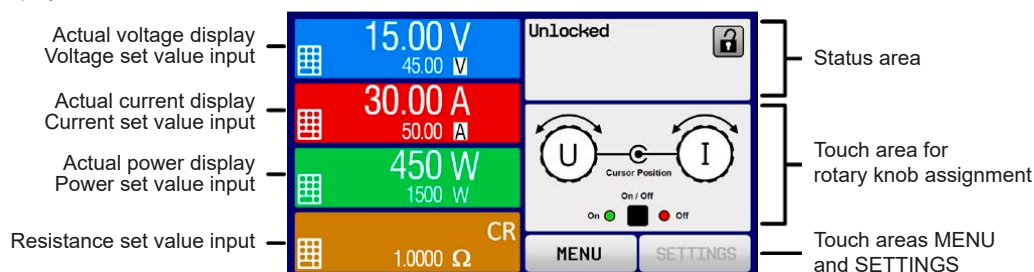
1.9.6 The control panel (HMI)

The HMI (Human Machine Interface) consists of a display with touchscreen, two rotary knobs, a pushbutton and an USB-A port.

1.9.6.1 Touchscreen display

The graphic touchscreen display is divided into a number of areas. The complete display is touch sensitive and can be operated by finger or stylus to control the equipment.

In normal operation the left hand side is used to show actual values and set values and the right hand side to display status information:



Touch areas may be enabled or disabled:



MENU

Black text or symbol = Enabled

SETTINGS

Grey text or symbol = Disabled

This applies to all touch areas on the main screen and all menu pages..

• Actual / set values area (left hand side)

In normal operation the DC output values (large numbers) and set values (small numbers) for voltage, current and power are displayed. The resistance set value of the variable internal resistance is only displayed during active resistance mode.

While the DC output is switched on, the actual regulation mode, **CV**, **CC**, **CP** or **CR** is displayed next to the corresponding actual value, as shown in the figure above.

The set values can be adjusted with the rotary knobs next to the display screen or can be entered directly via the touchscreen. When adjusting with the knobs, pushing the knob will select the digit to be changed. Logically, the values are increased by clockwise turning and decreased by anti-clockwise turning.

General display and settings ranges:

Display	Unit	Range	Description
Actual voltage	V	0.2-125% U_{Nom}	Actual values of DC output voltage
Set value of voltage ⁽¹⁾	V	0-102% U_{Nom}	Set value for limiting the DC output voltage
Actual current	A	0.2-125% I_{Nom}	Actual value of DC output current
Set value of current ⁽¹⁾	A	0-102% I_{Nom}	Set value for limiting the DC output current
Actual power	W	0.2-125% P_{Nom}	Actual value of output power, $P = U * I$
Set value of power ⁽¹⁾	W	0-102% P_{Nom}	Set value for limiting DC output power
Set value of internal resistance ⁽¹⁾	Ω	0-100% R_{Max}	Set value for the simulated internal resistance
Adjustment limits	A, V, W	0-102% nom	U-max, I-min etc.
Protection settings	A, V, W	0-110% nom	OVP, OCP etc.

⁽¹⁾ Valid also for values related to these physical values, such as OVD for voltage and UCD for current

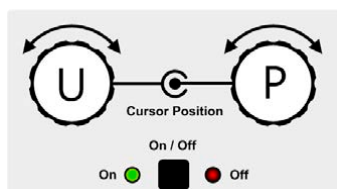
• Status display (upper right)

This area displays various status texts and symbols:

Display	Description
Locked	The HMI is locked
Unlocked	The HMI is unlocked
Remote:	The device is under remote control from....
Analog	the built-in analog interface
USB & others	the built-in USB port or a plug-in interface module
Local	The device has been locked by the user explicitly against remote control
Alarm:	Alarm condition which has not been acknowledged or still exists.
Event:	An user defined event has occurred which isn't yet acknowledged.
Master	Master-slave mode activated, device is master
Slave	Master-slave mode activated, device is slave
Function:	Function generator activated, function loaded
 / 	Data logging to USB stick active or failed

• Area for assigning the rotary knobs

The two rotary knobs next to the display screen can be assigned to various functions. This area shows the actual assignments. These can be changed by tapping this area, as long as it's not locked. The display changes to:



The physical quantities below the depiction of the knobs shows the current assignment. On a power supply, the left knob is always assigned to the voltage U, while the right knob can be switched by tapping the depiction.

The area will then show the assignment:

U I

Left rotary knob: voltage
Right rotary knob: current

U P

Left rotary knob: voltage
Right rotary knob: power

U R

Left rotary knob: voltage
Right rotary knob: resistance

The other set values can't be adjusted via the rotary knobs, unless the assignment is changed. However, values

can be entered directly with a ten-key pad by tapping on the small icon . Alternatively to the knob depiction, the assignment can also be changed by tapping the colored set value areas. **This method of entering values allows for set value steps.**

1.9.6.2 Rotary knobs

 As long as the device is in manual operation, the two rotary knobs are used to adjust set values, as well as setting the parameters in SETTINGS and MENU. For a detailed description of the individual functions see section „3.4 Manual operation“ on page 44.

1.9.6.3 Pushbutton function of the knobs

The rotary knobs also have a pushbutton function which is used in all value adjustment to move the cursor by rotation as shown:



1.9.6.4 Resolution of the displayed values

In the display, set values can be adjusted in fixed increments. The number of decimal places depends on the device model. The values have 3 to 5 digits. Actual and set values always have the same number of digits.

Adjustment resolution and number of digits of set values in the display:

Voltage, OVP, UVD, OVD, U-min, U-max			Current, OCP, UCD, OCD, I-min, I-max			Power, OPP, OPD, P-max			Resistance, R-max		
Nominal	Digits	Min. step width	Nominal*	Digits	Min. step width	Nominal*	Digits	Min. step width	Nominal	Digits	Min. step width
≤80 V	4	0.01 V	4 A / 6 A	4	0.001 A	≤3000 W	4	1 W	<10 Ω	5	0.0001 Ω
200 V	5	0.01 V	10 A - 25 A	5	0.001 A	MS <10 kW	3	0.01 kW	10 Ω - 60 Ω	5	0.001 Ω
≥360 V	4	0.1 V	30 A - 60 A	4	0.01 A	MS ≥10 kW	4	0.01 kW	120 Ω - 750 Ω	5	0.01 Ω
			≥120 A	4	0.1 A				1080 Ω - 5625 Ω	5	0.1 Ω
			MS ≥300 A	4	0.1 A						
			MS ≥1200 A	5	0.1 A						

* MS = Master-slave

1.9.6.5 USB port (front side)

The frontal USB port, located to the right of the rotary knobs, is intended for the connection of standard USB sticks and can be used for loading or saving sequences for the arbitrary and the XY generator, as well as for recording measured data during running operation.

USB 2.0 sticks are widely accepted. USB 3.0 sticks work, but not from all manufacturers. The stick must be **FAT32** formatted and should have a **maximum capacity of 32 GB**. All supported files must be held in a designated folder in the root path of the USB drive in order to be found. This folder must be named **HMI_FILES**, such that a PC would recognize the path G:\HMI_FILES if the drive were to be assigned the letter G.

The control panel of the device can read the following file types and names from a stick:

wave_u<arbitrary_text>.csv wave_i<arbitrary_text>.csv	Function generator for an arbitrary function on voltage (U) or current (I) The name must begin with <i>wave_u</i> / <i>wave_i</i> , the rest is user defined.
profile_<arbitrary_text>.csv	Previously saved user profile. A max. of 10 files to select from is shown when loading an user profile.
iu<arbitrary_text>.csv ui<arbitrary_text>.csv	IU or UI table for the XY function generator. The name must begin with <i>iu</i> or <i>ui</i> , the rest can be user defined.
pV<arbitrary_text>.csv fC<arbitrary_text>.csv	PV or FC table for the XY function generator. The name must begin with <i>pV</i> or <i>fC</i> , the rest can be user defined.
pV_day_et_<arbitrary_text>.csv pV_day_ui_<arbitrary_text>.csv	Day trend data file to load for the simulation modes DAY I/T and DAY U/I of the extended PV function.

The control panel of the device can save the following file types and names to an USB stick:

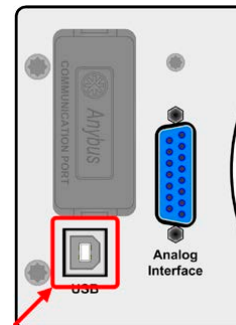
usb_log_<nr>.csv	File with log data recorded during normal operation in all modes. The file layout is identical to the those generated from the Logging feature in EA Power Control. The <nr> field in the file name is automatically counted up if equally named files already exist in the folder.
profile_<nr>.csv	Saved user profile. The number in the file name is a counter and not related to the actual user profile number in the HMI. A max. of 10 files to select from is shown when loading an user profile.
pV<nr>.csv	PF function table data, as calculated by the device. Can be loaded again.
fC<nr>.csv	FC function table data, as calculated by the device. Can be loaded again.
wave_u<nr>.csv wave_i<nr>.csv	Set point data (here: sequence points) from arbitrary function generator of either voltage U or current I
pV_record_<nr>.csv	Data from the data recording option in the extended PV function according to EN 50530.

1.9.7 USB port (rear side)

The USB port on the rear side of the device is provided for communication with the device and for firmware updates. The included USB cable can be used to connect the device to a PC (USB 2.0 or 3.0). The driver is delivered with the device and installs a virtual COM port. Details about remote control can be found in form of a programming guide on the included USB stick or on the web site of the manufacturer.

The device can be addressed via this port either using the international standard ModBus RTU protocol or by SCPI language. The device recognises the message protocol used automatically.

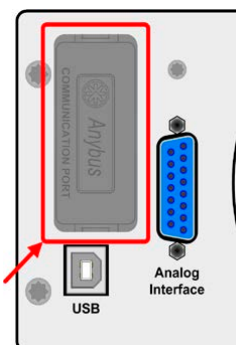
If remote control is in operation the USB port has no priority over either the interface module (see below) or the analog interface and can, therefore, only be used alternatively to these. However, monitoring is always available.



1.9.8 Interface module slot

This slot on the back side of the device (only with standard models, units with option 3W installed are different) is available for various modules of the IF-AB interface series. The following options are available:

Article number	Name	Description
35400100	IF-AB-CANO	CANopen, 1x Sub-D 9pole male
35400101	IF-AB-RS232	RS 232, 1x Sub-D 9pole male (null modem)
35400103	IF-AB-PBUS	Profibus DP-V1 Slave, 1x Sub-D 9pole female
35400104	IF-AB-ETH1P	Ethernet, 1x RJ45
35400105	IF-AB-PNET1P	ProfiNET IO, 1x RJ45
35400107	IF-AB-MBUS1P	ModBus TCP, 1x RJ45
35400108	IF-AB-ETH2P	Ethernet, 2x RJ45
35400109	IF-AB-MBUS2P	ModBus TCP, 2x RJ45
35400110	IF-AB-PNET2P	ProfiNET IO, 2x RJ45
35400111	IF-AB-CAN	CAN, 1x Sub-D 9pole male
35400112	IF-AB-ECT	EtherCAT, 2x RJ45



The modules are installed by the user and can be retrofitted without problem. A firmware update of the device may be necessary in order to recognize and support certain modules.

If remote control is in operation the interface module has no priority over either the USB port or the analog interface and can, therefore, only be used alternately to these. However, monitoring is always available.



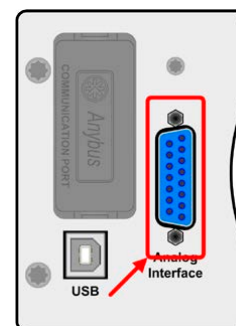
Switch off device before adding or removing modules!

1.9.9 Analog interface

This 15 pole Sub-D socket on the back side of the device is provided for remote control of the device via analog and digital signals.

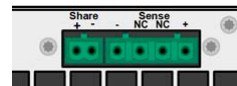
If remote control is in operation this analog interface can only be used alternately to the digital interface. However, monitoring is always available.

The input voltage range of the set values and the output voltage range of the monitor values, as well as reference voltage level can be switched in the settings menu of the device between 0-5 V and 0-10 V, in each case for 0-100%.



1.9.10 Share Bus connection

The 2 pole Phoenix socket "Share" on the back side of the device is provided for connection to equally named sockets on compatible power supply series to achieve a balanced load current distribution during parallel connection. The socket is also used to connect the power supply to compatible electronic loads, in order to build a two-quadrants operation setup. Following power supply and electronic load series are compatible:



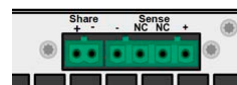
- PS 9000 1U - 3U *
- PSI 9000 2U - 24U
- PSI 9000 3U
- PSE 9000 3U
- ELR 9000
- EL 9000 B / EL 9000 B HP / EL 9000 B 2Q

* From hardware revision 2, see type label (in case it doesn't show "Revision" on type label, it's revision 1)

1.9.11 Sense connector (remote sensing)

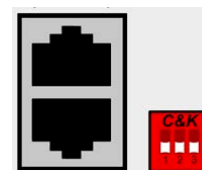
In order to compensate for voltage drops along the DC cables to the load, the Sense input can be connected to the load.

The maximum possible compensation is given in the technical specifications.



1.9.12 Master-Slave bus

A further port is provided on the back side of the device, comprising two RJ45 sockets, which enables multiple identical devices to be connected via a digital bus (RS485) to create a master-slave system. Connection is made using standard CAT5 cables. These can theoretically have a length of up to 1200 m, but it's recommended to keep the connections as short as possible.

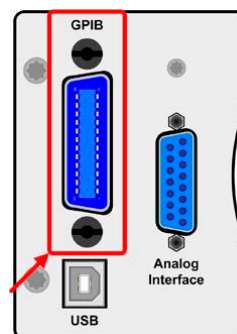


1.9.13 GPIB port (optional)

The optional GPIB connector, which is available with option 3W, will replace the interface slot of standard version devices. The device then offers a three-way interface with GPIB, USB and analog.

The connection to a PC or other GPIB port is done with standard GPIB cables from stock, which can have straight or 90° connectors.

When using cable with 90° connectors, the USB port will be inaccessible.



2. Installation & commissioning

2.1 Transport and storage

2.1.1 Transport



- The handles on the front side of the device are **not** for carrying!
- Because of its weight, transport by hand should be avoided where possible. If unavoidable then only the housing should be held and not on the exterior parts (handles, DC output terminal, rotary knobs).
- Do not transport when switched on or connected!
- When relocating the equipment use of the original packing is recommended
- The device should always be carried and mounted horizontally
- Use suitable safety clothing, especially safety shoes, when carrying the equipment, as due to its weight a fall can have serious consequences.

2.1.2 Packaging

It's recommended to keep the complete transport packaging for the lifetime of the device for relocation or return to the manufacturer for repair. Otherwise the packaging should be disposed of in an environmentally friendly way.

2.1.3 Storage

In case of long term storage of the equipment it's recommended to use the original packaging or similar. Storage must be in dry rooms, if possible in sealed packaging, to avoid corrosion, especially internal, through humidity.

2.2 Unpacking and visual check

After every transport, with or without packaging, or before commissioning, the equipment should be visually inspected for damage and completeness using the delivery note and/or parts list (see section „1.9.3. *Scope of delivery*“). An obviously damaged device (e. g. loose parts inside, damage outside) must under no circumstances be put in operation.

2.3 Installation

2.3.1 Safety procedures before installation and use



- The device may, according to model, have a considerable weight. Therefore the proposed location of the equipment (table, cabinet, shelf, 19" rack) must be able to support the weight without restriction.
- When using a 19" rack, rails suitable for the width of the housing and the weight of the device are to be used. (see „1.8.3. *Specific technical data*“)
- Before connecting to the mains ensure that the supply voltage is as shown on the product label. Overvoltage on the AC supply can cause equipment damage.

2.3.2 Preparation

Mains connection for a PSI 9000 2U series device is done via the included 2 meters long 3 pole mains cord. In case a different AC wiring is required, make sure that the other cable has at least a cross section of 2.5 mm² (AWG 12) is used.

Dimensioning of the DC wiring to the load/consumer has to reflect the following:



- The cable cross section should always be specified for at least the maximum current of the device.
- Continuous operation at the approved limit generates heat which must be removed, as well as voltage loss which depends on cable length and heating. To compensate for these the cable cross section should be increased and the cable length reduced.

2.3.3 Installing the device

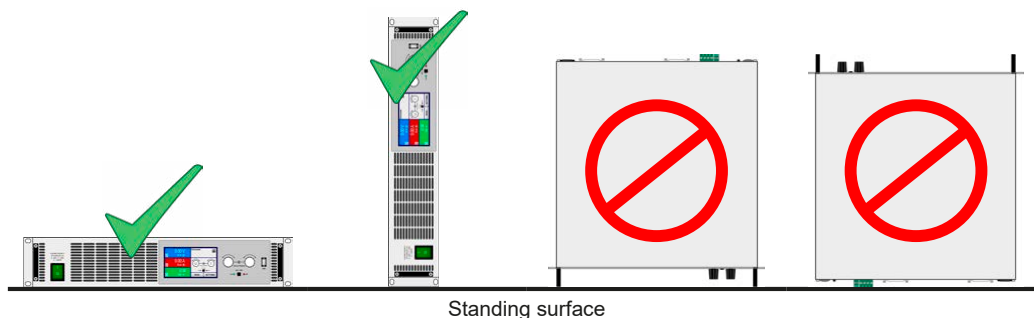


- Select the location for the device so that the connection to the load is as short as possible.
- Leave sufficient space behind the equipment, minimum 30 cm (1 ft), for ventilation.

A device in a 19" housing will usually be mounted on suitable rails and installed in 19" racks or cabinets. The depth of the device and its weight must be taken into account. The handles on the front are for sliding in and out of the cabinet. Slots on the front plate are provided for fixing the device (fixing screws not included).

With all models of this series, mounting brackets are included to convert the front plate from a 19" to desktop. In order to do that, the 19" mounting brackets can be removed after loosening the screws on the front grips and replacing the brackets by included metal strip, or vice versa.

Acceptable and unacceptable installation positions:



2.3.4 Connection to AC supply



- The device can be connected to any wall socket or multi-socket outlet, as long as those feature a safety contact (PE) and are capable for 16 A.
- When connecting the device to a multi-socket outlet, along with other electric devices, it's important to consider the total power consumption of all devices on the outlet, so that the maximum current (power ÷ minimum voltage) doesn't exceed the definition for the wall socket, the multi-socket outlet and/or main distribution
- Before plugging in the input plug ensure that the device is switched off by its mains switch!

The device is delivered with a 3-pole mains cord for standard wall socket connection and supply. If it shall be connected to a 2-phase or 3-phase supply, following phases are required:

Nominal power	Phases	Connection
1 kW - 3 kW	L (1/2/3), N, PE	Wall socket

The default input values of all models in this series are: 230 V, 16 A, 50 Hz. It's fused with 16 A. The maximum input current depends on the higher current intake at low AC voltage (for minimum input voltage see technical specs). Custom made cables thus require to have a cross section of 1.5 mm² (AWG16) minimum per lead, recommend is 2.5 mm² (AWG12).

2.3.5 Connection to DC loads



- In the case of a device with a high nominal current and hence a thick and heavy DC connection cable it's necessary to take account of the weight of the cable and the strain imposed on the DC connection. Especially when mounted in a 19" cabinet or similar, where the cable hangs on the DC output, a strain reliever should be used.
- Connection to and operation with transformerless DC-AC inverters (for example solar inverters) is restricted, because the inverter can shift the potential of negative output (DC-) against PE (ground). Mind the max. allowed potential shift (see technical specifications)!

The DC load output is on the rear side of the device and isn't protected by a fuse. The cross section of the connection cable is determined by the current consumption, cable length and ambient temperature.

For cables **up to 1.5 m** (5 ft) and average ambient temperature up to 50°C (122 °F), we recommend:

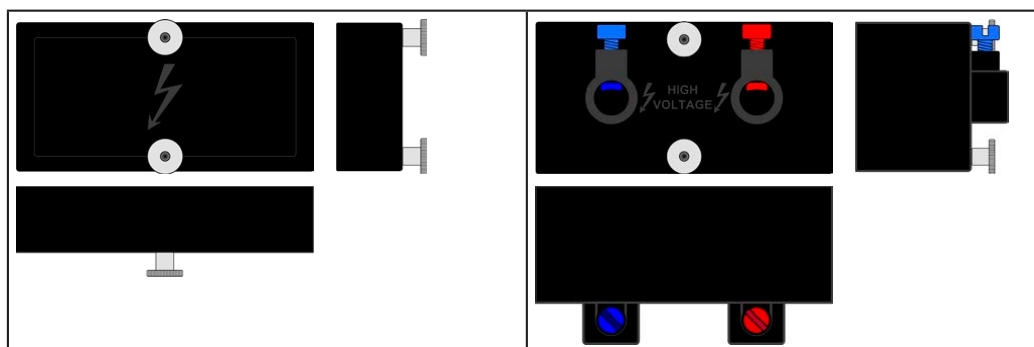
up to 10 A :	0,75 mm ² (AWG18)	up to 15 A :	1,5 mm ² (AWG14)
up to 30 A :	4 mm ² (AWG10)	up to 40 A :	6 mm ² (AWG8)
up to 60 A :	16 mm ² (AWG4)	up to 120 A :	35 mm ² (AWG1)

per lead (multi-conductor, insulated, openly suspended). Single cables of, for example, 35 mm² may be replaced by e. g. 2x 16 mm² etc. If the cables are long then the cross section must be increased to avoid voltage loss and overheating.

2.3.5.1 DC terminal types

The table below shows an overview of the various DC terminals. It's recommended that connection of load cables always utilizes flexible cables with ring lugs.

Type 1: Models up to 80 V output voltage	Type 2: Models from 200 V output voltage
M8 (8 mm) bolt on a brass block Recommendation: M8 ring lug with a 8.4 mm hole	Screw clamp connection M6, on copper rail Recommendation: M6 ring lug with a 6.5 mm hole



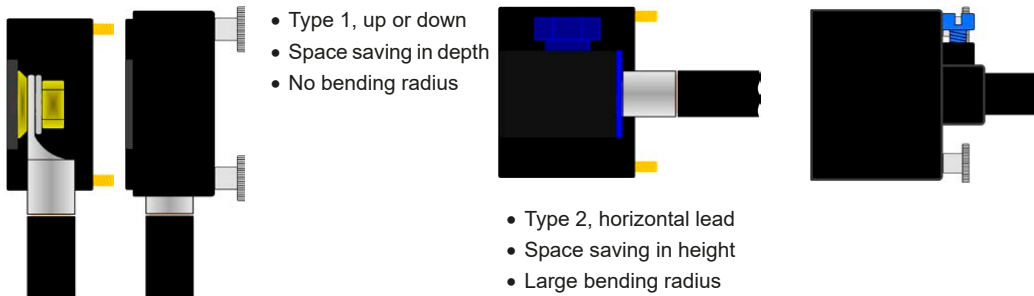
2.3.5.2 Cable lead and plastic cover

A plastic cover for contact protection is included for the DC terminal. It should always be installed. Both cover type are fixed to the DC terminal, by knurled nuts. Furthermore the cover for type 1 has break outs so that the supply cable can be laid in various directions.



The connection angle and the required bending radius for the DC cable must be taken into account when planning the depth of the complete device, especially when installing in a 19" cabinet or similar. For type 2 connectors only a horizontal lead can be used to allow for installation of the cover.

Connection examples:



2.3.6 Grounding of the DC output

Grounding one of the DC output poles is permissible, but causes potential shift against PE on the opposite pole. Because of insulation, there is a max. allowed potential shift defined for the DC output poles, which depends on the device model. Refer to „1.8.3. Specific technical data“ for details.

2.3.7 Connection of remote sensing



- Both pins „NC“ of the Sense connector must not be wired!
- Mind the electric strength of the sense cables, especially with models of ≥ 500 V rating!
- The two screws next to connectors Share/Sense must always be mounted!



- *Remote sensing is only effective during constant voltage operation (CV) and for other regulation modes the sense input should be disconnected, if possible, because connecting it generally increases the oscillation tendency*
- *The cross section of the sense cables is noncritical. However, it should be increased with increasing cable length. Recommendation for cables up to 5 m (16.4 ft): 0.5 mm^2*
- *Sense cables should be twisted and laid close to the DC cables to damp oscillation. If necessary, an additional capacitor should be installed at the load/consumer to eliminate oscillation*
- *The sense cables must be connected + to + and - to - at the load, otherwise both systems may be damaged*
- *In master-slave operation, the remote sensing should be connected to the master unit only*

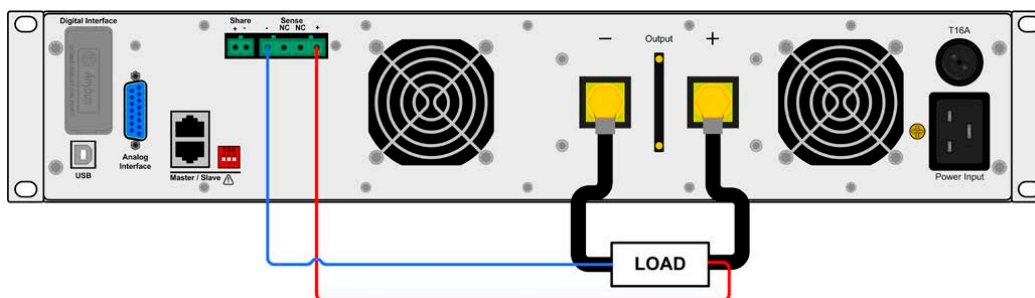


Figure 7 - Example for remote sensing wiring

2.3.8 Connecting the Share bus

The "Share" bus connector on the back side is intended to balance the current of multiple units in parallel operation, especially when using the integrated function generator of the master unit. Alternatively, it can be connected to a compatible electronic load, like from series ELR 9000, in order to run a two-quadrants operation. For further information about this mode of operation can be found in section „3.11.4. Two quadrant operation (2QO)“.

For the connection of the share bus the following must be paid attention to:



- Connection is only permitted between compatible devices (see „1.9.10. Share Bus connection“ for details) and between a max. of 16 units
- If a two-quadrants operation system has to be set up where multiple power supplies are connected to one electronic load unit or a group of electronic loads, all units should be connected via Share bus.
- When not using one or several units of a system configured with Share bus, because less power is required for an application, it's recommended to disconnect the unit's from the Share bus, because even when not powered they can have a negative impact on the control signal on the bus due to their impedance. Disconnection can be done by simply unplugging them from the bus or using switches.
- The Share bus is referenced to DC minus. When building a series connection (where allowed, depending on model), the DC minus will shift its potential and so will the Share bus

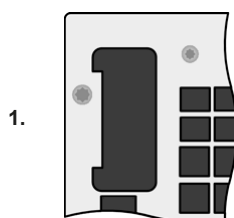
2.3.9 Installation of an interface module

The optionally obtainable interface modules can be retrofitted by the user and are exchangeable with each other. The settings for the currently installed module vary and need to be checked and, if necessary, corrected on initial installation and after module exchange.



- Common ESD protection procedures apply when inserting or exchanging a module.
- The device must be switched off before insertion or removal of a module
- Never insert any other hardware other than an interface module into the slot
- If no module is in use it's recommended that the slot cover is mounted in order to avoid internal dirtying of the device and changes in the air flow.

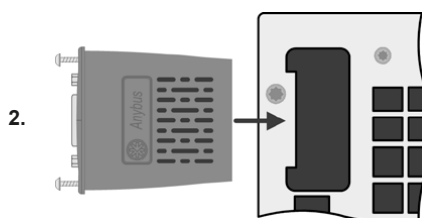
Installation steps:



With the help of a Torx 8 screw driver either remove the slot cover (dummy module) an already installed module.

The screws can be used to assist in pulling out the module.

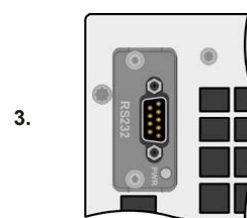
Make sure the screws are fully retracted. If not, unscrew them further and remove the module.



Insert the interface module into the slot. The shape ensures correct alignment.

When inserting take care that it's held as close as possible to a 90° angle to the rear wall of the device. Use the green PCB, which you can recognize on the open slot as guide. At the end is a socket for the module.

On the bottom side of the module are two plastic nibs which must click into the green PCB so that the module is properly aligned on the rear wall of the device.



The screws (Torx 8) are provided for fixing the module and should be fully screwed in. After installation, the module is ready for use and can be connected.

Removal follows the reverse procedure.

2.3.10 Connecting the analog interface

The 15 pole connector (Type: Sub-D, D-Sub) on the rear side is an analog interface. To connect this to a controlling hardware (PC, electronic circuit), a standard plug is necessary (not included in the scope of delivery). It's generally advisable to switch the device completely off before connecting or disconnecting this connector, but at least the DC output.



The analog interface is galvanically isolated from the device internally. Unless absolutely required, don't connect any ground of the analog interface (AGND) to the DC minus output as this will cancel the galvanic isolation.

2.3.11 Connecting the USB port (rear side)

In order to remotely control the device via this port, connect the device with a PC using the included USB cable and switch the device on.

2.3.11.1 Driver installation (Windows)

On the initial connection with a PC the operating system will identify the device as new hardware and will try to install a driver. The required driver is for a Communication Device Class (CDC) device and is usually integrated in current operating systems such as Windows 7 or 10. But it's strongly recommended to use and install the included driver (on USB stick) to gain maximum compatibility of the device to our softwares.

2.3.11.2 Driver installation (Linux, MacOS)

We can't provide drivers or installation instructions for these operating systems. Whether a suitable driver is available is best carried out by searching the Internet.

2.3.11.3 Alternative drivers

In case the CDC driver described above isn't available on your system, or for some reason don't function correctly, commercial suppliers can help. Search the Internet for suppliers using the keywords "cdc driver windows" or "cdc driver linux" or "cdc driver macos".

2.3.12 Initial commission

For the first start-up after installation of the device, the following procedures have to be executed:

- Confirm that the connection cables to be used are of a satisfactory cross section!
- Check if the factory settings of set values, safety and monitoring functions and communication are suitable for your intended application of the device and adjust them if required, as described in the manual!
- In case of remote control via PC, read the additional documentation for interfaces and software!
- In case of remote control via the analog interface, read the section in this manual concerning analog interfaces!

2.3.13 Commission after a firmware update or a long period of non-use

In case of a firmware update, return of the equipment following repair or a location or configuration change, similar measures should be taken to those of initial start up. Refer to „2.3.12. Initial commission“.

Only after successful checking of the device as listed may it be operated as usual.

3. Operation and application

3.1 Personal safety



- In order to guarantee safety when using the device, it's essential that only persons operate the device who are fully acquainted and trained in the required safety measures to be taken when working with dangerous electrical voltages
- For models which can generate a voltage which is dangerous by contact, or is connected to such, the included DC terminal cover, or an equivalent, must always be used
- Whenever the load and DC output are being re-configured, the device should be disconnected from the mains, not only the DC output switched off!

3.2 Operating modes

A power supply is internally controlled by different control circuits, which shall regulate voltage, current and power to the adjusted values and hold them constant, if possible. These circuits follow typical laws of control systems engineering, resulting in different operating modes. Each operating mode has its own characteristics which are explained below in short form.



- *Unloaded operation is not a normal operation mode of a power supply and can thus lead to false measurements, for example when calibrating the device*
- *The optimal working point of the device is between 50% and 100% voltage and current*
- *It's recommended to not run the device below 10% voltage and current in order to meet technical specification values like ripple or transient times*

3.2.1 Voltage regulation / Constant voltage

Voltage regulation is also called constant voltage operation (CV).

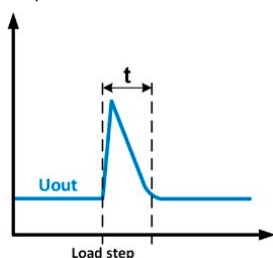
The DC output voltage of a power supply is held constant on the adjusted value, unless the output current or the output power according to $P = U_{OUT} \cdot I_{OUT}$ reaches the adjusted current or power limit. In both cases the device will automatically change to constant current or constant power operation, whatever occurs first. Then the output voltage can't be held constant anymore and will sink to a value resulting from Ohm's law.

While the DC output is switched on and constant voltage mode is active, then the condition "CV mode active" will be indicated on the graphic display by the abbreviation **CV** and this message will be passed as a signal to the analog interface, as well stored as status which can also be read as a status message via digital interface.

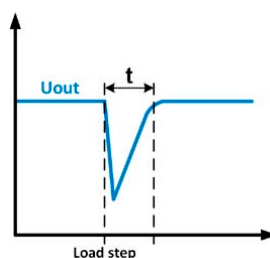
3.2.1.1 Load step compensation

For constant voltage mode (CV), the technical date "Settling time after load step" (see 1.8.3) defines a time that is required by the internal voltage regulator of the device to settle the output voltage after a load step. Negative load steps, i. e. high load to lower load, will cause the output voltage to overshoot for a short time until compensated by the voltage regulator. The same occurs with a positive load step, i. e. low load to high load. There the output collapses for a moment. The amplitude of the overshoot resp. collapse depends on the device model, the currently adjusted output voltage and the capacity on the DC output and can thus not be stated with a specific value.

Depictions:



Example for neg. load step: the DC output will rise above the adjusted value for a short time. t = transient time to settle the output voltage.



Example for pos. load step: the DC output will collapse below the adjusted value for a short time. t = transient time to settle the output voltage.

3.2.2 Current regulation / constant current / current limiting

Current regulation is also known as current limiting or constant current mode (CC).

The DC output current is held constant by the power supply, once the output current to the load reaches the adjusted limit. Then the power supply automatically switches to CC. The current flowing from the power supply is determined by the output voltage and the load's true resistance. As long as the output current is lower than the adjusted current limit, the device will be either in constant voltage or constant power mode. If, however, the power consumption reaches the set maximum power value, the device will switch automatically to power limiting and sets the output current according to $I_{MAX} = P_{SET} / U_{IN}$, even if the maximum current value is higher. The current set value, as determined by the user, is always an upper limit only.

While the DC output is switched on and constant current mode is active, then the condition "CC mode active" will be indicated on the graphic display by the abbreviation **CC** and this message will be passed as a signal to the analog interface, as well stored as status which can also be read as a status message via digital interface.

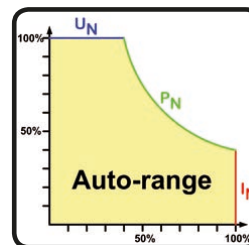
3.2.2.1 Voltage overshootings

In certain situations it's possible that the device generates a voltage overshooting. Such situations are when the device is in CC, with the actual voltage being unregulated, and either a jump in the current set value is initiated which would bring the device out of CC or when the load is suddenly cut from the power supply by an external means. Peak and duration of the overshooting aren't exactly defined, but as rule of thumb it shouldn't exceed a peak of 1-2% of the rated voltage (on top of the voltage setting) while the duration mainly depends on the charging state of the capacities on the DC output and also the capacity value.

3.2.3 Power regulation / constant power / power limiting

Power regulation, also known as power limiting or constant power (CP), keeps the DC output power of a power supply constant if the current flowing to the load in relation to the output voltage and the resistance of load reaches the adjusted value according to $P = U \cdot I$ resp. $P = U^2 / R$. The power limiting then regulates the output current according to $I = \sqrt{P / R}$, where R is the load's resistance.

Power limiting operates according to the auto-range principle such that at lower output voltages higher current flows and vice versa in order to maintain constant power within the range P_N (see diagram to the right).



While the DC output is switched on and constant power mode is active, then the condition "CP mode active" will be shown on the graphic display by the abbreviation **CP**, as well stored as status which can also be read as a status message via digital interface.



When using remote sensing, the power supply can deliver a higher voltage on the DC output than adjusted, which results in additional power and may also cause the device to enter power limitation without explicitly indicating CP in the display.

3.2.3.1 Power derating

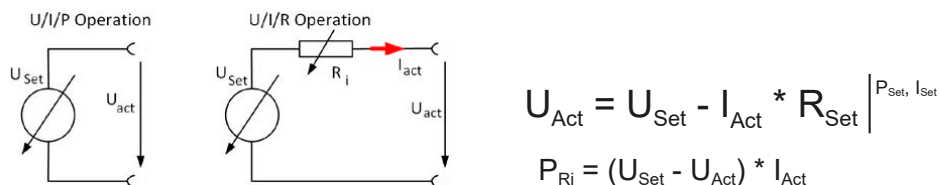
Due to European standard fusing of wall sockets (16 A) and the extended input voltage range, power supply models as from 1500 W have a fixed derating. It becomes active below a certain input voltage level (for value see „1.8.3. Specific technical data“) and will derate the maximum available output power for a 1500 W model down to 1000 W and for a 3000 W model down to 2500 W. The derating only affects the available output power, thus the full range for power set value adjustment remains, though the device will switch earlier to constant power operation. This situation of constant power can't be indicated by status CP. Active derating can then only be detected by reading the actual values of voltage and current and by calculating the power.

3.2.4 Internal resistance regulation

Internal resistance control (short: CR) of power supplies is the simulation of a virtual internal resistor which is in series to the load. According to Ohm's law, this resistance causes a voltage drop, which will result in a difference between the adjusted output voltage and the actual output voltage. This will also work in CC or CP mode whereas the actual output voltage will differ even more from the adjusted voltage, because both modes limit the output voltage additionally. CR mode is actually running in CV, but will be indicated as **CR** on display once the adjusted resistance value is reached.

The adjustable resistance range of a particular model is given in the technical specifications. The voltage regulation in dependency of the resistance set value and the output current is done by calculation in a fast ARM controller, being only a little slower than other controllers inside the control circuit.

Clarification:



With resistance mode being activated the function generator will be unavailable and the actual power value provided by the device doesn't include the simulated power dissipation of Ri.

3.3 Alarm conditions



This section only gives an overview about device alarms. What to do in case your device indicates an alarm condition is described in section „3.6. Alarms and monitoring“.

As a basic principle, all alarm conditions are signaled optically (text + message in the display), acoustically (if activated) and as a readable status and alarm counter via the digital interface. In addition, the alarms OT and OVP are reported as signals on the analogue interface. For later acquisition, an alarm counter can be read from the display or via digital interface.

3.3.1 Power Fail

Power Fail (PF) indicates an alarm condition which may have various causes:

- AC input voltage too low (mains undervoltage, mains failure)
- Defect in the input circuit (PFC)

As soon as a power fail occurs, the device will stop to supply power and switch off the DC output. The condition of the DC output after a PF alarm during normal operation can be set up. See „3.4.3. Configuration via MENU“.



Switching off the device by the mains switch can't be distinguished from a mains blackout and thus the device will signalize a PF alarm every time the device is switched off. This can be ignored.

3.3.2 Overtemperature

An overtemperature alarm (OT) can occur from an excess temperature inside the device and temporarily causes it to switch of the power stage(s). This can occur if the ambient temperature exceeds the maximum ambient temperature rating for the device. After cooling down, the device can automatically switch the power stage back on, depending on the setting of parameter “DC output after OT alarm”. See section „3.4.3.1. Menu “General Settings”“.

3.3.3 Overvoltage protection

An overvoltage alarm (OVP) will switch off the DC output and can occur if:

- the power supply itself, as a voltage source, generates an output voltage higher than set for the overvoltage alarm threshold (OVP, 0...110% U_{Nom}) or the connected load somehow returns voltage higher than set for the overvoltage alarm limit
- the OV threshold has been adjusted too close above the output voltage. If the device is in CC mode and if it then experiences a negative load step, it will make the voltage rise quickly, resulting in a voltage overshoot for a short moment which can already trigger the OVP

This function serves to warn the user of the power supply acoustically or optically that the device probably has generated an excessive voltage which could damage the connected load application.



- The device isn't fitted with protection from external overvoltage
- The changeover from operation modes CC -> CV can generate voltage overshoots

3.3.4 Overcurrent protection

An overcurrent alarm (OCP) will switch off the DC output and can occur if:

- the output current in the DC output exceeds the adjusted OCP limit.

This function serves to protect the connected load application so that this isn't overloaded and possibly damaged due to an excessive current.

3.3.5 Overpower protection

An overpower alarm (OPP) will switch off the DC output and can occur if:

- the product of the output voltage and output current in the DC output exceeds the adjusted OPP limit.

This function serves to protect the connected load application so that this isn't overloaded and possibly damaged due to an excessive power consumption.

3.4 Manual operation

3.4.1 Switching on the device

The device should, as far as possible, always be switched on using the toggle switch on the front of the device. Alternatively, this can be done using an external cutout (contactor, circuit breaker) of suitable current capacity.

After switching on, the display will first show some device related information (model, firmware versions etc.) and then a language selection screen for 3 seconds. A few seconds later it will show the main screen.

In setup (see section „3.4.3. Configuration via MENU“ in the second level menu **General settings** is an option **Output after power ON** in which the user can determine the condition of the DC output after power-up. Factory setting here is **OFF**, meaning that the DC output on power-up is always switched off. **Restore** means that the last condition of the DC output will be restored, either on or off. All set values are always saved and restored.



For the time of the start phase the analog interface can signal undefined statuses on the output pins such as ALARMS 1. Those signal must be ignored until the device has finished booting and is ready to work.

3.4.2 Switching off the device

On switch-off the last output condition and the most recent set values are saved. Furthermore, a PF alarm (power failure) will be reported, but can be ignored.

The DC output is immediately switched off and after a short while fans will shut down and after another few seconds the device will be completely powered off.

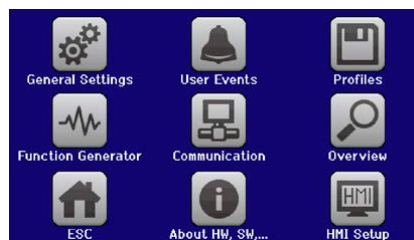
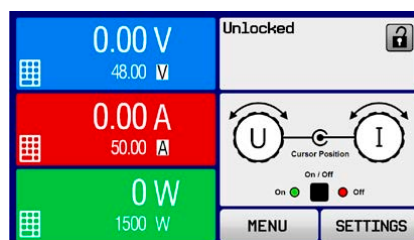
3.4.3 Configuration via MENU

The MENU serves to configure all operating parameters which are not constantly required. These can be set by finger touch on the MENU touch area, but only if the DC output is switched OFF. See figure to the right.

If the DC output is switched on the settings menu won't be shown, only status information.

Menu navigation is by finger touch. Values are set using the rotary knobs. The assignments of the rotary knobs, if multiple values can be set in a particular menu, isn't always depicted. Following rule for such situations: upper value -> left knob, lower value -> right knob.

Some setting parameters are self-explanatory, others are not. The latter will be explained on the pages following.



3.4.3.1 Menu "General Settings"

Setting	Description
Allow remote control	Selection NO means that the device can't be remotely controlled over either the digital or analog interfaces. If remote control isn't allowed, the status will be shown as Local in the status area on the main display. See also section 1.9.6.1
Analog interface range	Selects the voltage range for the analog set inputs, actual value outputs and reference voltage output. • 0...5 V = corresponds to 0...100% set / actual values, reference voltage 5 V • 0...10 V = corresponds to 0...100% set / actual values, reference voltage 10 V See also section „3.5.4 Remote control via the analog interface (AI)“ on page 57
Analog interface Rem-SB	Selects how the input pin REM-SB of the analog interface shall be working regarding levels (see „3.5.4.4 Analog interface specification“ on page 58) and logic: • Normal = Levels and function as described in the table in 3.5.4.4 • Inverted = Levels and function will be inverted Also see „3.5.4.7. Application examples“
Analog Rem-SB action	Selects the action on the DC output that is initiated when changing the level of analog input REM-SB: • DC OFF = the pin can only be used to switch the DC output off • DC AUTO = the pin can be used to switch the DC output off and on again, if it has been switched on before at least from a different control location
Analog interface pin 6	Pin 6 of the analog interface (see section 3.5.4.4) is by default assigned to only signal the device alarms OT and PF. This parameter allows to also enable signaling only one of both (3 possible combinations): • Alarm OT = Enable/disable signaling of alarm OT on pin 6 • Alarm PF = Enable/disable signaling of alarm PF on pin 6
Analog interface pin 14	Pin 14 of the analog interface (see section 3.5.4.4) is by default assigned to only signal the device alarm OVP. This parameter allows to also enable signaling further device alarms (7 possible combinations): • Alarm OVP = Enable/disable signaling of alarm OVP on pin 14 • Alarm OCP = Enable/disable signaling of alarm OCP on pin 14 • Alarm OPP = Enable/disable signaling of alarm OPP on pin 14
Analog interface pin 15	Pin 15 of the analog interface (see section 3.5.4.4) is by default assigned to only signal the regulation mode CV. This parameter allows to enable signaling a different device status (2 options): • Regulation mode = Enable/disable signaling of CV reg mode on pin 15 • DC status = Enable/disable signaling of DC output status on pin 15
DC output after OT alarm	Determines how the DC power stages shall react after an overtemperature (OT) alarm has occurred and the power stages have cooled down again: • OFF = DC power stage(s) will be off • AUTO = The device will automatically restore the situation before the OT alarm, which usually means the DC power stage(s) to be on
DC output after power ON	Determines the condition of the DC output after power-up. • OFF = DC output is always off after switching on the device. • Restore = DC output condition will be restored to the condition prior to switch off.
DC output after PF alarm	Determines how the DC output shall react after a power fail (PF) alarm has occurred: • OFF = DC output will be switched off and remain until user action • AUTO = DC output will switch on again after the PF alarm cause is gone and if it was switched on before the alarm occurred

Setting	Description
DC output after remote	Determines the condition of the DC output after leaving remote control either manually or by command. • OFF = DC output will be always off when switching from remote to manual • AUTO = DC output will keep the last condition
Enable R mode	Activates (Yes) or deactivates (No) the internal resistance control. If activated, the resistance set value can be adjusted additionally to the other set values. For details refer to „3.2.4. Internal resistance regulation“
USB decimal point format	Switches the decimal point format of values and also the CSV file separator for USB logging and for other features where CSV file can be loaded • US = Comma separator (US standard for CSV files) • Default = Semicolon separator (german/european standard for CSV files)
Log value with unit (V,A,W)	CSV files generated from USB logging by default add physical units to values. This can be deactivated by setting this option to No
Calibrate device	Touch area Start starts a calibration routine (see „4.3. Calibration“), but only if the device is in U/I or U/P mode.
Reset device to defaults	Touch area Start will initiate a reset of all settings (HMI, profile etc.) to default values
Restart device	Will initiate a warm start of the device
Master-slave mode	Selecting MASTER or SLAVE enables the master-slave mode (short: MS) and sets the selected position for the unit in the MS system. Default setting: OFF . This applies to the digital MS bus, the analog Share bus and two-quadrants operation. For details see sections „3.11.1. Parallel operation in master-slave mode (MS)“ and „3.11.4. Two quadrant operation (2QO)“.
Repeat master init.	Touch area Initialize will repeat the initialization of the master-slave system in case the automatic enumeration of the slave units by the master is once unsuccessful so the system would have less total power than expected or has to be repeated manually in case the master unit couldn't detect a missing slave

3.4.3.2 Menu “User Events”

See „3.6.2.1 User defined events“ on page 62.

3.4.3.3 Menu “Profiles”

See „3.9 Loading and saving an user profile“ on page 64.

3.4.3.4 Menu “Overview”

This menu page displays an overview of the set values (U, I, P or U, I, P, R) and alarm settings as well as settings limits. These can only be displayed, not changed.

3.4.3.5 Menu “About HW, SW...”

This menu page displays an overview of device relevant data such as serial number, article number etc., as well as an alarm history which lists the number of device alarms that probably occurred since the device has been powered.

3.4.3.6 Menu “Function Generator”

See „3.10 The function generator“ on page 65.

3.4.3.7 Menu “Communication”

This sub menu offers settings for digital communication via the optional or built-in interface. The touch area for the installed interface module or the optional GPIB port opens one or more settings pages, depending on the interface in use. There is furthermore an adjustable communication timeout, to make it possible to successfully transfer fragmented messages (data packets) using higher values. In the screen for “Com Protocols” you can enable both or disable one of the two supported communication protocols, ModBus and SCPI. This can help to avoid mixing both protocols and to receive unreadable messages, for example when expecting a SCPI response and getting a ModBus response instead.



For all Ethernet interfaces with two ports: „P1“ is related to port 1 and „P2“ to port 2, like printed on the module face. Two-port interfaces will use one IP only.

PSI 9000 2U Series

IF	Level 1	Description
Profibus DP	Node Address	Selection of the Profibus or node address of the device within range 1...125 via direct input
	Function Tag	String input box for an user-definable text which describes the Profibus slave function tag. Max. length: 32 characters
	Location Tag	String input box for an user-definable text which describes the Profibus slave location tag. Max. length: 22 characters
	Installation Date	String input box for an user-definable text which describes the Profibus slave installation date tag. Max. length: 40 characters
	Description	String input box for an user-definable text which describes the Profibus slave. Max. length: 54 characters

IF	Level 1	Description
GPIB	Node Address	Adjustment of the GPIB node address (only with option 3W installed) in the range 1...30

IF	Level 1	Level 2	Level 3	Description	
Ethernet / ModBus-TCP, 1 & 2 Port	IP Settings 1	DHCP		The IF allows a DHCP server to allocate an IP address, a subnet mask and a gateway. If no DHCP server is in the network then network parameters will be set as defined in item “Manual”	
		Manual	IP address	This option is activated by default. An IP address can be manually allocated.	
			Gateway	Here a gateway address can be allocated if required..	
			Subnet mask	Here a subnet mask can be defined if the default subnet mask isn't suitable.	
		DNS address 1		Here the addresses of the first and second Domain Name Servers (DNS) can be defined, if needed.	
		DNS address 2			
		Port		Range: 0...65535. Default ports: 5025 = Modbus RTU (all Ethernet interfaces) Reserved ports which can't be set: 502 = Modbus TCP (always active, no need to be set)	
	IP Settings 2-P1	AUTO		Settings for the Ethernet port such as transmission speed are set automatically.	
	IP Settings 2-P2	Manual	Half duplex	Manual selection for transmission speed (10MBit/100MBit) and duplex mode (full/half). It's recommended to use the “AUTO” option and only revert to “Manual” if these parameters fail. Different Ethernet port settings for 2-port modules are possible, as these include an Ethernet switch	
			Full duplex		
			10MBit		
			100MBit		
	Host name				Free choice of host name (default: Client)
	Domain name				Free choice of Domain (default: Workgroup)
	TCP Keep-Alive		Enable TCP keep-alive		

IF	Level 1	Description
Profinet/IO, 1 & 2 Port	Host name	Free choice of host name (default: Client)
	Domain name	Free choice of Domain (default: Workgroup)
	Function Tag	String input box for an user-definable text which describes the Profinet slave function tag. Max. length: 32 characters
	Location Tag	String input box for an user-definable text which describes the Profinet slave location tag. Max. length: 22 characters
	Station Name	String input box for an user-definable text which describes the Profinet station name. Max. length: 200 characters
	Description	String input box for an user-definable text which describes the Profibus slave. Max. length: 54 characters
	Installation Date	String input box for an user-definable text which describes the Profibus slave installation date tag. Max. length: 40 characters

PSI 9000 2U Series

IF	Ebene 1	Level 2	Level 3	Description
CAN	Base ID			Setup of the CAN base ID (11 Bit or 29 Bit, hex format). Default: 0h
	Baud Rate			Setup of the CAN bus speed or baud rate in typical value between 10 kbps and 1Mbps. Default: 500 kbps
	Termination			Activates or deactivates CAN bus termination with a built-in resistor. Default: OFF
	Broadcast ID			Setup of the CAN broadcast ID (11 Bit or 29 Bit, hex format). Default: 7ffh
	ID Format			Selection of the CAN ID format between Base (11 Bit ID, 0h...7ffh) and Extended (29 Bit, 0h...1fffffffh)
	Cyclic Communication	Base ID Cyclic Read		Setup of the CAN base ID (11 Bit or 29 Bit, hex format) for cyclic read of up to 5 object groups (see " Cyclic Read Timing "). The device will automatically send specific object data to the IDs defined with this setting. For more information refer to the programming guide. Default: 100h
		Base ID Cyclic Send		Setup of the CAN base ID (11 Bit or 29 Bit, hex format) for cyclic send of the three set values for U, I and P along with status in one single message. For more information refer to the programming guide. Default: 200h
		Cyclic Read Timing	Status	Activation/deactivation and time setting for the cyclic read of status to the adjusted „ Base ID Cyclic Read + 1 “ Range: 20...5000 ms. Default: 0 (deactivated)
			Actual val.	Activation/deactivation and time setting for the cyclic read of actual values to the adjusted „ Base ID Cyclic Read + 2 “ Range: 20...5000 ms. Default: 0 (deactivated)
			Set val.	Activation/deactivation and time setting for the cyclic read of set values of U & I to the adjusted „ Base ID Cyclic Read + 3 “ Range: 20...5000 ms. Default: 0 (deactivated)
			Limits 1	Activation/deactivation and time setting for the cyclic read of adjustment limits of P & R to the adjusted „ Base ID Cyclic Read + 4 “ Range: 20...5000 ms. Default: 0 (deactivated)
			Limits 2	Activation/deactivation and time setting for the cyclic read of adjustment limits of P & R to the adjusted „ Base ID Cyclic Read + 4 “
	Data Length			Determines the DLC (data length) of all messages sent from the device. AUTO = length varies between 3 and 8 bytes, depending on object Always 8 Bytes = length is always 8, filled up with zeros

IF	Level 1	Level 2	Description
CANopen	Node Address		Selection of the CANopen node address in the range 1...127 via direct input
	Baud Rate	AUTO	Automatic detection of the bus baud rate.(speed)
		LSS	Automatically sets baud rate and node address
		Manual	Manual selection of the baud rate that is used by the CANopen interface. Possible selections: 10 kbps, 20 kbps, 50 kbps, 100 kbps, 125 kbps, 250 kbps, 500 kbps, 800 kbps, 1Mbps (1Mbps = 1 Mbit/s, 10 kbps = 10 kbit/s)

IF	Level 1	Description
RS232	-	The baud rate is selectable, other serial settings can't be changed and are defined like this: 8 data bits, 1 stop bit, parity = none Baud rates: 2400, 4800, 9600, 19200, 38400, 57600, 115200

PSI 9000 2U Series

Element	Description
Com Timeout	Timeout USB/RS232 [ms] Default value: 5 , range: 5...65535 ms Defines the max. time between two subsequent bytes or blocks of a transferred message. For more information refer to the external programming documentation "Programming Guide ModBus & SCPI".
	Timeout ETH [s] Default value: 5 , range: 5...65535 s If there was no communication between the controlling unit (PC, PLC etc.) and the device for the adjusted time, it will close the socket connection. This timeout will be ineffective as long as the option "TCP keep-alive" (see above, table for Ethernet module) is activated and "keep-alive" is working as expected within the network. Setting 0 deactivates the timeout permanently.
	Enable interface monitoring Default value: off Enable or disables the interface monitoring feature. For details refer to section 3.5.3.4.
	Timeout interface monitoring [s] Default value: 5 , range: 5...65535 s Defines the timeout in seconds for the interface monitoring featured. The timeout would only be active if the interface monitoring itself is enabled. See above at Enable interface monitoring . Further details can be found in section 3.5.3.4.
Com Protocols	Enabled Default setting: both enabled Enables or disables SCPI or ModBus communication protocols for the device, if not needed. The change is immediately effective after submitting it with ENTER button.
	ModBus specification compliance Default setting: Limited Switches between Limited and Full compliance to the ModBus specification in terms of message format when using ModBus RTU or TCP and also the use of the Read Coils function. For details and the background refer to the external documentation "Programming Guide ModBus & SCPI"
Logging	Enable USB logging Default setting: disabled Enables/disables the "log to USB stick" feature. Once enabled, you can define the log interval (multiple steps between 500 ms and 5 s) and the control method. For details refer to „3.4.10. Recording to USB stick (logging)“.

3.4.3.8 Menu "HMI Setup"

These settings refer exclusively to the control panel (HMI).

Element	Description
Language	Selection of the display language between German, English (default), Russian or Chinese
Backlight	The choice here is whether the backlight remains Always on or if it should be switched off when no input via screen or rotary knob is done for 60 s. As soon as there is the next input, the backlight returns automatically. Furthermore the brightness can be selected in 10 steps.
HMI Lock	See „3.7 Control panel (HMI) lock“ on page 63.
Limits Lock	See „3.8 Limits lock“ on page 64
Key Sound	Activates or deactivates sounds when touching a touch area in the display. It can usefully signal that the action has been accepted.
Alarm Sound	Activates or deactivates the additional acoustic signal of an alarm or user defined event which has been set to Action = ALARM . See also „3.6 Alarms and monitoring“ on page 61.
Status page	Enables/disables two display related options for the main screen (status page): Show meter bar: in U/I/P mode, i. e. resistance mode not activated, a meter bar for 0-100% actual values of voltage, current and power is shown. Also see „3.4.8. The meter bars“. Alternative status page: switches the main screen of the device with its actual and set values of voltage, current, power and - if activated - resistance to a simpler display with only voltage and current, plus status. See „3.4.7. Switching the main screen view“. Default setting: both disabled

3.4.4 Adjustment limits (Limits)



Adjustment limits are only effective on the related set values, no matter if using manual adjustment or remote control setting!

Defaults are that all set values (U, I, P, R) and the corresponding adjustment limits are adjustable from 0 to 102% of rated value.

The full range may be obstructive in some cases, especially for protection of applications against overvoltage. Therefore upper and lower limits for current (I) and voltage (U) can be set separately, which then limit the range of the adjustable set values.

For power (P) and resistance (R) only upper value limits can be set.



► How to configure the adjustment limits

1. On the main screen, tap **SETTINGS** to access the SETTINGS menu.
2. Tap the arrows   to select **3. Limits**.
3. In each case a pair of upper and lower limits for U/I or the upper limit for P/R are assigned to the rotary knobs and can be adjusted. Tap the selection area for another choice .
4. Accept the settings with .



The set values can be entered directly using the ten-key pad. This appears when the touch area for direct input is tapped (bottom center)



The adjustment limits are coupled to the set values. It means, that the upper limit may not be set lower than the corresponding set value. Example: If you wish to set the limit for the power set value (P-max) to 1000 W while the currently adjusted power set value is 2000 W, it would require to first reduce the set value to 1000 W or less.

3.4.5 Changing the operating mode

In general, the manual operation distinguishes between two operating modes which are tied to set value input using the rotary knobs or ten-key pad. This assignment must be changed if one of the three set values is to be adjusted which is currently not available.

► How to change the operating mode (two options)

1. Unless the device is in remote control or the panel is locked, you can switch the operation anytime. Either tap the depiction of the right-hand knob (see figure to the right) to change its assignment between I, P and R, which is also displayed on top of the knob depiction, or
2. directly tap on the colored areas, like shown in the figure to the right. The unit next to the set values, when inverted, indicates the assignment of the knob. In the example in the figure it has U and P assigned, which means U/P mode.



Depending on the selection the right rotary knob will be assigned different setting values, the left knob is always assigned to the voltage.



In order to avoid constant changing of the assignments it's possible, e.g. with selection U/I being active, to vary the other value P or R by direct input. Also see section 3.4.6.

The actual operating mode that results while the DC output is switched on solely depends on the set values. For more information see section „3.2. Operating modes“.

3.4.6 Manual adjustment of set values

The set values for voltage, current and power are the fundamental operating possibilities of a power supply and hence the two rotary knobs on the front of the device are always assigned to two of the values in manual operation.

As a fourth value there is the internal resistance, for which the resistance mode (R mode) has to be activated in the MENU first. Refer to „3.4.3. Configuration via MENU“ and „3.2.4. Internal resistance regulation“ for details.

Set values can be entered manually in two ways: via **rotary knob** or **direct input**. The important difference is, that rotating the knob adjusts a value *gradually*, while direct input causes a *step or jump*.



Entering a value changes it immediately and no matter if the DC output is switched on or off.

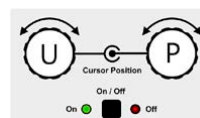


When adjusting the set values, upper or lower limits may come into effect. See section „3.4.4. Adjustment limits (Limits)“. Once a limit is reached, the display will show a note like "Limit: U-max" etc. for 1.5 seconds next to the adjusted value.

► How to adjust values with the rotary knobs

1. First check whether the value to be changed is already assigned to one of the rotary knobs. The main screen displays the assignment as depicted in the figure to the right.
2. If, as shown in the example, the assignment is voltage (U, left) and power (P, right), and it's required to set the current, then the assignments can be changed by tapping this touch area. A set of selection fields would then appear.
3. After successful selection, the desired value can be set within the defined limits. Selecting a digit is done by pushing the knob which shifts the cursor right to left (selected digit will be underlined):

120.00 A → 120.00 A → 120.00 A



► How to adjust values via direct input:

1. In the main screen, depending on the rotary knob assignment, values can be set for voltage (U), current (I), power (P) or resistance (R) via direct input by tapping on the set/actual value display areas, e.g in the uppermost area of voltage.
2. Enter the required value using the ten-key pad. Similar to a pocket calculator the key **C** clears the input.



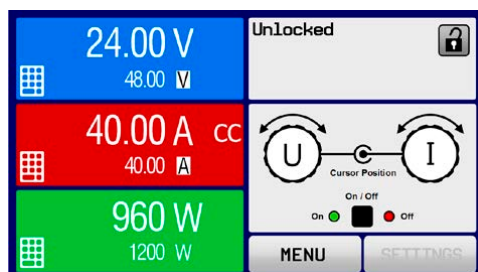
Decimal values are set by tapping the point key. For example, 54.3 V is set with 5 4 . 3 and ENTER.

3. The display switches to the main page and the set values take effect..

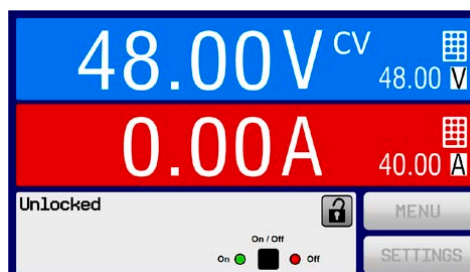
3.4.7 Switching the main screen view

The main screen, also called status page, with its set values, actual values and device status can be switched from the standard view mode with three or four values to a simpler mode with only voltage and current display. The advantage of the alternative view mode is that actual values are displayed with **bigger numbers**, so they can be read from a larger distance. Refer to „3.4.3.8. Menu "HMI Setup"" to see where to switch the view mode in the MENU. Comparison:

Standard status page



Alternative status page



Limitations of the alternative status page:

- Set and actual values of power are not displayed and the set value of power is only indirectly accessible
- The set value of resistance isn't displayed and only indirectly accessible
- No access to the settings overview (MENU button) while the DC output is on



In alternative status page mode, the set values of power and resistance are not adjustable while the DC output is switched on. They can only be accessed and adjusted in SETTINGS while the DC output is off.

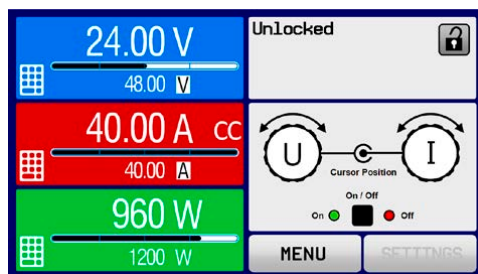
Rules for manual handling of the HMI in alternative status page mode:

- The two rotary knobs are assigned to voltage (left knob) and current (right knob) all the time, except for menus
- Set values input is the same as in standard status page mode, with knobs or by direct input
- Regulation modes CP and CR are displayed alternatively to CC at the same position

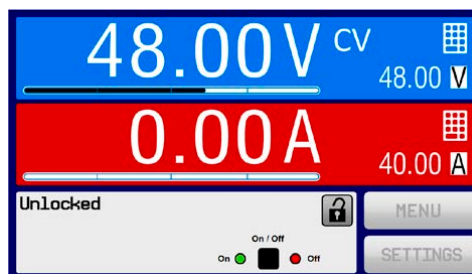
3.4.8 The meter bars

Additionally to the actual values being displayed as numbers, a meter bar for U, I and P can be enabled in the MENU. The meter bars remain hidden as long as resistance mode, i. e. U/I/R is activated. Refer to „3.4.3.8. Menu “HMI Setup”“ to see where to enable the meter bars in the MENU. Depiction:

Standard status page with meter bar



Alternative status page with meter bar



3.4.9 Switching the DC output on or off

The DC output of the device can be manually or remotely switched on and off. This can be restricted in manual operation by the control panel being locked.



Switching the DC output on during manual operation or digital remote control can be disabled by pin REM-SB of the built-in analog interface. For more information refer to 3.4.3.1 and example a) in 3.5.4.7.

► How to manually switch the DC output on or off

1. As long as the control panel isn't fully locked press the button ON/OFF. Otherwise you are asked to disable the HMI lock first.
2. This button toggles between on and off, as long as a change isn't restricted by an alarm or the device is locked in "remote".

► How to remotely switch the DC output on or off via the analog interface

1. See section „3.5.4 Remote control via the analog interface (AI)“ on page 57.

► How to remotely switch the DC output on or off via the digital interface

1. See the external documentation "Programming Guide ModBus & SCPI" if you are using custom software, or refer to the external documentation from LabView VIs or other software provided by the manufacturer.

3.4.10 Recording to USB stick (logging)

Device data can be recorded to USB stick (2.0 / 3.0 may work, but not all vendors are supported) anytime. For specifications of the USB stick and the generated log files refer to section „1.9.6.5. USB port (front side)“.

The logging stores files of CSV format on the stick. The layout of the log data is the same as when logging via PC with software EA Power Control. The advantage of USB logging over PC logging is the mobility and that no PC is required. The logging feature just has to be activated and configured in the MENU.

3.4.10.1 Configuration 1

Also see section 3.4.3.7. After USB logging has been enabled and the parameters “Logging interval” and “Start/Stop” have been set, logging can be started anytime from within the MENU or after leaving it, depends on the selected start/stop mode.

3.4.10.2 Configuration 2

Also see section 3.4.3.1. There are additional settings for the CSV file itself as generated by the USB logging features. You can switch the column separator format between german/european standard (“Default”) or US american standard (“US”). The other option is used to deactivate the physical unit that is added by default to every values in the log file. Deactivating this option simplifies the CSV file processing in MS Excel.

3.4.10.3 Handling (start/stop)

With setting “**Start/stop with DC output ON/OFF**” logging will start each time the DC output of the device is switched on, no matter if manually with the front button “On/Off” or remotely via analog or digital interface. With setting “**Manual start/stop**” it’s different. Logging is then started and stopped only in the MENU, in the logging configuration page.

Soon after logging has been started, the symbol  indicates the ongoing logging action. In case there is an error while logging, such as USB stick full or removed, it will be indicated by another symbol . After every manual stop or switching the DC output off the logging is stopped and the log file closed.

3.4.10.4 Log file format

Type: text file in german/european or US american CSV format (depending on the selected setting)

Layout (default german format shown):

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	U set	U actual	I set	I actual	P set	P actual	R set	R actual	R mode	Output/Input	Device mode	Error	Time
2	2,00V	11,92V	1,20A	1,20A	7344W	15W	N/A	N/A	OFF	ON	CC	NONE	00:00:00,942
3	2,00V	11,90V	1,20A	1,20A	7344W	15W	N/A	N/A	OFF	ON	CC	NONE	00:00:01,942
4	2,00V	11,89V	1,20A	1,20A	7344W	15W	N/A	N/A	OFF	ON	CC	NONE	00:00:02,942
5	2,00V	11,87V	1,20A	1,20A	7344W	15W	N/A	N/A	OFF	ON	CC	NONE	00:00:03,942

Legend:

U set / I set / P set / R set: Set values

U actual / I actual / P actual / R actual: Actual values

Error: device alarms

Time: elapsed time since logging start

Device mode: actual regulation mode (also see „3.2. Operating modes“)

Important to know:

- R set and R actual are only recorded if UIR mode is active (refer to section 3.4.5)
- Unlike the logging on PC, every log start here creates a new log file with a counter in the file name, starting generally with 1, but minding existing files

3.4.10.5 Special notes and limitations

- Max. log file size (due to FAT32 formatting): 4 GB
- Max. number of log files in folder HMI_FILES: 1024
- With setting “**Start/stop with DC output ON/OFF**”, the logging will also stop on alarms or events with action “Alarm”, because they switch off the DC output
- With setting “**Manual start/stop**” the device will continue to log even on occurring alarms, so this mode can be used to determine the period of temporary alarms like OT or PF

3.5 Remote control

3.5.1 General

Remote control is possible via the built-in analog or USB port or via one of the optional interface modules (only with standard models) or via the GPIB port (only with option 3W installed). Important here is that only the analog or one digital interface can be in control. It means that if, for example, an attempt were to be made to switch to remote control via the digital interface whilst analog remote control is active (Pin REMOTE = LOW) the device would report an error via the digital interface. In the opposite direction, a switch-over via Pin REMOTE would be ignored. In both cases, however, status monitoring and reading of values are always possible.

3.5.2 Control locations

Control locations are those locations from where the device can be controlled. Essentially there are two: at the device (manual operation) and external (remote control). The following locations are defined:

Displayed location	Description
-	If neither of the other locations is displayed then manual control is active and access from the analog and digital interfaces is allowed. This location isn't explicitly displayed
Remote	Remote control via any interface is active
Local	Remote control is locked, only manual operation is allowed.

Remote control may be allowed or inhibited using the setting **Allow remote control** (see „3.4.3.1. Menu “General Settings”). In inhibited condition the status **Local** will be displayed top right. Activating the lock can be useful if the device is remotely controlled by software or some electronic device, but it's required to make adjustments at the device or deal with emergency, which would not be possible remotely.

Activating condition **Local** causes the following:

- If remote control via the digital interface is active (**Remote:**), then it's immediately terminated and in order to continue remote control once **Local** is no longer active, it has to be reactivated at the PC
- If remote control via the analog interface is active (**Remote: Analog**), then it's temporarily interrupted until remote control is allowed again by deactivating **Local**, because pin REMOTE continues to signal 'remote control = on', unless this has been changed during the **Local** period

3.5.3 Remote control via a digital interface

3.5.3.1 Selecting an interface

The standard models of series PSI 9000 2U support, in addition to the built-in USB port, the following optional ly available interface modules:

Short ID	Type	Ports	Description*
IF-AB-CANO	CANopen	1	CANopen slave with generic EDS
IF-AB-RS232	RS232	1	Standard RS232, serial
IF-AB-PBUS	Profibus	1	Profibus DP-V1 slave
IF-AB-ETH1P	Ethernet	1	Ethernet TCP
IF-AB-PNET1P	ProfiNet	1	Profinet DP-V1 slave
IF-AB-MBUS	ModBus TCP	1	ModBus TCP protocol via Ethernet
IF-AB-ETH2P	Ethernet	2	Ethernet TCP, with switch
IF-AB-MBUS2P	ModBus TCP	2	ModBus TCP protocol via Ethernet, with switch
IF-AB-PNET2P	ProfiNet	2	Profinet DP-V1 slave, with switch
IF-AB-CAN	CAN	1	Modified ModBus RTU via CAN
IF-AB-ECT	EtherCAT	2	Basic EtherCAT slave with CANopen over Ethernet (CoE)

* For technical details of the various modules see the extra documentation "Programming Guide Modbus & SCPI"

Models with option 3W installed offer an additional pre-installed GPIB port next to the default USB port.

3.5.3.2 General

With the standard models of series PSI 9000 2U, one of the plug-in and retrofittable modules listed in 3.5.3.1 can be installed. It can take over remote control of the device alternatively to the built-in USB port on the back side or analog interface. For installation see section „2.3.9. *Installation of an interface module*“ and separate documentation.

The modules require little or no settings for operation and can be directly used with their default configuration. All specific settings will be permanently stored such that, after changeover between the various models, no reconfiguration will be necessary.

3.5.3.3 Programming

Programming details for the interfaces, the communication protocols etc. are to be found in the documentation “Programming Guide ModBus & SCPI” which is supplied on the included USB stick or which is available as download from the manufacturer’s website.

3.5.3.4 Interface monitoring

Interface monitoring is a configurable functionality introduced in firmwares KE 2.31 and HMI 2.20. Its goal is to monitor (or supervise) the communication line between the device and a superior control unit, such as PC or PLC, and to ensure that the device wouldn’t continue working uncontrolled in case the communication line fails. A failing line can mean that it’s either physically interrupted (damaged cable, bad contact, cable pulled) or the interface port inside the device hangs.

The monitoring is always only valid for one of the digital interfaces, the one being used for remote control. It thus means that the monitoring can become temporarily inactive when the device leaves remote control. It’s furthermore based on an user-definable timeout which would run out if not at least one message is sent to the device within the given time frame. After every message, the timeout would start again and reset with the next message coming. In case it runs out, following reaction of the device is defined:

- Exit remote control
- In case the DC output is switched on, either switch the DC output off or leave it on, as defined by the parameter **DC output after remote** (see 3.4.3.1)

Notes for the operation:

- The monitoring can be deactivated or activate anytime via remote control
- The timeout of the monitoring can be changed anytime via remote control; the new value would only be valid after the current timeout has elapsed
- The interface monitoring doesn't deactivate the Ethernet connection timeout (see 3.4.3.7), so these two timeouts can overlap

3.5.4 Remote control via the analog interface (AI)

3.5.4.1 General

The built-in, galvanically isolated 15-pole analog interface (short: AI) is on the rear side of the device offers the following possibilities:

- Remote control of current, voltage, power and internal resistance *
- Remote status monitoring (CV, DC output)
- Remote alarm monitoring (OT, OVP, OCP, OPP, PF)
- Remote monitoring of actual values
- Remote on/off switching of the DC output

Setting the **three** set values of voltage, current and power via the analog interface always takes place concurrently. It means, that for example the voltage can't be given via the AI and current and power would be set with the rotary knobs, or vice versa. The internal resistance¹ set value can additionally be adjusted, if resistance mode is activated via pin R-ACTIVE.

The OVP set value and other supervision (events) and alarm thresholds can't be set via the AI and therefore must be adapted to the given situation before the AI is going to be in control. Analog set values can be supplied by an external voltage or generated from the reference voltage on pin 3. As soon as remote control via the analog interface is activated, the displayed set values will be those provided by the interface.

The AI can be operated in the common voltage ranges 0...5 V and 0...10 V, both representing 0...100% of the nominal value. The selection of the voltage range can be done in the device setup. See section „3.4.3. Configuration via MENU“ for details. The reference voltage sent out from pin 3 (VREF) will be adapted accordingly:

0-5 V: Reference voltage = 5 V, 0...5 V set values (VSEL, CSEL, PSEL, RSEL) correspond to 0...100% nominal values, 0...100% actual values correspond to 0...5 V at the actual value outputs (CMON, VMON).

0-10 V: .Reference voltage = 10 V, 0...10 V set values (VSEL, CSEL, PSEL RSEL) correspond to 0...100% nominal values, 0...100% actual values correspond to 0...10 V at the actual value outputs (CMON, VMON).

All set values are always additionally limited to the corresponding adjustment limits (U-max, I-max etc.), which would clip setting excess values for the DC output. Also see section „3.4.4. Adjustment limits (Limits)“.

Before you begin, please read these important notes about the use of the interface:



After powering the device and during the start phase the AI signals undefined statuses on the output pins such as ALARMS 1. Those must be ignored until it's ready to work.

- Analog remote control of the device must be activated by switching pin REMOTE (5) first. Only exception is pin REM-SB, which can be used independently since KE firmware version 2.07
- Before the hardware is connected that will control the analog interface, it shall be checked that it can't provide voltage to the pins higher than specified
- Set value inputs, such as VSEL, CSEL, PSEL and RSEL (if R mode is activated), must not be left unconnected (i. e. floating) during analog remote control. In case any of the set values isn't used for adjustment, it can be tied to a defined level or connected to pin VREF (solder bridge or different), so it gives 100%

3.5.4.2 Resolution

The analog interface is internally sampled and processed by a digital micro-controller. This causes a limited resolution of analog steps. The resolution is the same for set values (VSEL etc.) and actual values (VMON/CMON) and is 26214. Due to tolerances, the truly achievable resolution can be slightly lower.

¹ Unless the device has not already been delivered with KE firmware version 2.10 or higher, the internal resistance mode requires a hardware modification in the factory

3.5.4.3 Acknowledging device alarms

In case of a device alarm occurring during remote control via analog interface, the DC output will be switched off the same way as in manual control. The device would indicate an alarm (see 3.6.2) in the front display and, if activated, acoustically and also signal most of them on the analog interface. Which alarms actually are signaled can be set up in the device configuration menu (see 3.5.4.4).

Some device alarms (OVP, OCP and OPP) have to be acknowledged. Also see „3.6.2. Device alarm and event handling“. Acknowledgment is done with pin REM-SB switching the DC output off and on again, means a HIGH-LOW-HIGH edge (min. 50ms for LOW), when using the default level setting for this pin.

3.5.4.4 Analog interface specification

Pin	Name	Type*	Description	Levels	Electrical specification
1	VSEL	AI	Set voltage value	0...10 V or. 0...5 V correspond to 0..100% of U_{Nom}	Accuracy 0-5 V range: < 0.4% ***** Accuracy 0-10 V range: < 0.2% *****
2	CSEL	AI	Set current value	0...10 V or. 0...5 V correspond to 0..100% of I_{Nom}	Input impedance R_i >40 k...100 k
3	VREF	AO	Reference voltage	10 V or 5 V	Tolerance < 0.2% at $I_{max} = +5$ mA Short-circuit-proof against AGND
4	DGND	POT	Ground for all digital signals		For control and status signals
5	REMOTE	DI	Switching manual / remote control	Remote = LOW, $U_{Low} < 1$ V Manual = HIGH, $U_{High} > 4$ V Manual, if pin not wired	Voltage range = 0...30 V $I_{Max} = -1$ mA bei 5 V U_{Low} to HIGH typ. = 3 V Rec'd sender: Open collector against DGND
6	ALARMS 1	DO	Overheating or power fail alarm	Alarm= HIGH, $U_{High} > 4$ V No alarm= LOW, $U_{Low} < 1$ V	Quasi open collector with pull-up against V_{cc} ** With 5 V on the pin max. flow +1 mA $I_{Max} = -10$ mA at $U_{CE} = 0,3$ V $U_{Max} = 30$ V Short-circuit-proof against DGND
7	RSEL	AI	Set internal resistance value	0...10 V or. 0...5 V correspond to 0..100% of R_{Max}	Accuracy 0-5 V range: < 0.4% ***** Accuracy 0-10 V range: < 0.2% *****
8	PSEL	AI	Set power value	0...10 V or. 0...5 V correspond to 0..100% of P_{Nom}	Input impedance R_i >40 k...100 k
9	VMON	AO	Actual voltage	0...10 V or. 0...5 V correspond to 0..100% of U_{Nom}	Accuracy 0-5 V range: < 0.4% ***** Accuracy 0-10 V range: < 0.2% *****
10	CMON	AO	Actual current	0...10 V or. 0...5 V correspond to 0..100% of I_{Nom}	at $I_{Max} = +2$ mA Short-circuit-proof against AGND
11	AGND	POT	Ground for all analog signals		For -SEL, -MON, VREF signals
12	R-ACTIVE	DI	R mode on / off	Off = LOW, $U_{Low} < 1$ V On = HIGH, $U_{High} > 4$ V On, if pin not wired	Voltage range = 0...30 V $I_{Max} = -1$ mA bei 5 V U_{Low} to HIGH typ. = 3 V Rec'd sender: Open collector against DGND
13	REM-SB	DI	DC output OFF (DC output ON) (ACK alarms *****)	Off = LOW, $U_{Low} < 1$ V On = HIGH, $U_{High} > 4$ V On, if pin not wired	Voltage range = 0...30 V $I_{Max} = +1$ mA at 5 V Rec'd sender: Open collector against DGND
14	ALARMS 2	DO	Overvoltage alarm Overcurrent alarm Overpower alarm	Alarm = HIGH, $U_{High} > 4$ V No alarm = LOW, $U_{Low} < 1$ V	Quasi open collector with pull-up against V_{cc} ** With 5 V on the pin max. flow +1 mA $I_{Max} = -10$ mA at $U_{CE} = 0,3$ V, $U_{Max} = 30$ V Short-circuit-proof against DGND
15	STATUS***	DO	Constant voltage regulation active DC output	CV = LOW, $U_{Low} < 1$ V CC/CP/CR = HIGH, $U_{High} > 4$ V Off = LOW, $U_{Low} < 1$ V On = HIGH, $U_{High} > 4$ V	

* AI = Analog Input, AO = Analog Output, DI = Digital Input, DO = Digital Output, POT = Potential

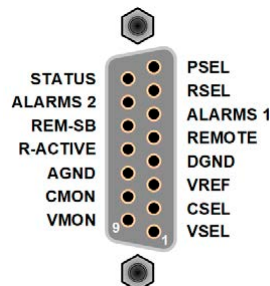
** Internal V_{cc} approx. 10 V

*** Only one of both signals possible, see section 3.4.3.1

**** Only during remote control

***** The error of a set value input adds to the general error of the related value on the DC output of the device

3.5.4.5 Overview of the Sub-D Socket



3.5.4.6 Simplified diagram of the pins

	Digital Input (DI) The DI is internally pulled up and thus it requires to use a contact with low resistance (relay, switch, contactor etc.) in order to clearly pull the signal down to DGND.		Analog Input (AI) High resistance input (impedance >40 kΩ....100 kΩ) for an operational amplifier circuit.
	Digital Output (DO) A quasi open collector, realised as high resistance pull-up against the internal supply. The design doesn't allow the pin to be loaded, but to switch signals by sinking current.		Analog Output (AO) Output from an operational amplifier circuit, with low impedance. See specifications table above.

3.5.4.7 Application examples

a) Switching the DC output with pin REM-SB



A digital output, e. g. from a PLC, may be unable to cleanly pull down the pin as it may not be of low enough resistance. Check the specification of the controlling application. Also see pin diagrams above.

In remote control, pin REM-SB is used to switch the DC output of the device on and off. This function is also available without remote control being active and can on the one hand block the DC output from being switched on in manual or digital remote control and on the other hand the pin can switch the DC on or off, but not standalone. See below at "Remote control has not been activated".

It's recommended that a low resistance contact such as a switch, relay or transistor is used to switch the pin to ground (DGND).

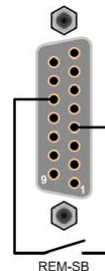
Following situations can occur:

• Remote control has been activated

During remote control via analog interface, only pin REM-SB determines the states of the DC output, according to the levels definitions in 3.5.4.4. The logical function and the default levels can be inverted by a parameter in the setup menu of the device. See 3.4.3.1.



If the pin is unconnected or the connected contact is open, the pin will be HIGH. With parameter "Analog interface Rem-SB" being set to "Normal", it requests 'DC output on', so when activating remote control with pin REMOTE, the DC output will instantly switch on.



• Remote control isn't active

In this mode of operation pin REM-SB can serve as lock, preventing the DC output from being switched on by any means. This results in following possible situations:

DC output	+	Level on pin REM-SB	+	Parameter „Analog interface Rem-SB“	→ Behavior
is off	+	HIGH	+	Normal	→ The DC output isn't locked. It can be switched on by pushbutton On/Off (front panel) or via command from digital interface.
		LOW	+	Inverted	
	+	HIGH	+	Inverted	→ The DC output is locked. It can't be switched on by pushbutton On/Off (front panel) or via command from digital interface. When trying to switch on, a pop-up in the display resp. an error message will be generated.
		LOW	+	Normal	

In case the DC output is already switched on, toggling the pin will switch the DC output off, similar to what it does in analog remote control:

DC output	+	Level on pin REM-SB	+	Parameter „Analog interface Rem-SB“	→ Behavior
is on	+	HIGH	+	Normal	→ The DC output remains on, nothing is locked. It can be switched on or off by pushbutton or digital command.
		LOW	+	Inverted	
	+	HIGH	+	Inverted	→ The DC output will be switched off and locked. Later it can be switched on again by toggling the pin. During lock, pushbutton or digital command can delete the request to switch on by pin.
		LOW	+	Normal	

b) Remote control of current and power

Requires remote control to be activated (Pin REMOTE = LOW)

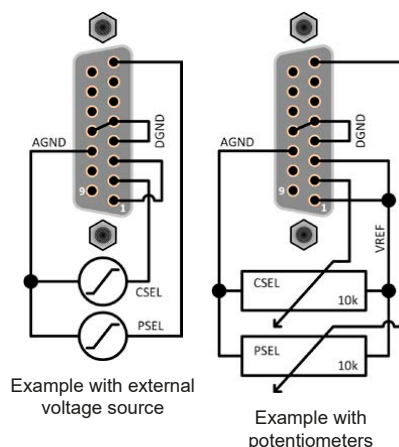
The set values PSEL and CSEL are generated from, for example, the reference voltage VREF, using potentiometers for each. Hence the power supply can selectively work in current limiting or power limiting mode. According to the specification of max. 5 mA load for the VREF output, potentiometers of at least 10 kΩ must be used.

The voltage set value VSEL is directly connected to VREF and will thus be permanently 100%.

If the control voltage is fed in from an external source it's necessary to consider the input voltage ranges for set values (0...5 V oder 0...10 V).

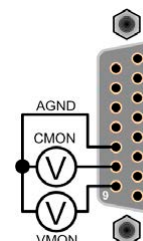


Use of the input voltage range 0...5 V for 0...100% set value halves the effective resolution.



c) Reading actual values

The AI provides the DC output values as current and voltage monitor. These can be read using a standard multimeter or similar.



3.6 Alarms and monitoring

3.6.1 Definition of terms

There is a clear distinction between device alarms (see „3.3. Alarm conditions“) such as overvoltage protection or overheating protection, and user defined events such as **OVD** (overvoltage detection). Whilst device alarms serve to protect the device and the connected load by initially switching off the DC output, user defined events can switch off the DC output (**Action = ALARM**), but can also simply give an acoustic signal to make the user aware. The actions driven by user defined events can be selected:

Action	Impact	Example
NONE	User defined event is disabled.	
SIGNAL	On reaching the condition which triggers the event, the action SIGNAL will show a text message in the status area of the display.	
WARNING	On reaching the condition which triggers the event, the action WARNING will show a text message in the status area of the display and pop up an additional warning message, plus additionally emit an acoustic signal (if activated)	
ALARM	On reaching the condition which triggers the event, the action ALARM will show a text message in the status area of the display with an additional alarm pop-up, and additionally emit an acoustic signal (if activated). Furthermore the DC output is switched off. Certain device alarms are also signaled to the analog interface or can be queried via the digital interface.	

3.6.2 Device alarm and event handling

A device alarm incident will usually lead to DC output switch-off. Alarms have to be acknowledged (see below), which can only happen if the cause of the alarm isn't persistent anymore. Not all of them require the acknowledgment BEFORE the device can continue its operation, such as alarms OT and the PF. The user can define the condition of the DC output for these two alarms, so that the device could also automatically continue to work like before the alarm. The alarm indication would then remain in the display until the user confirms them.

► How to acknowledge an alarm in the display (during manual control)

1. If the alarm is indicated as a pop-up, tap **OK**.
2. If the alarm has already been acknowledged, but is still displayed in the status area, then first tap the status area to display the pop-up, and then acknowledge with **OK**.



In order to acknowledge an alarm during analog remote control, see „3.5.4.5. Overview of the Sub-D Socket“. To acknowledge in digital remote control, refer to the external documentation “Programming Guide ModBus & SCPI”. Some device alarms are configurable:

Alarm	Meaning	Description	Range	Indication
OVP	OverVoltage Protection	Triggers an alarm if the DC output voltage reaches the defined threshold. The DC output will be switched off.	0 V...1.1*U _{Nom}	Display, analog IF, digital IF
OCP	OverCurrent Protection	Triggers an alarm if the DC output current reaches the defined threshold. The DC output will be switched off.	0 A...1.1*I _{Nom}	
OPP	OverPower Protection	Triggers an alarm if the DC output power reaches the defined threshold. The DC output will be switched off.	0 W...1.1*P _{Nom}	

These device alarms can't be configured and are based on hardware:

Alarm	Meaning	Description	Indication
PF	Power Fail	AC supply over- or undervoltage. Triggers an alarm if the AC supply is out of specification or when the device is cut from supply, for example when switching it off with the power switch. The DC output will be switched off which could be only temporarily, depending on the situation and setting DC output after PF alarm (see 3.4.3.1).	Display, analog IF, digital IF
OT	OverTemperature	Triggers an alarm if the internal temperature reaches a certain limit. The DC output will be switched off which could be only temporarily, depending on the setting DC output after OT alarm (see 3.4.3.1).	Display, analog IF, digital IF
MSP	Master-Slave Protection	Triggers an alarm if the master of an initialized master-slave system loses contact to any slave unit or if a slave has not yet been initialized by the master. The DC output will be switched off. The alarm can be cleared by either deactivating master-slave mode or reinitializing the MS system.	Display, digital interface

► How to configure the device alarms

1. While the DC output is switched tap the touch area **SETTINGS** on the main screen.
2. On the right side tap the down arrow to select **2. Protect**.
3. Set the limits for the equipment alarm relevant to your application if the default value of 110% is unsuitable.



The set values can be entered using the ten-key tab. This will appear by tapping the touch area "Direct input".

The user also has the possibility of selecting whether an additional acoustic signal will be sounded if an alarm or user defined event occurs.

► How to configure the alarm sound (also see „3.4.3. Configuration via MENU“)

1. While the DC output is switched tap the touch area **MENU** on the main screen
2. In the menu page, tap **HMI Settings**.
3. In the following menu page, tap **Alarm Sound**.
4. In the settings page tap the button to select between alarm sound on or off and confirm with



3.6.2.1 User defined events

The monitoring functions of the device can be configured for user defined events. By default, events are deactivated (action = NONE). Contrary to device alarms, the events only work while the DC output is switched on. It means, for instance, that you can't detect undervoltage (UVD) anymore after switching the DC output off and the voltage is still sinking.

The following events can be configured independently and can, in each case, trigger the actions NONE, SIGNAL, WARNING or ALARM.

Event	Meaning	Description	Range
UVD	UnderVoltage Detection	Triggers an event if the output voltage falls below the defined threshold.	0 V...U _{Nom}
OVD	OverVoltage Detection	Triggers an event if the output voltage exceeds the defined threshold.	0 V...U _{Nom}
UCD	UnderCurrent Detection	Triggers an event if the output current falls below the defined threshold.	0 A...I _{Nom}
OCD	OverCurrent Detection	Triggers an event if the output current exceeds the defined threshold.	0 A...I _{Nom}
OPD	OverPower Detection	Triggers an event if the output power exceeds the defined threshold.	0 W...P _{Nom}



These events must not be confused with alarms such as OT and OVP which are for device protection. User defined events can, however, if set to action ALARM, switch off the DC output and thus protect the load, like a sensitive electronic application.

► How to configure user defined events

1. Tap the touch area **SETTINGS** on the main screen..
2. On the right side tap the arrows   to select **4.1 Event U** or **4.2 Event I** or **4.3 Event P**.
3. Set the monitoring limits with the left hand rotary knob and the triggered action with the right hand knob relevant to the application (also see „3.6.1. Definition of terms“).
4. Accept the settings with .



User events are an integral part of the actual user profile. Thus, if another user profile or the default profile is selected and used the events could be either differently configured or not at all.



The set values can be entered using the ten-key tab. This will appear by tapping the touch area "Direct input".

3.7 Control panel (HMI) lock

In order to avoid the accidental alteration of a value during manual operation, the rotary knobs or the touchscreen can be locked so that no alteration of values will be accepted without prior unlocking.

► How to lock the HMI

1. In the main page, tap the lock symbol  (upper right corner).
2. In the settings page **HMI Lock** you are then asked to chose between a complete HMI (**Lock all**) lock or one where the On/Off button is still usable (**ON/OFF possible**), resp. chose to activate the additional PIN (**Enable PIN**). The device would later request to enter this PIN every time you want to unlock the HMI, until the PIN is deactivated again.
3. Activate the lock with . The status **Locked** as shown in the figure to the right.

Locked



If an attempt is made to alter something whilst the HMI is locked, a requester appears in the display asking if the lock should be disabled.

► How to unlock the HMI

1. Tap any part of the touchscreen of the locked HMI, or turn one of the rotary knobs or press the button "On/Off" (only in **Lock all** situation).
2. This request pop-up will appear: .
3. Unlock the HMI by tapping on **Tap to unlock** within 5 seconds, otherwise the pop-up will disappear and the HMI remains locked. In case the additional **PIN code lock** has been activated in the menu **HMI Lock**, another requester will pop up, asking you to enter the **PIN** before it finally unlocks the HMI.

3.8 Limits lock

In order to avoid the alteration of the adjustment limits (also see „3.4.4. *Adjustment limits (Limits)*“) by an unprivileged user, the screen with the adjustment limit settings (short: "Limits") can be locked by a PIN code. The menu pages **3.Limits** in **SETTINGS** and **Profiles** in **MENU** will then become inaccessible until the lock is removed by entering the correct PIN or in case it has been forgotten, by resetting the device as last resort.

► How to lock the Limits

1. While the DC output is switched off, tap the touch area  on the main screen.
2. In the menu tap **HMI Setup** and then on **Limits Lock**.
3. In the next page set the check mark for **Lock**.



The same PIN as with the HMI lock is used here. It should be set before activating the Limits lock. See „3.2. Operating modes“

4. Activate the lock by leaving the settings page with .



Be careful to enable the lock if you are unsure what PIN is currently set. In doubt use ESC to exit the menu page. In menu page "HMI Lock" you can define a different PIN, but not without entering the old one.

► How to unlock the limits settings

1. While the DC output is switched off, tap the touch area  on the main screen.
2. In the menu tap **HMI Setup** and then on **Limits Lock**.
3. In the next page tap on touch area **Unlock** and then you will be asked to enter the 4-digit PIN.
4. Deactivate the lock by entering the correct PIN and submitting with ENTER.

3.9 Loading and saving an user profile

The menu **Profiles** serves for selection between a default profile and up to 5 user profiles. A profile is a collection of all settings and set values. Upon delivery, or after a reset, all 6 profiles have the same settings and all set values are 0. If the user changes settings or sets target values then these create a working profile which can be saved to one of the 5 user profiles. These profiles or the default one can then be switched. The default profile is read-only. The purpose of a profile is to load a set of set values, settings limits and monitoring thresholds quickly without having to readjust these. As all HMI settings are saved in the profile, including language, a profile change can also be accompanied by a change in HMI language.

On calling up the menu page and selecting a profile the most important settings can be seen, but not changed.

► How to save the current values and settings as an user profile:

1. Tap the touch area  on the main screen
2. In the menu page, tap .
3. In the selection screen (right) choose between user profile 1-5 in which the settings are to be saved. The profile will then be displayed and the values can be checked, but not changed.
4. Save using the touch area .



3.10 The function generator

3.10.1 Introduction

The built-in **function generator** (short: **FG**) is able to create various signal forms and apply these to the set value of voltage or current.

The standard functions are based on an **arbitrary generator** and directly accessible and configurable using manual control. For remote control, the fully customizable arbitrary generator replicates the functions with sequences containing 8 parameters each.

The following functions are retrievable, configurable and controllable:

Function	Short description
Sine wave	Sine wave generation with adjustable amplitude, offset and frequency
Triangle	Triangular wave signal generation with adjustable amplitude, offset, rise and fall times
Rectangular	Rectangular wave signal generation with adjustable amplitude, offset and duty cycle
Trapezoid	Trapezoidal wave signal generation with adjustable amplitude, offset, rise time, pulse time, fall time, idle time
DIN 40839	Simulated automobile engine start curve according to DIN 40839 / EN ISO 7637, split into 5 curve parts (sequence points), each with a start voltage, final voltage and time
Arbitrary	Generation of a process with up to 99 freely configurable curve points, each with a start and end value (AC/DC), start and end frequency, phase angle and duration
Ramp	Generation of a linear rise or fall ramp with start and end values and time before and after the ramp
UI, IU	XY generator, USB stick loadable current or voltage curves (table, CSV)
PV, FC	Functions to simulate a solar panel (PV function) or fuel cells (FC function), both with table calculation based upon adjustable parameters, plus opportunity to store on USB stick

3.10.2 General

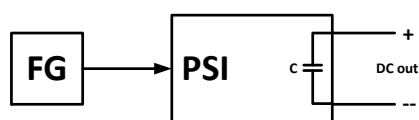
3.10.2.1 Limitations

The function generator isn't accessible, neither for manual access nor for remote control, if resistance mode (U/R adjustment, also called UIR operation) is active.

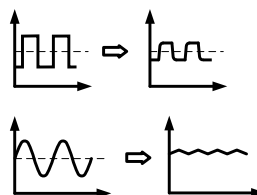
3.10.2.2 Principle

The power supply unit can't be considered as high power function generator, because it's only post-connected to the FG. Thus the typical characteristics of a voltage and current source remain. Rise and fall times, caused by capacitor charge/discharge, affect the resulting signal on the DC output. While the FG is able to generate a sine wave with 1000 Hz or more, the power supply will never be able to follow the generated signal 1:1.

Depiction of principle:



Affect of the power supply on functions:



The resulting wave form on the DC output heavily depends on the frequency of the selected wave, its amplitude and the device's output capacitance. The effects of the power supply on the wave can only be partially compensated. A high-speed modification can help to decrease rise and fall times. This has a positive impact on periodic functions like rectangle or sine wave. Alternatively, the resulting wave form on the DC output can also be improved by attaching additional load (fixed & ohmic or variable & electronic).

3.10.2.3 Resolution

Amplitudes generated by the arbitrary generator have an effective resolution of approx. 52428 steps. If the amplitude is very low and the time long, the device would generate less steps and set multiple identical values after another, generating a staircase effect. It's furthermore not possible to generate every possible combination of time and a varying amplitude (slope).

The XY generator, which works in table mode, has an effective resolution of 3276 steps for the set value range of 0-100% rated value.

3.10.2.4 Possible technical complications

Operation of switching mode power supplies as a voltage source can, when applying a function to the output voltage, lead to damage of the output capacitors due to continuous charging/discharging which causes overheating. Furthermore the actual voltage progression may differ from what's expected.

3.10.2.5 Minimum slope / maximum ramp time

When using a rising or falling offset (i. e. DC part) at functions like ramp, trapezoid, triangle and even sine wave, a minimum slope, calculated from the rated values of voltage or current, is required or else the adjusted settings would be neglected by the device. Calculating the minimum slope can help to determine if a certain ramp over time can be achieved by the device or not. Example: model PSI 9080-120 2U is going to be used, with 80 V and 120 A rating. **Formula: minimum slope = $0.000725 \cdot \text{rated value} / \text{s}$** . For the example model it results in $\Delta U / \Delta t$ of 58 mV/s and $\Delta I / \Delta t$ of 87 mA/s. The maximum time which can be achieved with the minimum slope then calculates as approximately 1379 seconds according to formula **$t_{\text{Max}} = \text{rated value} / \text{min. slope}$** .

3.10.3 Method of operation

In order to understand how the function generator works and how the value settings interact, the following should be noted:

The device operates, including in function generator mode, always with the three set values U, I and P.

The selected function can be used on one of both the values U or I, the other two are then constants and have a limiting effect. That means if, for example, a voltage of 10 V is set for the DC output, a load is connected and a sine wave function should operate on the current with an amplitude of 20 A and offset 20 A, then the function generator will create a sine wave progression of current between 0 A (min) and 40 A (max). This will also result in an output power between 0 W (min) and 400 W (max). The output power, however, is limited to its set value. If this was 300 W then, in this case, the current would be limited to 30 A and, if clamped to an oscilloscope, it could be seen as truncated at 30 A and never reach the target of 40 A.

Master-slave systems have further characteristics which have to be considered:



At the end of the configuration of every standard function you are requested to set up global set values, the so-called "U/I/P limits". These limits are transferred to all slave units of master-slave systems. It's recommended to carefully configure them so the MS system can work as expected and the slaves wouldn't impact the function run in a negative way.

3.10.4 Manual operation

3.10.4.1 Function selection and control

Via the touch screen one of the functions described in 3.10.11 can be selected, configured and controlled. This is only permissible while the DC output is switched off.



► How to select a function and adjust parameters

1. While the DC output is switched off tap the touch area  on the main screen.
2. In the menu overview tap on the touch area  and then on the desired function.
Note: this touch area is locked in R mode (adjustable resistance).
3. Depending on the choice of function there follows a request to which value the function generator is going to be applied:  or .
4. Adjust the parameters as you desire, like offset, amplitude and frequency for a sine wave, for example.
5. Do not forget to adjust the overall limits of voltage, current and power, which you can access with touch area .



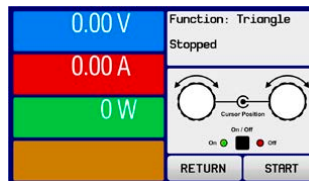
When entering function generator mode, those limits are reset to safe values, which can prevent the function from working at all. For example, if you apply the selected function to the output current, then the overall current limit should not interfere and should at least be as high as offset + amplitude.

Setting the various functions is described below. After setting it up, the function can be loaded.

► How to load a function

1. After setting the values for the required signal generation, tap on the touch area .

The device will then load the data into the internal controller and changes the display. Shortly afterwards the static values are set (power and voltage or current), the DC output is switched on and the touch area  enabled. Only then can the function be started.



The static values are applied to the DC output immediately after loading the function, because it switches the DC output on automatically in order to settle the start situation. These static values represent start and end values for the progress of the function, so that the function doesn't need to start from 0. Only exception: when applying any function to the current (I), there is no adjustable static current value, so the function would always start from 0 A.

► How to start and stop a function

1. The function can be started either by tapping  or pushing the "On/Off" button, if the DC output is currently switched off. The function then starts immediately. In case START is used while the DC output is still switched off, the DC output will be switched on automatically.
2. The function can be **stopped** either by tapping  or operating the "On/Off" button. However, there is a difference:
 - a) The  button stops only the function, the DC output remains ON with the static values.
 - b) The "On/Off" button stops the function and switches off the DC output.



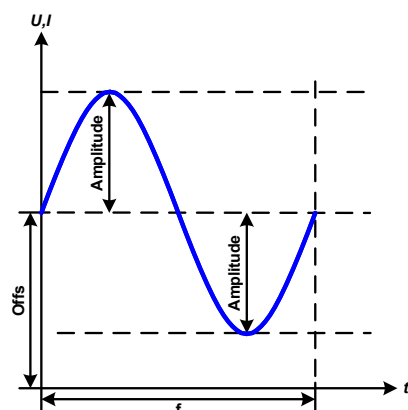
Device alarms such as overvoltage, overheating or power fail stops the function progress automatically and the DC output is switched off.

3.10.5 Sine wave function

The following parameters can be configured for a sine wave function:

Value	Range	Description
I(A), U(A)	0...(Nominal value - (Offs)) of U, I	A = Amplitude of the signal to be generated
I(Offs), U(Offs)	(A)...(Nominal value - (A)) of U, I	Off = Offset, based on the zero point of the mathematical sine curve, may not be smaller than the amplitude.
f (1/t)	1...10000 Hz	Static frequency of the signal to be generated

Schematic diagram:



Application and result:

A normal sine wave signal is generated and applied to the selected set value, e. g. voltage (U). At a constant load resistance, the output voltage and thus also the output current will follow a sine wave.

For calculating the maximum power output the amplitude and offset values for the current have to be added.

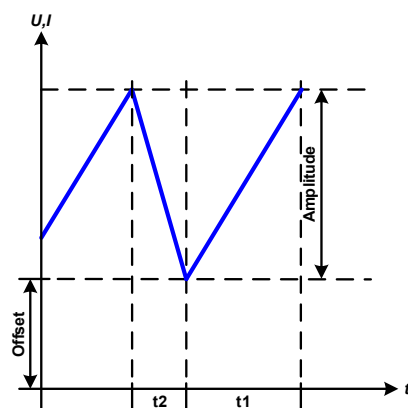
Example: an output voltage of 60 V is set together with sin(I) with an amplitude of 12 A and an offset of 15 A. The resulting maximum power output is then achieved at the highest point of the sine wave and is $(12 \text{ A} + 15 \text{ A}) * 60 \text{ V} = 1620 \text{ W}$.

3.10.6 Triangular function

The following parameters can be configured for a triangular wave function:

Value	Range	Description
I(A), U(A)	0...(Nominal value - (Offs)) of U, I	A = Amplitude of the signal to be generated
I(Offs), U(Offs)	0...(Nominal value - (A)) of U, I	Offs = Offset, based on the foot of the triangular wave
t1	0.1 ms...36000 s	Rising edge time Δt of the triangular wave signal
t2	0.1 ms...36000 s	Falling edge time Δt of the triangular wave signal

Schematic diagram:



Application and result:

A triangular wave signal for output current (only effective in current limiting) or output voltage is generated. The positive and negative slope times can be set independently.

The offset shifts the signal on the Y-axis.

The sum of the intervals t1 and t2 gives the cycle time and its reciprocal is the frequency.

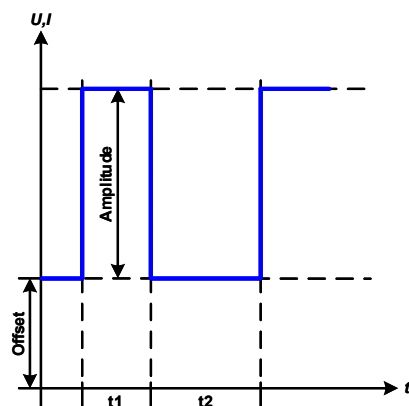
Example: a frequency of 10 Hz is required and would lead to periodic duration of 100 ms. This 100 ms can be freely allocated to t1 and t2, e. g. 50 ms:50 ms (isosceles triangle) or 99.9 ms:0.1 ms (right-angled triangle or sawtooth).

3.10.7 Rectangular function

The following parameters can be configured for a rectangular wave function:

Value	Range	Description
I(A), U(A)	0...(Nominal value - (Offs)) von U, I	A = Amplitude of the signal to be generated
I(Offs), U(Offs)	0...(Nominal value - (A)) von U, I	Offs = Offset, based on the foot of the rectangular wave
t1	0.1 ms...36000 s	Time (pulse width) of the upper level (amplitude)
t2	0.1 ms...36000 s	Time (pause width) of the lower level (offset)

Schematic diagram:



Application and result:

A rectangular or square wave signal for output current (only effective in current limiting) or output voltage is generated. The intervals t1 and t2 define how long the value of the amplitude (pulse) and how long the value of the offset (pause) are effective.

The offset shifts the signal on the Y-axis.

Intervals t1 and t2 can be used to define a duty cycle. The sum of t1 and t2 gives the cycle time and its reciprocal is the frequency.

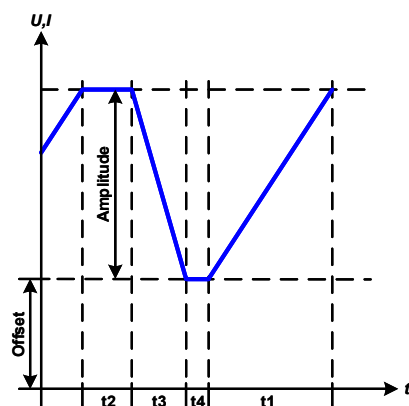
Example: a rectangular wave signal of 25 Hz and a duty cycle of 80% are required. The sum of t1 and t2, the period, is $1/25 \text{ Hz} = 40 \text{ ms}$. For a duty cycle of 80% the pulse time (t1) is $40 \text{ ms} \cdot 0.8 = 32 \text{ ms}$ and the pause time (t2) is 8 ms.

3.10.8 Trapezoidal function

The following parameters can be configured for a trapezoidal curve function:

Value	Range	Description
I(A), U(A)	0...(Nominal value - (Offs)) of U, I	A = Amplitude of the signal to be generated
I(Offs), U(Offs)	0...(Nominal value - (A)) of U, I	Offs = Offset, based on the foot of the trapezium
t1	0.1 ms...36000 s	Time for the positive slope of the trapezoidal wave signal.
t2	0.1 ms...36000 s	Time for the top value of the trapezoidal wave signal.
t3	0.1 ms...36000 s	Time for the negative slope of the trapezoidal wave signal.
t4	0.1 ms...36000 s	Time for the base value (offset) of the trapezoidal wave signal

Schematic diagram:



Application and result:

Here a trapezoidal signal can be applied to a set value of U or I. The slopes of the trapezium can be varied by setting different times for rise and fall.

The periodic duration and repetition frequency are the result of four time elements. With suitable settings the trapezium can be deformed to a triangular or rectangular wave. It has, therefore, universal use.

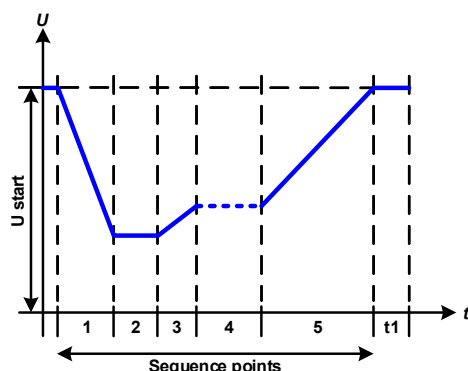
3.10.9 DIN 40839 function

This function is based on the curve defined in DIN 40839 / EN ISO 7637 (test impulse 4), and is only applicable to voltage. It shall replicate the progress of automobile battery voltage during engine starting. The curve is divided into 5 sequences (see diagram below) which each have the same parameters. The standard values from the DIN are set already as default values for the five sequence points.

The following parameters can be configured for the DIN40839 function:

Value	Range	Seq	Description
Ustart	0...Nominal value of U	1-5	Start voltage of the ramp
Uend	0...Nominal value of U	1-5	End voltage of the ramp
Seq.time	0.1 ms...36000 s	1-5	Time of the ramp
Seq.cycles	∞ or 1...999	-	Number of repetitions of the entire curve
Time t1	0.1 ms...36000 s	-	Time after cycle before repetition (cycle <> 1)

Schematic diagram:



Application and result:

The function isn't suitable for standalone operation of a power supply, but optimal for power supply in conjunction with an electronic load, for example one from ELR 9000 series. The load acts as a sink for the rapid fall of the output voltage of the power supply enabling the output voltage progress to follow the DIN curve.

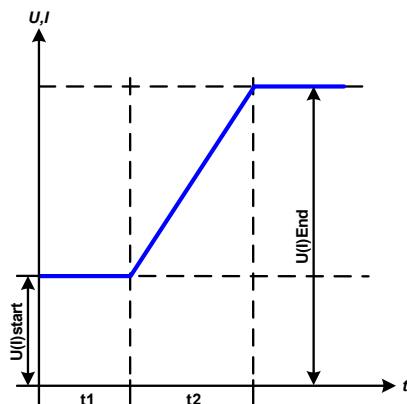
The curve conforms to test impulse 4 of the DIN. With suitable settings, other test impulses can be simulated. If the curve in sequence point 4 should be a sine wave, then these 5 sequence points have to be transferred to the arbitrary generator.

3.10.10 Ramp Function

The following parameters can be configured for a ramp function.

Value	Range	Description
Ustart / Istart	0...Nominal value of U, I	Start value (U, I)
Uend / Iend	0...Nominal value of U, I	End value (U, I)
t1	0,1 ms...36000 s	Time before ramp-up or ramp-down of the signal
t2	0.1 ms...36000 s	Ramp-up or ramp-down time

Schematic diagram:



Application and result:

This function generates a rising or falling ramp between start and end values over the time **t2**. Time **t1** creates a delay before the ramp starts.

The function runs once and stops at the end value.

Important to consider are the static values of U and I which define the start levels at the beginning of the ramp. It's recommended that these values are set equal to those in **Ustart/Istart**, unless the load at the DC output should not be provided with voltage before the start of the ramp. In that case the static values should be set to zero.



10h after reaching the ramp end, the function will stop automatically (i. e. $I = 0\text{ A}$ resp. $U = 0\text{ V}$), unless it has been stopped manually before.

3.10.11 Arbitrary function

The arbitrary, i. e. freely definable function offers the user a wider scope. There are 99 freely configurable sequence points available. While all have the same set of parameters, they can be configured differently so that a complex function process can be created. The 99 sequence points or a part of them can run one after another in a sequence point block and this block can then be repeated up to 999 times or infinitely. A sequence point or sequence point block is always assigned to either current or voltage, thus a mix of assignment to current or voltage isn't possible.

The arbitrary curve overlays a linear progression (DC) with a sine curve (AC), whose amplitude and frequency are shaped between start and end values. If the start frequency (f_s) = end frequency (f_e) = 0 Hz, the AC values have no impact and only the DC part is effective. Each sequence point is allocated a time in which the AC/DC curve from start to finish will be generated.

The following parameters can be configured for each sequence in the arbitrary function (the table lists parameters for current, for voltage it would be U_s , U_e etc.):

Value	Range	Description
Is(AC)	0...50% Nominal value of I	Start amplitude of the AC part of the curve
Ie(AC)	0...50% Nominal value of I	End amplitude of the AC part of the curve
fs(1/T)	0 Hz...10000 Hz	Start frequency of the AC part of the curve
fe(1/T)	0 Hz...10000 Hz	End frequency of the AC part of the curve
Angle	0°...359°	Start angle of the AC part of the curve
Is(DC)	Is(AC)...(Nominal value - Is(AC)) of I	Start value of the DC part of the curve
Ie(DC)	Ie(AC)...(Nominal value - Ie(AC)) of I	End value of the DC part of the curve
Seq.time	0.1 ms...36000 s	Time for the selected sequence



The sequence point time (seq. time) and the start and end frequency are related. The minimum value for $\Delta f/s$ is 9.3. Thus, for example, a setting of $f_s = 1$ Hz, $f_e = 11$ Hz and Seq.time = 5 s would not be accepted as $\Delta f/s$ is only 2. A seq. time of 1 s would be accepted, or, if the time remains at 5 s, then $f_e = 51$ Hz must be set.

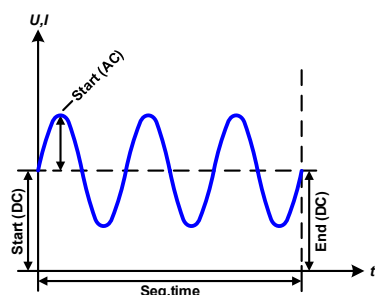


The amplitude change between start and end is related to the sequence time. An arbitrarily small change over an extended time isn't possible. See section „3.10.2.5. Minimum slope / maximum ramp time“ for more information.

After the settings for the selected sequence point are accepted with SAVE, further points can be configured. In a second settings screen, which can be reached by tapping NEXT in the sequence point selection screen, following global settings for all 99 points are adjustable:

Value	Range	Description
Start seq.	1 ... End seq.	First sequence point in the block
End seq.	Start seq. ... 99	Last sequence point in the block
Seq. Cycles	∞ or 1 ... 999	Number of cycles of the block

Schematic diagram:



Applications and results:

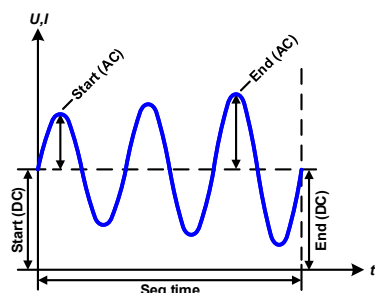
Example 1

Focusing 1 cycle of 1 sequence point

DC values for start and end are the same, also the AC amplitude. With a frequency >0 a sine wave progression of the set value is generated with a defined amplitude, frequency and Y-shift (offset, DC value at start and end)

The number of sine waves per cycle depend on the sequence point time and the frequency. If the sequence time were 1 s and the frequency 1 Hz, there would be exactly 1 sine wave. If the time were 0.5 s at the same frequency, there would only be a half sine wave.

Schematic diagram:



Applications and results:

Example 2

Focusing 1 cycle of 1 sequence point:

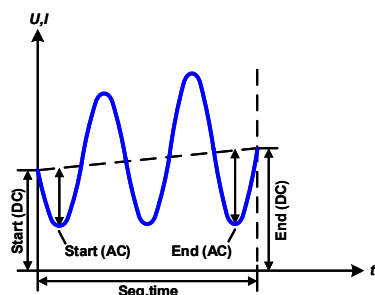
The DC values at start and end are the same but the AC (amplitude) not. The end value is higher than the start so that the amplitude increases with each new half sine wave continuously through the sequence. This, of course, only if the sequence point time and frequency allow for multiple waves to be created e. g. for $f=1$ Hz and Seq. time = 3 s, three complete waves would be generated (for angle = 0°) and reciprocally the same for $f=3$ s and Seq. time=1 s.

Example 3

Focusing 1 cycle of 1 sequence point

The DC values at start and end are unequal, as are also the AC values. In both cases the end value is higher than the start so that the offset increases from start to end (DC) and the amplitude also with each new half sine wave.

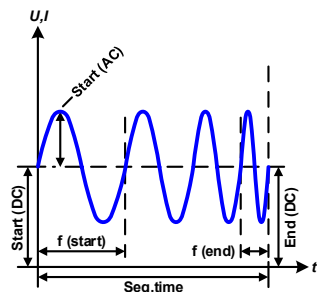
Additionally the first sine wave starts with a negative half wave because the angle is set at 180° . The start angle can be shifted at will in 1° steps between 0° and 359° .



Example 4

Focusing 1 cycle of 1 sequence point:

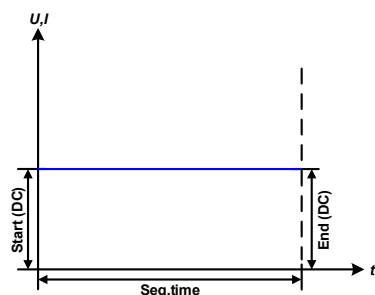
Similar to example 1 but with another end frequency. Here this is shown as higher than the start frequency. This impacts the period of the sine waves such that each new wave will be shorter over the total span of the sequence point time.



Example 5

Focusing 1 cycle of 1 sequence point:

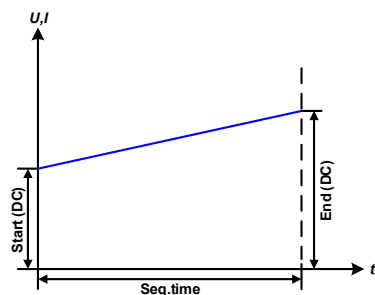
Similar to example 1 but with a start and end frequency of 0 Hz. Without a frequency no sine wave part (AC) will be created and only the DC settings will be effective. A ramp with a horizontal progression is generated.



Example 6

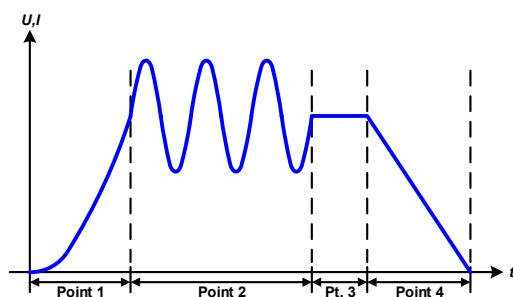
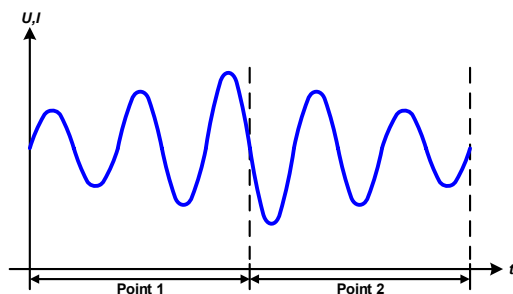
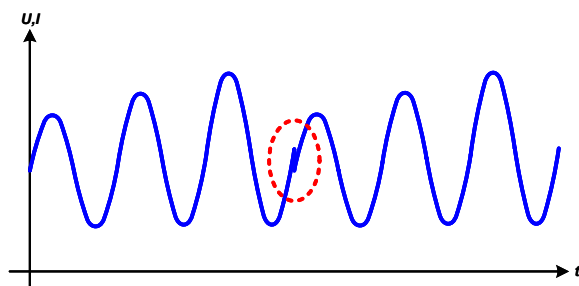
Focusing 1 cycle of 1 sequence point:

Similar to example 1 but with a start and end frequency of 0 Hz. Without a frequency no sine wave part (AC) will be created and only the DC settings will be effective. Here start and end values are unequal and a steadily increasing ramp is generated.



By linking together a number of differently configured sequence points, complex progressions can be created. Smart configuration of the arbitrary generator can be used to match triangular, sine, rectangular or trapezoidal wave functions and thus, e. g. a curve of rectangular waves with differing amplitudes or duty cycles could be produced.

Schematic diagram:



Applications and results:

Example 7

Focusing 2 cycles of 1 sequence point:

A sequence point configured as in example 3 is run. As the settings demand that the end offset (DC) is higher than the start, the second sequence point run will revert to the same start level as the first, regardless of the values achieved at the end of the first run. This can produce a discontinuity in the total progression (marked in red) which may only be compensated with careful choice of settings.

Example 8

Focusing 1 cycle of 2 sequence points:

Two sequence points run consecutively. The first generates a sine wave with increasing amplitude, the second with a decreasing amplitude. Together they produce a progression as shown left. In order to ensure that the maximum wave in the middle occurs only once, the first one must end with a positive half wave and the second one with a negative half wave as shown in the diagram..

Example 9

Focusing 1 cycle of 4 sequence points:

Sequence point 1: 1/4th sine wave (angle = 270°)

Sequence point 2: 3 Sine waves (ratio of frequency to sequence time 1:3)

Sequence point 3: Horizontal ramp (f = 0)

Sequence point 4: Falling ramp (f = 0)

3.10.11.1 Loading and saving the arbitrary function

The 99 sequence points of the arbitrary function, which can be manually configured with the control panel of the device and which are applicable either to voltage (U) or current (I), can be saved to or loaded from a common USB stick via the front side USB port. Generally, all 99 points are saved or loaded using a text file of type CSV (semicolon separator), which represents a table of values.

In order to load a sequence point table for the arbitrary generator, following requirements have to be met:

- The table must contain 99 rows (100 are also accepted for compatibility to previous firmwares), with 8 subsequent values in 8 columns and must not have gaps
- The column separator (semicolon, comma) must be as selected by MENU parameter **USB file separator format**; it also defines the decimal separator (dot, comma)
- The files must be stored inside a folder called HMI_FILES which has to be in the root of the USB stick
- The file name must always start with WAVE_U or WAVE_I (not case-sensitive)
- All values in every row and column have to be within the specified range (see below)
- The columns in the table have to be in a defined order which must not be changed

Following value ranges are given for use in the table, related to the manual configuration of the arbitrary generator (column headers like in Excel):

Column	Parameter	Range
A	AC start amplitude	0...50% U or I
B	AC end amplitude	0...50% U or I
C	Start frequency	0...10000 Hz
D	End frequency	0...10000 Hz
E	AC start angle	0...359°
F	DC start offset	0...(Nominal value of U or I) - AC start amplitude
G	DC end offset	0...(Nominal value of U or I) - AC end amplitude
H	Sequence point time in μ s	100...36.000.000.000 (36 billion μ s)

For details about the parameter and the arbitrary function refer to „3.10.11. Arbitrary function“.

Example CSV:

	A	B	C	D	E	F	G	H
1	20,00	30,00	5	5	90	50,00	50,00	50000000
2	30,00	20,00	5	5	90	50,00	50,00	30000000
3	0,00	0,00	0	0	0	0,00	0,00	1000
4	0,00	0,00	0	0	0	0,00	0,00	1000
5	0,00	0,00	0	0	0	0,00	0,00	1000
6	0,00	0,00	0	0	0	0,00	0,00	1000

The example shows that only the first two sequence points are configured, while all others are set to default values. The table could be loaded as WAVE_U or WAVE_I when using, for example, the model PSI 9080-120 2U, because the values would fit both, voltage and current. The file naming, however, is unique. A filter prevents you from loading a WAVE_I file after you have selected **Arbitrary --> U** in the function generator menu. The file would not be listed at all.

► How to load a sequence point table from an USB stick:

1. Do not plug the USB drive yet or remove it.
2. Access the function selection menu of the function generator with **MENU -> Function Generator -> Arbitrary -> U/I**, to see the main screen of sequence point selector, as depicted to the right.



3. Tap touch area  File Import/Export, then  LOAD from USB and follow the instructions on screen. If at least one valid files has been recognized (for file and path naming see above), the device will show a list of files to select from with .

4. Tap touch area  LOAD from USB in the bottom right corner. The selected file is then checked and loaded, if valid. In case it's not valid, the device will show an error message. Then the file must be corrected and the steps repeated.

► How to save a sequence point table to an USB stick:

1. Do not plug the USB stick yet or remove it.
2. Access the function selection menu of the function generator via **MENU -> Function Generator -> Arbitrary -> U / I**



3. Tap on **File Import/Export**, then **SAVE to USB**. The device will request you to plug the USB stick now.
4. After plugging it, the device will try to access the stick and find the folder HMI_FILES and read the content. If there are already WAVE_U or WAVE_I files present, they will be listed and you can either select one for overwriting with , otherwise select **-NEW FILE-** for a new file.



5. Finally save the sequence table with **SAVE to USB**.

3.10.12 UI and IU table functions (XY table)

The UI and IU functions offer the user the possibility to set a DC output current dependent on the DC output voltage, or a DC output voltage dependent on the DC output current. The function is table driven with exactly 4096 values, which are distributed over the whole measured range of actual output voltage (0...125% U_{Nom}) or output current (0...102% I_{Nom}). The table can either be uploaded from an USB stick through the front side USB port of the device or via remote control (ModBus protocol or SCPI). The functions are defined like this:

UI function: $U = f(I)$ -> the device will work in CV regulation mode

IU function: $I = f(U)$ -> the device shall work in CC regulation mode with a load that is in CV mode

With the **UI function**, the equipment measuring circuit determines the level of the output current. For each of the effective 3277 possible values of the output current a voltage value is maintained by the user in the UI table which can be any value between 0 and rated value. The values uploaded from an USB stick will always be interpreted as voltage values.

With the **IU function**, the equipment measuring circuit determines the output voltage in order to pick a corresponding current value from the user-defined table. The power supply is supposed to work in CC mode here and is thus depending on the load to run a voltage regulation (CV) in order to let the table result in a correct behavior.



Uploading of a table from an USB stick must use text files in CSV format (.csv). Plausibility is checked on loading (values not too high, number of values correct) and possible errors reported in which case the table won't be loaded.*



The 4096 values in the table are only checked for size and count. If all the values were to be graphically plotted, a curve would be created which could include significant step changes in current or voltage. That could lead to complications for connected loads if, for example, the internal current measurement in the power supply swings slightly so that the voltage jumps backwards and forwards between two values in the table, which, in the worst case, could be 0 V and the maximum voltage.

3.10.12.1 Loading UI and IU tables from USB drive

The so-called UI or IU value tables can be loaded from a file via a standard USB stick that is formatted as FAT32. In order to load the file, it has to meet following specifications:

- The file name always begins with IU or UI (not case-sensitive), depending on which of the two function you load the table for
- The file must be a text file of type Excel CSV (semicolon as separator) and must only contain one column with exactly 4096 values without gaps
- Values with decimal places must use a decimal separator as depending on the selection with parameter **USB file separator format** (US: separator = comma, decimal separator = dot)
- No value may exceed the nominal value of the device. For example, if you have an 80 V model and you are going to load a table with values for voltage, none of the 4096 values may be higher than 80 V (the adjustment limits from the device's front panel don't apply here)
- The file(s) has/have to be put inside a folder named HMI_FILES in the root of the USB stick



If these specifications are not met, the device won't accept the file and put out an error message in the display. Files with names beginning different to UI or IU are not recognized for this purpose. The USB drive may contain multiple UI/IU files with different names and list them for the selection of one.

► How to load an UI or IU table from an USB drive:

1. Do not plug the USB drive yet or pull it out if already plugged.
2. Open the function selection menu of the function manager with **MENU -> Function Generator -> XY Table**
3. In the next screen select the desired function with either **UI Table** or **IU Table**.
4. Configure the global parameters for U, I and P, if necessary.



5. Tap touch area **LOAD from USB** and plug the USB drive when requested, in order to select one out of X compatible files from the drive. In case the file isn't accepted, the device will report an error in the display and also tell what's wrong with the file.
6. Once the file is accepted, you will be requested to remove the USB drive.



7. Submit and load the function with **LOAD** to start and control it as with other function (also see „3.10.4.1. Function selection and control“).

3.10.13 Simple PV function (photovoltaics)

3.10.13.1 Preface

This function uses the standard XY generator to make the power supply simulate solar panels or solar cells with certain characteristics. The device calculates an IU table from four typical values.

While the function is running, the user can adjust a parameter "Irradiance" between 0% (darkness) and 100% (bright light) in 1% steps to simulate different light situations.

The most important characteristics of a solar panel are:

- the short-circuit current (I_{SC}), the max. panel current at almost 0 V
- the open circuit voltage (U_{OC}), which almost reaches its maximum value even in low light situations
- the maximum power point (MPP), at which the solar panel can provide the maximum output power

The voltage of the MPP (here: U_{MPP}) lies typically 20% below U_{OC} , the current of the MPP (here: I_{MPP}) lies typically 5% below I_{SC} . In case there are no definite values for the simulated solar cell available, I_{MPP} and U_{MPP} can be set to this rule of thumb. The device limits the I_{MPP} value to I_{SC} as upper limit, the same applies to U_{MPP} and U_{OC} .



3.10.13.2 Safety notices



Due to high capacities on the DC outputs of the power supplies of this series, not every available solar inverter can be operated without problems. Check the technical specifications of the solar inverter and probably contact the manufacturer for an evaluation.

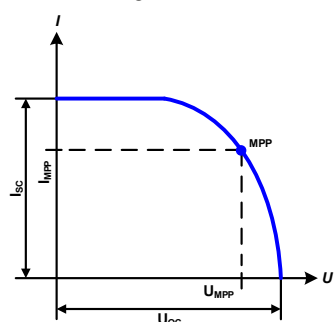
3.10.13.3 Usage

In the PV table function, which is based upon the XY generator with IU characteristics, the MPP is defined by the two adjustable parameters U_{mpp} and I_{mpp} (also see diagram below). These parameters are usually stated in data sheets of solar panels and have to be entered here.

The following parameters can be set for the PV table function:

Value	Range	Description
Uoc	U _{mpp} ...Nominal device voltage	Open circuit voltage at no load
Isc	I _{mpp} ...Nominal device current	Short-circuit current at max. load and low voltage
U _{mpp}	0 V...Uoc	DC output voltage at the MPP
I _{mpp}	0 A...Isc	DC output current at the MPP

Schematic diagram:

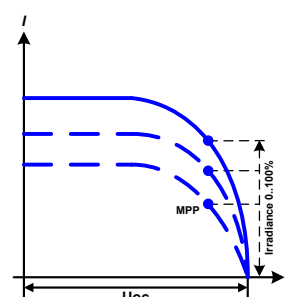


Application and result:

Adjust all four parameters on screen to the desired values. Whether the calculated IU and P curves, which result from those values, make sense or not can be verified with a tool like Excel by generating a diagram.

While the simulation is running, the user can see from the actual values (voltage, current, power) of the DC output, where the operating point of the power supply resp. of the simulated solar panel is. The adjustable value **Irradiance** (0%...100% in 1% steps, see screenshot below) helps to simulate different light situations from darkness (no power output) to the minimal amount of light that is required to make the panel provide full power.

Varying this parameter shifts the MPP and the PV curve along the Y axis. Also see diagram to the right. The value Irradiance is here used as a factor for the current I_{mpp}. The curve itself isn't permanently re-calculated.



► How to configure the PV table

1. In the function generator menu tap on  then  and then



2. Adjust the four parameters as required for the simulation.

3. Do not forget to adjust the global limits for voltage and power in the next screen which you can access



with touch area . The voltage (U) setting should be at least as high as U_{oc}, or higher.

4. After setting the values for the required signal generation, tap on touch area .



While loading, the IU function is calculated and sent to the internal XY generator. After this, the function is ready to run.

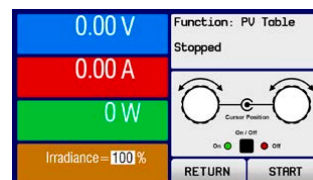


The function can be saved to USB stick as table after every calculation, as well as read via any of the digital interfaces.

From the screen where the XY function generator is controlled manually (start/stop), you can go back to the first screen of PV table function and use the formerly locked touch area to save the table to USB drive. In order to do so, follow the on-screen instructions. The table can be used to analyze the values or to visualize it in Excel or similar tools.

► How to work with the PV table function

1. With an appropriate load connected, for example a solar inverter, start the function as described in 3.10.4.1.
2. Adjust value **Irradiance** with the left rotary knob between 100% (default) and 0%, in order to simulate different light situations. The actual values on the display indicate the working point and can show whether the simulation has arrived at the MPP or not.
3. Stop the function run anytime as described in 3.10.4.1.



3.10.14 FC table function (fuel cell)

3.10.14.1 Preface

The FC table function is used to simulate the characteristics of voltage and current of a fuel cell. This is achieved by setting up some parameters which define points on a typical fuel cell curve, which is then calculated as UI table and passed to the internal function generator.

The user has to adjust value for four support points. The device will request to enter them step by step, indicating the actual point on screen with small graphics. When finished, these points will be used to calculate the curve.

Generally, following rules apply when setting up those values:

- $U_{\text{Point1}} > U_{\text{Point2}} > U_{\text{Point3}} > U_{\text{Point4}}$
- $I_{\text{Point4}} > I_{\text{Point3}} > I_{\text{Point2}} > I_{\text{Point1}}$
- Values of zero are not accepted

It means, the voltage has to decrease from point 1 to point 4, while the current has to increase. In case the rules are not followed, the device will reject the values with an error and reset them to 0.

3.10.14.2 Usage

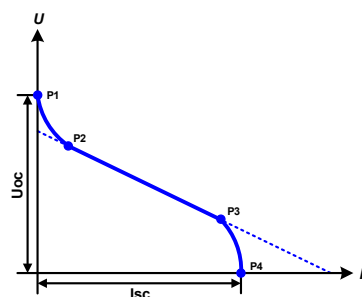
The following parameters can be set for the FC table function:

Value	Range	Description
Point 1: Uoc	0 V... U_{Nom}	Open circuit voltage at no load
Point 2+3: U	0 V... U_{Nom}	Voltage and current define the position of these two points in the U-I coordinate system, which represent two supporting points on the curve to be calculated
Point 2+3: I	0 A... I_{Nom}	
Point 4: Isc	0 A... I_{Nom}	DC output current at the MPP



All these parameters are freely adjustable and thus an unrealistic curve could result. In some situations, the device would show a "Calculation error" after you tapped LOAD and loading of the function will be aborted. In this situation, check your settings, probably revise and try again.

Schematic diagram:



Application and result:

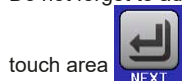
After setting up the four supporting points P1 thru P4, whereas P1 is at position Uoc and 0 A and P4 is at position Isc and 0 V, the device will calculate the function as UI table and load it to the XY generator.

Depending on the load current, which can be between 0 A and Isc, the device will set a variable output voltage, whose progress between 0 V and Uoc should result in a curve similar to the one depicted to the left.

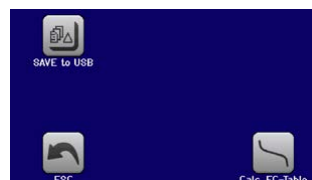
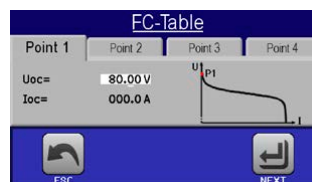
The slope between P2 and P3 is depending on the values adjusted for P2 and P3 and can be freely modified as long as P3's voltage is lower than the one of P2 and P3's current is higher than the one of P2.

► How to configure the FC table

1. In the function generator menu tap on  then  and then .
2. Adjust the parameters of the four supporting points, as required for the simulation.
3. Do not forget to adjust the global limits for voltage and power in the screen which you can access with



4. After setting the values for the required signal generation, tap on touch area .



After the function has been loaded to the internal XY generator, the simulation is ready to start.

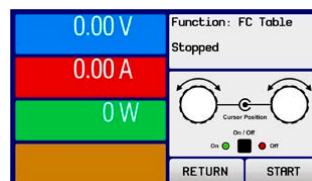


The function can be saved to USB stick as table, as well as read via any of the digital interfaces.

From the screen where the XY function generator is controlled manually (start/stop), you can go back to the first screen of the FC table function and use the formerly locked touch area to save the table to USB drive. In order to do so, follow the on-screen instructions. The table can be used to analyze the values or to visualize it in Excel or similar tools.

► How to work with the FC table function

1. With an appropriate load connected, for example a DC-DC converter, start the function as described in 3.10.4.1.
2. The output voltage will be set depending on the load current, which is defined by the connected load, and will decrease with increasing current. Without any load, the voltage will rise to the adjusted Uoc value.
3. Stop the function run anytime as described in 3.10.4.1.



3.10.15 Extended PV function according to EN 50530

3.10.15.1 Introduction

This extended PV table function according to standard EN 50530 is used to simulate solar panels in order to test and rate solar inverters. It's available since firmware versions KE 2.19 and HMI 2.11 and offers manual configuration and control, as well as remote control. It's also based on the XY generator, same as the simple PV table function from 3.10.13, but enables more specific tests and evaluations due to adjustable parameters. Which parameters are available is explained below. The impact of the parameters on the PV curve and the simulation is described in the standard paper of EN 50530, which user can refer to in case more detailed description is required. This section only deals about configuration and control of the PV simulation.

3.10.15.2 Differences to the simple PV function

The extended PV function has five additional or different characteristics compared to the simple PV function:

- The simulation distinguishes between a single test run and an automatic test run, called day trend, which is based upon an user-defined curve built from up to 100,000 points
- There are two invariable and one variable panel technology available to choose from
- There are more parameters available to adjust during runtime
- It allows for data recording during runtime and to save the data either to USB stick or read via digital interface
- It allows to select between two different parameter sets to adjust during runtime

3.10.15.3 Technologies and technology parameters

When configuring the PV simulation it's required to select the solar panel technology to simulate. The technologies **cSI** and **Thin film** are invariable in their parameters, while technology **Manual** is variable in all parameters, but within specific limits. This allows for the variation of the simulation and when copying the fixed parameter values from **cSI** or **Thin film** to **Manual**, it even enables their variation as well.

One advantage of the invariable technologies is that their technology parameters are automatically set to their defined defaults in the configuration procedure.

Overview of the technology parameters used in the PV curve calculation and their defaults:

Abbr.	Name	Manual	cSI	Thin film	Unit
FFu	Fill factor for voltage	>0...1 (0.8)	0.8	0.72	-
FFi	Fill factor for current	>0...1 (0.9)	0.9	0.8	-
Cu	Scaling factor for U_{OC} ⁽¹⁾	>0...1 (0.08593)	0.08593	0.08419	-
Cr	Scaling factor for U_{OC} ⁽¹⁾	>0...1 (0.000109)	0.000109	0.0001476	m ² /W
Cg	Scaling factor for U_{OC} ⁽¹⁾	>0...1 (0.002514)	0.002514	0.001252	W/m ²
alpha	Temperature coefficient for I_{SC} ⁽²⁾	>0...1 (0.0004)	0.0004	0.0002	1/°C
beta	Temperature coefficient for U_{OC} ⁽¹⁾	-1...<0 (-0.004)	-0.004	-0.002	1/°C

(1) U_{OC} = Open circuit voltage of a solar panel

(2) I_{SC} = Short-circuit current (=max. current) of a solar panel

3.10.15.4 Simulation mode

Apart from the panel technology there is also a simulation mode to select. Four options:

Mode U/I	Controllable simulation. Voltage (U_{MPP} , in V) and current (I_{MPP} , in A) in the maximum power point (MPP) are variable during runtime. The purpose of this mode is to directly shift the MPP into various directions.
Mode E/T	Controllable simulation. During runtime, the irradiation (E from german "Einstrahlung", in W/m ²) and surface temperature (T, in °C) of the simulated solar panel are adjustable. This also impacts the curve and the resulting MPP. The purpose of this mode is to analyze the impact of temperature and/or irradiation on the performance of a solar panel.
Mode DAY U/I	Automatic simulation run, processing a day trend curve consisting of up to 100,000 points defined by values for U_{MPP} , I_{MPP} and time.
Mode DAY E/T	Automatic simulation run, processing a day trend curve consisting of up to 100,000 points defined by values for irradiation, temperature and time.

3.10.15.5 Day trend

The so-called day trend is a special simulation mode for long-term tests. It processes a curve consisting of up to 100,000 user-definable points. For every processed point on that curve, the PV curve is calculated anew.

Every point is defined by 3 values of which one is the dwell time. When defining long dwell times the day trend curve can be supported by an interpolation feature which can be optionally activated. It will calculate and set intermediate points between two succeeding curve points. Hence it should be considered to run the day trend with or without interpolation.

The day curve points have to be loaded into the device, either from a CSV file on USB stick or via digital interface. The user selects the number of points according to the requirements of the simulation.

Formats of the CSV files to load from USB stick when manually configuring the function:

- For **Mode DAY E/T** (required file name format: PV_DAY_ET_<arbitrary_text>.csv)

	A	B	C	D
1	1	100	25	300000
2	2	101	25	2000
3	3	102	25	2000
4	4	103	25	2000
5	5	104	25	2000
6	6	105	25	2000
7	7	106	25	2000
8	8	107	25	2000
9	9	108	25	2000

Column A = **Index**

An ascending number between 1 and 100,000 (the first empty index will cause the simulation to stop)

Column B = **Irradiation (E)** in W/m²

Allowed range: 0...1500

Column C = **Temperature (T)** in °C

Allowed range: -40...80

Column D = **Dwell time** in milliseconds (ms)

Allowed range: 500...1.800.000

- For **Mode DAY U/I** (required file name format: PV_DAY_UI_<arbitrary_text>.csv)



Attention! The values in columns B and C are real values which must not exceed the ratings of the device or the device will neglect to load the file.

	A	B	C	D
1	1	63.5	120.3	500
2	2	63.6	121.1	500
3	3	63.7	121.9	500
4	4	63.8	122.7	500
5	5	63.9	123.5	500
6	6	64	124.3	500
7	7	64.1	125.1	500
8	8	64.2	125.9	500
9	9	64.3	126.7	500

Column A = **Index**

An ascending number between 1 and 100,000 (the first empty index will cause the simulation to stop)

Column B = **Voltage U_{MPP}** in V

Allowed range: 0...rated output voltage of the device

Column C = **Current I_{MPP}** in A

Allowed range: 0...rated output current of the device

Column D = **Dwell time** in milliseconds (ms)

Allowed range: 500...1.800.000



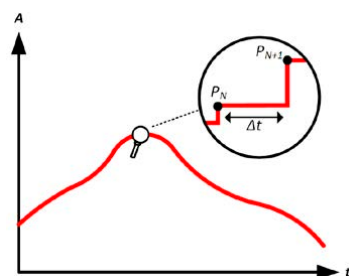
The number format and the column separator in the CSV files is determined by the regional settings of the PC or the software used to create the files. The format must match the selection for the device setting "USB file separator format" in the General Settings menu of the device, else the device would neglect loading the file. For example, an american Excel should by default use the dot as decimal separator and the comma as column separator, which would match the selection "USB file separator format = US".

3.10.15.6 Interpolation

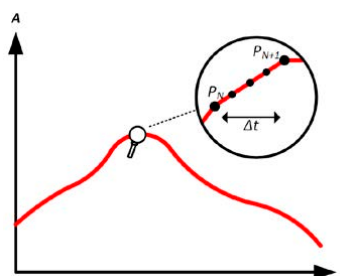
The interpolation feature can calculate and set intermediate steps when running the PV function in day trend mode, i. e. **DAY E/T** or **DAY U/I**. The calculation is always done between to succeeding points on the day trend curve. The dwell time of every curve point is adjustable between 500 and 1,800,000 milliseconds (see above, format of the day trend data file). While there are no extra points calculated when using the minimum time of 500 ms, following applies to higher dwell time definitions:

- The number of intermediate steps is determined from the dwell time and spread as equally as possible, where any of the steps can have its own dwell time between 500 and 999 ms
- The intermediate steps also respect the slope between the current and the next day trend curve point and thus every step also includes a corresponding value alteration

Visualization:



Without interpolation - the curve results in steps



With interpolation - the curve remains linear

An example: the dwell time of the 3450th curve point is defined as 3 minutes, which is 180 seconds. There will be $180 / 0.5 - 1 = 359$ intermediate steps calculated and set until reaching the 3451st point. In mode DAY U/I the MPP voltage changes from 75 V to 80 V and the MPP current changes from 18 A to 19 A. When calculated, this would mean a $\Delta U/\Delta t$ of 27.7 mV/s and a $\Delta I/\Delta t$ of 5.5 mA/s. Depending on the device in use, such small steps in voltage or current may not be doable. However, the device would try to set the first intermediate step with 75.0138 V and 18.0027 A.

3.10.15.7 Data recording

There is the option to record data during the simulation run, in any mode. The data can be stored to USB stick once the simulation is finished or read via digital interface, which even allows for reading the data while the simulation is still running.

As long as the simulation is running, the device will record one data set every 100 ms into an internal buffer. This interval isn't adjustable. The max. number of data sets, here also called indexes, is 576,000. This results in a max. record time of 16 hours. The indexes are internally counted with every new record. When reaching the max. number, the index will restart from 1, overwriting former data. Every index will contain 6 values.

When configuring the PV simulation, the recording feature is locked at first (button greyed out). Only when stopping the simulation and leaving the control screen back to the configuration, the button becomes accessible. It then allows to store a CSV with a specific number of rows. This number depends on the current index counter. Contrary to remote control where it's possible to address every index of the max. 576,000 the save to USB feature will always store all indexes between 1 and the counter. Every next simulation run also resets the counter.

CSV file format when saving the recorded data to USB stick (in the example all values are with unit):

	A	B	C	D	E	F	G
1	Index	U actual	I actual	P actual	Umpp	Impp	Pmpp
2	1	0,29V	0,000A	0,0W	0,00V	0,000A	0,0W
3	2	0,29V	0,000A	0,0W	0,00V	0,000A	0,0W
4	3	0,29V	0,000A	0,0W	0,00V	0,000A	0,0W
5	4	0,29V	0,000A	0,0W	0,00V	0,000A	0,0W
6	5	0,30V	0,000A	0,0W	0,00V	0,000A	0,0W
7	6	0,28V	0,000A	0,0W	0,00V	0,000A	0,0W
8	7	0,28V	0,000A	0,0W	0,00V	0,000A	0,0W
9	8	0,28V	0,000A	0,0W	0,00V	0,000A	0,0W

Index = Ascending number

Uactual = Actual voltage on the DC output

Iactual = Actual current on the DC output

Pactual = Actual power on the DC output

Umpp / Impp / Pmpp = Voltage, current and power in the MPP of the currently calculated PV curve



The global parameter "USB logging with units (V,A,W)" in the General Settings of the device MENU selects whether the values in the CSV file are with or without physical unit. Default is with unit. Another parameter, "USB decimal point format" selects whether the device saves the CSV with comma (US) or semicolon (Standard) and defines the decimal point (dot and comma). The example CSV above shows the european format with decimal comma.

3.10.15.8 Configuration step by step



Starting point

In MENU->Function Generator->2nd page->XY-Table you will find the PV functions. Select **PV DIN EN 50530**.



Step 1: Technology selection

The extended PV function requires to select the panel technology of the solar panel which is going to be simulated. In case **cSI** or **Thin Film** don't match your requirements or you are not sure about their technology parameters, select **Manual**.

When selecting **Thin film** or **cSI** the configuration continues with **Step 2**.



Step 1-1: Adjust technology parameters

If technology **Manual** was selected in the previous screen, all displayed technology parameters can be adjusted by tapping on them and entering the desired value. It's recommended to adjust these values very carefully, because wrong settings can result in a PV curve which doesn't work as expected.

When resetting the device, these values are reset to defaults which are the same as with technology **cSI**. Also see the overview in 3.10.15.3. It means they don't necessarily have to be adjusted. If any of the other technologies was selected, this screen would be skipped and these parameters set to the defined values.



Step 2: Enter the solar panel's base parameters

The open circuit voltage (U_{OC}), the short-circuit current (I_{SC}), as well as voltage (U_{MPP}) and current (I_{MPP}) in the expected MPP are the base parameters to calculate a PV curve from. U_{OC} and I_{SC} are upper limits which are usually read from the data sheet of a solar panel and entered here for the simulation. Two parameters each are connected via the fill factors:

$$U_{MPP} = U_{OC} \times FF_u \quad / \quad I_{MPP} = I_{SC} \times FF_i$$

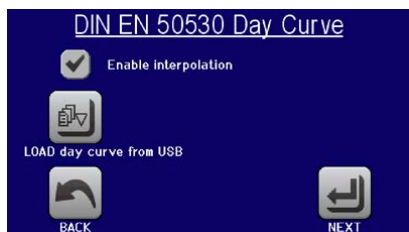


Step 3: Select simulation mode

For a description of the available simulation modes see 3.10.15.4.

Furthermore, the recording feature can be enabled (=activated) here. The recorded data can later be stored to USB drive as CSV file with button **SAVE records to USB**, after returning to this screen from the simulation run. Also see section 3.10.15.7.

When selecting **E/T** or **U/I** the configuration continues with **Step 4**.



Step 3-1: Load day trend data

If mode **DAY E/T** or **DAY U/I** was selected this additional screen will appear where you can load the required day trend data (1-100,000 points) with button **LOAD day curve from USB** and from a CSV file with a specific format (see 3.10.15.5) and name (see 1.9.6.5).

There is furthermore the option to enable (=activate) the interpolation feature (see 3.10.15.6).



Step 4: Global limits

This configuration screen allows to limit voltage and power globally for the simulation. The current, in this table based simulation, is taken from the calculated PV table which also is an IU table.

The output voltage of the power supply is already defined by setting up U_{OC} in step 2, so it's recommended to adjust value U to same or higher, else the PV curve may not be working as expected. The power should not be limited at all.

Recommendation: leave both values untouched

The configuration will be finished and the settings submitted with button . The function generator would then switch to control mode.

3.10.15.9 Controlling the simulation

After loading the configured parameters the FG will switch to control mode. Now the simulation can be started with either the "On/Off" button or touch area .

According to the configured simulation mode, the orange-brown display area would show the adjustable simulation parameters, which could only be modified via direct input, not by the rotary knobs, because with every step of the knob the curve would be re-calculated.

The screen example on the right shows simulation mode **E/T**.

In case any of the day trend modes would have been configured, the display area would be empty. These modes run automatically once started and will stop when the total time of all points' dwell time is reached. The other modes, **E/T** and **U/I**, would only stop by user interaction or due to a device alarm.



3.10.15.10 Stop criteria

The simulation run could unintentionally stop due to several reasons:

1. A device alarm occurred, which would switch off the DC output (PF, OVP, OCP, OPP)
2. An user event occurred whose action has been defined to cause an alarm, which means to switch off DC
3. Day trend mode has finished

Situation 2 can be avoided by carefully setting up other parameters, unrelated to the function generator. With the simulation stop in all three situation the data recording would also stop.

3.10.15.11 Test analysis

After simulation stop by whatever reason recorded data can be saved to USB stick or read via digital interface, of course only if data recording has been activated in the configuration. Activating the data recording feature during the simulation run isn't possible when manually controlling the FG, but in remote control. When saving to USB stick, it would always save all data recorded until the current index counter. Via digital interface there is the option read any portion of the data, which will also have an impact on the time required to read the data.

The data can later be used to visualize, analyze and determine characteristics of the simulated solar panel and also of the solar inverter which is usually used as load when running such tests. More details can be found in the standard paper.

3.10.15.12 Reading the PV curve

The last PV curve (or table) which has been calculated during the simulation run can later be read from the device via digital interface (partly or completely) or stored to USB stick. This can serve to verify the adjusted parameters. When running mode DAY E/T or DAY U/I this makes less sense, because there the curve would re-calculated with every processed index and the read curve would always be the one belonging to the last day trend curve point.

When reading the PV table, you will receive up to 4096 current values. The table data could be visualized in an XY diagram in tools like Excel.

3.10.16 Remote control of the function generator

The function generator can be remotely controlled but configuration and control of the functions with individual commands is different from manual operation. The external documentation "Programming Guide ModBus & SCPI" explains the approach. In general the following apply:

- The function generator isn't directly controllable via the analog interface; the only impact to the function run can come from pin REM-SB switching the DC output off, which will pause the function, so it could continue later with pin REM-SB switching the DC output on again and in case the function hasn't been stopped otherwise.
- The function generator is unavailable if R mode (resistance) is activated
- Some functions are based on the arbitrary generator, some on the XY generator. Therefore, both generators have to be controlled and configured separately

3.11 Other applications

3.11.1 Parallel operation in master-slave mode (MS)

Multiple devices of same kind and model can be connected in parallel in order to create a system with higher total current and hence higher power. For master-slave operation, the units are usually connected with their DC outputs, their Share bus and their digital master-slave bus.

The master-slave bus is a digital bus which makes the system work as one big unit regarding adjusted values, actual values and status.

The Share bus is intended to balance the units dynamically in their output voltage, especially if the master unit runs a function like sine wave etc. In order for this bus to work correctly, at least the DC minus poles of all units have to be connected, because DC minus is the reference for the Share bus.

3.11.1.1 Restrictions

Compared to normal operation of a single device, master-slave operation has some *restrictions*:

- The MS system reacts differently to alarm situations (see below in 3.11.1.6)
- Using the Share bus makes the system reacts as dynamically as possible, but it's still not as dynamic as single unit operation

3.11.1.2 Wiring the DC outputs

The DC output of every unit in the parallel operation is simply connected to the next unit using cables with cross section according to the maximum current and with short as possible length.

3.11.1.3 Wiring the Share bus

The Share bus is wired from unit to unit with an ideally twisted pair of cables with non-critical cross section. We recommend to use 0.5 mm² to 1.0 mm².



- The Share bus is poled. Take care for correct polarity of the wiring!
- Share bus operation can become critical when worked dynamically and with high voltages or with potential shifts. It's thus recommended to connect the negative DC pole of the devices with short as possible cables or, ideally, copper bars. The device should be as close as possible to each other, also blocks of power supply and electronic load units in two-quadrant operation.
- The Share bus need the DC minus connection between the units as reference, which must not be disconnected between units which are still connected via the Share bus!



A max. of 16 units can be connected via Share bus.

3.11.1.4 Wiring and set-up of the master-slave bus

The master-slave connectors are built-in and can be connected via network cables (≥CAT3, patch cable). After this, MS can be configured manually (recommended) or by remote control. The following applies:

- A maximum of 16 units can be connected via the bus: 1 master and up to 15 slaves
- Connection only between devices of same kind, i. e. power supply to power supply, and of the same model, such as PSI 9080-60 2U to PSI 9080-60 2U
- Units at the end of the bus must be terminated (see below)



The master-slave bus must not be wired using crossover cables!

Later operation of the MS system implies:

- The master unit displays, or makes available to be read by the remote controller, the sum of the actual values of all the units
- The ranges for setting the values, adjustment limits, protections (OVP etc.) and user events (UVD etc.) of the master are adapted to the total number of units. Thus, if e. g. 5 units, each with a power of 1.5 kW, are connected together to a 7.5 kW system, then the master can be set in the range 0...7.5 kW.
- Slaves are no operable as long as being controlled by the master
- Slave units will show the alarm **MSP** in the display as long as they not have been initialized by the master. The same alarm is signaled after a connection drop to the master unit occurred.
- In case the function generator of the master unit is going to be used, the Share bus must be connected as well

► How to connect the master-slave bus:

1. Switch off all units that are to be connected and connect them together with network cables (CAT3 or better, not included). It doesn't matter which of the two master-slave connection sockets (RJ45, backside) is connected to the next unit.
2. Depending on the desired configuration the units can then be connected at the DC side.
3. The two units at the beginning and end of the chain should be terminated, if long connection cables are used. This is achieved using a 3-pole DIP switch which is positioned on the back side of the unit next to the MS connectors.



Now the master-slave system must be configured on each unit. It's recommended to configure first all the slave units and then the master unit.

► Step 1: Configuring all slave units

1. Enter **MENU** then **GENERAL SETTINGS** and press until reaching the master-slave settings.
2. Activate the MS mode with touch area **SLAVE**. A warning requester will appear which has to be acknowledged with OK, otherwise the change will be reverted.
3. Accept the settings with the touch area and return to the main page.

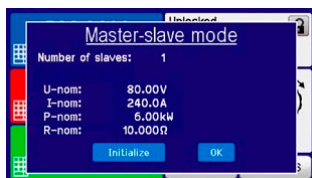
The slave is then configured for master-slave. Repeat the procedure for all other slave units.

► Step 2: Configuring the master unit

1. Enter **MENU** then **GENERAL SETTINGS** and press until reaching the master-slave settings.
1. Specify the unit as master with touch area **MASTER**. A warning requester will appear which has to be acknowledged with OK, otherwise the change will be reverted.
2. Accept the settings with the touch area and return to the main page.

► Step 3: Initializing the master

The master unit and the whole master-slave system must now be initialized, which is done automatically after the master unit has been activated for MS. In the main page, after quitting the setting menus, a pop-up will appear:



Tapping **Initialize** repeats the search for slaves in case the detected number of slaves is less than expected, the system has been reconfigured, not all slave units are already set as **Slave** or the cabling/termination is still not OK. The result window shows the number of slaves, plus the total current, power and resistance of the MS system.

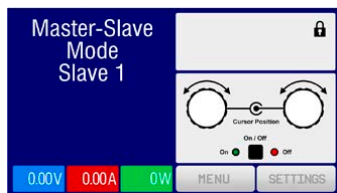
In case there are no slaves found, the master will still initialize the MS system with only itself.



The initialization process of the master and the master-slave system will, as long as MS mode is still activated, be repeated each time the units are powered. The initialization can be repeated anytime via the MENU in GENERAL SETTINGS, PAGE: 10.

3.11.1.5 Operating the master-slave system

After successful configuration and initialization of the master and slave units, these will show their status in the displays. While the master merely shows "Master" in the status area, the slave(s) will continuously show like this, as long they are in remote control by the master:



It means, as long as a slave unit is in control by the master, it won't display any set or actual values, but it will show the DC output status and possible alarms.

The slaves can no longer be controlled manually or remotely, neither via the analog nor via digital interfaces. They can, if needed, be monitored by reading actual values and status.

The display on the master unit changes after initialization and all set values are reset. The master now displays the set and actual values of the total system. Depending on the number of units, the total current and power will multiply. The following applies:

- The master can be treated as a standalone unit
- The master shares the set values across the slaves and controls them
- The master is remotely controllable via the analog or digital interfaces
- All settings for the set values U, I and P (monitoring, settings limits etc.) will be adapted to the new total values
- All initialized slave will reset any limits (U_{Min} , I_{Max} etc.), supervision thresholds (OVP, OPP etc.) and event settings (UCD, OVD etc.) to default values, so these don't interfere the control by the master



In order to easily restore all these settings values to what was before activating MS operation, it's recommended to make use of the user profiles (see „3.9. Loading and saving an user profile“)

- If one or more slaves report an device alarm, this will be displayed on the master and must be acknowledged there so that the slave(s) can continue operation. Since an alarm causes the DC output to be switched off and it can only reinstate automatically after PF or OT alarms, it can be required to switch it on again by the operator or by a remote control software.
- Loss of connection to any slave will result in shutdown of all DC outputs, as a safety measure, and the master will report this situation in the display with a pop-up "Master-slave safety mode". Then the MS system has to be reinitialized, either with or without re-establishing connection to the disconnected unit(s) before
- All units, even the slaves, can be externally shut down on the DC outputs using the pin REM-SB of the analog interface. This can be used as some kind of emergency off, where usually a contact (maker or breaker) is wired to this pin on all unit in parallel.

3.11.1.6 Alarms and other problem situations

Master-slave operation, due to the connection of multiple units and their interaction, can cause additional problem situations which don't occur when operating individual units. For such occurrences the following regulations have been defined:

- Generally, if the master loses connection to any slave, it will generate an MSP (master-slave protection) alarm, pop up a message on the screen and switch off its DC output. The slaves will fall back to single operation mode, but also switch off their DC output. The MSP alarm can be deleted by either initializing the master-slave system again. This can be done either in the MSP alarm pop-up screen or in the MENU of the master or via remote control. Alternatively, the alarm is also cleared by deactivating master-slave on the master unit
- If one or more slave units are cut from AC supply (power switch, blackout, supply undervoltage) and come back later, they're not automatically initialized and included again in the MS system. Then the init has to be repeated.
- If the master unit is cut from AC supply (power switch, blackout) and comes back later, the unit will automatically initialize the MS system again, finding and integrating all active slaves. In this case, MS can be restored automatically.
- If multiple units are defined as master the master-slave system can't be initialized

In situations where one or multiple units generate a device alarm like OV, PF or OT following applies:

- Any alarm of a slave is indicated on the slave's display and on the master's display
- If multiple alarms happen simultaneously, the master only indicates the most recent one. In this case, the particular alarms can be read from the slave units displays or via digital interface during remote control or remote supervision.
- All units in the MS system supervise their own values regarding overvoltage, overcurrent and overpower and in case of alarm they report the alarm to the master. In situations where the current is probably not balanced between the units, it can occur that one unit generates an OCP alarm though the global OCP limit of the MS system was not reached. The same can occur with the OPP alarm.

3.11.1.7 Important to know



- *In case one or several units of a parallel system are not going to be used and remain switched off, depending on the number of active units and the dynamics of the operation it may become necessary to disconnect the inactive units from the Share bus, because even when not powered the units can have a negative impact on the Share bus due to their impedance.*
- *Slave devices with a display have an extra option in the configuration page for master-slave which can be activated to switch off the back light of the display after some time. This can be helpful, because after initialization of the MS system the slaves' displays are not needed anymore. The feature itself is, however, identical to the option in the HMI settings.*

3.11.2 Series connection

Series connection of two or multiple devices is basically possible. But for reasons of safety and isolation, some restrictions apply:



- Both, negative (DC-) and positive (DC+) output poles, are coupled to PE via type X capacitors, limiting the max. allowed potential shift (see technical specs for values)
- The Share Bus must not be wired and used!
- Remote sensing must not be used!
- Series connection is only allowed with devices of the same kind and model, i. e. power supply with power supply, like for example PS/PSI 9080-60 2U with PSI 9080-60 2U or PS 9080-60 2U

Series connection in Master-Slave mode isn't supported. It means, all units have to be controlled separately regarding set values and DC output status, whether it's manual control or digital remote control.

According to the limit of the potential shift that comes with series connection, units with a certain nominal output voltage must not be connected in series at all. For example, it's not permissible to connect two or more 360 V models in series, because the DC minus is only isolated up to ± 400 V DC against PE. On the opposite, two 200 V units are allowed to be connected in series.

The analog interfaces of units in series connection are allowed to be wired in parallel, because they are galvanically isolated from the device and the DC output. The grounds (AGND, DGND) on the analog interface are also allowed to be directly connected to PE, like it automatically happens when controlling and directly connecting it to a PC.

3.11.3 Operation as battery charger

A power supply can be used as a battery charger, but with some restrictions, because it misses a battery supervision and a physical separation from the load in form of a relay or contactor, which is featured with some real battery chargers as a protection.

Following has to be considered:

- No false polarity protection inside! Connecting a battery with false polarity will damage the power supply severely, even if it's not powered.
- All models of this series have an internal base load which could, more or less slowly, discharge a connected battery while the DC output is switched off, means while it's not charging. It's thus recommended to disconnect the battery while the device isn't operated.

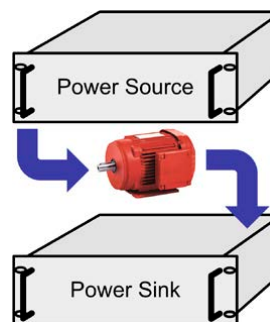
3.11.4 Two quadrant operation (2QO)

3.11.4.1 Introduction

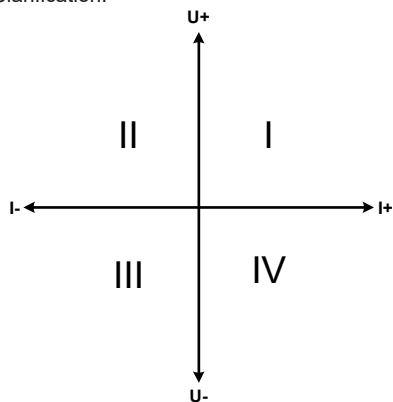
This way of operating refers to the use of a source, in this case a power supply of this series PSI 9000 2U, and a sink, for example a series ELR 9000 electronic load. The source and the sink function alternately in order to test a device, such as a battery, by deliberate charging and discharging as part of a functional or final test

The user can decide whether the system is operated manually or the power supply only as the dominant unit or both devices should be controlled by PC. We recommend to focus on the power supply, which is intended to control the load's behavior regarding voltage and current via the Share Bus connection.

Two quadrant operation is only suitable for constant voltage operation (CV).



Clarification:



A combination of source and sink can only map the quadrants I + II. This means that only positive voltages are possible. The positive current is generated by the source or application and the negative current flows into the load..

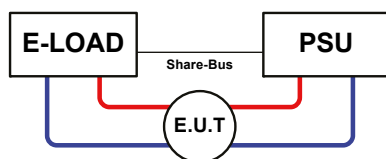
The maximum approved limits for the application should be set in the power supply. This can be done via the interface. The electronic load should preferably be in operating mode CV. The load will then, using the Share Bus, control the output voltage of the power supply.

Typical applications:

- Fuel cells
- Capacitor tests
- Motor driven applications
- Electronic tests where a high dynamic discharge is required.

3.11.4.2 Connecting devices to a 2QO

There are several ways to connect source(s) and sink(s) to make a 2QO:

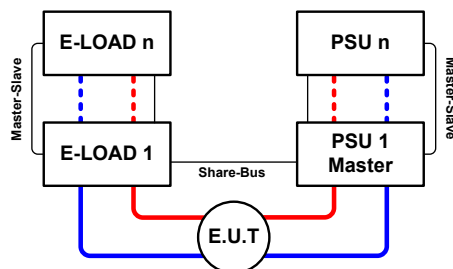


Configuration A:

1 e-load and 1 power supply, plus 1 test object (E.U.T).

This is the most common configuration for 2QO.

The nominal values for U and I of the two devices should match, but at least the voltage. For example, an ELR 9080-170 and PSI 9080-120 2U would match. The system is controlled by the power supply unit, which has to be set to be "Master" in the setup menu, even though there is no master-slave operation running.



Configuration B:

Multiple e-loads and Multiple power supplies, plus 1 test object (E.U.T), for raising the total performance.

The combination of load units and power supply units each create a block, a system with certain power. Here it's also necessary to match the nominal values, but at least the voltage of the two systems, i. e. an 80 V DC input of the loads to a max. 80 V DC output of the power supplies. The max. number of 16 units can't be exceeded. Regarding the Share bus connection, all e-load units have to be slaves, while one of the PSUs has to be set as master.

3.11.4.3 Settings on the devices

Regarding the 2QO operation where the Share bus connection is sufficient, the load unit(s) are required to be set as SLAVE or OFF (unless part of a MS system of loads) in the parameter "Master-slave mode". The option "PSI/ELR system" has to be activated for the master load of a possibly configured MS system of loads.

On any of the power supplies, preferably PSU 1, master-slave mode must be activated (setting "MASTER"), even if there is only one power supply. Also see 3.4.3.1.

For safety of the connected E.U.T / D.U.T and to prevent damage, we recommend to adjust supervision thresholds like OVP, OCP or OPP on all units to the desired levels, which will then switch off the DC output resp. the DC input in case of excess.

3.11.4.4 Restrictions

After all electronic loads have been connected to the Share bus with one power supply as master, they can't limit their input voltage anymore to what you adjust as "U set" on the device. The correct voltage level comes from the master unit and has to be adjusted there.

3.11.4.5 Application example

Charging and discharging a battery with 24 V/400 Ah, using configuration A from above.

- Power supply PSI 9080-120 2U with: $I_{\text{Set}} = 40 \text{ A}$ (1/10 of battery capacity), $P_{\text{Set}} = 5000 \text{ W}$
- Electronic load ELR 9080-170 set to: $I_{\text{Set}} = \text{max.}$ discharging current of the battery (eg. 100 A), $P_{\text{Set}} = 3500 \text{ W}$, plus probably UVD = 20 V with event type "Alarm" to stop discharging at a certain low voltage threshold
- Assumption: battery has a voltage of 26 V at test start
- DC input(s) and DC output(s) of all units switched off



In this combination of devices it's recommended to always switch on the DC output of the source first and then the DC input of the sink.

Part 1: Discharge of the battery to 24 V

Setup: Voltage on the power supply set to 24 V, DC output of power supply and DC input of load activated

Reaction: the e-load will load the battery with a maximum current of 100 A in order to discharge it to 24 V. The power supply delivers no current at this moment, because the battery voltage is still higher than what is adjusted on the power supply. The load will gradually reduce the input current in order to maintain the battery voltage at 24 V. Once the battery voltage has reached 24 V with a discharge current of approx. 0 A, the voltage will be maintained at this level by charging from the power supply.



The power supply determines the voltage setting of the load via the Share bus. In order to avoid deep discharge of the battery due to accidentally setting the voltage on the power to a very low value, it's recommended to configure the undervoltage detection feature (UVD) of the load, so it will switch off the DC input when reaching minimum allowed discharge voltage. The settings of the load, as given via the Share bus, can't be read from the load's display.

Part 2: Charging the battery to 27 V

Setup: Voltage on the power supply set to 27 V

Reaction: the power supply will charge the battery with a maximum current of 40 A, which will gradually reduce with increasing voltage as a reaction to the changing internal resistance of the battery. The load absorbs no current at this charging phase, because it's controlled via the Share bus and set to a certain voltage, which is still higher than the actual battery voltage and the actual output voltage of the power supply. When reaching 27 V, the power supply will deliver only the current needed to maintain the battery voltage.

4. Service and maintenance

4.1 Maintenance / cleaning

The device needs no maintenance. Cleaning may be needed for the internal fans, the frequency of cleanse is depending on the ambient conditions. The fans serve to cool the components which are heated by the inherent power loss. Heavily dirt filled fans can lead to insufficient airflow and therefore the DC output would switch off too early due to overheating or possibly lead to defects.

Cleaning the internal fans can be performed with a vacuum cleaner or similar. For this the device needs to be opened.

4.2 Fault finding / diagnosis / repair

If the equipment suddenly performs in an unexpected way, which indicates a fault, or it has an obvious defect, this can't and must not be repaired by the user. Contact the supplier in case of suspicion and elicit the steps to be taken.

It will then usually be necessary to return the device to the supplier (with or without guarantee). If a return for checking or repair is to be carried out, ensure that:

- the supplier has been contacted and it's clarified how and where the equipment should be sent.
- the device is in fully assembled state and in suitable transport packaging, ideally the original packaging.
- optional extras such as an Interface interface module is included if this is in any way connected to the problem.
- a fault description in as much detail as possible is attached.
- if shipping destination is abroad, the necessary customs papers are attached.

4.2.1 Firmware updates



Firmware updates should only be installed when they can eliminate existing bugs in the firmware in the device or contain new features.

The firmware of the control panel (HMI), of the communication unit (KE) and the digital controller (DR), if necessary, is updated via the rear side USB port. For this the software "EA Power Control" is needed which is included with the device or available as download from our website together with the firmware update, or upon request.

However, be advised not to install updates promptly. Every update includes the risk of an inoperable device or system. We recommend to install updates only if...

- an imminent problem with your device can directly be solved, especially if we suggested to install an update during a support case
- a new feature has been added which you definitely want to use. In this case, the full responsibility is transferred to you.

Following also applies in connection with firmware updates:

- Simple changes in firmwares can have crucial effects on the application the devices are use in. We thus recommend to study the list of changes in the firmware history very thoroughly.
- Newly implemented features may require an updated documentation (user manual and/or programming guide, as well as LabView VIs), which is often delivered only later, sometimes significantly later

4.3 Calibration

4.3.1 Preface

The devices of series PSI 9000 feature a function to readjust the most important output values when doing a calibration and, if required, re-adjustment in case these values have moved out of tolerance. The re-adjustment is limited to compensate small differences of up to 1% or 2% of the max. value. There are several reasons which could make it necessary to readjust an unit: component aging, component deterioration, extreme ambient conditions, high frequent use.

In order to determine if a value is out of tolerance, the parameter must be verified first with measurement tools of high accuracy and with at least half the error of the PSI device. Only then a comparison between values displayed on the PSI device and true DC output values is possible.

For example, if you want to verify and possibly readjust the output current of model PSI 9080-120 2U at the max. 120A, which is stated with a max. error of 0.2%, you can only do that by using a suitable shunt with max. 0.1% error or less. Also, when measuring such high currents, it's recommended to keep the process short, in order to avoid the shunt heating up too much. It's furthermore recommended to use a shunt with at least 25% reserve.

When measuring the current with a shunt, the measurement error of the multimeter on the shunt adds to the error of the shunt and the sum of both must not exceed the max. error of the device under calibration.

4.3.2 Preparation

For a successful calibration and readjustment, a few tools and certain ambient conditions are required:

- A measurement device (multimeter) for voltage, with a max. error of half the PSI's voltage error. That measurement device can also be used to measure the shunt voltage when readjusting the current
- If the current is also going to be calibrated: a suitable DC current shunt, ideally specified for at least 1.25 times the max. output current of the PSI and with a max. error that is half or less than the max. current error of the PSI device
- Normal ambient temperature of approx. 20-25°C
- Warmed up PSI unit, which has been run for at least 10 minutes under 50% power
- An adjustable load, such as an electronic load, which is capable of consuming at least 102% of the max. voltage and current of the PSI device

Before you can start calibrating, a few measures have to be taken:

- Let the PSI device warm up in connection with the voltage / current source
- In case the remote sensing input is going to be calibrated, prepare a cable for the remote sensing connector to DC output, but leave it yet unconnected
- Abort any form of remote control, deactivate master-slave mode, deactivate resistance mode (R mode)
- Install the shunt between PSI device and load and make sure the shunt is cooled somehow
- Connect external measurement device to the DC output or to the shunt, depending on whether the voltage is going to be calibrated first or the current

4.3.3 Calibration procedure

After the preparation, the device is ready to be calibrated. From now on, a certain sequence of parameter calibration is important. Generally, you don't need to calibrate all three parameters, but it's recommended to do so.

Important:



When calibrating the output voltage, the remote input "Sense" on the rear of the device has to be disconnected.

The calibration procedure, as explained below, is an example with model PSI 9080-120 2U. Other models are treated the same way, with values according to the particular PSI model and the required load.

4.3.3.1 Calibrating the set values

► How to calibrate the voltage

1. Connect a multimeter to the DC output. Connect a load and set its current to approx. 5% of the nominal current of the power supply, in this example ≈6 A, and 0 V (if the load is electronic).
2. In the display tap MENU, then „General Settings“, then go down to “Calibrate device” and then tap **START**.
3. In the next screen select: **Voltage calibration**, then **Calibrate output val.** and **NEXT**. The power supply will switch the DC output on, set a certain output voltage and show the measured value as **U-mon**.
4. The next screen requests you to enter the measured output voltage from the multimeter at **Measured value=**. Enter it using the keypad, that appears when tapping the value. Assure yourself the value is correct and submit with **ENTER**.
5. Repeat point 4. for the next three steps (total of four steps).



► How to calibrate the current

1. Set the load to approx. 102% nominal current of the PSI device, for the sample model with 120 A this would be 122.4 A, rounded to 123 A.
2. In the display, tap MENU, then „General Settings“, then go down to “Calibrate device” and then tap **START**.
3. In the next screen select: **Current calibration**, then **Calibrate output val.** and **NEXT**. The device will switch on the DC output, set a certain current limit while loaded by the load/sink and show the measured output current as **I-mon**.
4. The next screen requests you to enter the output current **Measured value=** measured with the shunt. Enter it using the keypad, assure yourself the value is correct and submit with **ENTER**.
5. Repeat point 4. for the next three steps (total of four steps).

4.3.3.2 Calibrating the remote sensing

In case you are generally using the remote sensing feature, it's recommended to also calibrate this feature for best results. The procedure is identical to the calibration of voltage, except for it requires to have the sensing connector (Sense) on the rear to be plugged and connected with correct polarity to the DC output of the PSI.

► How to calibrate the output voltage for remote sensing

1. Connect a load and set its current to approx. 5% of the nominal current of the power supply, in this example ≈6 A, and 0 V (if the load is electronic). Connect a multimeter to the DC terminal of the load and connect the remote sensing input (Sense) to the DC terminal of the load with correct polarity.
2. In the display, tap MENU, then „General Settings“, then go down to “Calibrate device” and then tap **START**.
3. In the next screen select: **Sense volt. cali.**, then **Calibrate output val.** and **NEXT**.
4. The next screen requests you to enter the measured sensing voltage **Measured value=** from the multimeter. Enter it using the keypad, that appears when tapping the value. Assure yourself the value is correct and submit with **ENTER**.
5. Repeat point 4. for the next three steps (total of four steps).

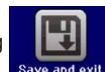
4.3.3.3 Calibrating the actual values

Actual values of output voltage (with and without remote sensing) and output current are calibrated almost the same way as the set values, but here you don't need to enter anything, just confirm the displayed values. Please proceed the above steps and instead of “Calibrate outp. value” select “Calibrate actual val.” in the sub menus. After the device shows measured values on display, wait at least 2s for measured value to settle and then tap NEXT until you are through all steps.

4.3.3.4 Save and exit

After calibration you may furthermore enter the current date as "calibration date" by tapping  in the selection screen and enter the date in format YYYY / MM / DD.

Last but not least save the calibration data permanently by tapping



Leaving the calibration selection menu without tapping "Save and exit" will discard calibration data and the procedure would have to be repeated!

5. Contact and support

5.1 Repairs

Repairs, if not otherwise arranged between supplier and customer, will be carried out by the manufacturer. For this the device must generally be returned to the manufacturer. No RMA number is needed. It's sufficient to package the equipment adequately and send it, together with a detailed description of the fault and, if still under guarantee, a copy of the invoice, to the following address.

5.2 Contact options

Questions or problems with operation of the device, use of optional components, with the documentation or software, can be addressed to technical support either by telephone or e-Mail.

Headquarter	e-Mail	Telephone
EA Elektro-Automatik GmbH Helmholtzstr. 31-37 41747 Viersen Germany	Technical support: support@elektroautomatik.de All other issues: ea1974@elektroautomatik.de	Switchboard: +49 2162 / 37850 Support: +49 2162 / 378566



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Squirrel 2020 series

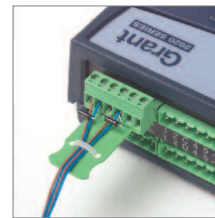
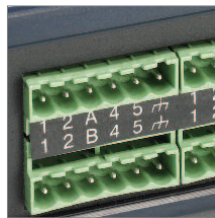
Powerful data loggers for standard and high speed applications

Overview

The Squirrel 2020 series are high performance universal data loggers packed with powerful features to provide great flexibility to handle a wide range of routine and demanding applications.

Hand-held and lightweight, the Squirrel 2020 models are easy, fast and convenient to use – either as stand-alone loggers or as PC-linked data acquisition systems in industrial and scientific research and quality assurance applications.

Twin processors, multiple 24-bit analogue-to-digital converters, up to 16 universal channels and a choice of communications methods ensure that the Squirrel 2020 series provides state-of-the-art data logging and communication capability for sophisticated applications needs.



Key features

- » Fully configurable via the integrated keypad
- » 8 true differential or 16 single ended universal analogue inputs for voltage, current or resistance
- » Analogue inputs can be used with thermistors, thermocouples, 2,3 or 4 wire RTD temperature sensors and 4-20mA signals
- » Logging rates of up to 100Hz on up to 2 channels (2F8 only)
- » Ethernet (2F8 only), USB and RS232 communication ports
- » Large non-volatile internal memory storage for up to 14 million readings
- » Removable MMC / SD card

- » Sensor power and FET outputs for use with external devices
- » Clear 128*68 dot graphical LCD display

Analogue inputs supported

- » Thermistors
- » Thermocouples
- » Pt100 / Pt1000 (maximum of four 3- or 4-wire Pt100 / Pt1000 sensors — model 2F8 only)
- » Voltage
- » Current
- » Resistance

The Squirrel 2020 series comprises two models:

- » **Squirrel 2020 – 1F8**
 - Up to 20 readings per second on 1 channel
- » **Squirrel 2020–2F8 (high speed model)**
 - Up to 100 readings per second on 2 channels
 - In-built Ethernet connectivity
 - Up to four 3- or 4-wire Pt100 / Pt1000 sensor inputs



- » Up to 16 universal inputs
- » High precision (0.05% of reading + 0.025% of range)
- » Advanced data management to MMC/SD card or PC
- » Flexible communications (USB, Ethernet, RS232)
- » High speed option (100Hz)



Communications

Ethernet (2F8 only), USB and RS232 serial ports are inbuilt. This allows simple connection to either a PC based TCP/IP network, a wireless to PC connection or to a GSM modem for remote data downloading. This flexibility enables global data access and retrieval as well as complete system integration of the SQ2020 series into complex and critical applications

Multiple configurations stored in the logger:

Up to six logger configurations (channel type, names, logging speeds, triggers etc.) together with the current configuration can be held in the logger's internal memory. Additional configuration settings can also be loaded from the external MMC/SD memory card. This allows the operator to quickly and easily switch between logger configurations without the need for a PC

Software configuration via SquirrelView:

The SquirrelView software (supplied with the SQ2020 series data loggers) allows logger configuration, data download and export whilst giving the user full control over SQ2020. The optional SquirrelView Plus gives the user access to many advanced data analyses and archiving/transfer features. Refer to SquirrelView data sheet for specifications.

Concurrent sampling:

The SQ2020 series uses multiple analogue and digital converters that enables true concurrent sampling and logging. It Allows the user to configure a channel to log at a rate of 100Hz(20Hz on 1F8) whilst retaining different sample speeds on the other channels. Ideal for measuring dynamic parameters that change at different rates such as temperature and pressure.

Capabilities

- » Create complex schedules of logging rates, triggers and alarm outputs
- » Scale and view readings in real time on the integral display or on a PC running SquirrelView
- » Select logging rates up to 100 readings per second on up to 2 channels (20Hz maximum on Squirrel model 2020-1F8)
- » Derive up to 16 calculated (virtual) channels from real input channels using mathematical functions

Applications



Manufacturing



Biological Sciences



Medical Research

Squirrel 2020 Technical Specifications

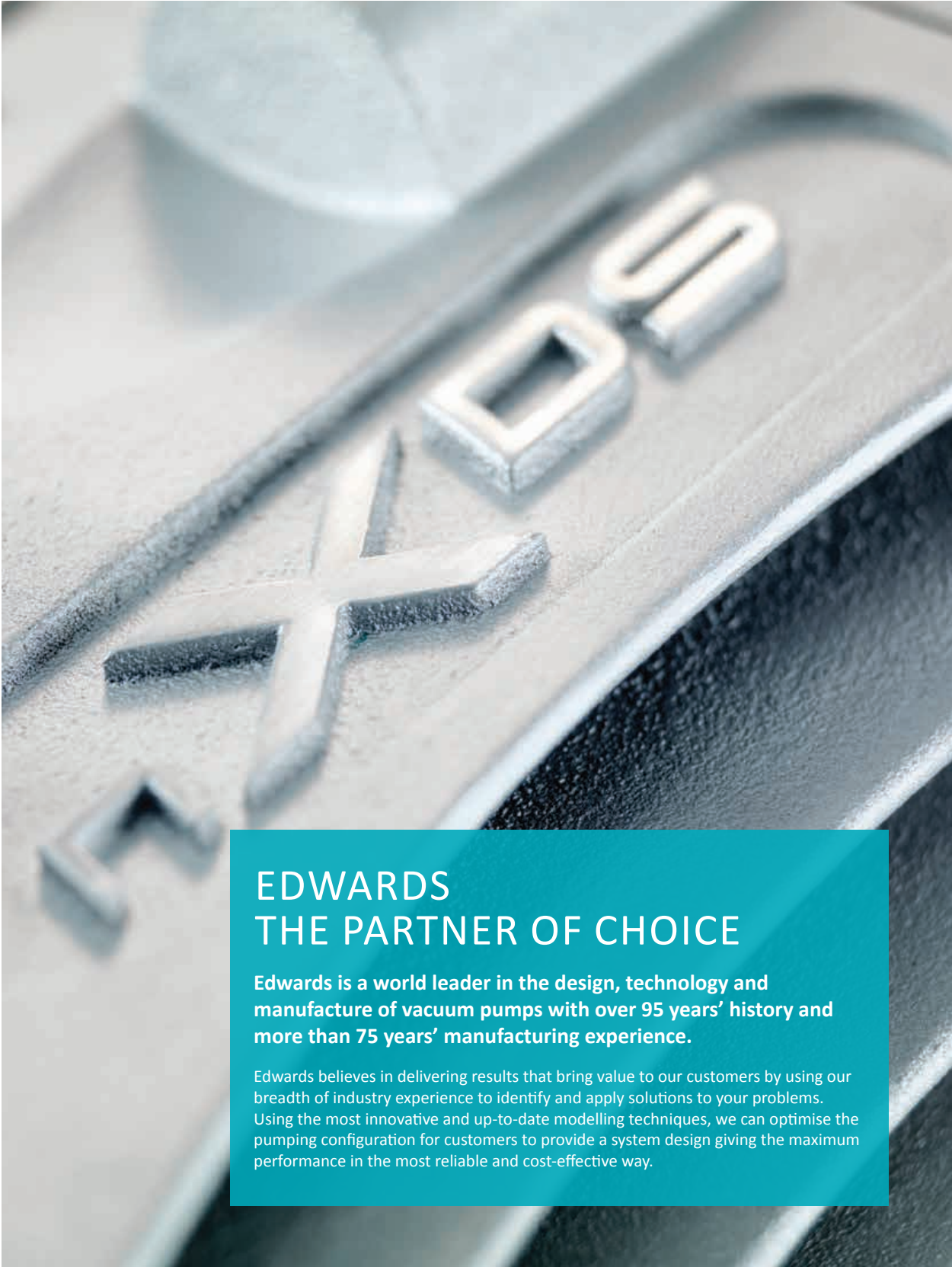
	SQ2020-1F8	SQ2020-2F8
Analogue input channel options	Analogue to digital converters: 1 Differential: 8 Single Ended*: 16 3 or 4 wire: 0	Analogue to digital converters: 2 Differential: 8 Single Ended*: 16 3 or 4 wire: 4
Additional channels * Please refer to our Technical Note for the configuration of these inputs	Pulse: (2 x fast-64kHz) & (2 x slow - 100Hz) Event/digital: 8 state inputs or 1 x 8 bit binary Single Ended*: 2 3 or 4 wire: 1 temperature	Pulse: (2 x fast-64kHz) & (2 x slow - 100Hz) Event/digital: 8 state inputs or 1 x 8 bit binary Single Ended*: 2 3 or 4 wire: 1 temperature
Logging speed	20 readings / sec on 1 channel	100 readings / sec on 2 channels
Communication	Standard: RS232 (Auto bauding to 115200 baud) USB 1.1 & 2.0 compatible External options: GSM, Wifi and PSTN Modems	Standard: RS232 (Auto bauding to 115200 baud) USB 1.1 & 2.0 compatible Ethernet 10/100 base TCP/IP. Requires external power supply. External options: GSM, Wifi and PSTN Modems
Analogue inputs	Accuracy: (at 25°C) voltage and resistance ($\pm 0.05\%$ readings + 0.025% range) Common mode rejection: 100dB Linearity: 0.015% Input impedance: > 1M Ω Series mode line rejection: 50/60Hz 100dB	
Analogue - digital conversion	Type: Sigma - Delta Resolution: 24bit Sampling rate: up to 10, 20* or 100* readings per sec. per ADC. No 100Hz on 1F8 (* with mains rejection off)	
Thermistor Ranges	Y & U-type: - 50 to 150°C Pt100/ Pt1000: - 200 to - 850°C (2 wire only on 1F8) Customer specific thermistor range	
Thermocouple Ranges; Differential and Single Ended	K-type: - 200 to 1372°C T-type: - 200 to 400°C N-type: - 200 to 1300°C	R-type: - 50 to 1768°C S-type: - 50 to 1768°C J-type: -200 to 1200°C B-type: 250 to 1820°C C-type: 0 to 2320°C D-type: 0 to 2320°C
Working environment	- 30 to 65°C, RH up to 95% (non-condensing)	
Voltage Ranges; Differential and Single Ended	- 0.075 to 0.075V, - 0.15 to 0.15V, - 0.3 to 0.3V, - 0.6 to 0.6V, 0.6 to 1.2V, 0.6 to 2.4V, - 3.0 to 3.0V, - 6.0 to 6.0 V, -6.0 to 12.0V, - 6.0 to 25.0V	
High voltage input range	4.0 to 20.0V, 4.0 to 40.0V, 4.0 to 60.0 (max 2 may be selected)	
Current Ranges, Differential (Requires external 10 Ω shunt)	-30.0 to 30.0mA, 4 to 20mA	
Resistance Ranges, all 2 wire	0.0 to 1250 Ω , 0.0 to 5000 Ω , 0.0 to 20000 Ω , 0.0 to 300000 Ω	
Resistance range 3 and 4 wire (2F8)	0.0 to 500 Ω , 0.0 to 4000 Ω	
Digital/Alarm Outputs	4 open drain FET (18V 0.1A)	
Memory	Internal: up to 128M (up to 14 million readings) External: Up to 1Gb - removable MMC/ SD (for transferring internal memory and storing setups only)	
Internal memory modes	Stop when full or overwrite	
Calculated channels	Up to 16 virtual channels derived from physical input channels	
Resolution	Up to 6 significant digits	
Display/Keypad	128*64 dot graphical display, 4 button keypad	
Power supply	Internal: 6 x AA alkaline batteries External: 10-18VDC. Reverse and polarity and over-voltage protected	
Power consumption@ 9V	Sleep mode: 600 μ A Logging: 40 - 80 mA	
Power output for external device	Regulated 5VDC at 50mA or logger supply voltage at 100mA	
Time and Date	In-built clock in 3 formats	
Programming / logger setup	Squirrelview or Squirrelview Plus Software	
Dimensions (w x d x h), weight	235 mm x 175 mm x 55 mm, 1.2 kg, enclosure material ABS	

Please note: SQ2020 is supplied with software, manual, USB cable, wall bracket, batteries and 4 current shunt resistors.

CAS Dataloggers | 8437 Mayfield Road | Chesterland, OH 44026
(800) 956-4437
sales@dataloggerinc.com
www.DataLoggerInc.com

nXDS DRY SCROLL PUMPS





EDWARDS THE PARTNER OF CHOICE

Edwards is a world leader in the design, technology and manufacture of vacuum pumps with over 95 years' history and more than 75 years' manufacturing experience.

Edwards believes in delivering results that bring value to our customers by using our breadth of industry experience to identify and apply solutions to your problems. Using the most innovative and up-to-date modelling techniques, we can optimise the pumping configuration for customers to provide a system design giving the maximum performance in the most reliable and cost-effective way.

THE INTELLIGENT CHOICE

Edwards nXDS is the great new shape of dry vacuum pumping

The nXDS has taken scroll vacuum technology to the next level. Improved performance, exceptional pumping capability, quiet operation and extended service intervals make nXDS the ultimate dry choice.

Quiet operation

Better working environment

Hermetically sealed for a lubricant-free vacuum environment

Contamination free process and no oil to dispose of

Low power consumption

Low cost of ownership

Intelligent and easy to use controls

Flexibility of operation

Superior vapour handling

Wider range of applications

Long service intervals

Maximised up-time

Applications

You can be assured Edwards has the application expertise and the RV pump or integrated system solution to meet your needs.

Mass spectrometry

- GCMS, LCMS, ICPMS, MALDI, RGA, surface science, leak detectors

Electron microscopy

- TEM, SEM, sample coatiers

Sample preparation

- Gel dryers, glove boxes, rotary evaporators, centrifuges

Research and development

- Chamber evacuation, coating systems, turbopump backing

High energy physics

- Beam lines, accelerators, mobile pump carts, turbopump backing, laser evacuation

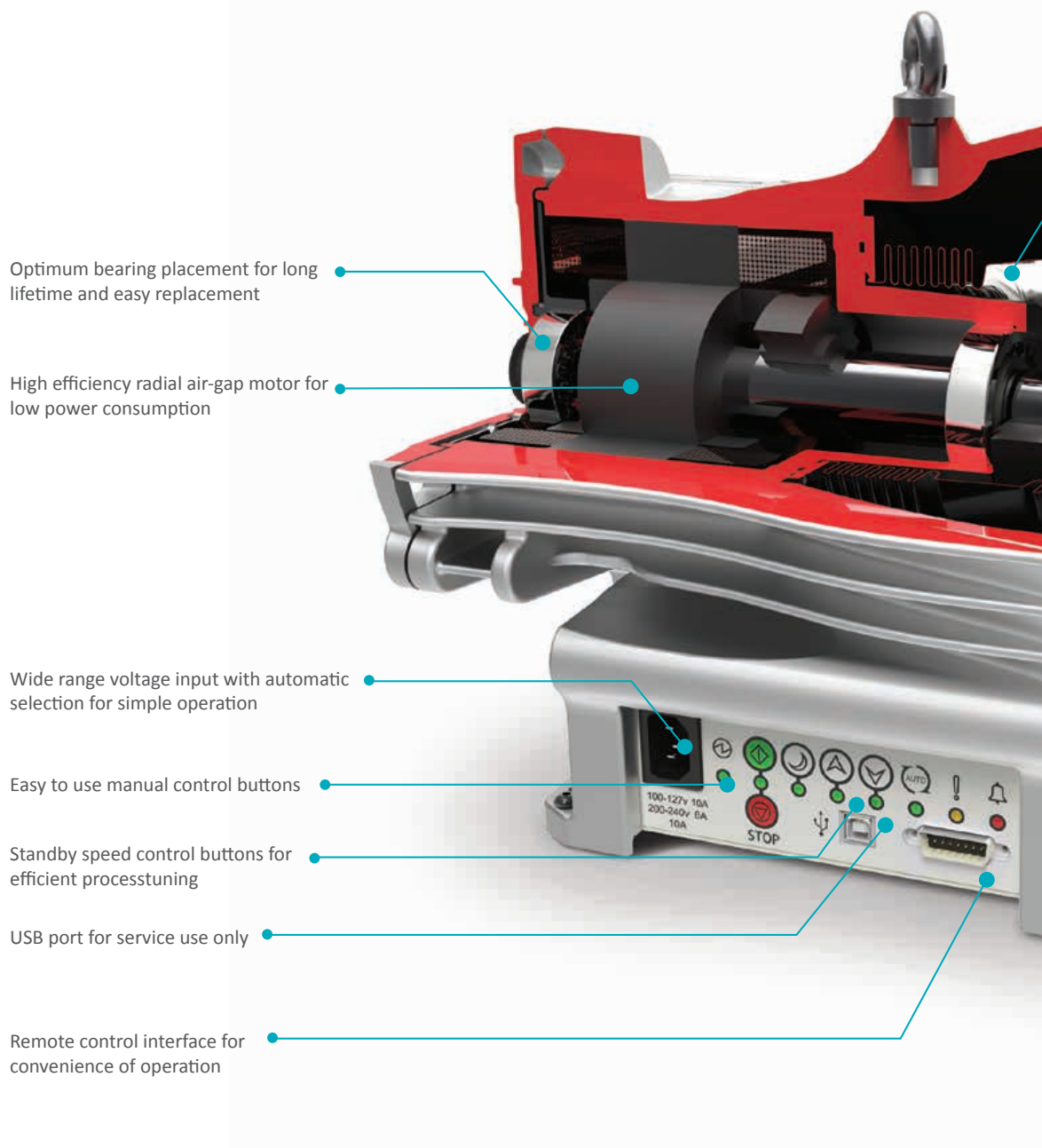
Industrial

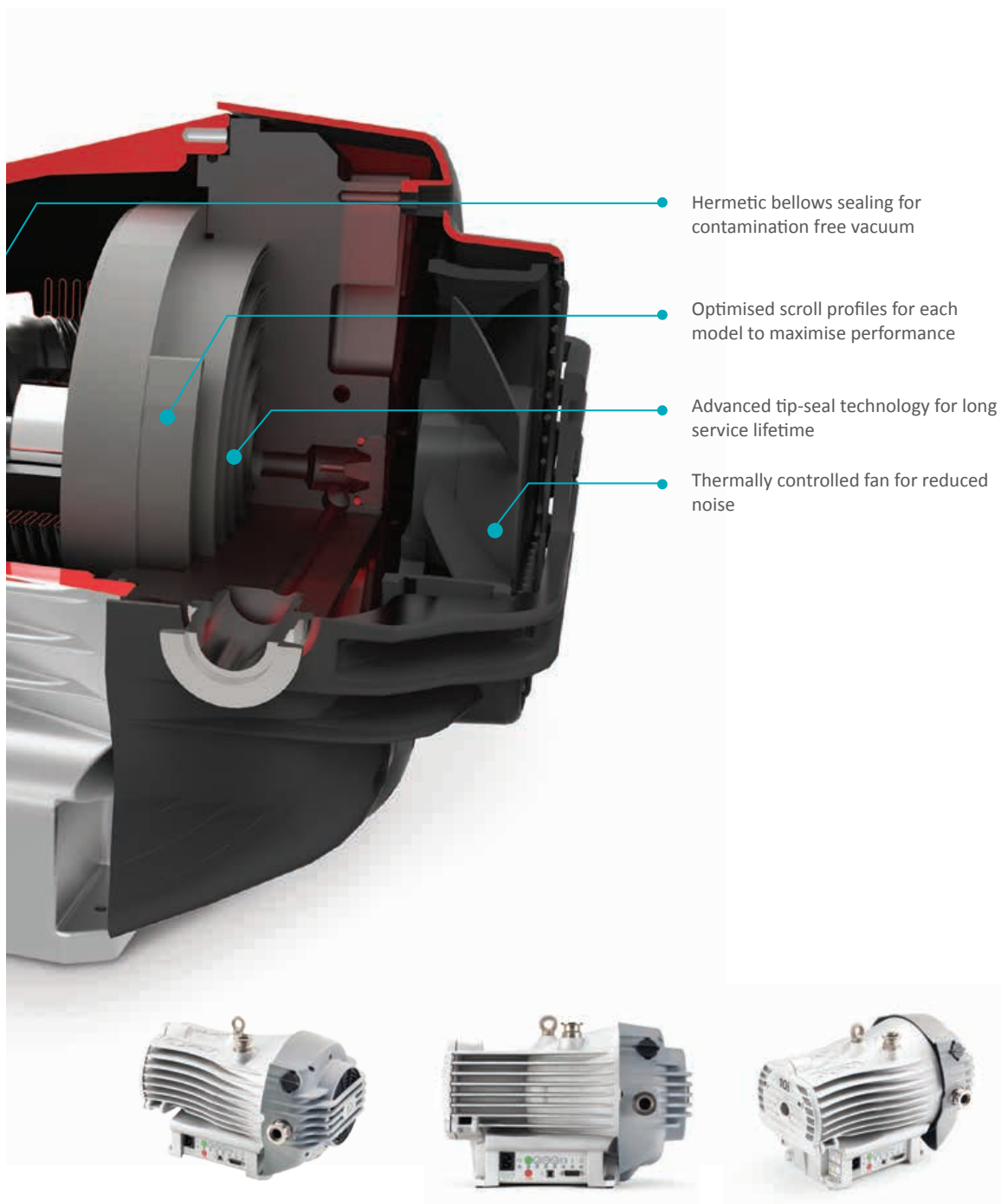
- Gas recovery and recirculation, glove boxes, brake line and air conditioning evacuation, coating systems, freeze drying, gas bottle filling/emptying, refrigeration system manufacture, degassing/curing (oil, epoxy resin)

Chemical

- Gel dryers, glove boxes, rotary evaporators, centrifuges, solvent recovery, distillation/extraction/filtration

nXDS scroll pump sectional view





Performance

nXDS has been designed to combine the latest advances in scroll technology with an intelligent drive coupled with the long established, truly dry, hermetically sealed mechanism of the XDS series.

Class leading pumping speeds are an improvement over existing XDS models and, with the drive, are of course consistent worldwide. Likewise, ultimate vacuum pressures which are below 10^{-2} mbar are now comparable with those of oil-sealed rotary vane pumps – without the inconvenience of oil.

Hermetic sealing ensures that the vacuum environment is not contaminated by bearing lubricant and, conversely, the bearings are not contaminated by any process gas being pumped.

Quiet running

The modern laboratory is often a busy place with many other appliances running, all contributing to the background noise. With its low noise power level of 52 dB(A), the nXDS pump makes only a very small contribution to the total noise. This level is up to twenty times less than those of competitor products.

nXDS is available in four sizes:

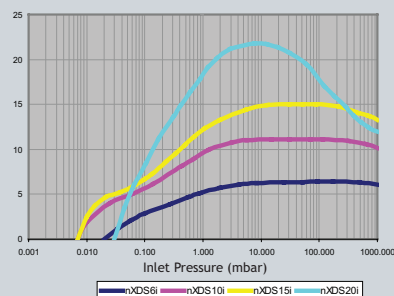
- nXDS6i
- nXDS10i
- nXDS15i
- nXDS20i

Other variants

For more aggressive applications, 'C' Variants are available which feature Chemraz® internal valves and stainless steel fittings for extra protection from the pumped media.

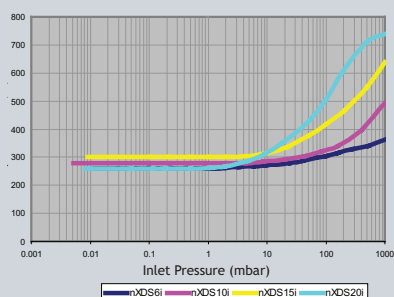
R variants are available for specialist applications such as gas recirculation, rare gas pumping and recovery or other applications where the dilution of the pumped gas is undesirable, or where sealing is integral to minimising potential gas loss.

Pumping Speed (m³/h)



Summary of pump speeds

Power W



Summary of input powers

Pump controller

The advanced controller allows for several modes of control:

Manual

Push button START, STOP and STANDBY. Accurate speed control of 1% of maximum running speed.

Parallel remote

From your own control system via the 15 way d-sub connector giving the same START, STOP and STANDBY with the option of analogue speed control.

Serial communication remote

Option of either RS232 or RS485 with a choice of Edwards' proprietary 'DX' protocol or industry standard Modbus protocol. A USB port has been included for service use only.

The pump controller is able to accept voltages from 100-127 and 200-240V (+/- 10%) without the need for intervention.



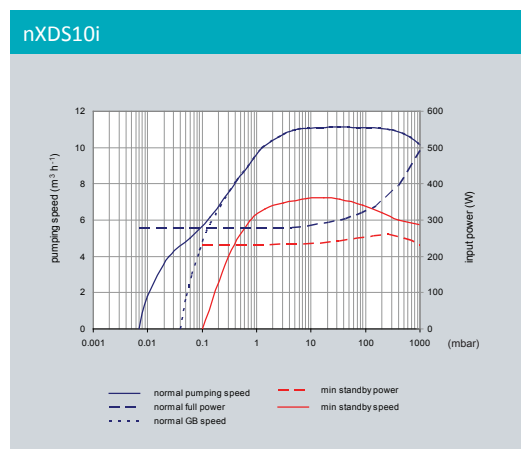
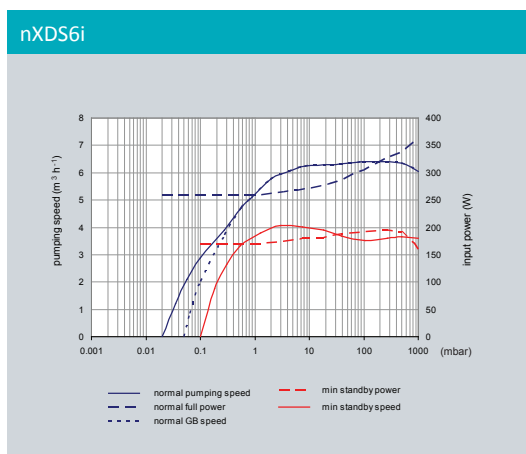
Technical data

		nXDS6i	nXDS10i	nXDS15i	nXDS20i
Nominal rotational speed		1800 rpm			
Displacement	m ³ h ⁻¹ (ft ³ min ⁻¹)	6.8 (4.0)	12.7 (7.5)	17.1 (10.1)	28.0 (16.5)
Peak pumping speed	m ³ h ⁻¹ (ft ³ min ⁻¹)	6.2 (3.6)	11.4 (6.7)	15.1 (8.9)	22.0 (13.0)
Ultimate vacuum (total pressure)	mbar (Torr)	0.020 (0.015)	0.007 (0.005)	0.007 (0.005)	0.030 (0.022)
Minimum standby rotational speed	rpm	1200			
Speed control resolution (percentage of full rotation speed)	%	1			
Max inlet pressure for water vapour	mbar	35	35	35	20
Max water vapour pumping rate	gh ⁻¹	110	145	280	220
Maximum continuous inlet pressure	mbar	200	200	200	50
Voltage input	V	100-127, 200-240 (+/-10%)			
Voltage frequency	Hz	50/60			
Motor power 1-ph*	W	260	280	300	260
Power connector 1-ph		IEC EN60320 C13			
Recommended fuse		10A, 250V a.c. rms			
Weight	kg (lb)	26.2 (58)	25.8 (57)	25.2 (56)	25.6 (56)
Inlet flange		NW25			
Exhaust flange		NW25			
Noise level**	dB(A)	52			
Vibration at inlet flange	mms ⁻¹ (rms)	< 4.5			
Leak tightness (static)	mbar ls ⁻¹	< 1x10 ⁻⁶			
Operating temperature range	°C (°F)	+10 to +40 (+41 to +104)			

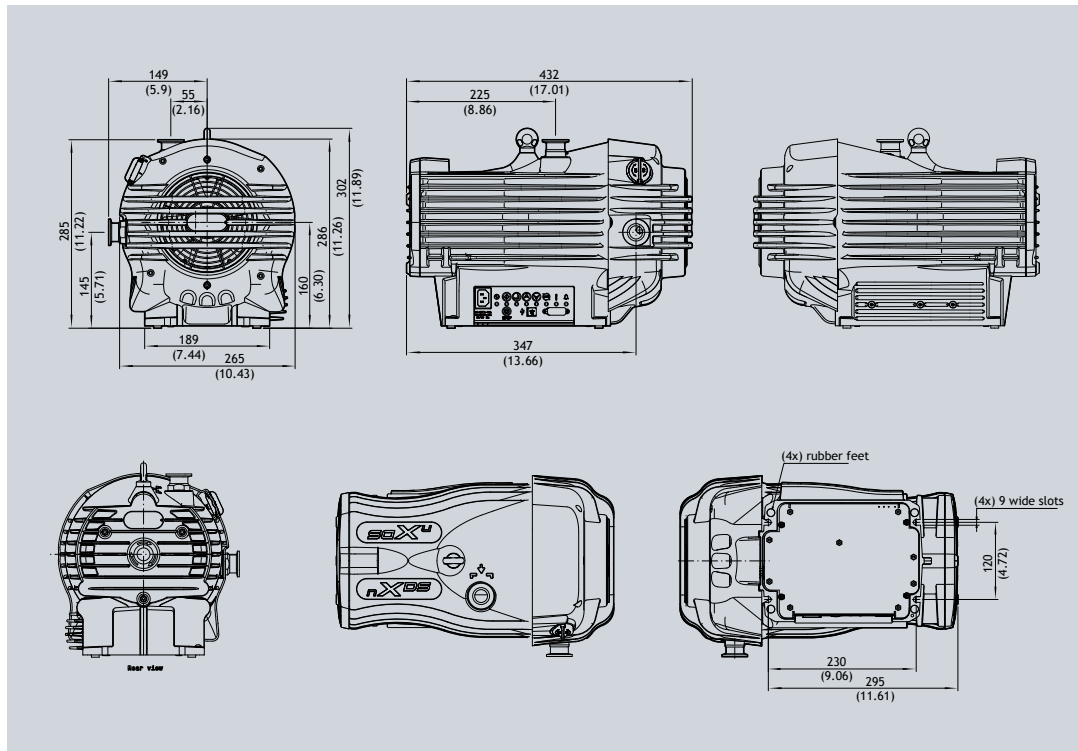
* Typical. See graphs on page 6.

** For low fan speed, typical at ultimate end when load/ambient conditions allow.

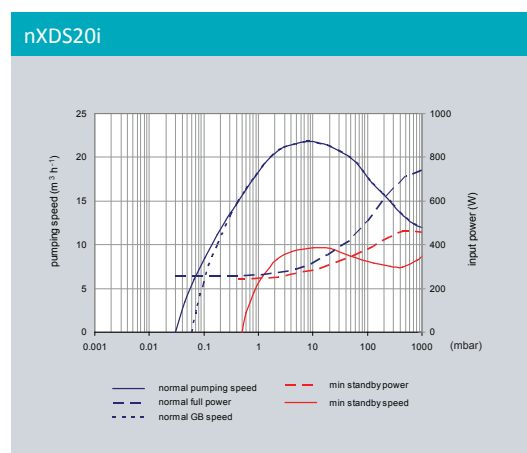
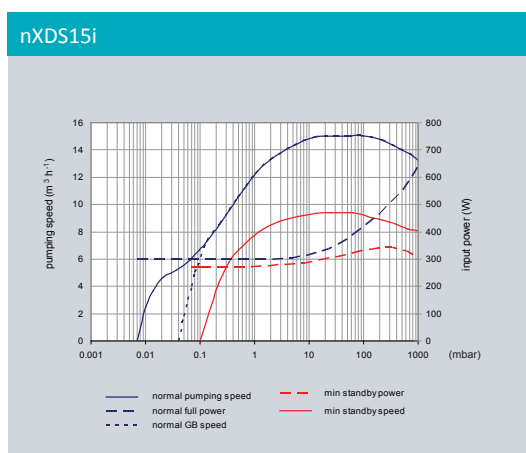
Pumping speed and power curves



Dimensions



All variants are the same Dimensions in mm (in)

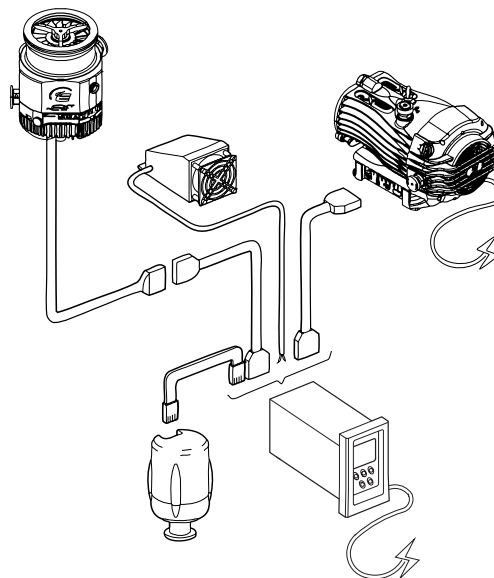


Controllers

The TIC (Turbo and Instrument Controller) automatically recognises the nXDS pump when connected to the backing pump connector as the controller adopts serial communications mode when connected to the nXDS. There is no need to use a relay box to interface to nXDS.

Speed control and pump run hours etc can be readily accessed from the display. The TIC can also control an nEXT turbopump plus, up to three gauges at the same time as a nXDS pump.

Customers already owning a TIC can upgrade their software to enable interfacing to nXDS.



Ordering information

Standard product		Corrosion resistant (C) variants		(R) Variants without gas ballast	
nXDS6i	A735 01 983	nXDS6iC	A735 02 983	nXDS6iR	A735 03 983
nXDS10i	A736 01 983	nXDS10iC	A736 02 983	nXDS10iR	A736 03 983
nXDS15i	A737 01 983	nXDS15iC	A737 02 983	nXDS15iR	A737 03 983
nXDS20i	A738 01 983	nXDS20iC	A738 02 983	nXDS20iR	A738 03 983

Spares and accessories

TIC (Turbo) 200W	D397 12 000
TIC (Turbo and Instruments) 200W	D397 22 000
Gas Ballast Adaptor Kit	A735 01 809
Gas Ballast Adaptor Blank (nXDS)	A735 01 806
Gas Ballast Adaptor (nXDS) 0.25 mm hole	A735 01 806
Gas Ballast Adaptor Blank (nXDS) no restriction	A735 01 806
Silencer (NW25)	A505 97 000
Inlet/Outlet Filter 5µm (NW25/NW25)	A505 97 805
Tip Seal Service Kit	A735 01 801
Bearing Service Kit	A735 01 802

Electrical Supply Cable 2m, UK	A505 05 000
Electrical Supply Cable 2m, North Europe	A505 06 000
Electrical Supply Cable 2m, North America/Japan	A505 07 000
Electrical Supply Cable 2m, No plug	A505 08 000
TIC interface cable 1.0m	D397 00 835
TIC interface cable 2.0m	D397 00 836
TIC interface cable 5.0m	D397 00 837

Service

Your business success depends on maximum equipment uptime and minimum total cost of ownership, and we constantly strive to support those objectives. As a global leader in vacuum technology and processes, we understand how vacuum pumps and systems perform in real life. Our wide portfolio of services is designed with you in mind: to help keep your processes and equipment running in the most economical and environmentally efficient manner.

Services include:

- Overhaul and repair using genuine Edwards OEM parts
- OEM spares and kits available for immediate despatch
- Remanufactured products available for cost-effective expansion and backups
- Global network of expert field service engineers available to respond quickly to unexpected equipment failures
- Extended warranty, to help manage the cost of the unexpected

Our Expert Advantage Service Plans provide you with the on-going support necessary to continuously improve your operational efficiency and meet your business objectives. As service offerings may vary slightly from product to product, please contact your Edwards representative to discuss your specific requirements.





GLOBAL CONTACTS

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Vita

Tyler Steiner grew up in Hazleton, Pennsylvania where he completed his primary and secondary schooling. Following high school, Tyler went on to pursue a higher education degree from the Pennsylvania State University. He obtained a Bachelor of Science degree in Nuclear Engineering with a minor in Planetary Science and Astronomy. Prior to completion of his undergraduate program, Tyler decided his next step would be graduate school. He chose to pursue a Doctor of Philosophy degree in Nuclear Engineering from the University of Tennessee, Knoxville. His research interests include designing, building, and testing experiments for nuclear and/or space purposes.