In-Pile High-Temperature Testing Vehicle for Nuclear Thermal Rocket Instrumentation, Materials, and Fuel Testing

Brandon Wilson[1], Tyler Steiner[2], Emily Hutchins[2], Lawrence Heilbronn[2] and N. Dianne Bull Ezell[1]

[1]*Oak Ridge National Laboratory, Oak Ridge, TN, 37830*
[2]*University of Tennessee-Knoxville, Knoxville, TN, 37996*

wilsonba1@ornl.gov, 330-605-2190

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NASA is collaborating with industry and national laboratory partners on nuclear thermal propulsion (NTP) and nuclear electric propulsion for enabling crewed missions to Mars in the 2030s.[1] Within the Mars Design Reference Architecture 5.0, NASA has identified NTP as the preferred propulsion option.[2] Certifying a NTP rocket for a Mars mission will require extensive irradiation studies to understand the impact of neutron and gamma radiation on typical rocket components. Oak Ridge National Laboratory and the University of Tennessee, Knoxville Nuclear Engineering Department developed a nuclear test bed enabling materials, sensors, and fuel to be studied and certified in prototypic NTP environments.

I. INTRODUCTION

Nuclear thermal rockets create an ultra-harsh environment in which materials and sensors have rarely, if ever, been experimentally tested. The nuclear thermal propulsion (NTP) environment includes a high neutron and gamma radiation flux, temperature levels exceeding 2000°C, and corrosive liquid hydrogen. Degradation, corrosion, and failure of materials in this environment are a major concern. To identify and certify materials and sensors that can survive this environment, experimental testing of these items must be performed to qualify the rocket for human transportation. Currently, there is no testing facility that can produce these environments simultaneously, and only a few facilities that can reproduce two of the three major components of the environment (high radiation, >2000°C temperatures, flowing hydrogen). In the 1960's, NTP rocket engines were built and tested in the Nevada desert, but modern-day procedures would prevent a similar 'build-test-evaluate-rebuild' style approach to NTP engine development.[3] To address this gap and to facilitate development and certification of materials and sensors for a nuclear thermal rocket, Oak Ridge National Laboratory (ORNL) is developing a testing platform that will be able to closely replicate the environment of the rocket. The In-Pile Steady-State, Extreme Temperature Testbed (INSET) is a high-temperature materials and sensor testing vehicle designed to be placed in a research reactor to produce high-temperature radiation environments (with current development to add flowing hydrogen through it). Using The Ohio State Research Reactor (OSURR), INSET is designed to provide a one-of-a-kind environmental testing platform for certifying and testing materials and sensors at a relatively low cost. This paper discusses this unique testing vehicle, its current upgrades, and the upcoming experiments planned for helping certify and raise the TRL levels for NTP components.

II. EXPERIMENTAL DESIGN

II.A. Current Design

INSET is designed to be an inexpensive vacuum furnace compatible with a reactor environment. Motivation for the current design of INSET can be found in the work by Steiner et al. Ref 4. INSET uses direct current (DC) to resistively heat a filament (housed inside a vacuum tight vehicle) to produce high temperatures. Test items are placed inside the vehicle and can be exposed to high temperatures in-pile (in a nuclear reactor) and out-of-pile. The unique capability to generate elevated temperatures in a reactor environment enables INSET to serve as a testbed for NTP interests.

INSET can be divided into two major regions: the semi-custom multipurpose flange (MPF) and the body (shown in Figures 1 and 4, respectively). The MPF is made from aluminum-6061 and has an outer diameter of 8 in. The MPF consists of four 1.33 in. ConFlat® (CF) passthroughs and one 2.75 in. CF passthrough. The 2.75 in. passthrough is used for electrical power delivery into the system. The power passthrough is rated up to 5 kV and 30 A. The 1.33 in. passthroughs are designated for thermocouples, gas removal, and gas introduction (when applicable). The MPF is secured to the body through an 8 in. CF interface and an aluminum gasket. The CF flanges are used to ensure a reliable seal. A vacuum pump is used to remove gas from the system and create a vacuum environment. As such, the primary heat transfer mechanism within INSET is radiative heat transfer.

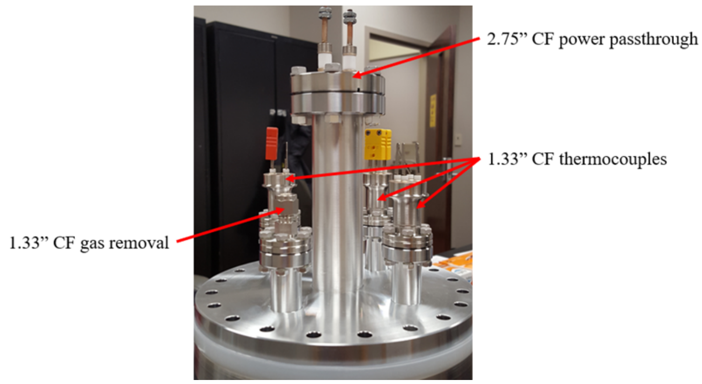

Fig. 1: INSET multipurpose flange.

The body of INSET consists of an 8 in. outer diameter CF blank secured to the bottom of an 8 in. outer diameter CF pipe nipple. The CF pipe nipple is 13 in. tall with an inner diameter of 6 in. The MPF connects to the top of this assembly. All structural components are made from aluminum-6061 to mitigate activation during irradiation. An out-of-pile twin of INSET (called OUTSET) has been constructed using 304L stainless steel to enable inexpensive benchtop testing.

The body of INSET houses the insulation and the resistive heater. INSET uses SIGRATHERM® GFA5 graphite felt as the resistive heater filament. When electrical power is driven to this filament, it generates elevated temperature levels through Ohmic heating. The graphite filament is housed within a ceramic crucible to structurally contain the filament while electrically insulating nearby thermocouples. Thermocouples are used to monitor the heater temperature and are housed in a Poco graphite shell that is slip-fitted over the ceramic crucible containing the filament. Figure 2 shows the heater assembly in both a virtual and physical capacity. Current is driven to this heater assembly using molybdenum tubing. This tubing connects the heater filament to the power supply through the MPF. An image of the circuit is shown in Figure 3, in which the dashed arrows along the Mo tubing represent a possible current flow path. The dashed line within the heater represents the resistive graphite filament.

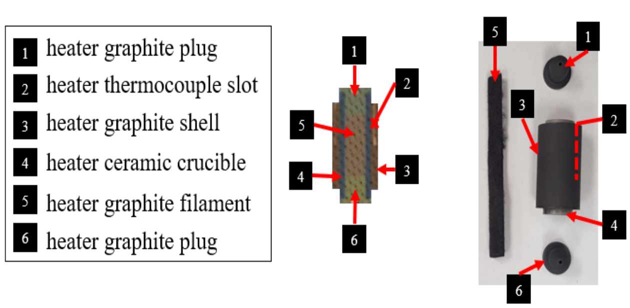

Fig. 2: INSET heater: legend (left), virtual heater (middle) and physical heater (right).

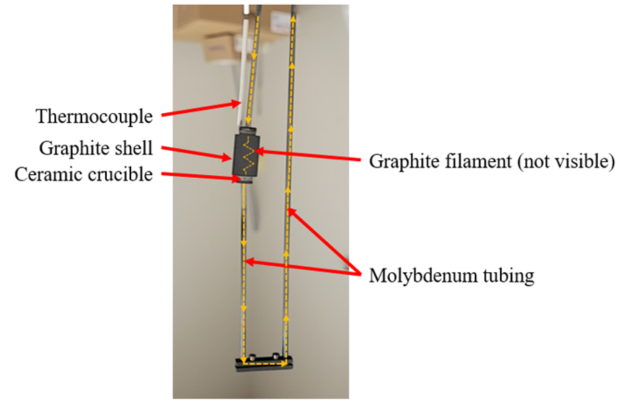

Fig. 3: INSET heater circuit.

Also located within the body is the thermal insulation. Thermal insulation is required to contain the thermal energy emitted by the heater as well as to ensure that the external surface of INSET maintains a safe operating temperature. The external surface of the apparatus must not reach a temperature that can interfere with the reactor environment—namely, the moderator (i.e., we do not want to boil water on the outside of the irradiation tube). The insulation also prevents the structural aluminum-6061 from undergoing phase transitions to ensure integrity of the vacuum vehicle. SIGRATHERM® GFA5 graphite felt is used as both the heater filament and thermal insulation. The inner wall of the body is lined with layers of this felt for thermal insulation. The innermost, and heater-facing, layer of thermal insulation is low-emissivity Mo foil. This Mo tends to highly scatter thermal photons to help contain the thermal energy emitted via radiative heat transfer within the heated region.

II.B. Past Experiments

INSET has been successfully deployed in-pile at the OSURR three times. INSET is designed to go into the 10 in. dry tube irradiation facility at the OSURR. This drywell facility sits adjacent to the core and allows for cables, gas lines, and other instrumentation to be attached to INSET without interacting with the reactor's moderator (water). At 450 kW, the OSURR generates a total neutron flux of around 1E12 n/cm^2/s in the 10 in. dry tube facility.[5] Each irradiation of INSET experienced a total neutron fluence of around 1E16 n/cm^2. The first deployment of INSET sought to investigate the irradiation damage of candidate cermet fuel cladding samples for NTP systems.[4] The second deployment was intended to test gas flow meters under consideration for use in NTP systems.[6] The third, and most recent, in-pile test used INSET to heat flowing He to evaluate the survivability and reliability of two candidate pressure sensors and one resistance temperature detector (RTD).[6] Figure 4 shows an INSET vehicle with thermocouples and a vacuum line installed before it was irradiated.

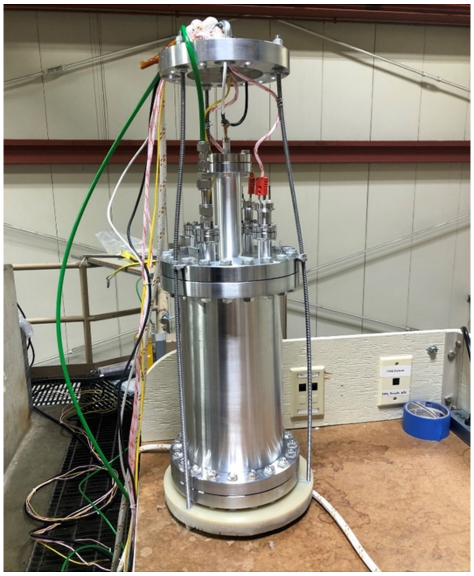

Fig 4: Photograph of INSET vehicle before an irradiation at the OSURR.

The fuel surrogates tested in the first in-pile use of INSET were cylinders of 1 mm thickness and 3 mm diameter. Four of these cylinders were irradiated and heated. Three of the material samples were Mo, machined using three different methods. The fourth sample was a Mo-Zr cermet. The test was limited to remaining below 800°C to prevent annealing any irradiation damage. To induce elevated temperatures below 800°C, INSET was heated using 40 W of DC power. This produced a recorded thermocouple temperature near the samples of around 455°C and was held for around 15 minutes. This work is detailed in Steiner et al.[4]

INSET served as a testbed for NTP candidate air flow meters during its second deployment. The air flow meters failed before INSET heating from radiation damage. This introduced an opportunity for INSET to be heated in-pile without the presence of any additional instruments or materials. INSET was then heated to 1525°C in-pile to verify and quantify the relative performance of INSET in-pile to out-of-pile benchtop tests. INSET performed the same in-pile as it did out-of-pile. To reach 1525°C, INSET was heated using 600 W of DC power and was sustained for roughly 10 minutes. This work is recorded in Floyd et al.[6]

Lastly, during the third irradiation, two candidate pressure sensors and one candidate RTD were coupled to INSET for testing. This required flowing He gas into INSET, past the heater, to the RTD, and finally to the pressure sensors. The constraint applied to INSET required the RTD to reach a temperature of 100°C for 15 minutes. 100 W of electrical power was supplied to INSET for 50 minutes to generate the desired conditions at the RTD. The heat was transported from the heater, through a vacuum, through aluminum tubing, and to He gas that carried the thermal energy to the instrumentation. This introduced the thermal lag requiring the 50 minutes of heating. The heater external surface was heated to around 350°C. Details of this deployment can be found in Floyd et al.[6]

Limitations of the current INSET heater were identified through out-of-pile testing.[4] INSET has been shown to reliably sustain 1100°C steady state for 120 minutes. INSET has also been heated to 1600°C steady state for 10 minutes. To achieve temperatures expected in NTP environments (>2000°C), a redesign of the heating element is currently under development.

II.C. New Design

The current INSET apparatus described in the previous section is being redesigned in two stages. The first stage will include a new resistive heating element, and the second stage will incorporate hydrogen flow through the specimen region. The heating element redesign will enable higher temperatures, larger test specimen volumes, and longer steady-state operation. The first stage of the update replaces the graphite filament and Mo circuit, as shown previously in Figures 2 and 3, with a pure tungsten coil. The updated heating element functions largely the same as the Poco graphite shell, ceramic crucible, and graphite filament. The coil will attach to copper power passthrough wires and will be supplied with DC to resistively heat the tungsten to the targeted temperature. A specimen sample holder will be located inside the tungsten coil. However, the desired location of the specimen or instrumentation to be tested can be easily accommodated, remaining true to the versatile nature of the INSET experiment. Sensors sensitive to RF noise can be placed outside the heating element as well.

This new design is based on the work supported by the previous efforts made during the POODLE program (Radioisotope Propulsion Program).[7] This program developed a 5-kW tungsten heater to simulate radioisotope heat sources for radioisotope thrusters; it was capable of reaching at least 2000°C for approximately 30 days.[7] A schematic of the new tungsten heating element for INSET can be seen in Figure 5. As shown in the figure, the return lead will be on the outside of the coil to allow for the specimen holder.

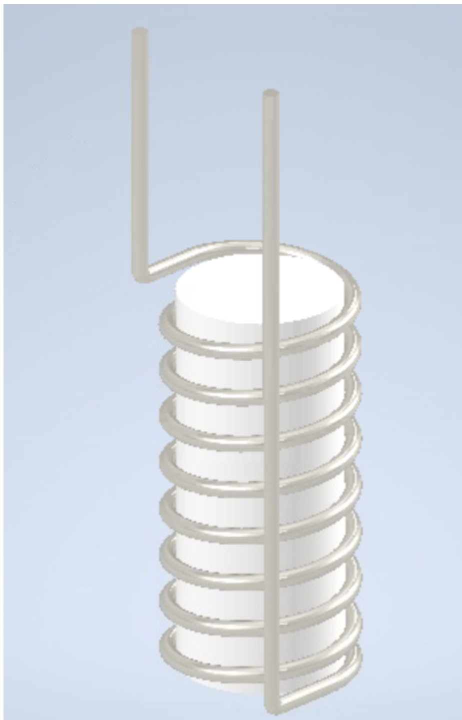

Fig. 5: Redesigned INSET heater around specimen capsule.

The thermal insulation within INSET will be similar to the current design, with low-emissivity Mo foil used as a "thermal mirror" to keep photons in the heated volume, as well as graphite felt to insulate the aluminum-6061 body. Type C thermocouples will be instrumented in the specimen region and plenum around the heater for temperature measurements.

The second stage, hydrogen flow, will occur in several steps. First, INSET will be outfitted with the appropriate tubing and instrumentation for high-temperature gas flow and corrosion/leak resistance to hydrogen. It is planned that the gas tubing will enter through the MPF, connect to the specimen holder, and exit through either a new MPF on the bottom of INSET or back through the top MPF. There will be flow meters attached to the tubing and a hydrogen air sensor outside of INSET to detect the presence of any hydrogen leakage. Out-of-pile gas flow tests will be conducted initially with inert gases at increasing temperatures. Once demonstrated with inert gases, gas with a low concentration of hydrogen—working up to pure hydrogen—will be introduced. Upon successfully demonstrating the high-temperature heating and hydrogen gas flow out-of-pile, this process will be repeated for in-pile experiments.

II.D. Upcoming Experiments

INSET, with the new tungsten heating element and interior sample holder, is planned for a high-temperature radiation experiment in the summer of 2022. Tungsten RTD wires will be tested in INSET for their resistivity changes with temperature and radiation fluence. Additionally, surrogate fuel particles with ZrC coatings will be tested for their behavior and survivability in the high-temperature radiation environment. This experiment will also push for higher temperature operation, >2000°C, and longer dwell times than previous experiments. This in-pile demonstration of the heating element and the new interior sample holder will act as both a safety demonstration and a stepping-stone to reaching our ultimate goal of flowing hydrogen in INSET. With high temperatures, radiation, and flowing hydrogen, we hope that INSET will accelerate the verification and qualification of sensors and materials for the nuclear thermal rocket program.

III. OUT-OF-PILE OPERATION IN I&C TESTBED

In addition to using INSET in a reactor, the INSET vehicle is also being deployed out-of-pile as a mock reactor for an I&C control algorithm testbed. ORNL has developed a non-nuclear mock reactor testbed that enables users to test advanced control logic, instrumentation, and system responses before application to a nuclear reactor. As development of advanced reactor technology continues into unknown territory for I&C, ensuring appropriate non-nuclear testbeds has a significant impact on the level of success for this technology. Demonstration using the mock reactor testbed is a good intermediate step before deploying new autonomous control schemes. From this testbed, researchers learn about instrumentation response for dynamic system modeling, as well as control schemes for single- or multi-system control logic. Autonomous controls will be required for the successful deployment of space reactor technology.

The non-reactor version of INSET (OUTSET) is used to heat working fluids and act as a mock reactor heating source for the testbed. The fully instrumented testbed includes a flowing hydrogen loop, OUTSET heating prototypic of NTP temperatures, and a multi-drum–controlled mock reactor, see Figure 6. The control drums and hydrogen loop (including OUTSET) are connected to a controller that allows for autonomous control algorithms to physically control them. Users' software can individually control each drum or group them together. Both types of control are of interest depending on the reactor application. A data acquisition system monitors the output of flow sensors, pressure sensors, temperature sensors, and feedback from the motor controllers and drum position. Ultimately, this is a first demonstration of flowing hydrogen loops prior to in-pile irradiation experiments flowing hydrogen.

Fig. 6: Schematic of the mock-reactor; the control drums analog is located on the right, OUTSET is stationed in the middle, and the computer and controllers for the testbed are on the left.

IV. CONCLUSIONS

ORNL is developing a testing vehicle, INSET, to create environments similar to that of nuclear thermal rockets (high temperature, radiation, and hydrogen) for testing and qualification of materials and sensors for the nuclear thermal rocket program. ORNL has demonstrated and conducted experiments in the past using INSET at the OSURR, reaching steady-state (10 minutes) temperatures of up to 1525°C and fluences of 1E16 n/cm^2. ORNL is currently upgrading INSET's heating element and interior to enable the vehicle to operate at sustained temperatures greater than 2000°C, hold larger specimens, and ultimately to have the ability to flow hydrogen. In addition to testing and certifying materials and instrumentation, INSET (OUTSET) will also be used in a mock reactor I&C testbed as a substitute for a reactor core. A hydrogen flow loop, with pumps, valves, and turbines, will be combined with INSET as a substitute reactor to produce the high temperatures for the mock reactor I&C testbed.

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