Planned Irradiation of IN-Pile Steady State Extreme Temperature Testbed

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ABSTRACT

Advanced reactor designs such as high-temperature gas-cooled reactors (HTGRs), molten salt reactors (MSRs), small modular reactors (SMRs), microreactors, and space reactor systems are planned to operate in high prototypic temperatures, which will present limitations on the materials and instrumentation capable of properly operating in such extreme conditions. Limited data are available on survivability at high temperatures under neutron irradiation for candidate fuels, materials, and sensors for these environments. Certifying components for these reactors will require combined effects testing, irradiating components at the prototypic high temperatures expected for different reactor designs. The IN-pile Steady-state Extreme Temperature testbed (INSET) meets this requirement. INSET is a high-temperature material and instrumentation testing vehicle that is scalable to various research reactors to achieve the prototypic temperature levels while exposing candidate samples to prototypic neutron fluences expected in different advanced reactor designs such as nuclear thermal rockets, microreactors, and HTGRs. INSET can currently provide vacuum conditions as well as steady-state temperatures up to 2,000 °C, and it can be exposed to a neutron fluence using research reactors with large irradiation ports. It uses DC power to resistively heat graphite elements to heat sample holders within the experiment containment. Due to the versatile design of INSET, any desired location of the sample or instrumentation can be easily accommodated. The test vehicle was recently updated with a new graphite heating element and internal structures to create a more durable and repeatable experiment. Plans to update INSET to accommodate flowing gas are also being developed. The previous INSET design successfully irradiated samples in the Ohio State University Research Reactor (OSURR) three times, and a fourth irradiation is planned for the summer of 2023 to demonstrate the updated INSET test vehicle before the next phase of material and instrumentation testing.

1. INTRODUCTION

Many advanced nuclear technologies are planned to have operating conditions at higher temperatures than current Generation III reactors. High-temperature gas-cooled reactors (HTGRs), molten salt reactors (MSRs), small modular reactors (SMRs), microreactors, and space reactor systems are all examples of advanced nuclear reactor designs that will operate under more extreme conditions than those observed in traditional light-water reactors (LWRs). These designs estimate neutron fluence starting at 10^{17} n · cm^{-2} and have operating temperatures between 750 °C and 2,000 °C [1, 2, 3]. Limited data are available on the survivability and performance of existing materials and instrumentation in this neutron fluence and temperature regime. Testing these advanced reactor components in a neutron flux and high-temperature environment are required for the system's qualification and licensing; however, there are no facilities available to test these components in both high temperatures and under neutron irradiation.

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The IN-pile Steady state Extreme Temperature testbed (INSET) was developed by Oak Ridge National Laboratory (ORNL) and the University of Tennessee, Knoxville (UTK). INSET is a modular, high-temperature furnace for testing materials and instrumentation. It was developed as a low-cost option to meet the need for adaptable testing capabilities. INSET can be irradiated in any reactor facility that has a minimum 8 in. diameter drywell, but the modular design of the test vehicle provides flexibility in the test facility requirements. The cost to build an INSET test vehicle for irradiation is around $10,000. The most recent design iteration of INSET was influenced by commercial high-temperature furnaces for nuclear fuel development. The updates to the testbed include a new graphite heating element and internal structure.

A previous design iteration of INSET was irradiated successfully three times, and a fourth irradiation of the updated INSET is scheduled for 2023. This summary focuses on the updates to INSET and the results from out-of-pile testing.

2. EXPERIMENT DESIGN

INSET is a low-activation, high-temperature vacuum furnace compatible with operation in a research reactor. It can expose test items to high temperatures, neutron radiation, gamma radiation, and custom atmospheric conditions simultaneously. The previous and current designs of INSET are referred to as INSET 1.0 and INSET 2.0, respectively. INSET 2.0 can accommodate larger test items and temperatures above 2,000 °C because of the larger heating element and redesigned insulation.

Table I. Comparison of INSET 1.0, INSET 2.0, and OUTSET 2.0.

	INSET 1.0	***INSET 2.0***	***OUTSET 2.0***
Body	Aluminum 6061	Aluminum 6061	304L Stainless Steel
	20 cm OD × 15 cm ID × 33 cm H	20 cm OD × 15 cm ID × 33 cm H	20 cm OD × 15 cm ID × 33 cm H
Gaskets	Aluminum 6061	Aluminum 6061	OFHC Copper
	(4) 3.4 cm OD, (1) 7.0 cm OD, (2) 20 cm OD	(4) 3.4 cm OD, (1) 7.0 cm OD, (2) 20 cm OD	(4) 3.4 cm OD, (1) 7.0 cm OD, (2) 20 cm OD
Bolts	Aluminum 6061	Aluminum 6061	304L Stainless Steel
Multi-Purpose Flange	Aluminum 6061	Aluminum 6061	304L Stainless Steel
	20 cm CF Flange: (4) 3.4 cm CF Ports & (1) 7.0 cm CF Port	20 cm CF Flange: (4) 3.4 cm CF Ports & (1) 7.0 cm CF Port	20 cm CF Flange: (4) 3.4 cm CF Ports & (1) 7.0 cm CF Port
Electrical Connectors	Copper, Brass	Copper	Copper
	Threaded Rods, Coupling Nuts	In-Line Screw Down Splices	In-Line Screw Down Splices
Insulation (Body)	Graphite	Carbon	Carbon
	SIGRATHERM® GFA Felt	Low-Density Rayon Insulation Board	Low-Density Rayon Insulation Board
Power Feed-through	304L Stainless Steel	304L Stainless Steel	304L Stainless Steel
	7.0 cm OD CF 5kV, 25 A, 2 Cu Pins	7.0 cm OD CF 5kV, 100 A, 2 Cu Pins	7.0 cm OD CF 5kV, 100 A, 2 Cu Pins
Heating Element	Fully Dense Graphite, SIGRATHERM®	Fully Dense Graphite	Fully Dense Graphite

	GFA Felt		
	Plugs: 1 cm H × 0.9 cm OD Shell: 2 cm H × 1.4 cm OD	Cylindrical Wrap: 9 cm OD × 6 cm ID × 9 cm H	Cylindrical Wrap: 9 cm OD × 6 cm ID × 9 cm H
Outer Cage	Garolite (G10)	Aluminum 6061	304L Stainless Steel

A complementary out-of-pile version of INSET constructed out of stainless steel instead of aluminum, the OUT-of-pile Steady state Extreme Temperature testbed (OUTSET), was also developed for low-cost benchtop testing and non-nuclear material and instrumentation testing at high temperatures [4]. Table I shows a comparison of INSET 1.0 versus INSET 2.0 as well as INSET versus OUTSET.

2.1. Previous Design

INSET 1.0 is similar to the updated design except for the internal insulation structure and the size and configuration of the heating element (see Fig. 1). The previous design’s heating element and electrical circuit required hours of preparation. The loose graphite felt readily shifted after assembly, thereby creating an electrical short with the heater circuit.

Figure 1. Insulation and heating element of INSET 1.0 (top) versus INSET 2.0 (bottom) [4].

INSET 1.0 was demonstrated to reach and remain at thermocouple temperatures between 20 °C and 1,027 °C for multiple hours; however, its highest recorded temperature was around 1,600 °C for a short period of time [5]. INSET 1.0 completed three irradiations, testing molybdenum-zirconium cermet discs, two flow meters, and a helium flow loop with a resistance temperature detector (RTD) and pressure sensor, respectively [3, 5]. Even with the limitations of INSET 1.0, this design completed three successful irradiations at the Ohio State University Research Reactor (OSURR). The heating element's small volume limited the maximum temperature and test article size [5].

2.2. Current Design

The motivation behind INSET 2.0 includes: enabling higher temperatures, fashioning a larger heated region, and ensuring the experiment's repeatability. Target temperatures are generated by resistively heating the graphite heating element using DC power. To reach full power (2kW), the furnace operates at 50 volts DC with 40 amps running through the heating element. Test items are typically placed inside the heating element, but it is possible to adapt INSET to accommodate more unique placements of test items. INSET 2.0 consists of three major regions: the multi-purpose flange (MPF), body, and outer cage.

The MPF is a 20 cm. outer diameter (OD) ConFlat® (CF) flange with five custom ports; see Fig. 2. There is one 7 cm. OD CF port in the center of the MPF, surrounded by four 3.4 cm. OD CF ports. CF flange feedthroughs are connected to each of these ports. DC power is delivered by two copper conductors on a 7 cm. OD power feedthrough, rated up to 100 A and 5 kV. One of the 3.4 cm. ports is always connected to a 3.4 cm. CF to Swagelok® adapter. This adapter connects to a vacuum pump system for removing gas inside INSET. The other three 3.4 cm. CF ports are typically instrumented with Type C and Type K thermocouple feedthroughs.

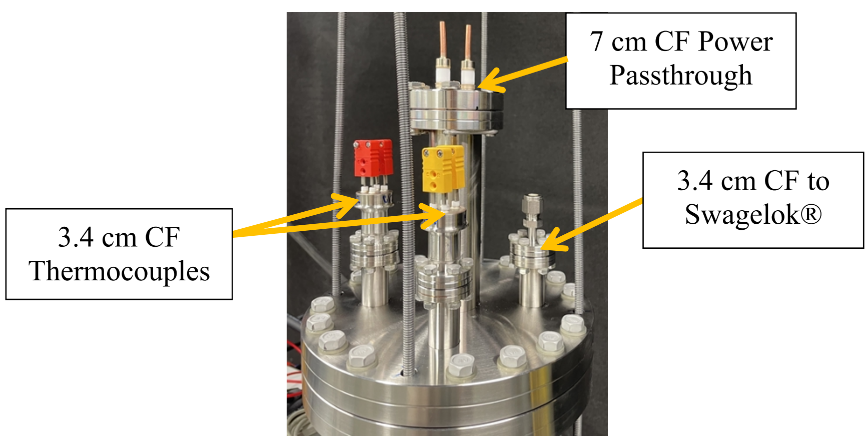

Figure 2. INSET MPF.

The Type C thermocouples monitor the temperature of the heating element and sit just below the insulation lid in the heated volume. Type K thermocouples are placed along the insulation grooves and in the plenum between the top of the insulation and bottom of the MPF. The underside of the MPF has four threaded holes to attach an inner aluminum cage that holds the insulation and heater.

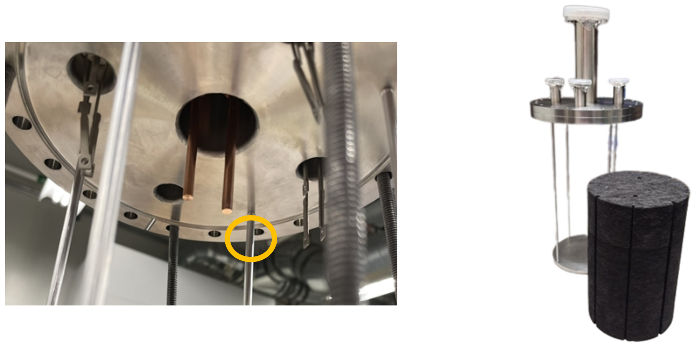

Figure 3. Inner cage attachment to MPF (left) and cage assembled (right).

Figure 3 shows one of the attachment points of the inner cage to the MPF and the cage assembled next to the insulation. The inner cage acts as a stabilizer and support for the heated region and insulation within INSET. Four cage arms attach to the four threaded holes, and a bottom plate is secured to the arms with screws. The vertical grooves around the outside of the graphite insulation offer a snug fit within the arms of the inner cage, as shown on the far right in Fig. 4.

Figure 4. INSET insulation and inner cage assembly process.

The graphite insulation in Fig. 4 is low-density rayon graphite insulation board typically used in high-temperature vacuum furnaces. The insulation prevents the body of INSET from exceeding 400 °C and interfering with reactor operations. The top of the graphite insulation has four small holes through its center for thermocouple wires and two larger holes for the power lines and ceramic insulation. Inside the graphite, there is a layer of molybdenum foil. The foil reflects radiated thermal energy back into the heated volume due to its low emissivity. To keep the foil lining the top and bottom insulation plug in place, the foil circles are fabricated with tabs that can be pushed into the low-density graphite. A boron nitride ring is located at the bottom of the insulation cylinder, and the ring electrically insulates the heating element from the graphite insulation. The heating element is a flat, cylindrical wrap and is fabricated from fully dense graphite. Test items up to 5.7 cm. OD and 10 cm. height can be placed within the graphite heating element. Figure 4 shows the heating element alongside the graphite insulation.

The body of INSET 2.0 is a 33 cm. tall, 20 cm. OD CF pipe nipple. The bottom is secured to a 20 cm. OD CF blank with a gasket and bolts. The top of the CF pipe is attached with a gasket and bolts to the MPF. A support structure exists outside the MPF and body of INSET, shown in Fig. 5; the outer cage holds the MPF and insulation capsule above the body of INSET for convenient assembly. Two aluminum plates below the 7 cm. CF port slide out of the way once internal assembly is complete to lower and secure the MPF to the body. INSET can be lowered into and raised from a reactor drywell using the hook at the top of the outer cage.

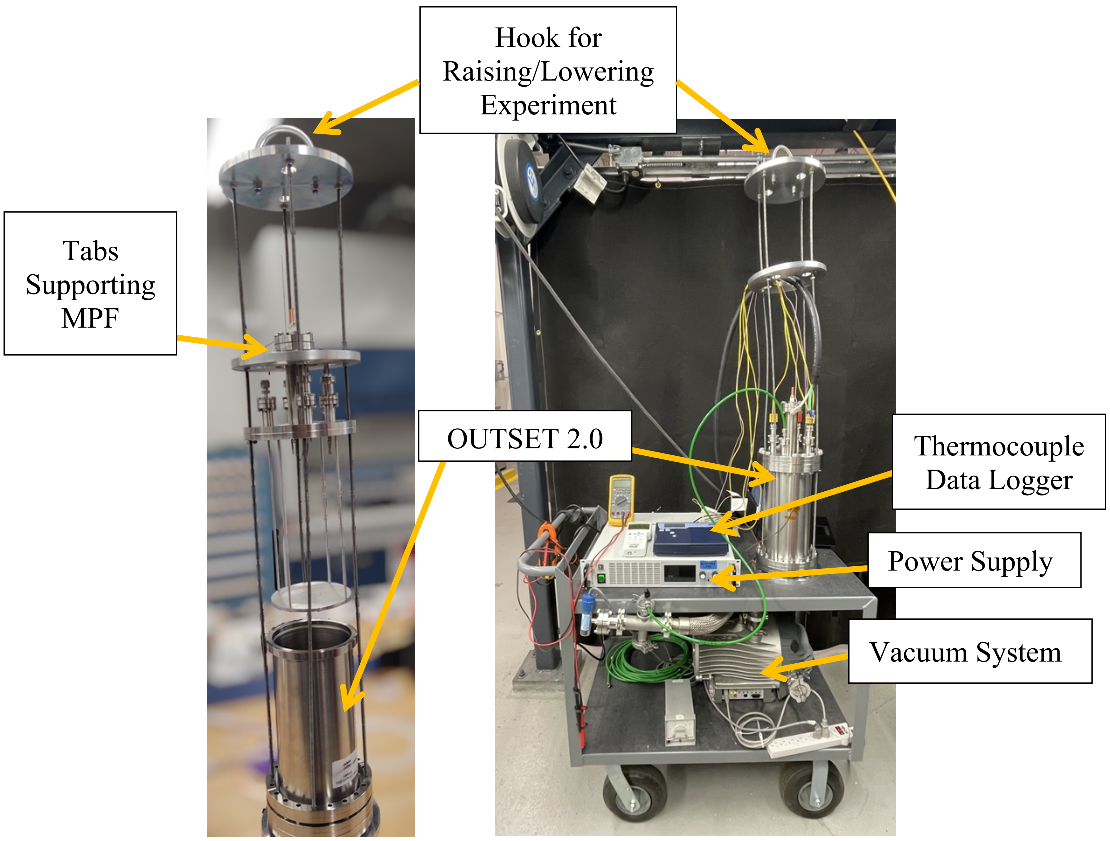

Figure 5. OUTSET before lowering MPF (left) and set up for benchtop testing (right).

2.2.1. Modeling

INSET has been rendered in CAD for thermal and neutronic modeling, as shown in Fig. 6. A thermal model is currently under development using the ANSYS software package. This thermal model will be used to verify the radiative heat transfer in INSET.

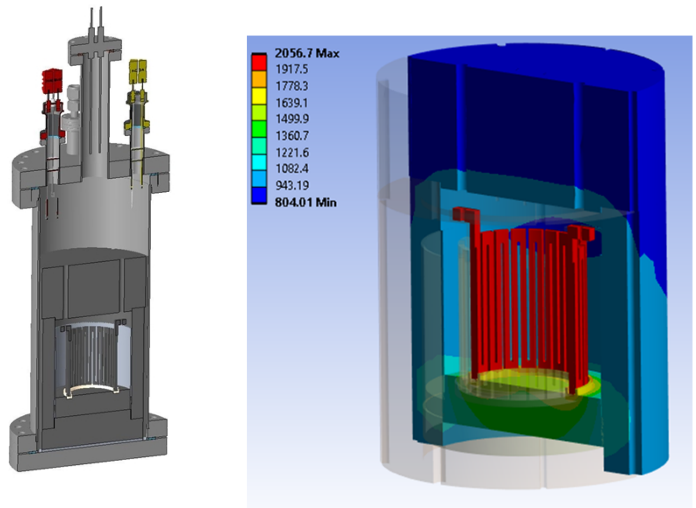

Figure 6. INSET CAD cross section (left) and ANSYS cross section (right).

A neutronic analysis of INSET will also be performed using the Monte Carlo N-Particle (MCNP) and SCALE Oak Ridge Isotope Generation (ORIGEN) codes to determine the activation, neutron flux, and gamma flux of the INSET testbed and its test items. Figure 7 shows INSET inside the OSURR MCNP model using the materials and dimensions of each part on INSET, where each color corresponds to a unique material card.

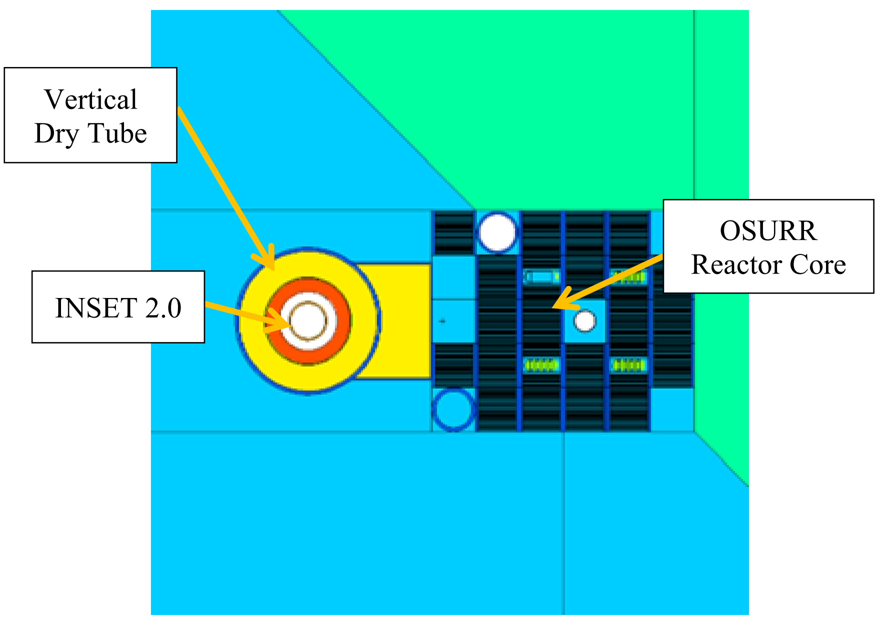

Figure 7. INSET MCNP model.

Tallies in MCNP calculate the neutron and gamma fluxes at specified material surfaces on INSET. Calculated in MCNP, the heated area of INSET experiences a neutron flux of around $1.2 \times 10^{12}\ \mathrm{n \cdot cm^{-2} \cdot s^{-1}}$ at full reactor power (450 kW) in the OSURR. The gamma dose in this same area at the same power level is around 4.8 MRads/h. The neutron flux, reactor operation time, and decay time are used as inputs for the ORIGEN code to determine neutron activation of INSET. The activation is modeled to determine when INSET can be safely handled and shipped back to ORNL after irradiation.

INSET was designed to be low activation to enable handling times on the order of days to weeks post-irradiation, depending on the irradiation power and length.

3. IRRADIATION CONDITIONS

The OSURR has been selected as the irradiation facility for the first irradiation of INSET 2.0. INSET will be placed in the 9.5 in. ID moveable dry tube. The dry tube is placed directly next to the reactor core, as demonstrated by the MCNP model in Figure 7. The expected neutron fluence in the 9.5 in. ID dry tube for a 7-hour irradiation at 450 kW (full power) will be around 2.5×10^{16} n · cm^{-2}. The drywell's shielding plug has a cable pathway for the power cables, instrumentation, and gas lines necessary for the operation and in situ temperature measurements of INSET.

The irradiation will occur over a two-day period with a total irradiation time of 14 hours. For day one, the OSURR will step up in power over the course of 7 hours while monitoring the measurements and operation of INSET. The performance of INSET will be monitored again on the second day with the reactor at full power for 7 hours.

INSET is set up for irradiation with the same equipment shown in Fig. 5 for OUTSET. A thermocouple data logger, vacuum pump system, and power supply will be connected to INSET through the shielding plug on the dry tube. The thermocouple data logger will record the temperature data from the C-Type and K-Type thermocouples during the irradiation, and the air inside INSET will be removed using the vacuum pump. The power supply will deliver up to 2 kW of DC power to INSET. At this power level, it is planned that the heating element will reach and sustain 2,000 °C longer than the previous design iterations of this experiment [3, 5, 7].

4. CONCLUSIONS

Many advanced reactor designs plan to operate at high temperatures, limiting the materials and instrumentation operable in such an extreme environment. Testing these candidate materials and instrumentation in the prototypic high-temperature environment is a requirement for component certification and licensing. INSET is a low-cost, modular test vehicle that meets this requirement. INSET 1.0 successfully completed three separate irradiations to demonstrate the high temperature furnace with materials, instrumentation, and an instrumented gas flow loop, respectively [3, 5]. The maximum temperature and test article size was limited by the small heating element volume, motivating the updated design of INSET 2.0 [5]. INSET 2.0 has an updated heating element and internal insulation structure that can expose test articles as large as 5.7 cm. OD to steady-state temperatures up to 2,000 °C. Out-of-pile testing of OUTSET 2.0 is being completed prior to an in-pile irradiation later this year. A thermal and neutronic computational analysis is also completed on INSET 2.0 to validate the out-of-pile operation and predict the activation of the experiment for shipping and storage. An irradiation of INSET 2.0 is planned for later this year to demonstrate the updated heating element and internal structure. Future work after the irradiation will include testing a sample within the heating element and incorporating a gas flow loop through the inside of the test vehicle.

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