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INTRODUCTION

Microreactors, or small, transportable reactors with a capacity of 0.1 – 50MWe [1], are sought to provide heat and power for myriad applications in remote areas, military installations, emergency operations, humanitarian missions, and disaster relief zones. These small, transportable reactor designs, while offering many advantages, are largely untested and unproven. A non-nuclear system and component testing capability are needed to demonstrate that these designs are safe, to verify and validate models, and to convince customers that the systems are robust, reliable, and efficient.

Idaho National Laboratory has constructed the microreactor agile non-nuclear experimental testbed (MAGNET) to assist with the development, demonstration, and validation of microreactor components and systems. MAGNET will support microreactor technology maturation to reduce uncertainty and risk relative to the operation and deployment of this unique class of systems. Stakeholders for this testbed include microreactor developers, energy users, and regulators. Regulators will be engaged early in the design and testing to expedite regulatory approval and licensing.

System Description

Within MAGNET, systems and components can be safely tested, providing valuable information on operating regimes, failure modes, and thresholds. Various microreactor designs are being proposed, classified according to their core cooling method; heat pipes, gas-cooled (pebble bed or prismatic), molten salt, liquid metal, or light water. For this reason, the goal is to provide a testbed that is broadly applicable to multiple microreactor concepts. Each reactor type poses a different set of design and operational challenges and performance claims stated by commercial vendors that have not been independently verified and validated through rigorous testing.

The initial set of tests to be performed in MAGNET will demonstrate the feasibility and performance of heat-pipe-cooled reactors, since this concept is unique to very small nuclear reactors. However, the testbed is designed to accommodate other designs in addition to heat-pipe-cooled reactors.

To further the technological maturity of microreactors, MAGNET is designed to serve the following functions:

- Provide a general-purpose testbed for performance evaluation of microreactor design concepts
- Provide detailed reactor core and heat removal section thermal-hydraulic performance data for prototypical geometries and operating conditions
- Enhance the readiness of novel reactor components such as heat pipes
- Provide test article and flow loop temperature-time histories during reactor startup, shutdown, steady-state, and off-normal operations
- Provide displacement and temperature field data for potential design performance verification and accompanying analytical model validation
- Evaluate the interface between simulated reactor components and the heat removal heat exchanger for geometric compatibility, functionality, and heat transfer capability
- Test the interface of the reactor heat removal section to auxiliary systems, such as power conversion systems or process heat applications
- Evaluate concepts for passive decay heat removal
- Measure the effects of non-uniform heating profiles
- Demonstrate the effects of heat pipe or flow channel single and cascade failures
- Identify and develop advanced sensors and power conversion equipment for autonomous operation and for in-operando data collection and monitoring
- Assess structural integrity of the core block, (i.e., thermal stress, strain, aging/fatigue, creep, and deformation)
- Study the effects of cyclic loading on materials and components
- Demonstrate the applicability of advanced manufacturing techniques, such as additive manufacturing and diffusion bonding, for nuclear reactor applications
- Enhance the technical readiness level of components and help address technical knowledge gaps to support high-temperature reactor components and systems.

Performance testing of systems or relevant components will be conducted under prototypical conditions that ensure safe operation of the microreactor. This performance testing will focus on thermal and structural performance. MAGNET will have the capability to connect to potential auxiliary systems (e.g., power conversion unit [PCU], desalination equipment, chemical processes [such as high temperature steam electrolysis], district heating). MAGNET will not simulate all physical processes and phenomena, only some that yield important safety and performance data.

MAGNET is configured in a plug-and-play arrangement. Modeling and simulation (M&S) will be employed to aid in the design of experiments. Such information will be extremely helpful in guiding the placement of sensors and predicting operating performance under a range of normal or accident conditions. M&S will also prove useful in the scaling of prototypical hardware for each test. The use of computational control and model feedback will emulate thermal response times and magnitudes.

System Design

MAGNET was designed to support heat-pipe-cooled or gas-cooled test article designs of 250 kW or less with temperatures of 750°C or less. The closed-loop cooling system is designed for compressed N_2 and He moved by a reciprocating, single-stage compressor (COMP-01). The hot section of this cooling system has a design temperature of 650°C. The cooling loop has three distinct design temperature sections, which are denoted by different colors on the process and instrumentation diagram (P&ID) (Figure 1). The compressor is sized for half the flow required for a 250-kW test article, but the system design allows for a future compressor in parallel enabling a full system design flow rate. The system design pressure is 22 bar. A heat sink (HX-01) is provided by a shell and tube heat exchanger with the compressed gas coolant on the tube side and a 50% ethylene glycol chilled water solution on the shell side. The chilled water is provided by a 960,000-BTU/HR, scroll-type chiller. A compact-platelet, recuperative heat exchanger (RHX-01) will pre-heat coolant gas by recovering heat from the test article outlet. Test articles will be mounted in a vacuum chamber with jacketed cooling. This vacuum chamber serves as an environmental chamber allowing testing under vacuum or inert gas environments and serving as a final containment barrier. MAGNET has also been designed for potential future integration with a PCU.

In the closed-loop cooling system (refer to the P&ID Figure 1), an inert gas is supplied by compressed gas cylinders (the first test article will run with compressed N_2 as the coolant) via a self-venting regulator. The self-venting regulator will regulate system pressure and allow for gas expansion and contraction during system heat up and cool down. COMP-01 provides head for the coolant to overcome system pressure losses. The instrumentation and control (I&C) system uses the output signal from the mass flow meter (MFM-01) as the process variable for control of the variable frequency drive on the compressor to match the required mass flow rate for a given test. The compressed gas is pre-heated by recuperated exhaust heat in RHX-01. The compressed gas flows into the environmental chamber where it removes heat from the installed test article. A test section bypass line allows the system to run without flowing gas through the environmental chamber, if necessary, which will allow system operation with no test article in place for shake down testing. Hot gas out of the test article flows through the hot side of RHX-01 before being cooled to ambient by HX-01 with chilled water supplied by the chiller in the co-located thermal energy distribution system (TEDS). COMP-01 and MFM-01 are located in the low-temperature section of the flow loop.

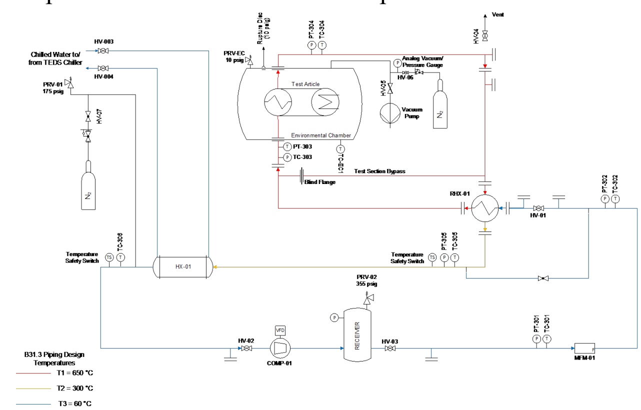

Figure 1. P&ID for the microreactor agile non-nuclear experimental testbed (MAGNET).

The nominal maximum operating temperature is 600°C with a nominal maximum operating pressure of 20 barg. The system was designed with temperatures emulating typical, air-Brayton cycles, so the test article inlet temperature is designed for 360°C with an outlet temperature of 600°C with an operating pressure of 12 barg. A 250-kW test article requires 0.939 of compressed N_2 with an inlet temperature of 360°C and an outlet temperature of 600°C for steady-state heat removal.

For an environmental container (EC), multiple options were investigated, including vacuum chambers, waste-pumping tanks, and a standard, 20-foot shipping container. The primary requirement for the EC was the ability to run experiments on test articles in an inert atmosphere (i.e., the container needed to be mostly airtight). Discussions of potential future test articles brought up potential tests on space power applications, so a vacuum chamber was chosen for the ability to run experiments in a low vacuum, ≤ 10e-3 torr. Size requirements dictated the ability to house a test article of 2 m in length and 0.5 m in diameter with plenty of room for instrumentation, so a rectangular vacuum chamber of 5’ × 5’ × 10’ in length was chosen.

Multiple options for a recuperative heat exchanger (RHX-01) were explored, but many manufacturers either felt that the 600°C hot-side inlet temperature was too close to the creep limit of stainless steel or that the combination of pressure and temperature was too challenging. We chose Clean Energy Systems to design and fabricate a compact-platelet, diffusion-bonded heat exchanger for RHX-01 and provided them with the design values listed in Table I.

TABLE I. Recuperative HX Sizing Criteria

Parameter	Value
Gas	Compressed N_2

Mass Flow Rate (kg/s)	0.938
Design Pressure (bar_g)	22
Design Temperature (°C)	650
Cold Side	
Nominal Inlet Pressure (bar_g)	12
Nominal dP (bar)	0.375
T_{COLDin} (°C)	38
$T_{COLDout}$ (°C)	360
Hot Side	
Nominal Inlet Pressure (bar_g)	10.625
Nominal dP (bar)	0.375
T_{HOTin} (°C)	600
T_{HOTout} (°C)	Heat balance

The final heat sink for the MAGNET gas cooling loop, HX-01, is not subject to exceptional temperatures or pressures and multiple choices were available. After investigation of selections from multiple manufacturers, of multiple types, a shell-and-tube type, counter-flow HX was chosen for its low cost and relatively small size. Table II presents the bounding design parameters given to vendors for the selection of HX-01.

TABLE II. HX-01 Sizing Criteria

Parameter	Value
Tube Side	
Fluid	Compressed N_2
Mass Flow Rate (kg/s)	0.938
Design Pressure (bar_g)	22
Nominal Inlet Pressure (bar_g)	12
T_{N2in} (°C)	275
T_{N2out} (°C)	20
Shell Side	
Fluid	Ethylene Glycol (50%)
T_{CWin} (°F)	44
T_{CWout} (°F)	64

Roots-type blowers, screw-type compressors, and reciprocating compressors were all considered to provide head to overcome system pressure losses. Lead time, price, and ease of system integration factors led to the decision to purchase an off-the-shelf, reciprocating compressor despite its inherent pressure pulsation. A variable speed compressor rated for half of the required system flow (COMP-01) was selected. 43.7 ACFM at 290 psig is the performance that the manufacturer could meet with an “off-the-shelf” unit. For future capacity increases, the system is designed with tees on either side of the compressor to install a second compressor in parallel or a compressor bypass if a PCU with an integral compressor is added.

Experimental Capabilities

In March of 2022, MAGNET demonstrated its operability by testing a scale mockup of a heat-pipe-cooled microreactor with a single heat pipe for cooling, six electric resistance heaters, and a gas-gap calorimeter to remove heat from the condenser end of the heat pipe. The test consisted of a slow ramp up of cooling flow followed by a heat up of the core. In addition, a digital twin of MAGNET and the test article was demonstrated by having the digital twin read data in real time and making corrections to manually induced transients.

A larger scale mockup with 37 heat pipes and 54 electric resistance heaters will focus on thermal cycling and observing the response of material components to a greater degree. The additive manufacturing methods and their capabilities will be evaluated by non-destructive testing. Visual and X-ray inspection for cracks and delamination of the joints are of particular interest. Operational testing of the system will include a similar suite of thermal imaging and direct contact temperature measurements, as well as strain measurements via gauges and digital image correlation (DIC).

After initial thermal cycling tests and examination, steady state operation for an extended 1000-hour steady state test will be performed. The other major outcome of the 37-hole test article test campaign will be the testing of an integrated, advanced heat exchanger. This operational test will also include transient operation of the system outside of shutdown and start-up. The heaters will be controlled by a reactivity feedback model. The same measurement and analysis techniques applied to the core block will also be applied here. Preliminary accident conditions such as loss of flow and loss of coolant will be examined near the end of the initial test campaign. Finally, heat pipe failure testing will be conducted to determine effects and conditions that lead to cascading heat pipe failure.

Additional proposed experiments include examinations of monoliths manufactured from graphite, molybdenum, and/or ZrC/SiC. These examinations will observe structural integrity and welding or bonding integrity, and evaluate creep, stress, or bowing in the structure. A gas-Brayton cycle PCU will be added to MAGNET to demonstrate integrated energy system operation with on-site micro-grid and digital real-time simulator experimental facilities [2].

RESULTS

The single heat pipe test was intended only to demonstrate MAGNET operations. As such, there are no experimental results outside of the data collected to show temperature distribution along the heat pipe. This data is represented in Figure 2 as a plot of temperature versus time.

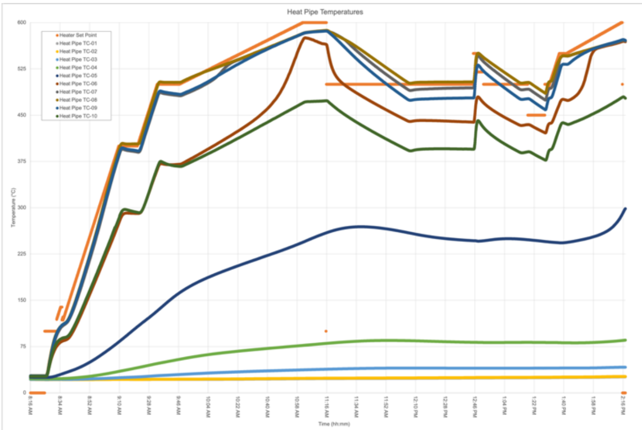

Figure 2. Axial heat pipe temperature distribution and heater temperature set point.

Following some system modifications to allow testing of helium microreactor components, MAGNET is fully operational

CONCLUSIONS

INL's MAGNET provides a unique capability to prove the safety and reliability of microreactor technologies by providing verification and validation of microreactor concepts by non-nuclear demonstration under prototypical conditions.

MAGNET was constructed to safely test and provide operational data for operating, threshold, and failure modes for a variety of microreactor design concepts. MAGNET's inherent flexibility and proven success in testing a heat-pipe-cooled, electrically-heated, microreactor mockup will provide data required to demonstrate the feasibility, safety, and reliability of a variety of microreactor concepts, components, and system designs.

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