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Microreactor Demonstration and Testing Progress in FY19

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Abstract
Microreactors are an emerging technology for providing energy at remote locations and/or for relatively low power applications. As vendors are looking into specific microreactor designs, one goal of the DOE-NE Microreactor program is to develop advanced core, heat removal, and power conversion technologies and testing facilities at which design features can be experimentally proven. FY19 tasks included designing a nonnuclear test bed and test articles to advance microreactor development through proof-of-principle experiments without the complex infrastructure required for a full nuclear test bed. The nonnuclear test bed capability is being established at Idaho National Laboratory, and both Idaho and Los Alamos National Laboratories are designing test articles to demonstrate technology in the test bed.

1.0 Introduction

Microreactors are an attractive technology option for kick-starting nuclear innovation if they can be operated at high temperature, yielding high power conversion thermal efficiencies comparable or better than in commercial light water reactors. Microreactors are currently the smallest variation of Small Modular Reactors (SMRs). SMRs are "newer generation reactors designed to generate electric power up to 300 MWe and whose components and systems can be shop-fabricated and then transported as modules to the sites for installation as demand arises." (IAEA, 2016). Vendors are developing microreactor designs to provide an affordable, potentially mobile source of electricity. Various microreactor designs are possible including gas-cooled, heat pipe-cooled, molten salt-cooled, and sodium-cooled fast reactors. In heat pipe microreactors, high-temperature heat pipes using liquid sodium or potassium working fluid transport fission heat from the core to a heat removal section which in turn transfers heat to the power conversion system working fluid. The initial test article to be deployed in the testbed at INL will be an electrically heated heat pipe reactor sub-assembly.

Microreactors designed to produce power of 0.1-20 MWt using heatpipe technology offer the potential for more affordable nuclear energy for a range of applications. In these reactors, heat pipes, fuel rods, and/or moderator are intermixed in the reactor core assembly. Heat pipes extend from the core region into the heat removal section where the power conversion unit working fluid flows through holes or channels, transferring heat from the heat pipes to the working fluid. For initial testing, the heat removal working fluid can be a low pressure gas for testing that addresses thermal stresses. In the final application, heat addition to the power conversion working fluid typically occurs at high pressure, supporting operation of an air-Brayton, supercritical CO_2 (SCO2), or He-recuperated Brayton cycle. The objectives and requirements for the nonnuclear demonstrations are described in Sections 3 and 4. The location of the nonnuclear test bed has been identified, and design is underway (see Section 5). Three different test articles have been proposed for testing in the near future as will be discussed in Section 6. This test bed platform provides vendors with an opportunity to demonstrate specific features of their designs in the future.

The driving force for establishing a test bed is that industry has expressed need for direct support from the laboratories on how best to accelerate technology maturity. Industry is willing to work with the laboratories to develop generic prototypes that capture intricate details of their design without giving away proprietary information. These generic prototypes can then be tested and simulated at the laboratories to provide insights back to the industry. Equally importantly, industry partners have expressed benefits of having a neutral test bed that any vendor is allowed to use without worrying about proprietary information. The US NRC could independently evaluate industry proposed designs at a smaller scale. Finally, equipment vendors and power conversion system developers have expressed a desire for a test bed where they can demonstrate their equipment. Test beds at industry locations will be limited in access by competitors, but a national lab allows everyone to have equal access (uniform user facility)/open source. In addition, we are building next generation of nuclear engineers/maintaining proficiency and providing required knowledge transfer and training to carry out experiments.

2.0 Background

Microreactors with heat pipe technology are attractive for various reasons: they are transportable, economic, and capable of higher temperatures/efficiency than commercial reactors, etc.. If operated at high temperatures (> 600°C), micro reactors are capable of achieving 32 % thermal efficiency for power production or, possibly higher for a supercritical CO_2 Brayton cycle. Structural materials that can hold fuel rods and heat pipes typically comprises one of two material categories: steel or ceramic composition. Metals such as stainless steel, grade 91 steel, and molybdenum-based alloys have structural stability but are neutron absorbers ; ceramics such as graphite, SiC/ZrC, and AlN are more neutronically efficient but are not as robust and integrity of the monolith is still being examined. A non-solid core containing molten salt or other material is also an option. Structural materials in microreactors serve three purposes:

1) they assure that the heat could be removed from the core geometry during normal, abnormal and accident scenarios (including for example during conduction assisted passive cool-down);
2) they act as barriers to fission products to retain them within the core 'vessel' at all times; and
3) they assure that geometry influenced reactivity temperature coefficient (RTC) is repeatable and predictable.

To achieve the functionality in the numbered items above, structures need to be constructed of thermal creep-resistant and corrosion resistant materials. Given high temperature in-service conditions, no single material can achieve these objectives. Stainless steels 304/316 and Inconel 617 are robust, well-known materials, but stainless steel in particular cannot be operated above about 600°C. Grade 91 stainless steel is being examined as a better alternative for reactors but still is constrained with a maximum of 600°C. Additionally, refractory metal alloys such as titanium-zirconium-molybdenum (TZM) and molybdenum-niobium (Mo1%Nb) can easily withstand high temperatures and large thermal stresses but are known to be vulnerable to recrystallization during thermal cycling stress relief and to oxidize when exposed to even trace quantities of oxygen or water vapor. Similarly, ceramics and ceramic composites such as graphite, SiC, and ZrC have the ability to operate at high temperatures while also serving as a neutron moderator, allowing for reduced fuel mass. These ceramic materials have matured significantly but may still require metal backup or structure within the monolith to maintain ductility. Advanced coatings and additive manufacturing methods exist to overcome these drawbacks but only on a case-by-case basis. Not surprisingly, microreactor industry is adapting different materials and fabrication methods for fabricating core internals.

Other materials being studied for use in microreactors include:

- Moderator:
  - Purpose is to increase neutron efficiency and decrease fuel mass.
  - Yttrium hydride ($YH_{x=1.5-2}$) material performs well.
  - Zirconium hydride is less expensive but has performance issues at high temperatures, so combination of the two may be desired.
  - Positive predicted reactivity coefficients may drive need for another additive.
- Reflector:
  - Beryllium oxide (BeO) or Magnesia (MgO) are ideal but expensive.
  - Alumina (Al_2O_3) is less expensive.
- Fuel:

- Metal Uranium Molybdenum Alloy (U-10 Moly) fuel with 19.75% enrichment exists at Y-12 but has low melting temperature.
  - Uranium Oxide (UO_2) with enrichment up to 5% is commonly manufactured but is associated with high melting temperatures and low conductivity.
  - Uranium Nitride has high conductivity and melting temperature, but neutron capture occurs in N-14. Wider spread fabrication capabilities are being examined.
  - Tristructural-isotropic (TRISO) particle fuel offers the advantage of containing all fission products but still requires technological development and testing for final use.
- Cladding types are being examined/tested separately from this microreactor program.

Presently, the nuclear industry relies on nuclear-grade steels and/or zircalloy for fabricating internal core structures not extensible to higher temperatures. High temperature materials such as refractory metal alloys, inconel, HT-9, graphite, and silicon carbide have been used in the industry only in special cases. The traditional approach to inserting these materials into service involves building an American Society of Mechanical Engineers (ASME) code case that is likely to take at least a decade. A quicker way to final implementation may be to make use of standard materials but open design space by leveraging new manufacturing techniques such as additive once it is proved effective. Given that most irradiation doses/correction effects received by the materials during their short service in microreactors are modest, alternatives to the conventional fabrication approach such as diffusion bonding or additive manufacturing are possible. The combined skills of multiple national laboratories will be applied to develop a new approach that is primarily based on at-scale testing combined with accompanying Destructive Evaluation (DE), Non-Destructive Assay (NDA) and 3-D modeling and simulation (M&S). An experimental test bed is required to demonstrate the efficacy of such an accelerated qualification approach.

3.0 Objectives and Technical Approach

The goal of the non-nuclear testbed is to advance the technical maturity of this new type of nuclear reactor. Specifically, the testbed is being designed with the following goals:

1) Provide displacement and temperature field data that could be used for verifying potential design performance and validate accompanying analytical models.
2) Show structural integrity of monolith: thermal stress, strain, aging/fatigue, creep, deformation,
3) Evaluate interface between heat pipes and heat exchanger for both geometric compatibility, heat pipe functionality, and heat transfer capabilities,
4) Develop potential high performance integral heat exchangers based on advanced manufacturing techniques, incorporating high efficiency heat transfer from the heat pipes to the power cycle working fluid,
5) Test interface of the heat exchanger to power conversion system for energy production or for process heat,
6) Demonstrate the applicability of advanced fabrication techniques such as additive manufacturing or diffusion bonding to nuclear reactor applications,
7) Identify and develop advanced sensors and power conversion equipment, including instrumentation for autonomous operation,
8) Study cyclic loading and reactivity feedback, and
9) Enhance readiness of the public stakeholders – particularly DOE laboratories and US NRC – to design, operate, and test new types of high-temperature reactor components.

Success is defined as testing relevant components to ensure safe operation of the reactor.

Development of an electrically heated demonstration unit will provide necessary experience with components and respective instruments that are manufactured using advanced manufacturing and fabrication methods in order to support aggressive high performance designs. Operation of the test unit will provide a wealth of prototypical data on core thermal behavior, heat pipe and primary heat exchanger performance, and passive decay heat removal. These data will support verification and validation of detailed microreactor thermal hydraulic models under startup, shutdown, steady-state, and off-normal transient behavior. This information will also be needed for assessment of coupled core neutronics effects.

A step-by-step development approach is being adapted for the testing program. Heat pipe reactor similitude offers the easiest starting point (due to the fact that heat pipes are practically isothermal along their length) for integrated testing. In heat pipe reactors, thermal stresses are qualitatively simple as they are primarily induced by temperature gradients between the fuel and the heat pipe in the transverse or 'radial' directions. So fabrication features such as planar welds and diffusion bonds in the transverse direction are only marginally impacted by the induced thermal stresses. Simplifying assumptions can be made to the accompanying simulations.

In the first phase, heat pipe technology will be examined, starting with general heat pipe/heat exchanger tests and potentially an additively manufactured test article. Additional geometries and/or heat pipe reactor (HPR) vendor designs may also be tested. These geometrical prototypes will accurately represent fabrication details of the core and the heat exchangers including but not limited to types of welds/bonds. Initial focus of heat exchangers will be direct air cooled heat-exchangers at lower pressures although supercritical (SCO_2) microchannel heat exchangers at higher pressures may be of interest in the future. Similarly initial core and heat exchanger tests will be monolithic although future tests may be based on shell-and-tube style heat removal; in both cases, fuel rods will be represented by embedded heaters. A suite of embedded sensors and stand-off detectors will be relied upon to measure temperatures and local displacements. Initial tests will focus on comparing measured values of temperature to finite element analysis (FEA) predictions to validate FEA predictions of full-scale units.

In the second testing phase, focus will shift from heat pipe cooled reactors to other proposed designs, such as a gas-cooled reactor. In a gas-cooled reactor design, internal temperatures along the length of the core can vary by up to 300 to 400^{o}C while the core pressure could be as high as 1000 psi. The associated thermal stress field is extremely complex, and creep modeling is an order-of-magnitude harder. In some cases it will be difficult to even attribute observed failure to a set of measured parameters. Similar to the heat pipe phase, prototype reactor geometries will be fabricated and tested following an approach similar to that described above for the heat pipe reactor.

While exact designs vary significantly – e.g., heat pipe cooled vs gas cooled – there are numerous similarities. Most designs are incorporating advanced manufacturing techniques to join together either subtractively and/or additively manufactured parts. A common example is diffusion bonding of additively manufactured printed circuit heat-exchanger plates. Implicitly, structures in all these designs are simultaneously subjected to high temperatures and potentially large thermal gradients. As a result thermal stress induced structural creep at critical locations such as welds and diffusion bonds becomes a concern. While structural analysis tools have progressed considerably, they have not achieved maturity sufficient to analyze reactor-scale geometries at a resolution necessary to directly model each fabrication detail. Industry designers would benefit from partnering with national laboratories to combine knowledge and experience.   The heat pipe-to-heat exchanger interface is common to all heat pipe microreactors being examined and will be one of the primary focus areas for a nonnuclear microreactor test. Testing various components to understand operation is important; three different test articles are being proposed in the near future:

- A single core monolith block with holes for fuel rods and heat pipes will be examined to understand heater interface and block response.
- A single heat pipe experiment will be performed to obtain data on steady-state and transient heat pipe behavior, the effects of thermal contact resistance, electrical heater interface with the core block, and high-temperature heater performance (including zonal heating) .
- A larger scale test article where the core monolith and heat pipes (~37) interface with an advanced heat exchanger to provide thermal output and understand the power mechanisms driving all heat pipe microreactor designs.

Details of the articles will be described in Section 6, and requirements for the 37 heat pipe test are given in the next section.

4.0. System Requirements for 37 heat pipe test

The first set of tests will be conducted using a non-nuclear test article that incorporates heat pipes. Electrical heaters will be employed to simulate the heat generated by the nuclear fuel. Except for the research test article, support systems will meet all applicable codes and standards. A breakdown of responsibilities by Lab is given in Appendix A.

Test Article Specifications include:

- Heat-pipe cooled,
- Power: nominal 100 kWth (37 heat pipes at 3 kW/heat pipe),
- Working fluid: Na,
- Temperature at evap. exit of the heat pipe – 650°C,
- 316SS (material of construction) Block: <1 m length,
- 316SS wick construction,
- Heat Exchanger (HX): < 1 m,
- Simply supported test article,
- Interface to PCU: Air, sCO2 or nitrogen Brayton cycle,
- Heat pipe analysis conducted in HTPIPE, HPAPPRX, and SOCKEYE,
- Checked and approved drawings with appropriate GD&T shall be generated for all test article and test bed components ,
- All material certifications shall be kept on a common file space, and
- Test article will be fabricated using best available engineering practices.

Thermal Requirements

- Test article temperatures will range from room temperature up to 750°C. Test article will generally be fully thermally insulated during testing.
- Commercially available electrical resistance cartridge heaters will be used to simulate heating from the reactor fuel rods.

- Nominal power 100 kWth at evaporator exits.
- Nominal temperature 650°C at evaporator exits.
- Sodium heat pipe working fluid is used.
- Heat pipe array is operated in horizontal orientation.
- Heat pipes will be manufactured by LANL using best available engineering practices.
- Point kinetic model will be developed to provide simulated reactivity feedback.

Electrical requirements

- Electrical service up to 250 kW from 208 VAC three phase will be provided.
- Heat exchanger cooled with either open air or closed nitrogen loop is used.
- Test article adheres to electrical and mechanical codes and standards.
- Electrical power (AC) can be supplied to core manually at constant power.
- Electrical power can be supplied to core with reactivity feedback simulation.
- Electrical safety reviews will be implemented.
- Electrical grounding implications will be reviewed before instrumentation integration.
- Dirty power (power quality) isolation transformer will be included.
- Appropriate electrical schematics will be generated and documented for the systems.

Enclosure Chamber requirements include:

- Chamber inert (nitrogen) down to 15 ppm of oxygen by successive dilution or other methods,
- Chamber size to accommodate instrumentation and test article contingencies (A & B & others),
- Test stand meets applicable codes and standards,
- Test bed complies with industry standard safety practices,
- Pressure safety reviews will be implemented, and
- Oxygen deficiency safety will be addressed.

Testing requirements (Initial Startup Test Matrix)

- Experiments may require up to 300 hours of continuous testing.
- Initial slow heatup test to characterize elasticity of structure (without heat pipes). This test will be performed at LANL to condition the test article before it is sent to INL. The test article will be heated up to operating temperature in a large furnace.
- Thermal energy balance test (steady state). Perform calorimetry on the gas-cooled heat exchanger while monitoring flow rate and temperature increase of coolant gas.

Instrumentation requirements and options

The experiments must be instrumented with a resolution such that the data can be used to validate high-fidelity computer models. Types of instrumentation to be provided include acoustic sensors, pyrometry, thermocouples, flow and pressure monitoring, vibration sensors, etc. Wireless embedded sensors may be used where possible.

- Strain, inferred stress, thermal creep, structural deformation, and integrity in the core monolith will be monitored/measured.

- Computational fluid dynamics and finite element modeling will be performed on the heat removal heat exchanger prior to fabrication to identify potential regions of high thermal stress that may influence the heat exchanger.
- Heat pipes will be instrumented for power in, power out, inlet and outlet pressure to HX, HX mass flow rate, temp. gradients and distribution (axial, radial, temporal), HX strain, plastic deformation, cycle fatigue.
- Potential internal heat pipe instrumentation/sensors should also be considered for measurement of: vapor flow rate, liquid and vapor pressure, potential temperature distribution at startup (during transient scenarios).
- The monolith may be instrumented with an array of accelerometers that could be used to measure the resonant frequencies, mode shapes and damping ratios of the monolith.
- Thermal imagers - Selective infrared imaging will be performed on the core monolith and heat exchanger outer surfaces to reveal regions of high thermal gradients. During much of the testing, the entire test article will be fully thermally instrumented such that thermal imaging of the external surfaces will not be possible.
- High-speed Digital Image Correlation (DIC) – LANL will provide a DIC system for full-field strain measurement.
- The associated instrumentation and sensors microreactor report as part of a different work breakdown structure (WBS) will contain more information on proposed measurement techniques.

Data requirements

The Test Bed data acquisition system can be accessed locally or remotely via a 100 GB data network. Test data will be available to the INL High-Performance Computing (HPC) enclave. Within the INL Energy Systems Laboratory (ESL), data acquisition computers, as well as workstations for test engineers and vendor representatives, will be available. Protocols for handling of proprietary data must be pre-arranged and applicable non-disclosure agreements (NDAs) must be in place before testing commences. Export control of the design configuration and test data may be necessary. The HPC interface, cyber security, data access and storage will be additional considerations. Primary data will be acquired using calibrated instruments (with calibration reports documented in server). Secondary data collected by instruments will be calibrated from traceable standards. All data will be stored via an accessible server.

<u>Quantities to Measure:</u>

1. Electrical power to evaporator
2. Volumetric flow rate of gas at heat exchanger entrance
3. Pressure of gas at heat exchanger entrance
4. Evaporator entrance temperature
5. Evaporator midpoint temperature
6. Evaporator exit temperature
7. Condenser entrance temperature
8. Condenser midpoint temperature
9. Condenser exit temperature
10. Core strain (reactivity feedback, elastic deformation, creep)
11. Heat exchanger strain (elastic deformation, creep)
12. Core stress state

13. Heat exchanger stress state
14. Heat exchanger guard heater power (as applicable)
15. Thermal gradient across core insulation (as applicable)
16. Thermal gradient across heat exchanger insulation (as applicable)

Fire suppression

If deemed appropriate based on safety analysis, use of alternative to water, such as MetalX (powder) may be requiredin the unlikely event of a fight sodium fire inside the test enclosure. Laboratory personnel will be trained for potential of sodium fire, oxygen deficiency, etc.

Project requirements

1. In anticipation of future research directions, where appropriate, the project will observe guidelines for the NQA-1 R&D quality standard. The graded approach applies.
2. Incremental testing will be conducted to control risk.
3. Project files will be shared via secure file server.
4. Design reviews will be held as appropriate (SRR, PDR, CDR, TRR, SVR).
5. All key findings will be documented in peer-reviewed reports and technical publication.
6. All procured components will be traceable and documented on common file server.
7. Appropriate Piping and Instrumentation (P&ID) diagrams will be generated for the system.
8. Where applicable, vetted vendors will be selected with NQA-1 compatible quality programs (for future commercial-grade dedication).

5.0. Non-nuclear Test Bed

A non-nuclear microreactor test bed (NMTB) is being designed at Idaho National Laboratory to assist with the development, demonstration and validation of microreactor components and systems. The purpose of the test bed is to support technology maturation that will reduce uncertainty and risk relative to the operation and deployment of this unique class of systems. Within the NMTB, systems and components can be safely tested to failure, providing valuable information on failure modes and thresholds. The goal is to provide a test bed that is broadly applicable to multiple microreactor concepts. Advanced manufacturing techniques can be evaluated nondestructively. The stakeholders for this test bed include microreactor developers, energy users and regulators. Regulators can be engaged early in the design and testing to expedite regulatory approval and licensing.

There are various types of microreactors being proposed, including heat-pipe cooled, gas-cooled, molten salt, light water, or pebble bed. The performance claims stated by commercial vendors have not been independently verified through rigorous testing. Each reactor type poses a different set of design and operational challenges. The first set of tests to be performed in the test bed are targeted towards demonstrating the feasibility and performance of heat-pipe cooled reactors, since this concept is unique to very small nuclear reactors. However, the testbed will be constructed to accommodate other designs in addition to heat-pipe cooled reactors

The NMTB will be configured in a plug-and-play arrangement. Modeling and simulation (M&S) will be employed to design experiments and to help in interpretation of experimental results. M&S results will be extremely helpful to guide the placement of sensors and to predict operating performance under a range of normal or accident conditions. M&S will also be useful for scaling of prototypical hardware for each test.

The initial test article will be an electrically heated heat pipe reactor subassembly with 37 heat pipes and 54 electric cartridge heaters. The first phase of testing will be carried out using a once-through flow configuration with compressed air as the coolant. The initial test bed process and instrumentation diagram (P&ID) is shown in Fig. 1 – this P&ID also shows pressure and temperature measurement stations at each section of the test bed loop.

The following test article parameters were used to determine required air flow:

Maximum Test Article Power	150 kW
Test Article Compressed Air Inlet Temperature	360°C
Test Article Compressed Air Outlet Temperature	600°C
Test Article Compressed Air Inlet Pressure	10 bar_g
Calculated Compressed Air Mass Flow Rate	0.575 kg/s (1,186 SCFM)

A customized vacuum chamber will serve as the test article enclosure. The chamber will be rectangular in construction, rated to 10^{-4} torr for potential testing at vacuum, and designed for back fill with inert gases. Instrument and view ports will accommodate thermocouples, thermal imaging, fiber optic sensors, power for heaters, and capacity for future instrumentation and control (I&C). The chamber will also include a roots-type, dry vacuum pump and capacity for future addition of a higher vacuum pump.

A commercially available, rotary screw air compressor has been identified to supply flow to the test article at the required inlet pressure and mass flow rate. A refrigerant-based air dryer will ensure that the compressed air is dry at the process inlet. A worst-case pressure drop of 1 bar from the compressor outlet to the test article inlet was assumed. A maximum allowable working pressure (MAWP) of 25 bar_g was chosen allowing future flexibility to use CO_2, N_2, or He as a working fluid, with their associated power conversion cycle pressures.

A mass flow meter will monitor gas flow and provide an analog output signal to a control valve to regulate gas flow to the test article based on an appropriate control algorithm.

The compressed air will flow through a recuperative heat exchanger (RHX) to pre-heat cooling air into the test article and recover as much heat as possible from the heated test article exhaust stream. The RHX will be a compact-platelet heat exchanger (CPHX). The following are design conditions for the RHX:

Maximum Allowable Working Pressure	25 bar_g
Cold Air Inlet Pressure	11 bar_g
Cold Air Inlet Temperature	20°C
Cold Air Outlet Temperature	360°C
Hot Air Inlet Temperature	560°C
Hot Air Outlet Temperature	232°C
Pressure Drop (Both Sides)	< 10 %

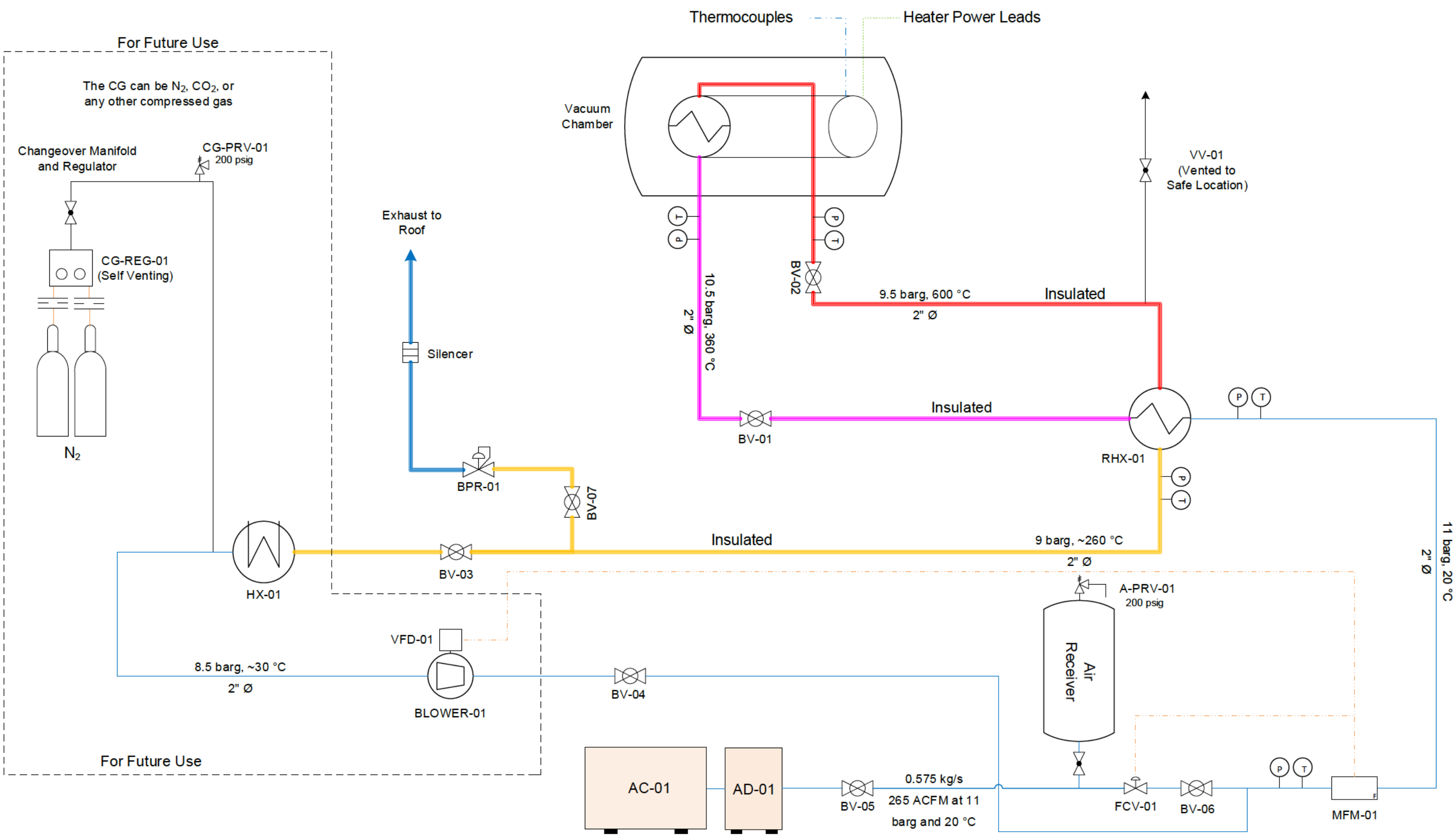


Figure 1 Test Bed P&ID (items inside dotted line are for future use)

The process pressure will be maintained by a spring-type, carbon steel, back-pressure regulator with stainless steel trim before the air is exhausted through a silencer and out through a side wall or the roof of the enclosure.

Pressure and temperature will be monitored at the inlet and outlet of the test chamber and at the inlet to each side of the RHX. All I&C will be monitored and controlled by a custom LabView virtual instrument.

The dotted lines on the P&ID indicate future design considerations for recirculating compressed gas coolant.

Figure *2* shows a rendering of the vacuum chamber with a test article inside. The test article support structure will be designed to roll in and out of the test chamber to allow direct access to the test article during test setup and instrumentation.

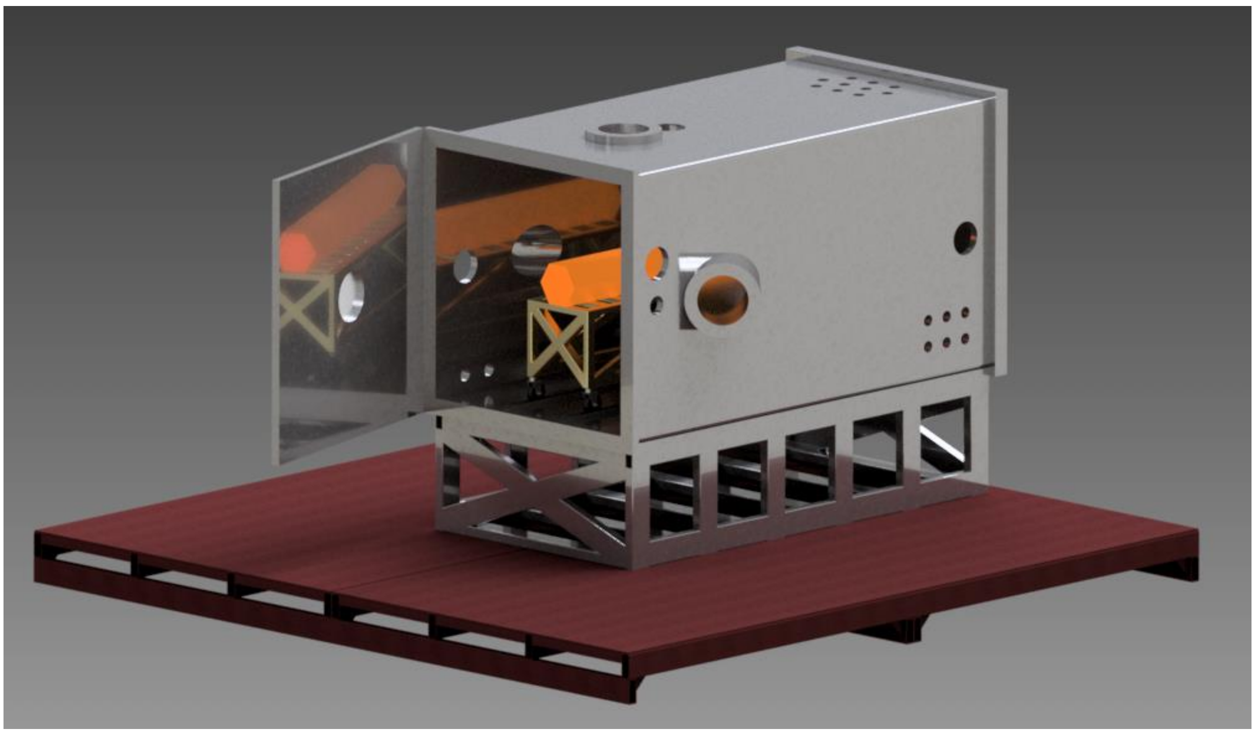


Figure 2. Rendering of Test Bed Skid and Chamber (with test article inside)

6.0. Non-nuclear Test Article

Development of one or more electrically heated microreactor demonstration units will provide necessary experience with the advanced manufacturing and fabrication methods required to support aggressive high performance designs. Operation of these test units will provide a wealth of prototypical data on core thermal behavior, heat pipe and primary heat exchanger performance, and passive decay heat removal. These data will support verification and validation of detailed microreactor thermal hydraulic models under startup, shutdown, steady-state, and off-normal transient behavior. This information will also be needed for assessment of coupled core neutronics effects. Once the test bed is established, numerous test articles can be demonstrated and technological parameters can be assessed for viability in microreactor designs.

6.1. Test article for single heat pipe experiment (Block 7)

Preliminary testing is being performed at LANL and INL using a Block 7 design that incorporates a single heat pipe and six-heaters in a hexagonal-shaped test article as seen in Figure 3. This preliminary experiment is intended to demonstrate heater characteristics, cooling strategies, heat losses, and the effects of contact resistance. These tests will also provide preliminary experimental parameters for heat pipe system models .

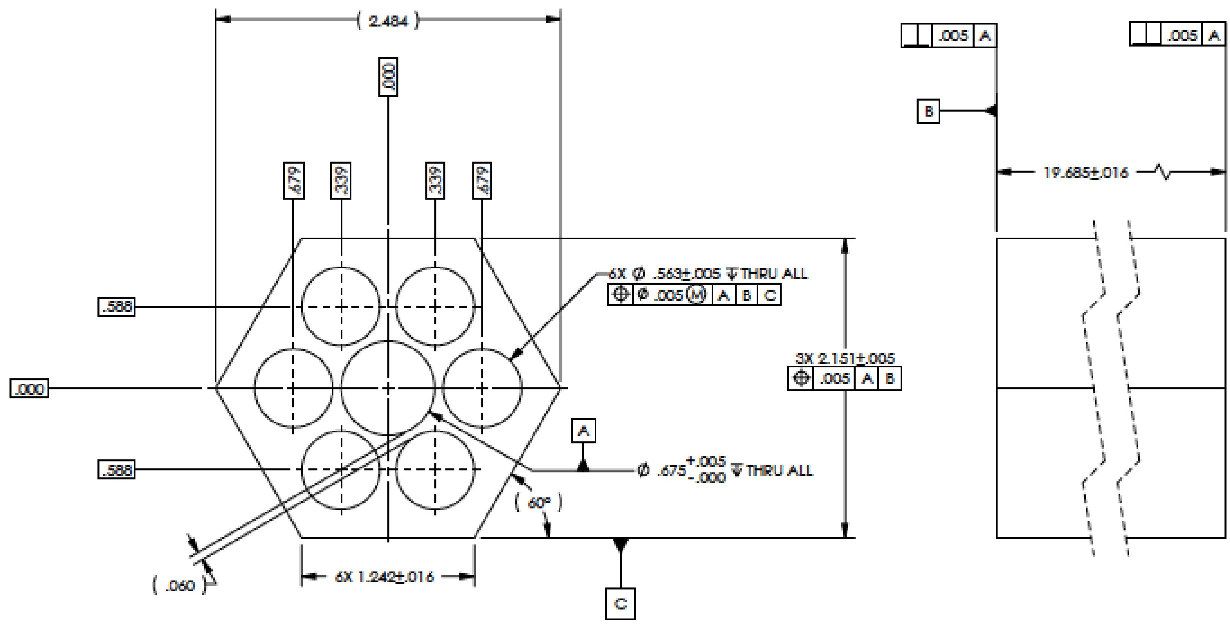


Figure 3. LANL drawings of a Block 7 test article monolith for single heat pipe test. Web thickness was selected due to the current capability in metal additive manufacturing. Overall length of the test article exceeded all available powder bed additive manufacturing fabrication capabilities and was selected to test out other advanced manufacturing processes such as diffusion bonding or tier welding.

An initial 6-inch long version of the single heat pipe geometry has been fabricated and tested at INL. This experiment incorporates a center water-cooled tube as a simulated heat pipe. A schematic and photographs of the test setup and a thermal image of one of the tests are provided in Fig. 4. This test is set up to measure the center heat removal rate from the cooling water using a precision delta-T meter. This measurement, along with the known electrical power input to the heaters allows for determination of extraneous heat losses. The results of these tests are being compared to predictions obtained from a finite-element model for temperature and heat flux distribution. Preliminary finite element analysis results are presented in Fig. 5. The temperature distributions shown in the figure are reasonably close to experimental values obtained from thermocouples located on the heater centerlines and on the outer hex block surface (not shown). Note that the model includes thermal insulation surrounding the outer surfaces of the hex block such that most of the heat removal is associated with the center water-cooled tube. For the heater power specified in this particular analysis case, the maximum predicted temperatures are close to the measured heater centerline temperatures.

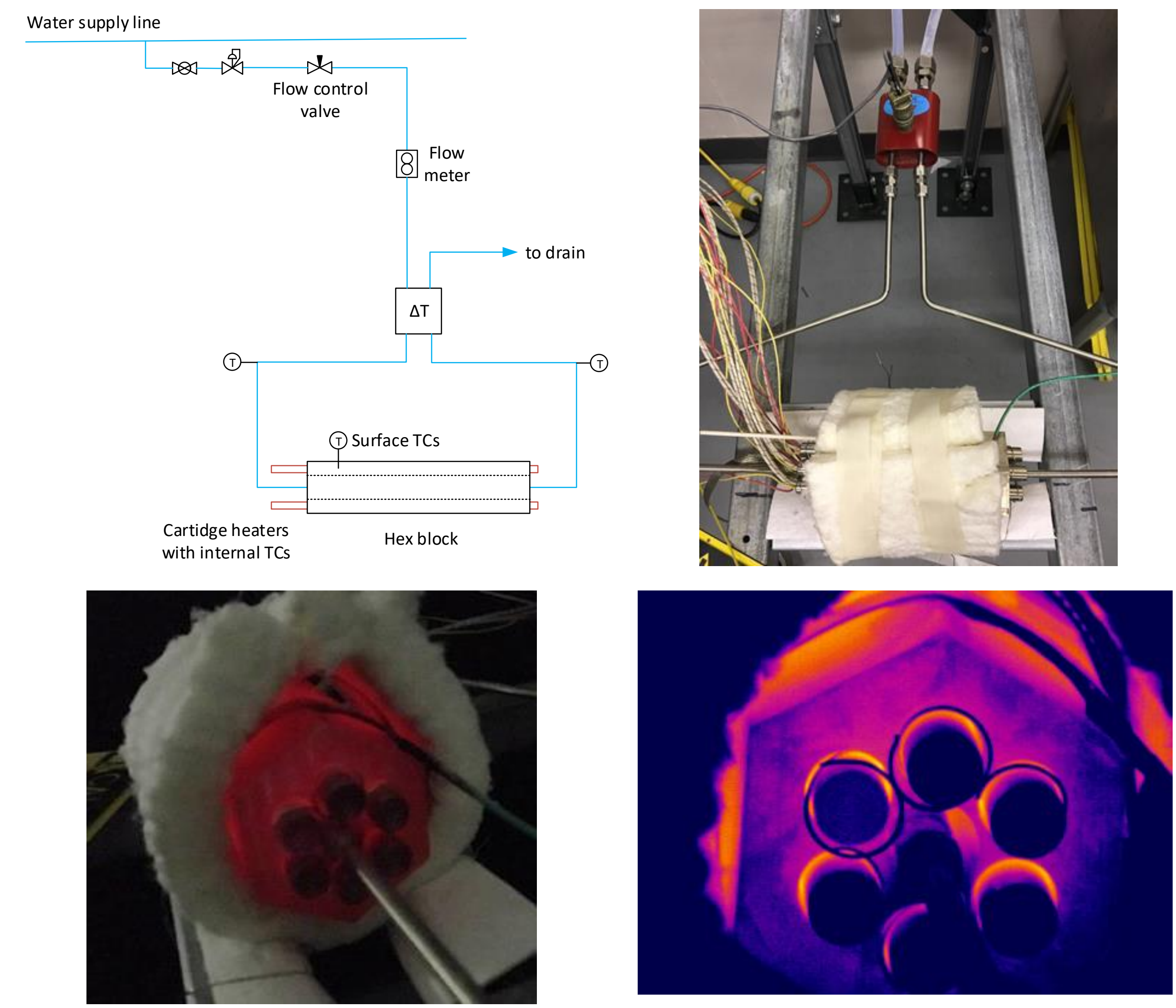


Figure 4. Preliminary single heat pipe experiment; (a) schematic of test setup; (b) photograph of test setup; (c) visible-spectrum photograph of hex block at ~650°C; (d) quantitative thermal imaging camera image of heated block.

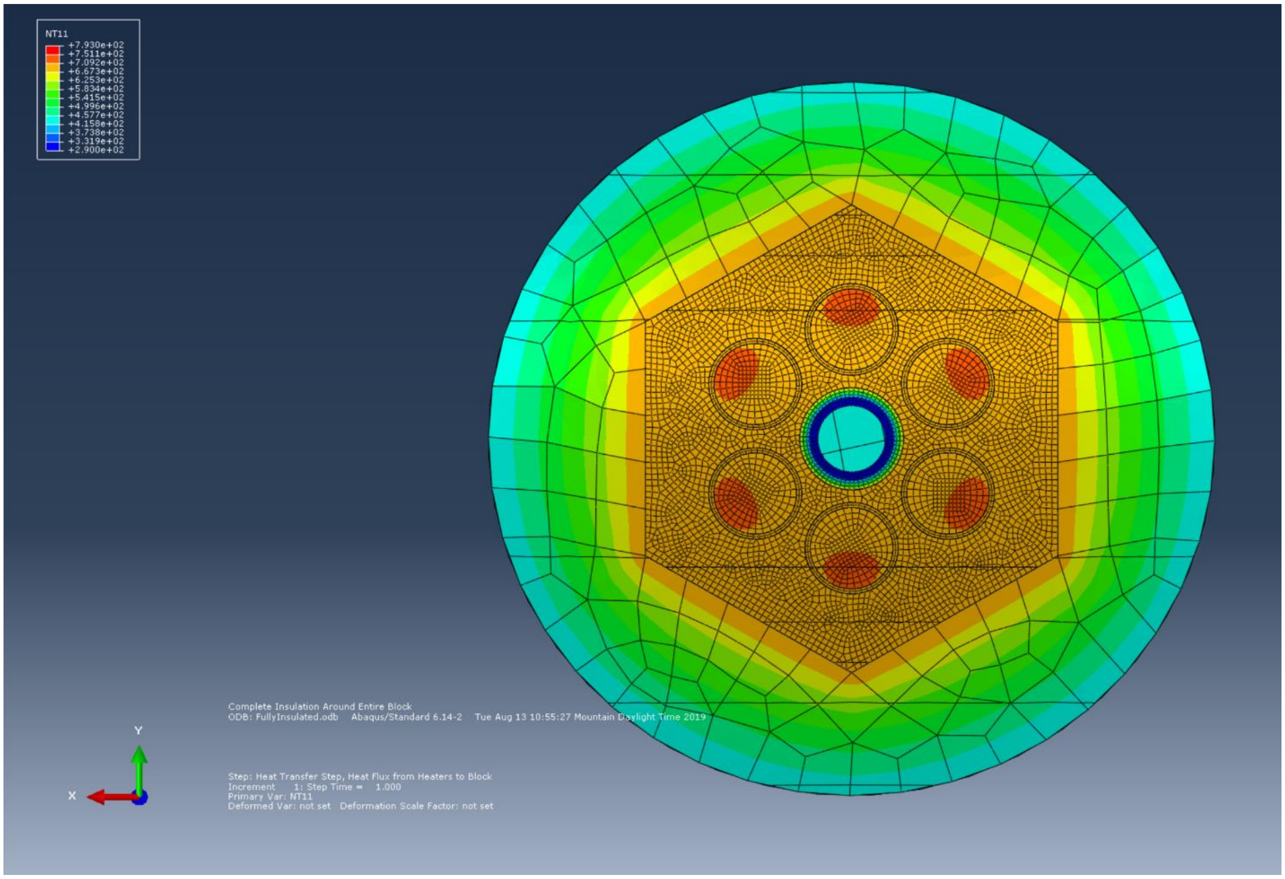


Figure 5. Finite element thermal analysis results for water-cooled simulated single heat pipe experiment.

LANL has fabricated the test article shown in Fig. 3 using additive manufacturing (AM) on the EOS M400-4 powder bed machine with 316L SS powder. LANL has built eight 11-inch long sections on two separate build plates utilizing the same process parameters and tool path. An image of the 11" long sections on a base plate is shown in Figure 6. These were fabricated in less than two days. The sections were band-sawed off of the build plate in preparation for joining and faced using a facing mill to ensure the ends were flat and parallel.

The method employed by LANL to join the two sections together was tier welding by using an electron beam welding system. Tier welding utilizes the high power and penetration of an electron beam to perform welding through cross sections with enclosed volumes.

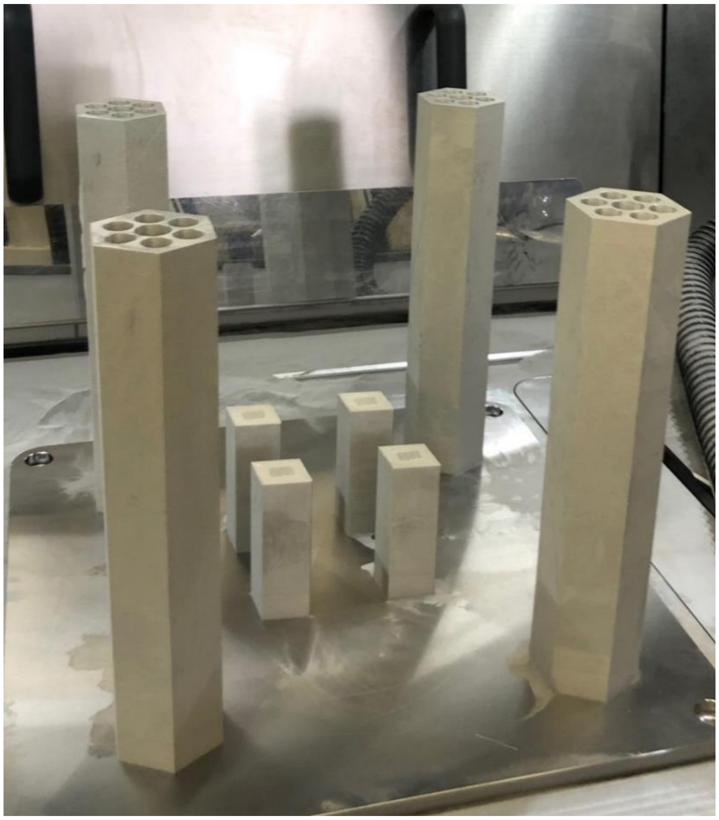


Figure 6. Four 11" tall sections of the Block 7 design within the build chamber of an EOS M400-4. Center blocks are to be used for mechanical testing.

Utilizing our new Probeam K110 system, the following process parameters were used to perform tier welds on the Block 7 design. Tests were performed on one of the monolith blocks that were 11” long to dial in the right parameter set. An image of cross-sectioned initial attempts can be seen in Figure 7.

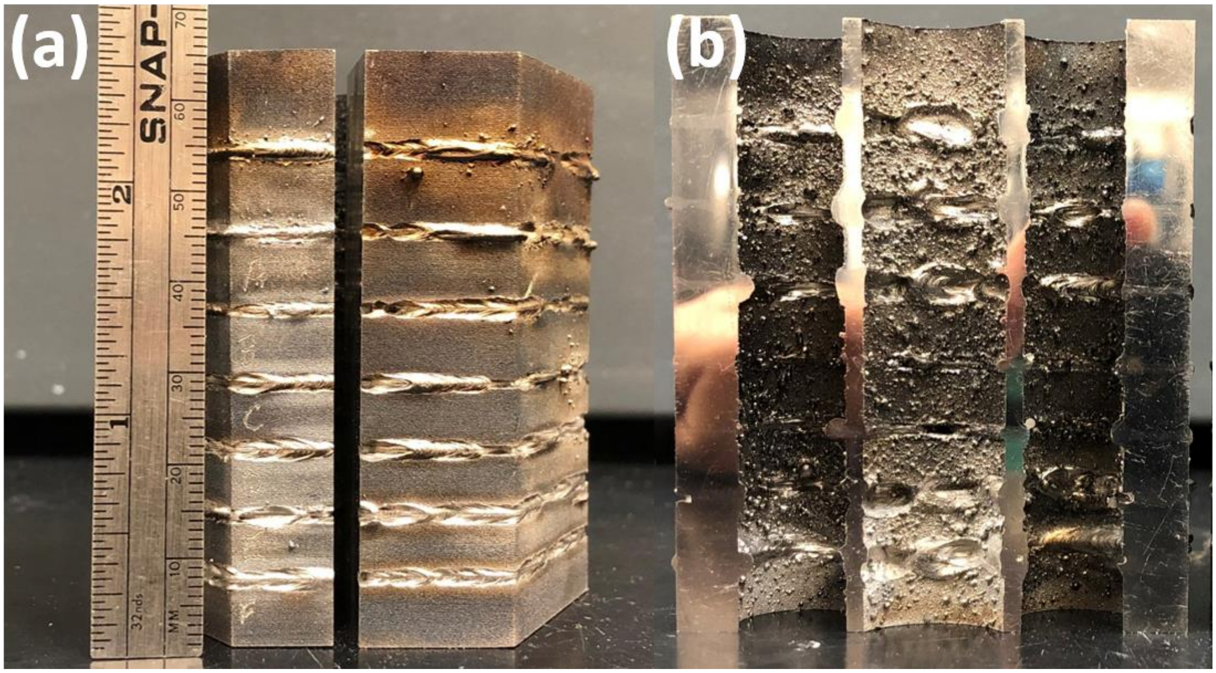


Figure 7. (a) image of tier weld development on a portion of an AM fabricated Block 7 article. Currents were varied between 35 mA and 17 mA. (b) Cross section showing penetration and spatter from each tier weld seen in (a).

Currents utilized in Figure 7 range from 35 mA to 15 mA. It was found that 17mA provided the most reasonable results in terms of penetration and minimized spatter. Therefore, a butt weld was performed using this current and showed promising results. The butt weld is seen in Figure 8. Two 11" long sections were then joined using the Probeam K110 system yielding a component that is seen in Figure 9. Two round pins were used to key and maintain alignment of the part during the tier welding process. A clamp was used to initially hold the parts together for a running tacking pass and then was removed for the 17mA pass performed while rotating the block. The result of the pins was not perfect and a more robust three pin design with diamond shaped pins will be used in the future.

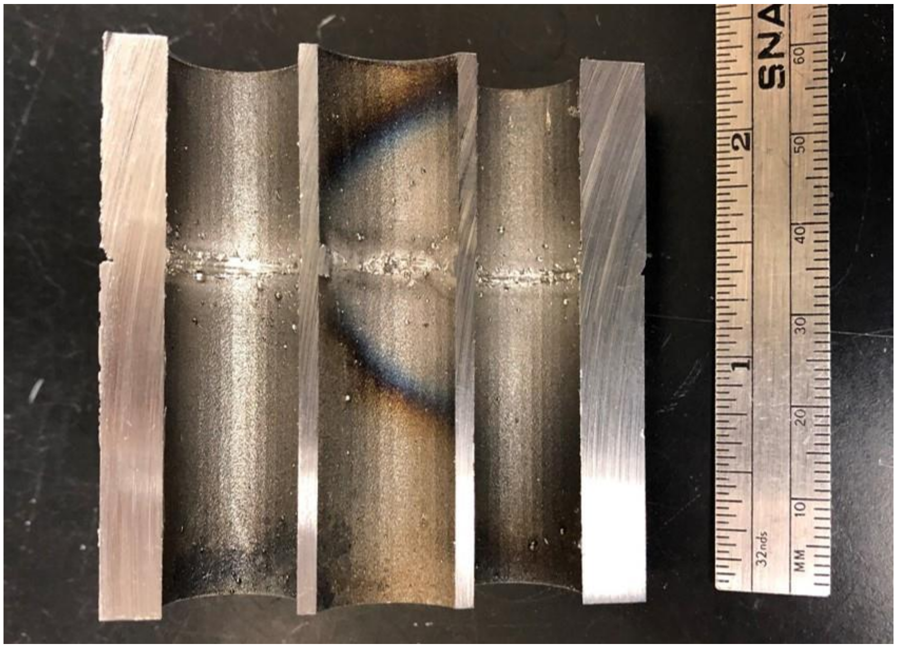


Figure 8. Butt weld of two AM fabricated Block 7 coupons using a 17 mA weld set-up. Note the excellent penetration and lack of spatter. No pins were used to maintain alignment for this test weld and some misalignment is visible.

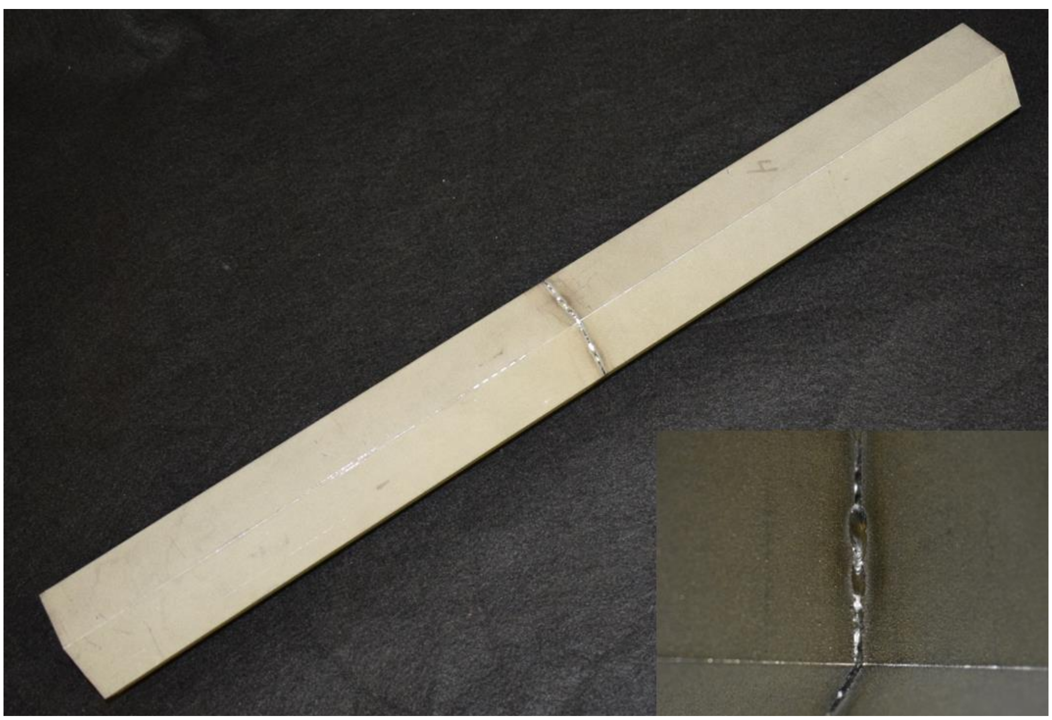


Figure 9. Image showing completed 22" long Block 7 design with a single tier weld performed during a rotary butt weld in an electron beam welder. Inset shows surface quality of the weld. Imperfections in fill at the corners as seen in the inset can be easily remedied with a cover pass.

Due to the size of the webbing, reaming will be performed to clean off spatter from the inside of the tubes. In addition, small amounts of material will be removed until the heat pipes can be successfully press-fit into the holes. Once this is concluded, LANL will add a single heat pipe to the center hole and ship that part to INL for testing similar to Figure 4.

More detailed thermal analyses were also performed for the Block 7 single heat pipe demonstration. The first was a power balance using a maximum heater sheath temperature of 760°C and perfectly insulated block walls. This power balance found that for the heat pipe to start up it is necessary to keep the heat pipe in a helium environment and add a copper helium conductive pathway between the block and the heat pipe. As shown in Figure 10, the power balance resulted in a heat pipe temperature of 685°C.

ambient	He, Cu	N2		
e1	0.3	0.3	-	heater emissivity
e2	0.3	0.3	-	block hole emissivity 1
e3	0.3	0.3	-	block hole emissivity 2
e4	0.3	0.3	-	heat pipe emissivity
k	0.27	0.02	W/m-K	gas conductivity
h	21	5	W/m2-K	gas natural convection film coefficient
d0	0.01270	0.01270	m	heater diameter
d1	0.01372	0.01372	m	block hole diameter 1
d2	0.01715	0.01715	m	block hole diameter 2
d3	0.01588	0.01588	m	heat pipe diameter
r0	0.00635	0.00635	m	heater radius
r1	0.00686	0.00686	m	block hole radius 1
r2	0.00857	0.00857	m	block hole radius 2
r3	0.00794	0.00794	m	heat pipe radius
	He + Cu	**N2**		
T1	**760**	**760**	**C**	**heater surface temperature**
T2	**704.1671**	**668.3163**	**C**	**block inside temperature 1**
T3	**704.1671**	**668.3163**	**C**	**block outside temperature 2**
T4	**685.6549**	**570.0221**	**C**	**heat pipe surface temperature**
qheater	1995	792.2938	W	heater power
qcond1	1732.676	449.3314	W	gas conduction from heater to block
qrad1	262.3245	423.4267	W	radiation from heater to block
qcond2	1978.828	802.8805	W	gas conduction from block to heat pipe
qrad2	16.17231	69.87701	W	radiation from block to heat pipe
qrad3	1009.378	599.6864	W	radiation from heat pipe to ambient
qconv	981.2113	192.6074	W	gas convection from heat pipe to ambient

Figure 10. Block 7 power balance.

For further analysis, a CAD model of the Block 7 experiment was made and then imported into ANSYS Workbench 2019 R1. Figure 11 shows the CAD model of the block 7 and heat pipe.

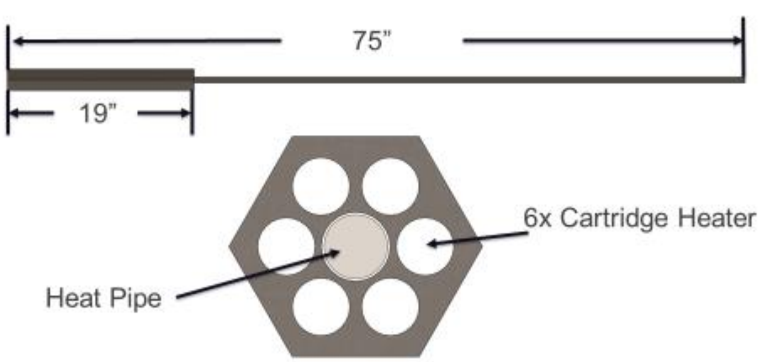


Figure 11. Block 7 and heat pipe model.

The CAD model was put into ANSYS for a coupled steady state thermal and static structural simulation. Once in ANSYS workbench the geometry was partitioned in design modeler to provide a structural mesh consisting of approximately 700,000 nodes and 150,000 hexahedral elements. In addition to the block and heat pipe, a conduction path was added to the model to simulate the conduction of the helium and helium with copper in the small gaps between the heaters and the block and the block and the heat pipe, respectively. Figure 12 shows a front view of the mesh.

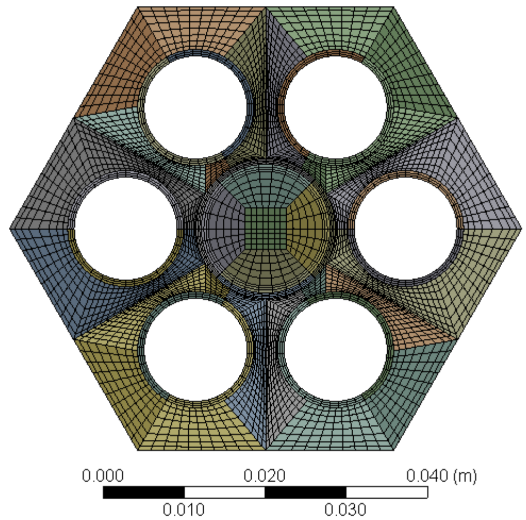
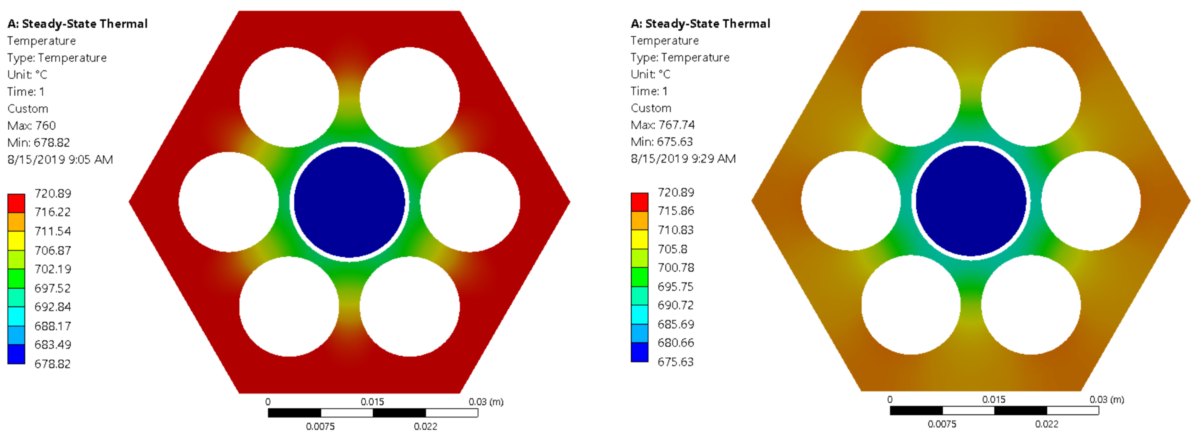


Figure 12. Block 7 and heat pipe model mesh.

The boundary conditions or the ANSYS simulation included a fixed condition on the back surface of the block and heat pipe, adiabatic on the exterior block walls, radiation from the heaters to the block, and convection and radiation on the condenser section of the heat pipe. For the first simulation a constant sheath temperature of 760 °C was used. The heat pipe temperature resulting from this boundary condition was approximately 680 °C. An additional simulation was ran using the calculated thermal power provided by the heaters. Figure 13 compares the temperature profiles in each case.



Constant Temperature 760 C **Constant Power 1995 W**

Figure 13: Block 7 temperature profile resulting from different boundary conditions.

As the coupling of the expanding heated block to the relatively cold heat pipe represents the limiting thermal resistance for the system, results are sensitive to the thermal bridge condition. During these tests a close fitting copper wire coil will thermally link the heat pipe exterior to the block interior hole. This coil will improve thermal conduction between the block and the heat pipe. In addition to the temperature profiles, the deformation was also studied. For both the constant temperature case and the constant heat flux case the maximum deformation was 0.015 m at the end of the heat pipe. This is because the majority of the deformation is caused by thermal expansion and the heat pipe temperatures in both cases were very similar. Figure 14 shows the deformation on the model.

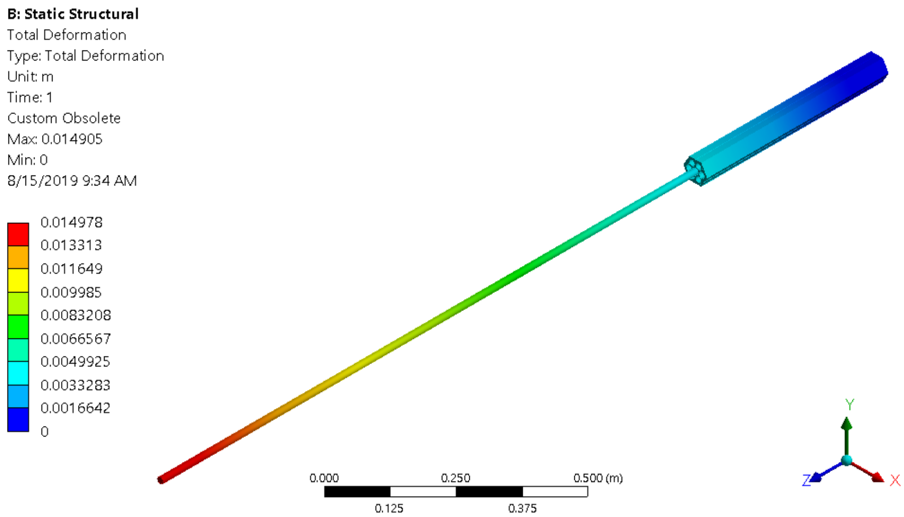


Figure 14. Block 7 deformation resulting from thermal expansion.

6.2. Preparation for 37 heat pipe article

Research and development efforts in three areas are underway in preparation for a 37 heat pipe test article development in FY20. First, an e-fill machine for loading heat pipes into the article is being procured. Second, wicks are being purchased for the heat pipes. Finally, studies are being performed to determined what type of heat exchanger will work best for the test article. The former two items are described in this section and the latter will be detailed in a different but related report for the microreactor project. Details of the 37 heat pipe test article are also described in that report.

Fabrication of the 37 heat pipe test article will follow a process similar to that used for the 7 hole article but this part will be much longer and will require more parts to be joined. In addition, a heat exchanger will interface with heat pipes to produce high-temperature process heat for power conversion or other applications. Integration of the heat pipes and the heat exchanger with the core is still an active area of investigation and analysis. Although the majority of FY19 heat exchanger research will be described in the separate report, two types of heat exchanges are under consideration: a printed-circuit style heat exchange and a modified shell-and-tube configuration. Heat pipe reactor cores typically include hundreds or even thousands of closely spaced small-diameter holes to accommodate fuel and heat pipes in a large steel monolith. Fabrication of the core with conventional drilling techniques to the required tolerances is not possible for the core depths under consideration (e.g., 1.5 m). An alternative fabrication method would be to stack and join a large number of relatively thin pre-drilled plates using diffusion-bonding, welding, or other techniques. The same technique could also be used to fabricate a mating monolithic primary heat exchanger section for heat removal with a design similar to printed-circuit heat exchangers (PCHEs). A PCHE heat exchanger section would include numerous relatively thin plates with chemically etched channels through which the coolant gas would flow transverse to the heat pipe condenser sections. The specific geometry of the gas flow channels will be optimized for high heat removal with minimal pressure drop. The heat pipe condenser sections could be formed from pre-drilled through-holes as an integral part of the PCHE plates. Other heat exchanger designs such as shell and tube are also under consideration. In this case, the heat pipe array forms the tubes of the shell-and-tube geometry. A second heat exchanger designed specifically for passive rejection of decay heat is also included in the system design. Refinement of the engineering design and fabrication challenges associated with these materials and complex geometries could be accomplished through the development and operation of an appropriately scaled test, but a workable interface between the heat pipes and heat exchanger still needs to be explored further before any one design is built.

Heat Pipe Fill Machine

To date, low volume production of alkali metal heat pipes reflects their developing technology readiness level. In 2002, Los Alamos built a general-purpose alkali metal fill system for use at NASA Marshall Space Flight Center. This system allowed the fill of individual potassium, sodium, or lithium heat pipes in a low oxygen, water, and nitrogen inert gas environment (typically <1 ppm). Although this system was dependable with moderate flexibility and complexity, this system still required a *skilled* operator. Further, this system was design to fill only a few individual heat pipe modules per day. While the fill system performed well for low volume development efforts, the system was ill suited for automated industrial fill of alkali metal heat pipe arrays. Recent interest in very small modular nuclear reactors motivates the development of a rapid and cost-effective fill system that fills and seals arrays of heat pipes with high purity alkali metal, such as sodium, in a mass production environment. Thus, an alternative heat pipe reactor fill tool (the “fill tool”) to address challenges associated with heat pipe manufacturing, e.g., those related to mass production, is needed.

During FY 2018 under a different but related program, a fill system was developed to charge a seven heat pipe core with high purity sodium and to close the core heat pipes under high vacuum by laser welding under vacuum. A high precision sodium metering mechanism was developed and techniques to fill and weld the assembly were outlined. By the beginning of FY 2019 the project had reached a point where the single degree of freedom and the eFill7 system had reached maturity. Work commenced in earnest on scaling the eFill system to larger sized heat pipe cores. During FY 2019 a two degree of freedom eFill61 design was generated to enable fill of an array of heat pipes across two dimensions and is planned to be used for the 37 heat pipe test article.

Scaling of the hardware to arbitrary size was addressed along with techniques for scaling structural supported. The structural support problem was solved was through modular use of 80/20 framing. Throughout FY 2019, techniques were develop to robustly achieve heat pipe closure by placing and welding plugs on the end of heat pipe reactor cores of arbitrary size. The eFill7 system had a plug sheet that would drop into the heat pipe holes. This plug sheet would be put into position either through a pusher rod or the fill stem itself. The plugs would be then welded to the end of the core via a high powered laser. Applying the same approach to the eFill61 would position the plug sheet outside of the chamber, making vacuum closure impossible. Many ideas were discussed. One consisted of a plug sheet with plugs resting between heat pipe holes during fill. To cover the heat pipe holes with plugs a linear pusher would shift the plug sheet about a heat pipe diameter allowing it to drop into core block hole-pattern. The plugs are then electron beam welded to the core block as shown in Figure 15, which is satisfactory until an alternative can be found.

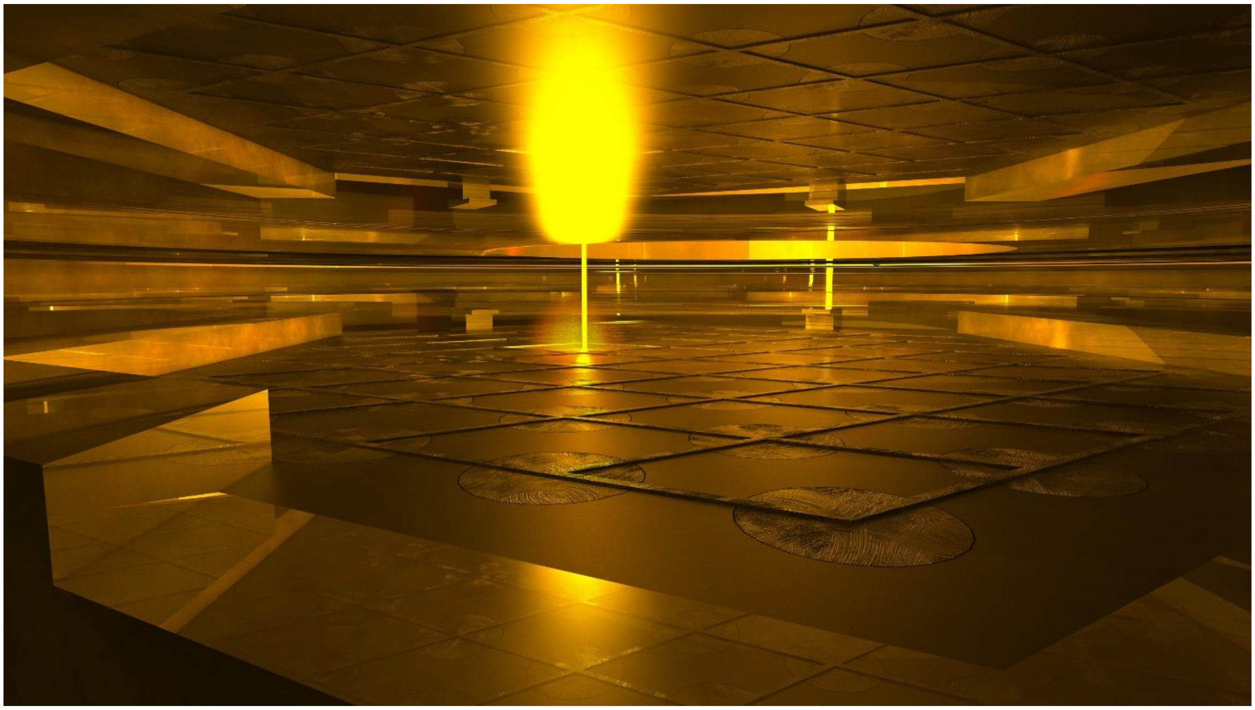


Figure 15. Laser weld of plug sheet to core block.

The following fill sequence was also developed to ensure quality.

1. Prepare sodium source to achieved desired pre-fill purity.
2. Position closure assembly on monolith face.
3. Attach monolith to chamber assembly.
4. Attach chamber assembly to sodium process assembly.
5. Evacuate sodium process assembly and chamber assembly by successive dilution with helium to 0.1 mbar pressure and then to 10^{-6} mbar.
6. Heat sodium process assembly above 110°C and prime sodium assembly with sodium.
7. Open chamber access gate valves.
8. Position rotary platforms to align sodium process assembly with heat pipe cavity.
9. Lower sodium process assembly into a monolith heat-pipe cavity.
10. Dispense sodium into heat pipe.
11. Solidify sodium in sodium process assembly (optional).
12. Raise sodium process assembly above core plane.
13. Repeat steps 8 to 12 filling all heat pipes.
14. Retract sodium process assembly into bellows and close gate valves.
15. Remove sodium process assembly with interior under dynamic vacuum.
16. Place laser transmission assembly atop gate valve.
17. Evacuate laser transmission assembly to 0.1 mbar helium pressure by successive dilution.
18. Move plug sheet into position.
19. Position rotary platforms to align weld assembly with heat-pipe cavity plug.
20. Laser weld plug while monitoring chamber pressure and RGA signature.
21. Repeat steps 19 and 20 to complete welding of all plugs to the monolith.
22. Conduct bulk weld inspection by chamber evacuation and helium leak test.

23. Separate chamber from monolith flange.
24. Remove closure webbing.
25. If warranted, examine individual heat-pipe welds with inspection tool.

Most key parts for the eFill61 have been ordered with delivery of the longest lead time items estimated to be November. Assembly of the eFill61 will begin in early FY20.

Wicks

Heat pipes serve in a range of applications such as electronics, spacecraft, and nuclear power conversion. This results from their flexibility in terms of size, heat transfer capability, and angle of operation. Fluid return to the hot zone through a high performance wick drives this versatility.
A comparison between thermosiphons and heat pipes demonstrates wick utility and adaptability. A wick creates capillary action that drives fluid circulation, while thermosiphons rely solely on gravity to operate. Thermosiphons must operate inclined, with the heated region being at the bottom. Because heat pipes rely on capillary action rather than gravity to function, they can operate at any angle within its wicking height and even in microgravity environments, such as in space.

The shape of the heat pipe wick imposes order on a saturated liquid by (1) forming menisci between the condensate and the vapor and (2) allowing condensate to flow toward the heated zone. Simple heat pipe wicks are homogeneous with a uniform pore structure requiring condensate to flow axially through the same pore structure that forms the surface menisci. Figure 16(a) depicts a cross section of a homogeneous wick. A homogeneous wick that produces a high capillary pressure rise typically has high resistance to condensate flow limiting the axial heat transfer rate.

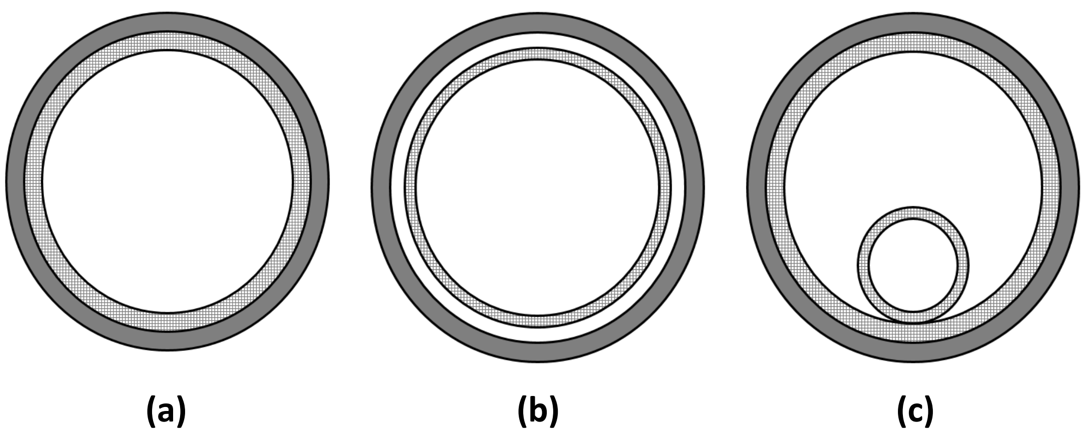


Figure 16. a) Homogeneous, b) concentric annular, and c) artery wick geometries.

In the heated zone of a heat pipe, evaporation of the liquid produces vapor and increases pressure on the concave side of the wick's meniscus. This pressure rise drives vapor toward the cooled zone and returns condensate to the heated zone through the wick. For a heat pipe to work correctly, the maximum capillary pressure rise, governed by largest pore in the heated zone, must be greater than the pressure drops in the liquid and vapor regions: $\Delta p_{max} \geq \Delta p_l + \Delta p_v$. The pressure drop in heat pipe wicks, Δp_l, is viscous and so is linear with local mass flow rate. The effects of stable vaporization to the heated region combine with unstable condensation of vapor in the cooled region. Viscous and turbulent inertial effects (with possible pressure recovery) may contribute locally to the vapor zone pressure change, Δp_v. Compound wicks address the performance limitations of homogeneous wicks. Two compound wick geometries appear especially attractive for high power density liquid metal heat pipes: an annular gap and an artery wick. Figure 16(b) and (c) depict cross sections of each of these wicks. The annular wick allows condensate to freely flow toward the hot zone in a gap between the pipe inner surface and the outer surface of the porous material on which menisci form. Artery wicks are similar to homogeneous wicks in that their outer diameter mates with the inner diameter of the heat pipe and inner diameter sits at the liquid-vapor boundary. Artery wicks may incorporate one or more non-concentric arteries that create channels for free condensate motion. To maintain capillary continuity, a solid plug seals compound wicks on the end nearest the heated zone. A compound wick normally remains open at the cold end to ease fill. As a heat pipe warms, its working fluid expands. When the heat pipe is isothermal, excess condensate (typically 5% of charge) seals the condenser end of the wick ensuring capillary continuity.

During FY19 a procurement was placed for fifty concentric annular wicks with a design called the eWick. The eWick is a unique process developed by LANL subject matter experts. eWick is the key component to remove heat from core structures. Since core heat removal enabled by eWick is safety-critical, eWick function must comply with strict ASME NQA-1 Quality requirements at and above ML-2. The following materials and services were sought:

1. Custom built high temperature tube vacuum furnace to fabricate wicks.
2. Completed wick assemblies, (50 in total).

The eWick is a LANL defined process. LANL subject matter experts are not aware of any commercial source that offers a structure functionally equivalent to the eWick. A market survey conducted by a commercial company independently confirmed the lack of commercial sources for equivalent technology. The NQA-1 requirement further limits the availability of commercial sources.
The performance offered by the eWick is required to meet technical and safety objectives associated with the core demonstration. To meet this aggressive schedule qualified eWick components must be available by next year. UHI is the only source on the LANL IESL capable of assembling eWick to ASME NQA-1 standards consistent with program schedule. Competition was not sought since only one responsible source and no other suppliers or services will satisfy laboratory requirements.
In accordance with the SD330, Los Alamos National Laboratory Quality Assurance Program and P840-1, Quality Assurance for Procurements, ML-1/ML-2 procurements invoke ASME NQA-1-2008/NQA-1a-2009 Quality Assurance Requirements for Nuclear Facility Applications. Companies listed as an “Institutional Supplier” on the Institutional Evaluated Supplier List (IESL) meet such requirements unless indicated otherwise. The proposed supplier, UHI, is the only LANL approved NQA-1 supplier listed on the IESL qualified to support this technology.

LANL subject matter experts are not aware of any commercial source that offers a structure functionally equivalent to the eWick. UHI has extensive experience with relevant processes involved in construction of the eWick including but not limited to high pressure forming and construction of high temperature furnaces such as the DOE sponsored Aries HDH and Aries DMO.

Unusual and compelling urgency exists and the time available is insufficient for soliciting competition. The production of a reactor core demonstration is scheduled by DOE customers for next year. The performance offered by the eWick is required to meet technical and safety objectives associated with the core demonstration. To meet this aggressive schedule qualified eWick components must be available by early next year.

Upgrading of a non-NQA-1 supplier's quality assurance program to the NQA-1 standard, evaluation of the supplier, approval of the program and placement of the supplier on the IESL is a very costly and time consuming process that could take several months, and the NQA-1 audit results cannot be guaranteed. UHI is the only source on the LANL IESL capable of assembling eWick to ASME NQA-1 standards consistent with program schedule.

- LANL has previously produced eWick technology at the R&D level and has a broad experience base to ensure any contract price is fair and reasonable.
- LANL has previously invested in relationship development and training of this supplier. It would be neither cost effective nor efficient to attempt to educate a new supplier to support this effort.

Since eWick is central to any technology demonstration with heat pipes, any eWick delivery delay may adversely impact program deliverables, up to and including possible overall program cancellation. Qualifying non-NQA-1 sources to IESL takes significant time (months or more for a vendor to upgrade their program to NQA-1 standards, self-audit, and then participate in LANL NQA-1 audit). Source qualification would lead to significant program delays and would introduce cost that the program would be unable to fund. Also, attempts to solicit unqualified vendors introduces significant schedule risk since, for example, any source that we would attempt to qualify may not eventually pass the LANL NQA-1 audit. As of this writing quotes from UHI, in close agreement with independent estimates, have been obtained. The eWick package has entered the LANL procurement system. Management approvals have been obtained and the UHI has been contacted. We await a response from the vendor to conditions in the overall bid package.

7.0 Conclusion

A nonnuclear test bed will provide numerous opportunities for laboratories and vendors to demonstrate technology and design opportunities for microreactor designs that can eventually lead to nuclear testing and demonstration. In FY19, a test bed design has been established and preliminary test articles are being manufactured for testing in FY20. Additional test articles are being designed for fabrication in FY20. Functional requirements for the test bed and articles were developed during a working group meeting in April 2019 at LANL, and a preliminary design review meeting for the single heat pipe test article occurred in June 2019 at INL. Bi-weekly phone calls between relevant parties have taken place to establish communication and a path forward for further development, and we are in good shape to carry on with establishment of the test bed and to perform subsequent tests in FY20.

The nonnuclear test bed capability is an important functionality for the national laboratories to establish to test microreactor parts and to aid vendors in the demonstration of equipment. Advancing technology maturation in general is another goal of the nonnuclear test bed, so design and build of appropriate test articles is also important. Two test articles were established in FY19, and a single heat pipe experiment is being planned for early FY20, followed by a test of a third test article with 37 heat pipes in FY20. Once the test bed is established, others should be able to bring test articles to it for further demonstrations in the future.

Acknowledgements

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Appendix A. Breakdown of responsibilities by lab

1. LANL
    a. Monolith structure fabrication (core block)
    b. Heat pipe for single heat pipe experiment
    c. Procure wicks for 37 heat pipes for larger experiment
    d. Order parts for fill machine for heat pipes
    e. Design heat pipes and interface with heat exchanger for 37 heat pipe experiment
    f. Provide sensors such as DIC and/or more for temperature, stress, strain, fatigue, etc.
    g. Measure parts of core block before and after experiment (will need samples for XC2 analysis at LANL)
    h. Perform thermal analysis on proposed test article and analyze results of experiment.
2. INL
    a. Core block and heat removal section baseline for single heat pipe test (see drawing below).
    b. Design of potential interface with core block and heat removal section
        i. Simulate
        ii. Initial coolant flow may be open or closed
    c. Current plan is for PCHE
    d. Coolant (air) and associated hardware
        i. Blower
        ii. Ducting
        iii. exhaust
    e. Heaters
        i. Heater thermal output equal to or greater than 24 W/in^2 and controllable from 24 W/in^2 to 0 power.
        ii. Heater control on power or by temperature
    f. Test bed
        i. Test vessel
            1. Inert gas capability
            2. Vacuum capability of 10^{-X} Torr
            3. Adequate feed-throughs
            4. Material handling access ports
        ii. Power leads capable of handling 250 kW to the core block
        iii. Instrumentation
            1. Basic
                a. Coolant flow rate and temperatures
                b. External temperatures
                    i. TCs
                    ii. Thermal imaging camera
            2. Advanced
                a. Internal temperatures – fiber optic
    g. Detailed Analysis
        i. Core block
            1. Temperature distributions

2. thermal stresses

ii. heat removal section

1. CFD and temperature distributions (Star CCM)
2. Thermal stresses (ABAQUS)

iii. Heat pipe performance

1. Affects both core block and heat removal sections
2. Coupled with heat removal section fluid flow and heat transfer