MICROREACTORS: A TECHNOLOGY OPTION FOR ACCELERATED INNOVATION

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Meet the Presenters

Dr. Dasari V. Rao is a nuclear and mechanical engineer with 25 years of experience in safety and safeguards of nuclear and high hazard facilities. His technical areas of expertise include computational fluid dynamics, neutron and radiation transport, and risk assessment of nuclear energy systems. He has over thirty publications in these fields.

Dr. Rao is presently Director of the Office of Civilian Nuclear Programs at the Los Alamos National Laboratory. He is also Technical Advisor to Dr. Jess Gehin, National Technical Director for DOE Microreactor Program, and Principle Investigator for the NASA's Fission Surface Power project. Dr. Rao has been involved in the Microreactor R&D since its inception; and he is the lead designer at LANL for several concepts. Prior to that, he was Reactor Safety Committee Chair for Los Alamos Critical Machines and National technical Lead for Generic Safety Issue-191.

Dr. Holly Trellue earned her PhD in nuclear engineering from the University of New Mexico in 2003. She is a team leader at Los Alamos National Laboratory, the Technical Area Lead for Technology Maturation for the DOE-NE Microreactor Program, and has experience in reactor simulations and safeguards.

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Meet the Presenters (cont.)

Mr. Yasir Arafat is currently serving as the Technical Advisor to the DOE Microreactor Program from Idaho National Laboratory. He has 10 years experience in leading and executing research and development projects, primarily in advanced reactor development. He was the founder and Technical Lead of the Westinghouse eVinci™ Micro Reactor Program, where he was responsible for leading the overall product design, technical and programmatic development of the microreactor designs.

Mr. Arafat specializes in systems engineering, advanced manufacturing, thermochemical process modeling and simulation and innovation strategy. Mr. Arafat's nuclear systems design experience comprises the Westinghouse AP1000®, Westinghouse SMR, fusion power plant, eVinci & DeVinci microreactors and fission batteries. Mr. Arafat has been granted 4 patents for his inventions, with 10 additional patent applications under review.

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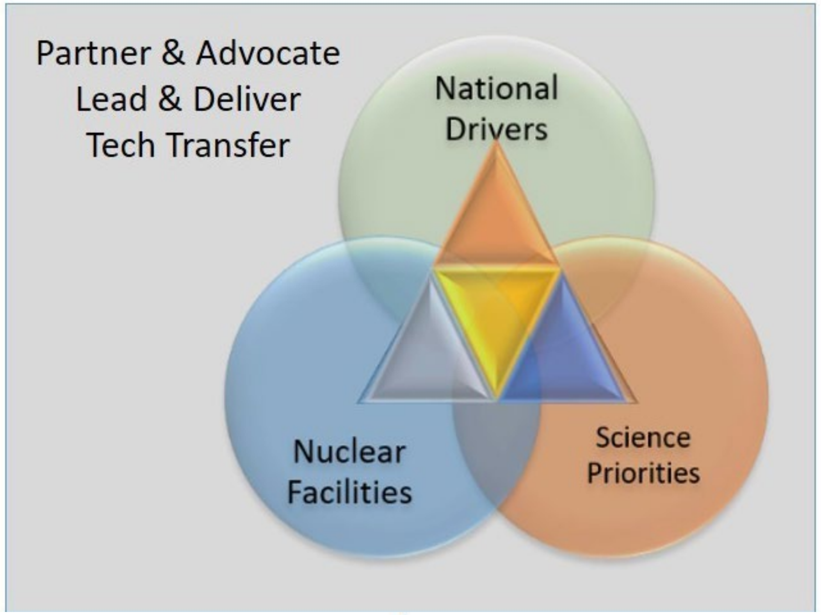
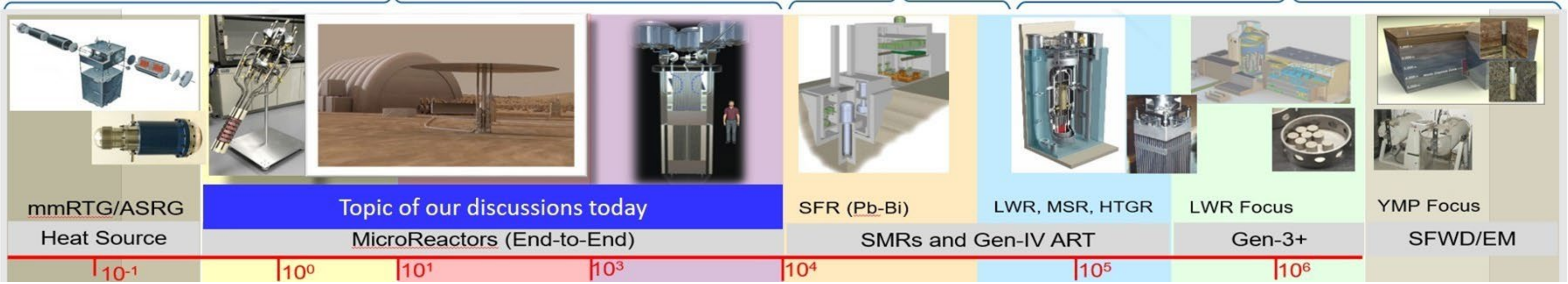
Microreactor R&D at a Glance

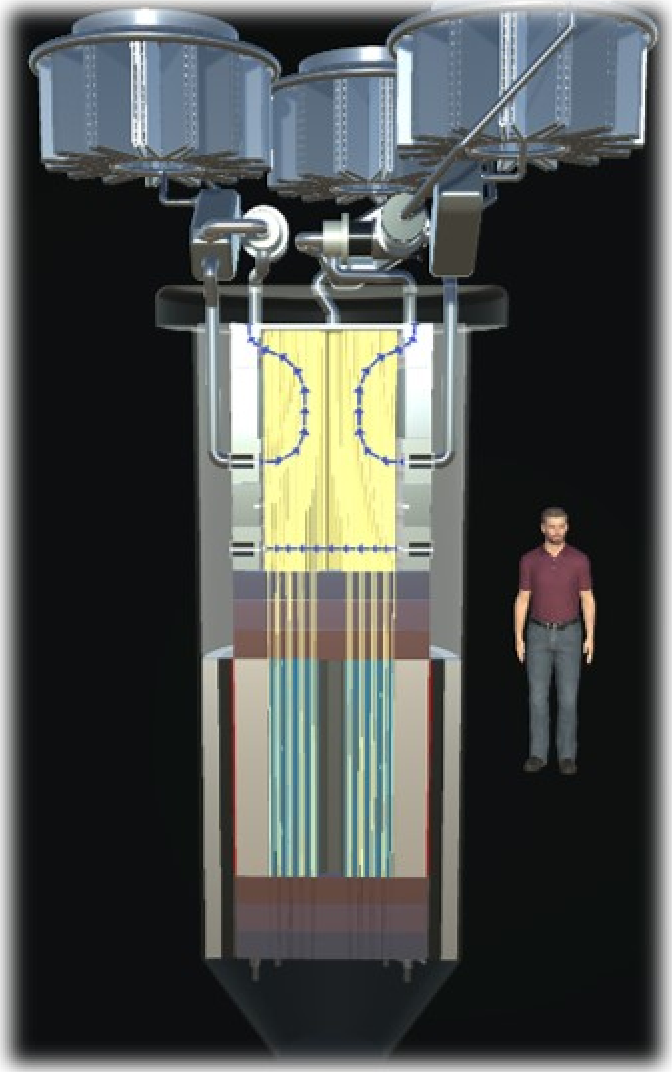
- **National Drivers**
  - Innovative, Affordable and Rapid
  - DoD and Civilian Microgrids
- **Nuclear Facilities and Technologies**
  - Fuels (HALEU)
  - High Temperature Moderators
  - Nuclear Data
- **Prototypes**
  - Advanced Manufacturing
  - Sensors and Structures
  - Sub-scale simulation test objects
- **Integration**
  - Multi-scale, nuclear validated codes
  - Test Beds: EDU and NDU
  - NRIC





Typical Microreactor Design

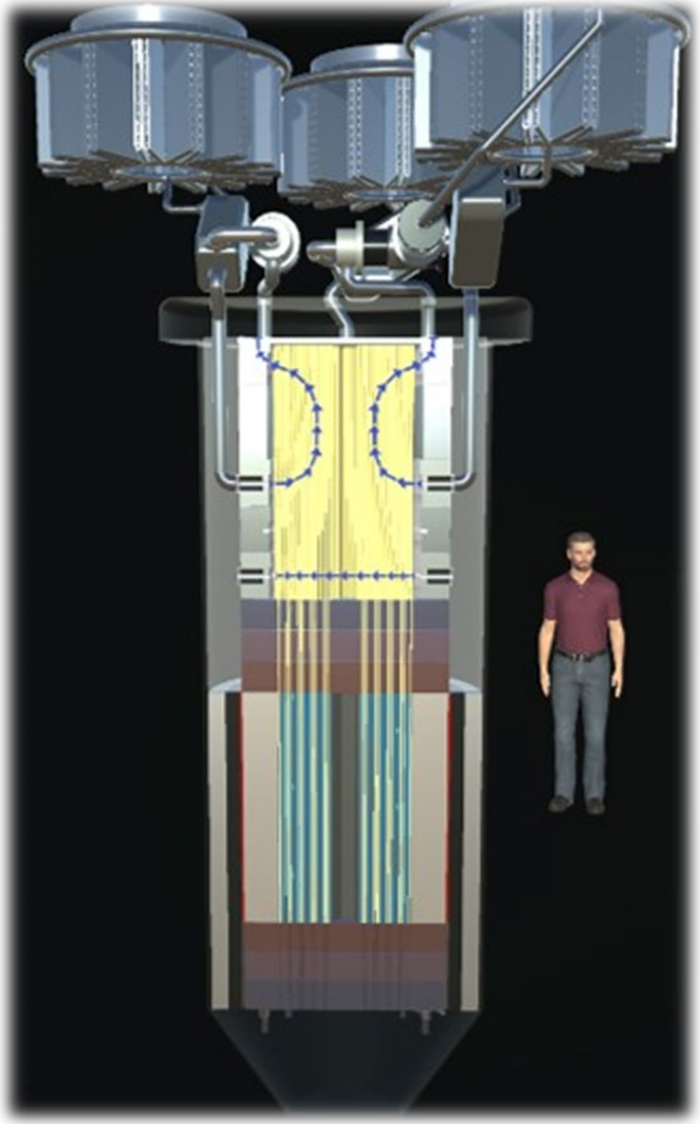
- Reactor designs include following options:
  - HALEU Metallic, Ceramic or TRISO Fuels
  - Fast, intermediate or thermal neutron spectrum enabled by a mixture of high temperature hydrides, beryllium and graphite
  - A large reflector that also performs as a thermal sink and houses control drums
  - Heat pipe-, gas-, molten salt- cooled
  - Brayton power conversion (with or without intermediate HX)
- Structural material options include
  - Metals
    - High temperature creep-resistant steel
    - Molybdenum
  - Ceramics
  - Graphite

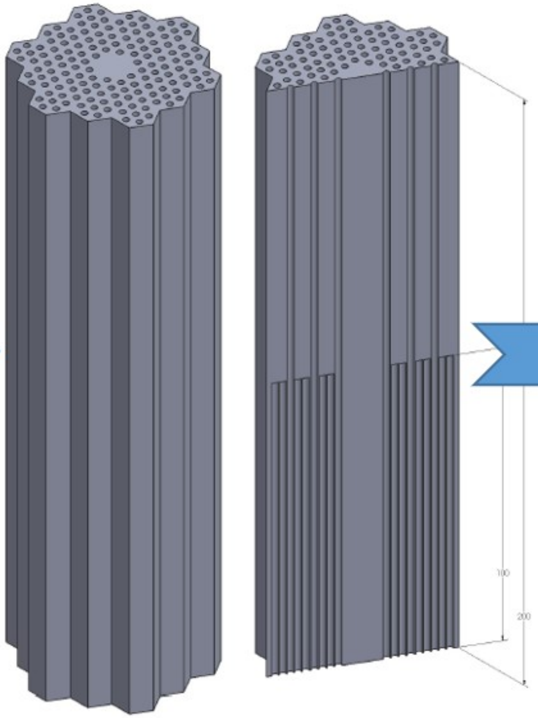


Key Technology Enablers

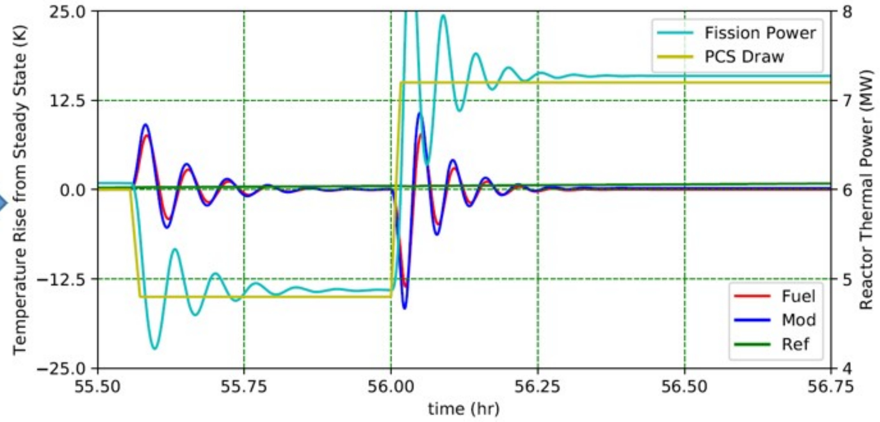
Factory Built ◆ Easy to operate ◆ Easy to license

Designs may vary, but challenges are similar…..
…. So, R&D focus is concept and technology neutral





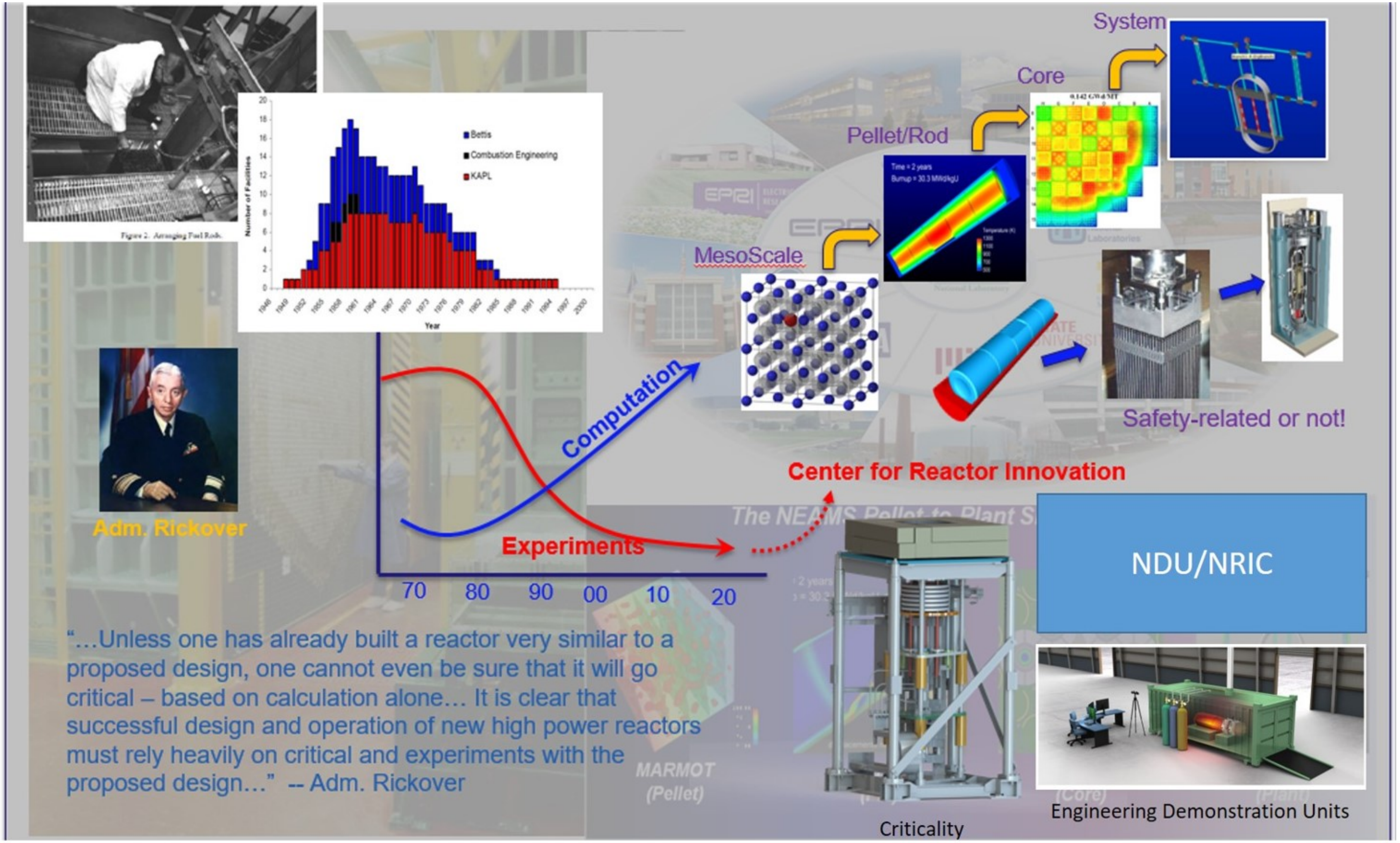
Understanding manufacturability and licenseability



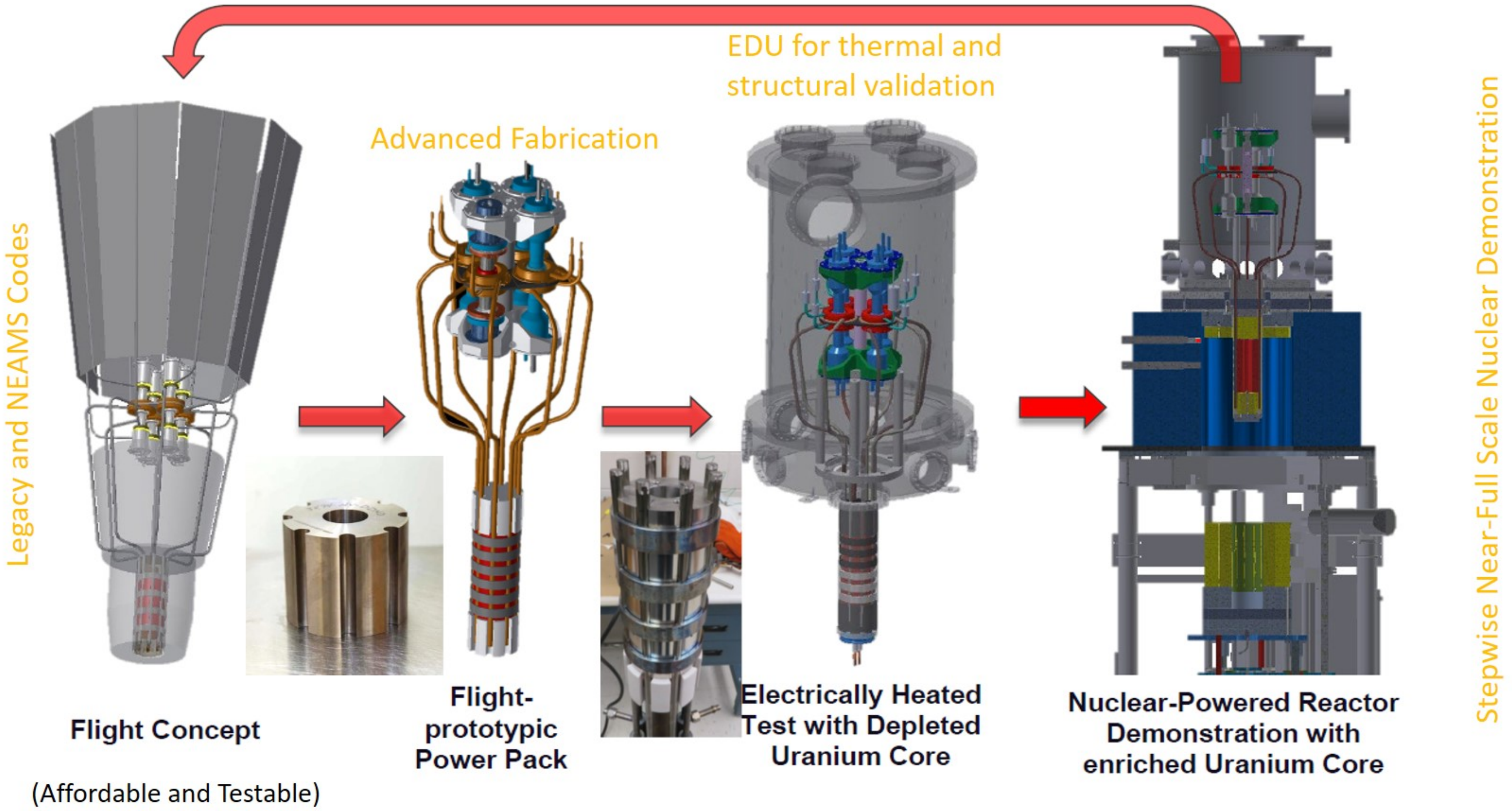
Demonstrating safety, stability and ease of operability

Challenge: Nuclear Demonstration Infrastructure is limiting Nuclear Innovation

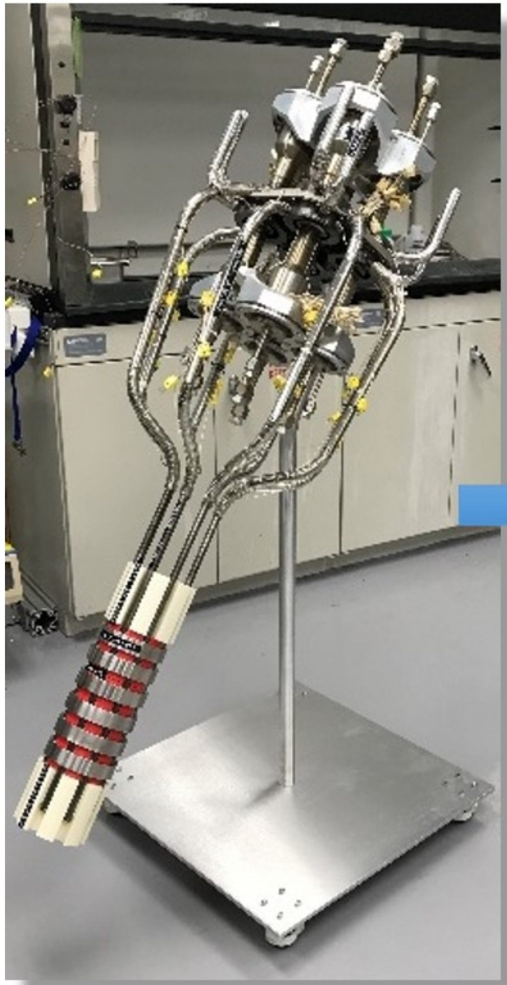
How to bridge the gap between Design State-of-the-art vs Regulatory State-of-the-art?

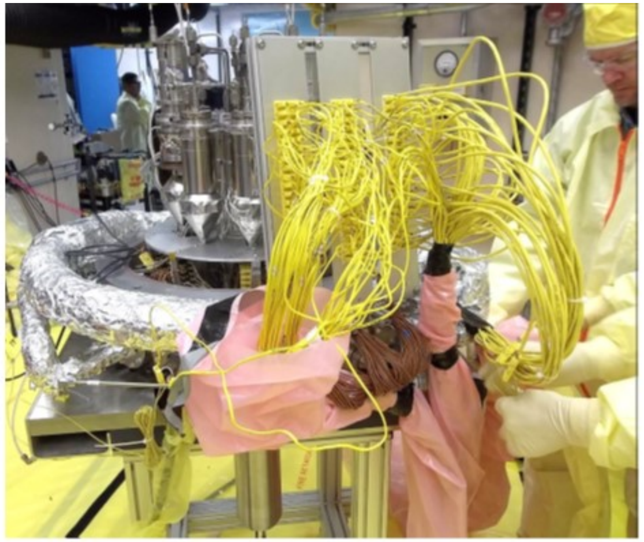


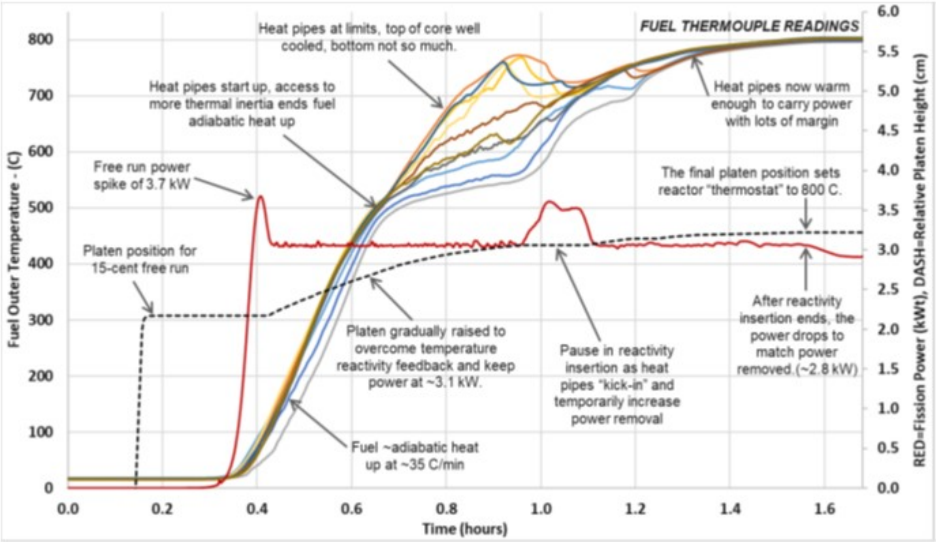
Microreactor Development Approach "Separation of variables": EDU vs NDU

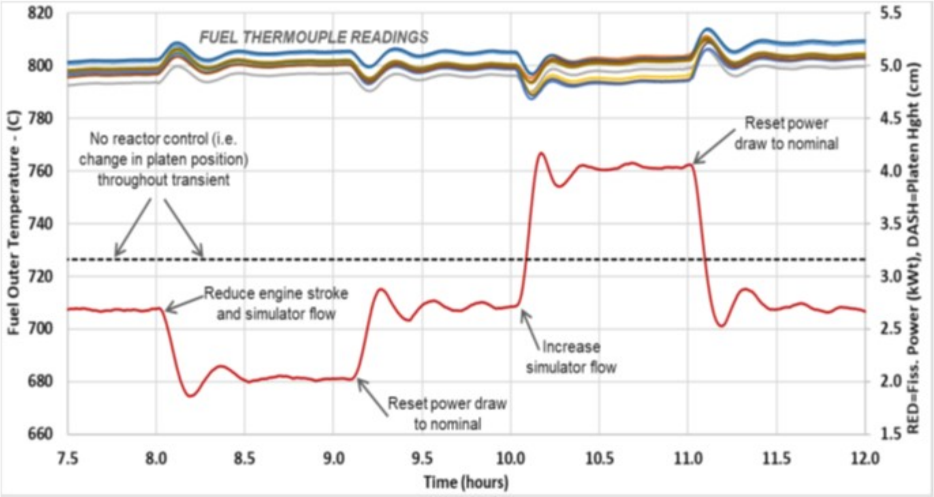


Microreactor Development Approach: Uncertainty Reduction
“Admiral Test” can be scaled!









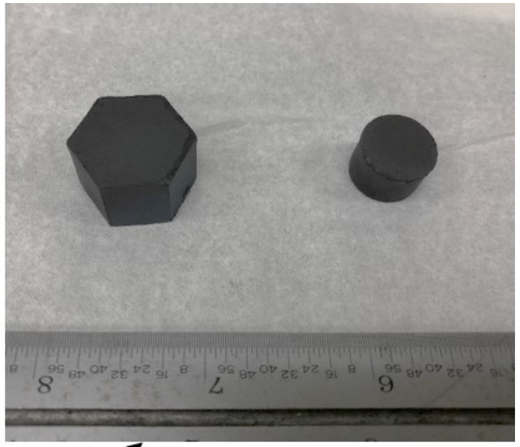
Materials and Technology Maturation

Materials – Fuels, Moderator, Structures

Heat Removal and Integrated Testing

Microreactor Materials

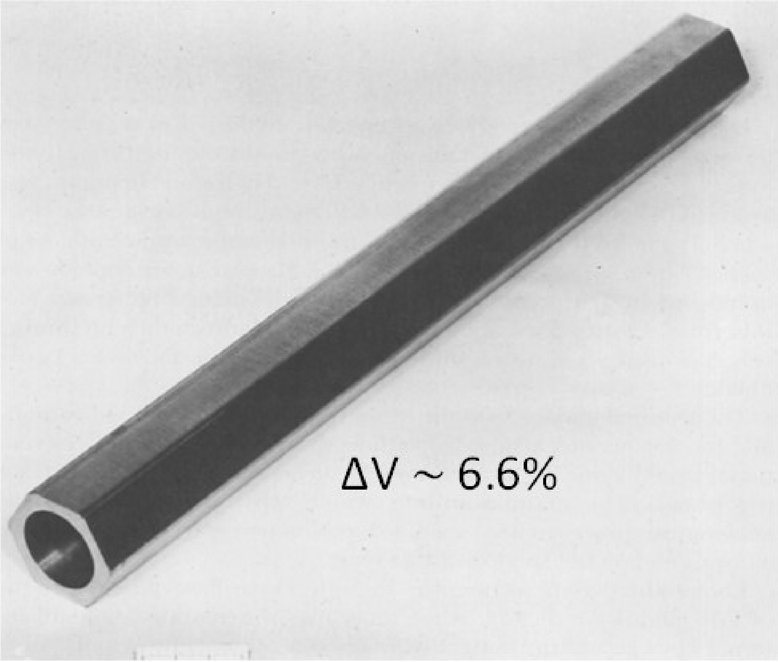
- Possible fuel materials include:
  - Uranium molybdenum (up to 19.75% enriched),
  - Uranium nitride (up to 19.75% enriched),
  - Uranium oxide (up to 5% enriched commercially),
  - Metallic (U-10Zr), and
  - TRISO particles.



- Advanced moderator materials examined include:
  - Zirconium hydride,
  - Yttrium hydride, which retains hydrogen at higher temperatures, and
  - Associated alloys.
  - Graphite and/or beryllium can also be used as a moderator.
- Reflector materials:
  - BeO or MgO are ideal.
  - Al_2O_3 is more economic.
  - Graphite is a possibility.

Metal hydrides for moderator applications is not a new concept

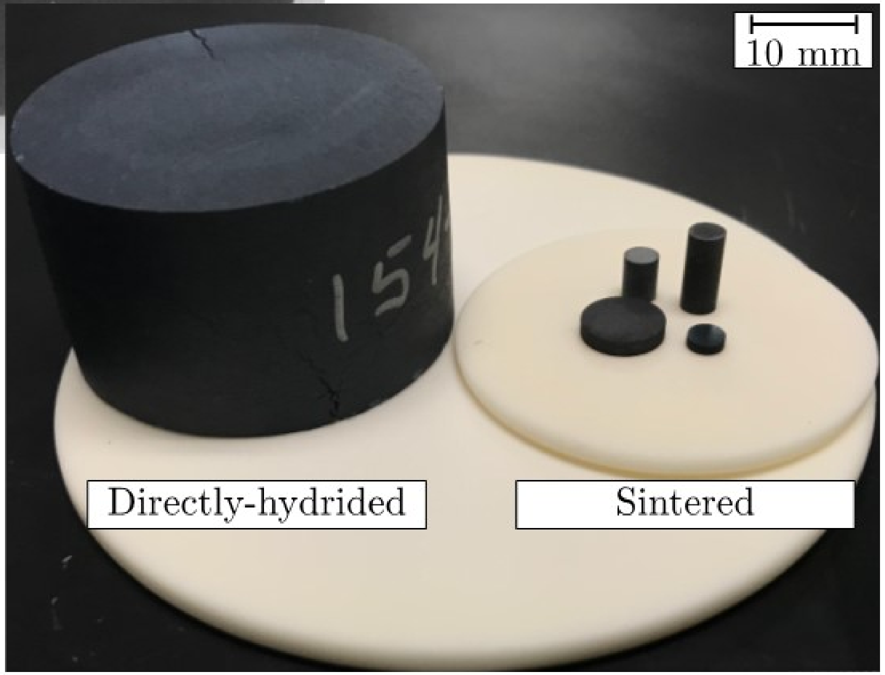
Machined section of ZrH_{1-x}



$\Delta V \sim 6.6\%$

Machined section of YH_{2-x}

$\Delta V \sim 4.5\%$



Powder metallurgy process for yttrium dihydride invented at LANL shows promising results

Pictures courtesy of Erik Luther and Adi Shivprasad

Yttrium dihydride (YH_{2-x}) is a promising candidate for moderator applications

- Why YH_{2-x} over traditionally-used moderators?
  - High thermal stability compared to other metal hydrides
  - Relatively low thermal neutron absorption cross section
  - Good elastic properties for a metal hydride
- Challenges associated with YH_{2-x} fabrication
  - Near net-shape parts are difficult to achieve for complex geometries
  - Massive hydriding may result in structural degradation

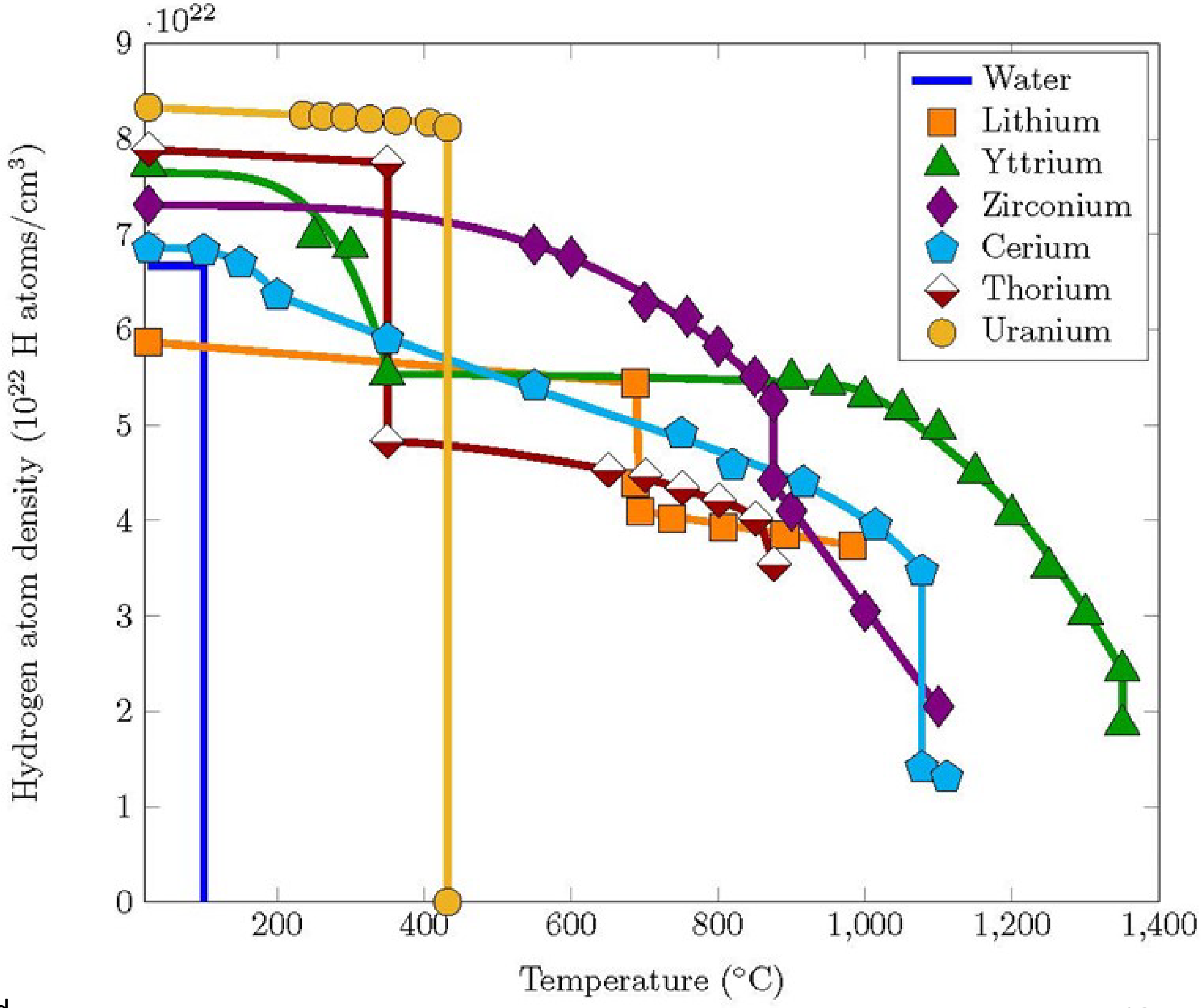
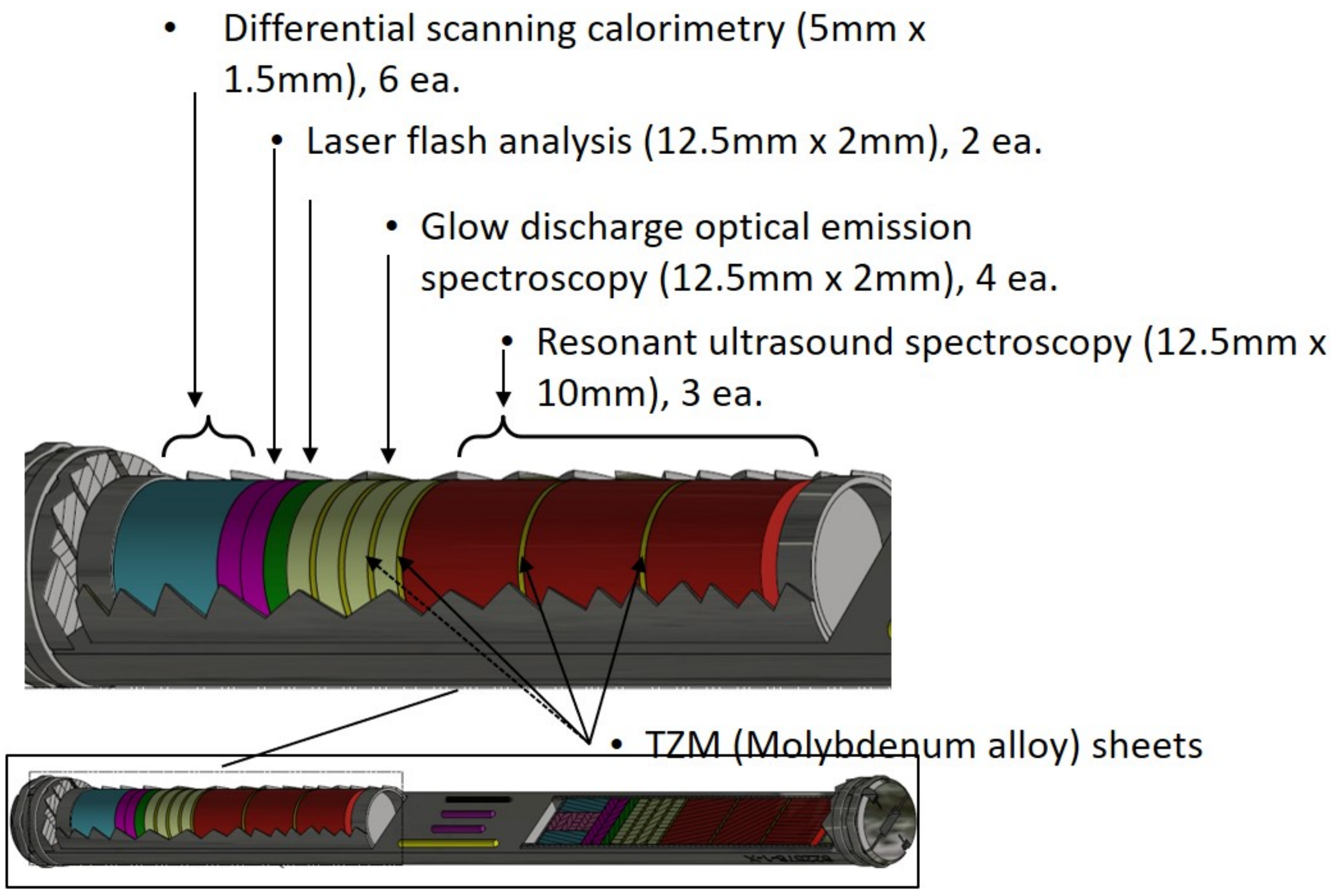


Figure courtesy of Adi Shivprasad

High temperature moderator materials: Irradiating YH_2 in ATR

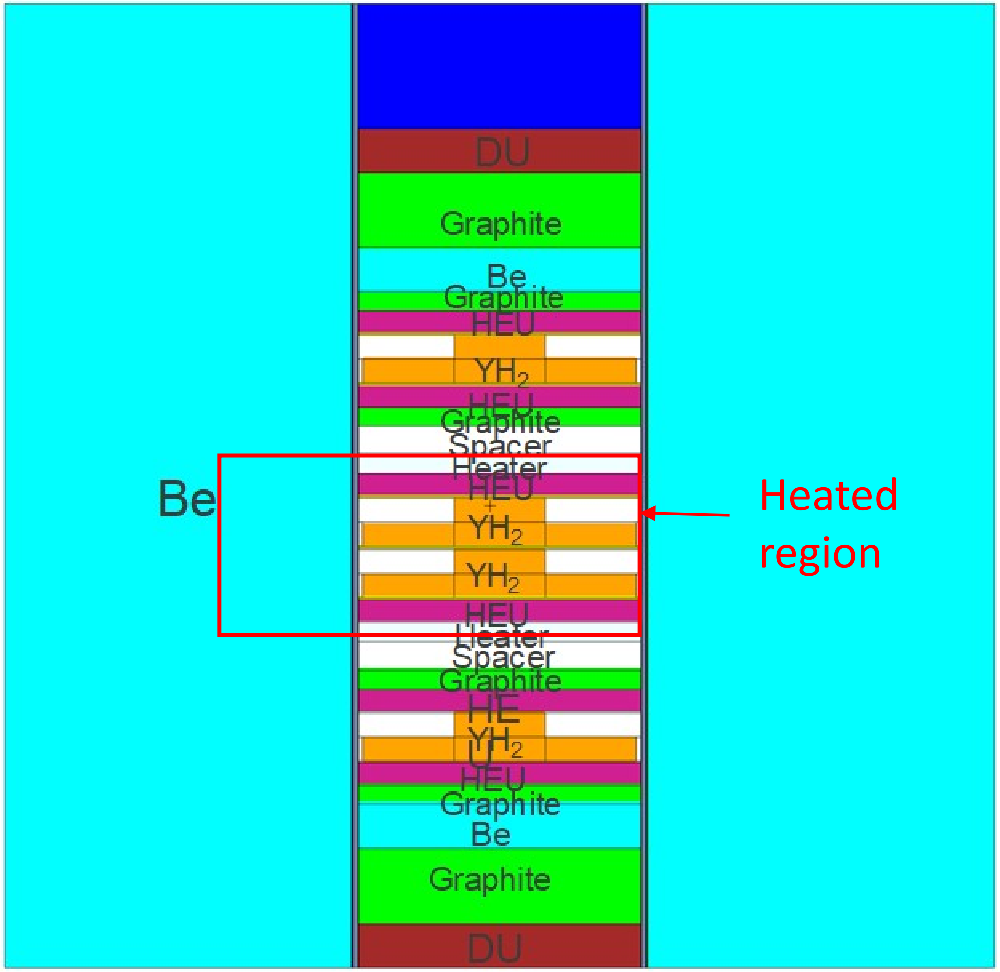
- ATR irradiation required to test suitability in nuclear environment.
  - Limited historical results are available, but almost no quantitative data (mechanical properties, etc.).
- Sample geometry based on desired post-irradiation examination (PIE).
  - DSC: Heat capacity
  - LFA: Thermal diffusivity
  - TEM: Microstructure
  - GD-OES: Elemental composition
  - RUS: Elastic properties



Pictures courtesy of Chase Taylor and Michael Davenport

Integral Critical Experiment Planned for National Criticality Experiments Research Center

- Goal is to understand short time frame reactivity feedback with and without YH_2.
- Items varied (between the spacer rings)
  - HEU for criticality
  - YH_2 discs inside this area
  - Heaters inside this area
  - Up to 335 C
- Thermal expansion considered negligible and thus, not accounted for
- All other areas assumed at constant temperature (21 C)



Picture courtesy of Theresa Cutler

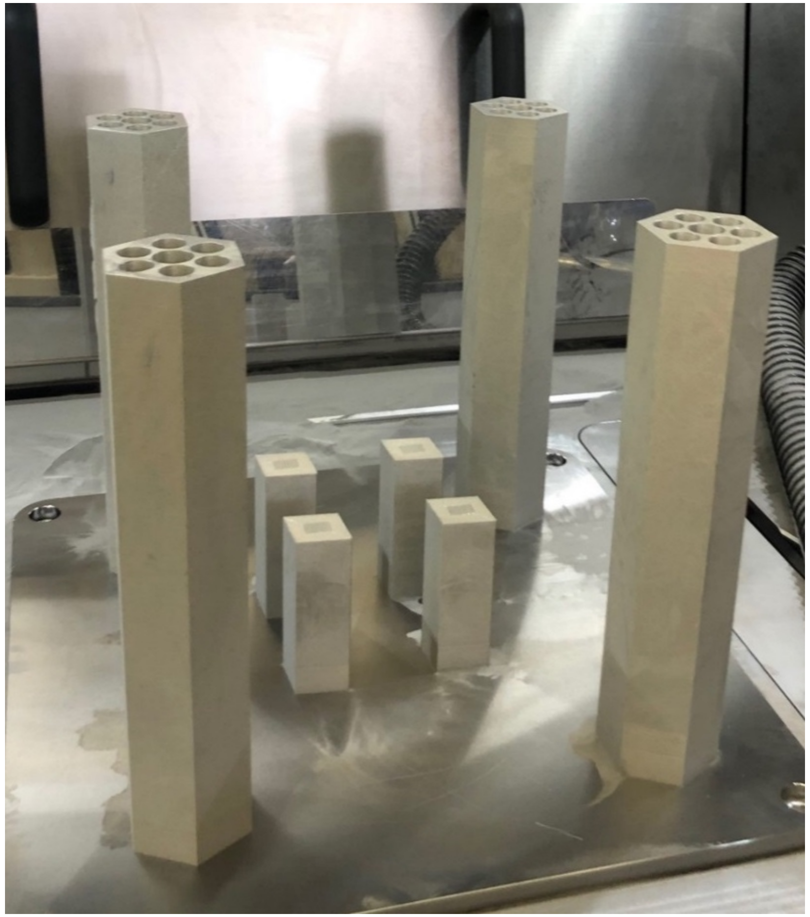
Advanced Heat Removal

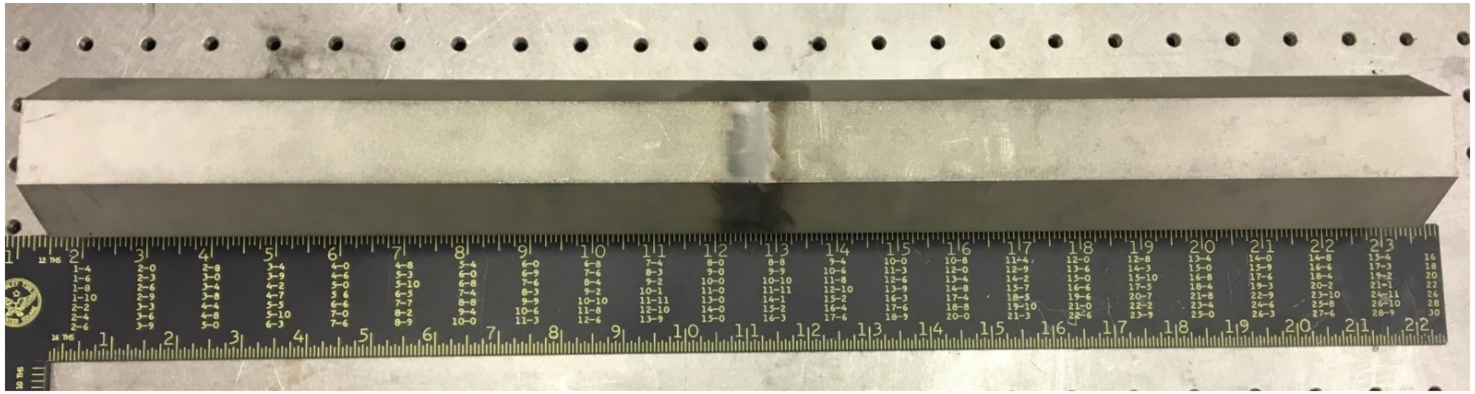
- Removal of fission heat from the reactor core will probably occur through either heat pipes or gas coolant but possibly other options.
- Characterization of heat transfer concepts being explored are:
  1. latent - phase change of a working fluid (i.e., heat pipes and vapor chambers),
  2. sensible - changes in temperature, (i.e., heat spreaders, thermal interface materials, thermoelectrics), and
  3. physical mechanisms (i.e., thermoacoustics).

Research Courtesy of Bob Reid and Donna Guillen

7 hole stainless steel monolith test articles for single heat pipe experiment

- Test articles comprise up to 0.5 m long pieces with a center hole for a single heat pipe and six outer holes for cartridge heaters (see picture to right).
- Both additive and traditional manufacturing are used for fabrication of test articles.
- Two 11-inch additively manufactured pieces are joined with electron beam tier welding (below).

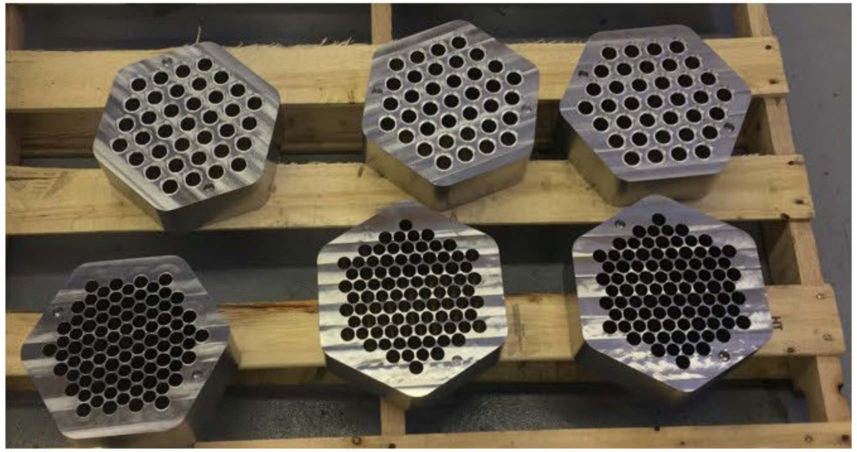


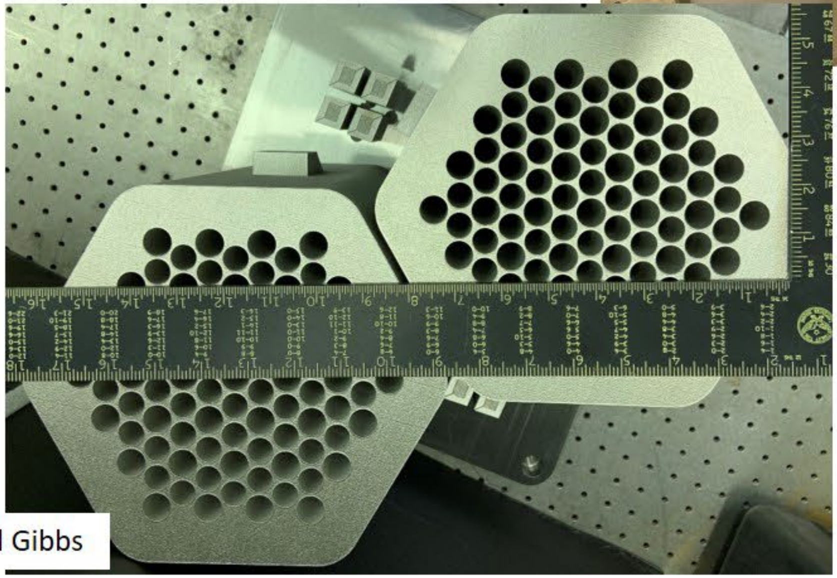


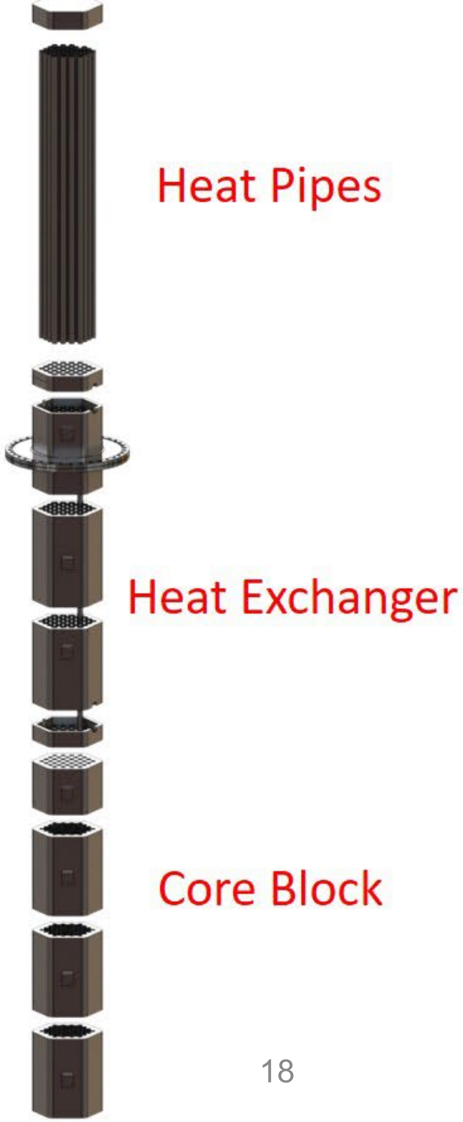
Pictures Courtesy of Colt Montgomery, John Carpenter, and Amber Black

37 heat pipe, 54 heater test article will produce thermal output (up to ~75 kWt)

- One meter long section of core block exists in the bottom half of the article and one meter of heat exchanger in the top.
- Heat pipes span both sections to provide heat removal.
- Both additively manufactured (AM) and machined 37 heat pipe test article pieces have been fabricated.



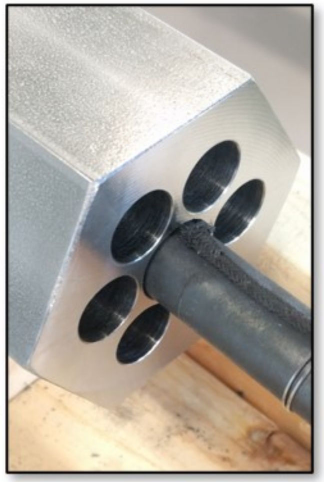




Pictures Courtesy of Bob Reid, Thomas Foreman, Michael Brand, and Paul Gibbs

Instrumentation/Sensor Development

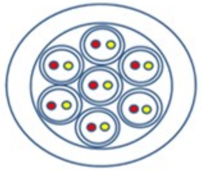
Thermowell



Heat pipe with thermocouple

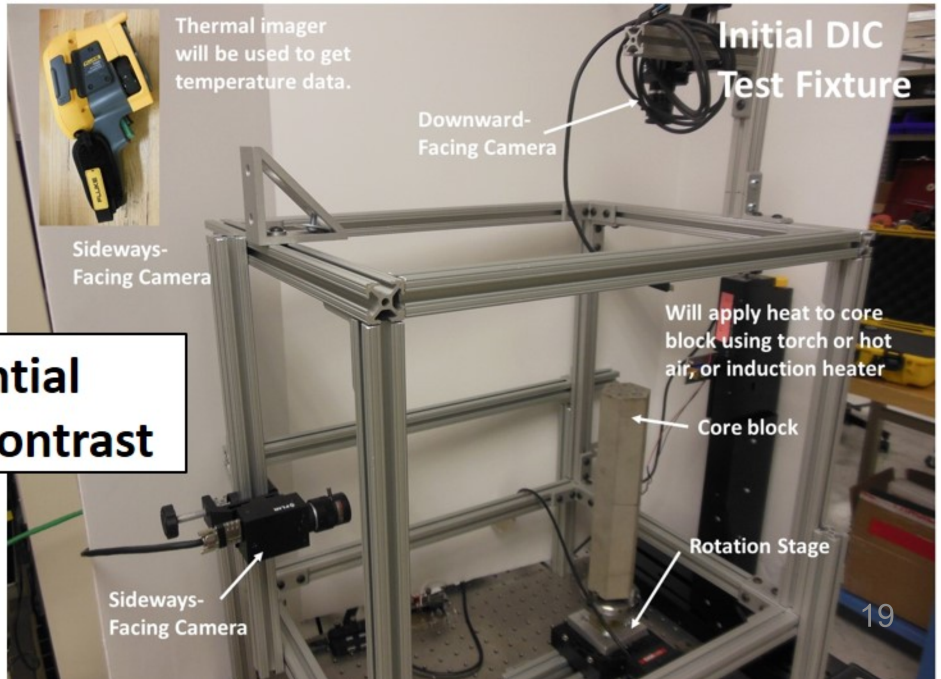
External thermocouple spot weld on commercial heat pipe

0.020” thermocouple weld



- Thermocouples for temperature measurements
- Fiber optic and acoustic distributed temperature sensors
- Differential Interface Contrast for structural integrity
- Stress and strain gauges
- *Collaboration with DOE Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET-ASI) In-Pile Instrumentation Program cross-cutting research activities*
- <u>Lower power capacity for initial testing</u>

Differential Interface Contrast



Pictures courtesy of Troy Unruh and David Mascareñas

Integrated Testing and Demonstration of Microreactor Technologies

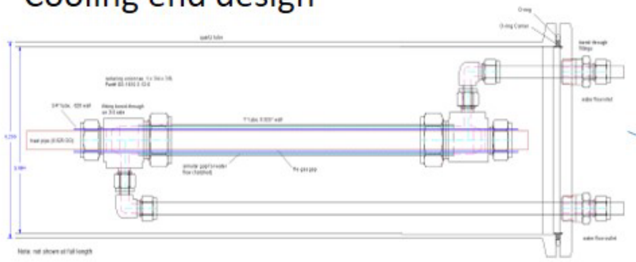
SPHERE: Single Primary Heat Extraction & Removal Emulator

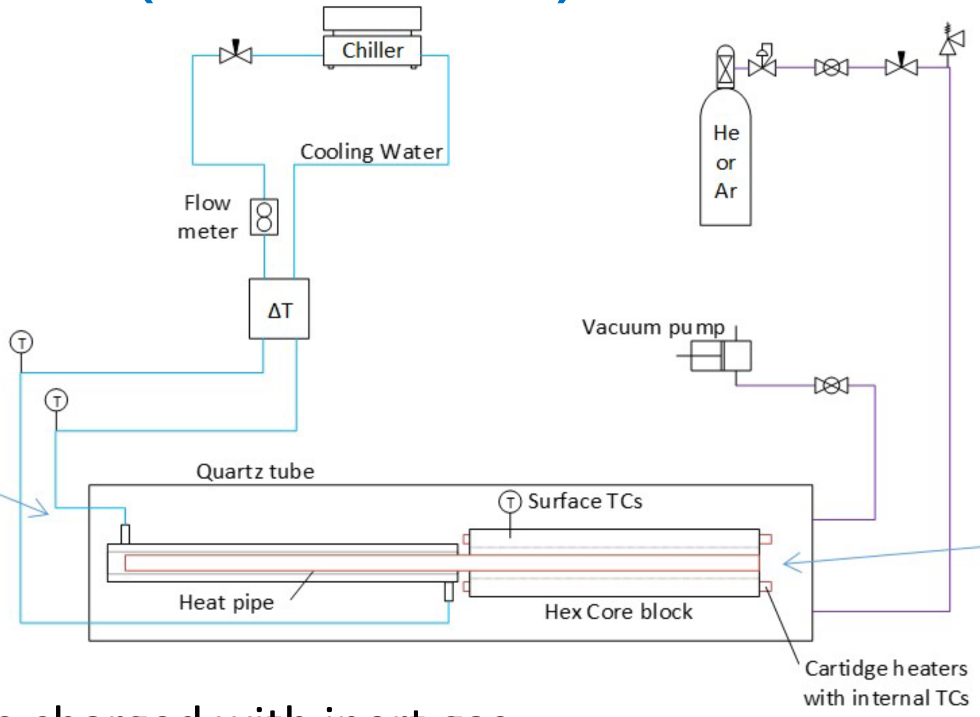
MAGNET: Microreactor AGile Non-nuclear Experimental Test-bed

DOE Mircroreactor Program Focus

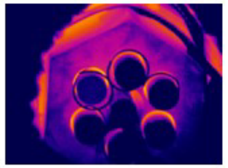
Single Primary Heat Extraction & Removal Emulator (SPHERE)

Cooling end design





Simulated Fuel End

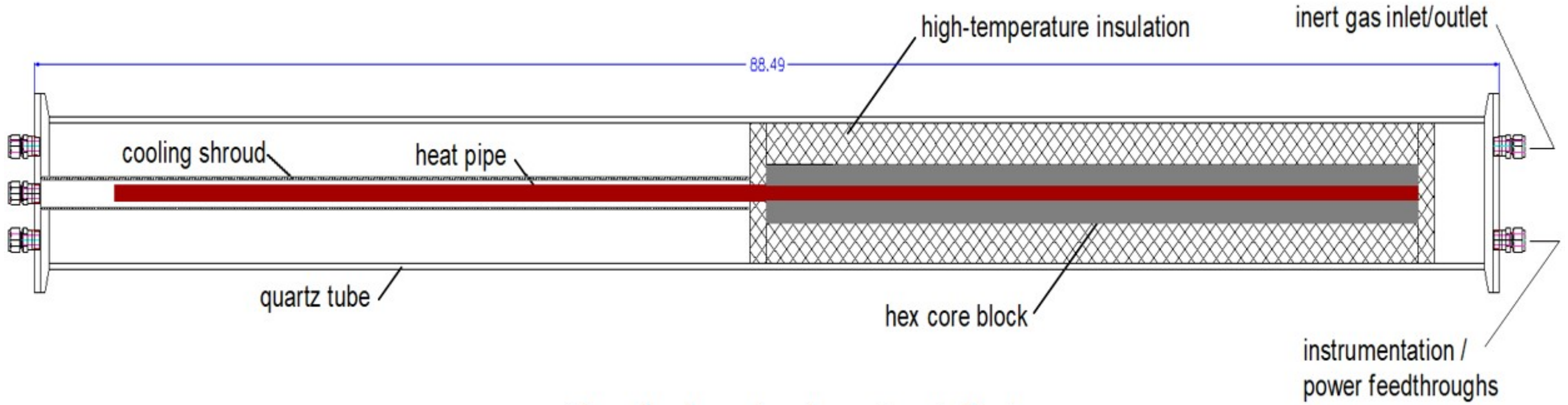


Power controller and instrumentation panel for single heat pipe experiment

- Quartz tube enclosure will be charged with inert gas
- Vacuum pump supports successive dilution for air removal
- Turbine flow meter and delta-T meter allow for determination of heat removal rate to the cooling water; comparison to total heater power at steady-state
- Cooling water is recirculated with heat rejection from a 2.5 kW circulating chiller

Benefits of SPHERE

- **Thermal performance evaluation** under a wide range of heating values and operating temperatures
- **Transient characterization** (e.g. startup) of heat pipe
  - Measurement of heat pipe axial temperature profiles during startup, steady-state, and transient operation using thermal imaging and surface measurements
  - Measurement of core block and heater temperatures during heat pipe operation
  - Measurement of heat removal rates from heat pipe condenser; comparison to total heater power input
- **Effective thermal coupling methods** between the heat pipe outer surface and the core block and between the cartridge heaters and the core block
- **Benchmark M&S tools** using generated data

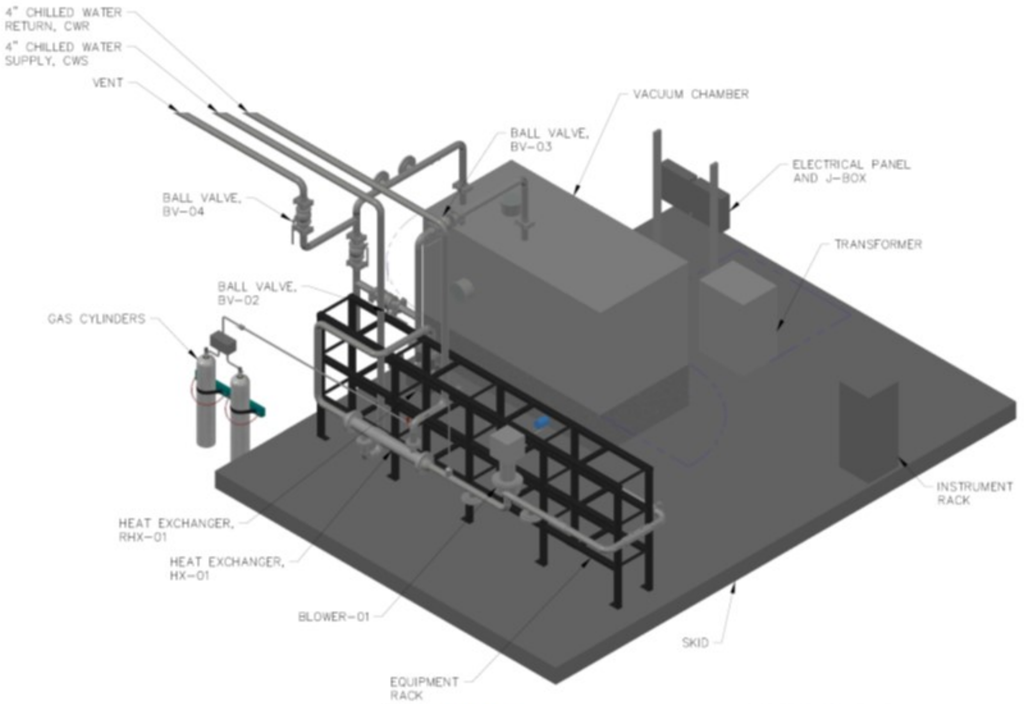


Single heat pipe test fixture

Microreactor AGile Non-nuclear Experimental Test-bed (MAGNET)

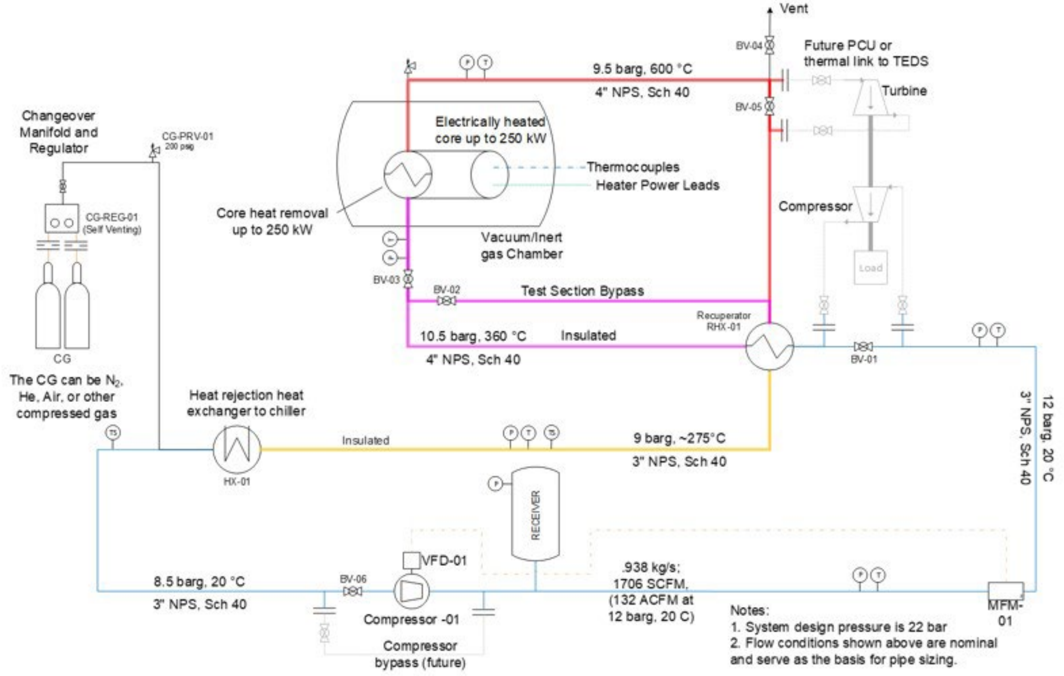
- "Attract" industry developers and regulators to perform integrated microreactor component and phenomena testing

- **250 kW electrically heated Microreactor Test Bed** in the System Integration Laboratory at the Energy System Laboratory (ESL)
  - Initial test article will be a 75 kW heat pipe reactor demonstration unit with 37 advanced technology high-temperature (~650ºC) sodium-charged heat pipes
- Multi-lab effort
  - INL: Test platform and microreactor advanced heat exchanger
  - LANL: 75kW heat pipe reactor test article
  - ORNL: Instrumentation and sensor

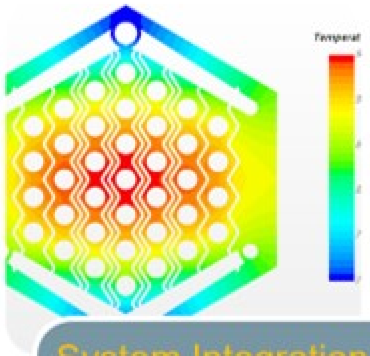


Benefits of MAGNET

1) Simulate reactor core and heat removal section, displacement and temperature field data for potential design performance verification and accompanying analytical model validation.
   - Demonstrate potential applicability of advanced fabrication techniques such as additive manufacturing and diffusion bonding to nuclear reactor designs.
   - Identify and develop advanced sensors and power conversion equipment, including instrumentation for autonomous operation.
2) Evaluate structural integrity of monoliths: thermal stress, strain, aging/fatigue, creep, deformation.
3) Test viability of interface between heat pipes and heat exchanger for both geometric compatibility, heat pipe functionality, and heat transfer capabilities.
4) Test viability of interface of heat exchanger to power conversion system for energy production.
5) Study cyclic loading and simulated reactivity feedback.



DOE Microreactor Program R&D Focus



System Integration & Analyses

- Market Research
- MR Regulatory Requirements
- Integrated M&S
- Technoeconomic Analyses

Technology Maturation

- Heat Pipes
- High Temperature Moderators
- Heat Exchangers
- Instrumentation & Sensors

Demonstration Support Capabilities

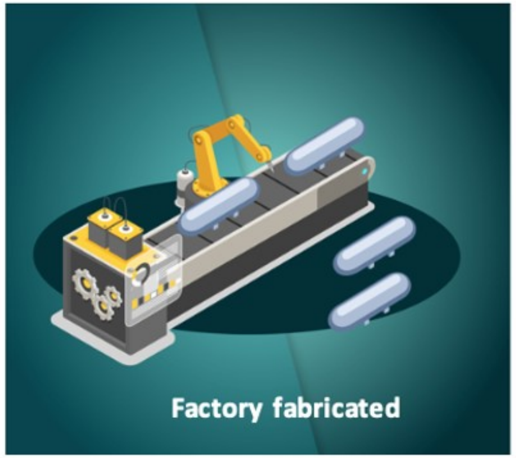
- Single Primary Heat Extraction & Removal Emulator (SPHERE)
- Microreactor AGile Non-nuclear Experimental Test-bed (MAGNET)

Nuclear Applications Demonstrations

- Hydrogen co- generation
- District heating
- Desalination
- Autonomous Operation
- Remote Monitoring

Current Technical Areas

Reimagine Nuclear Generation…



Factory fabricated

The majority of components of a microreactor are anticipated be fully assembled in a factory and shipped out to its location. This can eliminate difficulties associated with large-scale construction, reduce capital costs, and help get the reactor up and running quickly.

Transportable

Smaller unit designs can enable microreactors to be very transportable. This can make it easier for vendors to ship the entire reactor by truck, shipping vessel, airplane, or railcar.

Self-regulating

Simple and responsive design concepts can enable remote and semi-autonomous microreactor operations that may significantly reduce the number of specialized operators required on-site. In addition, microreactors plan to use utilize passive safety systems that can prevent the potential for overheating or reactor meltdown.

DOE Microreactor Program is undertaking some of the most important and challenging research and development efforts to accelerate microreactor deployments by mid-2020s

GEN IV International Forum[SM]

Upcoming Webinars

29 April 2010	GIF VHTR Hydrogen Production Project Management Board	Mr. Sam, Suppiah, CNL, Canada
28 May 2020	Performance Assessments for Fuels and Materials for Advanced Nuclear Reactors	Prof. Daniel LaBrier, ISU, USA
24 June 2020	Comparison of 16 Reactors Neutronic Performance in Closed Th-U and U-Pu Cycles	Dr. Jiri Krepel, PSI, Switzerland