U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Microreactor Sensors and Instrumentation Overview

Advanced Sensors and Instrumentation Annual Webinar

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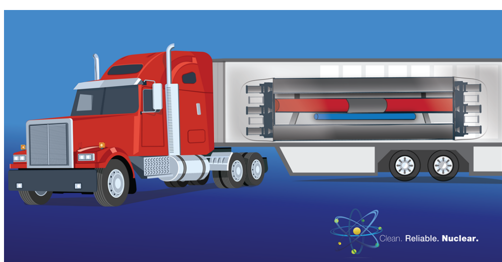
INL/MIS-19-56243

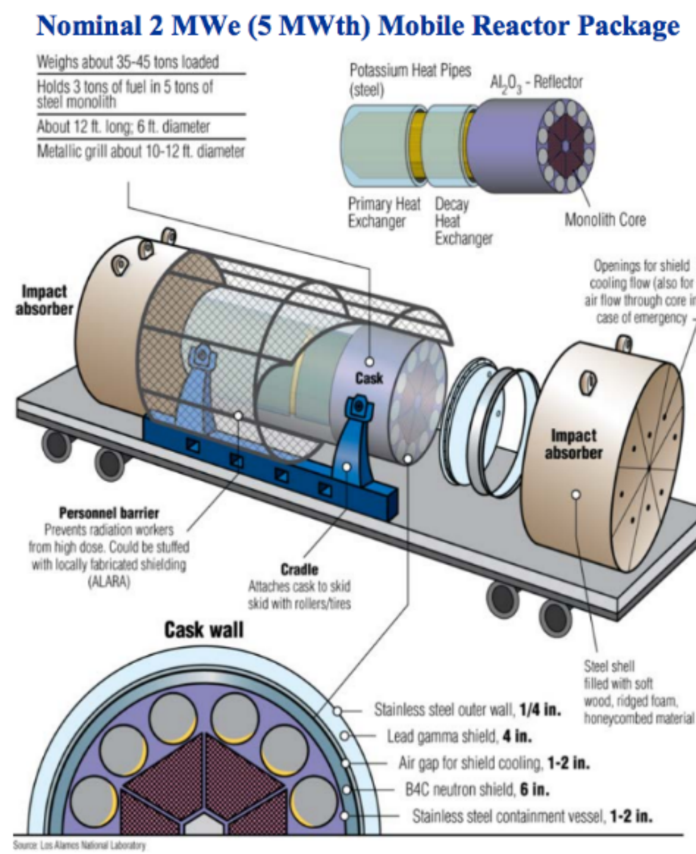
Microreactor Overview

Microreactor: 0.1 to 20 MWt electric non-LWR for DOD applications, remote communities, distributed hybrid power, disaster relief, mining sites, etc.

- Factory fabricated
- Estimated service life of ~5 -20 years
- Ease of transportation and siting
- Many concepts, most gas or heat pipe cooled
- Flexible operation
- Demonstration in 3-5 years



Ease of transportation of microreactor with minimal site preparation



LANL MegaPower Reactor concept

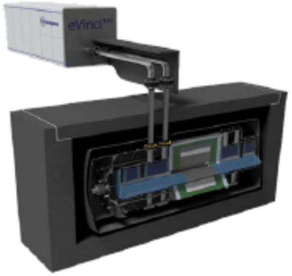
https://www.energy.gov/ne/articles/big-potential-nuclear-micro-reactors

DOE Views on Microreactor Benefits and Applications

Source: https://gain.inl.gov/SiteAssets/Micro-ReactorWorkshopPresentations/Presentations/02-Sowinski-MRProgramMission_June2019.pdf

Tom Sowinski
NE-52
Office of Nuclear Reactor Deployment

DOE believes microreactors have the potential to provide the commercial and defense sectors with a clean, reliable, and resilient energy supply technology



Potential benefits include:

- Enhanced inherent safety characteristics
- Smaller footprints significantly reducing source terms
- Semi-autonomous and remote control operations reducing staffing needs
- High temperature operation for both electricity and process heat production
- Highly integrated and transportable systems reducing on-site construction times

Potential applications include:

- Competitive electricity and process heat supplies for remote and off-grid communities and industrial locations
- Resilient and reliable energy supplies for remote and forward military bases
- Reliable and clean electricity supplies for disaster and emergency relief operations

Workshop Objective: Identify the unique needs of the micro-reactor industry along with associated DOE national laboratory capabilities and activities.

Source: https://gain.inl.gov/SiteAssets/Micro-ReactorWorkshopPresentations/Presentations/03-Gehin-DOEMicroReactorProgram.pdf

Jess Gehin, Ph.D.
Microreactor R&D Program NTD
Chief Scientist, Nuclear Science & Technology, INL

- The DOE-funded program will conduct fundamental R&D to reduce uncertainty and risk in the design and development of microreactors to facilitate rapid technology commercialization
- R&D is selected to support technology maturation that is broadly applicable to multiple reactor cooling/technology options to ensure that concepts can be licensed and deployed to meet specific use-case requirements
- Primary Objectives for FY19:
  - Engage with industry and DOD
  - Enable demonstration of microreactors
  - Mature key technologies specifically needed by microreactor developers
  - Assess microreactor specific regulatory and licensing issues

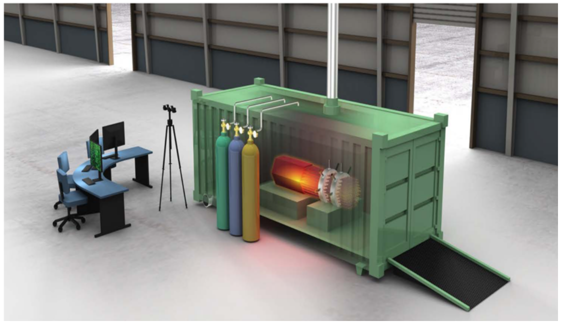
Sensors and instrumentation can help address these challenges

Microreactor Non-Nuclear Testbed

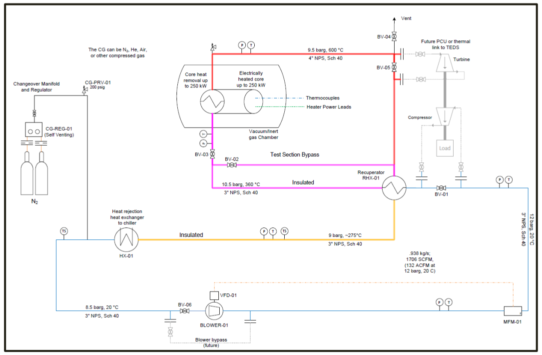
Non-Nuclear Testbed Strategy: Enable testing of microreactor components and prototypes using electrical-heating

Non-Nuclear Testbed Objectives:

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 components: thermal stress, strain, aging/fatigue, creep, deformation
3) Evaluate interface between heat exchanger for both geometric compatibility, functionality, and heat transfer capabilities
4) Test interface of heat exchanger to power conversion system for energy production
5) Demonstrate applicability of advanced fabrication techniques such as additive manufacturing to nuclear reactor problems
6) Identify and develop advanced sensors and power conversion equipment, including instrumentation for autonomous operation
7) Study cyclic loading and reactivity feedback
8) Enhance readiness of the public stakeholders – particularly DOE laboratories and US NRC – to design, operate and test high temperature reactor components.



Non-Nuclear Testbed Concept



Preliminary Non-Nuclear Testbed Component Diagram

Microreactors Offer New Technology Demonstration Opportunities

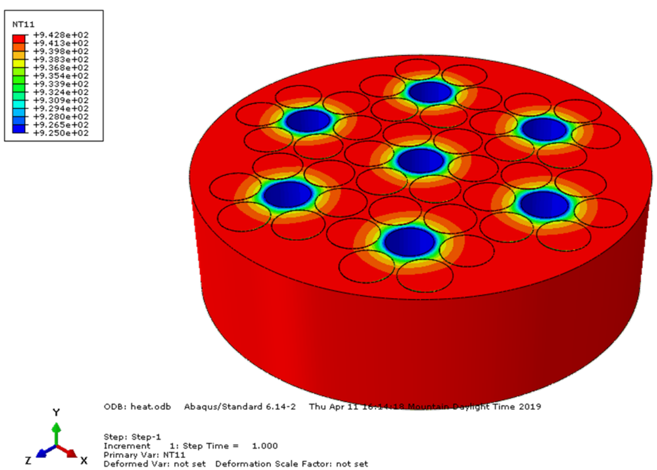
Demonstrations under investigation:

- Removal of heat with heat pipes or gas coolant instead of traditional primary and secondary water loops
- Presence of high temperature moderator material such as yttrium hydride to reduce required fuel mass
- Fabrication of a solid/other core block using new reactor-based materials to contain heat pipes
- Additive manufacturing utilization for fabrication of complicated core and/or heat exchanger designs
- Improved filling techniques for heat pipes
- Research on innovative instrumentation and sensors to address the above needs

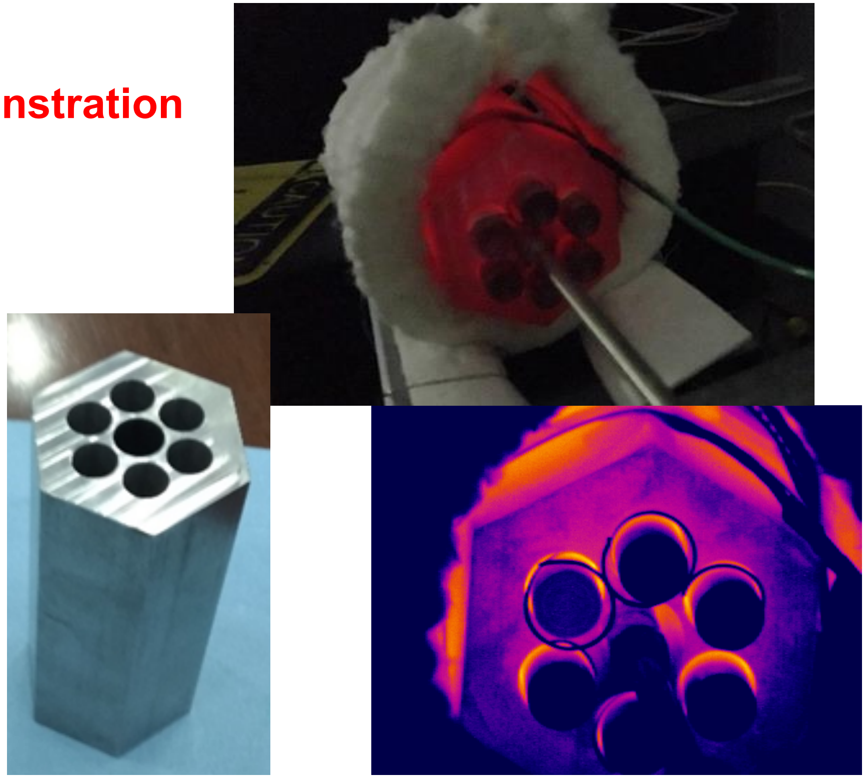
First 'Test Article'

Initial non-nuclear testbed testing will include:

- **LANL-developed sodium filled heat-pipes surrounded by 6 heaters**
- **Single heat pipe test will give valuable information for validating simulations**
- **Nominal 3 kWth power**
- **316 stainless steel core block**
- **Sensors and instrumentation demonstration**



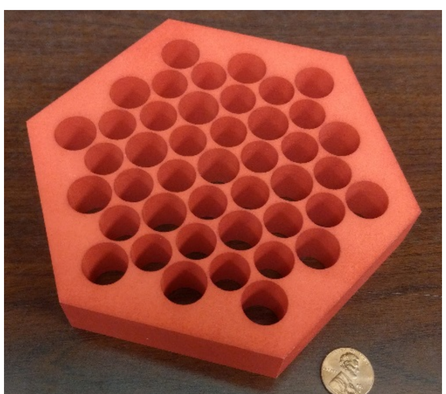
Preliminary Thermal Analysis



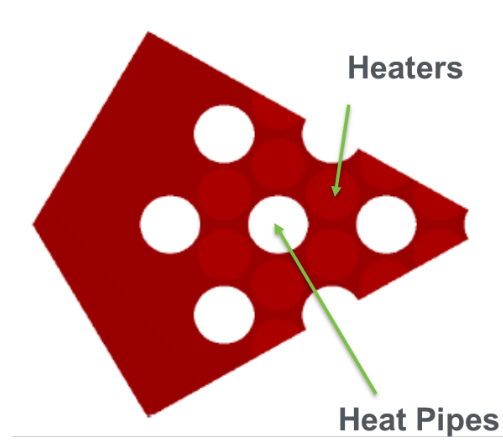
Initial thermal testing of electric heaters in core block

Second 'Test Article'

- 37 heat pipe test article with 54 heaters in surrounding locations is being fabricated at LANL
- Core block comprises additively manufactured stainless steel 316L
- Demonstration of heat pipe to heat exchanger interface is planned through a length of 1.7 m in the test article
- Plans include up to 300 hours of continuous testing and 100 kWt power
- Sets basis for more advanced heat pipe and heat exchanger designs and demonstrations
- Provides opportunity to evaluate sensors and instrumentation in prototypic geometry



Plastic mockup cross-section demonstrating size of test article



1/6th of test article showing heat pipe and heater location

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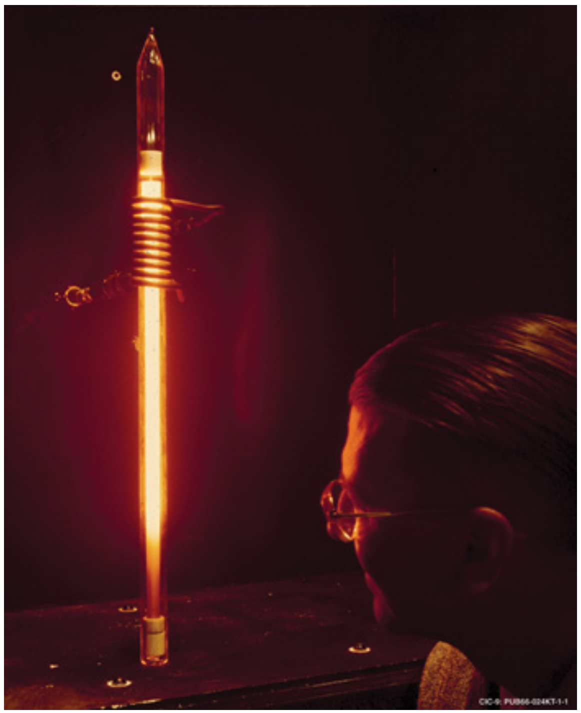
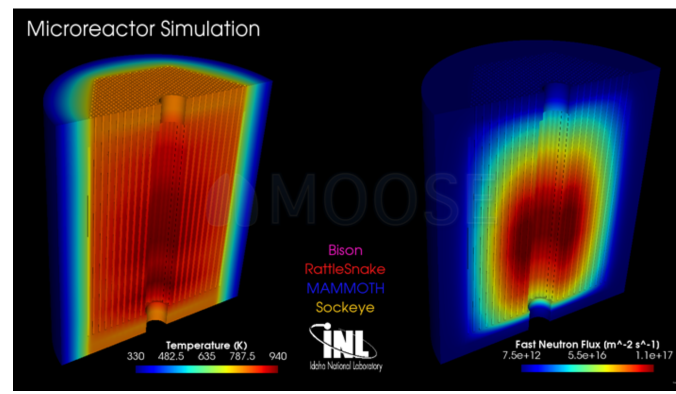
Sockeye: Advanced Heat Pipe Simulation Capability for Microreactors

Sockeye is designed to support heat pipe microreactor concepts and will require validation data from sensors and instrumentation



LANL Physicist George Grover Tests a Heat Pipe

- A heat-pipe reactor is typically a solid-block core with the fuel in holes inside the solid block
- The heat pipes remove the heat from the block as the liquid in the heat pipe is vaporized
- The heat is deposited in the condenser region of the heat pipe
- The condenser region can be sized to accommodate multiple heat exchangers, such as one for power conversion and two for redundant decay heat removal



Preliminary Heat-Pipe-Cooled Microreactor Simulation

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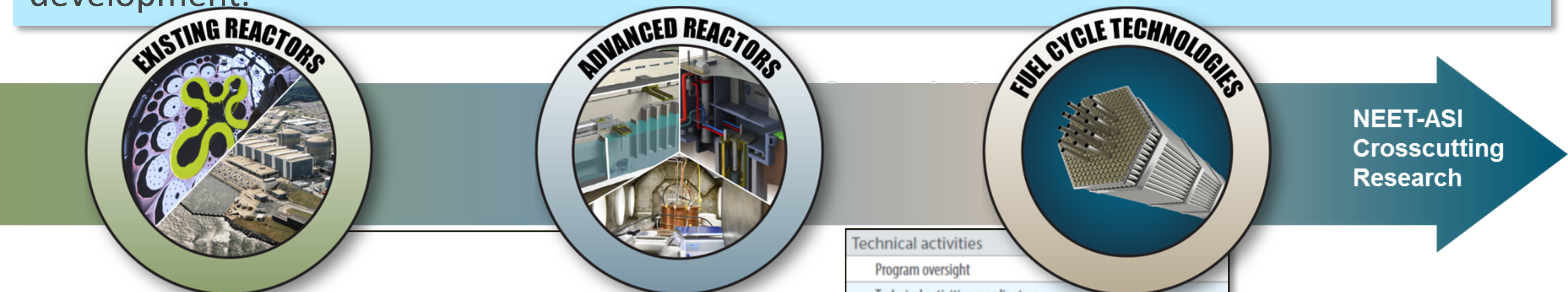
NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

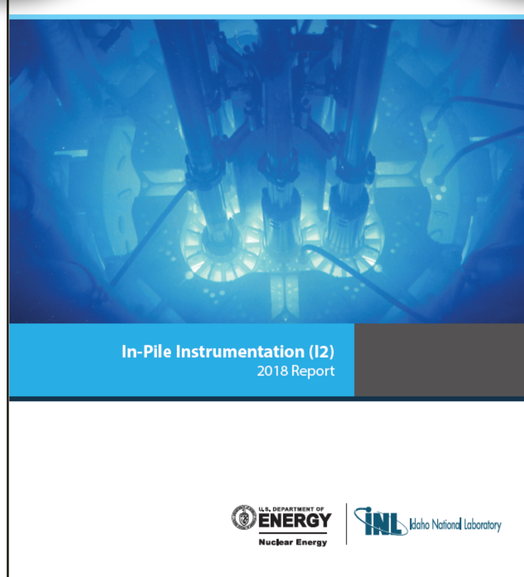
Collaborators: Los Alamos National Laboratory EST. 1943 · Argonne National Laboratory · INL Idaho National Laboratory

Advanced Sensors and Instrumentation

NEET ASI In-Pile Instrumentation

NEET ASI In-Pile Instrumentation (I2) Program: Seeks to establish the capability with DOE-NE Laboratories to design, fabricate, test and qualify sensors for monitoring and controlling existing and advanced reactors (including microreactors) and supporting fuel cycle development.





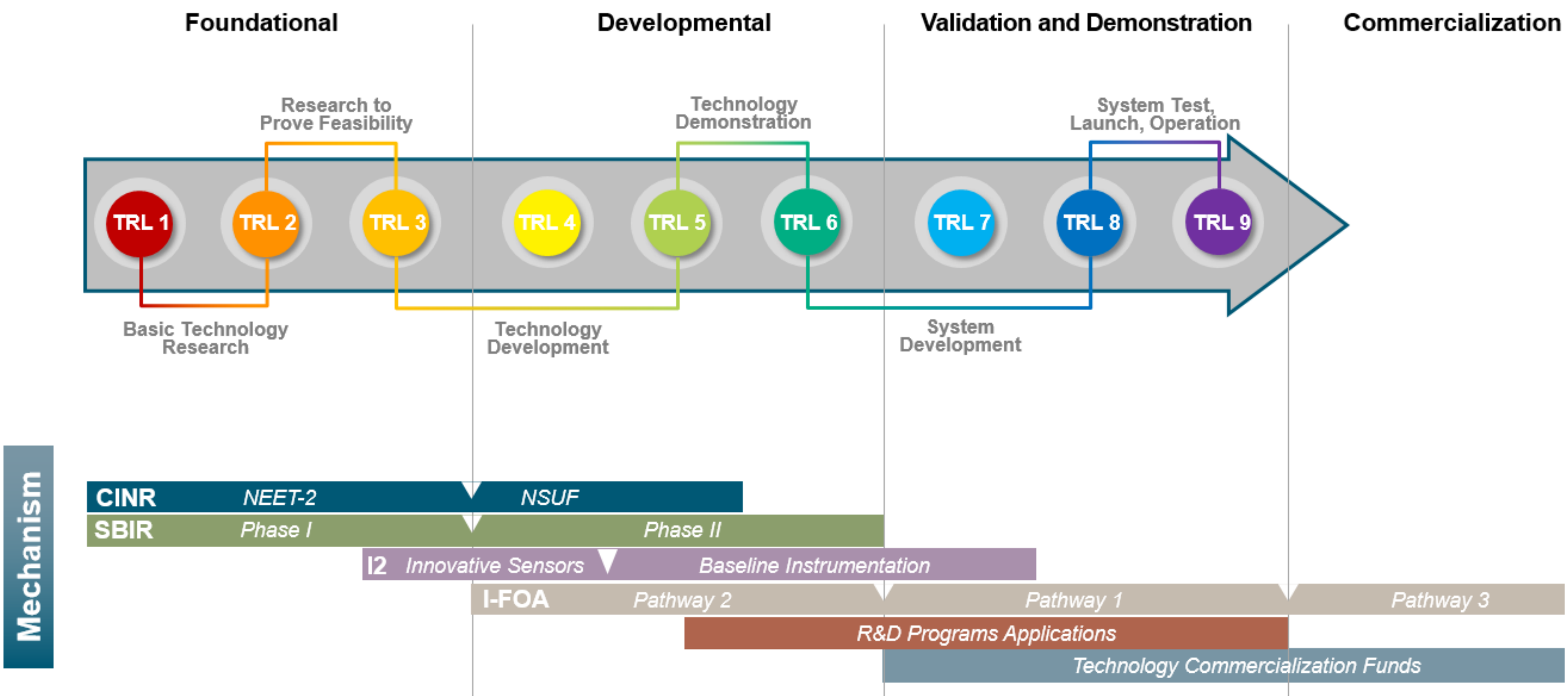
In-Pile Instrumentation 2018 Report

Technical activities
Program oversight
Technical activities coordinators
Thermocouples
SPND
Passive monitors
Miniature fission chamber
Ultrasonic Thermometer
Radiation tolerant fiber materials and sensors
LVDTs
Creep test rig
Instrumentation irradiation vehicle for ATR
Instrumentation irradiation vehicle for TREAT (MIMIC)
Photo-thermal radiometry for thermal conductivity
Probe method for thermal conductivity
Mechanical properties
Resonant ultrasound spectroscopy
Electro-impedance spectroscopy (EIS) for hydride characterization
IR thermography for structure characterization
AM printing process control and sensors fabrication
Modeling

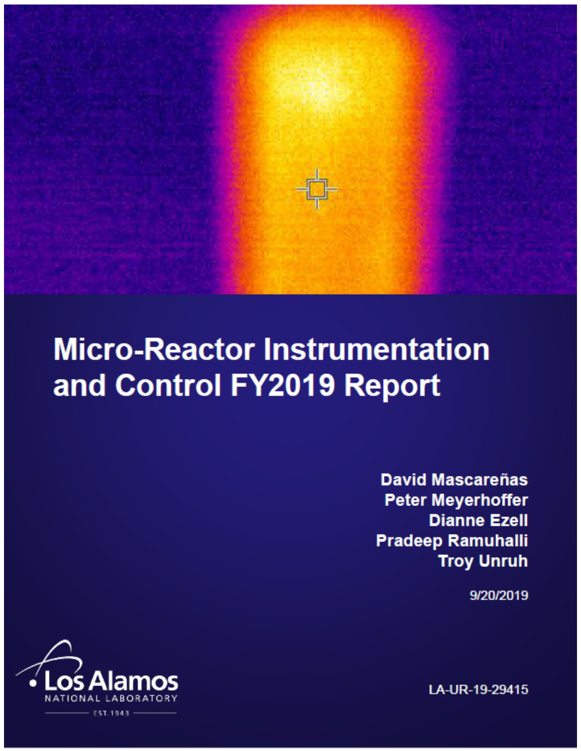
2018 Sensor Activities

Technology Maturation Strategy for ASI Sensors and Instrumentation Technologies

In-Pile Instrumentation (I2) for Microreactors: Leverage existing Advanced Sensor and Instrumentation developments for rapid validation and demonstration in microreactor testbed



Sensor and Instrumentation Deployment Strategy for Microreactors


Micro-Reactor Instrumentation and Control FY2019 Report

David Mascareñas
Peter Meyerhoffer
Dianne Ezell
Pradeep Ramuhalli
Troy Unruh

9/20/2019

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LA-UR-19-29415

Sensors and instrumentation summary

Testbed measurements include:

1. Electrical power to heat pipe evaporator
2. Volumetric flow rate of gas at heat exchanger entrance
3. Pressure of gas at heat exchanger entrance
4. Heat pipe evaporator entrance temperature
5. Heat pipe evaporator midpoint temperature
6. Heat pipe evaporator exit temperature
7. Heat pipe condenser entrance temperature
8. Heat pipe condenser midpoint temperature
9. Heat pipe condenser exit temperature
10. Core block deformation (reactivity feedback, elastic deformation, creep)
11. Heat exchanger strain reactivity (elastic deformation, creep)
12. Core block stress state
13. Heat exchanger stress state
14. Heat exchanger guard heater power (as applicable)
15. Heat exchanger inlet and outlet pressure and temperature, mass flow rate
16. Thermal gradient across core insulation (as applicable)
17. Thermal gradient across heat exchanger insulation (as applicable)

Microreactor Instrumentation Collaborators: Los Alamos National Laboratory, Oak Ridge National Laboratory, INL Idaho National Laboratory

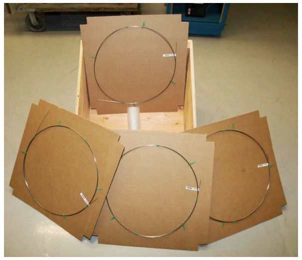
Traditional Sensors and Instrumentation for Microreactors

Thermal measurements:
- High Temperature Irradiation Resistant Thermocouples
- Optical fiber based temperature sensors (potential for embedding)
- Ultrasonic Thermometer

Dimensional measurements:
- Linear Variable Differential Transformers

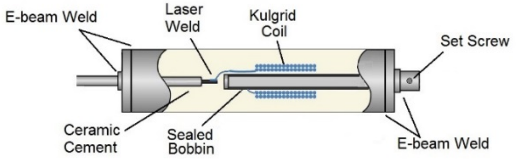
Pressure measurements:
- Linear Variable Differential Transformers
- Optical fiber based Fabry Perot pressure sensors

Nuclear measurements (non-nuclear noise assessment):
- Self-powered neutron or gamma detector
- Fission chambers



Thermocouples

Idaho National Laboratory



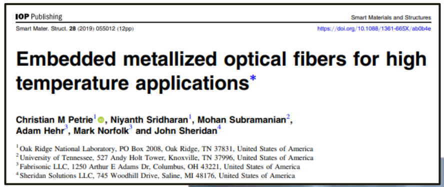
Ultrasonic Thermometer

Halden Linear Variable Differential Transformer

Structural and Visual Monitoring for Microreactors

Structural monitoring concepts:

- Ultrasonic Phased Arrays
- Acoustic Emission Sensors
- Laser Doppler Vibrometer with Steering Mirror
- Interferometry coupled with full-field, high resolution video based structural dynamics
- Accelerometers
- Thermal imaging
- Ultrasonic guided waves
- Resonance inspection
- Strain gauges/stand-off displacement sensors
- Optical fiber-based strain sensors (potential for embedding)



IOP Publishing — Smart Materials and Structures

Smart Mater. Struct. **28** (2019) 055012 (12pp) https://doi.org/10.1088/1361-665X/ab0b4e

Embedded metallized optical fibers for high temperature applications*

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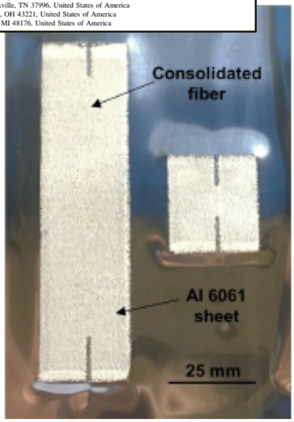
OAK RIDGE National Laboratory



Embedded fiber sensors previously developed at ORNL

Visual based techniques for instrumentation:

- Digital image correlation
- High-resolution, full field techniques
- Non-line of sight imaging

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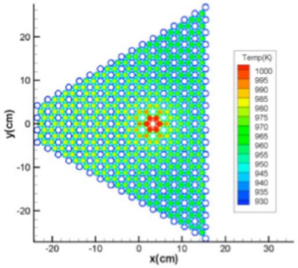
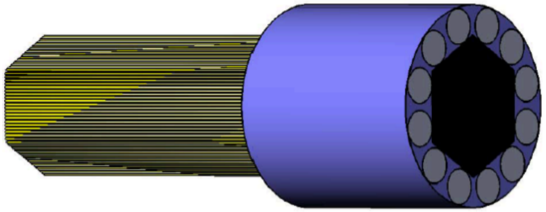
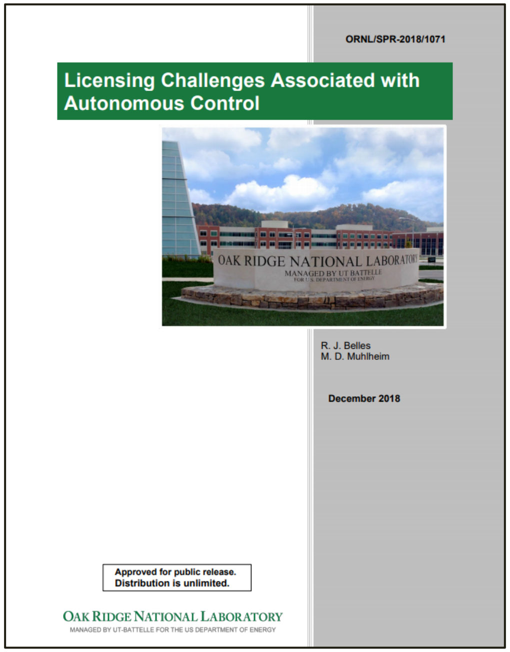




Potential monitoring of thermal stresses in monolithic heat pipe-based microreactor

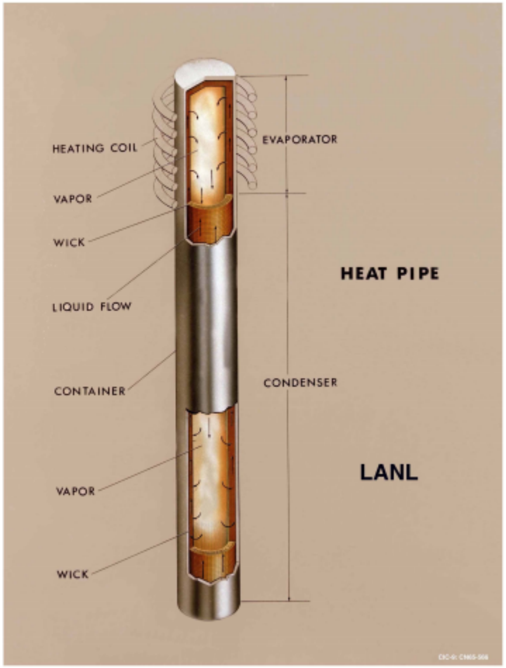
Possible Semi-Autonomous and Remote Operation of Microreactors

- Potential for
  - Reducing staffing needs
  - Enabling remote operations
  - Improving economics of operation
- Sensors and instrumentation needs for additional monitoring
  - Equipment and structural state
  - Reliable operation of actuation systems
  - Algorithms for assessing equipment and structural state
  - Decision-making regarding operating mode selection and control response



Additional Validation Data Desired for Sockeye

- Any *internal* data from heat pipe is very helpful
- Desired data is as follows:
  - Phase distribution (axial and radial)
    - Is liquid pooling at either end?
    - Influences capillary pressure gradients
  - (Annulus & core) pressure distribution
    - Allows friction/flow resistance closures to be inferred
  - (Annulus & core) temperature distribution
    - Allows heat transfer coefficients to be inferred
  - (Annulus & core) velocity distribution
    - Allows evaporation rate closures to be inferred
  - External temperature distribution
    - External heat transfer coefficients



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