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FRP FAST REACTOR PROGRAM

ART Fast Reactor Program
Fast Reactor Technology Development
Fast Reactor Sensor Development

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Co-authors and Acknowledgements

FRP
FAST REACTOR PROGRAM

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Presentation Outline

FRP
FAST REACTOR PROGRAM

- Overall ART Fast Reactor Program (FRP) Technology Development – Sensors

1. ART FRP Sensors Development
2. Testing Infrastructure
3. Fast Reactor Sensor needs

DOE FRP R&D Activities

FRP
FAST REACTOR PROGRAM

- Technology Innovations for Cost Reduction
  - Technology Development (FRP)
  - Advanced Materials (FRP)

- R&D to Address Key Licensing Issues
  - Safety analysis methods and modeling (FRP)
  - Validation and knowledge preservation (databases) (FRP)
  - Fuel qualification (AFC) – metallic fuels

FR SENSOR TECHNOLOGY DEVELOPMENT

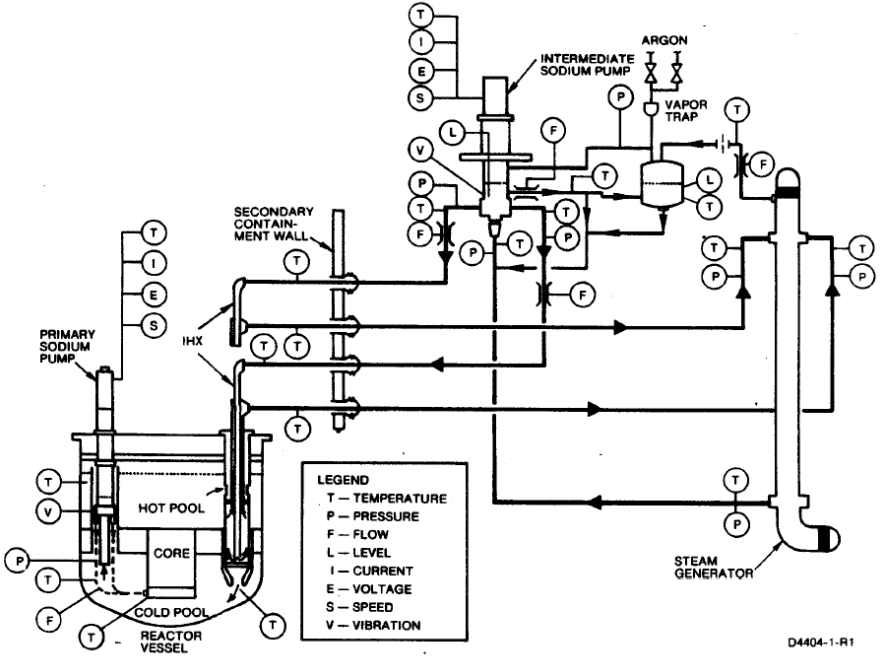
ART-FRP Technology Development - Sensors

- The ART FRP has been, is currently, or planned to be using or working on the following sensors or sensor areas:
  - Level measurement – inductive sensor, DP, multipoint TC, and continuity probe
  - Temperature measurement – COTS TCs and optical fibers
  - Flow measurement – COTS systems, permanent magnetic, eddy current flow sensor, ultrasonic sensor, fiber sensing pads (NEUP)
  - Hydrogen Measurement – in-sodium and cover gas measurement
  - Under-sodium view – ultrasonic system
  - Pressure sensors – COTS NaK-filled pressure transducer
  - Impurity monitoring system – plugging temperature indicator and optical system (NEUP)
  - Structural Health monitoring – COTS and various innovations via NEUPs
  - In-vessel and Ex-vessel Refueling system component technology - force feedback
  - HMI interface with data – Digital O&M
- I'll be stepping through some of these in the next slides

WHAT INSTRUMENTATION DO FAST REACTORS HAVE OR NEED?

Fast Reactor Instrumentation

- Process Temperature
  - TC and RTD
- Process Pressure
  - NaK filled pressure transducer – sodium
  - Conventional pressure instruments – gas, other liquids
- Process Sodium Flow
  - D/P, EM and Eddy current flow sensor
- Sodium Level
  - Inductive level sensors, array of TCs
- Current and Voltage
- Rotational Speed
- Vibration
  - Piezoelectric sensor
- Core Power (in-vessel and ex-vessel)
  - Source range, intermediate range, and power range NI



Generic Pool-type SFR - Instrumentation

Fast Reactor Instrumentation

- Impurity monitoring for coolant
  - Oxygen sensors or sample and analyze
  - Hydrogen sensor
  - Plugging Temperature Indicator (PTI)
- Fuel Failure detection
  - Delayed neutron detectors
  - Tag gas
- Position Indication – various CRDM and Fuel Handling
- Leak Detection – various – piping, reactor vessel, etc
- Loose Part Monitoring – Primary system - high temperature piezoelectric sensors
- In-service Inspection and Repair
  - Under-sodium Viewing
  - Weld inspections
  - Health monitoring system (SHM)
  - Other
- Fire Detection
- Other sensors and instrumentation

- A lot of RDT Standards govern fast reactor sensor development

TABLE 6-2

TRIP INPUTS FOR REACTOR SHUTDOWN SYSTEMS

PRIMARY SHUTDOWN SYSTEM	SECONDARY SHUTDOWN SYSTEM
Primary Power Range Nuclear High Flux	Secondary Flux/Total Flow
Primary Power Range Nuclear Low Setting	Secondary Flux-Increasing Delayed Flux
High Startup Flux	Secondary Flux-Decreasing Delayed Flux
Primary Flux-Decreasing Delayed Flux	Low Primary Loop Flow
Primary $Flux^2$/Loop Pressure	High Primary Loop Flow
IHX Primary Outlet Temperature	Low Secondary Flow
Reactor Vessel Coolant Level	Loss of Offsite Power
Flux/Primary Closed Loop Flow	Reactor Outlet Plenum Temperature
Closed Loop IHX Primary Outlet Temperature	Closed Loop Outlet Temperature
Experiment-Associated Trip Functions	Experiment-Associated Trip Functions
Primary Flux-Increasing Delayed Flux	Flux/Closed Loop Flow
Pressure Permissive	High Closed Loop Flow
Manual Scram	Power Permissive
	Manual Scram

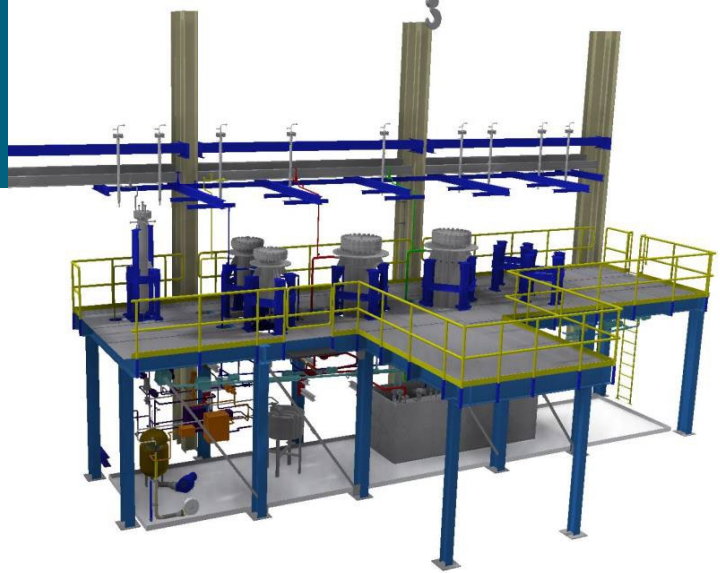
FFTF Sensor inputs for Reactor Shutdown

Source – HEDL-400

FAST REACTOR TESTING INFRASTRUCTURE AND SENSOR DEVELOPMENT

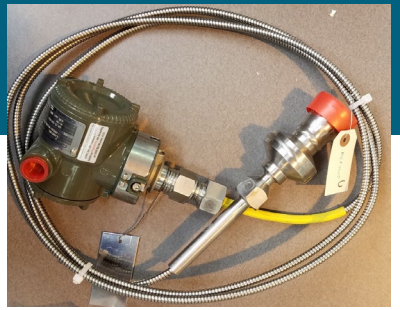
Mechanism Engineering Test Loop (METL) Overview

- **To test small or intermediate scale advanced liquid metal components and instrumentation in sodium: (examples)**
  - Gear Test Assembly (GTA) for Compact Refueling Machine
  - Thermal-Hydraulic Experimental Test Article (THETA)
  - Flow Sensor Test Article (F-STAr)
  - Gripper Test Article (GrTA)
- **METL consists of:**
  - ~3,000 kg of reactor-grade sodium – purified in cold trap
  - Two 18-inch test vessels and two 28-inch test vessels (Phase I)
  - Max system temperature = 537.8C (1000°F) (except for 28-inch test vessels – 648.9C (1200°F))
  - Test vessels can be isolated from main loop
- **Provides much needed U.S. infrastructure (both personnel and hardware) to test liquid metal systems and components**
- See: https://www.anl.gov/nse/mechanisms-engineering-test-loop-facility

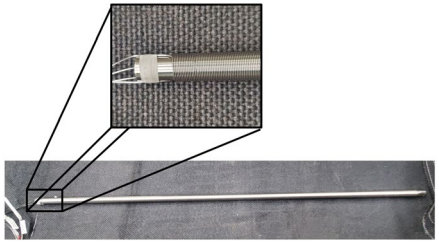


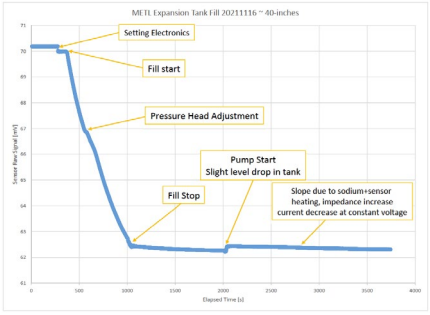
METL Sensors - Overview

- **METL Sensors**
  - **Temperature - TCs**
  - **Flow – COTS flowmeters, PM flowmeter, ultrasonic flow meter, and an NEUP sensor**
    - **20-19524 – Non-intrusive Flow Monitoring for Liquid Metal and Molten Salt-Cooled Reactors – Virginia PolyTech – Dr. Pickrell**
  - **Pressure – COTS NaK pressure transducer (sodium) and conventional pressure gauges for gas side.**
  - **Level – Inductive Level Sensor, TC rake, D/P sensor**

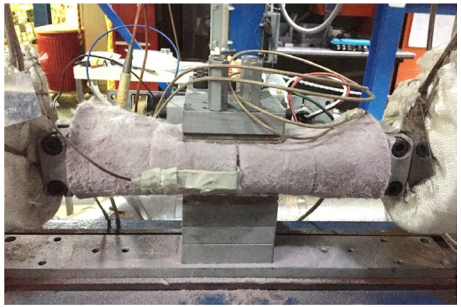


COTS NaK filled pressure transducer





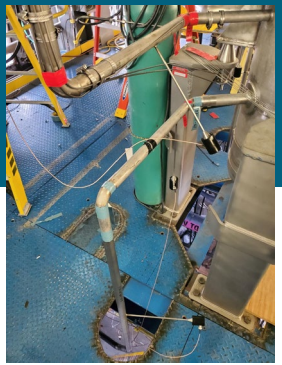
Inductive level sensor



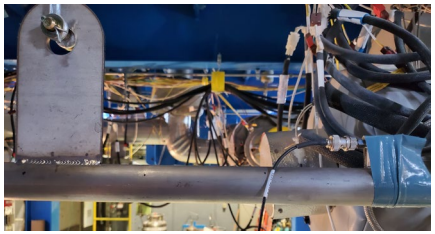
PM Flowmeter

METL Sensors - Overview

- **METL Sensors**
  - **Structural health monitoring system – commercial acoustic system, NEUP supplied (3)**
    - **21-24162 – Self-powered wireless sensor system for health monitoring of liquid sodium cooled fast reactors – Univ of Notre Dame – Dr. Zhang**
    - **21-24389 – High Temperature Electromagnetic Acoustic (EMAT) transducers for Structural Health Monitoring – Univ of Cincinnati – Dr. Corcoran**
    - **22-27082 – Dual Mode High Temperature MEMS Ultrasonic Sensor for Structural Health Monitoring of Liquid Metal Reactor – Univ of Illinois Chicago – Dr. Ozevin**
  - **Power – monitor power to heaters**
  - **Impurity Monitoring – Plugging Temperature Indicator (PTI) and Optical Sensor (NEUP)**
    - **23-29603 – Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors – Univ of Michigan - Dr. Burger**
  - **Leak Detection – Optical Sensors**

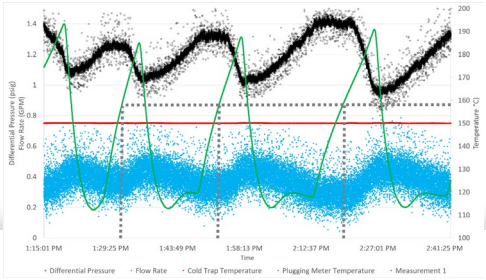


COTS Structural Health Monitoring System



Acoustic Emission Applied to piping and results

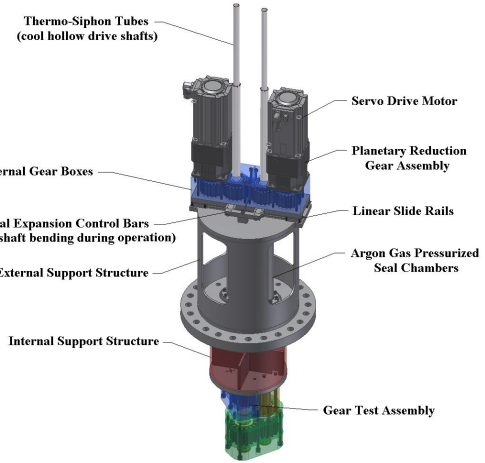
Plugging Meter



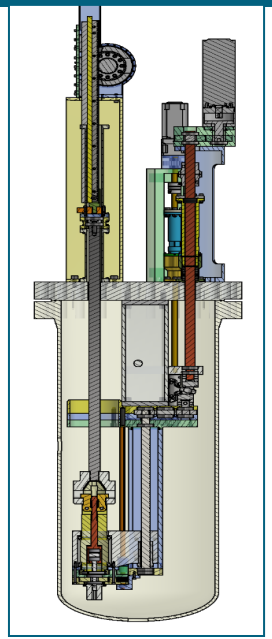
Plugging Meter Test Results

METL Test Articles (examples)

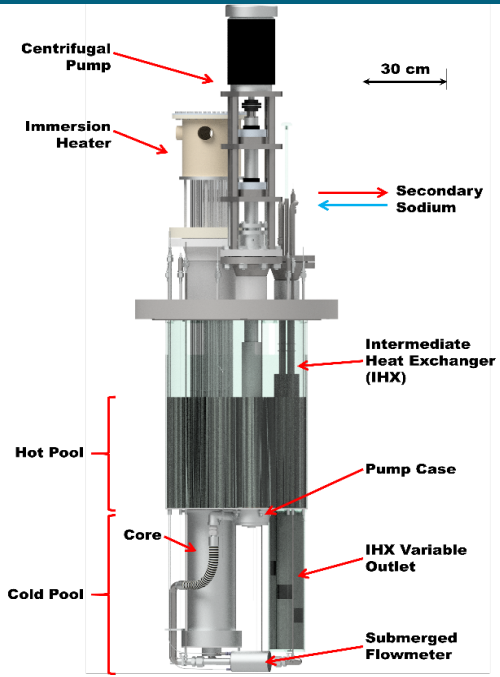
FAST REACTOR PROGRAM



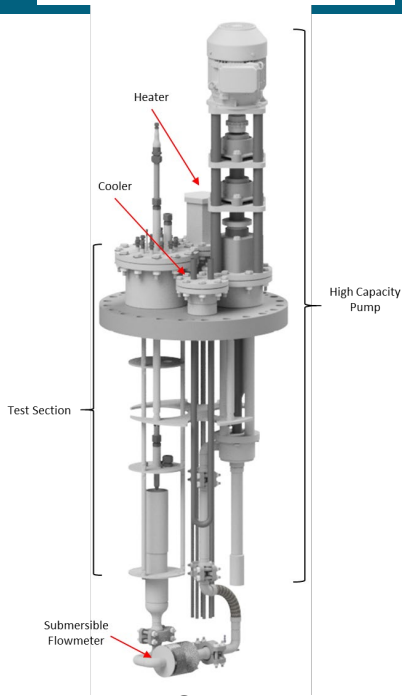
Gear Test Assembly (GTA)



Gripper Test Assembly (GrTA)



Thermal Hydraulic Experimental Test Article (THETA)

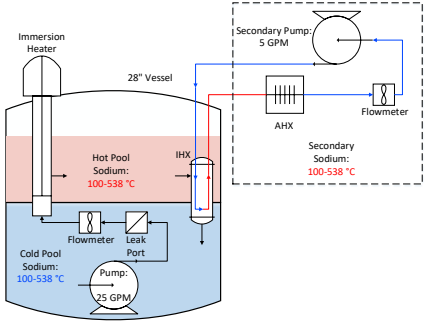


Flow Sensor Test Article (F-STAr)

THERMAL HYDRAULIC EXPERIMENTAL TEST ARTICLE (THETA)

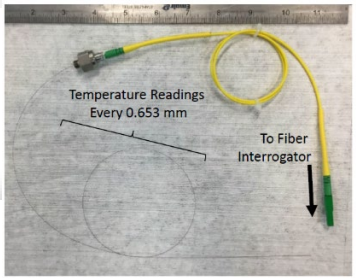
FAST REACTOR PROGRAM

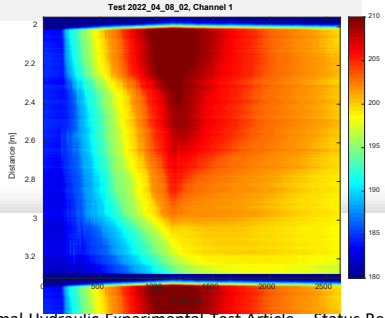
- THETA is a 28” METL test article
- Designed to provide experimental validation data for a variety of thermal hydraulic phenomena in an SFR under nominal and accident scenarios
- THETA primary systems is operations. Secondary system was filled this week and we are bringing it on-line.
- Scaled using a Richardson number approach to Argonne’s Advanced Burner Test Reactor (ABTR)[1]
- Hot / Cold pool volume: 151 L (40.75 gal) / 319 L (86.26 gal)
- Optical fiber distributed sensors provide unprecedented temperature measurement temporal/spatial resolution

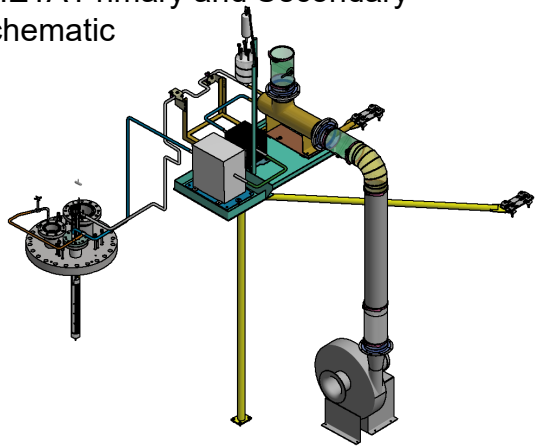


THETA Primary and Secondary Schematic

THETA Primary System







Secondary System Model

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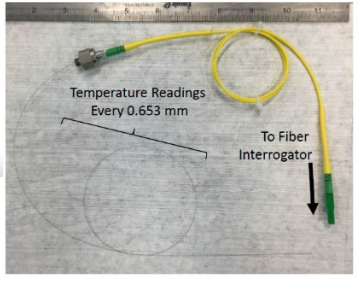
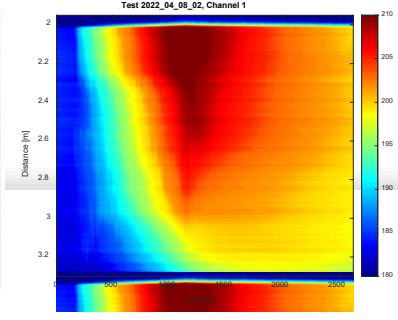
1. Weathered, “Thermal Hydraulic Experimental Test Article – Status Report for FY2019”, (2019) ANL-ART-176

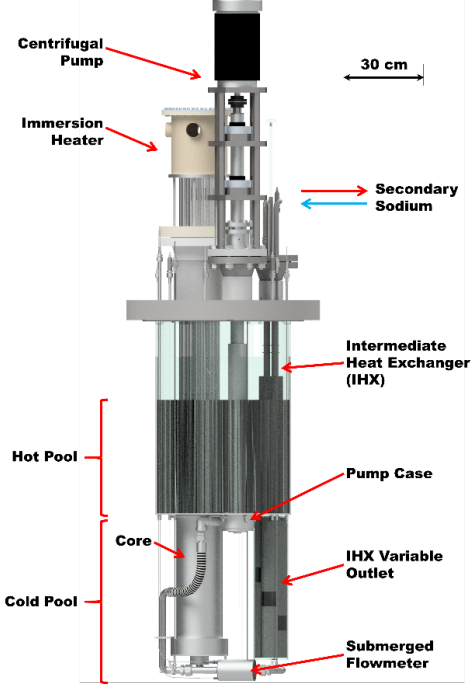
THETA Sensors and Development

- Temperature
  - TCs and optical fibers (distributed temperature measurement)
- Flow
  - Submerged PM flowmeter – primary sodium
    - 19-16811 – Liquid metal-cooled fast reactor instrumentation technology development – Univ of Wisconsin – Dr. Anderson
  - Pump RPM
  - PM flowmeter – secondary sodium
- Power
  - Power meter to electrically heated core
- Level – TC rake and continuity probe





THETA PM flowmeter

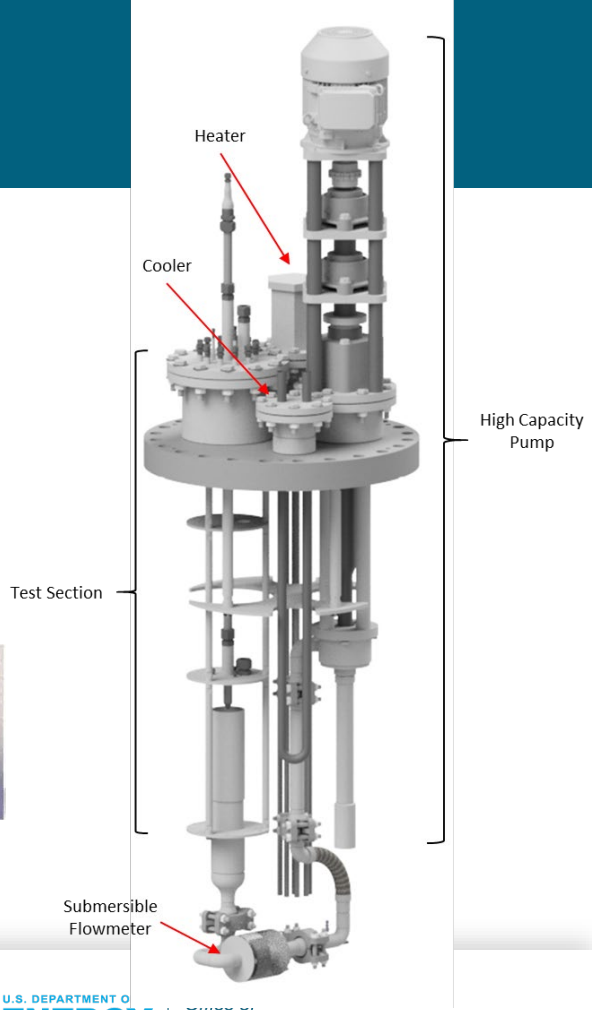


THETA Primary System Model

Flow Sensor Test Article (F-STAr)

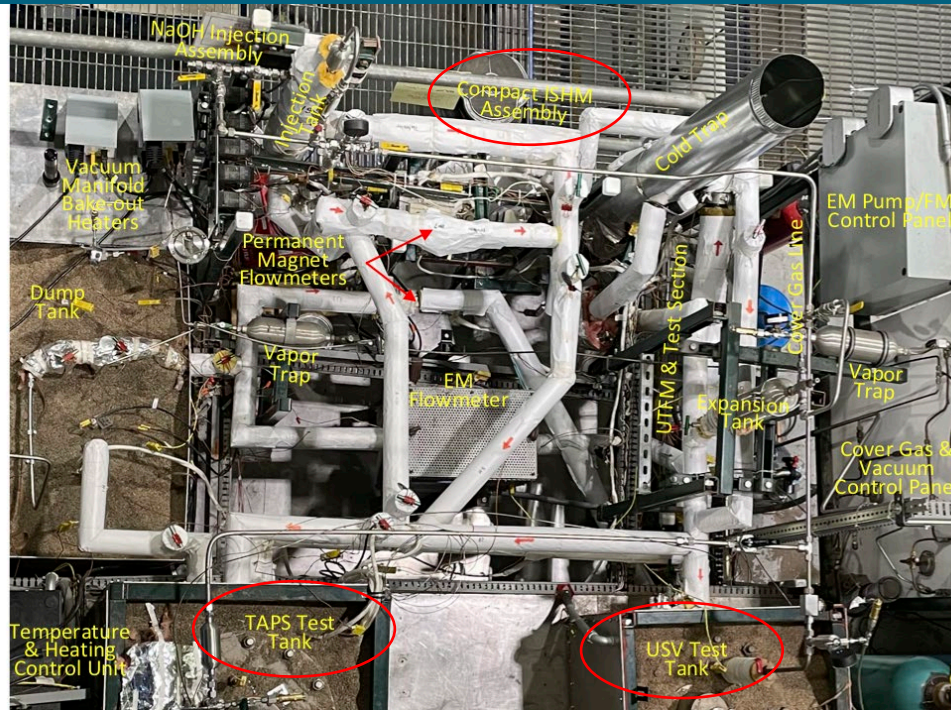
- Mission
  - Model the outlet of a SFR core assembly to test flow sensor instrumentation in a reactor-like outlet plenum.
  - Can measure flowrate from one outlet core assembly
  - Can measure flowrate from an array of scaled core assemblies
  - Test Article can be reconfigured for other testing needs such as fluidic diodes and temperature sensitive orifice testing
- F-STAr Sensors
  - Flow – Submersible PM flowmeter, Eddy Current flow sensors
  - Temperature – TC and Optical fibers
  - Level – TBD
  - Pump – speed, current, vibration, etc

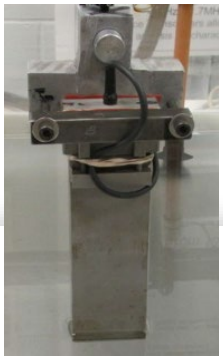
Eddy Current
Flow Sensor



USV/H2/TAPS Sensor Loop

- This loop is about 30 gallons of sodium and used for some instrumentation testing
- Sensors
  - Hydrogen – An **in-sodium hydrogen sensor** was fabricated and tested in the USV loop
    - In-sodium diffusion type hydrogen sensor
    - In-vapor diffusion type hydrogen sensor
  - Temperature – TC and Thermal Acoustic Power Sensor (TAPS)
  - Flow – EM flowmeter and PM flowmeter, microwave cavity flowmeter (testing under ASI program)
  - Undersodium Viewing (USV) technology demonstrated
    - Submerged USV Transducer
    - Waveguide USV System
    - Under lead viewing system being created under NEUP
      - 19-17355 – Development of Versatile Liquid Metal Testing Facility for Lead-cooled Fast Reactor Technology – Univ of Pittsburgh – Dr. Lee
      - This will be tested at Dr. Lee lead loop
  - Pressure – COTS NaK Filled pressure transducer





Under-Sodium Viewing

In-Sodium Hydrogen Sensor

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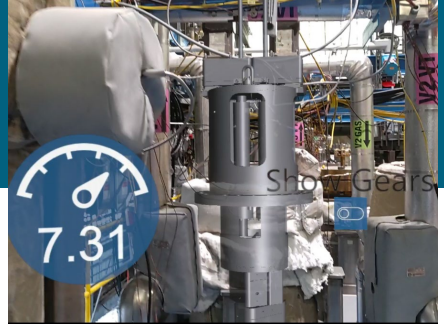
Adapter Flange

- An adapter flange is also available for smaller components or instrumentation testing.
- This flange has
  - one 8” 300# ANSI flange,
  - two 3.5” Grayloc ports,
  - four 1.5” Grayloc ports, and
  - one 1” Grayloc Port

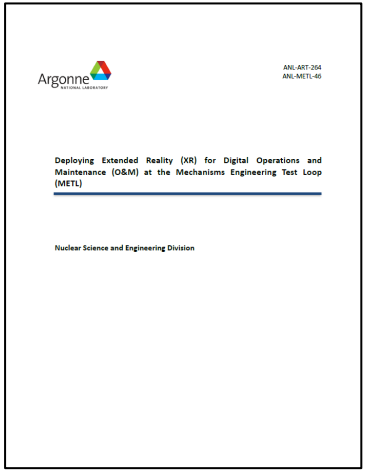
Other Items of Interest – Sensor Integration – Adv Controls

- Human Machine Interface – Digital Operations and Maintenance (O&M)
  - **Digital O&M** – Deploy a digital operations and maintenance system using extended reality to support the operations and maintenance of systems and components on a fast reactor using METL as a reactor plant surrogate – Report ANL-ART-264.
  - Digital Operations and Maintenance (Digital O&M) technologies will be employed in all advanced reactors to organize digital information, provide better human-machine interface, reduce operations and maintenance costs, and make the plant overall more reliable.



GTA – real-time data

Digital O&M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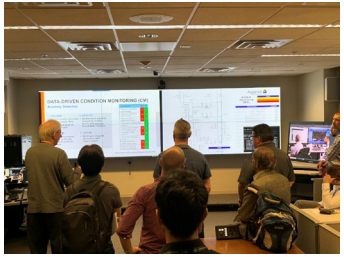
ANL-ART-264
ANL-METL-46

Deploying Extended Reality (XR) for Digital Operations and Maintenance (O&M) at the Mechanisms Engineering Test Loop (METL)

Nuclear Science and Engineering Division

- Diagnostic Software Demonstration
  - METL provides a unique facility for demonstrating diagnostic and prognostic software
  - Example – PROAID demos in September 2023



METL Prognostic Demonstration

Summary – FRP

- **In the FRP, we have the infrastructure to support sensor testing and development**
- **In addition, Argonne has salt and water loops for sensor testing and development**
- **A lot of on-going work on sensor development**
- **Some sensors not being developed or utilized by the FR program**
  - **High temperature nuclear instruments – SR, IR, PR**
    - **ORNL developing?**
  - **Delayed neutron detectors – failed fuel monitoring**
- **Need commercial supply chains for sensors and instruments for fast reactors**

- **Backup Slides have some information on Argonne LEAF Accelerator – Irradiation testing facilities**

ASI Sensor Development	Potential Location for Testing	Organization
Optical Fibers	THETA	INL and ORNL
Fiber Optic Sensor System for Multipoint Pressrue and Temperature Measurement	Temp - THETA	SBIR
Fiber Embedded Wireless Sensors	METL	SBIR
Microwave Resonant Cavity Transducer for Flow Sensing	USV Loop	ANL
Ultrasonic Sensors for Nuclear Reactor Applications	METL	SBIR
Innovative Monitoring Tech for Reactor Vessel of Micro-HTGR	METL	NEUP - TAMU
Printed Sensors for Monitoring Reactor Health	METL	SBIR
Advanced Controls	METL or THETA	ANL
Advanced Controls / Digital Twin	METL	INL
Comms - Develop Multi-Band Wireless	METL	INL
Adv Online Monitoring and Diagnostic Tech for NPP Management, Ops and Maintenance	METL	NEUP - Pitt
Machine Learning for Enhanced Diagnostic and Prognostic Capabilities of NPP Assets	METL	IFOA - Bluewave
AMS R&D Work in Support of Existing and New Generation Reactors	METL	AMS Corp

* List taken from FY23 ASI program webinar agenda

QUESTIONS?

Backup

NOVEMBER 1, 2023

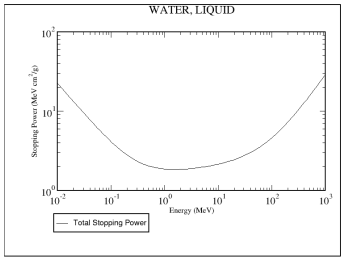
LOW ENERGY ACCELERATOR FACILITY (LEAF) IRRADIATION CAPABILITIES

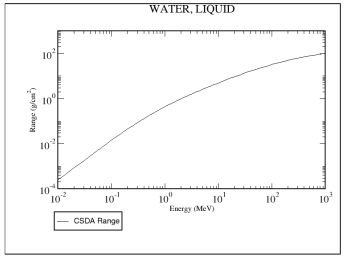
SERGEY CHEMERISOV - CHEMERISOV@ANL.GOV

RADIATION PRODUCED BY ELECTRON ACCELERATORS

Direct electron beam (beta) irradiations

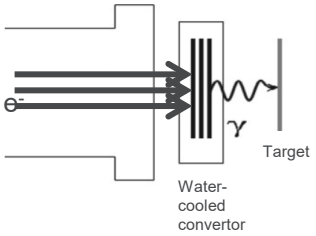
- Linear energy transfer
- Limited range

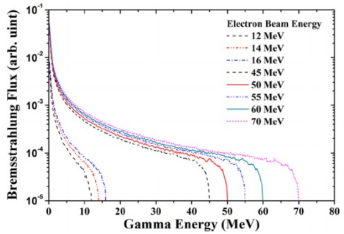




X-ray (Bremsstrahlung photon) irradiations

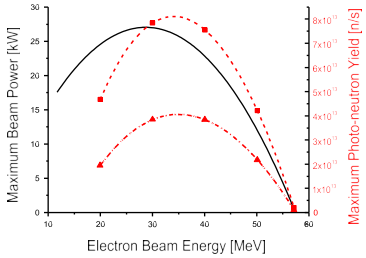
- Wide energy range
- Energy up to maximum electron beam energy

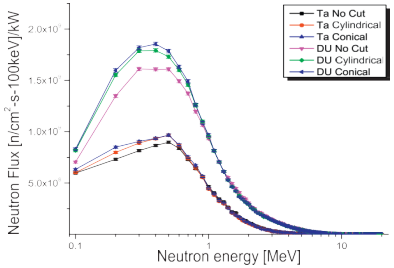




Neutrons from photo-nuclear reactions with target

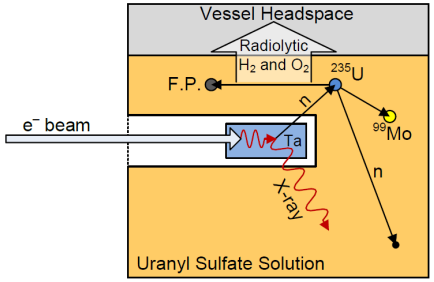
- Electron energies >10 MeV
- Point source
- Fission-like spectrum



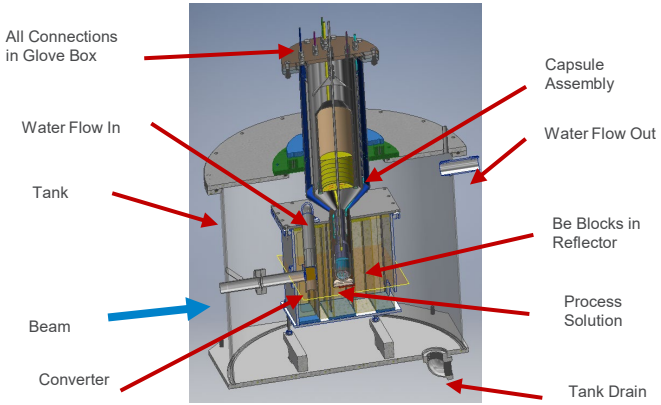


LINAC IRRADIATION CAPABILITIES

- High beta/gamma fields
- Direct beta field up to 1 MGy/s
- Limited penetration depth (20 cm of water)
- Photon (bremsstrahlung) 5.6 kGy/s
- Wide energy spectrum up to maximum energy of electron beam
- Neutron irradiation with flux up to $5x10^{11}$ n/cm^2



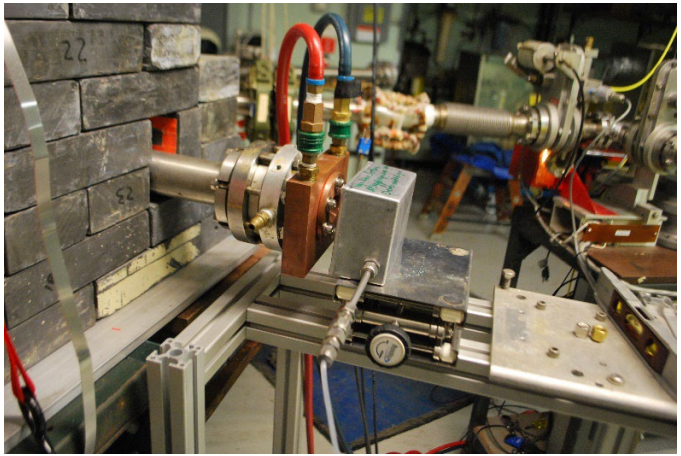
Argonne Molybdenum Research Experiment uses neutrons produced in Ta/U target to induce fission in Uranyl sulfate solution



Universal neutron irradiator uses Ta target and beryllium reflector to produce high flux of thermalized neutrons

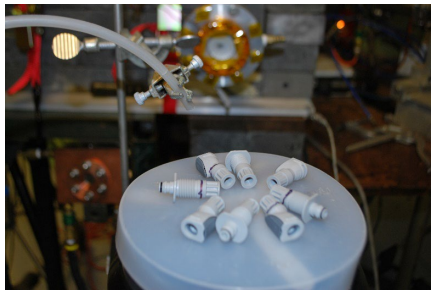
VDG IRRADIATION CAPABILITIES

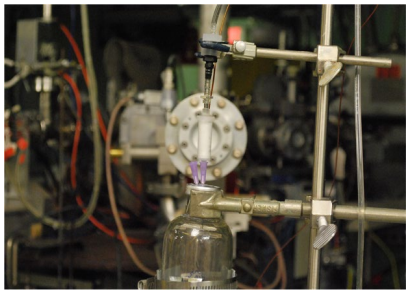
- High beta/gamma rates
- Direct beta field up to 0.1 MGy/s
- Limited penetration depth (1.5 cm of water)
- Photon (bremsstrahlung) 2.5 Gy/s
- Wide energy spectrum up to maximum energy of electron beam (3 MeV)
- No activation for common materials



Gamma irradiation of high radiation tolerant camera system

Beta irradiation of components for medical isotopes separation systems

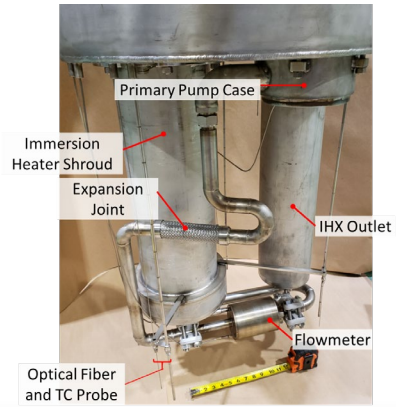


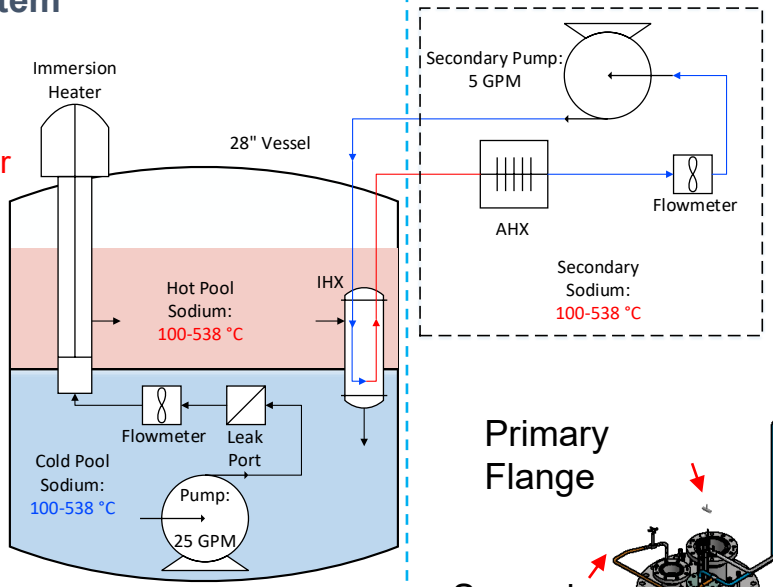


THETA System Status

Primary System

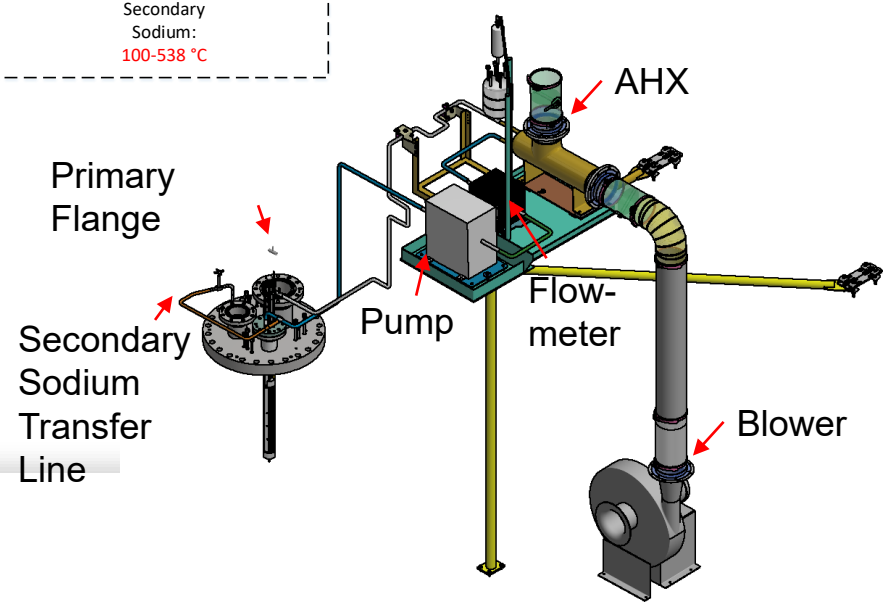
- Hot and cold pool
- Centrifugal pump
- Permanent magnet flowmeter
- 38 kWe electric core
- Primary system operational





Secondary System

- Installed recently with sodium.

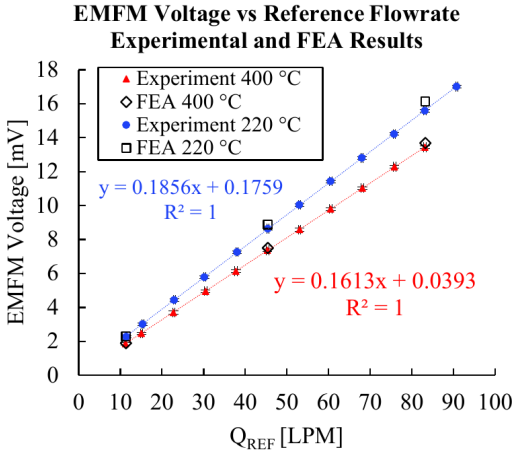


https://www.anl.gov/nse/thermal-hydraulic-experimental-test-article

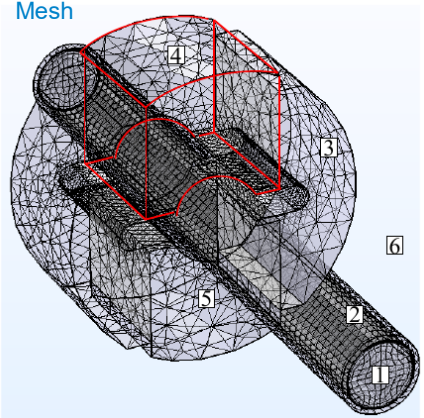
THETA Primary System Components

Submersible Electromagnetic Flowmeter

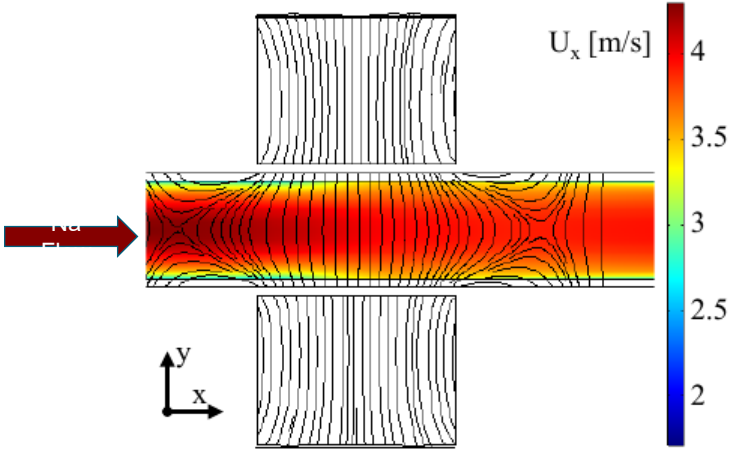
- Flowmeter FEA model (COMSOL Multiphysics) validated demonstrating the ability to determine induced voltage after considering subtle phenomena at various temperatures and flow rates that affect the magneto-hydrodynamics (electrical conductivity, density, viscosity, etc.)
- Journal paper describing THETA flowmeter work:
  - “Weathered, Grandy, Anderson, Lisowski, “High Temperature Sodium Submersible Flowmeter Design and Analysis,” in *IEEE Sensors Journal*, doi: 10.1109/JSEN.2021.3079713



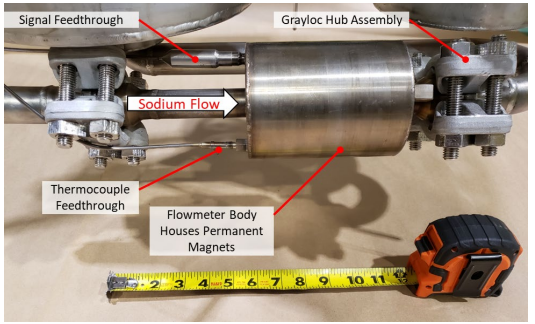
FEA Mesh



Velocity and Magnetic Flux Density



Flowmeter as Installed in THETA



Figures from: “Weathered, Grandy, Anderson, Lisowski, “High Temperature Sodium Submersible Flowmeter Design and Analysis,” in *IEEE Sensors Journal*, doi: 10.1109/JSEN.2021.3079713

NEUP R&D Contributions

FY Funding	Project FY-ID	Title	Organization	PI First Name	PI Last Name
2018	18-14908	Experimental measurements of fission product retention in liquid sodium	University of Wisconsin-Madison	Mark	Anderson
2018	18-15471	Integral Experimental Investigation of Radioisotope Retention in Flowing Lead for the Mechanistic Source Term Evaluation of LFR	University of New Mexico	Osman	Anderoglu
2019	19-16754	Simultaneous Corrosion/Irradiation Testing in Lead and Lead-Bismuth Eutectic: The Radiation Decelerated Corrosion Hypothesis	Massachusetts Institute of Technology	Michael	Short
2019	19-16811	Liquid metal-cooled fast reactor instrumentation technology development	University of Wisconsin-Madison	Mark	Anderson
2019	19-17355	Development of Versatile Liquid Metal Testing Facility for Lead-cooled Fast Reactor Technology	University of Pittsburgh	Jung-Kun	Lee
2020	20-19524	Non-Intrusive Flow Monitoring for Liquid Metal and Molten Salt-Cooled Reactors	Virginia Polytechnic Institute and State University	Gary	Pickrell
2021	21-24162	Self-powered wireless sensor system for health monitoring of liquid-sodium cooled fast reactors	University of Notre Dame	Yanliang	Zhang
2021	21-24389	High Temperature Electromagnetic Acoustic (EMAT) Transducers for Structural Health Monitoring	University of Cincinnati	Joseph	Corcoran
2022	22-27082	Dual Mode High Temperature MEMS Ultrasonic Sensor for Structural Health Monitoring of Liquid Metal Reactor	University of Illinois at Chicago	Didem	Ozevin
2022	22-26857	Characterizing Fast Reactor Failure Mode through Separate Effect and Prototypic Tests	Oregon State University	Guillaume	Mignot
2023	23-29603	Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors	University of Michigan	Milos	Burger