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Extreme Environment Materials

Gabriel Ilevbare

August 2017

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Gabriel Ilevbare Ph.D

Department Manager, Materials Science and Engineering

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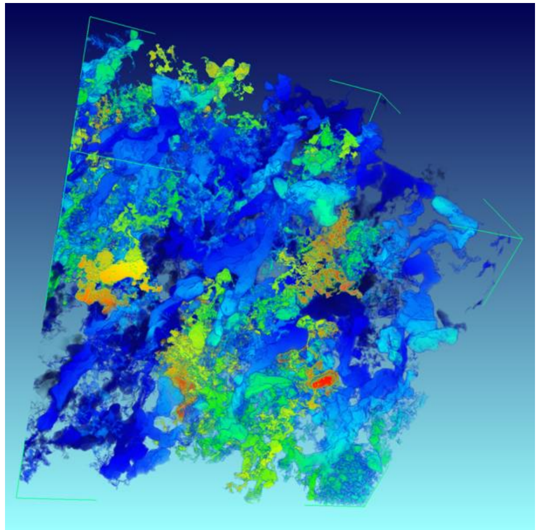

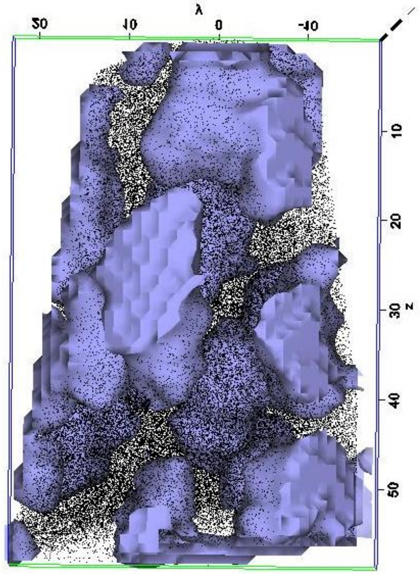

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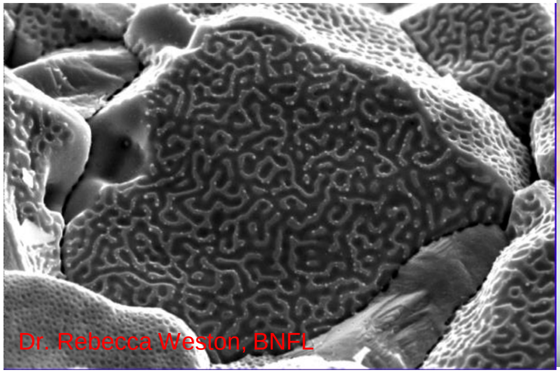
Why Are We Concerned about Materials in Extreme Environments

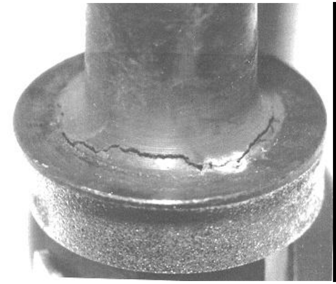
- The demand for more energy necessitates the drive towards higher energy density generation and storage
  - Consequently ever increasing physical and chemical demand have to be placed on materials to meet these higher energy demands
- Better understanding of material degradation under extreme environments would accelerate development and deployment of:
  - Smaller and higher energy density nuclear power reactors and components that operate at higher temperatures and pressures with longer services lives and efficiencies.
  - Smaller, higher energy density storage devices and that cost less and last longer
  - Lighter and more efficient vehicle engines that operate at higher temperatures
  - Advanced intelligent multifunctional materials that perform better under a wide range of extremes of environmental perturbations
  - Advanced sensors that can be embedded in components which are able to warn about impending materials failures
  - Minimize the impact of human activity on the environment

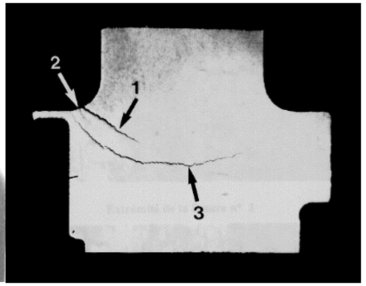
What Are Extreme Environments for Materials

- **When you think about extreme environments for materials what comes to mind?**
  - High Stress Levels?
  - High Levels of Strain?
  - High Temperature?
  - Elevated Pressure?
  - High Chemical Concentration/Reactivity?
  - High Photon or Radiation Flux?
  - Massive Electric of Magnetic Fields?
  - Perhaps a Combination of Two or More of These?

Irradiation

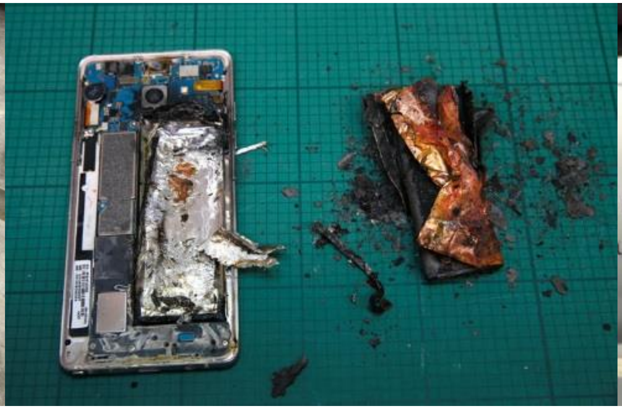






What Are Extreme Environments for Materials-Continued

- **What about the not so obvious extreme environments?**



From a materials perspective, an **"extreme environment"** is any environment that presents challenges that make it difficult for a material to perform well for its intended use within the designated safety envelope.

- *Some of these environments are inadvertently created through a lack of understanding of material/environment interactions*

- ***The goal is to improve such understanding to expand the safe operating envelope of current materials or design new ones to tolerate conditions beyond what is currently possible***

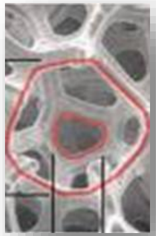
General Approach for Achieving Innovative Materials Design and Deployment *–Fundamental Research Needs*

Materials Properties Description
Develop first-principles, multi-scale description of the properties of complex materials, and operational envelope

Science-based Design
Advanced M&S tools for novel materials design to meet identified needs.

Fundamental Understanding
Materials R&D to characterize surface reactions and mechanical resilience in extreme environments. Including modeling and simulations to validate safety operating envelope

Engineering and fabrication
Design, engineering, and fabrication of components for novel energy system, demonstrations and deployment



Atomic structures and complex Properties Definitions

Digital real-time simulation to accelerate materials design

Materials testing and characterization

HEATRIC Printed Circuit Heat Recovery Unit

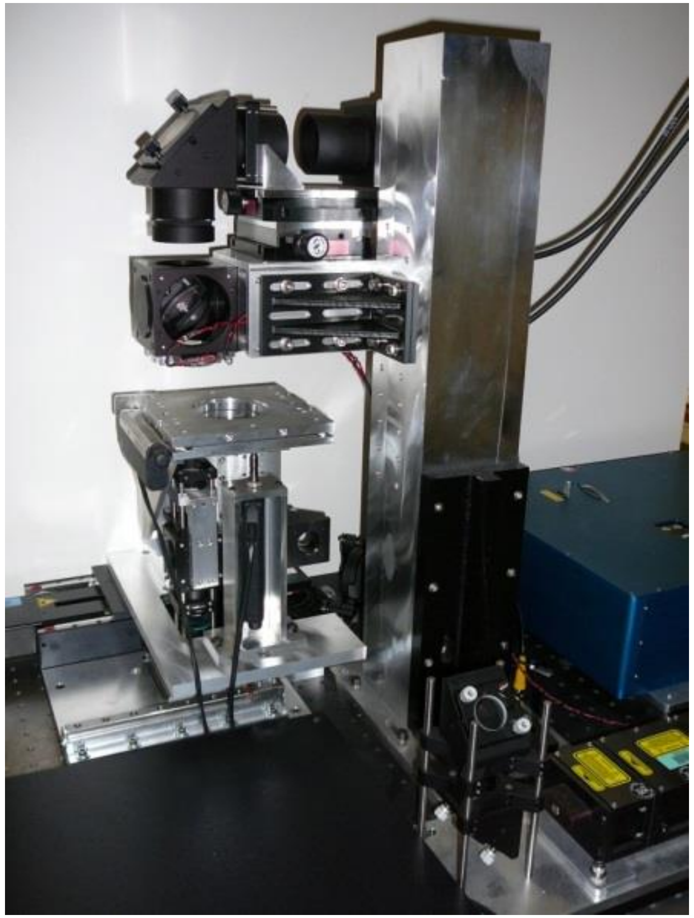
Outcomes

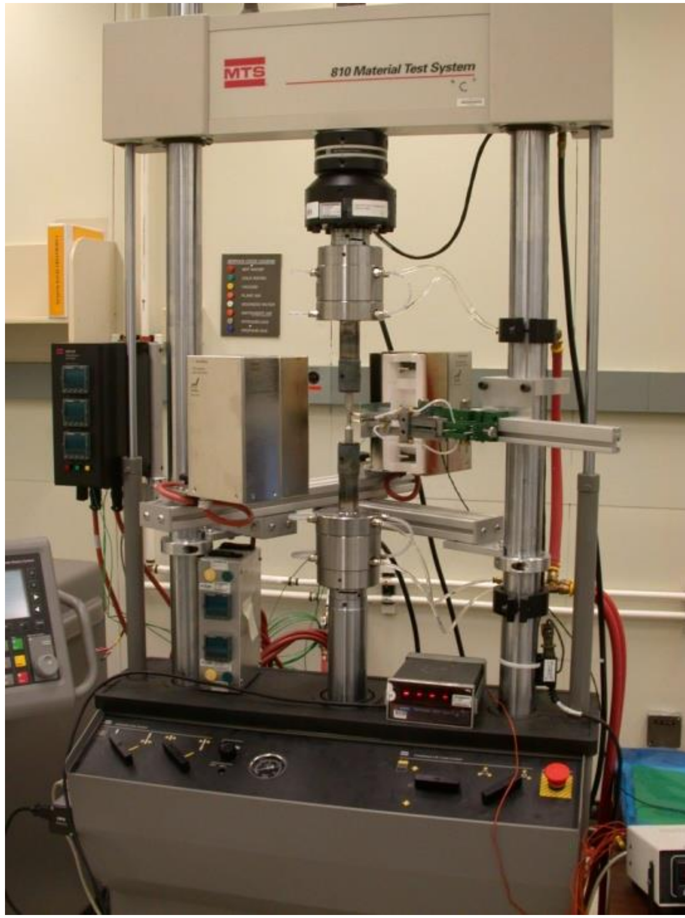
- Address all fundamental and fabrication related challenges in target material(s) in extreme service environments
- Deployment of fabricated component in the field

Measures of Success: Demonstrated resilient material(s) in engineered component under extreme service enviroment(s)

INL and MS&E Department Excels in Nuclear Materials Testing and Characterization

- **Nuclear Materials**
  - Radiation effects on thermal transport, mass transport, and mechanical behavior of materials with applications in nuclear energy
  - Harsh environments – radiation, temperature, pressure/stress, chemical
  - Experimentation and evaluation that validates structural materials and computational models for existing and ***very high temperature*** advanced nuclear systems
  - Focus:
    - Behavior models
    - Baseline properties (phy., chem., irrad.)
    - High Temp Degradation Mechanisms
    - Codes and Standards
  - INL is investigating VHTR materials including:
    - Stainless Steels, Ni-base Alloys
    - Graphite





Graphite R&D Program - Research Areas

ASME Code
- Establishes an ASME approved code (for 1st time)
- Develops property values for initial components and irradiation induced changes

Behavior Models
- Predicts irradiated material properties and potential degradation issues
- Irradiation behavior for continued safe operation

Baseline Properties
- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

Graphite R&D Program

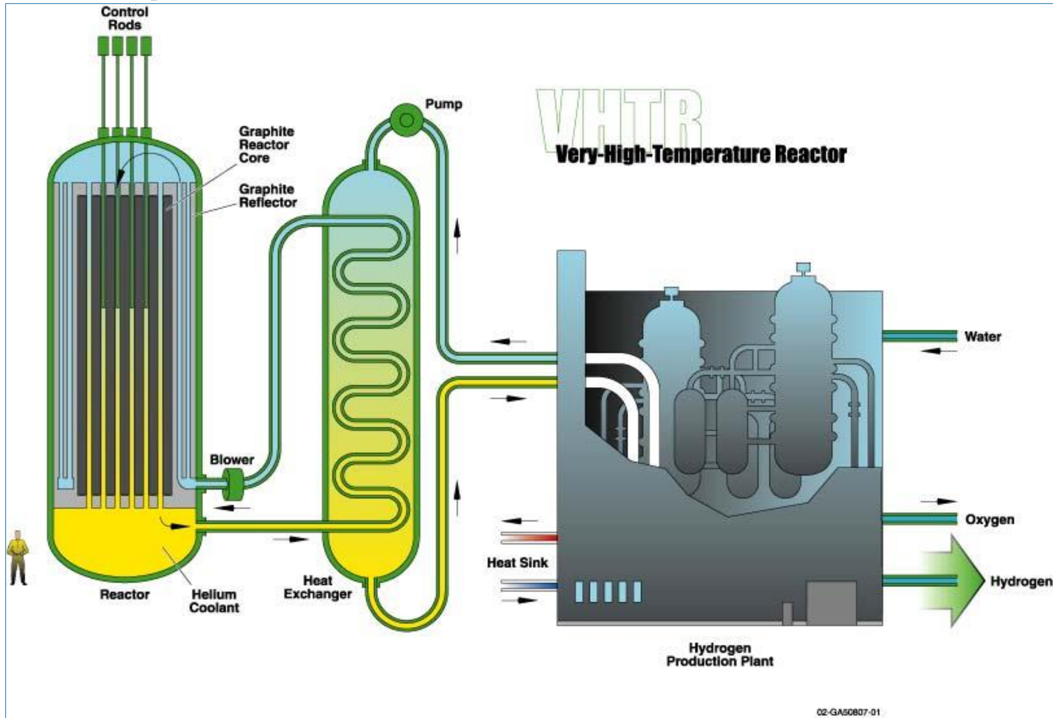
Define the safe working envelope for nuclear graphite and protection of fuel

Mechanisms and Analysis
- Data analysis and interpretation
- Understanding the damage mechanisms is key to interpreting data

Irradiation Behavior
- Determines irradiation changes to material properties
- Irradiation behavior for continued safe operation

Very High Temperature Reactors (VHTR)- The Design Envelope

- **Provide Technology Development to Support Future Design and Deployment of Very High Temperature Gas Cooled Reactors**
- **RPV >6m in diameter and 150 to 250 mm in thickness; Operating Temperature of 350C**
  - Due to weldability, Code qualification to 371ºC and technical maturity, down selection to A508/533 steel was made
- **Steam Generator up to 750ºC and Sixty Year Life**
  - Alloy 800H currently Code Qualified up to 760C and 300,000 hours
  - Low allowable stress at 750ºC for Alloy 800H suggests alloy with superior properties may be desirable to allow design for life of plant
- **Intermediate Heat Exchanger up to 950ºC (with life up to 20 years desirable)**
  - Alloy 617 was down-selected from possible alloys
  - Code qualification for elastic design up to 427ºC
  - Code qualification allowing design in inelastic regime up to 950ºC



Materials Properties and Performance Capabilities

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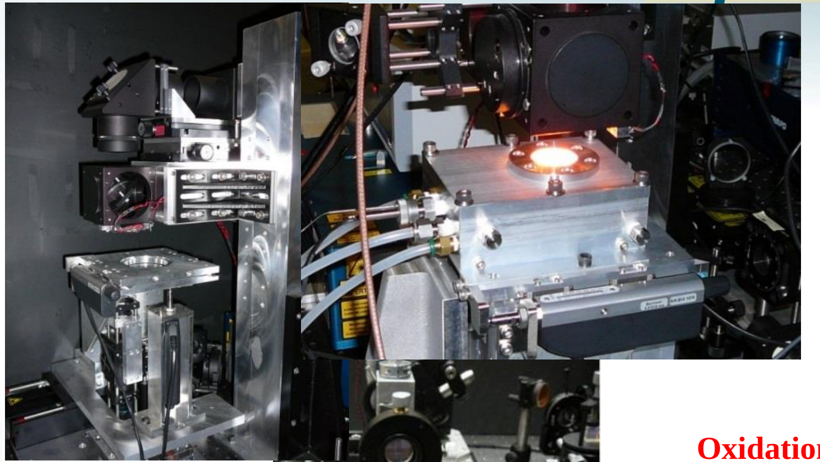
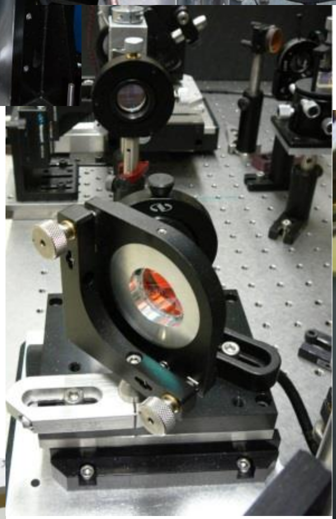
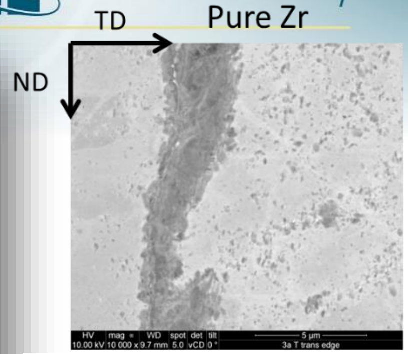
Mechanical Properties

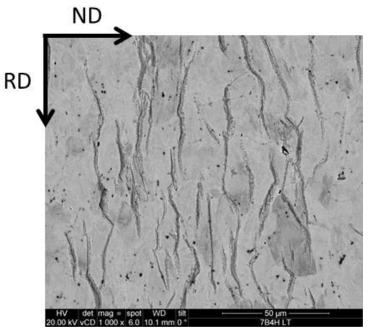
Non-destructive
Laser Based Characterization





Processing and Hydriding





Aging and environmental effects (static/crack growth

Oxidation kinetics

Composite Development & Characterization

Creep-fatigue

IASCC Hot cells

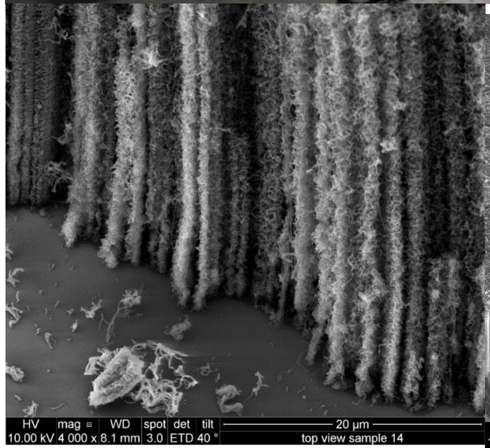
IASCC Testing in PWR & BWR

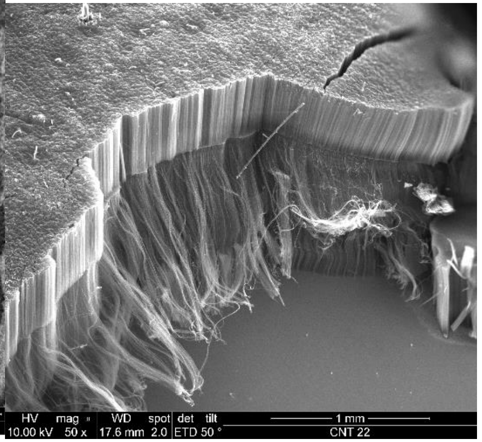
Other Capabilities in MS&E Department

- **Non-nuclear**
  - **Fabrication**
    - Thermomechanical processing of materials
    - Power metallurgy hot Isostatic press (PM-HIP) capabilities for metal/composite materials studies
    - Rolling mill capabilities
  - **Welding/Joining**
    - Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications
    - Monitoring and Control of the Hybrid Laser-Gas Metal-Arc Welding Process
    - Dissimilar metal joining capabilities (e.g., Al, Mg, Ti to steels)
      - filler metal designs
      - hybrid laser welding
      - Friction Stir welding
  - **Thermal spray**
    - Metallic and/or ceramic coating on various size and geometry substrates.
    - Measurement of thermal sprayed particle velocity, size and temperature for correlation to spray parameters and coating characteristics
  - **Nondestructive evaluation**
    - X-ray, ultrasonic, eddy current
  - **Chemical agent munitions and storage container inspection**
  - **Environmental Effects Lab**
    - Hydriding and de-hydriding neodymium based magnet materials
    - Corrosion

Spray Forming

Ultra-long Carbon Nano Tubes





Corrosion and Environmental Testing

Modeling and Simulation Capabilities

Bring basic science to applications, molecular-scale to industry-scale

Reactive flow in porous media, *molecules, pore scales, to reservoirs*

Multiphase Computational Fluid Dynamics (CFD)

Discontinuous and Continuous Computational Solid Mechanics:
- *Nucleation, coalesces and propagation of fractures*
- *DEM, SPH, FEM + elastic/inelastic – plasticity, creep, damage mechanics*

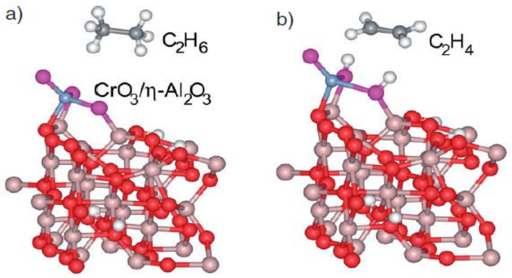
Computational Chemistry, Material and Science:
- *Ab initio methods, MD, meso scale and continuum FEM*
- *Computational thermodynamics*

Nonlinear dynamics of complex systems: *self-organizing*, *bifurcation*

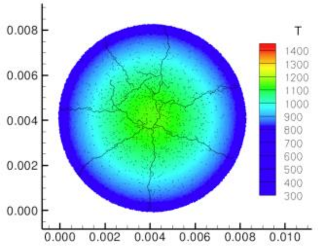
New Technologies & Processes for key EES&T missions:

- Advanced manufacturing
  - ***Materials***
  - ***Catalysis***
- Advanced transportation
  - ***Electrochemistry***
- Clean energy
  - ***Geothermal, UFD, CCS***
  - ***Unconventional fossil***
  - ***Bio-feedstock mechanics***
- Environmental management
  - ***Waste forms***
  - ***Fate and transport of contaminants***

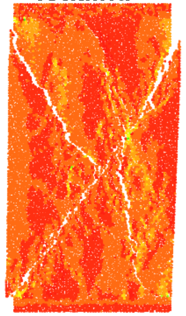
Catalysis atomistic modeling: Dehydrogenation of C_2H_6 on CrO_3-cluster attached to η-Al_2O_3 surface



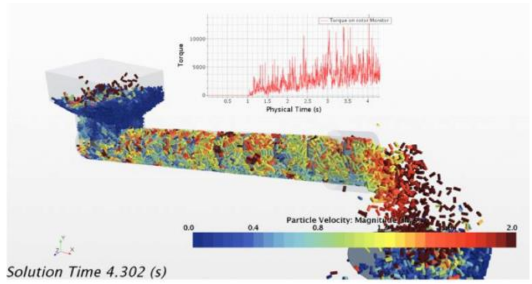
Discrete Element Modeling of thermal fracturing of nuclear fuel pellet during power cycles



Simulation of fracturing of polycrystalline brittle solid under uniaxial compression loading



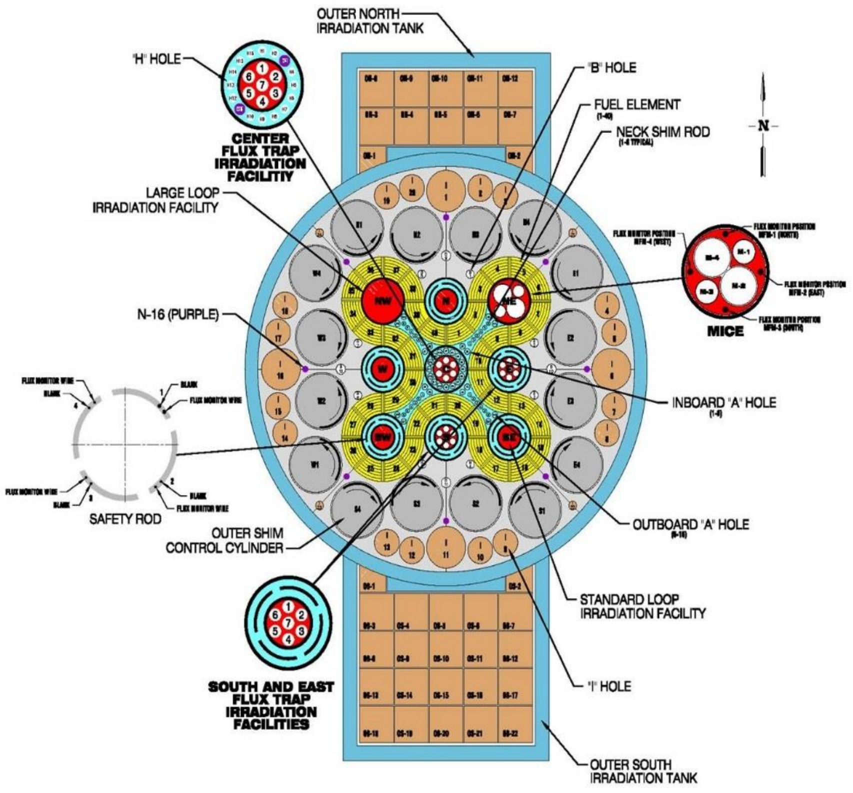
Simulations of bio-feedstock particles flow through auger feeder



Materials Irradiation Capability at the INL ATR

- Highest-power research reactor operating in the world (250MW)
- Provides high neutron fluxes while being operated in a radially unbalanced condition
- Serpentine fuel arrangement affords experimental versatility while ensuring maximum efficiency of core reactivity-control components
- Numerous Test Positions and Large Test Volumes
- Four different experiment types (Capsule, Hydraulic Shuttles, Lead Outs, and Pressurized Water Loop Experiments)
- Individual Experiment Temperature, Pressure, Flow, and Chemistry Control in Six Pressurized Water Test Loops with a Capacity for Up to Nine Experiment Loops
- Constant Axial Power (flux) Profile
- Operates in short-duration cycles, with (generally) 55 days between refueling outages

ATR Fuel & Experiment Layout

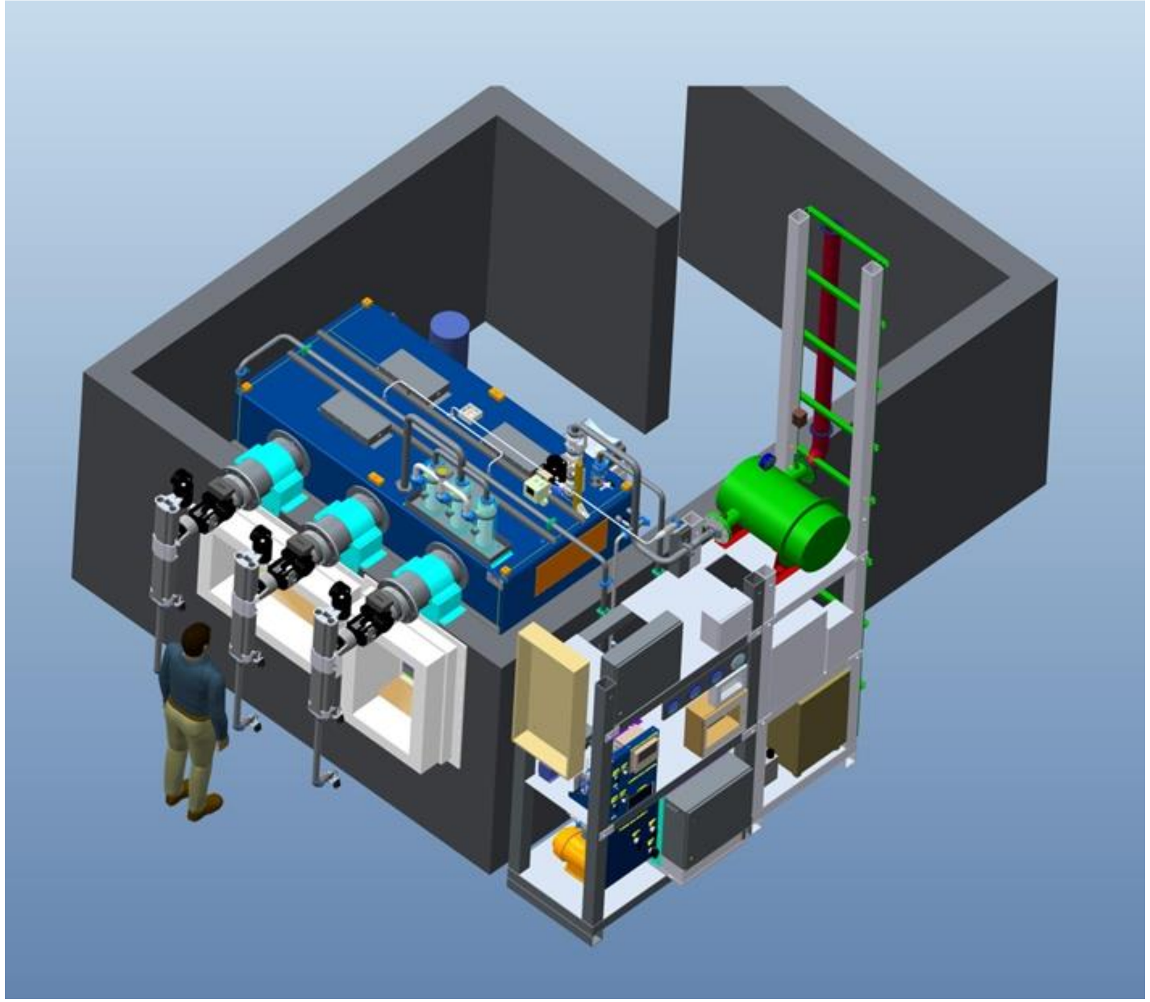


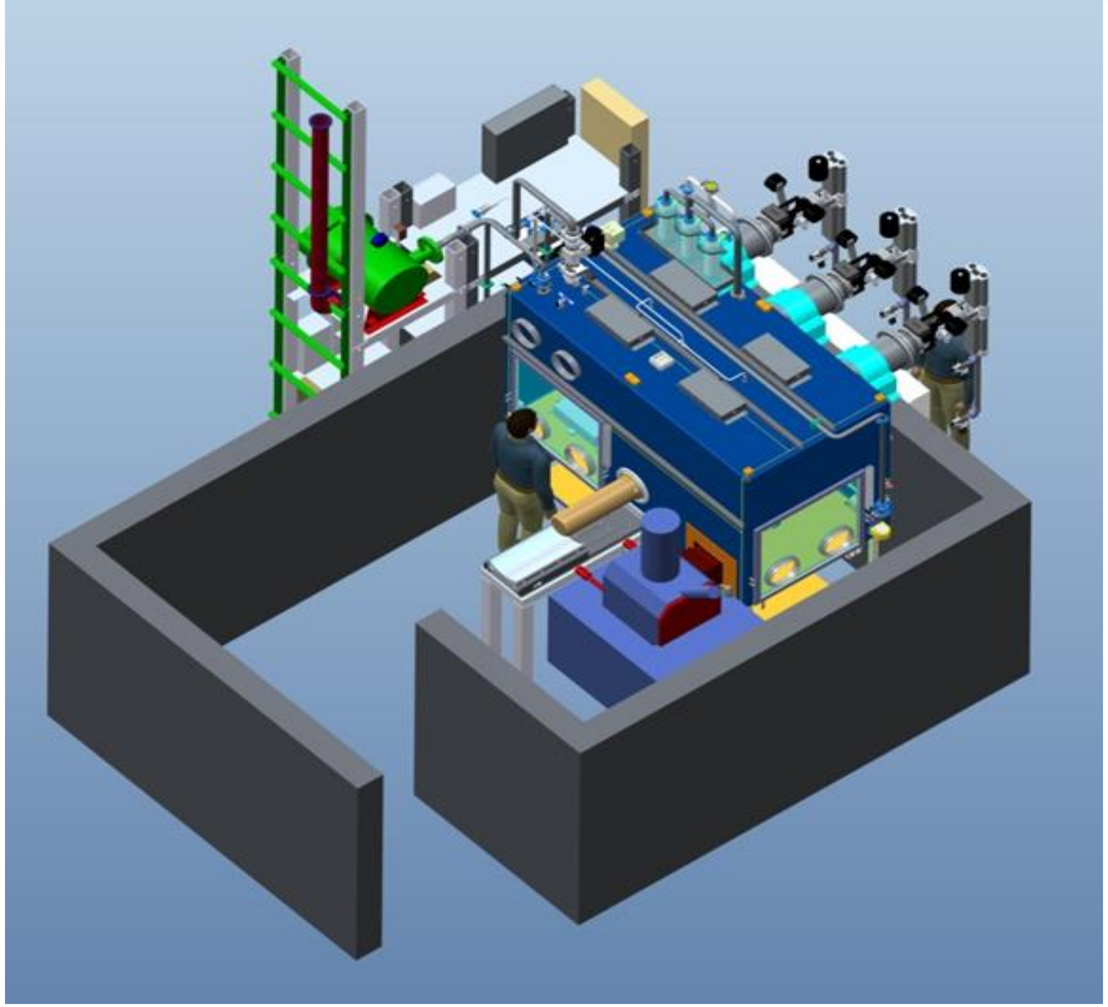
Irradiated Materials Characterization Laboratory -IMCL

Shielded Sample Preparation Area

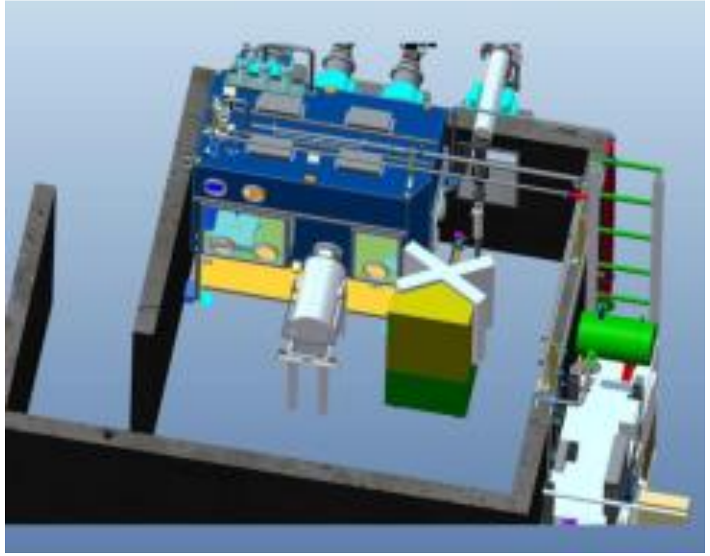
- Hot cell: Sample cutting, mounting, grinding, and polishing, and optical microscopy (air atmosphere)
- Identical capabilities in connected radiological glovebox (argon atmosphere) for handling of low dose rate samples
- Radiological hood for decontamination of small samples
- Cask transfer ports (2)

FIB/EPMA/SEM Shielding and Confinement Design



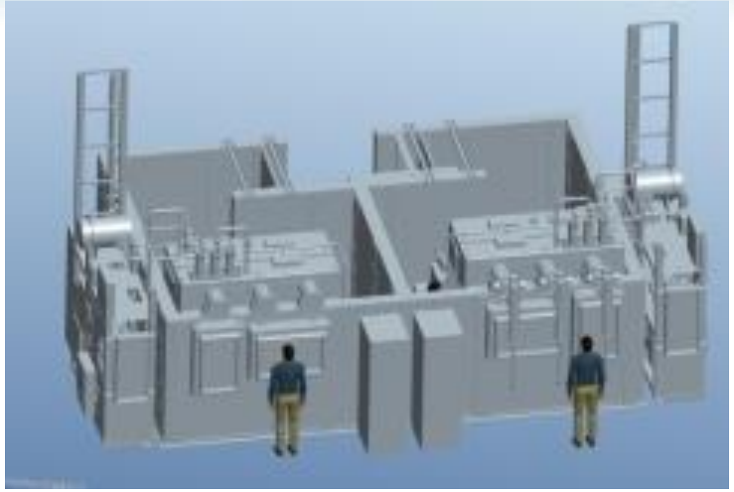


Electron Probe MicroAnalysis



- EPMA (Electron Probe MicroAnalysis) system currently operational
- Capable of analyzing full cross sections of irradiated fuel
- Many elements can be quantified with an error < 1%
- Analysis standards for U, Np, Pu, and Am

Focused Ion Beam Shielding and Confinement



- FEI Quanta gallium ion dual beam FIB
- FEI Helios xenon plasma FIB (20X faster milling time, < 1 nm resolution)
- Currently being installed, operational April 2018

INL MS&E Department Materials Research

- Other areas of interest at INL
  - Modeling and simulation for advanced materials development
  - Development of advanced high temperature alloys
  - Development of advanced lightweight alloys
  - Development of advanced materials for hybrid energy systems
  - Development of advanced materials for energy storage systems
  - Advanced and additive manufacturing of high temperature alloys for energy application
    - In-pile sensors
  - Development of advanced composite materials for energy application
  - In-pile testing
  - Joint development of capabilities in new and emerging areas in advanced materials
  - Student and staff exchange programs

Concluding Remarks

- Interested in stronger collaborative ties between INL and BSU
  - Seeking to explore areas of common interest in current and emerging areas
  - Connect innovation at BSU with INL capabilities and missions
    - INL is in the process of augmenting some of our current capabilities as well as building new ones
  - Tap into talent pool
  - Establish new strategically aligned university relationships