JUNE 4, 2020

ARGONNE NATIONAL LABORATORY: ADVANCED REACTOR CAPABILITIES

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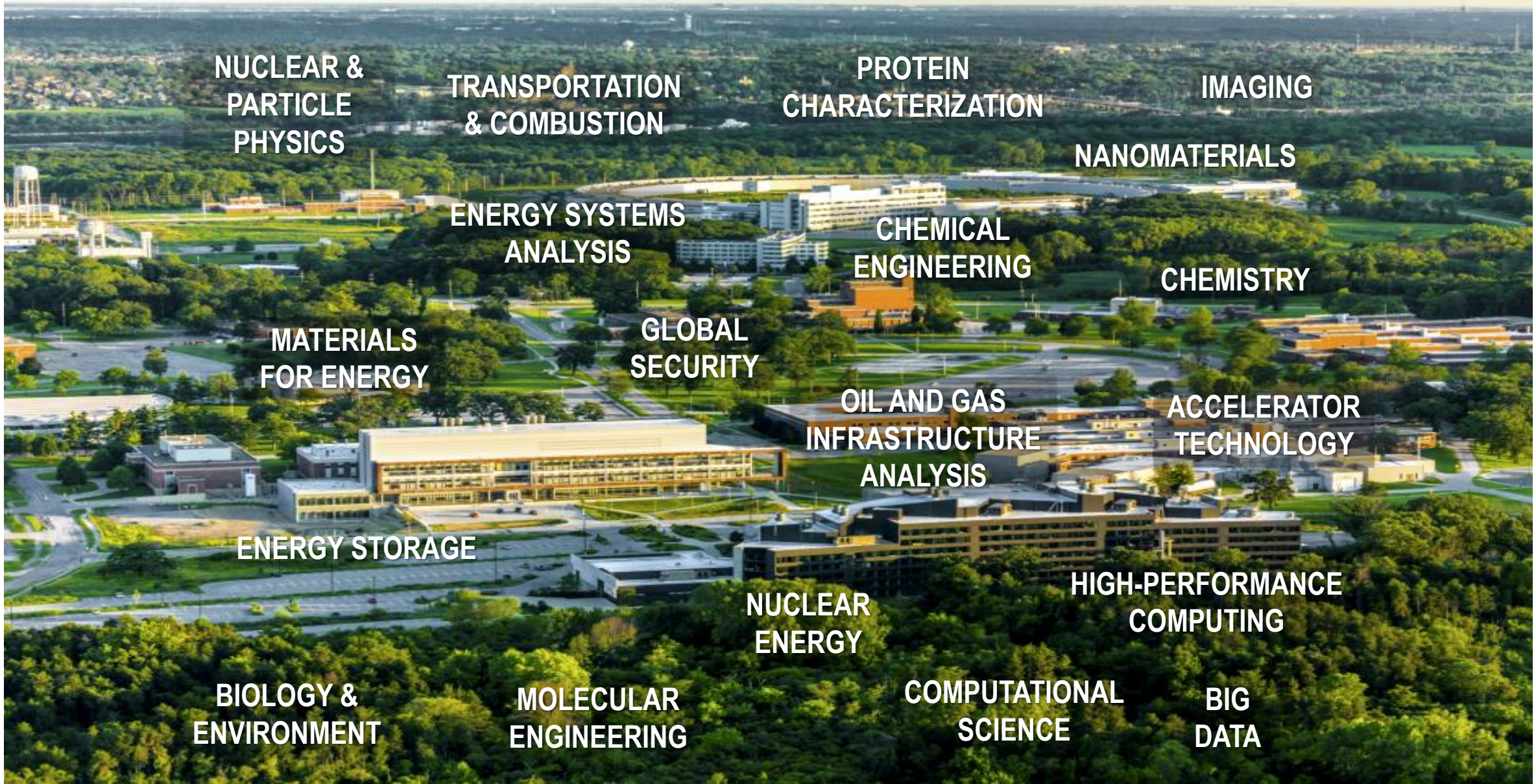
Nuclear Science and Engineering Division

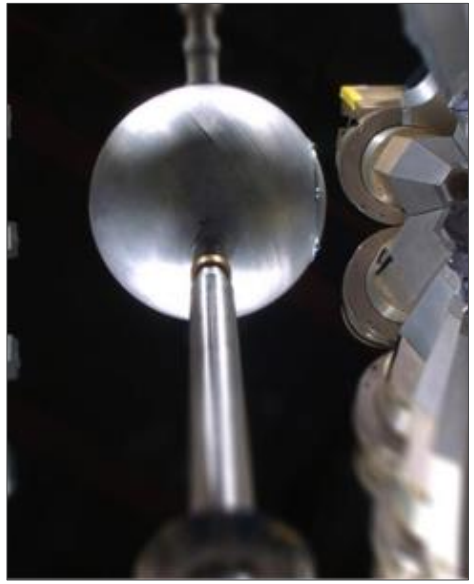
Argonne NATIONAL LABORATORY

ARGONNE'S RESEARCH INTERESTS

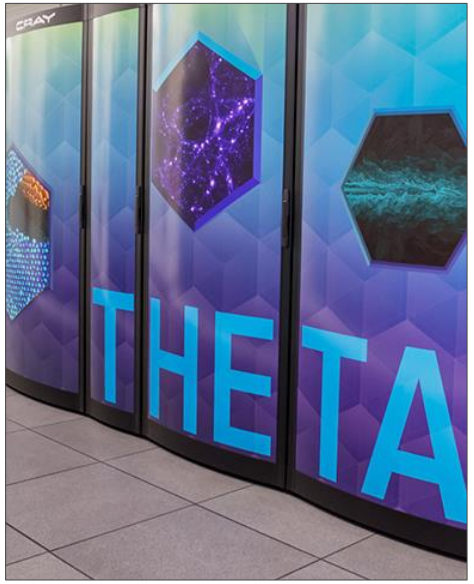


ARGONNE'S USER FACILITIES ALLOW RESEARCHES TO TACKLE SCIENTIFIC CHALLENGES ON ANY SCALE

Advanced Photon Source



Argonne Tandem Linear Accelerator System



Argonne Leadership Computing Facility

Center for Nanoscale Materials

Atmospheric Radiation Measurement – Southern Great Plains

BY THE NUMBERS

$831 M

FY18 OPERATING BUDGET

3,200

EMPLOYEES

> 1,500

SCIENTISTS & ENGINEERS

270

POSTDOCTORAL RESEARCHERS

8,200

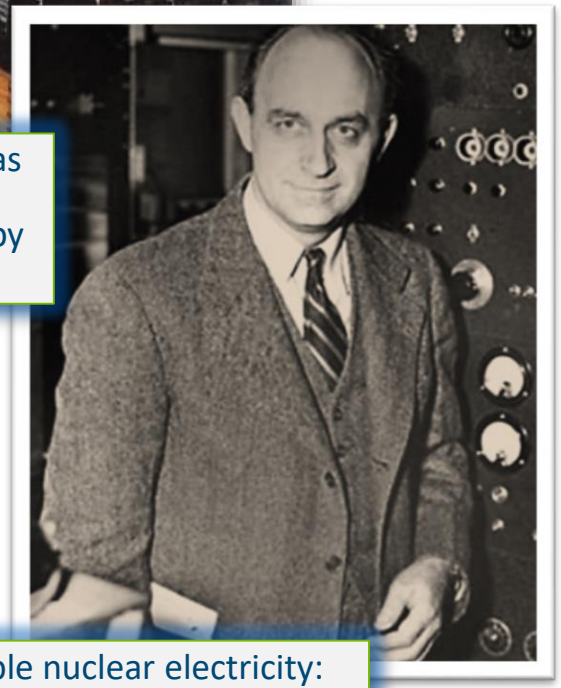
FACILITY USERS

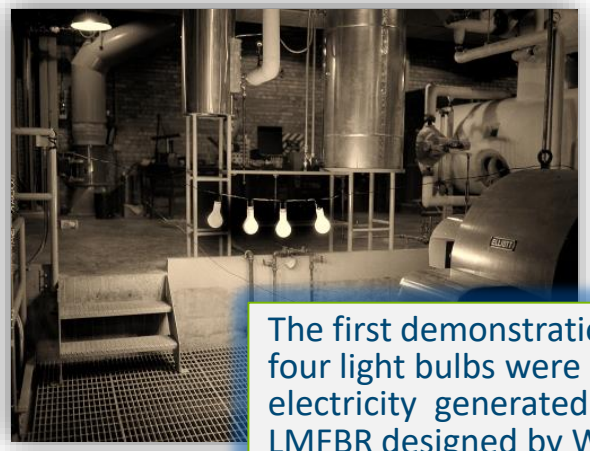
> 100

NON-FEDERAL RESEARCH PARTNERS

BIRTHPLACE OF NUCLEAR ENERGY

The world's first controlled-nuclear chain reaction was demonstrated by Fermi's team at the University of Chicago on Dec. 2, 1942. Operations moved to nearby "Argonne Lab" named after the surrounding forest.





The first demonstration of usable nuclear electricity: four light bulbs were lit on December 20, 1951 with electricity generated by EBR-1, the world's first LMFBR designed by Walter Zinn's team at Argonne.

- **Argonne's heritage dates back to Enrico Fermi and the first controlled chain reaction (CP-1)**
- **Argonne pioneered thermal and fast reactors, as well as fuel recycling technologies**
- **Our work forms the foundation for commercial reactors in use worldwide, and future advanced reactors to come**
- **Argonne continues to advance the science and technology foundations for nuclear energy**
- **Nuclear energy expertise also applied to advance other Argonne Initiatives**

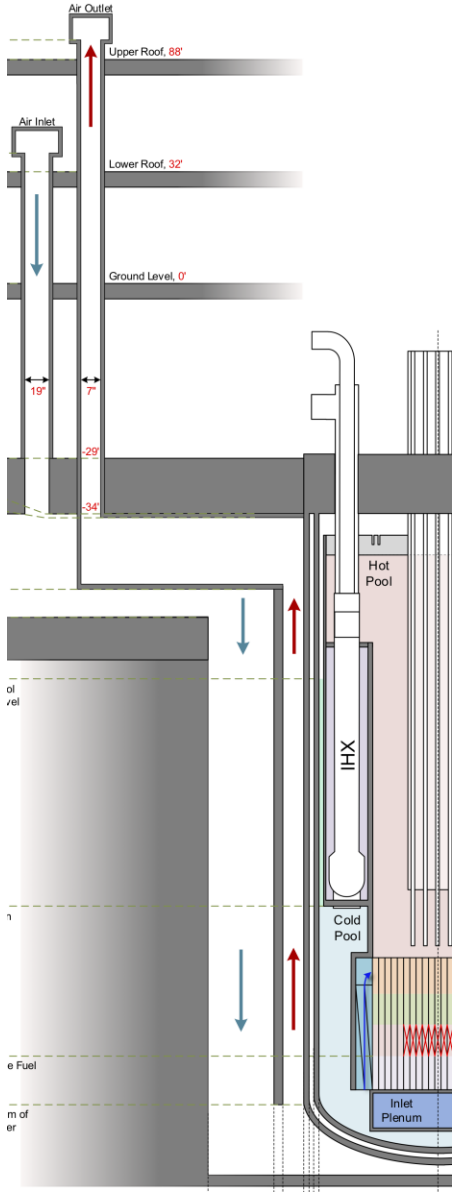
ADVANCED REACTORS: CAPABILITY EXAMPLES

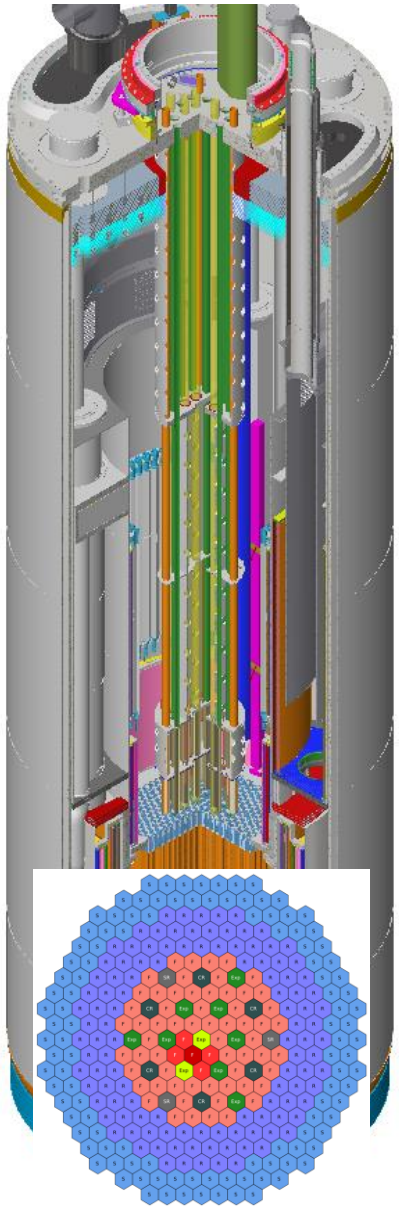
- **Fast Reactors**
  - **VTR Core Design and Safety Analysis**
  - **Sodium Component Testing**
  - **Fast Reactor Databases**
  - **Advanced Materials**
- **Gas Reactor Decay Heat Removal Validation Testing**
- **Molten Salt Property Measurements**
- **Cross-cutting Reactor Applications**
  - **Computational Modeling**
  - **Advanced Manufacturing**
  - **Radiation Damage Science**
  - **Artificial Intelligence/Machine Learning**

THE VERSATILE TEST REACTOR

Argonne Leads Nuclear Design and Safety Analysis Activities

- Objective is to establish fast neutron irradiation capabilities to help accelerate the testing of advanced nuclear fuels, materials, instrumentation, and sensors (CD-0, 2/2019)
- Leverages Argonne's extensive expertise in designing and operating fast reactors
- Incorporates the inherent safety features of metallic fuel and a pool-type coolant system, along with passive safety features for decay heat removal





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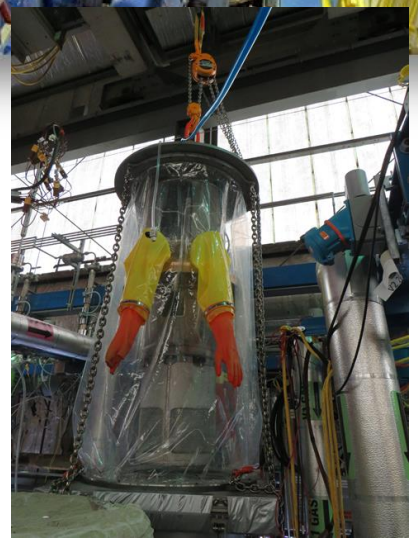
Mechanisms Engineering Test Loop (METL)

- **Provide a sodium test facility for small and intermediate-scale sodium components and instrumentation at prototypic conditions**
- **Provide an environment where the next generation of engineers can engage in fast reactor R&D**
- **Initial fill of sodium into METL in May 2018.**
  - **15 55-gallons drums were heated and transferred to the sodium dump tank.**
- **Gear Test Assembly (GTA) was fully assembled, water and air tested, and moved to B308 for commission**
  - ***First test article into METL December 2018***
  - ***Operated for ~9,800 simulated core assembly removal and insertion cycles under load***
  - ***First test vessel removed in August 2019***
- **Thermal Hydraulic Test Article (THETA) will use two test vessels to model pool stratification**
  - ***Complete design/fab in FY19 with startup in FY20***

https://www.anl.gov/nse/mechanisms-engineering-test-loop-facility



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Fast Reactor Databases:
https://frdb.ne.anl.gov/

TREXR: TREAT Experimental Relational Database

Website

TREXR

A limited selection of TREXR is available to the public. User registration is required for increased access.

About

TREXR is an organized, searchable collection of information that describes the hundreds of experiments conducted on nuclear reactor fuels in the Transient Reactor Test (TREAT) facility beginning in 1960. The experiments generally investigated the response of nuclear fuel samples to severe conditions similar to those associated with reactor accidents. The TREAT reactor was specifically designed and operated to provide such conditions. TREXR includes a collection of thousands of documents describing the design and operation of these tests as well as measured instrumental data for some of the tests. Reports and records can be viewed and saved, and instrumental data can be plotted live as well as downloaded in CSV format.

Request Access

Requests for user accounts to access the database can be made by visiting the website. Click on "Login" and follow the appropriate link and instructions under "Get an Account." For questions about the database, website, or your access permissions, contact Carolyn Tomchik (ctomchik@anl.gov).

FIPD: EBR-II Fuels Irradiation & Physics Database

Website

FIPD

FIPD is available to registered users.

About

FIPD is an organized collection of EBR-II test pin data and documentation. The database includes pin operation conditions calculated using a collection of ANL analysis codes developed during the IFR program, including axial distributions for power, temperatures, fluences, burnup, and isotopic densities. The database also contains pin measured data from post-irradiation examination, including pin fission gas release and gas chemistry measurements, and axial distributions from profilometry, gamma scans, and neutron radiography. There is also an extensive collection of documents associated with different pins and experiments, including raw PIE data, design
operational re

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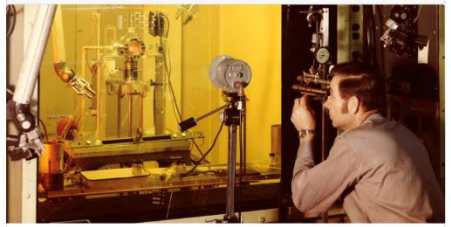
OPTD: Out-of-Pile Transient Database



Website

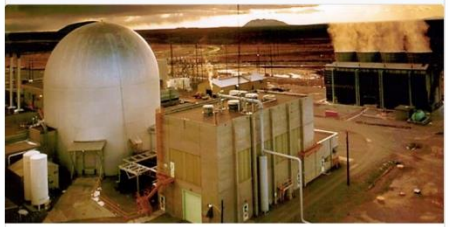
OPTD

OPTD is still in initial development, and only accessible to the development team.

About

OPTD is an organized, searchable archive of records describing a series of out-of-pile furnace transient tests conducted on metallic fuel samples at the Alpha-Gamma Hot Cell Facility (AGHCF) at Argonne National Laboratory. Fuel pins (or pin segments) previously irradiated in EBR-II were placed into one of two furnace apparatuses constructed in the AGHCF and overheated to examine the fuel-cladding compatibility of each sample, margins to failure, and failure mechanisms. Records describing the design, planning, and execution of the tests are included in the database as well as test summary reports, experimenter's notes, and post-test metallographic examinations of the samples.

ETTD: EBR-II Transient Test Database



Website

ETTD

ETTD is available to registered users.

About

The EBR-II Transient Test Database (ETTD) is an archive of data and documents describing transient tests performed in the EBR-II reactor during the 1984-1987 time period. The database provides links to tests that are grouped in five testing periods (each with different core load configuration) under which they were conducted, or several testing categories including:

- Reactivity feedback characterization tests
- Loss of flow with scram and transition to natural circulation
- Loss of flow without reactor scram with different levels of severity
- Dynamic frequency response tests

nk tests (with or without scram)
ssure reduction tests
ontrol tests (to demonstrate
features of the reactor)

bility to download and/or plot up
DAS channels (broadly grouped
power, control and safety rod
, intermediate sodium coolant
erheater steam temperatures,
e and balance of plant flow rate

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

New Fast Reactor Materials: Code Qualification for Alloy 709

Background:

- Alloy 709 (20Cr-25Ni) is an austenitic stainless steel with significant time-dependent strength advantage over 316H stainless steel as a SFR construction material
- Enhanced time-dependent strengths of Alloy 709 with respect to 316H can reduce commodity requirements, and thereby decrease the capital cost of the reactor plant
- Can also permit structural components to withstand higher cyclic and sustained loading, leading to higher safety margins, and the prospect of eliminating costly add-on hardware instituted in past designs, and other design innovations and simplifications

Status:

- Qualification efforts for ASME Division 5 Code Case for 100,000 h and 760C are ongoing
- Tests include tensile, creep, fatigue, and creep-fatigue

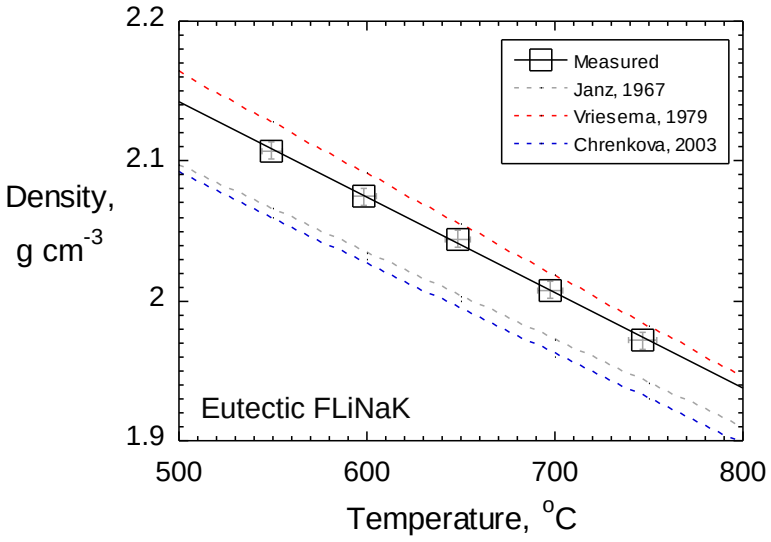
Alloy 709 plates fabricated from 45,000 lb commercial heat

ART-GCR Experimental Methods: Severe Accident Heat Removal

- The Natural Convection Shutdown Heat Removal Test Facility (NSTF) was initiated in 2010 in support of DOE-NE programs NGNP, SMR, and ART
  - Air-based testing program completed during FY13 - FY16
  - Water-based testing program on-going FY18 to present
- Top level objectives of NSTF program at Argonne:
  - examine passive safety and decay heat removal for advanced nuclear
  - generate NQA-1 qualified licensing data for industry
  - provide benchmark data for code V&V
- Concurrent with a broader scope and multiple collaborators
  - Experimental facilities at scales (½, ¼, etc.) for both air and water
  - Complimenting CFD modeling and 1D systems level analysis
  - Collaborating towards development of a central data bank

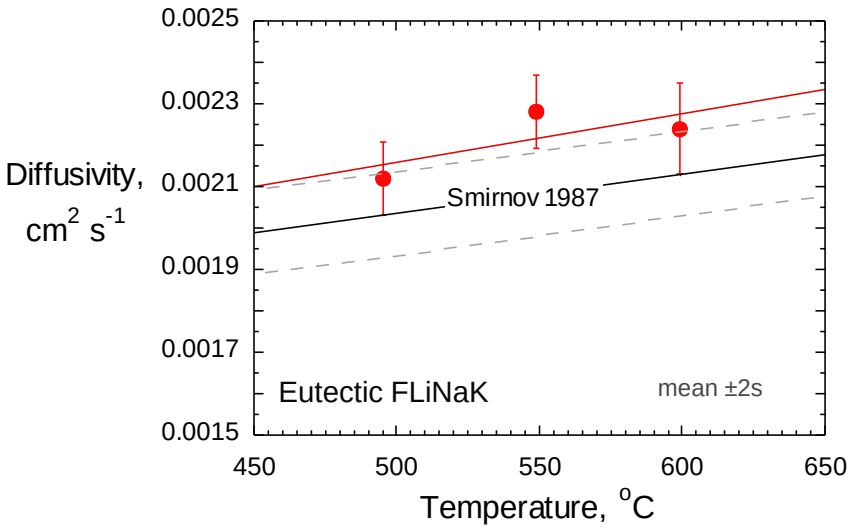
MOLTEN SALT PROPERTY MEASUREMENTS

- Thermophysical property data are needed to support MSR design, licensing, and operation
  - Predicting molten salt behavior during normal and transient conditions requires knowledge of heat capacity, density, viscosity, and thermal conductivity data over a range of temperatures and salt compositions
  - Available data are not sufficient or of suitable quality
    - $LiF\text{-}BeF_2\text{-}UF_4$ data from MSRE is available but most MSR developers are considering other salt mixtures for which reliable property values must be measured
  - Data quality necessary for licensing a reactor requires standardized methods with known precision and accuracy for benchmark salts



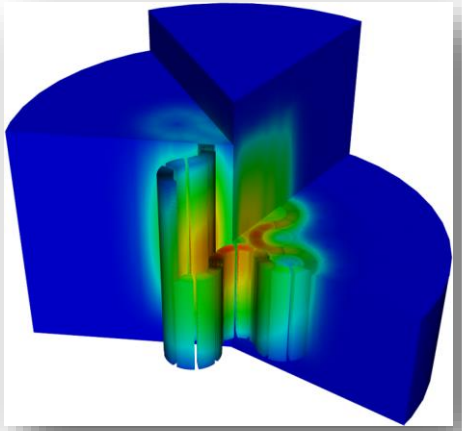
Property Measurements available at Argonne with actinide-bearing fuel salt and coolant salt

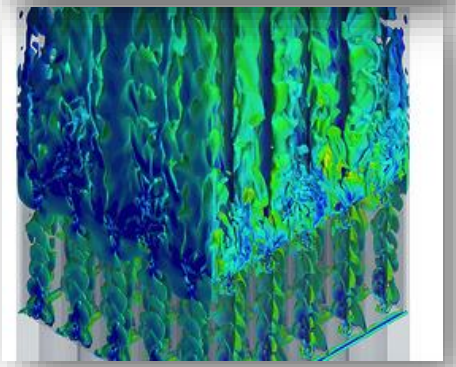
Property	Method
Density & volumetric thermal expansion	Archimedes method (in Ar-atmosphere radiological glovebox)
Heat capacity, melting point, phase equilibria	Differential scanning calorimetry (in Ar-atmosphere radiological glovebox)
Viscosity	Rotating spindle viscometer (in Ar-atmosphere radiological glovebox)
Thermal diffusivity & thermal conductivity	Laser flash analysis system (in radiological hood with equipment operated under Ar purge or vacuum)
Fission product & actinide solubility	Chemical analysis and DSC
Mass transfer diffusion coefficients	Restricted diffusion cells (in Ar-atmosphere radiological glovebox)

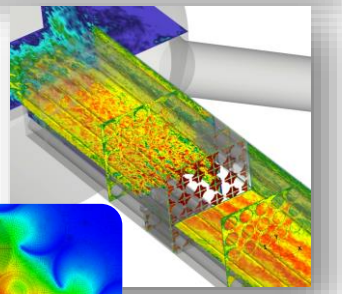


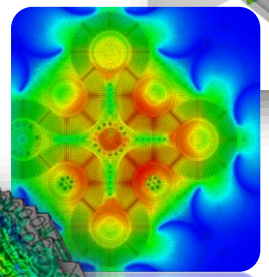
COMPUTATIONAL MODELING OF ADVANCED REACTORS

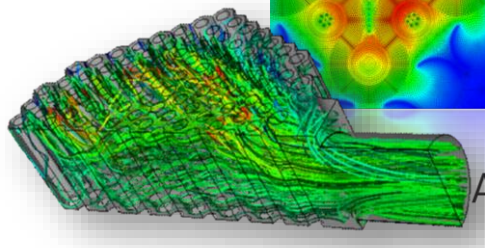
- **Developed and deployed the next generation System Analysis Module (SAM) for advanced reactors based on MOOSE framework**
- **Developing and integrating higher fidelity neutronics, heat and fluid transport, and structural mechanics tools for multi-physics simulations and mechanistic source term assessments**
  - Griffin/PROTEUS/MCC-3, Nek5000, Pronghorn and Diablo
- **Validating and applying these tools for reference liquid-metal fast reactor, HTGR, MSR/FHR and microreactor concepts in collaboration with industry and NRC**
  - MSRs with moving fuel and chemistry modeling
  - Pebble-bed concepts with double-heterogeneity in a moving core
  - Fast reactors with wider range of reactivity feedback phenomena
  - Micro-reactors with heat-pipe cooling
- **Benefits**
  - Improve prediction of reactor performance and safety behavior
  - Mechanistic approach with reduced empiricism and closer-to-first-principle solutions to reduce uncertainties, enable improved design and safety margins
  - Limit and optimize costly integral experiments





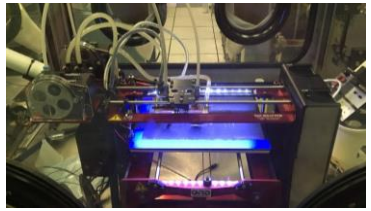




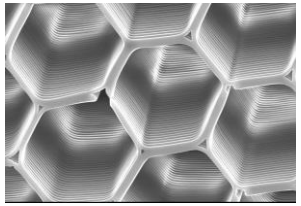


ADVANCED MANUFACTURING OF NUCLEAR FUELS & MATERIALS

- **Exploring additive manufacturing techniques employing powders encapsulated in filaments or slurries**
  - Address drawbacks of laser-sintering (expense, resolution, waste, warping)
  - Demonstrated capabilities to print UO_2 fuel pellets and matrices for fuels or HX
- **Applying atomic layer deposition (ALD) techniques to protect material surfaces**
  - Provide conformal coatings inside and outside complex shaped components
  - Explored in combination with techniques suited to deposition of thicker coatings
  - Applications to LWR Zy cladding, FR SS cladding, fuel particles in dispersion fuels
- **Developing low-temperature techniques for manufacture of ceramic composites**
  - Proposed for diverse applications (HTR and for LWR ATF)
  - Infiltration of a porous structure or direct synthesis on metallic or ceramic substrate

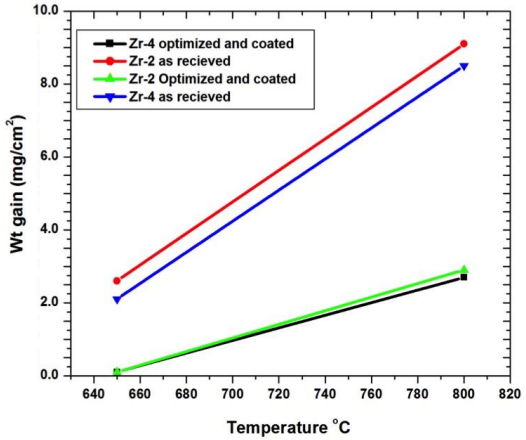


3D nuclear fuel printing capability implemented in a radioactive glovebox

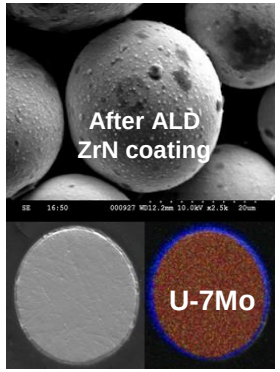


High resolution AM methods used to print intricate matrices for fuels or heat exchangers

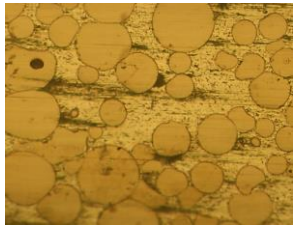
ALD coated Zirlo cladding segments



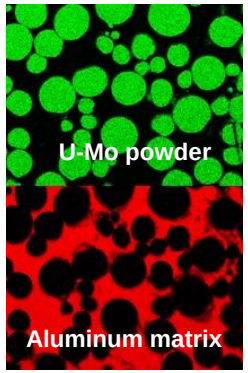
Air and autoclave testing of ALD coated Zircaloy samples show improved corrosion resistance



Conformal ALD ZrN Coating



Fuel Plate Cross Section



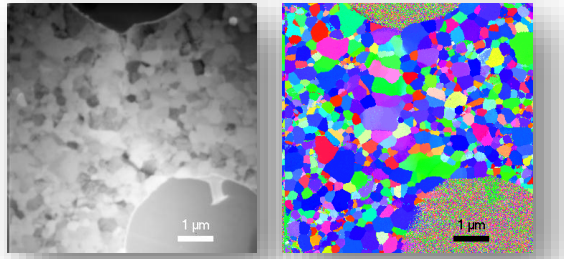
EDS Mapping of a Manufactured Fuel Plate

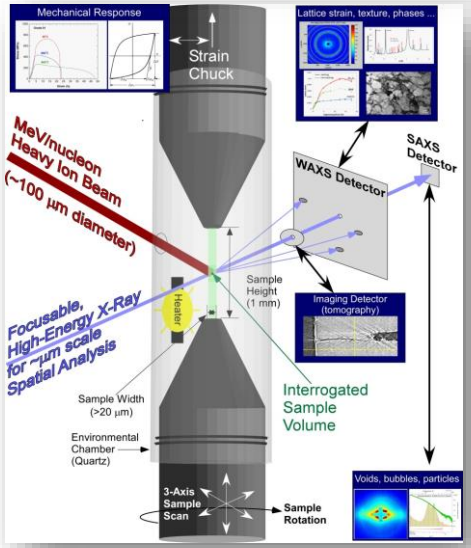
Increasing Fundamental Understanding of Radiation Damage

- **Employing *in situ* examination of microstructural effects in materials using IVEM and APS facilities**
- **APS provides focused high-energy X ray beams for probing nanostructure of materials with high time resolution**
- **Proposed a new beamline (XMAT) at the APS for *in situ* examination of radiation damage**
  - Employs a superconducting linear accelerator to irradiate material samples
  - Energetic heavy ions (MeV/nucleon) penetrate into bulk of material samples

Enables

- 2-3 orders of magnitude faster dose accumulation
- New insights into radiation damage
- Improved computational modeling
- Optimization of in-reactor testing

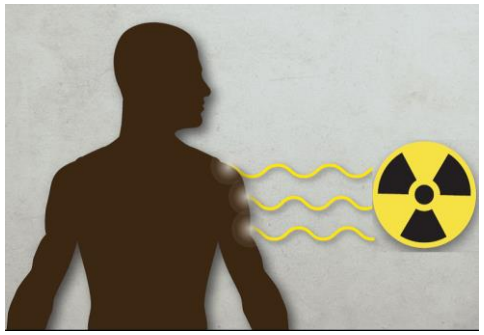




APPLICATION OF AI/ML TO OPERATIONS

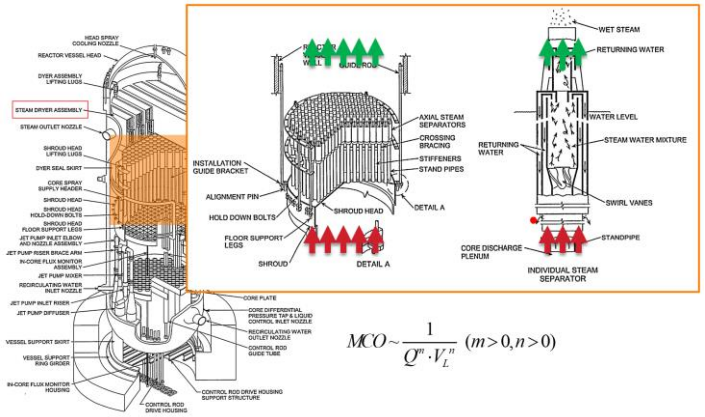
BWR Moisture Carryover Prediction

Elevated MCO: Turbine Damage, Human Dosage



1

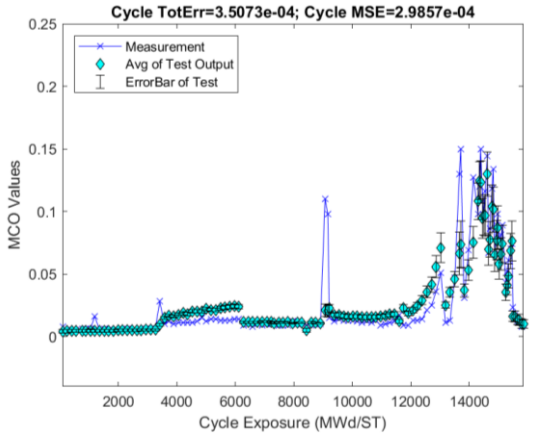
Feature Selection Based on Engineering Constraints

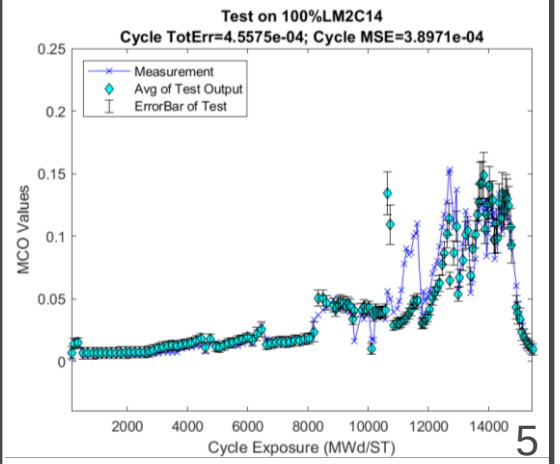


$$MCO \sim \frac{1}{Q^m \cdot V_L^n} \quad (m>0, n>0)$$

3

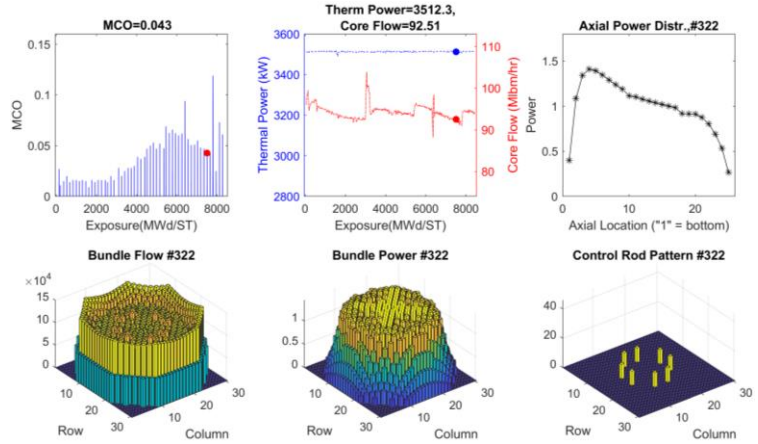
Predictive ML-Model is in Use at US BWR Plants





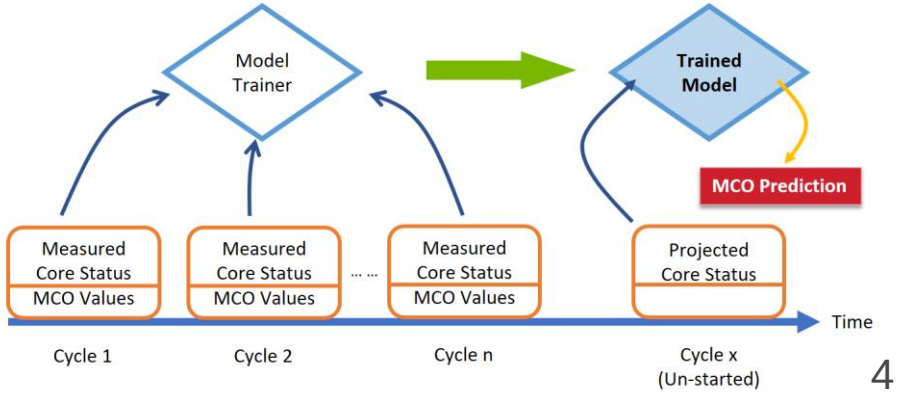
5

MCO tends to increase at the end of cycle



2

Train ML Model for Performance Improvement



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LEARN MORE ABOUT OUR WORK…

Argonne web page:

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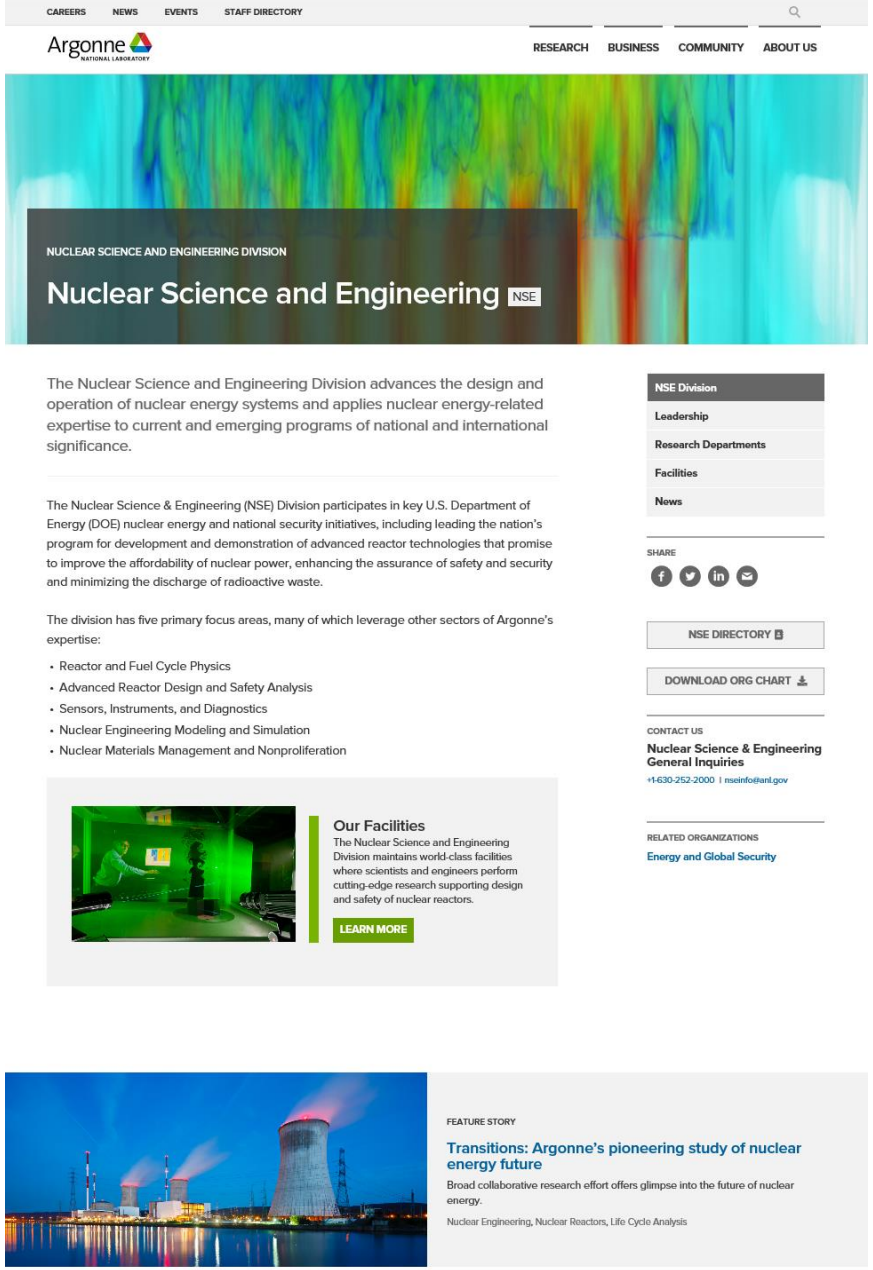
Nuclear Science and Engineering Division web page:

https://www.anl.gov/nse

Chemical and Fuel Cycle Technologies Division web page:

https://www.anl.gov/cfc



Thank you.