INL/MIS-22-70343-Revision-0

October 2022 NS&T Highlights

November 2022

Addison Marie Arave

Changing the World's Energy Future

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

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Addison Marie Arave

November 2022

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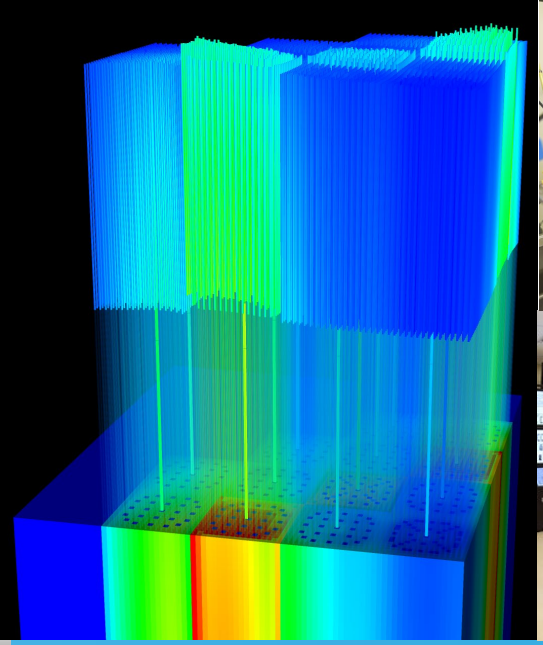
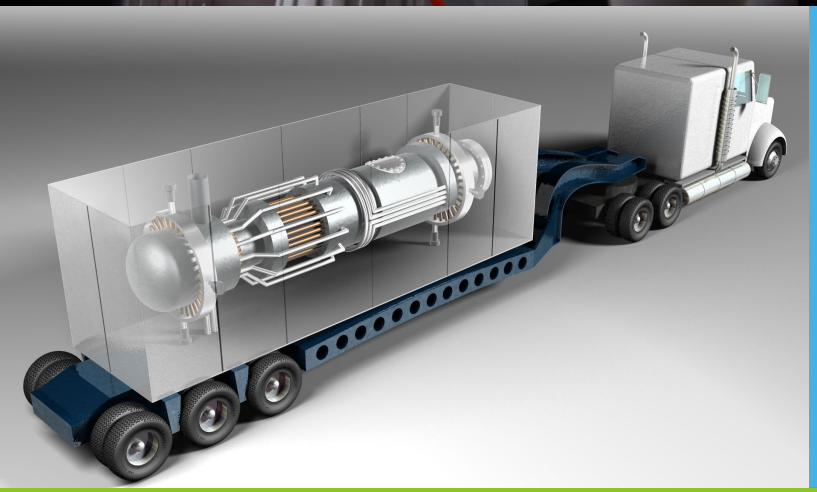


Nuclear Science & Technology

October 2022 Highlights

Idaho National Laboratory

The Frontiers Project

Partnership between INL and Wyoming featured at the Frontiers Project Meeting

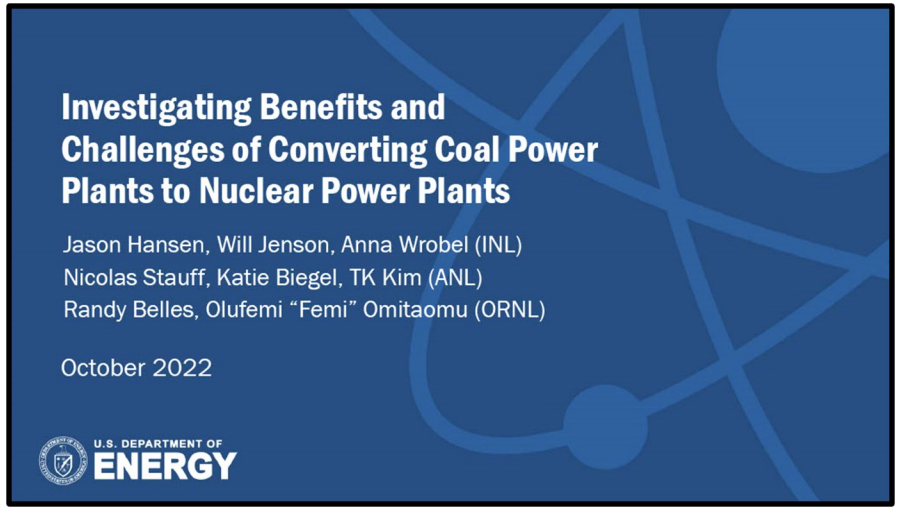
- In May, Idaho National Laboratory (INL) Director John Wagner and Wyoming Energy Authority (WEA) Director Glen Murrell signed a memorandum of understanding agreeing to collaborate on the research, development, demonstration, and deployment of advanced nuclear energy.
- On October 7, this collaboration was discussed at the Frontiers Project meeting in Jackson, Wyoming. The event was hosted by WEA, Wyoming Business Council, and the University of Wyoming School of Energy Resources, in partnership with the Atlantic Council Global Energy Forum and INL.
- The forum featured an international group of industry leaders, investors, academics, and policymakers such as Wyoming Governor Mark Gordon and Senator Cynthia Lummis.

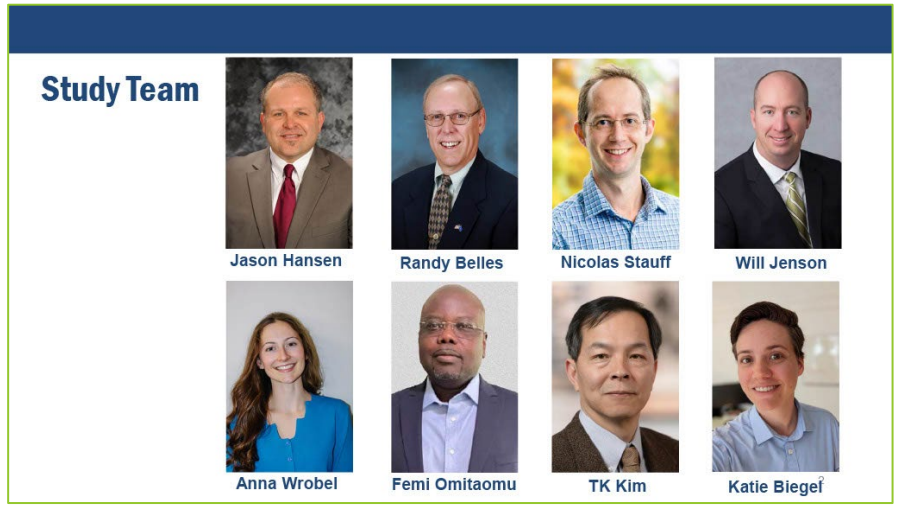
Jennifer Gordon, director of Nuclear Energy Policy Initiative at the Atlantic Council, moderates fireside chat with INL Director John Wagner (right) and Glen Murrell, director of Wyoming Energy Council at the Frontiers Discussion meeting.

DOE-NE Gateway for Accelerated Innovation in Nuclear

INL Commercialization Program Hosts Webinar on the Coal-to-Nuclear Report

- On October 4, Gateway for Accelerated Innovation in Nuclear (GAIN) hosted a webinar on “Converting Coal Plants to Nuclear Report—A Deep Dive.”
- The webinar, which drew 178 attendees, featured experts from the Systems Analysis and Integration team, who conducted the study.
- Panel discussions focused on siting evaluation, techno-economic analysis, economic impact, and general questions. GAIN has posted the materials on its webpage.
- Visit gain.inl.gov/SitePages/Coal2Nuclear.aspx to learn more.

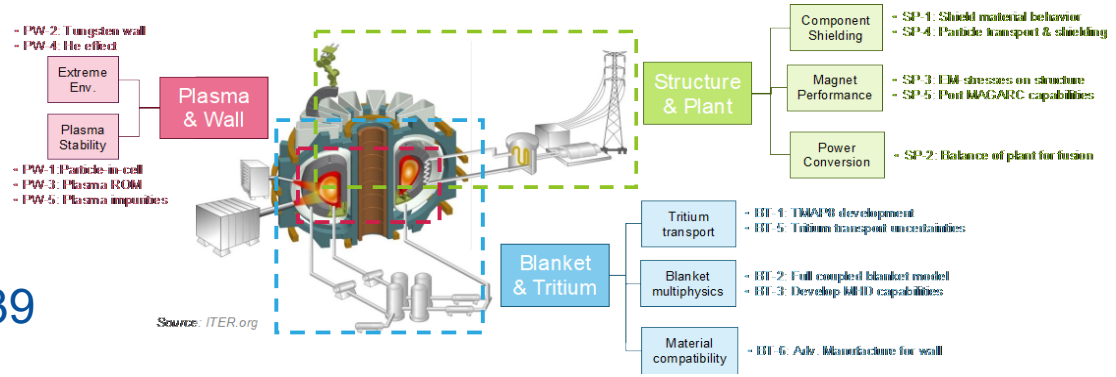


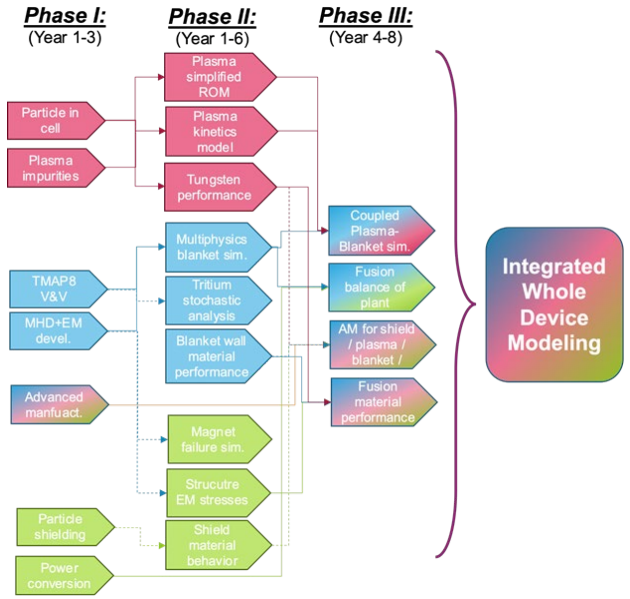


INL Program Development Funds

INL Hosts Fusion Modeling & Simulation Workshop

- Advances in fusion energy research and development (R&D) require comprehensive multiphysics modeling and simulation (M&S) resources.
- With fusion energy research defined as an “emerging capability” at INL, the Fusion Modeling and Simulation Workshop was convened on October 4 to bring together 39 INL experts in fusion technology and fission-based M&S.
- The goal was to generate ideas and pathways for software innovation in fusion by leveraging established INL M&S fission capabilities in new ways to achieve large-scale fusion reactor simulation—also known as Whole Device Modeling.
- 24 scope ideas were generated and organized into potential funding avenues, with 15 put forward as being particularly important for establishing a vibrant M&S program. Further, a roadmap was developed to inform long-term fusion-based M&S capabilities at INL.





Overview of the breakout topic areas and some proposed scopes (above).

A possible roadmap for integrated fusion device modeling capability (left).

REACTOR SYSTEMS DESIGN & ANALYSIS DIVISION / ADVANCED REACTOR TECHNOLOGY AND DESIGN
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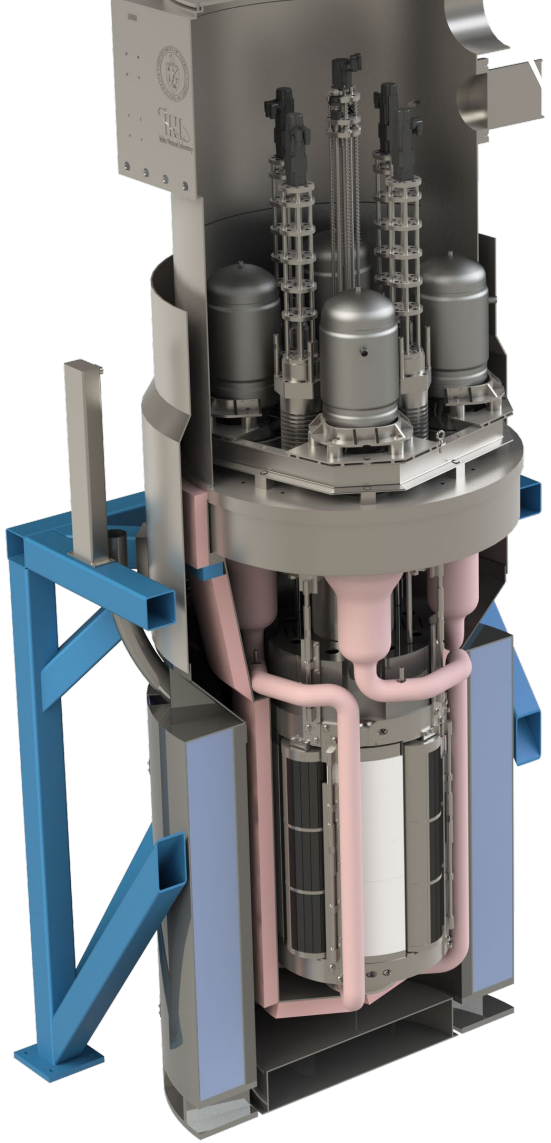
DOE-NE Microreactor Program

Microreactor Applications Research Validation and Evaluation Completes 90% Final Design Review

- The first INL-led reactor final design review in decades was conducted this September 7 and 8.
- This 2-day review included
  - 14 external and internal independent reviewers
  - 25 discipline interfaces
  - 450+ slides
  - 138 design and analysis files
  - 435 written comments (in addition to in-session comments)
  - A resolution plan to close the gaps.
- The Microreactor Applications Research Validation and Evaluation (MARVEL) team plans to address all comments and open items by the second quarter of fiscal year 2023. This enables an early start on MARVEL fabrication.



Rendering of the MARVEL reactor at 90% final design.

REACTOR SYSTEMS DESIGN & ANALYSIS DIVISION | ADVANCED REACTOR TECHNOLOGY AND DESIGN
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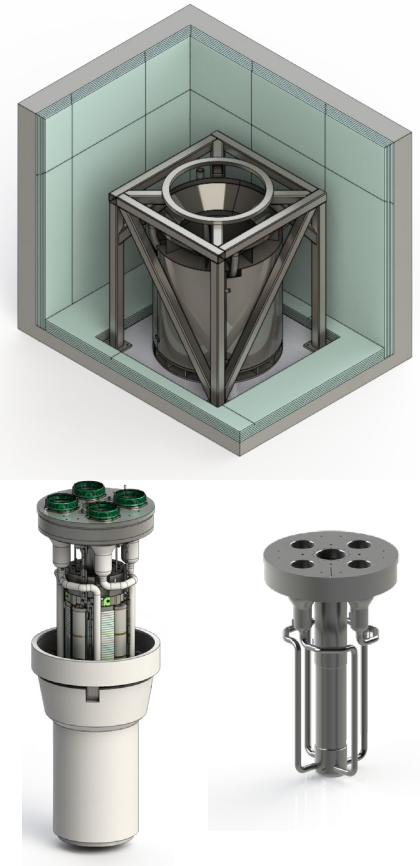
DOE-NE Microreactor Program

Microreactor Project Receives First Long Lead Procurement Approval

- The Idaho Office of the United States (U.S.) Department of Energy Office of Nuclear Energy (DOE-NE) approved MARVEL's first long-lead procurement request on October 4. This approval enables the MARVEL team to start preparing for fabrication.
- This request has been reviewed and approved per the criteria of DOE-STD-1189, meaning it has been determined that procurement of materials is not detrimental to public health and safety and has minimal risk to DOE investment.
- This long-lead procurement request includes 316H stainless steel material for the fabrication of the guard vessel, primary coolant system, support frame, and outer shell, in addition to high-assay low-enriched uranium fuel material from the Y-12 National Security Complex.
- Battelle Energy Alliance (BEA) selected Premier Technologies Inc. to fabricate metal parts for MARVEL. Manufacturability reviews are also complete, and the drawings were updated.



Rendering of relevant components

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Advanced Nuclear Demonstration Program

INL Analysis Code Audit Progresses Flexible Clean Energy Project

- This June, TerraPower and INL participated in an onsite audit of RELAP5-3D software quality assurance documents and procedures, which is a critical step in the commercial grade dedication process.
  - RELAP5-3D is the leading thermal hydraulics code in the nuclear industry and one of the premier international system codes. RELAP5-3D provides accurate modeling for the current fleet of light-water reactors (LWRs) as well as gas-cooled reactors and next generation nuclear reactor designs including molten salt and sodium-cooled reactors. RELAP5-3D has received Nuclear Quality Assurance Level 3 status with commercial grade dedication for reactor design licenses.
- TerraPower intends to utilize this INL technology for regulatory design basis transient analyses for Natrium.
  - The Natrium™ Reactor is a 345 MWe sodium fast reactor coupled with a molten salt-based integrated energy storage system designed by TerraPower and GE-Hitachi.
- Audit actions were closed this September, which supports TerraPower submitting a construction permit application in 2023.

TerraPower and INL staff during the June 2022 software quality assurance audit.

REACTOR SYSTEMS DESIGN & ANALYSIS DIVISION / THERMAL FLUID SYSTEMS METHODS AND ANALYSIS
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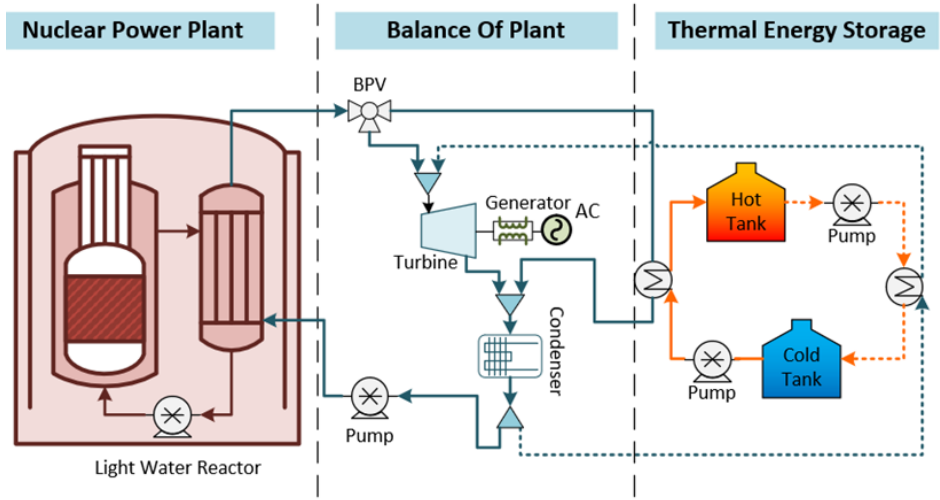
Research Highlight

DOE-NE Integrated Energy Systems Program

Multilevel Analysis and Design of Coupling Advanced Nuclear Reactors and Thermal Energy Storage Systems

- This report explored design and operation techniques of advanced nuclear reactors in a competitive energy market, as compared to current nuclear power plants.
- It highlighted the importance of thermal energy storage (TES) coupling.
  - TES enables nuclear power plants to respond nimbly to market variability and to participate in restructured markets.
  - TES systems store nuclear energy in its original form (heat), allowing for flexible use on the back end to provide electricity and/or heat.
- This would necessitate optimized system architecture to support development of flexible electrical generation from advanced nuclear power plants.
- Transient process models and control schemes were developed to demonstrate design and use cases physically capable of following required dynamic operations.
- All developed computational models are available to the public through the HYBRID repository.



Example showing simplified process flow diagrams for one TES-NPP coupling design.

Title: Multilevel Analysis, Design, and Modeling of Coupling Advanced Nuclear Reactors and Thermal Energy Storage in an Integrated Energy System
Authors: Rami M. Saeed; Amey Shigrekar; Daniel Mikkelson; Aidan Rigby; Courtney Otani; Marisol Garrouste; Konor Frick; Shannon Bragg-Sitton
Link: doi.org/10.2172/1890160

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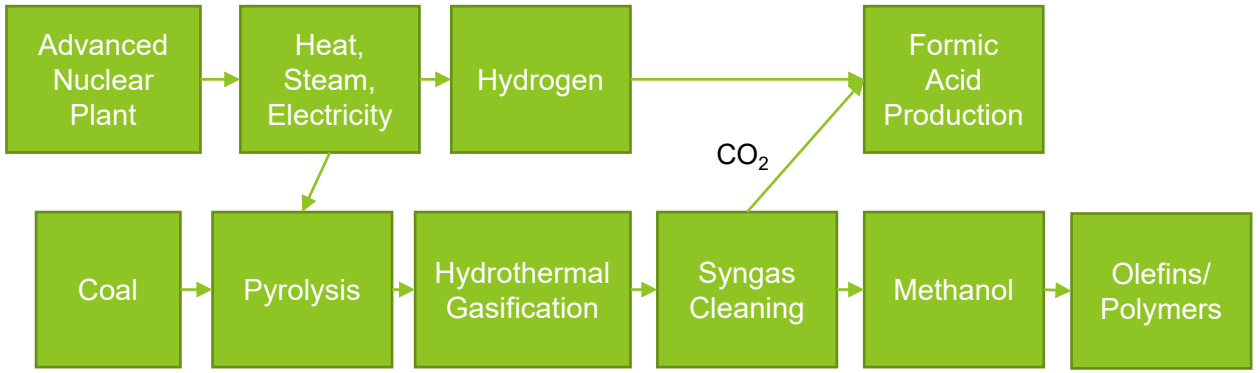
DOE-NE Integrated Energy Systems Program

Analysis of Carbon Conversion Pathways Aims to Preserve Coal Economies In Appalachia

- INL researchers have designed a carbon refinery that converts coal to syngas via pyrolysis and gasification for higher value product pathways that incorporate carbon capture. The design aims to maximize revenue from product streams.
- This project focused on the synthesis of non-fuel products from coal. Utilizing an advanced reactor for heat and steam eliminates carbon output from the traditional production routes.



A simplified flowsheet for the carbon refinery design. Using coal as a product feedstock and using advanced nuclear plants to produce hydrogen, formic acid, methanol, and polymers.

- Analyzed main product pathways:
  - Methanol: This main product has a variety of non-fuel pathways for further processing. Polypropylene, the highest market potential olefin-based polymer, had an annual market of 1.87 billion with expected annual growth of 3.2%.
  - Formic acid: This is an ideal product for carbon dioxide utilization because it could be synthesized directly using hydrogen from electrolysis. The process would consume 2 tons of CO_2 per ton and has a growing market. The global market size is currently $878.7 million annually with expected annual growth of 4.94%.
  - Activated carbon: Coal char from pyrolysis is converted to activated carbon. While activated carbon doesn't have a strong market potential, it is highly effective for mercury removal from the syngas. The main barrier to its use is cost, so making it in-house could make it more economical.

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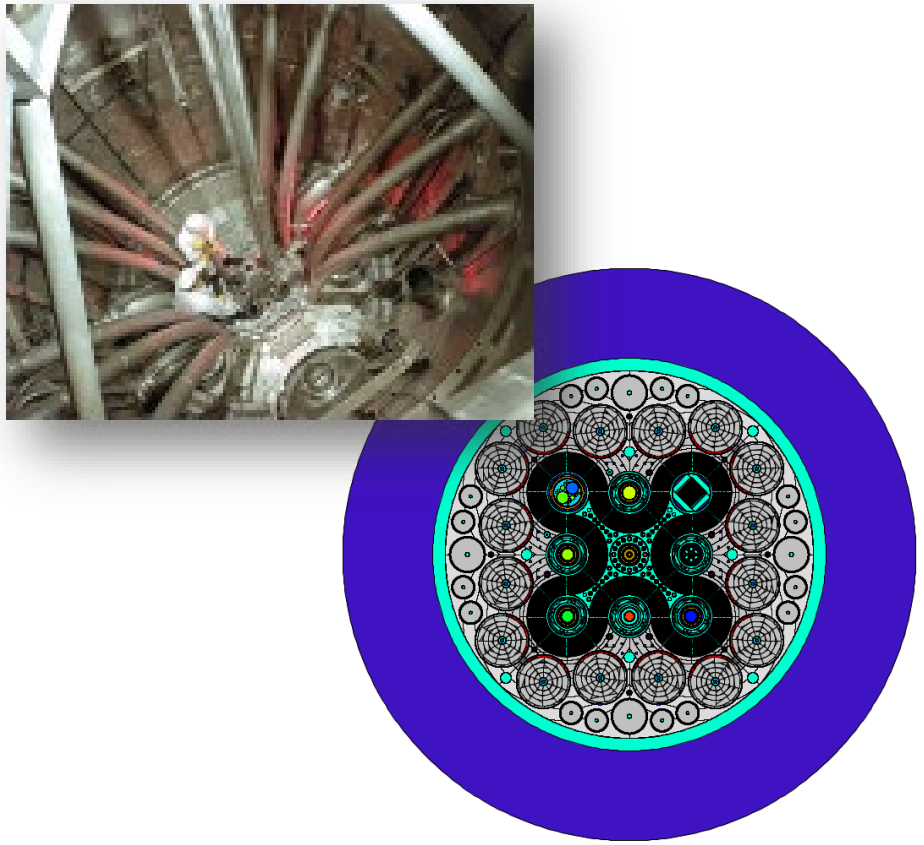
Advanced Test Reactor Program

New Code Deployed for Use in Advanced Test Reactor Engineering and Operation

- Nuclear Science and Technology deployed the MC21 application for Advanced Test Reactor (ATR) engineering and operation analysis. This was developed using the state-of-the-art Monte Carlo Code, MC21, provided by Naval Nuclear Laboratories (NNL).
- Application capabilities include:
  - Full, three-dimensional neutron transport simulations of the ATR.
  - More efficient and accurate modeling of the ATR.
  - Enhanced irradiation capabilities through cycle-specific core physics analysis.
  - Reduced time and cost of test measurements, augmenting ATR Critical Facility use.
- The Nuclear Quality Assurance Level 1 compliant ATR MC21 Application was developed in collaboration with ATR Reactor Engineering and NNL.



ATR Reactor (top) and the cross section of the ATR cycle 160B MC21 model (bottom).

REACTOR SYSTEMS DESIGN & ANALYSIS DIVISION / SPECIAL REACTOR CONCEPTS
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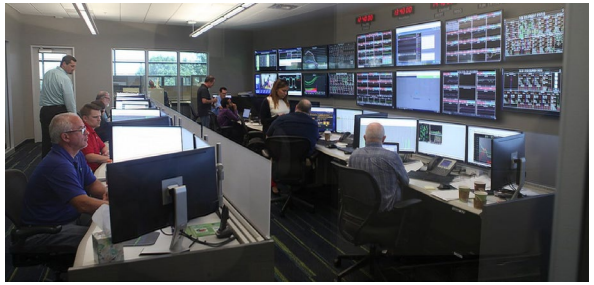
DOE-NE Light Water Reactor Sustainability Program

Business Case Study Kickoff for a Plantwide Digital Infrastructure Implementation

- As part of license renewal efforts at the Comanche Peak Nuclear Power Plant, Luminant is planning to perform significant Digital Upgrades.
- Luminant is leveraging INL research to enable this effort. This includes:
  - Digital Infrastructure Migration Framework research (doi.org/10.2172/1822876)
  - INL Business Case Analysis research (doi.org/10.2172/1660976)
  - INL Integrated Operations for Nuclear concepts.
- INL, in collaboration with Luminant and ScottMadden, Inc., has produced a report titled, "Initial Scoping Efforts for a Plantwide Digital Infrastructure Modernization Business Case Study." The report:
  - Establishes the envisioned scope for these digital upgrades.
  - Forms a vision for how increased digital capabilities can be cost effective and leveraged to maintain/improve safety and reliability. This includes utilizing the capabilities of Luminant's fleetwide Power Operations Center.
  - Bounds the effort of the business case analysis that is to be performed.
- Multiple trips to Comanche Peak by ScottMadden and INL personnel occurred to support this effort.

Comanche Peak Nuclear Power Plant.



Luminant Power Operations Center.

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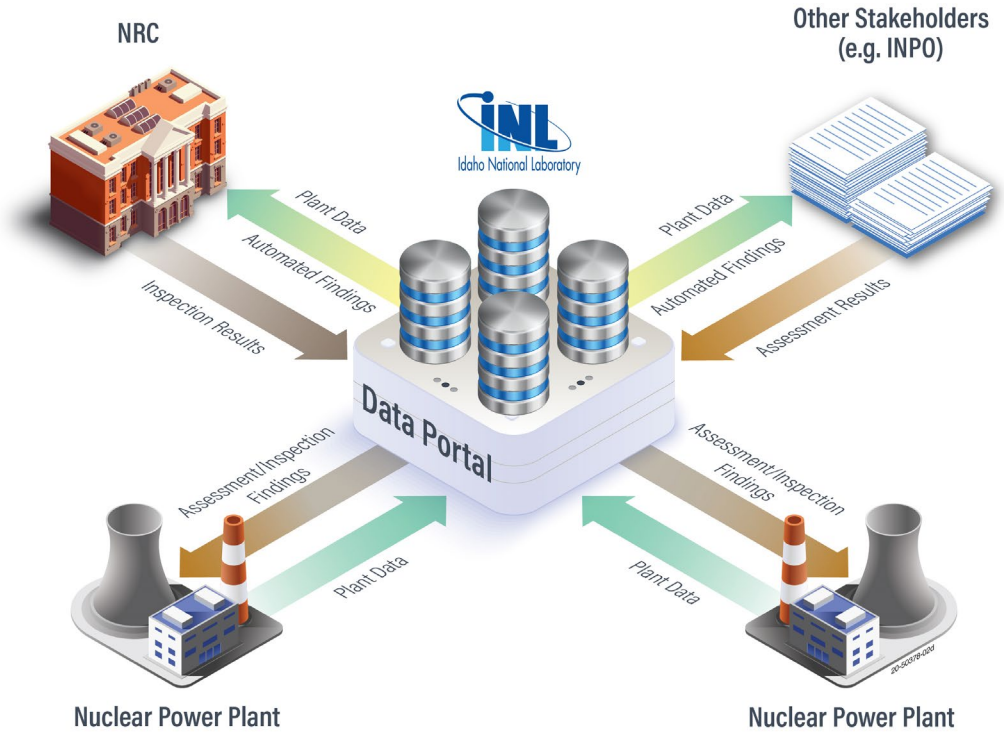
LWRS LIGHT WATER REACTOR SUSTAINABILITY

DOE-NE Light Water Reactor Sustainability Program

National Data Portal Developed for Nuclear Power Plant Assessments and Inspections

- Compliance assurance activities, including inspections, are labor-intensive endeavors that account for a disproportionate amount of operational costs in comparison with other forms of electricity generation.
- The Light Water Reactor Sustainability program has designed and developed a national data portal for use by nuclear industry-related organizations to facilitate coordination, data sharing, and reviews regarding compliance verification and demonstration.
- The data portal leverages Machine Intelligence for Review and Analysis of Condition Logs and Entries (MIRACLE), a 2022 R&D 100 award winner, to analyze plant performance using natural language processing and machine learning.
- A workshop using a specific inspection is planned for the spring of 2023 to demonstrate the data portal to nuclear utilities, the Nuclear Energy Institute, and the Nuclear Regulatory Commission.



A data portal stores and processes data from nuclear power plants to enable efficient regulation by the NRC and assessment by other stakeholders.

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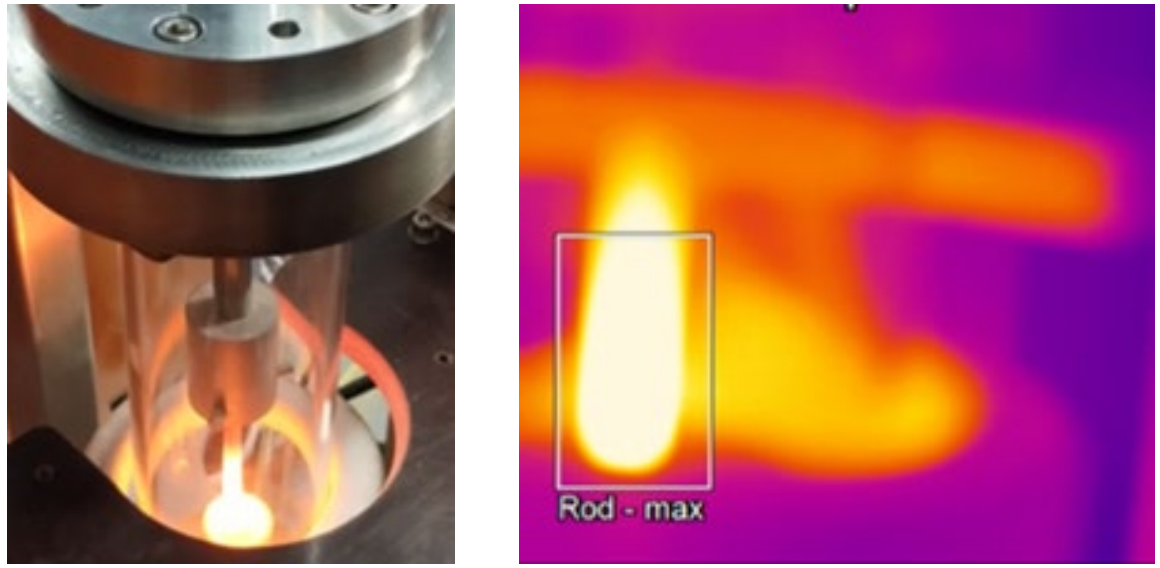
LWRS LIGHT WATER REACTOR SUSTAINABILITY

Laboratory Directed Research and Development – Innovative Fuel Cycle Solutions Initiative

Zone Refining of Surrogate Spent Fuel Rods by Induction Heating Demonstrated

- INL researchers demonstrated the inductive melting of a surrogate zirconium alloy fuel rod. This could simplify the reprocessing of used fuels into fresh nuclear fuel rods, which is a significant benefit to existing and advanced nuclear reactor fleets.
- Thermal energy (heat) was applied along the length of the surrogate U-10Zr alloy rod. The rod was successfully melted and the resulting molten droplets were collected for evaluation and characterization.
- This initial work indicates potential success for this approach. Continued research and development could improve upon this process by minimizing unit operations and improving economic efficiency.



Zone refiner as rod reaches melt temperature (left) and infrared image of melting rod (right).

FUEL SCIENCE & TECHNOLOGY | PYROCHEMISTY AND MOLTEN SALT SYSTEMS
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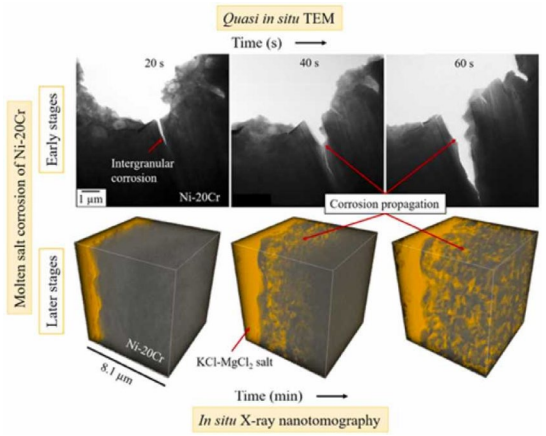
DOE Office of Science Basic Energy Sciences

Molten Salts in Extreme Environments Energy Frontier Research Center Renewed

- The Molten Salts in Extreme Environments (MSEE) Energy Frontier Research Center was renewed for $13.3M over 4 years to support the Basic Energy Sciences mission from the DOE Office of Science.
- INL is a key partner in this facility, so this represents a significant activity for INL's expanding efforts in the area of basic energy science.
- MSEE will investigate the basic science underpinning the bulk and interfacial behavior of molten salts in complex radiation environments.
- The center will leverage unique expertise and capabilities at three national laboratories and six universities.
- The principal investigators at INL are Kaustubh K. Bawane, Ruchi Gakhar, Gregory P. Horne, and Simon M. Pimblott.

MSEE
molten salts in extreme environments



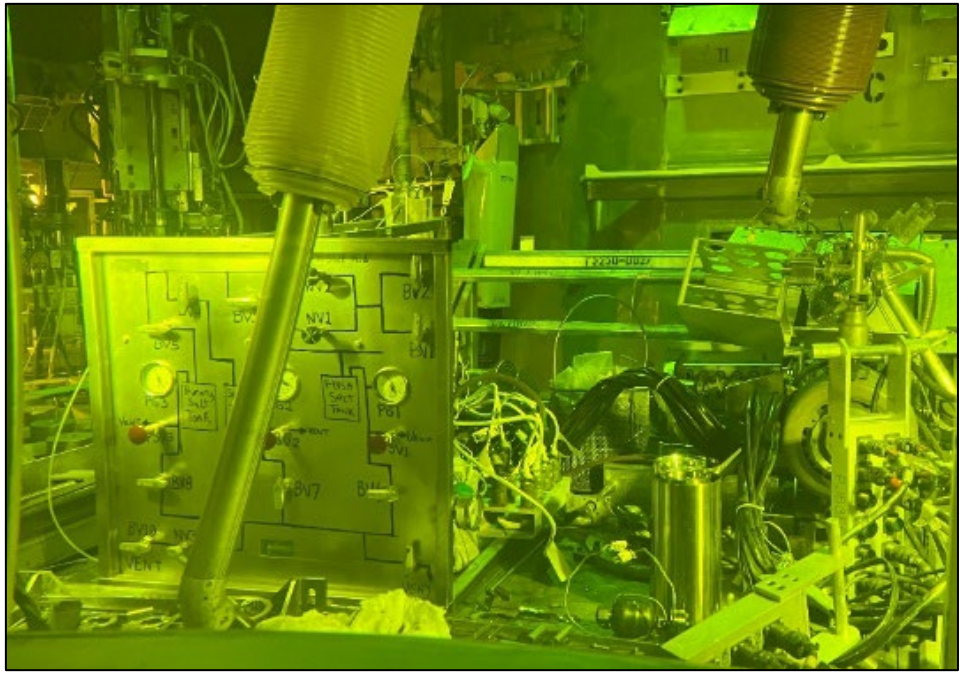
Quasi-in-situ transmission electron microscopy TEM (top) and in-situ three-dimensional (3D) synchrotron X-ray nano-tomography (bottom) to study early and later stages of molten salt corrosion in Ni-20Cr.

Title: Visualizing time-dependent microstructural and chemical evolution during molten salt corrosion of Ni-20Cr model alloy using correlative quasi in situ TEM and in situ synchrotron X-ray nano-tomography
Authors: K. Bawane et al.
Journal: Corrosion Science
Link: doi.org/10.1016/j.corsci.2021.109962

DOE-NE National Reactor Innovation Center

First Microloop Experiment Begins Operation in Fuel Conditioning Facility

- To support advanced reactor design and operation, a first-of-its-kind demonstration has begun flowing a plutonium-bearing fuel salt in an experimental microloop to study the corrosion effects on molten salt reactor structural materials.
- The PuCl3-NaCl salt was synthesized by INL staff. The flow loop is planned to operate for 1,000 hours before disassembly and examination.
- This project was constructed as part of a cooperative research and development agreement (CRADA) between TerraPower and INL. It was designed to examine the corrosion of structural materials when exposed to molten flowing salt (PuCl3-NaCl). This supports TerraPower's molten chloride fast reactor research and development.
- TerraPower staff visited INL in September 2022 to assist the project team with startup operations.



The microloop inside the hot cell shortly after salt began circulating.

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DOE-NE Nuclear Science User Facilities

ARM Architecture-Based Computing Cluster Deployed

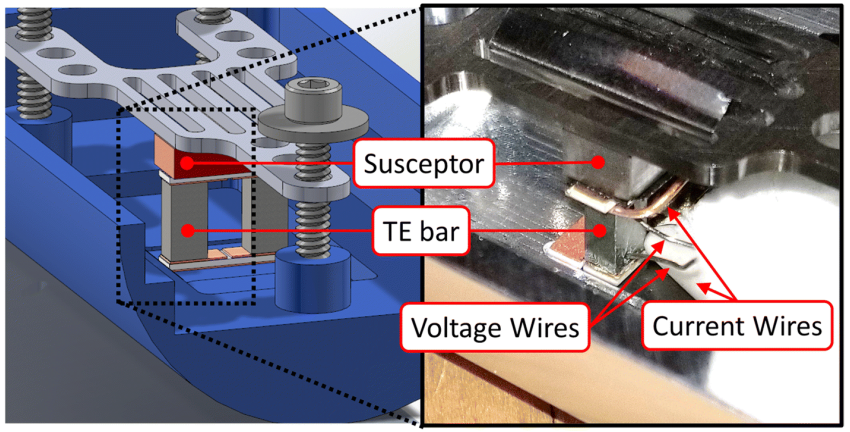
- A Cray high-performance computing (HPC) system has been procured and deployed, which has:
  - 768 cores
  - 512GB High Bandwidth Memory
  - Advanced reduced instruction set computer Machines architecture.
- The system will be used to test memory-bandwidth limited applications for nuclear energy.
  - The HPC team is benchmarking the performance of MOOSE (Multiphysics Object Oriented Simulation Environment)-based codes, as well as other modeling and simulation systems.
  - Information gained will be used to inform procurement of INL's next flagship computing cluster.
- The system will be transitioned to serve as a training cluster once testing is completed.
  - The target date for training cluster usage is December 2022.

A Hewlett Packard Enterprise (HPE) Apollo 80 2U chassis (above), which houses HPE Apollo 80 blades (below) within the new system.

DOE-NE Nuclear Science User Facilities

Experiment Identifies Promising Energy Source for In-Reactor Sensors

- Thermoelectric generation is a promising energy source to power remote sensors and other in-core instrumentation during both normal power plant operations and loss-of-power in accident conditions.
- In this experiment, a favorable thermoelectric material (n-type lead telluride) was irradiated in the core of the Massachusetts Institute of Technology Research Reactor (MITR) to monitor the material performance properties under test conditions.
- The lead telluride material system irradiated in the core of a nuclear reactor for 39 days has thermoelectric performance close to the non-irradiated material, even though the samples experienced significant microstructural changes under irradiation.
- In combination with previous studies of the effect of irradiation on the thermal conductivity of thermoelectric materials, supported by the Nuclear Science User Facilities (NSUF), this research will contribute to thermoelectric material property optimization for in-core applications in new and unexpected ways.
- NSUF provided the awarded project researchers access to MITR, the Center for Advanced Energy Studies, and the Michigan Ion Beam Laboratory through a Consolidated Innovative Nuclear Research Funding Opportunity Announcement award.



3D model of the thermoelectric bar held inside the test capsule for this experiment (left). Photograph of the thermoelectric bar inside the test capsule (right).

Title: Thermoelectric Properties of High-Performance n-Type Lead Telluride Measured *In Situ* in a Nuclear Reactor Core
Authors: N. Kempf, Y. Zhang (University of Notre Dame), Z. Luo, H. Xie, M. Kanatzidis (Northwestern University), J. Daw (INL)
Journal: Journal of Materials Chemistry A
Link: doi.org/10.1039/d2ta04409a

NSUF Nuclear Science User Facilities

DOE-NE Advanced Sensors and Instrumentation

First Instrumented Prototype Fuel Rod Created Using Equipment Procured from the Institute For Energy, Halden Norway

- The Halden Boiling Water Reactor in Norway was a key resource for assessing nuclear fuels and materials to qualify new LWR technologies before it was shut down in 2018.
- To avoid the loss of the unique capabilities developed at Halden, INL procured equipment modules designed to re-instrument sections of LWR fuel rods prior to irradiation in a test reactor.
- Using this equipment, engineers and technicians recently produced an instrumented prototypical fuel rod in the Measurement Science Laboratory using surrogate ceramics instead of uranium dioxide fuel.

Preparing to start cryodrilling of surrogate fuel rodlet.

Surrogate rodlet after drilling and welding but prior to installation of thermocouple.

Completed surrogate rodlet with thermocouple installed.

MEASUREMENT SCIENCE
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DOE-NE Advanced Fuels Campaign

Advanced Fuels Campaign Hosts International Guests for Framework for Irradiation Experiments Meeting

- Framework for Irradiation Experiments (FIDES) is an international consortium coordinated through the Nuclear Energy Agency, charged with providing a stable, sustainable, reliable platform for fuel and material testing using nuclear research reactors.
- As a member of FIDES, INL conducts irradiation-testing in the Transient Reactor Test (TREAT) Facility.
  - The TREAT reactor is an air-cooled, graphite-moderated, thermal spectrum nuclear test reactor for reactor fuels and structural materials.
- FIDES technical advisory group meetings and governing board meetings were held as part of a week-long assembly from October 14–21 at INL.
- Irradiation testing of nuclear fuels and materials is a key part of the DOE mission at INL. Hosting this group facilitates DOE and INL international leadership in this technical area.

FIDES Members from the following participating countries: Belgium, Czech Republic, Finland, France, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland, and the United States.

NUCLEAR FUELS AND MATERIALS
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Research Highlight

DOE-NE National Reactor Innovation Center and Microreactor Program

INL Collaborators Completed First Test Article Experiment in the Helium Component Test Facility

- The Helium Component Test Facility (He-CTF) provides additional capabilities for the Microreactor Agile Non-nuclear Experimental (MAGNET) Testbed for helium components. This was a collaboration between multiple directorates and organizations within INL.
  - Design, construction, start up, and shakedown testing was completed by September 2022.
  - Full testing of a demonstrator heat exchanger was completed in October 2022.

Staff operating He-CTF.

- Helium is a popular choice for cooling advanced reactors because of its high thermal conductivity, high specific heat capacity, and chemical inertness. This facility is important because it allows the testing of helium microreactor components in a non-nuclear environment. Helium test loops do exist in the U.S., but none are of this scale.
  - Open loop air supply (up to 3 bar, 220 g/s, and 350°C)
  - Helium (up to 20 bar, 70 g/s, and 650°C)
- The He-CTF in the Energy Systems Laboratory as part of the broader Dynamic Energy Transport and Integration Laboratory.
- National Reactor Innovation Center, the DOE Microreactor Program, support staff from Energy and Environment Science and Technology, Nuclear Science & Technology (NS&T), and many INL support organizations collaborated to complete this project.

Normalized Hot Test Data.

Reactor Systems Design & Analysis | Advanced Reactor Technology and Design
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National Reactor Innovation Center | Demonstration Infrastructure
Luke.Voss@inl.gov

Publications

- B. Beeler, Y. Zhang, A. Hasan, G. Park, S. Hu, Z. Mei. 2023. "Analyzing the effect of pressure on the properties of point defects in gamma U-Mo through atomistic simulations." MRS ADVANCES. https://doi.org/10.1557/s43580-022-00350-y
- C. Folsom, R. Armstrong, N. Woolstenhulme, A. Fleming, C. Hill, C. Jensen, D. Wachs. 2023. "Design of separate-effects In-Pile transient boiling experiments at the TREAT Facility." NUCLEAR ENGINEERING AND DESIGN. Vol. 397. https://doi.org/10.1016/j.nucengdes.2022.111919
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