INL/MIS-23-75649-Revision-0

September 2023 NS&T Highlights

December 2023

Addison Marie Arave

Changing the World's Energy Future

Idaho National Laboratory

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Addison Marie Arave

December 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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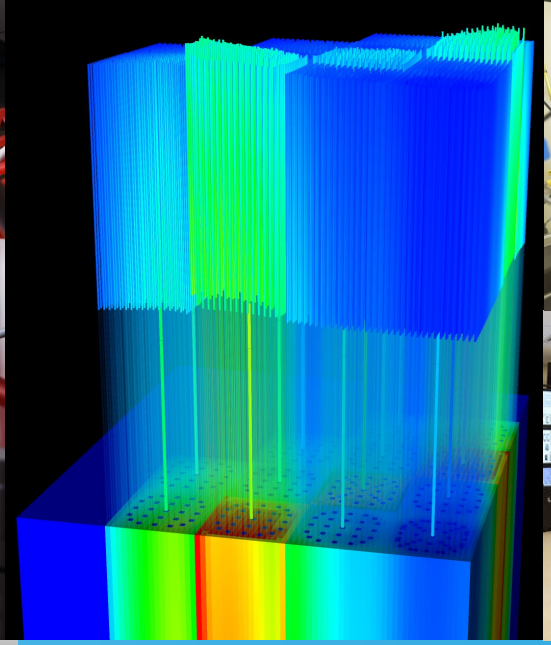
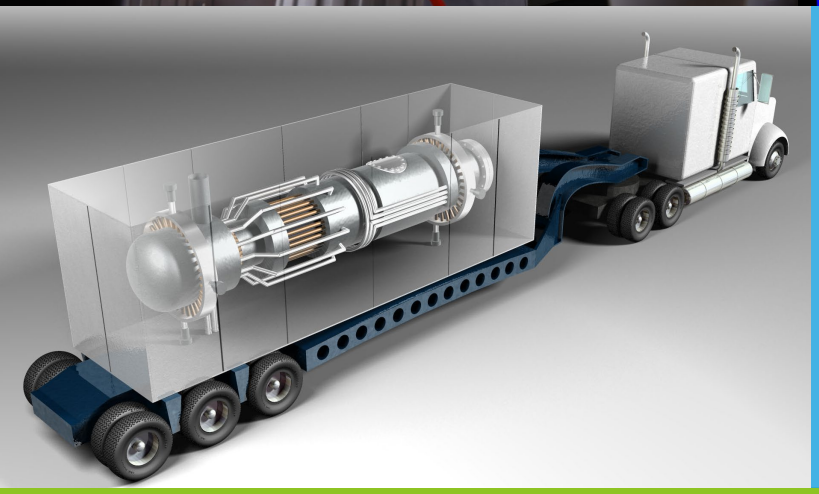


Nuclear Science & Technology

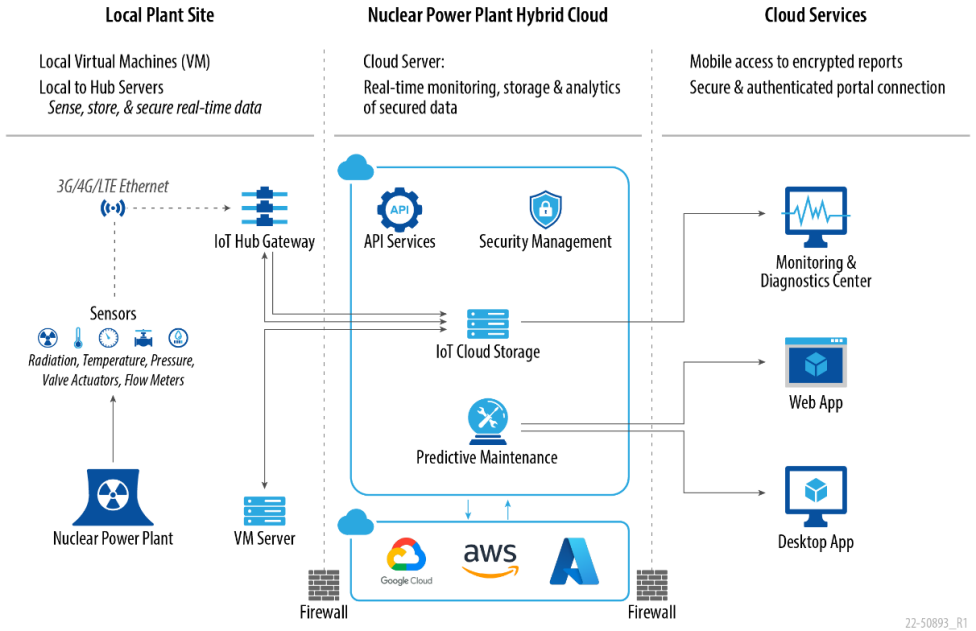
September 2023 Highlights

Idaho National Laboratory

DOE-NE Light Water Reactor Sustainability Program

Cloud-Based Applications May Enable a Scalable Predictive Maintenance Strategy

- Cloud computing may serve as a cost-effective alternative for onsite storage, computing, and analytics capabilities and resources at nuclear power plants.
- Research shows that flexible computing capacity would allow the plant to use and pay only for the resources required to perform a maintenance activity.
- This approach would help scalable predictive maintenance strategies become more cost effective.



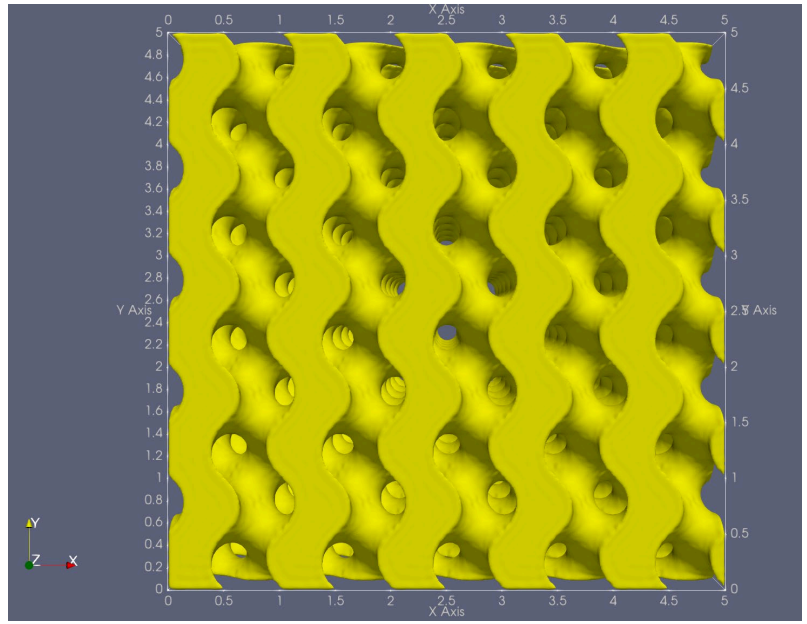
Proposed high-level architecture of the hybrid cloud.

Title: Assessment of Cloud-based Applications Enabling a Scalable Risk-informed Predictive Maintenance Strategy
Authors: C. Walker[1], V. Agarwal[1], T. Gruenwald[2], J. Nistor[2], P. Ramuhalli[3], M. Muhheim[3] ([1]Idaho National Laboratory, [2]Blue Wave AI Labs, [3]Oak Ridge National Laboratory)
INL Report: INL/RPT-23-74696

Laboratory Directed Research & Development

First Study Characterizing Potential Benefits from Additively Manufactured Nuclear Fuel Lattices

- Additive manufacturing (AM) offers the opportunity to unlock new types of innovative structures and designs.
- Triply Periodic Minimal Surface (TPMS) lattices are periodic structures found in nature being investigated for heat exchangers/heat sink applications. They offer increased convective heat transfer relative to traditional geometries, thanks to high surface area-to-volume ratios, smooth curvatures, and labyrinth-like flow paths.
- This study is the first to characterize the neutronic behavior of TPMS lattices and identify geometric parameters that can be tailored for either fast or thermal nuclear core designs.
- TPMS nuclear fuel lattices could reach much larger power densities than traditional fuel designs, thereby allowing extremely compact core designs.
- Future work will include testing of the TPMS nuclear fuel lattice in the Transient Reactor Test Facility (TREAT).



Example of gyroid lattice.

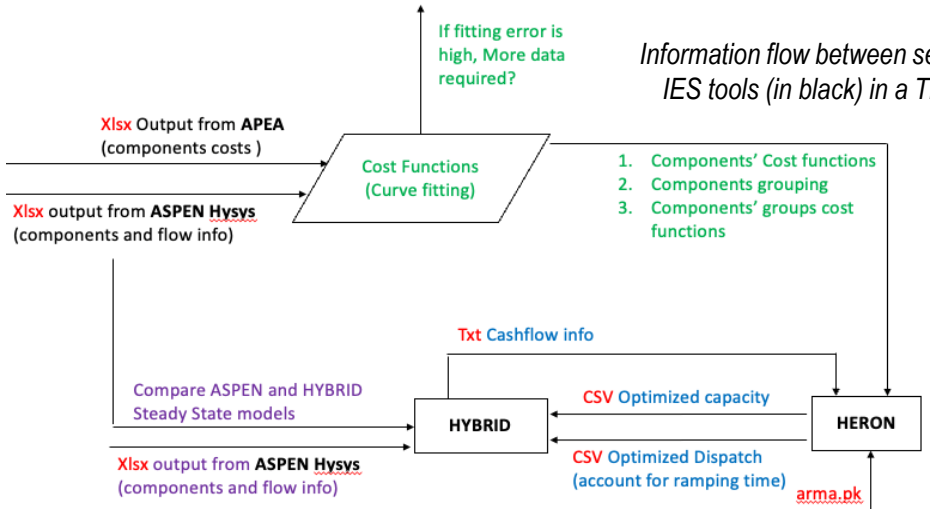
Title: Reactor Physics Characterization of Triply Periodic Minimal Nuclear Fuel Lattices
Authors: Nicolas Martin, Seokbin Seo, Silvino Balderrama Prieto, Casey Jesse, Nicolas Woolstenhulme
Journal: Progress in Nuclear Energy
Link: https://doi.org/10.1016/j.pnucene.2023.104895

Nicolas.martin@inl.gov

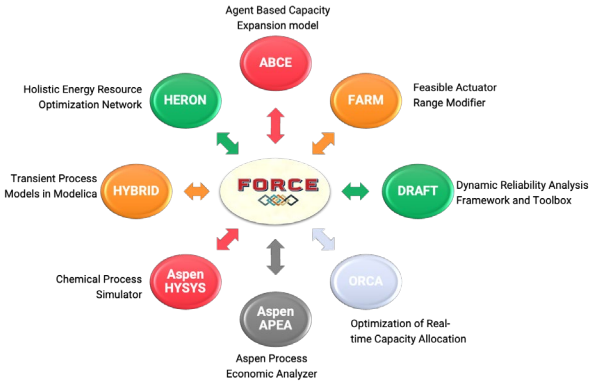
DOE-NE Integrated Energy Systems Program

Accelerated Integrated Energy Systems Technoeconomic Analysis by Integrating Tools with the Commercial Process Simulator

- A techno-economic analysis (TEA) of an Integrated Energy System (IES) requires several software tools that analyze each step from chemical processing to economic analysis.
- INL Researchers have developed a code that transfers and processes data between IES tools Aspen HYSYS, APEA, and HERON. Data processing includes dynamic cost functions based on component sizing.
  - HYSYS, APEA and HERON are simulation tools, used for energy systems modeling, IES component costs estimation and energy resource optimization.
- Automating data transfer between different IES and commercial software will accelerate the TEA of a mixed-energy system.
- This code will facilitate the sensitivity analysis and uncertainty propagation through IES software.
- This work is part of The Framework for Optimization of ResourCes and Economics, or FORCE.
- A demonstration is available on GitHub.



Information flow between several IES tools (in black) in a TEA.



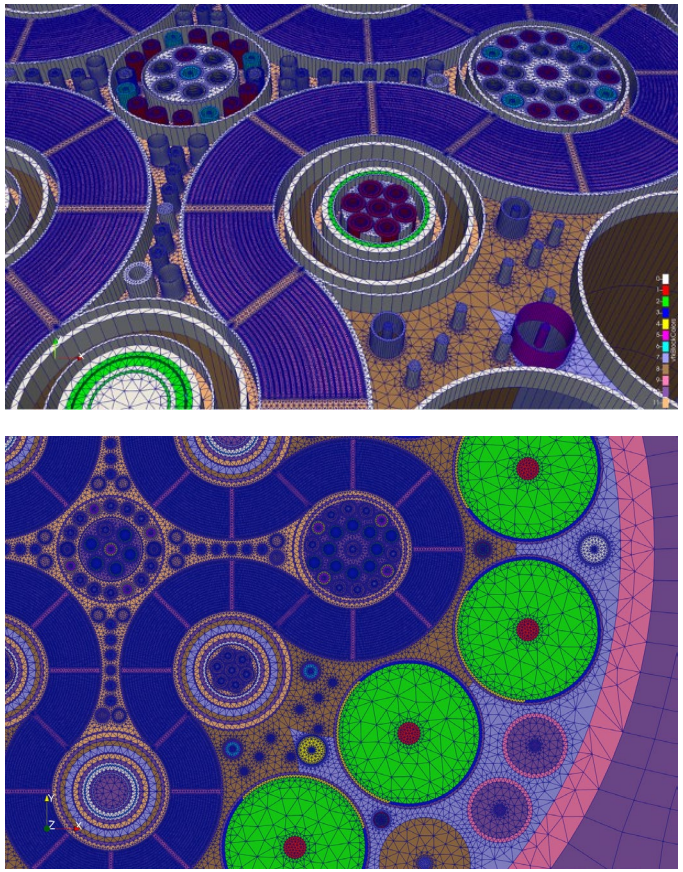
FORCE acts as a central hub for the codes used in IES analyses.

REACTOR SYSTEMS DESIGN AND ANALYSIS | DIGITAL REACTOR TECHNOLOGY AND DEVELOPMENT
botros.hanna@inl.gov, paul.talbot@inl.gov

DOE-NE Nuclear Energy Advanced Modeling and Simulation and Advanced Test Reactor Programs

Benchmarked Griffin Model of the Advanced Test Reactor

- The first complete workflow for simulation of the Advanced Test Reactor (ATR) has been developed. This workflow uses OpenMC for cross-section generation, Cubit scripts for mesh generation and Griffin for the eigenvalue calculation.
  - The OpenMC Python application program interface was used to generate the OpenMC model.
  - The Cubit application program interface was used to generate two-dimensional meshes for the core. Two-dimensional mesh refinement studies were performed to find an appropriate mesh size.
  - The MOOSE (Multiphysics Object-Oriented Simulation Environment) extruder function was used to generate three-dimensional meshes from the two-dimensional mesh with 23 axial regions.
- Using the discontinuous finite element method and the Griffin discrete ordinates solver, k_{eff} = 0.99970 was calculated for the critical state, relative to k_{eff} = 0.99934 for OpenMC. A perfect Griffin model would match the OpenMC calculation, but the results are acceptably close.
- This represents the first full mesh creation capability for ATR at Idaho National Laboratory and the ability to simulate the full core and validate against measured data. It lays the foundation for future multiphysics analysis of ATR for experiment simulation, safety analysis, and fuel performance.



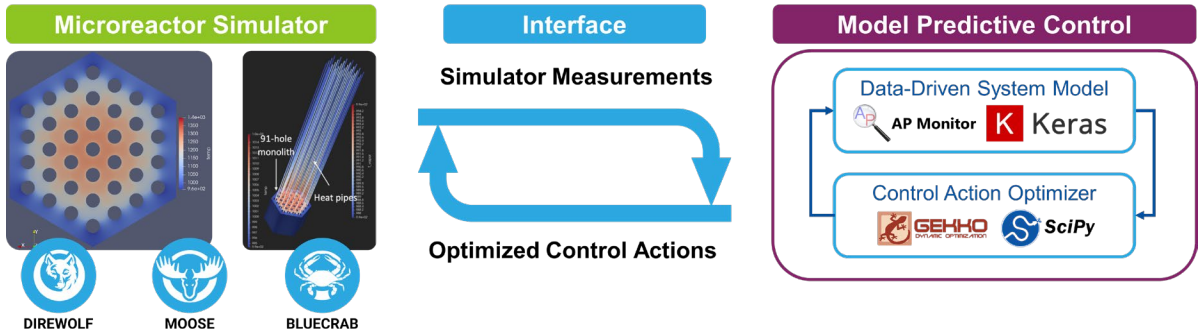
Examples of the ATR mesh used by Griffin.

mark.dehart@inl.gov

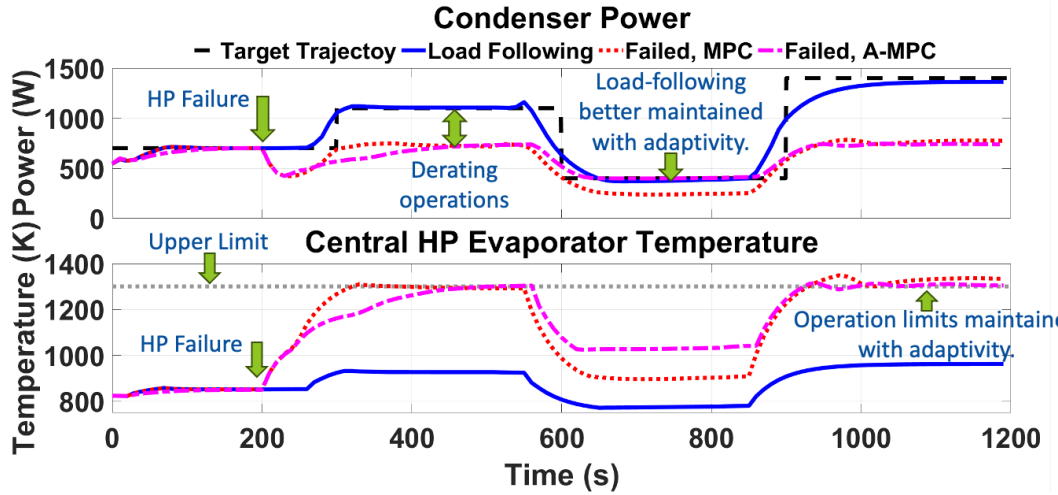
Laboratory Directed Research and Development

Autonomous Control fOr Reactor techNologies (ACORN) Software Developed to Achieve Autonomy of Operation

- INL-developed modeling and simulation tools were integrated with a model predictive controller which:
  - Demonstrated load-following during normal and abnormal conditions (as shown in the figure)
  - Included autonomous operations at steady states and power transients in a virtual environment.
- The developed capabilities will enable emerging reactors to regulate their operations, take optimized control actions in an autonomous manner, aid operators and proactively protect against potential anomalies.



ACORN autonomous reactor controls development platform.



Demonstration of the autonomous controller navigating the reactor through the failure of a heat pipe.

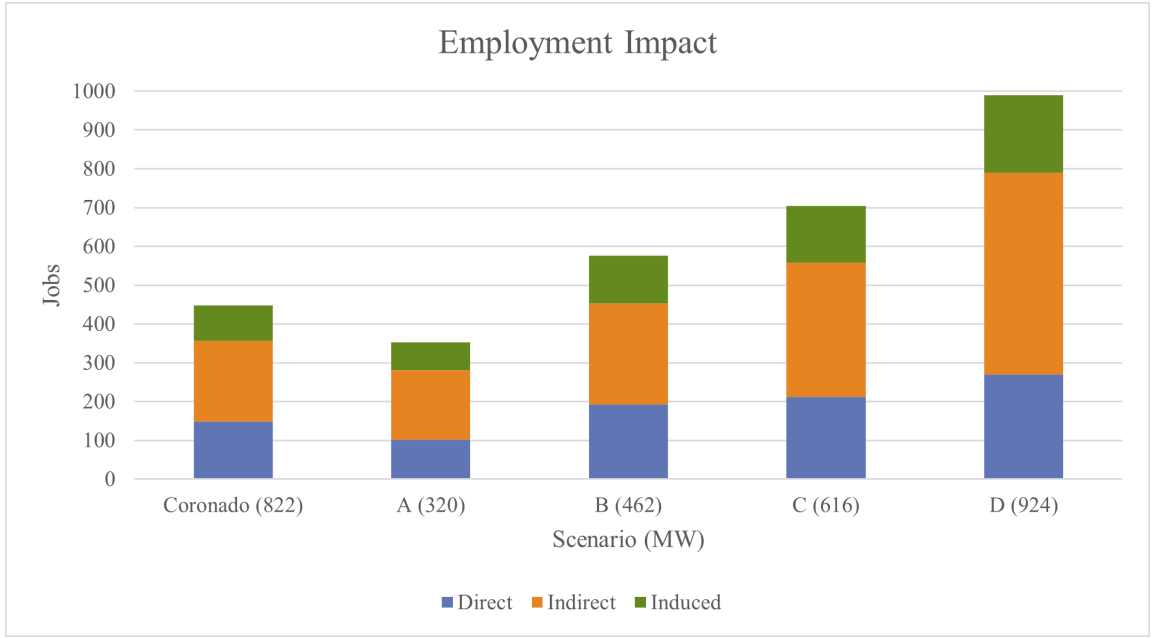
NUCLEAR SAFETY & REGULATORY RESEARCH | INSTRUMENTATION, CONTROLS, AND DATA SCIENCE
Linyu.Lin@inl.gov; Joseph.Oncken@inl.gov, Vivek.Agarwal@inl.gov

Research Highlight

DOE-NE Gateway for Accelerated Innovation in Nuclear Initiative

Gateway for Accelerated Innovation in Nuclear Published Case Study on Repurposing the Coronado Generating Station

- In collaboration with community and utility partners of Arizona's Coronado Generating Station (CGS) coal power plant, the socioeconomic characteristics of two counties were reported and two states of the world, one where CGS runs as a coal power plant and one where it runs as a nuclear power plant of various sizes, were compared.
- The analysis measures economic impact to jobs, labor income in the region, value added (i.e., new economic activity) and economic output. These metrics are assessed at the level of (I) the nuclear power plant (direct impacts); the supply chain supporting the power plant (indirect impacts); and the community surrounding the power plant (induced impacts)
- Nuclear plant replacements would create or sustain 350-1,000 jobs and up to $673 million in economic output in multiple scenarios.



Employment impact comparison of coal plant vs. nuclear replacement options.

Title: Estimating Economic Impacts of Repurposing the Coronado Generating Station with Nuclear Technology
Authors: Will Jenson, Nahuel Guaita, Levi Larsen, and Jason Hansen
Link: https://gain.inl.gov/SiteAssets/Coal2Nuclear/StJohn_econ.impacts.pdf

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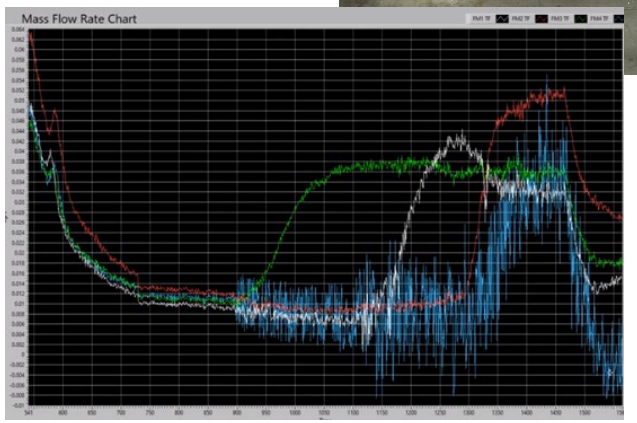
william.jenson@inl.gov, nahuel.guaita@inl.gov, levi.larsen@inl.gov, jason.hansen@inl.gov

DOE-NE Microreactor Program

MARVEL Project Successfully Initiates Primary Coolant Apparatus Testing

- The Primary Coolant Apparatus Test (PCAT) is a full size, thermal hydraulic replica of MARVEL.
- It is electrically heated with 36 heating elements. NaK is the primary coolant, and a Lead-Bismuth Eutectic is the secondary coolant, with four Stirling engines for power conversion.
- A recent PCAT project validated MARVEL's thermal hydraulic design. This work included:
  - Natural circulation verification by custom flow meters and thermocouples.
  - Demonstration of Stirling engine performance and operational characteristics.
- This demonstration enabled completion of 90% Final Design, while addressing a primary technical risk (validation of natural circulation of the primary coolant) for MARVEL.

PCAT before installation (right) and after installation (left).



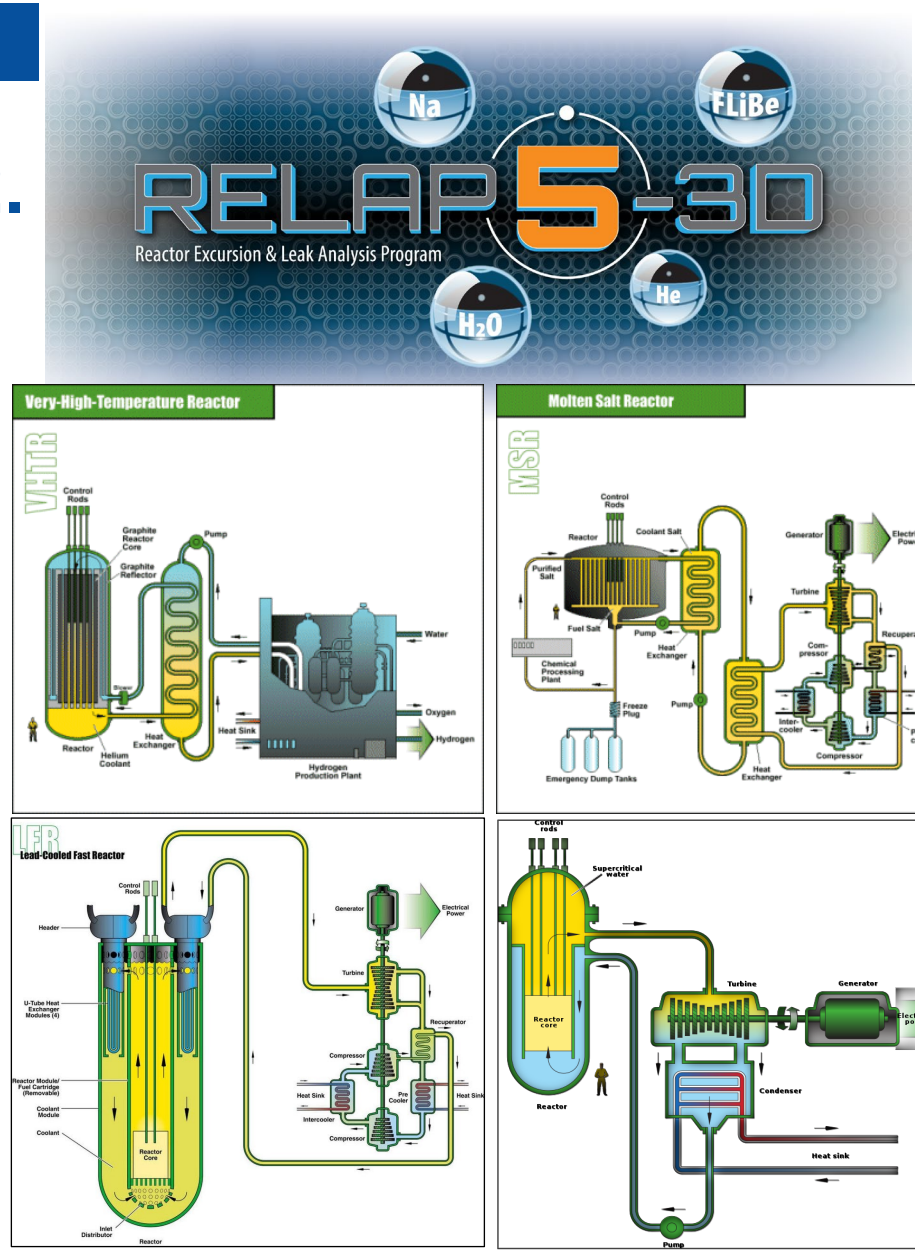
PCAT Measured Flow Rate vs Time.

REACTOR SYSTEMS DESIGN AND ANALYSIS
carlo.parisi@inl.gov, mw.patterson@inl.gov, john.jackson@inl.gov

RELAP5-3D Consortium

INL Releases RELAP5-3D Version 4.5.2.

- RELAP5-3D is a versatile modeling and simulation tool, capable of predicting complex phenomena occurring inside a nuclear reactor.
- It has a 44-year history of aiding the development and licensing of current and future nuclear reactors, including the latest advanced reactor designs.
- An updated version of this code was released on Sept. 7, the first code release in five years.
- New features include:
  - Dissolved Gas Model
  - “Forever Fortran” language
  - More primary coolant gases
  - Gas properties to cover new high temperature gas-cooled reactor ranges of operation
  - High-accuracy consistent constants



Diagrams depicting RELAP5-3D reactor system models.

REACTOR SYSTEMS DESIGN AND ANALYSIS | THERMAL FLUID SYSTEMS METHODS AND ANALYSIS
george.mesina@inl.gov, brandon.cox@inl.gov, paolo.balestra@inl.gov, carlo.parisi@inl.gov, yong-joon.choi@inl.gov, mauricio.tano@inl.gov, sujong.yoon@inl.gov

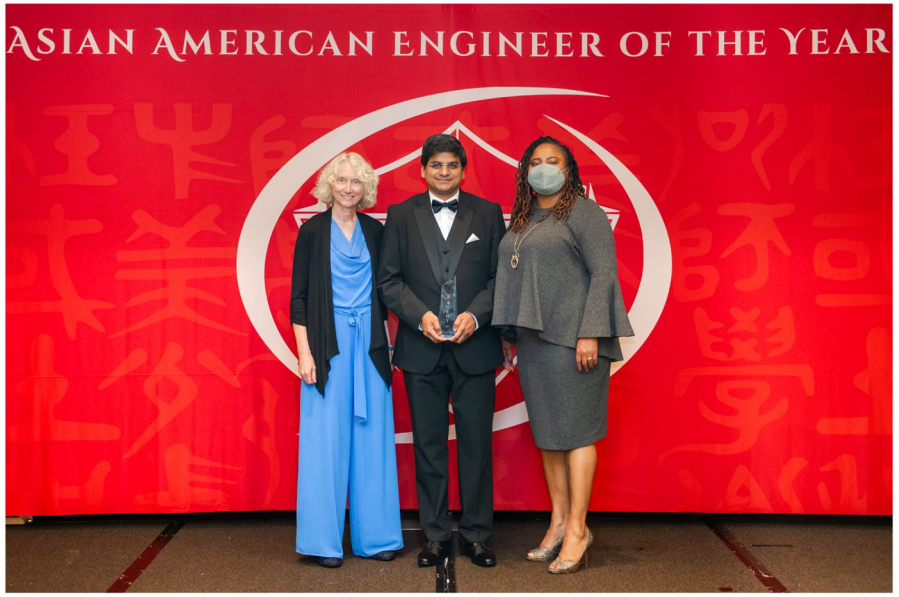
Innovations in Artificial Intelligence for Nuclear Applications Presented at Scientific Forum

- The 2023 International Atomic Energy Agency (IAEA) Scientific Forum: *Nuclear Innovation for Net-Zero,* opened by Director General Rafael Mariano Grossi and U.S. Secretary of Energy Jennifer Granholm, discussed a range of innovations and how quickly these novel technologies can come online to increase the contribution of nuclear power to achieving net zero.
- Dr. Vivek Agarwal presented on Artificial Intelligence and Machine Learning for Nuclear Operation and Maintenance in the session on Innovative Solutions to Support Nuclear Development.

From left to right: Paul Monks (United Kingdom), Shaun Jenkinson (Australia), Federica Pancotti (Italy), Toyoaki Yamauchi (Japan), Vivek Agarwal (USA), Gabi Schneider (Namibia).

Vivek Agarwal Received 2023 Asian American Most Promising Engineer of the Year Award

- The Asian American Engineer of the Year recognition honors the most distinguished professionals with their leadership, technical achievements, and remarkable public services.
- It is a prestigious forum for Corporate America, Academia, and Government to promote STEM (Science, Technology, Engineering & Mathematics) activities.
- In 2023, Dr. Vivek Agarwal was recognized for significant contributions to the clean energy field by advancing instrumentation and artificial intelligence capabilities.



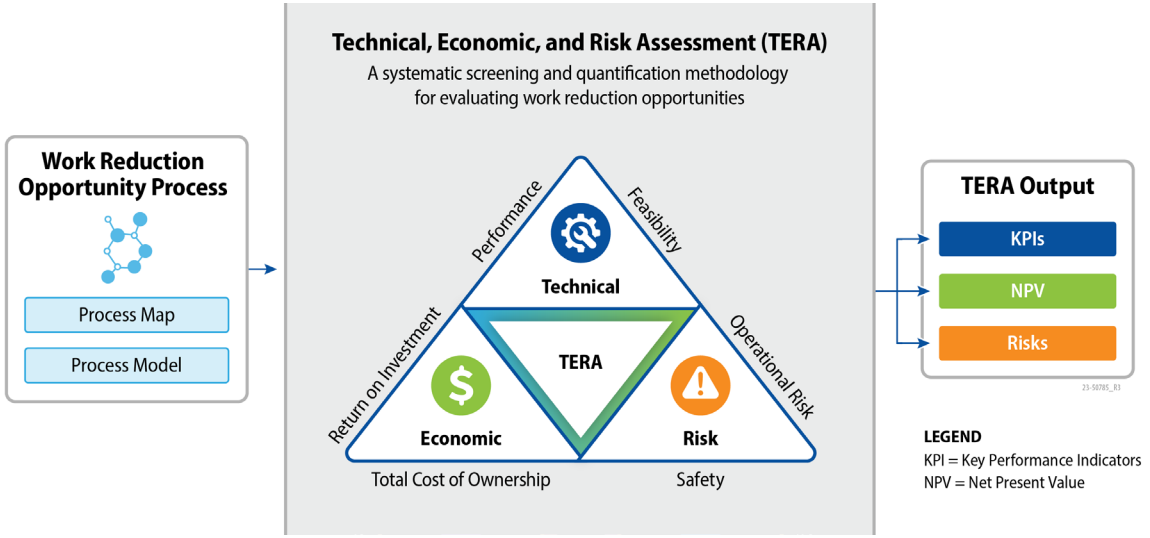
Nancy Lybeck (left), Vivek Agarwal (middle), and Toni Carter (right) at the 2023 Awards Ceremony

Nancy.Lybeck@inl.gov

DOE-NE Light Water Reactor Sustainability Program

Researchers Outline New Approach to Evaluate Work Reduction Opportunities in Nuclear Power Plants

- Light Water Reactor Sustainability (LWRS) Program researchers have developed a novel Technical, Economic and Risk Assessment (TERA) framework evaluate work reduction opportunities (WROs) in nuclear power plants.
- Using the TERA framework, stakeholders can make informed decisions on modernization investments, minimizing investment risks and optimizing costs in the nuclear sector.
- LWRS Program researchers, Southern Nuclear Company, and Sargent & Lundy, LLC evaluated work week planning and the condition reporting process as potential WROs.



A depiction of the TERA framework showing process model and output

Title: Development of a Technical, Economic, and Risk Assessment Framework for the Evaluation of Work Reduction Opportunities
Authors: R. Spangler[1], V. Agarwal[1], C. Primer[1], J. Hansen[1], S. Lawrence[1], C. Howard[2], J. McCague[2], M. Lohens[2], P. Golub[2], R. Herb[3], J. Budraitis[3] ([1]Idaho National Laboratory, [2]Sargent & Lundy, LLC, [3]Southern Nuclear Company)
INL Report: INL/RPT-23-74724

Ryan.Spangler@inl.gov, Vivek.Agarwal@inl.gov

LWRS LIGHT WATER REACTOR SUSTAINABILITY

IDAHO NATIONAL LABORATORY

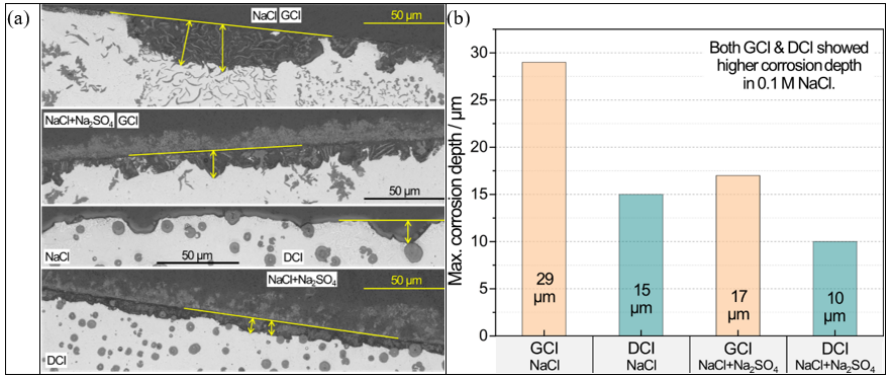
Research Highlight

DOE-NE Light Water Reactor Sustainability Program

Understanding Piping Degradation in Nuclear Power Plants to Reduce Aging Management Costs

- Underground pipes at nuclear power plants are aging and becoming susceptible to selective leaching.
- Aging management is costly and labor-intensive. With a better understanding of degradation phenomena, risk-informed, performance-based approaches could reduce those costs.

Failed cast iron pipe samples



a) Micrographs of cross sections of GCI (top two micrographs) showing extent of corrosion in NaCl and NaCl + Na2SO4 solutions and DCI (bottom two micrographs) exposed to the same solutions and b) plot of maximum measured corrosion depth of the two materials in the two solutions.

- To addresses knowledge gaps on selective leaching phenomenon, laboratory experiments were performed in which Grey Cast Iron (GCI) and Ductile Cast Iron (DCI) pipe samples were exposed to chemically-induced harsh environments to accelerate degradation.
- The results support progress toward determination of degradation rates that can be used in assessment of component fit-for-service for the plant remaining life.

Title: Novel Approaches and Technologies for Aging Management

Authors: S. Lawrence[1], V. Yadav[1], D. Schwen[1], D. van Wasshenova[1], J. Jun[2], J. Keiser[2], J. Wade IV[2], X. Chen[2], D. Du[3], P. Karve[3], S. Mahadevan[3] ([1]Idaho National Laboratory, [2]Oak Ridge National Laboratory, [3]Vanderbilt University)

INL report: INL/RPT-23-74593

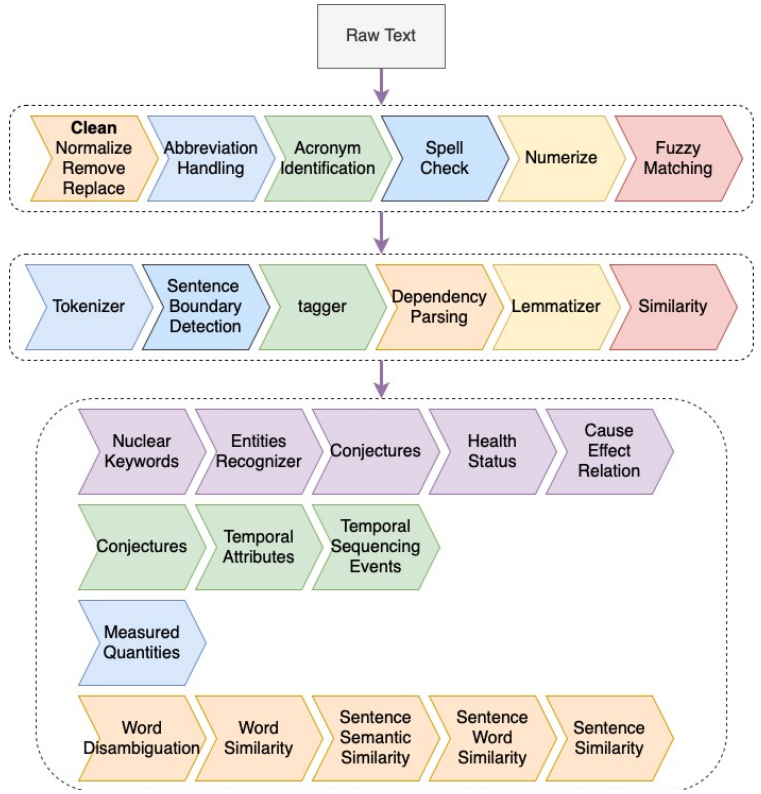
keiserjr@ornl.gov, junj@ornl.gov, Svetlana.Lawrence@inl.gov

LWRS LIGHT WATER REACTOR SUSTAINABILITY

DOE-NE Light Water Reactor Sustainability Program

Newly Developed Software Methods Aid Textual Data Interpretation

- Nuclear power plants generate and collect a large amount of equipment reliability textual data elements that contain information about the status of components, assets and systems.
- The ability of machines to understand textual elements limits the use of this data to assess system heath.
- Light Water Reactor Sustainability Program researchers developed software methods that identify, from textual data, entities such as physical objects (e.g., systems, assets), phenomena (e.g., failure, degradation), measured quantities and temporal or cause-effect relations between events.
- This unique set of machine learning and rule-based methods were coupled with a dictionary of nuclear related entities to enables the extraction of knowledge from nuclear power plants equipment reliability textual data.



Overview of the developed Natural Language Processing methods.

Title: Development of Analysis Methods that Integrate Numeric and Textual Equipment Reliability Data

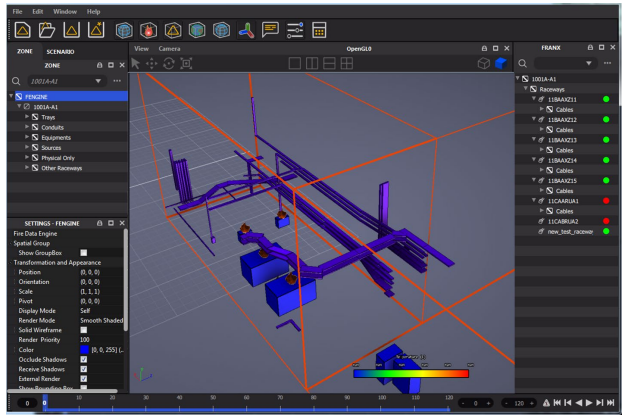
Authors: D. Mandelli, C. Wang, J. Cogliati, V. Agarwal

Report: INL Technical Report INL/RPT-23-74530

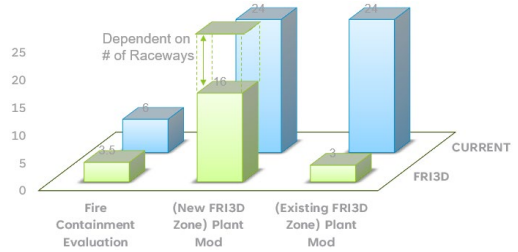
DOE-NE Light Water Reactor Sustainability Program

Fire Analysis Software FRI3D Achieves Major Commercialization Steps

- The Fire Risk Investigation in 3D (FRI3D) software, developed at Idaho National Laboratory, reduces the cost of performing detailed fire risk analysis.
- Fire consulting company Engineering Planning and Management Inc. (EPM) performed a nuclear power plant modification analysis using FRI3D and demonstrated cost savings.
- Four scenarios were evaluated for a compartment with >100 electrical raceways showing:
  - >75% time saving for already modeled compartments/rooms.
  - Moderate time savings for new compartments/rooms.
- The software is being commercialized by Centroid Lab in collaboration with the Light Water Reactor Sustainability Program.
- Centroid Lab has an initial agreement with Risk Spectrum for foreign nuclear power plant use and works with EPM for some domestic nuclear power plant use.



FRI3D user interface integrates a plants component database, 3D modeling, and probabilistic risk assessment.



Plant modification analysis time comparison.

Title: FRI3D Industry Adoption and Verification Tasks
S. Prescott, S. Schiavo, R. Christian (Idaho National Laboratory), R. Sampath (Centriod Lab)
INL report: INL/RPT-23-74213

Steven.Prescott@inl.gov

LWRS LIGHT WATER REACTOR SUSTAINABILITY

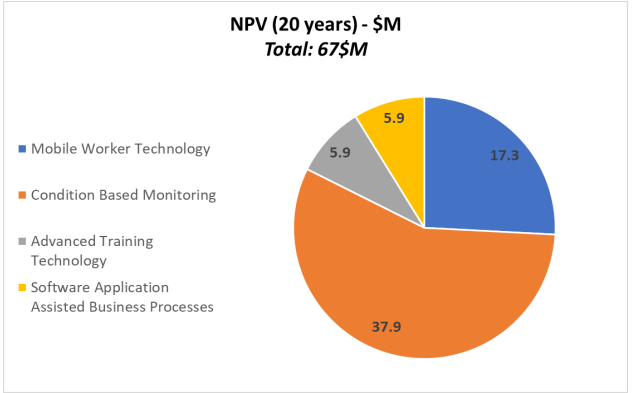
DOE-NE Light Water Reactor Sustainability Program

Integrating New Operation Concepts and Digital Technologies to Reduce Nuclear Plant Costs

- Light Water Reactor Sustainability Program researchers led a Digital Infrastructure (DI) Business Case Analysis (BCA) with Luminant Generation at Comanche Peak based on a previous similar BCA at Limerick plant.
  - Existing safety-related and non-safety-related instrumentation and control (I&C) system were evaluated.
  - The latest BCA includes lost generation impacts if I&C upgrades are not performed, contributing to a more realistic result.
- The team is also integrating ION (Integrated Operations for Nuclear) with DI research to maximize the aggregate impact of digital upgrades to lower nuclear plant costs.
  - ION aims to achieve light water reactor fleet electric market competitiveness by transforming the nuclear business model.
  - Integrating ION concepts into the DI enabled Luminant Generation to identify priority work reduction opportunities, that will result in significant cost reductions.

Scenario Title	Payback Period	Net Present Value (NPV)
Baseline (30 years of continued operation)	17.8 years	$74M
Baseline (50 years of continued operations)	17.8 years	$685M

NPV of I&C Digital Modernizations. Digital I&C upgrades pay for themselves and provide increasing returns as plant life is extended.



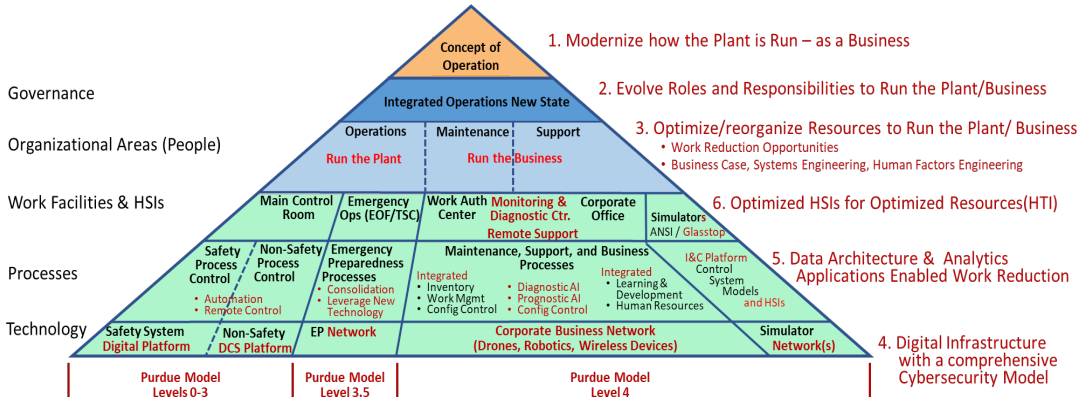
Net Present Value of Priority Work Reduction Opportunities (Luminant Generation's Comanche Peak plant).

Title: Pilot Business Case Analysis for Digital Infrastructure
Authors: P. Hunton, R. England
INL Report: INL/RPT-23-74393

DOE-NE Light Water Reactor Sustainability Program

Researchers Develop a Strategy to Improve Work Processes and Reduce Costs in Nuclear Power Plants

- The Light Water Reactor Sustainability (LWRS) Program's Integrated Operations for Nuclear (ION) efforts aims to achieve LWR fleet electric market competitiveness by transforming the nuclear business model.
- LWRS researchers collaborated with ScottMadden Inc. to identify nuclear plant work reduction opportunities (WROs) to enable a new ION concept of operation.
- Researchers have developed an ION Work Reduction Opportunity Strategy that converges Digital Infrastructure (DI), Human Technology, ION and related Data Architecture and Analytics (DA&A) research to integrate digital upgrades across the DI.
- This strategy provides a process to identify DA&A software attributes to realize WROs. It helps utilities to approve projects to implement them.



ION WRO Demonstration Steps.

Title: Integrated Operations for Nuclear: Work Reduction Opportunity Demonstration Strategy
Authors: P. Hunton (INL), S. Lawrie (ScottMadden Inc.)
INL Report: INL/RPT-23-74671

DOE-NE Nuclear Science User Facilities Program

Nuclear Science User Facilities Hosts Partner Visit to Capture Input from Representatives

- INL's Nuclear Science User Facilities (NSUF) hosted representatives from 20 partner facilities, including national laboratories, universities, and industry.
- The purpose of these partnerships is to form a nationwide infrastructure, making nuclear science research more accessible.
- This meeting provided an opportunity to capture attendees' input on topics affecting all NSUF partners such as data management, project planning and execution, adding new capabilities to existing partnerships, and innovative research available in the NSUF partner portfolio.

NSUF program staff and partner representatives.

NUCLEAR FUELS & MATERIALS
brenden.heidrich@inl.gov

NSUF Nuclear Science User Facilities

DOE-NE Nuclear Science User Facilities Program

Nuclear Science User Facilities Awards Third Round of Rapid Turnaround Experiments

- The Nuclear Science User Facilities program has awarded the third round of Rapid Turnaround Experiment awards for the 2023 fiscal year, totaling approximately $1.6 million.
- Twenty-two awards supported nuclear science and technology advancement by providing access to world-class capabilities at no cost to the researcher.
- The awards went to 14 principal investigators from universities, seven from national laboratories, and one from industry. Five Idaho National Laboratory researchers will receive access funding for their projects, including one NS&T researcher.
- Visit https://nsuf.inl.gov to learn about the projects.

NSUF ran three rounds of RTE solicitations in FY23, the first time since FY19. Total funding for new RTE awards for FY23 was $4.7 M.

NSUF Nuclear Science User Facilities

NUCLEAR FUELS & MATERIALS
brenden.heidrich@inl.gov

DOE-NE Nuclear Science User Facilities Program

Nuclear Science User Facilities Holds Industry Outreach Meeting with GAIN and EPRI

- The Nuclear Science User Facilities (NSUF) held its industry outreach meeting at the Electric Power Research Institute (EPRI) in Charlotte, NC on September 26-27.
- The United States nuclear power industry is one of the NSUF stakeholder communities that informs program direction.
- The meeting was an open forum for NSUF, GAIN, industry, and the Nuclear Regulatory Commission to exchange information and provide feedback on the following topics:
  - NSUF development progress, specifically partner facility capabilities for material and fuels development and impact on nuclear industry.
  - Use cases for NSUF which requires open publishing of results.
  - Review of new and ongoing NSUF experiments.
  - NSUF historic performance and future direction.
  - Needs for early development research on materials of interest.

NSUF and GAIN meet with representatives of the US nuclear industry at EPRI headquarters.

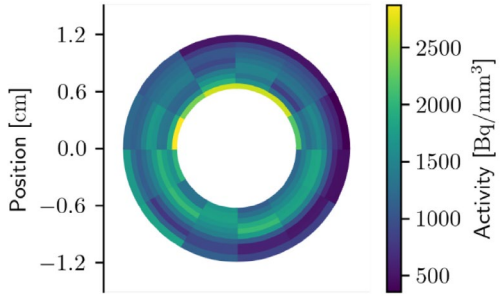
NUCLEAR FUELS & MATERIALS
brenden.heidrich@inl.gov

NSUF Nuclear Science User Facilities

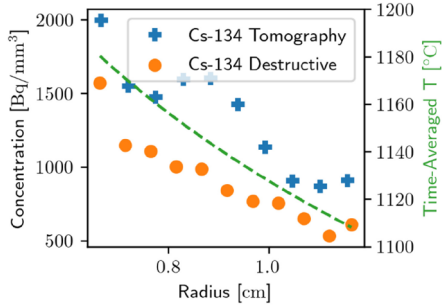
DOE-NE Advanced Gas Reactor Fuel Qualification Program

TRISO Fuel Fission-Product Transport Experiments Completed

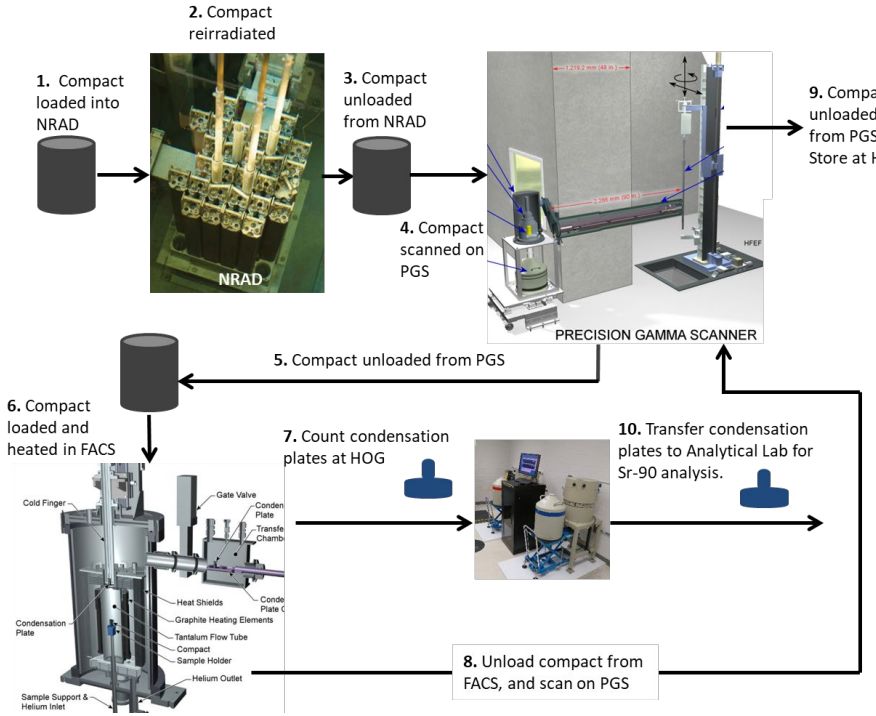
- In a suitably engineered high-temperature gas-cooled reactor, tristructural isotropic (TRISO)-coated particle fuels enable a “functional containment” where the fuel itself is the primary barrier to fission-product release, and a safety-significant containment structure may not be required.
- The final TRISO fuel compact destructive exams were completed in September, ending the 8-year AGR-3/4 experiment campaign.
- Data on short and long-lived fission-product release from the fuel under normal and off-normal conditions were collected for reactor safety analyses and model development.



Tomographic reconstruction of Cs-134 activity measured via non-destructive gamma tomography of graphite surrounding the AGR-3/4 fuel during irradiation.



Radial fission product concentration profiles from non-destructive and destructive measurements will be used to back-calculate transport parameters.



Process for reirradiating entire fuel compacts and then heating to measure short-lived fission products, unique to INL.

John.Stempien@inl.gov

Fuel Cycle Science and Technology Directorate

David Tolman Joins Fuel Cycle Science and Technology

- David Tolman has been named the Department Manager for Pyrochemical Science in the Fuel Cycle Science & Technology division.
- Tolman joined INL in 2015, working to deploy high temperature chemical processes on a variety of projects, including EBR-II driver fuel treatment and the Joint Fuel Cycle Studies.
- Prior to coming to INL, David worked for the Idaho Cleanup Project on EBR-II decommissioning activities at the Materials & Fuels Complex and on used fuel storage and handling activities at the Idaho Nuclear Technology and Engineering Center.

Pyrochemical Science Department Manager David Tolman.

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