INL/MIS-20-58810-Revision-0

NS&T Highlights March 2020

Joel Newman Hiller

April 2020

The INL is a U.S. Department of Energy National Laboratory
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Nuclear Science & Technology

March 2020 Highlights

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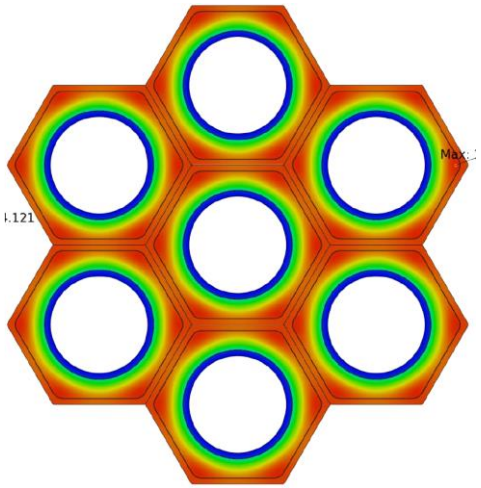
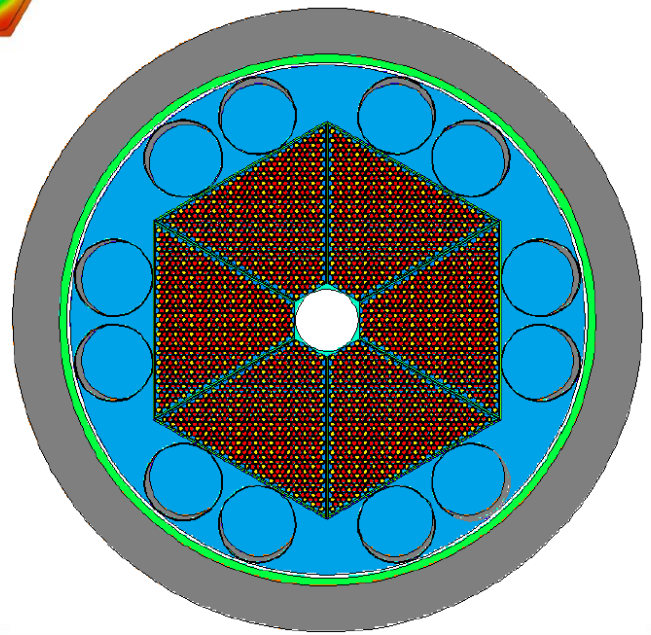
US Patent Granted for Microreactor Work

- Dr. James Sterbentz and Dr. James Werner have been awarded a U.S. patent for innovative portable microreactor designs.
  - Microreactors produce up to 2 MWe and could be dispatched in remote areas or areas affected by natural disasters.
  - Heat is removed from the core by heat pipes and transferred to an appropriate power conversion system.
- Leading U.S. manufacturing experts acknowledged that these designs could be readily manufactured.
- Full patent may be viewed at https://patentimages.storage.googleapis.com/d6/39/cb/8edeee0b11d090/US10559389.pdf





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MOOSE and BISON Achieve NQA-1 Milestone

- On February 13, software quality assessors from ASME's NQA-1 committee completed their assessment of the MOOSE framework and BISON nuclear fuels performance application to ensure that Department of Energy and ASME Nuclear Quality Assurance (NQA-1) requirements are being met. Both MOOSE and BISON earned a final grade of "Effective."
- MOOSE and BISON can be used in safety software applications (**QL-1** and **QL-2**), including at ATR, which requires an NQA-1 pedigree. The assessors noted good coordination and solid expertise among staff, few product-related issues and a high degree of technology use for development (MOOSE tools & methods).
- Efforts to bring Griffin (reactor physics/radiation transport) and RELAP-7 (advanced systems analysis) into line with NQA-1 safety software standards will begin immediately.

NQA-1
10CFR50 Appendix B

NQA-1 Milestone Achieved

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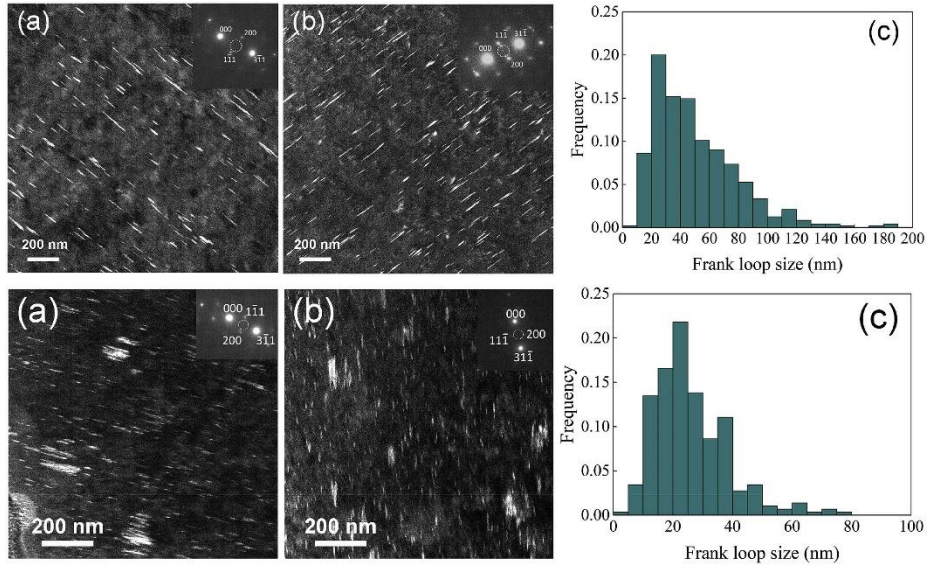
NSUF Project Enhances Understanding of Irradiated Reactor Materials

- The research team investigated the properties of two structural materials used in reactors: nickel-based alloy X-750 (funded by NSUF) and Type 304 stainless steel. The study used samples irradiated at low dose rates in the EBR-II reactor.
- During service, these materials can undergo significant changes. The research targets degradation of X-750 and 304 SS induced by the combination of stress, reactor irradiation, and temperature that can compromise the structural integrity and safety operation of nuclear power plants.
- The data will help researchers developing new reactors to utilize the most resilient structural materials to optimize safety and operational lifespan.
- Work published in Journal of Nuclear Materials (***J. Nucl. Mater.***, 528 (2020) 151851)



TEM rel-rod DF images showing the Frank loops in irradiated 304 SS (top row) and X-750 (bottom row). Compared to higher dose rate neutron irradiations, loops are much larger and less dense.

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NSUF Nuclear Science User Facilities

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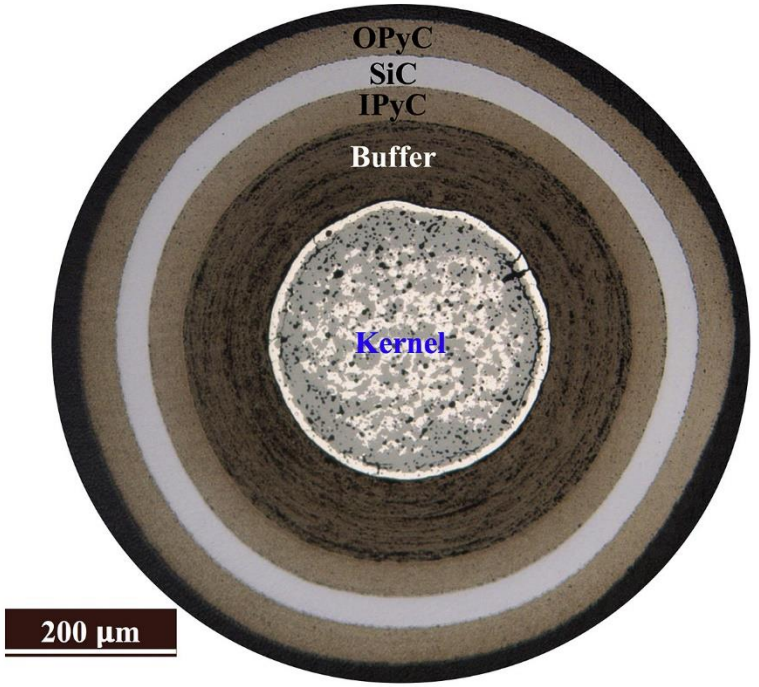
NSUF Project Improves Understanding of TRISO Fuel

- Tristructural isotropic (TRISO) coated particle fuel has been studied extensively, but little post-irradiation study has been done on the response of fuel kernels to safety testing.
- Researchers performed extensive studies using transmission electron microscopy (TEM) and atom probe tomography (APT) on a TRISO fuel-particle kernel that had been irradiated and subjected to safety testing at 1600°C.
- Two key finding were observed:
  - Two primary reconstruction phases occurred
  - No fission-gas bubbles could be attributed to high-temperature safety testing.
- The study, a collaboration between NSUF and DOE's Advanced Gas Reactor program, fills a knowledge gap regarding the suitability of TRISO as a candidate accident-tolerant fuel and as fuel for high-temperature gas-cooled reactors.
- Work published in Journal of Nuclear Materials. (***J. Nucl. Mater.***, 528 (2020) 151884)



Optical image of an as-fabricated AGR-1 fuel particle

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Nuclear Science & Technology

NSUF Nuclear Science User Facilities

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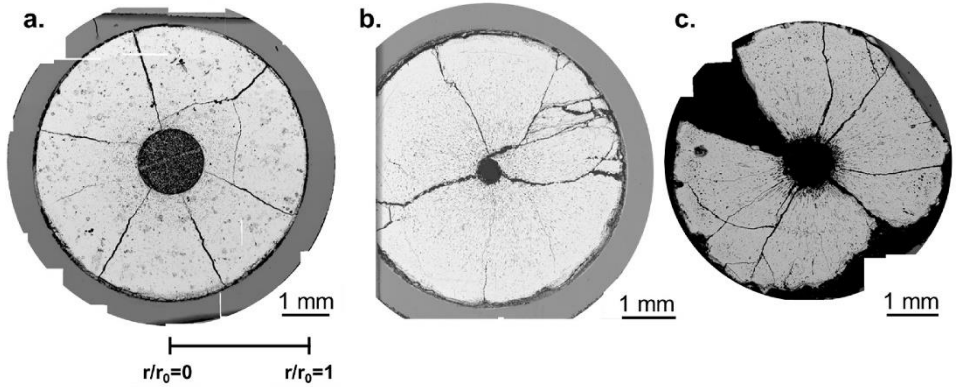
NSUF Project Improves Understanding of MOX Fuel Burnup

- Advanced reactors likely will reach higher burnup rates than existing reactors. Understanding the evolution of fuel microstructure is vital.
- The research team examined three mixed-oxide fuel (MOX) pellets irradiated to different burnup rates.
- The data provides an understanding of the evolution of the fuel microstructure, during extended reactor operation, to allow the use of advanced reactor fuels to much higher burnup than traditional LWR fuel.
- Work published in Journal of Nuclear Materials (***J. Nucl. Mater.***, 531 (2020) 152003)

Burnup	Low (3.4%)	Intermediate (13.7%)	High (21.3%)
Grain Structure	Little change	Pores began to form near central void along grain boundaries	Columnar grain growth
Fission Products	Only metallic FMPs	Perovskite forms near fuel centerline; PdPs visible in outer half	Increased number and size of perovskite and PdPs



BSE-SEM cross section of fuel pellets irradiated to (a) 3.4%, (b) 13.7%, and (c) 21.3%

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NSUF Nuclear Science User Facilities

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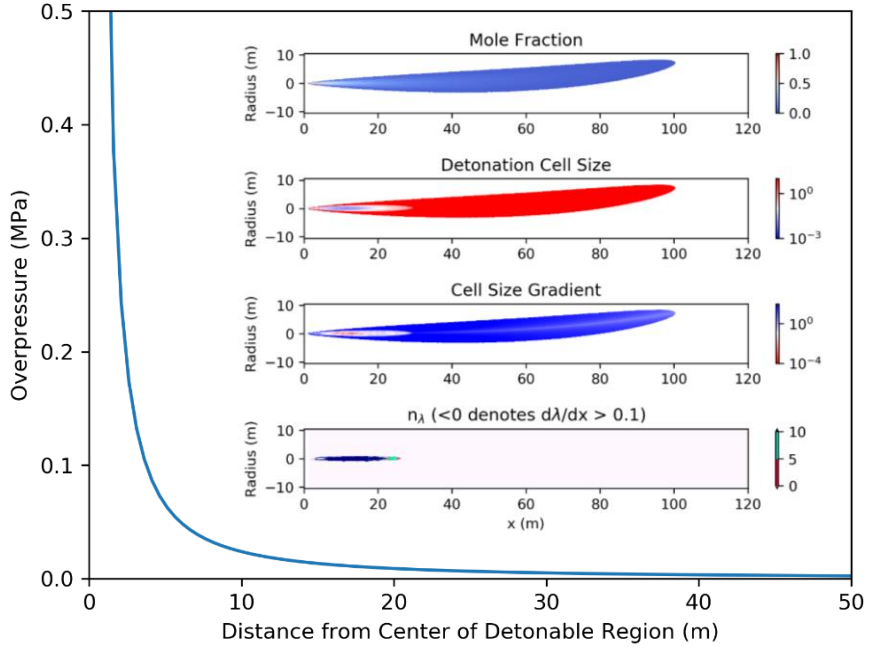
Safety Analysis Completed for Building Hydrogen Plants Near Nuclear Power Plants

- The NS&T Probabilistic Risk Assessment group completed a hazards analysis of locating a hydrogen plant within 1 km of a nuclear power plant. The group studied the detonation effects of a hydrogen flame jet and the detonation of a hydrogen cloud accumulation, using Calvert Cliffs Nuclear Power Plant.
- In cooperation with Sandia National Laboratory, the analysis provides essential data for a fault-tree analysis.
- The outcome of the study indicates a small impact, relative to an overpressure event by distance.
  - There would be no significant damage to reactor containment, switchyard or support facilities.
  - The detonation could disrupt external power supply.
  - Results will be used to evaluate changes to existing plant PRAs.



Calvert Cliffs NPP critical external structures; image from the USNRC.

Sandia National Laboratories

LWRS
LIGHT WATER REACTOR SUSTAINABILITY

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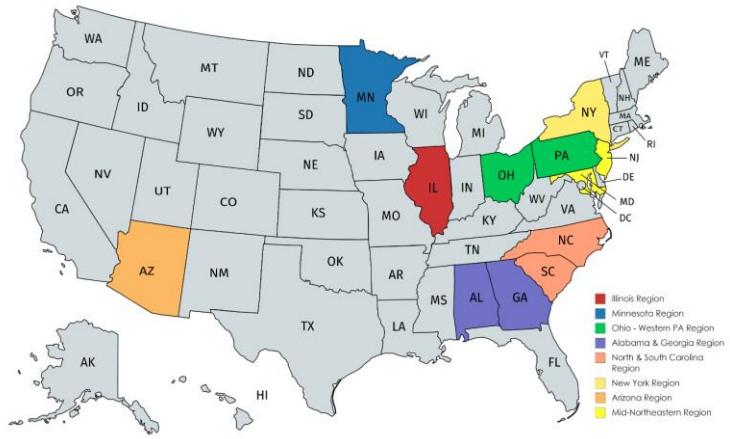
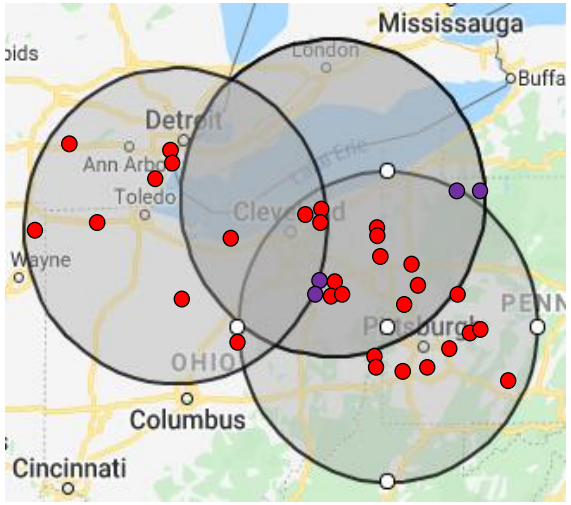
LWRS Program Study Supports Regional Large-Scale Nonelectric Markets for U.S. Nuclear Power Plants

- The study provides a sampling of market demand location, scale and accessibility of the wide variety of industrial product choices that can be produced using nuclear thermal energy and electricity. It presents examples and trade-off analyses of how U.S. LWR power plants can access these markets.
- The study focused on regional direct and indirect hydrogen markets (transportation, co-firing w/ natural gas, refining, ammonia and CO_2 sources for synthetic fuels)
- A survey of current electricity markets was used to project the impact on LWR plants in each region.
- Support was provided by Argonne National Laboratory.



Regions of Study



Location of oil refineries (purple), and steel mills (red) within 100 miles of the NPP facilities (shaded circles) in Ohio and Pennsylvania

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LWRS Program Researchers Develop Innovative Concept for Nuclear Power Plants Control Rooms

- Researchers brought together technologies developed in the LWRS Program Plant Modernization Pathway into an integrated operations concept called ADAPT (Analytics, Decision-support, and Advanced Procedure Tool) incorporating:
  - Prognostics and Diagnostics
  - Online Monitoring and Advanced Alarms
  - Computer-Based Procedures
  - Operator Decision Support
- The concept is documented in the report entitled, *Development of an Advanced Integrated Operations Concept for Hybrid Control Rooms.*
- On March 23–27 the team held a remote workshop with Palo Verde operators to collect feedback for further improvements.

The concept demonstrates how these technologies can transform plant operations to reduce operations and maintenance costs.

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Sawtooth Supercomputer Officially Made Available to Users

- On March 18, the new Sawtooth supercomputer was made available to users, following weeks of testing.
- Delivered in December 2019, Sawtooth consists of 2,079 compute nodes and 99,972 compute cores.
- The system is rated at 5.6 petaflops, which ranked #37 on the TOP500 supercomputer list in November 2019.
- Installation video: https://youtu.be/hfnonKFalqo

Made Available To Users March 18, 2020

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Lemhi Supercomputer Moved to Support Ongoing HPC Research

- On March 2–5 the High-Performance Computing team moved the Lemhi supercomputer to the Collaborative Computing Center.
- Four days were spent verifying hardware and software functionality.
- One rack was replaced to allow easier access to equipment for maintenance and troubleshooting.

- Operating Lemhi in EROB exceeded the power/cooling capabilities of the legacy HPC center. This relocation reduces operational risks for critical INL business computer systems.

The move reduces INL's overall data center risk and positions the system for additional years of productive modeling and simulation support.

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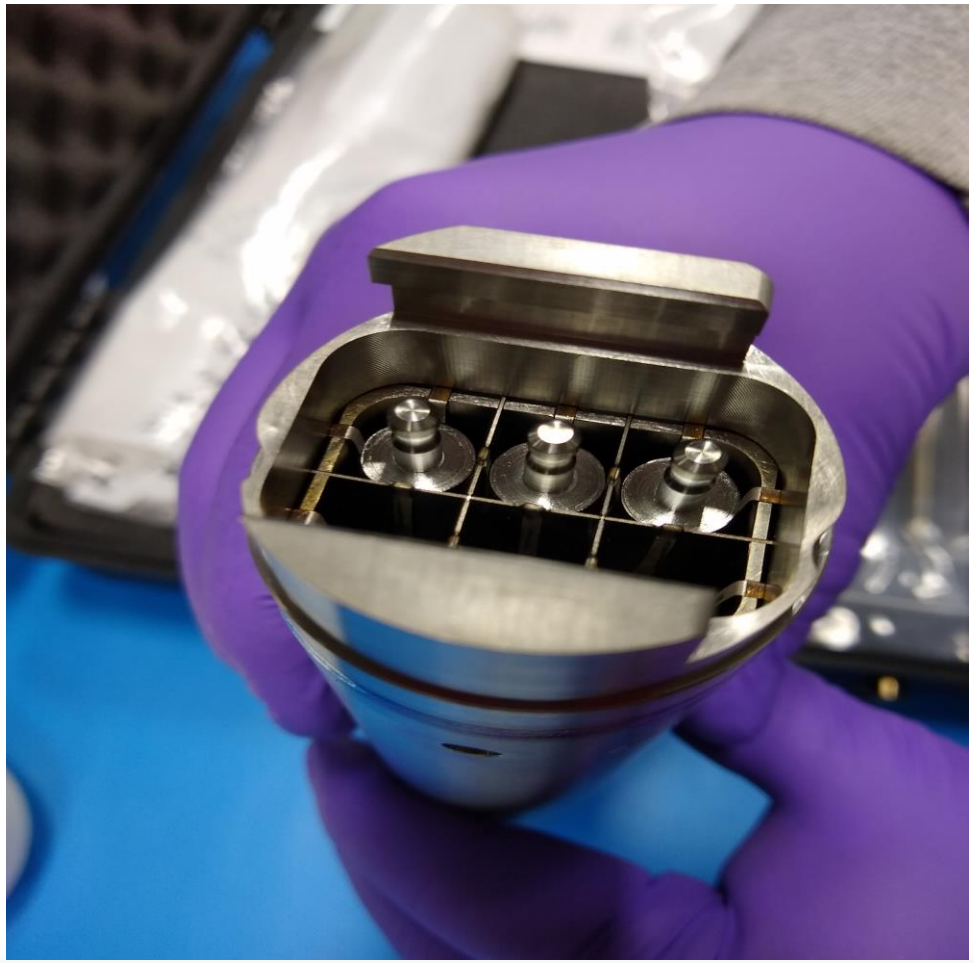
ATF-2 Test Train Irradiation Capabilities Expanded

- The test train was recently reconfigured to add 3 more Westinghouse pins and 4 more Framatome pins. Up to 18 pressurized-water reactor rodlets and 12 boiling-water reactor rodlets can now be irradiated simultaneously.
- Each pin can be independently removed, inspected and shipped for post-irradiation examination. Once irradiated rodlets are removed, new rodlets can be inserted.



The ATF-2 experiment loop remains the only facility in the western world capable of testing LWR fuels under prototypic PWR conditions.

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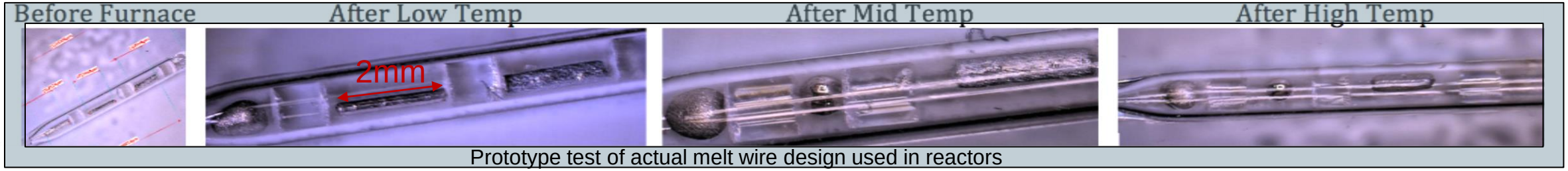
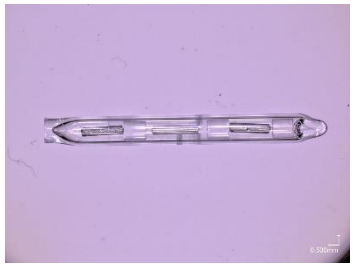
Melt Wire Package Completed for ATR Experiment on Innovative Microreactor Materials

- Melt wires are designed to identify temperatures ranging from 600°C to 800°C in the High Temperature Moderator Materials (HTMM) experiment.
- HTMM is an INL/Los Alamos National Laboratory collaborative effort to investigate hydride moderators for microreactors.



Prototype test of actual melt wire design used in reactors

Example of post irradiation examination in hot cell



Before Irradiation

After irradiation

Passive sensors fabricated at HTTL provide visual evidence during post-irradiation examination of localized peak irradiation temperature.

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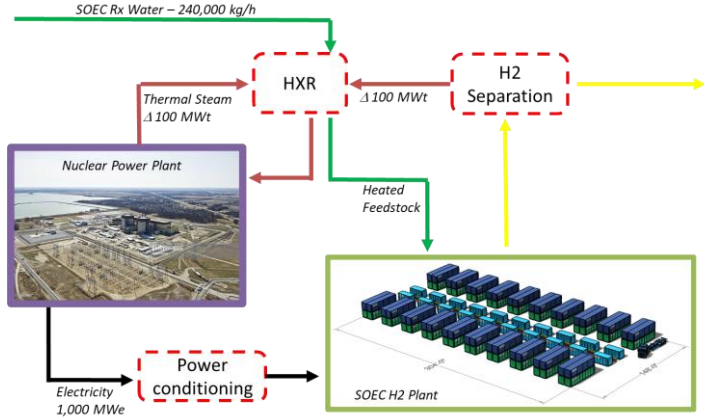
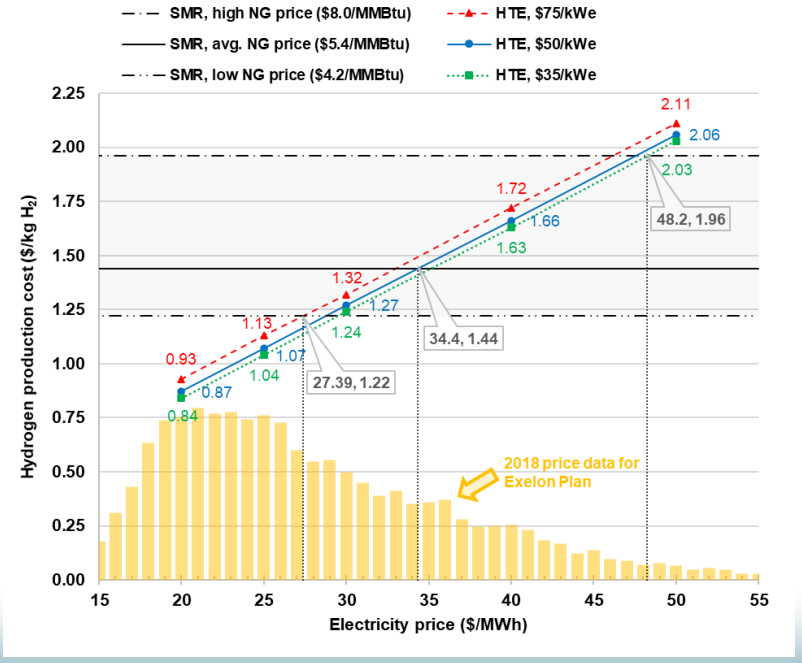
INL Completes Hydrogen Production CRADA

- The NS&T and EEST directorates completed a $1.5 million cooperative research and development agreement.
- The research was sponsored by the DOE's Office of Energy Efficiency and Renewable Energy, Exelon, and FuelCell Energy and was conducted coordinating with Argonne and Sandia National Laboratories, and the National Renewable energy Laboratory.
- The CRADA report confirms hydrogen production with power provided by nuclear power plants is economically viable, which is a vital step toward commercial realization. The report provides detailed design, capital and operational costs and plant scale optimization data.





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NS&T Staff Teach MOOSE Course at TMS 2020

- Larry Aagesen, Andrea Jokisaari, Daniel Schwen (NS&T Computational Mechanics and Materials Department) and Michael Tonks (University of Florida) taught the short course “Modeling the Coevolution of Microstructure and Properties using the MOOSE Framework” at the TMS 2020 Annual Meeting in San Diego, CA.
- The course focused on modeling material behavior at the microstructure level, using the phase-field method as implemented in the MOOSE framework.
- In addition to lectures introducing attendees to the fundamentals, the course included multiple hands-on sessions where participants solved example problems on their own computers.

Strong turnout demonstrates MOOSE is becoming the platform of choice for mesoscale materials modeling.

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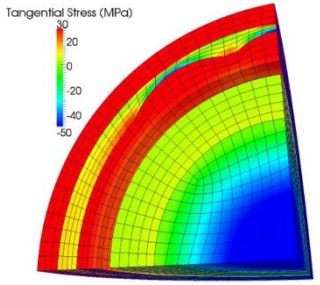
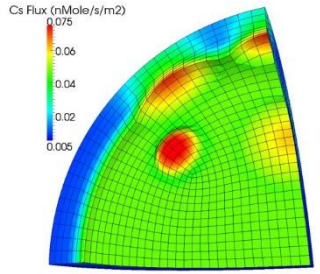
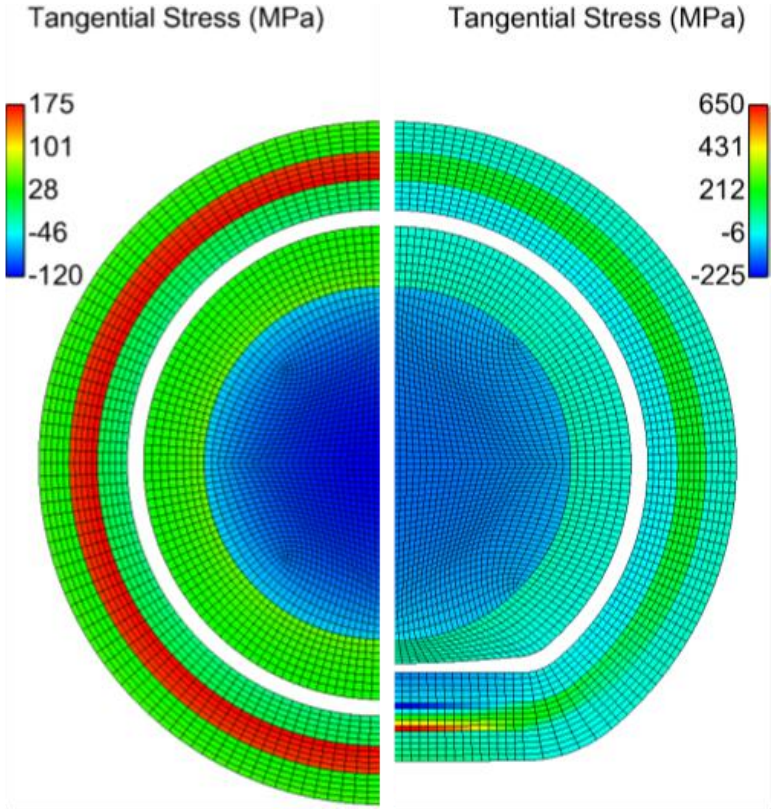
Westinghouse Trained on TRISO Modeling with BISON

- Westinghouse has interest in TRISO particles and compacts for its microreactor designs, but modeling of TRISO particles is not possible with their in-house codes.
- On February 24–26 INL researchers provided training to introduce Westinghouse personnel to BISON and its TRISO capabilities, including thermal, mechanical and fission gas capabilities.
- The BISON team anticipates providing follow-up training and support.







Westinghouse

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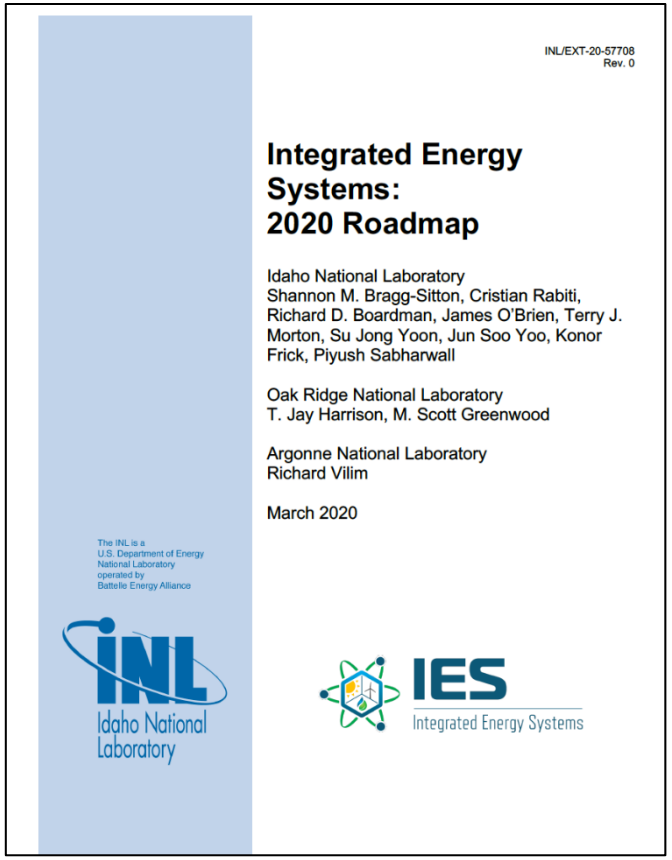
Integrated Energy Systems: 2020 Roadmap Issued

- The DOE Office of Nuclear Energy Crosscutting Technologies Development (CTD) Integrated Energy Systems program issued an updated technology development roadmap on March 12, 2020 for DOE programmatic review. The roadmap incorporates multiple energy generation systems to produce multiple energy products. Once approved by DOE-NE, the roadmap will be distributed to selected stakeholders for review and comment before making the document public.
- This roadmap presents a high-level overview of integrated system options and technology development needs for commercial deployment of IES for current fleet light-water reactors (LWRs), LWR-based small modular reactors (SMRs), and advanced reactors.
- The broad set of research needs are being addressed by multiple DOE R&D programs and by industry. Specific areas of research that will be addressed by the CTD IES program, along with associated timelines and budget needs, will be addressed in a follow-on CTD IES program plan.



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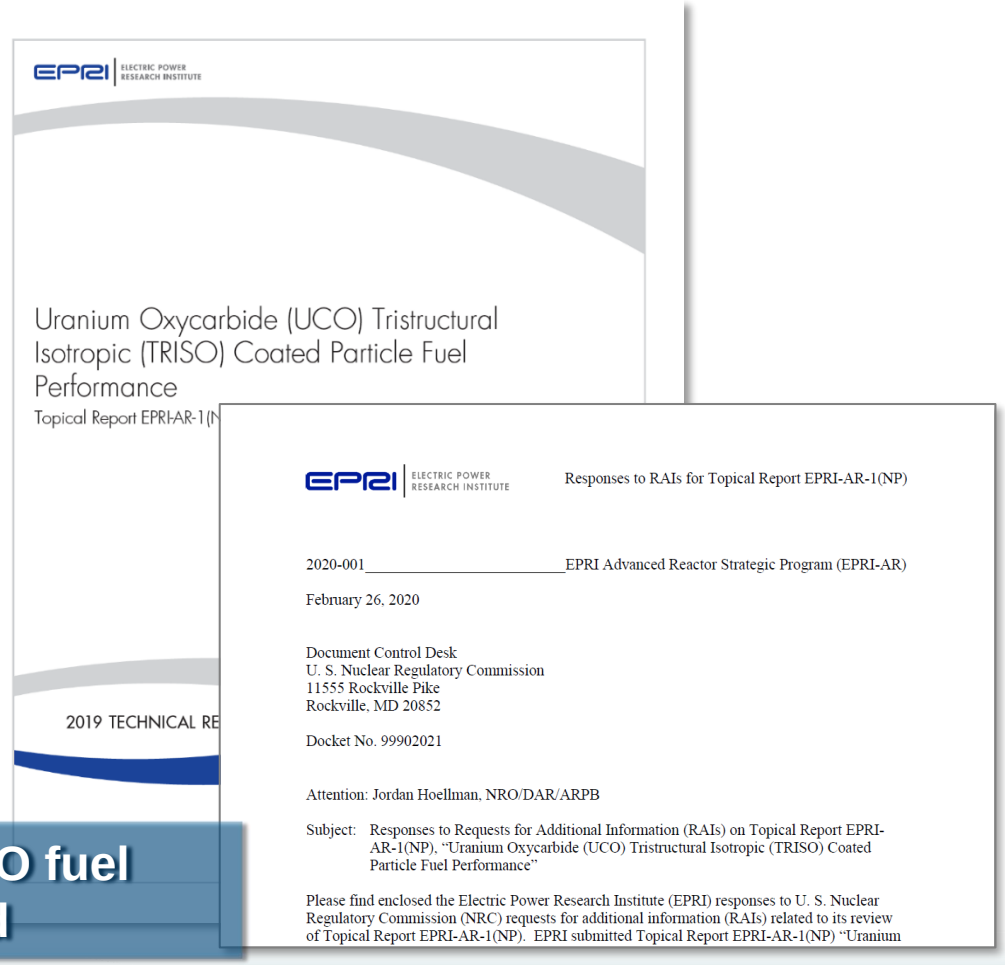
Responses Submitted to NRC on TRISO Fuel Performance Report

- INL staff collaborated with the Electric Power Research Institute to respond to all Requests for Additional Information (RAIs) submitted by the NRC related to the Topical Report EPRI-AR-1 (NP) "*Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance.*"
- RAI responses were submitted to the NRC on February 26. This is a major step toward the NRC issuing a formal Safety Evaluation Report regarding UCO TRISO fuel performance, which will be a landmark in the path toward qualification of this fuel for HTR licensing and commercialization.


EPRI ELECTRIC POWER RESEARCH INSTITUTE

Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance

Topical Report EPRI-AR-1(N

2019 TECHNICAL RE

EPRI ELECTRIC POWER RESEARCH INSTITUTE Responses to RAIs for Topical Report EPRI-AR-1(NP)

2020-001 EPRI Advanced Reactor Strategic Program (EPRI-AR)

February 26, 2020

Document Control Desk
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Docket No. 99902021

Attention: Jordan Hoellman, NRO/DAR/ARPB

Subject: Responses to Requests for Additional Information (RAIs) on Topical Report EPRI-AR-1(NP), "Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance"

Please find enclosed the Electric Power Research Institute (EPRI) responses to U. S. Nuclear Regulatory Commission (NRC) requests for additional information (RAIs) related to its review of Topical Report EPRI-AR-1(NP). EPRI submitted Topical Report EPRI-AR-1(NP) "Uranium

Key step towards UCO TRISO fuel qualification completed

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GAIN Awards Next Round of NE Vouchers

- On March 12, 2020, GAIN announced the second-round FY2020 Nuclear Energy Voucher recipients, Neutroelectric, LLC and Oklo Inc. NE Vouchers provide advanced nuclear technology innovators access to the extensive nuclear research capabilities and expertise available across the U.S. Department of Energy (DOE) national laboratory complex.

GAIN NE Voucher Recipient	Proposal	Partner Facility
Neutroelectric, LLC	Combined Effects Testing of High-Temperature and Neutron Fluence to Support the Qualification of NE-300, a High-Temperature Neutron Shielding Material	Oak Ridge National Laboratory
Oklo, Inc.	Address gaps in legacy data on fuel steel interactions	Idaho National Laboratory

GAIN
Gateway for Accelerated Innovation in Nuclear

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Julia Tripp Recognized as Fellow of Waste Management Symposia

- Julia Tripp of the Fuel Cycle Science and Technology Division was awarded Fellow of Waste Management Symposia at the Waste Management Conference in Phoenix March 8–12, 2020.
- Julia was recognized for her continuing contributions to waste management for over 30 years, including involvement on the Program Advisory Committee in the Decontamination and Decommissioning Track.

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Publications Summary

- Parisi, C., Ma, Z., Mandelli, D., Anderson, N., Zhang, H. (2020) **Risk-Informed Safety Analysis for Accident Tolerant Fuels**, *Nuclear Science and Engineering*, DOI: 10.1080/00295639.2020.1732699
- Permann, C.J., Gaston, D.J., Andrs, D., Carlsen, R.W., Kong, F., Lindsay, A.D., Miller, J.M., Peterson, J.W., Slaughter, A.E., Stogner, R.H., and Martineau, R.C. (2020). **MOOSE: Enabling Massively Parallel Multiphysics Simulation**, SoftwareX. 11. 100430. DOI: 10.1016/j.softx.2020.100430.
- Patnaik, S., Lopes, D. A., Bestmann, T. M., Spencer, B. W., Knight, T. W. **Experimental System for Studying Temperature Gradient-Driven Fracture of Oxide Nuclear Fuel out of Reactor**, *Review of Scientific Instruments*, vol. 91, no. 3, p. 035101, Mar. 2020.
- W. Jiang, B. W. Spencer, and J. E. Dolbow. **Ceramic Nuclear Fuel Fracture Modeling with the Extended Finite Element Method**, *Engineering Fracture Mechanics*, vol. 223, p. 106713, Jan. 2020.
- He, L., Bachav, M., Teysseyre, S. **A Transmission Electron Microscopy Study of EBR-II Neutron-Irradiated Austenitic Stainless Steel 304 and Nickel-Base Alloy X-750**, *Journal of Nuclear Materials*, 528 (2020) 151851. DOI: 10.1016/j.jnucmat.2019.151851

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Publications Summary

- Fu, Z., Van Rooyen, I., Bachav, M., Yang, Y. **Microstructure and Fission Products in the UCO Kernel of an AGR-1 TRISO Fuel Particle after Post Irradiation Safety Testing**, *Journal of Nuclear Materials*, 528 (2020) 151884. DOI: 10.1016/j.jnucmat.2019.151884
- Parrish, R., Aitkaliyeva, A., Cappia, F. **TEM Analysis of Irradiated MOX Fuel**, *Journal of Nuclear Materials*, 531 (2020) 152003. DOI: 10.1016/j.jnucmat.2020.152003