INL/MIS-22-66167-Revision-0

AFC Newsletter (January 2022)

January 2022

Phyllis L King

Changing the World's Energy Future

Idaho National Laboratory

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Advanced Fuels Campaign NEWSLETTER

Issue: January 2022

Overview

This month's status report includes progress summaries on ATF lab activities, advanced reactor fuels activities, silicon-carbide cladding activities, and capability development activities.

The AFC Newsletter provides technical status information from the campaign and is used for a variety of reporting requirements such as monthly briefings to NE-4 and routine internal reporting within our laboratories. Additionally, the newsletter provides a convenient method for communication internal and external to the program. The information is focused on technical accomplishments backed by program execution-type (budget and milestone) information. The technical leads' role in organizing and integrating activities within the AFC Goals (Figure 1) and the impacts of these activities are highlighted each month.

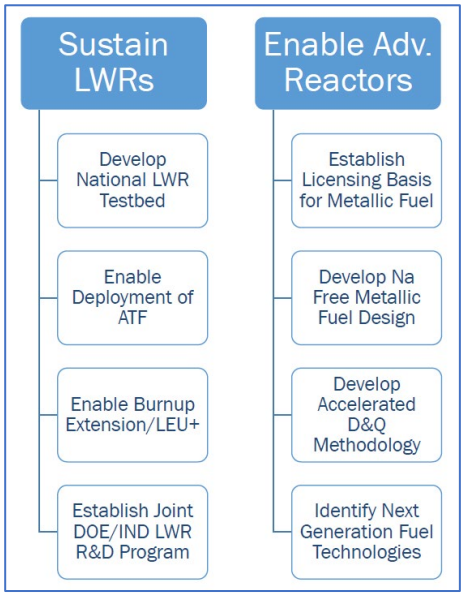


Figure 1. AFC Program Goals

This month, the AFC program made a small but important step toward nucleating and growing grass-roots ideas to develop methodologies that support accelerated fuel development and qualification. Back in November, I requested short proposals outlining small seed projects that leverage both existing ongoing work within the campaign and by our adjacent NE program partners (e.g., NEAMS, ASI, and NSUF). I was very pleased with the response which included many interesting ideas. In particular, I was happy to see broad engagement from the program's junior staff. I sincerely hope the campaign will be able use this approach to continue spurring innovation in the future. The projects moving forward this FY are listed below. Click on the title link to read a summary for each proposal. Also, be on the lookout for a combined annual summary report at the end of the year.

We hope you find January's newsletter informational.

-Dan

Advanced Reactor Fuels	
Title	**Lead PI**
Investigation of metallic fuel scalability for the purpose of reactor-agnostic metallic fuel qualification	Pavel Medvedev

Accelerated separate effects testing using novel and high throughput fabrication and characterization techniques	Jonathan Gigax
Setting the stage for accelerated fuel development and qualification with an engineering-drive real-world case study	Nicolas Woolstenhulme
Thermodynamically described separate effects testing to support accelerated fuel development and qualification	Walt Williams

Accident Tolerant Fuel	
Title	**Lead PI**
Evaluate the impact of burnup acceleration on UO2 microstructure evolution	Nathan Capps
Analyses to support accelerated burnup for LWRs	Mike Todosow
Demonstration of process similitude in accelerated ceramic fuel (UO2 and doped UO2) experiments	Alexander Duenas

ATF Lab Activities

ATF Fabrication Properties (Technical Lead: Josh White)

Primary program objectives for FY22 include:

- *Evaluate structure, properties, and performance of accident tolerant fuel systems to improve in-pile performance and performance predictions (ORNL, LANL)*
- *Develop fuel samples with simulated High Burnup Structure (HBS) to enable simplified property assessment (LANL)*
- *Assessment and development of advanced synthesis and fabrication methods applicable to both traditional oxide and high-density nontraditional fuel systems (LANL)*

[LANL] Equipment that combines field assisted sintering with sinter-forging capabilities was developed and is now in the final steps of assembly. In the past, it was demonstrated that flash sintering could produce dense nuclear fuel pellets in a few minutes, reducing the sintering period more than twenty times. Now, the flash sinter-forging equipment is expected to be able to produce net shaped ceramic oxides parts from their precursor powder in a few minutes. The structural frame has been completed and the software that controls its many sensors, furnace, and mechanical subsystems was written and it is now operational. Flash sinter-forging tests on ceramic oxides will soon take place to confirm the equipment ability to produce dense net shaped pellets. (R. Ingraci, E. Kardoulaki)

ATF Core Materials (Technical Lead: Andy Nelson)

Primary program objectives for FY22 include:

- *Investigate the impact of design and fabrication parameters on Zircaloy coating properties. Activities include production of surrogate test materials, development of novel testing techniques, and characterization of reference materials (LANL, ORNL)*
- *Investigation of the generic materials, application, and evaluation technologies development necessary for cross-cutting development of various SiC/SiC cladding concepts (ORNL, INL).*

[LANL] Machining is underway to prepare lab procured reference Cr-coated Zry-4 samples for ring pull, micro-cantilever and ion irradiation testing (B. Eftink)

[ORNL] Thermal diffusivity measurements were performed on Zircaloy-4 plates and Zircaloy-4 tubes up to 700℃ via Laser Flash Analysis (LFA) to investigate the sample geometry effects on thermal diffusivity. The consistent results proved the applicability of the LFA setup at Oak Ridge National Laboratory for investigating samples of curved geometries (such as Zircaloy tubes). LFA measurement was also performed on hydrogen-charged Zircaloy-4 tubes with the hydrogen concentration of 331 wppm to investigate the effects of Zr-hydride on thermal diffusivity. The hydrogen-charged Zircaloy-4 tubes show similar thermal diffusivity as bare Zircaloy-4 tube up to 200℃ but shows slightly lower diffusivity by 5% - 8% at higher temperature. The outcome of this preliminary work provides confidence that LFA performed on tube geometries is possible. The next steps in planned work include a broader investigation of hydrogen effects, as well as diffusivity measurements on a series of Cr coated Zircaloy tubes to understand the effects of the coatings on thermal transport (W. Zhong).

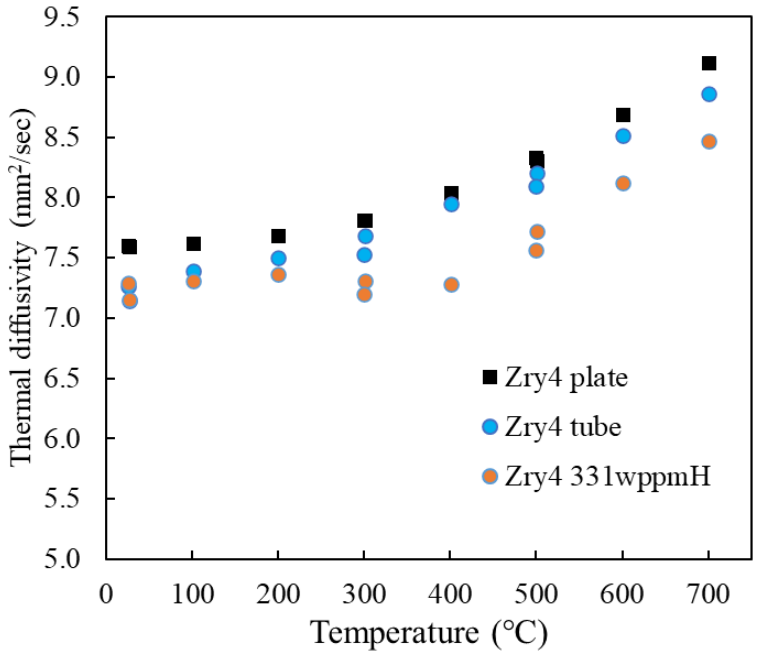


Figure 2. LFA results showing similar diffusivity values and same trends for both geometries. The results are in good agreement with the previously published results of Zircaloy plates measured by LFA.

[ORNL] An article titled "Mechanisms of stored energy release in silicon carbide materials neutron-irradiated at elevated temperatures", was published in *Materials & Design* 214 (2022) 110413.

Understanding the stored energy release behavior of SiC is crucial for the design of SiC-based fuel cladding for light water reactors because stored energy release affects response during accident conditions. Differential scanning calorimetry was used to evaluate the stored energy of monolithic SiC and SiC fiber–reinforced SiC matrix composite variants following neutron irradiation under light water reactor–relevant dose and temperature conditions. Stored energy release from irradiated SiC composites did not exceed the specific heat capacity, which is promising for accident tolerant fuel applications. The amount of irradiation induced volumetric swelling of the specimens was an indication of the total stored energy. Based on this observation, the energy release behavior was described by a swelling recovery model. (T. Koyanagi)

ATF Irradiation Testing (Technical Lead: Nicolas Woolstenhulme)

Primary program objectives for FY22 include:

- *Execution of ATF-2 integral scale irradiations in Advanced Test Reactor (ATR) pressurized water loop (INL)*
- *Separate effects irradiations of advanced cladding and core materials and fuels in the High Flux Isotope Reactor (HFIR) (ORNL)*

[INL] ATF-2C design, fabrication, and pin inspection activities continued to support experiment insertion in the Advanced Test Reactor 2A Loop during Cycle 171A in ~ May 2022. Technical checks of final design analyses are completing, and final design review planning began. ATF-2C hardware fabrication has taken top priority and all activities are on schedule. Fuel pellets are being grinded to size, and instrumented pin fabrication is being planned. ATF-2C will consist of four tiers. The bottom tier (Tier 1) will include SiC clad pins with surrogate Mo/W fuel pellets, Tier 2 will include Framatome fueled pins, Tier 3 will include SiC clad pins with surrogate Mo/W fuel pellets, and the top tier (Tier 4/5/6) will be Mitsubishi developed alloy clad UO2 pins, equipped with temperature and pressure sensors. (G. Hoggard)

[ORNL] HFIR irradiation vehicles containing axial tension and plane-strain cladding specimens fabricated by Framatome were disassembled at the ORNL 3025e Irradiated Materials Examination and Testing (IMET) hot cell facility (Figure 2). Each capsule contained four 12-mm long cladding specimens, coated or uncoated, machined for either tensile or plane-strain testing. This experiment was designed for a specimen target irradiation temperature between 300 and 400˚C. Following disassembly, visual inspection of the surface of the specimens was performed in cell to determine the coating integrity. The capsules' SiC thermometry will be analyzed in the Low Activation Materials Development Analysis (LAMDA) laboratory via dilatometry to confirm the experimental irradiation temperature. The post irradiation examination will further explore the coating performance under mechanical strain. (A. Le Coq, K. Linton)

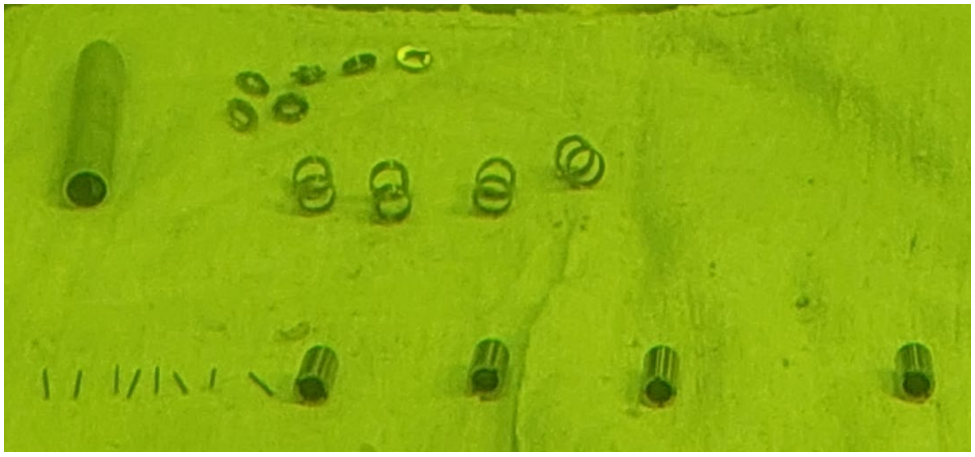


Figure 3. Axial tensile test cladding specimens being sorted and identified during capsule disassembly in the ORNL 3025e hot cell facility.

[ORNL] A report titled "HFIR SiC-SiC Composite Clad Tube Bowing Test: Pre-Irradiation Characterization" (ORNL/SPR-2021/2100) was submitted to Westinghouse Electric Company and General Atomics. This report describes the pre-irradiation characterization of the SiC-SiC composite clad tube bowing experiment that was irradiated in HFIR. This test will create data to help understand how SiC-SiC fuel cladding in light water reactors could undergo bowing because of the non-uniform fast neutron flux profiles. This experiment is combined with the SiC-SiC channel box experiment, which addresses similar data for control blade movements in boiling water reactors. The tube specimens were characterized by using traditional dimensional inspection and surface profilometry. These characterizations will provide detailed pre-irradiation data to evaluate the radiation-induced deformation. Fine engraving markers were inscribed along all outer surfaces of the specimen and mapped by using a digital microscope and a multidimensional stage. This approach allows marker spacings to be accurately measured and compared with similar measurements that will be made post-irradiation for local radiation-induced strain mapping. The experiment successfully completed two HFIR cycle irradiations, cycles 492 and 493, which finished on July 25, 2021. (J.W. Geringer, C. Petrie)

ATF Safety Testing (Technical Lead: Colby Jensen)

Primary program objectives for FY22 include:

- *Participation in the US lead NEA FIDES project on fuel performance under RIA conditions; High Burnup Experiments in Reactivity Initiated Accidents (HERA) irradiation tests (INL)*
- *Execution of out-of-pile fuel safety testing including LOCA-furnace testing and RIA simulation using the modified burst test apparatus (ORNL)*
- *Execute in-pile separate effects fuel safety testing in TREAT with focus on implementation of capsule-based experiments and advanced instrumentation (INL)*
- *Develop and demonstrate new experimental techniques to support fuel safety research including enhanced SATS capability to include fission gas release monitoring capability and development of stress relaxation testing procedure to generate empirical cladding*

creep data required for prediction of elastic, yield and burst properties of thin wall tubing under transient conditions (ORNL, INL)

[INL] First testing in a TREAT LOCA device prototype at Oregon State University were performed. Experiment data and post-test device evaluations are currently underway. A new test section was designed including improved instrumentation for the electrically heated critical heat flux measurement system in preparation for measurements that will provide unique data that will lead to improved RIA fuel performance predictions. Detailed evaluations of data from the TREAT SETH series have been extended to including water conditions in developing first-of-a-kind scaling analysis of transient fuel performance.

[INL] Assembly of the first HERA experiments on fresh fuels, tailored to mimic high burnup fuel conditions, is progressing. The first fueled rodlet has been built and leak checked. Additionally, some parts were received that did not pass INL QA standards, so new parts have been ordered. These parts must be received before capsule assembly can start.

ATF PIE (Technical Lead: Fabiola Cappia)

Primary program objectives for FY22 include:

- *Perform post irradiation examination of ATF-1 and ATF-2 experiments irradiated in the ATR. (INL)*
- *Prepare examination capabilities for full scale ATF lead test rods including enhancement of mechanical testing techniques and recovery of eddy current measurement systems (INL)*
- *Assess microstructural features in high burnup fuel pre- and post-simulated LOCA to improve interpretation of fragmentation behavior (ORNL)*

[INL] Visual examinations are the first non-destructive post-irradiation examination (PIE) performed on an experiment upon receipt in the hot cells. The visual examinations are currently limited to photo documentation through the hot cell window, which limits the resolution of the exams, hence the amount of information that can be extracted. To improve the quality of the visual exams, a new stage is being designed to allow execution of visual examinations using a through-wall digital periscope with enhanced resolution. The resolution of the pictures that can be achieved with the new stage will greatly enhance the capability to investigate cladding and/or coating status at an early stage of PIE (F. Cappia)

[INL] The revision of all ATF PIE planning and execution documents is complete. This satisfies completion of the INL FY22 Level 4 milestone titled, “Revise ATF PIE plan and PIE relevant document." (M4FT-22IN020205018) (F. Cappia)

Destructive examinations of Cr-coated and ARMOR coated ATF-2 rodlets are ongoing. Metallography, SEM, and EDS analyses are being performed on all the vendors’ sponsored ATF-2 cladding concepts. Cladding hydrogen content measurements have been completed on Cr-

coated cladding. Moreover, non-destructive examinations of the rods received last fall are being performed. Visuals examinations are complete and profilometry is being conducted.

ATF Fuel Performance Assessment (Technical Lead: Pavel Medvedev)

Primary program objectives for FY22 include:

- *Perform analysis of ATF technology as it relates to integral system performance and separate effects behaviors (BNL)*

[BNL] The modeling for a reference 17x17 Westinghouse fuel assembly is underway to explore options for "conventional" silver-indium-cadmium (AIC) control rods for configurations utilizing enriched fuel with greater than 5 w/o U235 to enable higher burnup. Focus will include the ability to control the higher excess reactivity due to the higher fuel enrichment while maintaining required control functions. (M. Todosow)

Advanced Reactor Fuels

AR Fabrication and Properties (POC: Randy Fielding)

Primary program objectives for FY22 include:

- *Monitor progress and support cross-cutting metal fuel fabrication technology development (INL)*

Nothing to report this month.

AR Core Materials (POC: Tarik Saleh)

Primary program objectives for FY22 include:

- *Fabrication of advanced fuel materials for irradiation testing of next generation fuel phases (LANL)*
- *Negotiate return of samples irradiated in BOR-60 and the Phenix reactor under collaboration with CEA and TerraPower (LANL)*

Nothing to report this month.

AR Irradiation Testing (Technical Lead: Nicolas Woolstenhulme)

Primary program objectives for FY22 include:

- *Develop accelerated fuel development and qualification methodologies (INL, ORNL, LANL)*
- *Execute FAST-1 accelerated Irradiation tests and PIE in the Advanced Test Reactor (ATR) (INL)*
- *Perform post-irradiation examination of legacy AFC experiments including IRT-1 samples (INL)*
- *Measure thermal conductivity of irradiated metal fuel samples (INL)*

[INL] The FAST-1 outboard-A (OA) capsules represent four of the 28 planned specimens in the FAST-1 group of tests. Unlike other FAST-1 capsules, the OA capsules are to be irradiated in cadmium-lined baskets like past AFC-series experiment to help separate spectral effects and create a tie to past data. These capsules were not completed in FY2021 due to fabrication difficulties with outer seal welds. Refabrication of these capsules was attempted again in FY2022 to prepare for insertion into ATR following its CIC outage. Work progress was significantly impacted by facility priority conflicts and resource shortfalls due to COVID, and the previous welding challenges have persisted in these recent attempts. At least one capsule, however, has been successfully produced thus far and the remaining three are underway. While more specimens and data are always better, all four capsules are not strictly needed to accomplish the objectives and irradiation will be performed in ATR 171A-1 for whatever number of acceptable capsules are produced in the coming month.

The other FAST-1 capsules began irradiation prior to CIC remain in ATR canal storage currently except for two which we shipped for low-burnup PIE. Irradiation preparations, including canal configurations and transfer to the vessel will begin at the conclusion of the outage. Preparations for cycle analyses and neutronic predictions is on-going.

PIE work in HFEF remains on-going. AFC-4C and AFC-3F capsules are in storage. Gamma scanning of JFCS AFC-IRT-1 C3 & C4 specimens was performed and the capsules are now in storage. Closeout reports are being finalized. Once the reports are complete, the JFCS support task will conclude. The previously mentioned two low burnup FAST-1 capsules were disassembled for PIE in late September 2021. NRAD and gamma scanning of these specimens was recently completed. (C. Murdock)

AR Safety Testing (Technical Lead: Colby Jensen)

Primary program objectives for FY22 include:

- *Execute joint JAEA/INL ARES fuel safety research experiments on commissioning TREAT sodium capsule testing n fresh metallic fuels (THOR-c) and transient testing historically irradiated metal (THOR-M) and MOX (THOR-MOXTOP) fuels (INL)*

[INL] As part of work for the Advanced Fuels Campaign, the transient heat sink overpower response (THOR) test rig is an irradiation capsule designed to simulate heat transfer approaching prototypic conditions. A modified Experimental Breeder Reactor-II Mark-IV fuel pin was needed for the THOR-C-2 (fresh metallic fuel) test. The pin was drilled, pressurized to 500 psi with helium, and rewelded. Next, researchers visually examined the fuel pin, completed a helium leak test, and radiographed the assembly for weld inspection, sodium level and fuel slug location. This work was completed in the Fuels and

Figure 4. Fuel pin drilled, pressurized and rewelded for THOR-C-2

Applied Science Building. The modified fuel pin is being loaded into the THOR capsule and is on schedule for irradiation at TREAT in February.

Startup and normalization of the Hodoscope at TREAT was completed to prepare for the THOR-C-2 transient. Facilities are set up and prepared to receive CINDI and THOR-C-1 experiments for gamma counting.

The THOR-M experiment (irradiated EBR-II metallic fuel) final design review kicked off in December and is scheduled to close in early February. THOR-M execution will follow completion of the THOR-C-2 commissioning test.

The HFEF THOR team has made better than expected progress on the design and preparing HFEF to handle a THOR capsule for both assembly and disassembly of the test. Component fabrication will start in the coming months. (T. Smuin)

Pre-characterization of the JAEA MOX pins at HFEF in preparation for future THOR-MOXTOP tests is on-going and some nondestructive results have been shared with JAEA. JAEA is pleased with the characterization results. Currently, INL, JAEA, CEA, and KAERI are discussing potential opportunities for future transient testing of fast reactor fuels. (T. Smuin)

Capability Development

I-Loop Design and Installation (POC: Nate Oldham)

[INL] Work package is on hold. (L. Strain)

TREAT LOCA Testing Infrastructure (POC: Nicolas Woolstenhulme)

Primary program objectives for FY22 include:

- *Design and installation of i-loop system components (INL)*
- *Development and commissioning of TREAT LOCA-capsule (INL)*
- *Development and commissioning of remote refabrication and instrumentation capability (INL)*

[INL] Final preparations are underway to complete the LOCA blowdown capsule design review (known as the Transient Water Irradiation System for TREAT or TWIST). A final design and safety analysis plan was recently completed, and all the engineering documents are under preparation for a final design kickoff in spring 2022, far in advance of program milestones (N. Woolstenhulme).

Refabrication and Instrumentation Capability (POC: Jason Schulthess)

[INL] The planning package was initiated for installation of the Rodlet Endcap Welding System (REWS) into the AFF facility for testing. Drilling demonstration on dry fuel pellets continued. A

journal article is being drafted to document developed approaches to refabrication and reinstrumentation. An evaluation of using cryo systems like those used at Halden in HFEF was initiated. (M. Cole)

FOA Support

Framatome (Kiran Nimishakavi)

Nothing to report this month.

General Electric (Raul Rebak)

GE/GNF continues the characterization of IronClad for light water reactors accident tolerant cladding, higher burn up and higher enrichment. However, the current focus of GE/GNF is to develop a robust coating for Zircaloy-2 that would survive commercial BWR environments. There are two lines of coating research, one is called ARMOR 1.5 (which is a modification of the architecture and/or the composition of the original ARMOR 1.0) and the other is the ARMOR 2.0 (which is not necessarily based on ARMOR 1.0).

GE submitted to DOE-ID on 17Jan2022 the Application for the Continuation of Project DE-NE0009047 for Budget Period 2.

Two journal papers were published in January 2022:

(1) Y. S. Garud, A. K. Hoffman and R. B. Rebak "Hydrogen Isotopes Permeation in Clean or Unoxidized FeCrAl: A Review" in Metallurgical and Materials Transactions A, https://doi.org/10.1007/s11661-021-06535-8

(2) S. Huang, E. Dolley, K. An, D. Yu, C. Crawford, M. A. Othon, I. Spinelli, M. P. Knussman, and R. B. Rebak, "Microstructure and tensile behavior of powder metallurgy FeCrAl accident tolerant fuel cladding," Journal of Nuclear Materials 560 (2022) 153524 https://doi.org/10.1016/j.jnucmat.2022.153524

Westinghouse Electric Company (Ed Lahoda)

Westinghouse met with utilities to align dates and requirements for future lead test assemblies (LTAs). An agreement with Southern Nuclear on the higher enrichment, higher burnup (HEHB) LTA schedule has been established. Defined the objectives and testing for the CRAFT program with EPRI to support increased fuel burnup limits for HEHB fuel.

Internally, Westinghouse is completing the upgrade to design and analysis codes to support the 75 MWd/kgU designed fuel. Manufacturing sites are being readied to manufacture ATF and HEHB LTAs in 2022 and 2023.

Silicon Carbide Cladding (FOA)

General Atomics (Ryan Hon)

The overall goal of this program is to design and fabricate a set of SiGA® Silicon Carbide (SiC) cladding components that will enable an in-depth, quantitative assessment of the effects of irradiation on unfueled SiC-SiC composite cladding in a commercial nuclear reactor. Specific program objectives in 2022 include:

- Formalizing the design basis
- Advancing the safety/licensing analysis
- Manufacturing of SiC-SiC specimens
- Advancing development gaps, specifically regarding joining and irradiation induced bowing.

GA-EMS has fabricated and mechanically tested reduced diameter SiC-SiC cladding that is intended to replicate fundamental cladding properties of those developed for its Accident Tolerant Fuel (ATF) SiGA® cladding design as closely as possible. Commercial irradiation specimens will be encapsulated and located in the guide tube location, necessitating reduced diameters. Mechanical test data of the reduced diameter cladding shows performance far exceeding calculated in reactor stress/strain requirements. Additional work included delivery of the commercial irradiation test plan document which defines requirements, specifications, sample sizes and geometries, and other key information about the pathway to encapsulation and irradiation of SiC-SiC specimens.

Documents

Articles

The Need For a Metallic Nuclear Fuels Qualification Plan, Nuclear News

Publications

- T. Huynh, A. Mehta, K. Graydon, J. Woo, S. Park, H. Hyer, L. Zhou, D. D. Imholte, N. E. Woolstenhulme, D. M. Wachs, Y. Sohn. 2022. "Microstructural Development in Inconel 718 Nickel-Based Superalloy Additively Manufactured by Laser Powder Bed Fusion." METALLOGRAPHY MICROSTRUCTURE AND ANALYSIS. https://doi.org/10.1007/s13632-021-00811-0
- R. Hernandez, R. J. Armstrong, S. B. Seo, C. P. Folsom, C. B. Jensen, N. R. Brown. 2022. "Sensitivity analysis of in-pile CHF experiments in the TREAT facility: Characterization of impacts of fuel system thermal properties." ANNALS OF NUCLEAR ENERGY. Vol. 165. https://doi.org/10.1016/j.anucene.2021.108645

- F. G. Di Lemma, T. Trowbridge, L. Capriotti, J. M. Harp, M. T. Benson, R. D. Mariani. 2022. "Postirradiation characterization of palladium as an additive for fuel cladding chemical interaction mitigation in metallic fuel." JOURNAL OF NUCLEAR MATERIALS. Vol. 558. https://doi.org/10.1016/j.jnucmat.2021.153403
- FY21 AFC Accomplishments Report
- AFC Newsletter – December Issue

Milestones

No milestones reported for January.

AFC SharePoint Site

Advanced Fuels Campaign SharePoint site

Look Ahead

March

- (ORNL) Initiate destructive examination of WEC lead test rods
- NRC Regulatory Information Conference (RIC), March 8-10 (virtual)
- Joint EPRI-DOE ATF/HBU/ CRAFT Workshop, March 28-April 1 (Charlotte, NC)
- (INL) Complete ARES project CRADA deliverable for pre-transient characterization of MOX pins

April

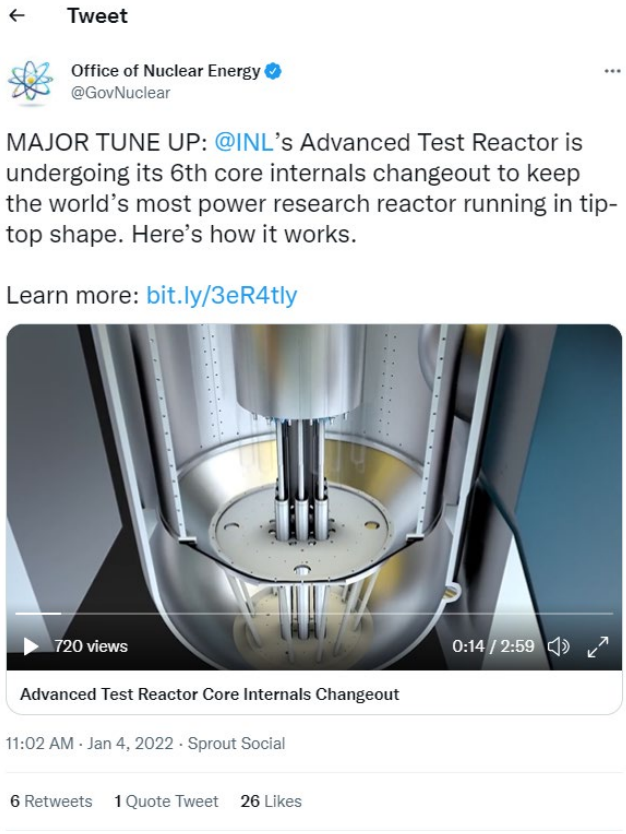
- AFC Leads Planning Meeting, April 6-7 (Idaho Falls, ID)
- FIDES Technical Advisory Committee and Governing Board Meetings, April 25-29 (Paris, France)
- (INL) Commence FIDES HERA JEEP experiment calibration tests in TREAT

May

- Materials Research Society (MRS) Annual Meeting. May 9-16 (Honolulu, HI)

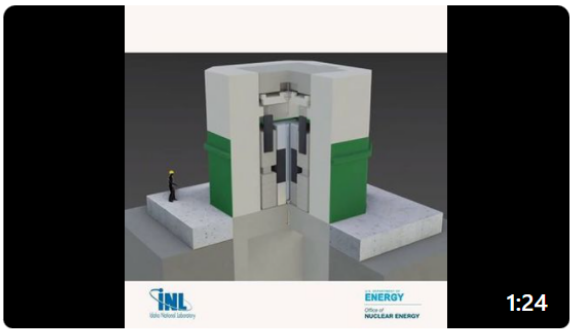
Social Media

Twitter



https://twitter.com/GovNuclear/status/1478441783029862400

Facebook



Accelerating Nuclear Fuel Testing at Idaho National Laboratory
Idaho National Laboratory
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