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Advanced Fuels

Frank Goldner, Ken Kellar
Fuel Cycle R&D

DOE-NEUP FY2022 Webinar
August 11, 2021

Advanced Fuels Campaign: Structure and Mission

- Mission:
  1) Support the development/qualification of Accident Tolerant and High Burnup Fuel (LWR) technologies
  2) Perform R&D on fuel technologies for future advanced reactors

AFC Advanced Fuels Campaign

Accident Tolerant Fuels

LWR fuels with improved performance to high burnup and enhanced accident tolerance

Advanced Reactor Fuels

Advanced reactor fuels with enhanced resource utilization for both once-through and recycle

Capability Development to Support Fuel Development and Qualification

Advanced characterization and PIE techniques
Advanced in-pile instrumentation
Separate effects testing for model development/validation
Steady-state and transient irradiation testing infrastructure

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

Fuels Product Line

Multi-scale, multi-physics, fuel performance modeling and simulation

FY21 NEUP Awards

FY 2021 Nuclear Energy University Program R&D Awards		
Title	**PI Last Name**	**Lead University**
Fuel Cycle Research and Development		
FC-2.1: Fuel-to-Coolant Thermomechanical Transport Behaviors Under Transient Conditions		
Fragmentation and Thermal Energy Transport of Cr-doped Fuels under Transient Conditions	Ban	University of Pittsburgh
Fuel-to-Coolant Thermomechanical Behaviors Under Transient Conditions	Brown	University of Tennessee at Knoxville
Experimental investigation and development of models and correlations for cladding-to-coolant heat transfer phenomena in transient conditions in support of TREAT and the LWR fleet.	Bucci	Massachusetts Institute of Technology
High-fidelity modeling of fuel-to-coolant thermomechanical transport behaviors under transient conditions	Watson	University of Florida
Post-DNB Thermo-mechanical Behavior of Near-term ATF Designs in Simulated Transient Condition	Yeom	University of Wisconsin-Madison
Estimation of low temperature cladding failures during an RIA transient	Motta	Pennsylvania State University
FC-2.2: High Burnup LWR Fuel Rod Behavior Under Normal and Transient Conditions		
Multiscale Modeling and Experiments for Investigating High Burnup LWR Fuel Rod Behavior Under Normal and Transient Conditions	Ahmed	Texas A&M University
Safety Implications of High Burnup Fuel for a 2-Year PWR Fuel Cycle	Brown	University of Tennessee at Knoxville
Characterizing Fuel Response and Quantifying Coolable Geometry of High-Burnup Fuel	Marcum	Oregon State University
Modeling high-burnup LWR fuel behavior under normal operating and transient conditions	Pastore	University of Tennessee at Knoxville

Proposed NEUP Scopes for FY22 Call

- IRP-FC-2: ATF Cladding Tests in the MITR Pressurized Water Loop
  - Federal POC: Frank Goldner (NE-4)
  - Technical POC: Nicolas Woostenhulme (INL)
- NEUP-FC-2.1: Next Generation LWR Fuels for SMR Applications
  - Federal POC: Frank Goldner (NE-4)
  - Technical POC: Nicolas Woolstenhulme (INL)
- NEUP-FC-2.2: Accident Tolerant Control Rods
  - Federal POC: Frank Goldner (NE-4)
  - Technical POC: Michael Todosow (BNL)
- NEUP-FC-2.3: Accelerated Fuel Development Methodology
  - Federal POC: Ken Kellar (NE-4)
  - Technical POC: Dan Wachs (INL)
- NEUP-FC-5: Accelerated Fast Reactor Metal Fuel Cladding Material Development
  - Federal POC: Ken Kellar (NE-4)
  - Technical POC: Stu Malloy (LANL)

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IRP-FC-2: ATF Cladding Tests in the MITR Pressurized Water Loop

NEUP Webinar
Aug 11, 2021
Nicolas.Woolstenhulme@inl.gov

IRP-FC-2: ATF Cladding Tests in the MITR Pressurized Water Loop

- Federal POC – Frank Goldner & Technical POC – Nicolas Woolstenhulme
  - Eligible to Lead: Universities Only, Up to 4 years and $5,000,000
- Proposals sought to study the behavior of Accident Tolerant Fuel (ATF) claddings in a prototypic LWR irradiation coolant loop environment
  - Coated zirconium alloys, FeCrAl alloys, and SiC/SiC composites
- Study phenomena influenced by reactor environment (corrosion/recession, hydrogen pickup, cladding creep, effects of coating defects, etc.)
  - Prototypic thermal, hydraulic, chemical, and nuclear environments provided via Massachusetts Institute of Technology Reactor (MITR)
  - Can be paired with out-of-pile, simulation, and analytic studies to elucidate in-reactor effects
  - Call is nominally for ATF cladding, but proposals could consider overlapping research on accident tolerant fuel assembly materials (e.g. channel boxes, control rods)
- Partnerships encouraged (ATF fuel vendors, utilities, regulator, national labs)
- This call is <u>not</u> intended to directly study fuel or fuel-cladding interaction
  - Fissile material not permitted in MITR water loop per NRC license
  - Note that other forms of nuclear heat can be used to simulate effects (e.g. gamma heated pellets to create cladding temperature gradients)

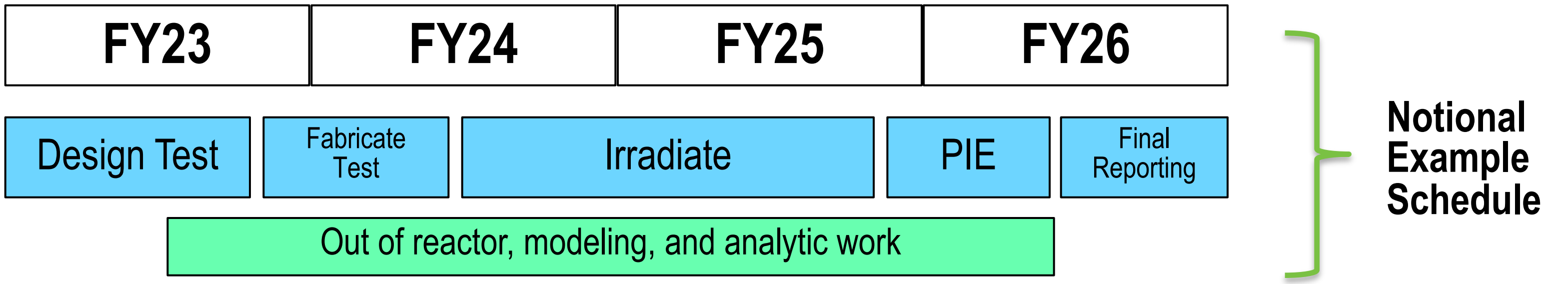
IRP-FC-2: ATF Cladding Tests in the MITR Pressurized Water Loop (2)

- MITR water loop capabilities
  - Can operate in either pressurize or boiling water reactor chemistry and thermal hydraulic conditions
  - Online instrumentation can be accommodated
  - Test holders design can be adapted, but generally fits 2 to 4 cladding tubes in cross section across ~0.5m long active core
  - Other samples can be installed in the same loop just above reactor and out of reactor to separate chemistry, radiolysis, and irradiation effects
  - Neutron spectra representative, and slightly more thermalized, than typical LWR
    - 2.6 and 5.0 E13 n/cm^2 thermal and fast (>1 MeV), respectively
    - ~250 full power days per calendar year
- IRP team will have access to:
  - MITR pressurized water loop for irradiation time
  - Irradiation test design and engineering support staff
  - MIT Post Irradiation Exam (PIE) facilities

Figure A3. Photographs of a sample module during assembly and the fully assembled sample stack before insertion into the autoclave.

Figure A4. The ACI top head and coolant lines after facility installation in the MITR and during installation of the thermal insulation and shielding.

IRP-FC-2: ATF Cladding Tests in the MITR Pressurized Water Loop (3)



- Irradiation duration and PIE limited by project duration
  - High fluence phenomena not likely achievable
  - Data outcomes via online instrumentation and limited PIE should be emphasized
- A few more brass tacks
  - Proposal should include funding to support irradiation charges, loop operation, and loop modifications specifically needed to permit your experiment.
  - Key staff MITR staff to abstain from proposal teams to help field questions about viability of your proposal
  - Contact technical POC to coordinate discussions
  - Expected outcomes include impactful publications and industry relevance in enabling ATF utilization

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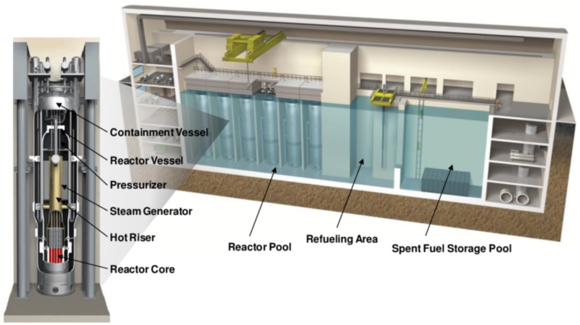
NEUP-FC-2.1: Next Generation LWR Fuels for SMR Applications

NEUP Webinar
Aug 11, 2021

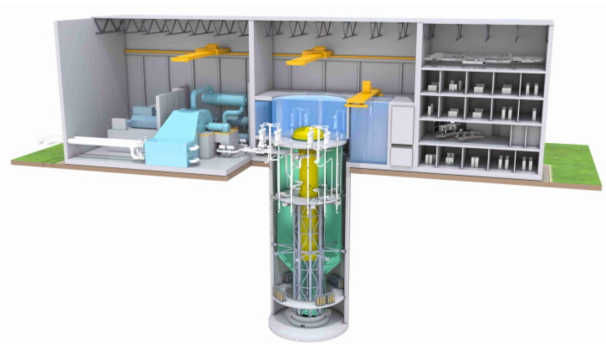
Nicolas.Woolstenhulme@inl.gov

NEUP-FC-2.1: Next Generation LWR Fuels for SMR Applications

- Federal POC – Frank Goldner & Technical POC – Nicolas Woolstenhulme
  - Eligible to Lead: Universities Only, Up to 3 years and $800,000
- Proposals sought to study next generation nuclear fuel designs for application in Small Modular Reactors (SMR)
  - ATF technologies: Coated zirconium alloys, FeCrAl alloys, and SiC/SiC composites
  - Fuel geometry and thermal hydraulic modifications/optimizations for SMR application
- Partnerships encouraged (Commercial SMR developers, fuel vendors, utilities, regulator, national labs)
- This call is for fuel design, not reactor design
  - Study of fuel and reactor system coupled response expected, but design of new SMR plants not anticipated
- This call is for water-cooled type SMRs only (NuScale, GEH BWRX-300)
  - Although interesting, this call is not for fuels expressly intended for liquid metal, inert gas, heat pipe, or molten salt type plants



NuScale Plant Rendering



GEH BWRX-300 Plant Rendering

NEUP-FC-2.1: Next Generation LWR Fuels for SMR Applications (2)

- Most mature SMR designs currently propose to use “baseline” fuel (i.e. UO_2 pellets in zirconium alloy cladding tubes) with only minor adaptations in assembly design
  - Why choose a fuel design that was optimized for much larger, actively cooled, type of reactor?
  - First-to-market strategy facilitated using currently qualified fuel performance data and existing supply chain
- But once SMR’s are on the grid, the value potential for fuel designs optimized for SMR retrofit may be enormous
  - Power uprates via fuel geometries optimized for natural circulation thermal hydraulic behavior in passively cooled plant designs (both normal operation and off-normal conditions)
  - Increased fuel utilization and/or plant capacity factor from improved fuel behavior and/or increased enrichments via ongoing ATF technology development
- Anticipated research areas
  - Fuel design option system trade study, plant response, and fuel cycle economic system modeling
  - Performance modeling of candidate fuel systems in SMR plants (e.g. neutronic, fuel performance, heat transfer)
  - Out-of-pile testing to support fuel design candidate studies (e.g. thermal hydraulic testing)

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NEUP-FC-2.2: Accident Tolerant Control Rods

NEUP Webinar
Aug 11, 2021
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NEUP-FC-2.2: Studies on Accident Tolerant Control Rods

Federal Manager: Frank Goldner

Technical POC: Michael Todosow (BNL)

- **Current Program Focus:**
  - In response to the accident at the Fukushima Daichi nuclear power plant, a significant effort was initiated by the Department of Energy, Office of Nuclear Energy (DOE-NE) in the Advanced Fuels Campaign (AFC) to develop fuels with enhanced accident tolerance, aka "Accident Tolerant Fuels (ATFs),"
  - Experiments and analyses have been underway to identify, characterize, and address the impact of candidate ATF fuel and/or cladding concepts on reactor performance and safety characteristics, AOOs, DBAs, and BDBA
  - Concepts proposed by national laboratories, industry, etc. have been considered
  - A current focus is on concepts identified, and being pursued by three industry teams in response to a Funding Opportunity Announcement (FOA)
  - The FOA concepts are currently irradiating Lead Rods (LRs) in commercial LWRs

- **The Advanced Fuels Campaign is currently investigating fuels and cladding with enhanced accident tolerance (aka Accident Tolerant Fuels) for implementation in commercial light-water reactors (LWRs). However, retention of "functionality" of other core components (e.g., control rods) is also critical to successfully surviving/limiting the consequences of Beyond Design Basis Accidents (BDBAs), as well as benefitting normal operation, Anticipated Operational Occurrences (AOOs) and Design Basis Accidents (DBAs).**

NEUP-FC-2.2: Studies on Accident Tolerant Control Rods (2)

- **Proposals are sought to assess the neutronic, and thermo-mechanical performance attributes of potential advanced materials and/or designs for BWR and PWR control rods that retain/enhance the poisoning effects/requirements (worth – individual and bank, etc.) while maintaining structural integrity/ functionality (e.g., ability to insert/ withdraw) during normal operation and accident conditions (temperatures, cooling, etc.).**

- **Also, materials and associated studies may be considered that address the retention of the structural integrity/geometry of the core which depends on the ability of components such as guide tubes, grid spacers, core support plate, etc. to retain "functionality" during normal operation and accident conditions.**

- **Consultation with existing DOE-NE ATF related programs in this area is encouraged/desirable.**

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NEUP-FC-2.3: Accelerated Fuel Development Methodology

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NEUP-FC-2.3: Accelerated Fuel Development Methodology

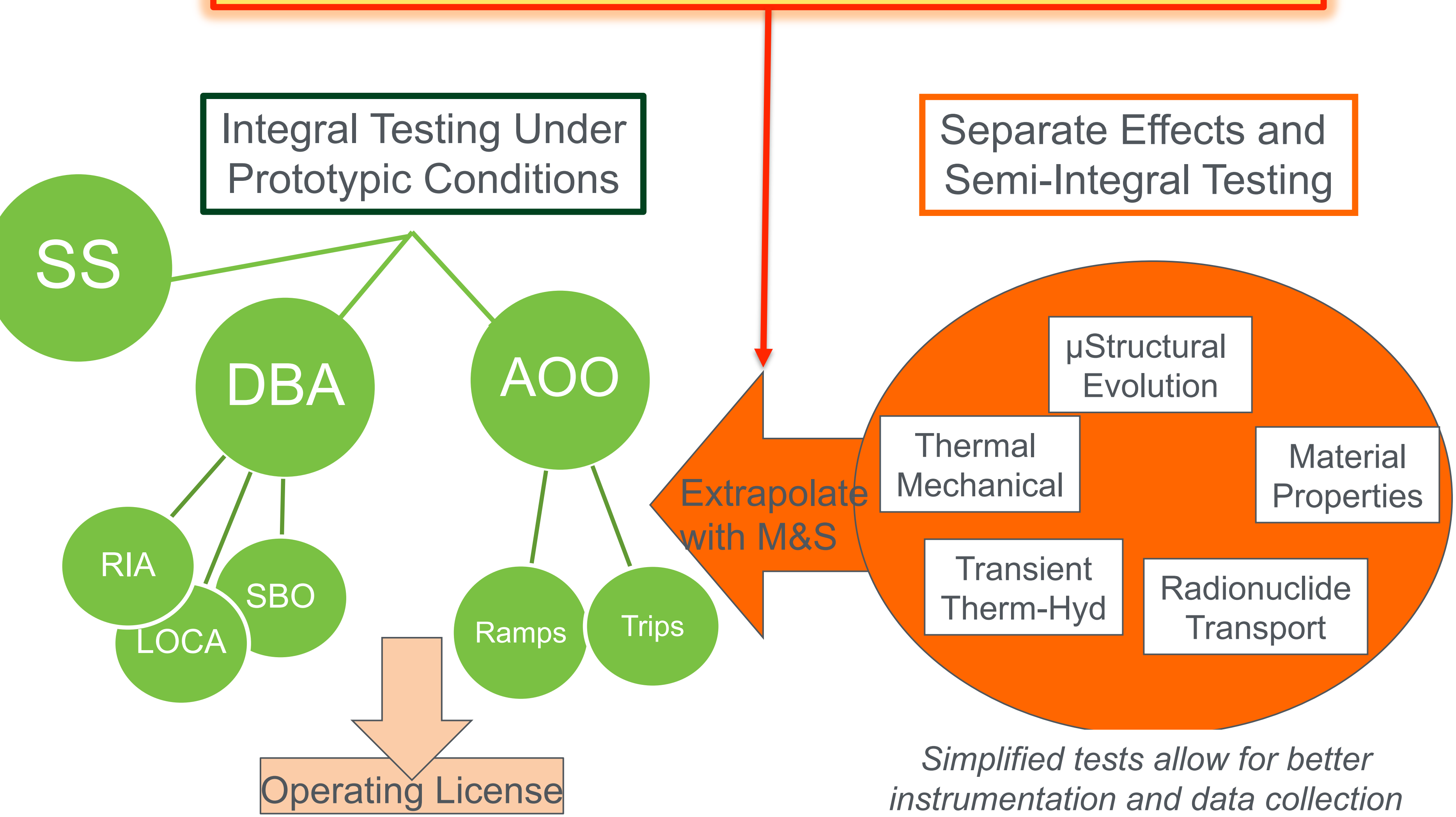
Federal Manager: Ken Kellar

Technical POC: Dan Wachs, INL

- The development and qualification process used for nuclear fuels and materials must be accelerated to drive significant innovation in advanced reactor technology.
  - This requires the quantitative integration of disparate data streams collected throughout the fuel development lifecycle; from discovery to deployment.
  - Historically, data collected during development was used ‘intuitively’ to mature a design to the next TRL and testing becomes increasingly more representative of service conditions at each level.
  - Ultimately, new fuel technology is ‘qualified’ based on the data collected from the most sophisticated, expensive, and time-consuming tests conducted under fully prototypic conditions at the end of this process.
- Accelerating innovation in nuclear fuel technology can be realized by:
  - Completing testing tasks more quickly and reliably (implementation of modern testbeds, integration of mod/sim with experiments, accelerated testing methods, …)
  - Expanding data streams and making better use of the collected data (reduce number of iterations during development, better extrapolation of existing data to new operating conditions, more complete development and validation of mod/sim tools, …)
- AFC is interested in adaptation of ‘Process Scaling’ methodologies to guide this approach

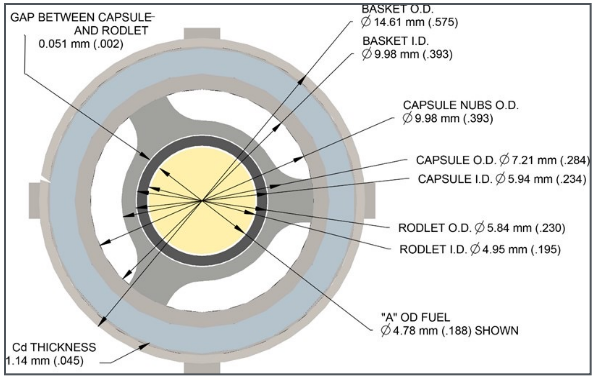
Modern Fuel Testing Strategy

Challenge: How to demonstrate that experiments are representative of the prototypic conditions and, thus, physical processes evaluated (experimentally and with mod/sim) can be reliably extrapolated?



NEUP-FC-2.3: Accelerated Fuel Development Methodologies

- Accelerated Testing
  - Reduced scale testing has long been used to support nuclear reactor systems technology development and licensing (reduced scale = lower cost).
  - Process time scales are also typically accelerated at reduced scale. Thus, slow processes (like irradiation testing) can be accelerated in time.
- Separate Effects & Semi-Integral Testing
  - Fully prototypic tests are extremely difficult to execute; very expensive, aren't readily suitable for real-time monitoring, not realistic for evaluation of design or safety limits, … thus it is very difficult to extrapolate results
  - Prototypic behavior can be predicted by measuring material properties and performing separate effects tests to model individual physical phenomena and simulate integrated system response.
- **Demonstrating Dynamic Process Similarity**
  - **In both cases, the applicability of the specific testing approach to the prototypic conditions of interest requires demonstrating the extent of process similarity between the two.**
  - **Common methodologies developed historically include Hierarchical Two-Tiered Scaling (H2TS), Fractional Scaling Analysis (FSA), and Dynamic System Scaling (DSS)**



Example: In the ATR "FAST" test, the fuel pin geometry was reduced by 1/3 while retaining the prototypic LHGR such that the temperature distribution remains prototypic while accelerating burnup accumulation by a factor of 9 (=3^2). However, manufacturing limitations (i.e. minimum cladding thickness or fuel-clad gap) or size of microstructural features (i.e. grain size) may not scale perfectly. How does that distort the experimental results?

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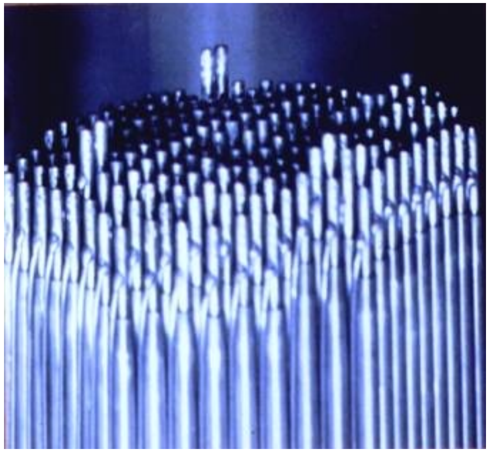
NEUP-FC-5: Accelerated Fast Reactor Metal Fuel Cladding Material Development-

DOE-NEUP FY2022 Webinar

August 11, 2021

NEUP-FC-5: Accelerated Fast Reactor Metal Fuel Cladding Material Development- Federal POC-Ken Kellar & Technical POC- Stu Maloy



Courtesy of F. Garner

Proposal Areas:

- Enhancement of reference cladding designs
- Development of new cladding concepts

Design Conditions

- Very high dose (up to 300-400 dpa)
- Irradiation temperature (up to 700ºC or beyond).
- Metal Cladding for sodium bonded metal fuel

Possible Cladding Examples

- Enhancement of ferritic martensitic steels such as HT9 or T91
- Improvement of Oxide Dispersion Strengthened (ODS) (e.g. 14YWT).
- Novel New Concepts

Areas to address in your proposals

- Critical aspects of cladding performance that prevent the particular concept from advancing to a higher technical readiness level.
- Investigation of irradiation performance, fabrication technology, or composite concepts (e.g. coatings or liners)
- Recognize the gaps to be overcome, and prove feasibility in comparison to existing cladding concepts,
- Strong knowledge of the present program plan for fast reactor cladding development is recommended.

Supplemental Information

Points of Contact

- Frank Goldner, DOE-NE (frank.goldner@nuclear.energy.gov)
- Ken Kellar, DOE-NE (kenneth.kellar@nuclear.energy.gov)
- Nicolas Woolsenthulme, INL (nicolas.woolstenhulme@inl.gov)
- Michael Todowsow, BNL (todosowm@bnl.gov)
- Dan Wachs, INL (daniel.wachs@inl.gov)
- Simon Pimblott, INL (simon.pimblott@inl.gov)
- Stu Maloy, LANL (maloy@lanl.gov)

Useful references

- FY20 Advanced Fuels Campaign Accomplishments Report
  https://nuclearfuel.inl.gov/afp/2020%20Accomplishments%20Report/inc/pdf/20-50497-R4_AFC_2020_Accomplishments_WEB.pdf
- FY19 Advanced Fuels Campaign Accomplishment Report
  https://nuclearfuel.inl.gov/afp/AFC%20Accomplishments%20Reports/AFC%202019%20Accomplishments%20Report.pdf
- FY18 Advanced Fuels Campaign Accomplishments
  https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_8757.pdf

Thank You

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