U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Fuel Cycle Research and Development

U.S. DOE Development of Accident Tolerant Fuels

Shannon Bragg-Sitton

Deputy National Technical Director

DOE Advanced Fuels Campaign

April 14, 2016

OECD/NEA Expert Group on ATF for LWRs

Paris, France

Reduced from INL/MIS-14-33610

AFC High Level Technical Objectives (5-year)

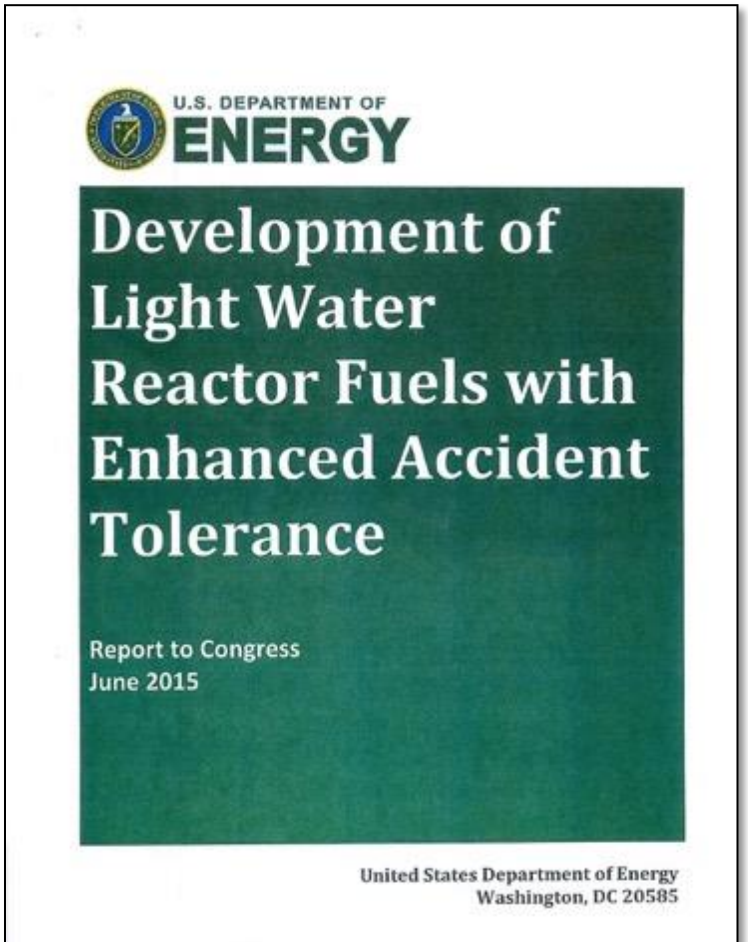
- Identify and select advanced LWR fuel concepts for development towards lead test rod testing by 2022.

- Complete the conceptual design for the baseline advanced reactor fuel technologies with emphasis on the fundamental understanding of the fuel fabrication and performance characteristics for recycle fuels.

- Achieve state-of-the art infrastructure that can be used to perform fuel research and development from a “science-based” approach accelerating further development of selected concepts.

- Integrate with the development of the predictive, multi-scale, multi-physics fuel performance code.

DOE ATF Report to Congress – June 2015


U.S. DEPARTMENT OF ENERGY

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
June 2015

United States Department of Energy
Washington, DC 20585

- ***Defines the general attributes of ATF***
- ***Lays out an aggressive 10-year schedule starting in 2012.***
- ***Establishes 2022 insertion of a LFA or LFR in an operating commercial LWR as the goal.***

https://nuclearfuel.inl.gov

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

AFC is supported by a large part of the U.S. nuclear complex

National Laboratories

- INL Idaho National Laboratory
- Oak Ridge National Laboratory
- Brookhaven National Laboratory
- Argonne National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory

Universities

- UF University of Florida — The Foundation for The Gator Nation
- University of Illinois — Urbana-Champaign • Chicago • Springfield
- UT The University of Tennessee — Knoxville, Chattanooga, Martin, Tullahoma, Memphis
- ATM Texas A&M University
- Georgia Tech
- MIT
- W
- M

Nuclear Industry

- GE imagination at work
- Westinghouse
- AREVA
- Duke Energy
- TVA
- Southern Company
- EPRI Electric Power Research Institute

AFC Advanced Fuels Campaign

Fuel System Material Areas

Cladding Systems

- Zircaloy-based
  - *coatings*
- Advanced Metallic
  - *FeCrAl*
  - *Mo-core composite*
- Ceramic
  - *SiC/SiC composites*

Fuel Systems

- Advanced/Enhanced UO_2
  - *Improve μ-structure*
  - *UO_2-based composites*
- High fissile density
  - *U_3Si_2*
  - *UN-U_3Si_2*
  - *UN-U_3Si_5*
  - *U-Mo coextruded w/ cladding*
- Coated Particle-based
  - *Fully Ceramic Matrix (FCM)*

Design, Fabrication and Performance RD&D

Modeling, Simulation and Assessment of Accident Tolerant Fuel

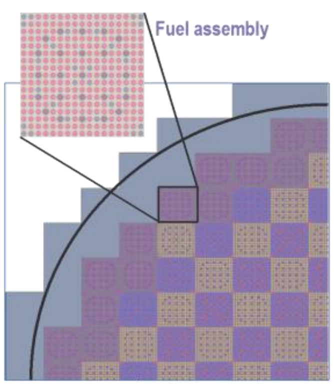
U.S. DEPARTMENT OF ENERGY

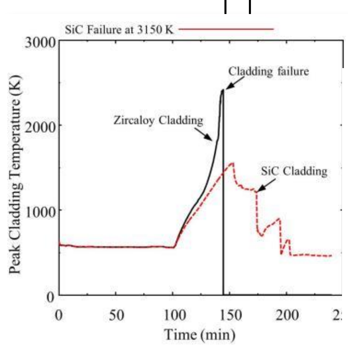
Nuclear Energy

Steady State Performance

Neutronics and thermal hydraulics code sets are adequate to handle ATF. Current focus on:

- FeCrAl, SiC cladding
- FCM, nitride, silicide fuels

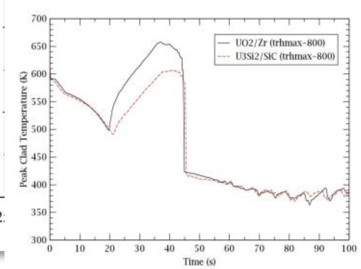




Off-Normal (DBA and BDBA)

Existing Codes (MELCOR, MAAP, TRACE, RELAP)

- Specific to UO_2-Zr
- Modified to provide insight into performance trends
- Inherent assumptions in the physics may not be applicable to ATF



TRACE – LBLOCA

Advanced Modeling and Simulation

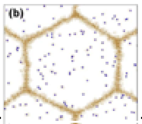
Basic fuel performance and properties for inclusion in existing Industry Proprietary Codes. These codes will be used by Industry to apply for exemption for a LTA insertion in 2022. There are also activities funded by the DOE-NEUP program in the university community.

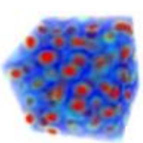
ATF High Impact Problem – NEAMS funded activity to develop a MBM implementation of U-Si and FeCrAl.

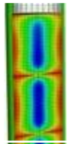
ATF IRP – MIT project that will utilize MBM and MIT tools to analyze ATF up to the point of fuel failure. Effectively estimating the “coping time” provided by ATF technology.

TREAT Analysis – NEAMS funded activity to develop a full core model for TREAT that provides analysis of the TREAT core coupled with transient fuel experiments.

LWRS RISMC Pathway analysis of reactor accident scenarios with ATF



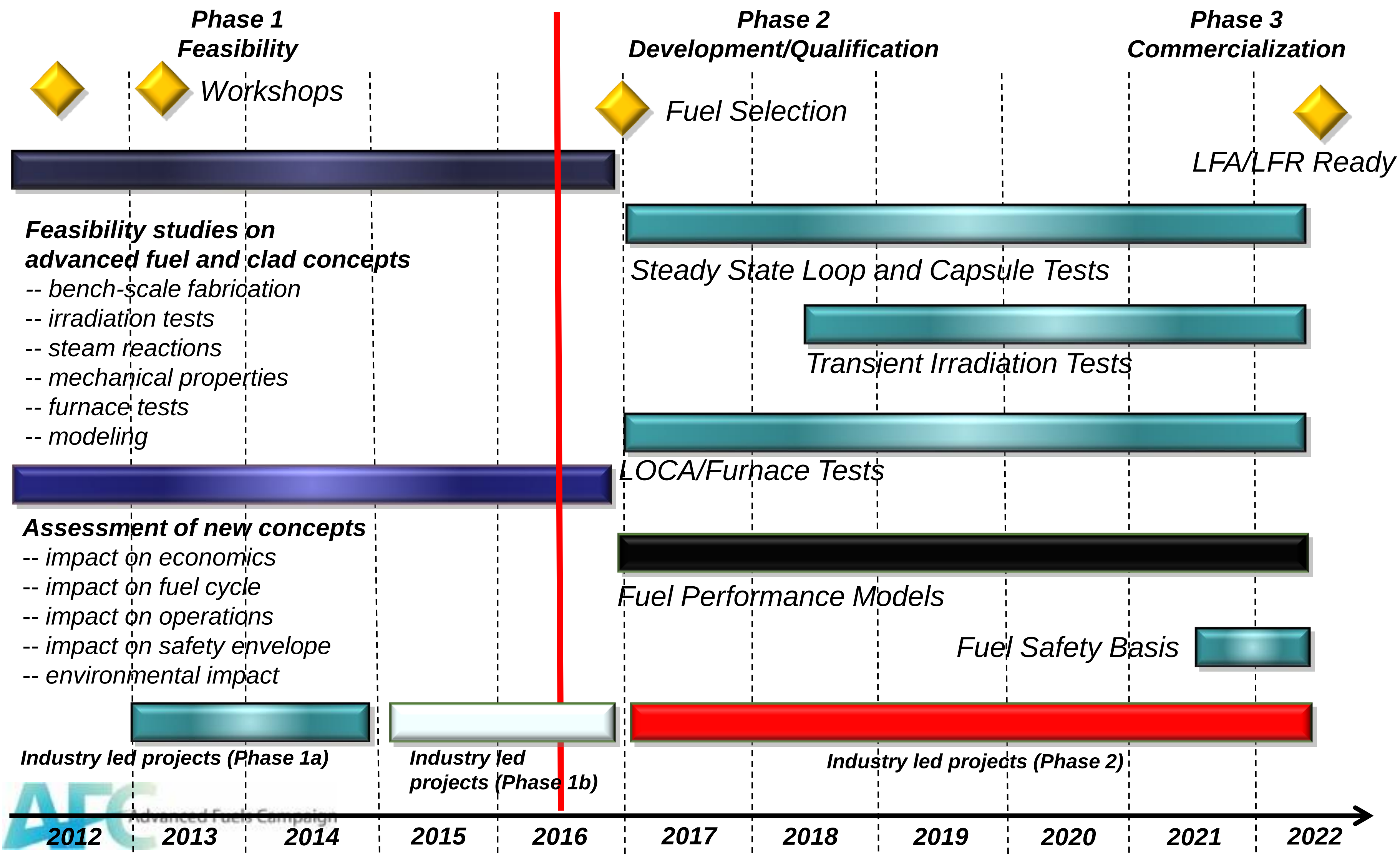




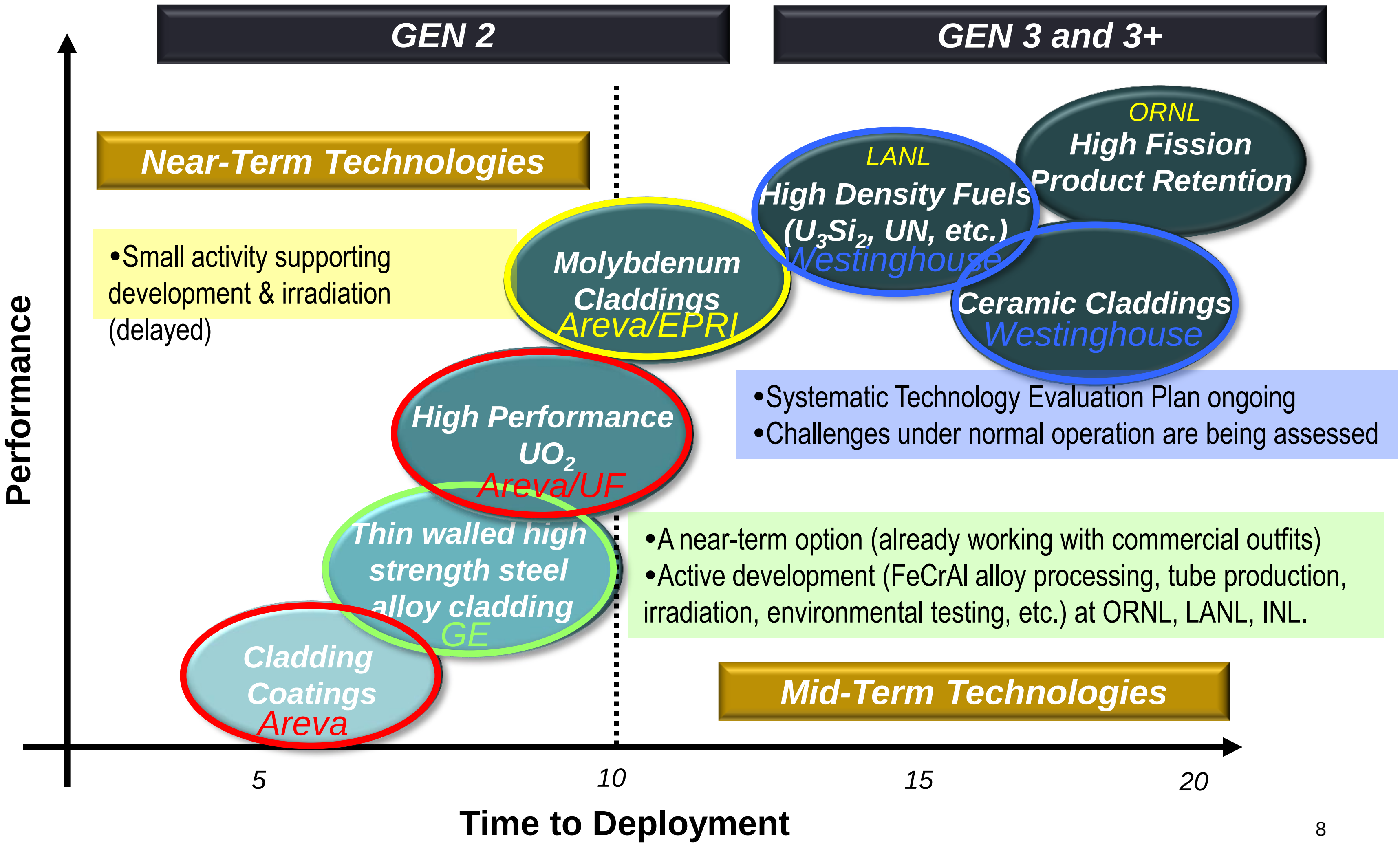
All analysis activities are dependent upon the fuel system material property and performance models.

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



A variety of technologies are under study as possible ATF

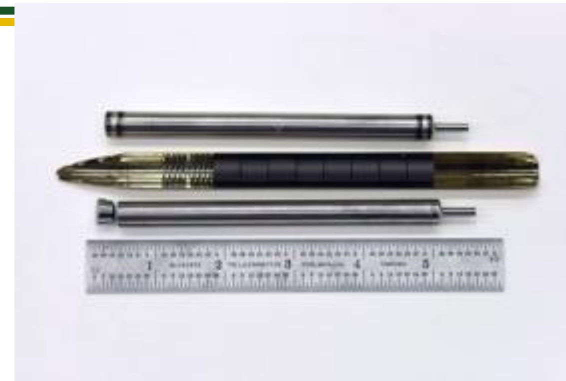


U.S. DEPARTMENT OF ENERGY

Nuclear Energy

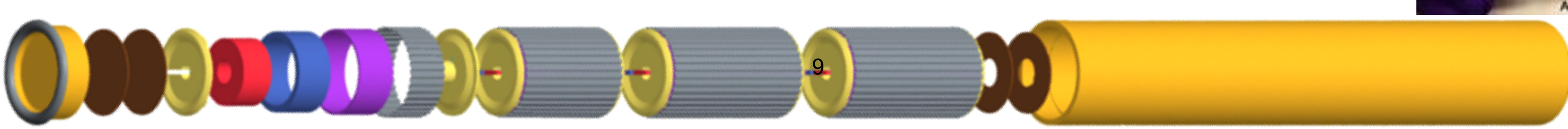
2015 Accident Tolerant LWR Fuel Development Major Accomplishments

- **Initiated irradiation of the ATF-1a series of (17) experiments in ATR**
  - 3 rodlets removed for PIE
- **Completed conceptual design of the ATF-2 loop irradiation in ATR**
- **FeCrAl, SiC Implementation Plans underway**
- **Initiated SiC microcracking experiment in HFIR**
- **High density fuel R&D**



ATR ATF-2 PWR Loop Test

HFIR SiC High Radial Heat Flux Test



U.S. DEPARTMENT OF ENERGY

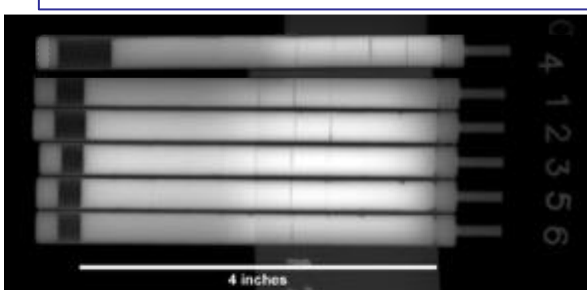
Nuclear Energy

U.S. DOE-supported Industry Teams Mid-way Through Phase 1b of ATF projects

AREVA

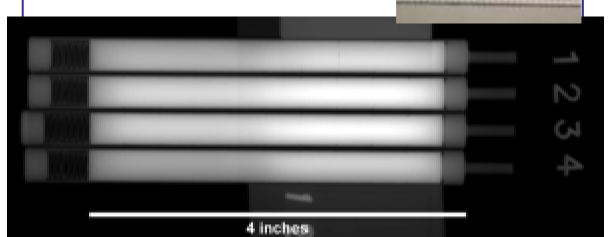
- ***Cr coated Zr***
- ***Increased fuel conductivity***

  Additives
  - *SiC powder or whiskers*
  - *Diamond*
  - *Chromia dopant*



GE

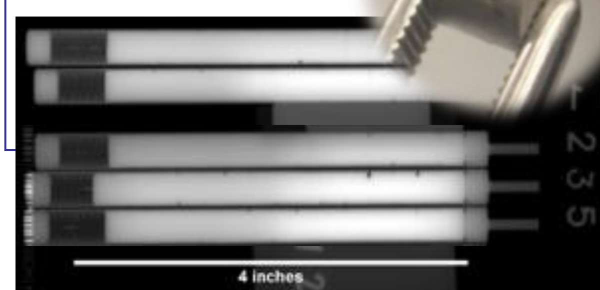
- *Develop advanced **ferritic/martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding** to improve behavior under severe accident scenarios*
- *Objectives:*
  - *Characterize candidate steels*
  - *Study tube fabrication methods, neutronics, fuel economy, thermo-hydraulic calculations, regulatory approval path*
  - *Initiate ATR testing with UO_2 and two cladding materials.*



Westinghouse

- ***Cladding** concepts:*
  *- **SiC** and SiC ceramic matrix composites;*
  *- **coated Zr alloys***
- ***High density/high thermal conductivity fuel pellets***
- *U_3Si_2 pellets sintered using finely ground powder*
- *Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures of 1400 ° C*

U_3Si_2 Pellet



Advanced Fuels Campaign

FY2015 Awarded University Integrated Research Project – Analysis of ATF (MIT PI: Jacopo Buongiorno)

The objective of this proposed integrated research project (IRP) is to **develop computational tools to evaluate accident tolerant fuel (ATF) options for near term applications**. The computational tools will be predominantly developed under the framework of the Nuclear Energy Advanced Modeling and Simulation (NEAMS). The NEAMS tools: RattleSNake (neutronics), MARMOT (meso-scale fuel performance), BISON (engineering scale fuel performance) and RELAP-7 (thermal-hydraulic system analysis) will be further enhanced in order to model ATF options.

FY2015 Awarded University Integrated Research Project – Analysis of ATF (Major Tasks)

Reactor Physics and Economics

Thermal Hydraulics and Safety

Estimate Time to Failure

Ti or Zr MAX phases (Si, Al)
Metallic Coating: FeCrAl, Cr
Enhanced UO_2 (BeO, SiC)

Experimental Evaluation under normal Operation

Fuel Performance Modeling under Severe/transient conditions

Experimental Evaluation under Severe/transient conditions

Fuel Performance Modeling under normal operation

Advanced High Density LWR Fuel Highlights

Advanced Accident Tolerant Ceramic Fuel Development

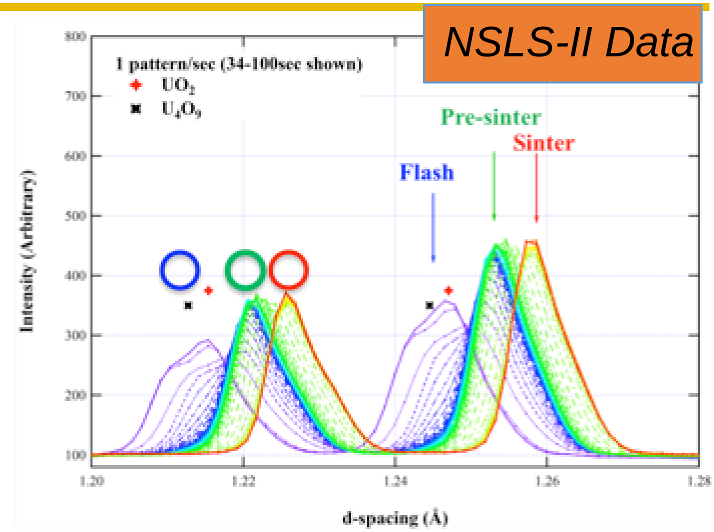
- *Further refinement of the CTR-N synthesis of UN has been achieved targeting lower residual C and O.*

Fabrication of Enriched Ceramic Fuel

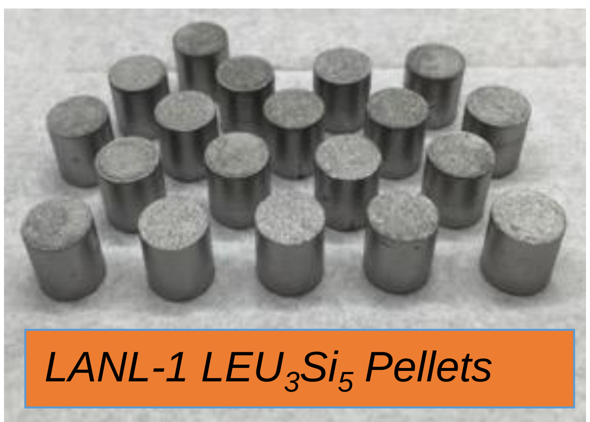
- *Depleted and low enriched U_3Si_5 and UN/15U_3Si_5 pellets fabricated for the LANL-1 irradiation test. Fuel fabrication initiated for the Westinghouse FOA Phase-1B UN/30U_3Si_2 fuel test.*

Advanced Technique & Fuel Material Development

- *UO_2 has now been shown to FLASH at room temperature. Initial in-situ FLASH sintering experiments performed on $UO_{2.16}$.*

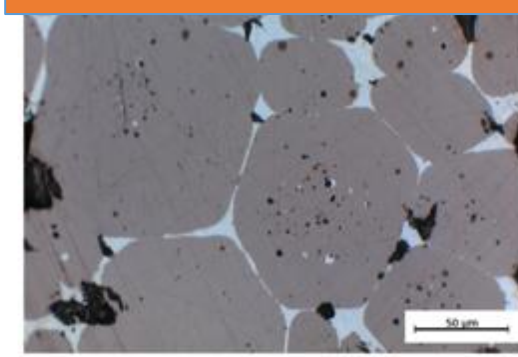


NSLS-II Data



LANL-1 LEU$_3$Si$_5$ Pellets

UN/15U_3Si_5 μ-structure

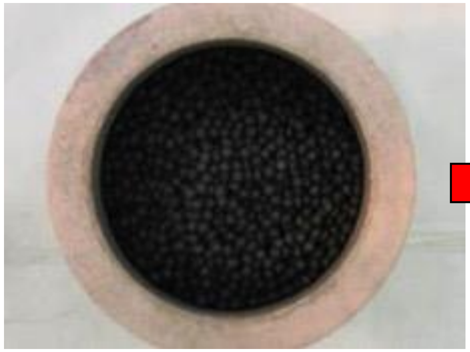


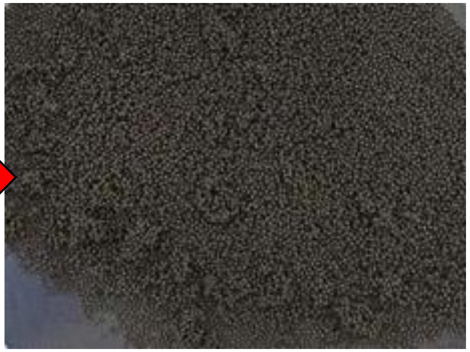
$UO_{2.16}$ FLASH at 45°C

Fully Ceramic Matrix (FCM) Fuel Development - Over 1.5 kg of 800µm Uranium Nitride Kernels Uniformly Produced for TRISO Coating

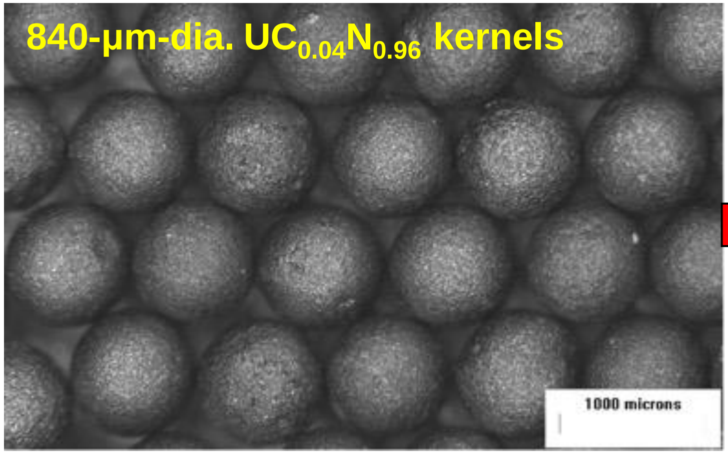
Tungsten crucible filled with UO_3+C feedstock

After a huge volume shrinkage (~12x), dense UN kernel are harvested

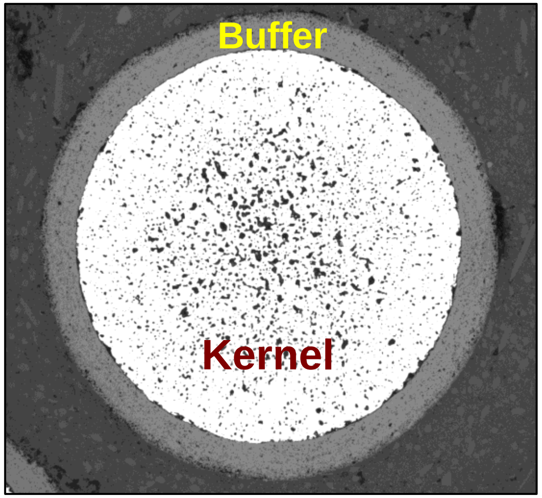




After 8 hours of processing in various temperatures/environments



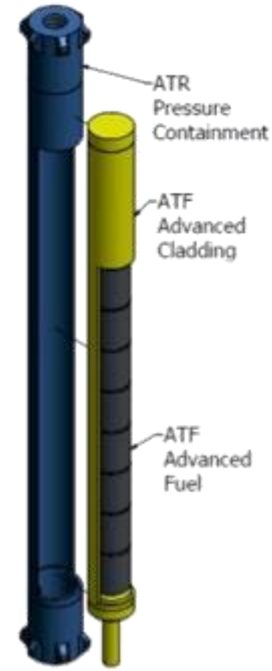
Fluidized bed Coating



Current work: FBCVD Coating development

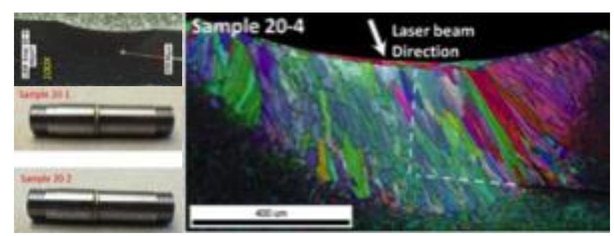
ATF Irradiation Testing Highlights

- **ATF-1 Capsule Irradiation**
  - Irradiated 19 ATF-1 capsules in ATR
  - Continued design and fabrication of additional concepts:
    Mo cladding, ORNL-FCCI, WEC-1B, LANL-1, ORNL-FCM, AREVA-1B
  - Fabricated, inspected, and qualified 16 rodlets and 19 capsules
  - Installed fabrication and inspection enhancements



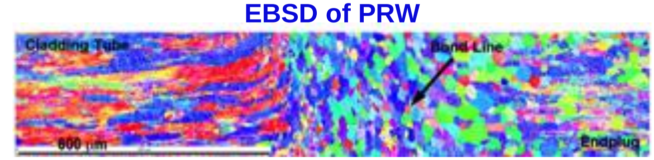
- **ATF-2 Loop Irradiation Testing**
  - Agreed to test train configuration and dimensions with industry teams
  - Started ATF-2 conceptual design and analysis
  - Initiated collaboration with Halden to support in-situ instrumentation development and testing

- **HFIR SiC Microcracking Experiment**



- **Halden 3D Experiment Collaboration**
  - Began discussions for a bi-lateral loop experiment in Halden

EBSD of PRW

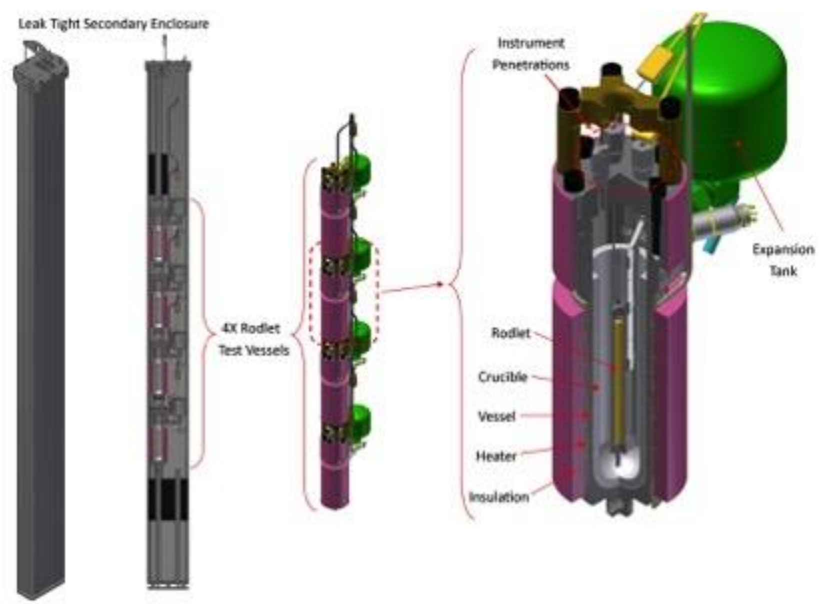


U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Transient Testing

- **TREAT Restart is progressing rapidly**
  - All system inspections are complete and fuel inspections are underway
  - Operator qualification is on track to support first critical in mid-16 and first experiments in early-17
- **ATF-3 Series Experiments**
  - ATF-3 draft test plan complete
    - *Collaboration with FOA teams to develop near-term testing needs*
    - *BISON benchmark cases for RIA completed (foundation for transient design)*
    - *Instrumentation selection and screening*
  - Static test vehicle conceptual design complete and prototype fabrication underway
  - Recirculating loop vehicle pre-conceptual design complete
  - Hodoscope detector recovery underway



Static Capsule Test Device

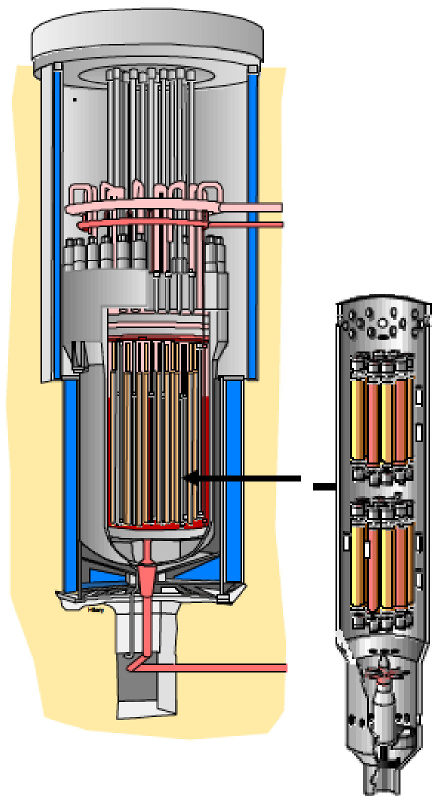
AFC Advanced Fuels Campaign

Halden ATF Collaborations

- FeCrAl Alloy and SiC creep test (under irradiation)
- ATF cladding and fuel experiment under the EHRP
- 3D MOOSE-BISON-MARMOT V&V Experiment
- BWR/PWR Loop discussion underway – NDA negotiation initiated.

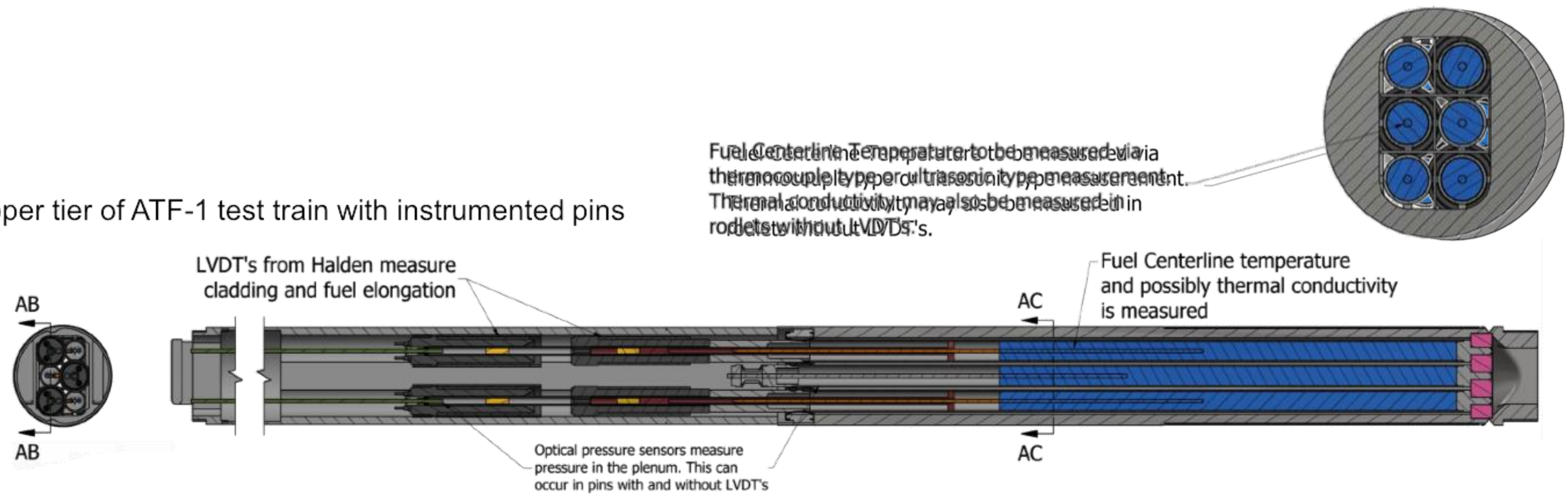
The Halden Boiling Water Reactor (HBWR) is a versatile tool for nuclear fuels and materials investigations:

- More than 300 positions individually accessible
- About 110 positions in central core
- About 30 positions for experimental purposes (any of 110/300)
- Height of active core 80 cm
- Usable length within moderator about 160 cm
- Experimental channel Ø:
  - 70 mm in HBWR moderator
  - 35-45 mm in pressure flask
- Loop systems for simulation of BWR/PWR conditions



Prototypic LWR Environment Testing in ATR and Halden

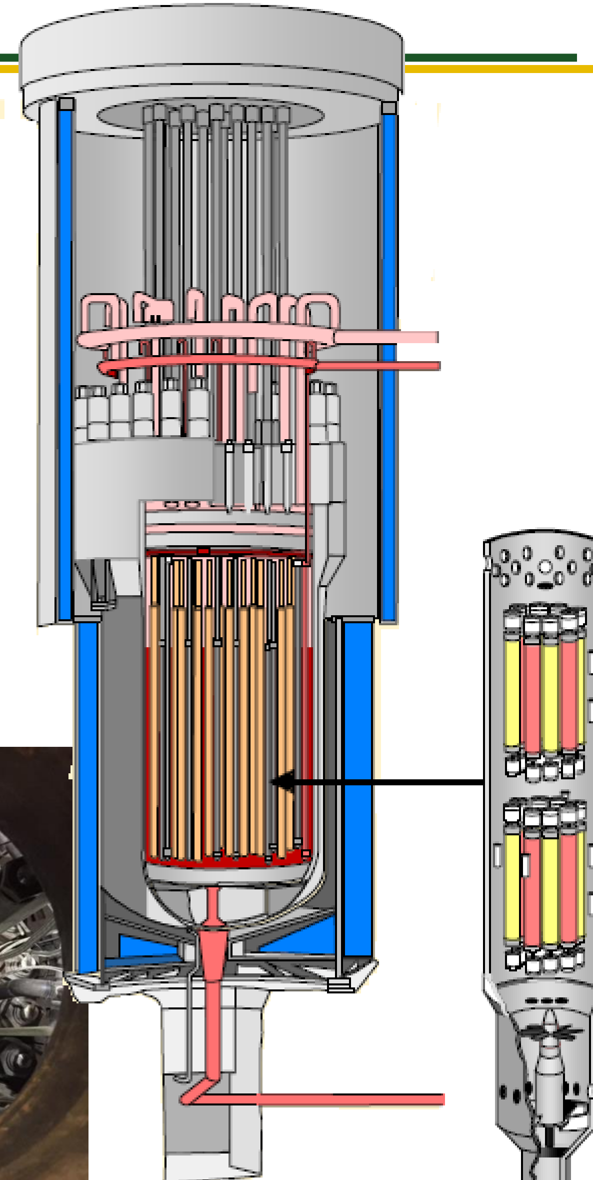
- **ATF-2 experiment will test ATF concepts in an ATR water loop under PWR conditions**
- **IFE/Halden-developed sensors will be used in ATF-2 to monitor in-situ fuel performance and conduct measurements between cycles in ATR canal**
- **IFE/Halden is supporting the ATF-2 experiment through information exchange, sensor testing in ATR, instrumented pin fabrication development, and data processing/interpretation**
- **Results and data from ATF-2 data will support 2022 ATF irradiation in a commercial reactor**



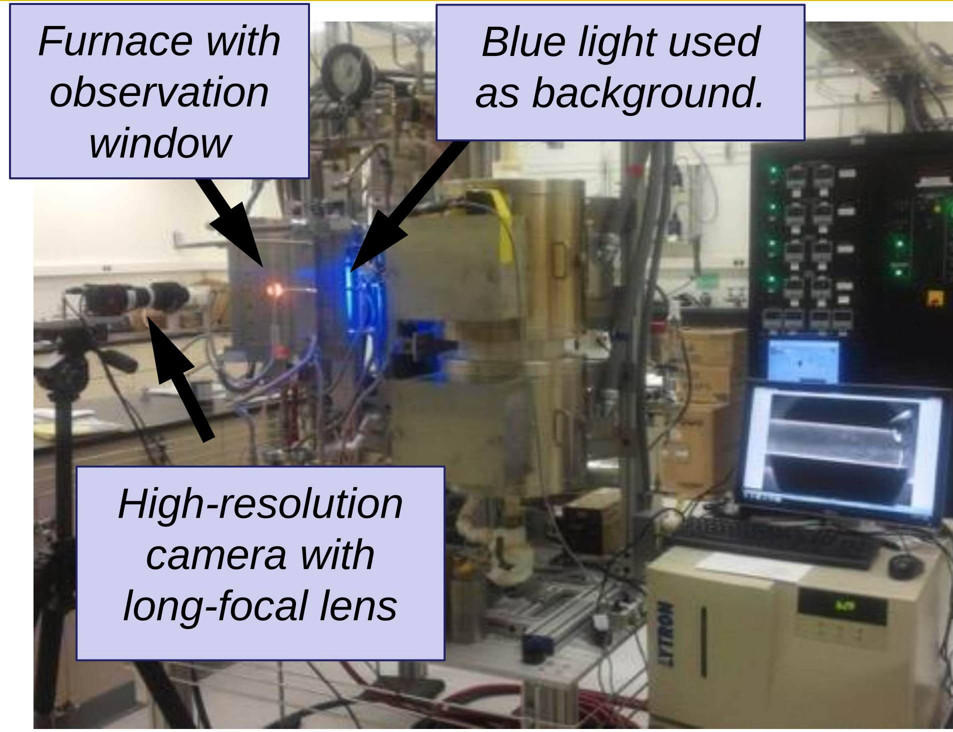
Upper tier of ATF-1 test train with instrumented pins

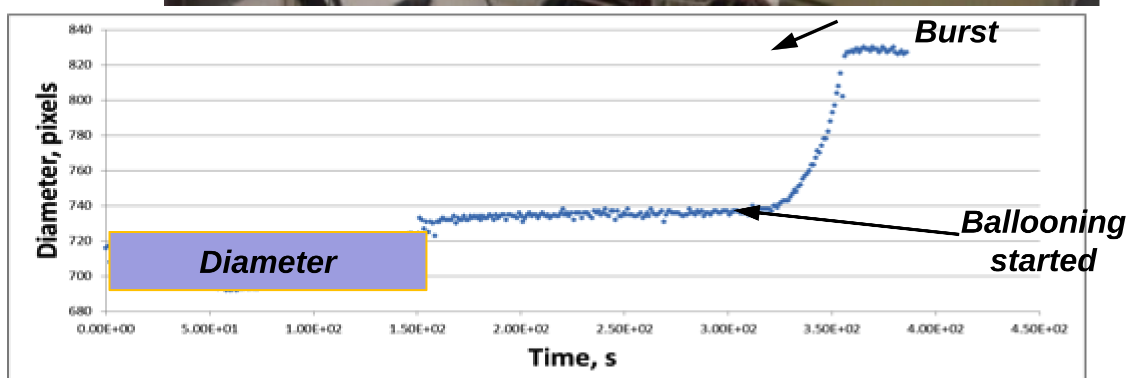
DOE/IFE Bilateral ATF Loop Irradiation in Halden

- **DOE is pursuing a bilateral irradiation in the Halden Reactor**
- **Irradiation of ATF concepts in prototypic PWR and/or BWR conditions**
- **Advantages include:**
  - Cross comparison of in-pile instrumentation
  - Supplement ATF-2 experiments in ATR with additional testing capacity in Halden
  - Can simulate BWR environments
  - Additional in-situ instrumentation capabilities
- **Concepts include:**
  - U_3Si_2 fuel
  - SiC and SiC/Zr claddings
  - FeCrAl cladding
  - and more …



In situ Cladding Ballooning Measurement During Integral LOCA Testing





Images obtained during the trial burst test from at 1100°C

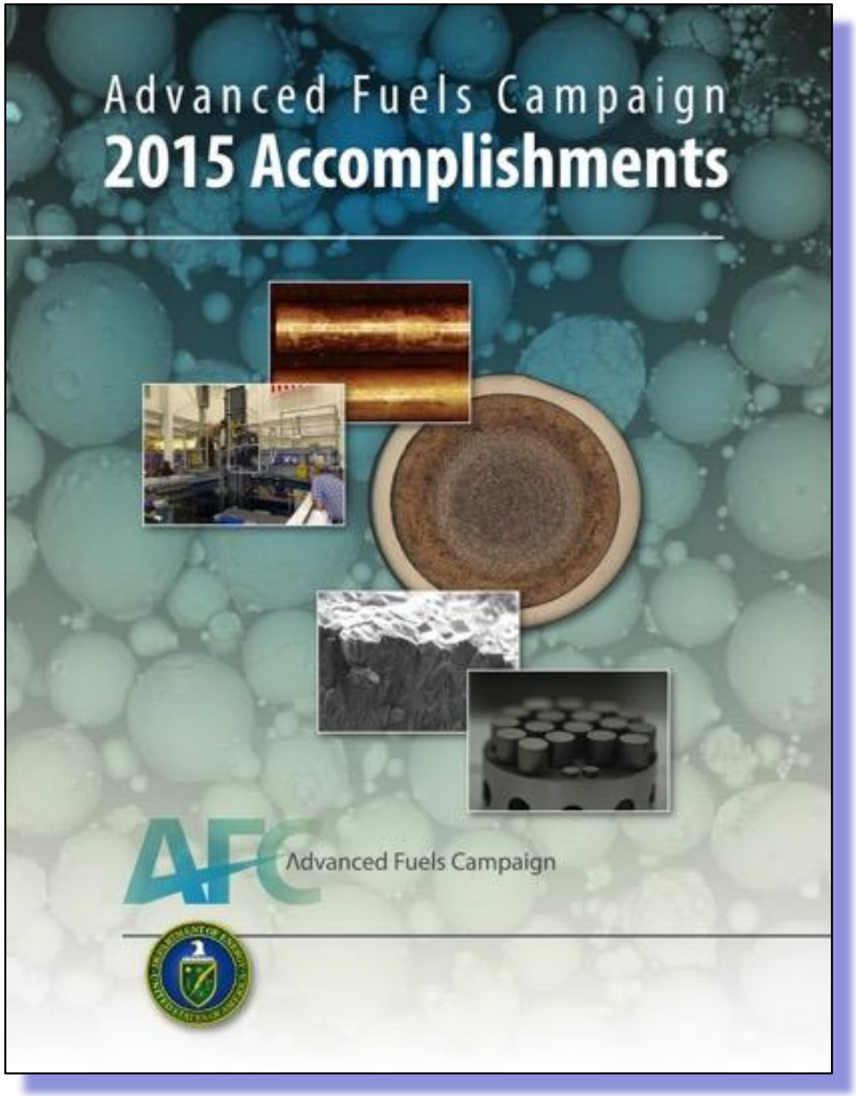
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Summary

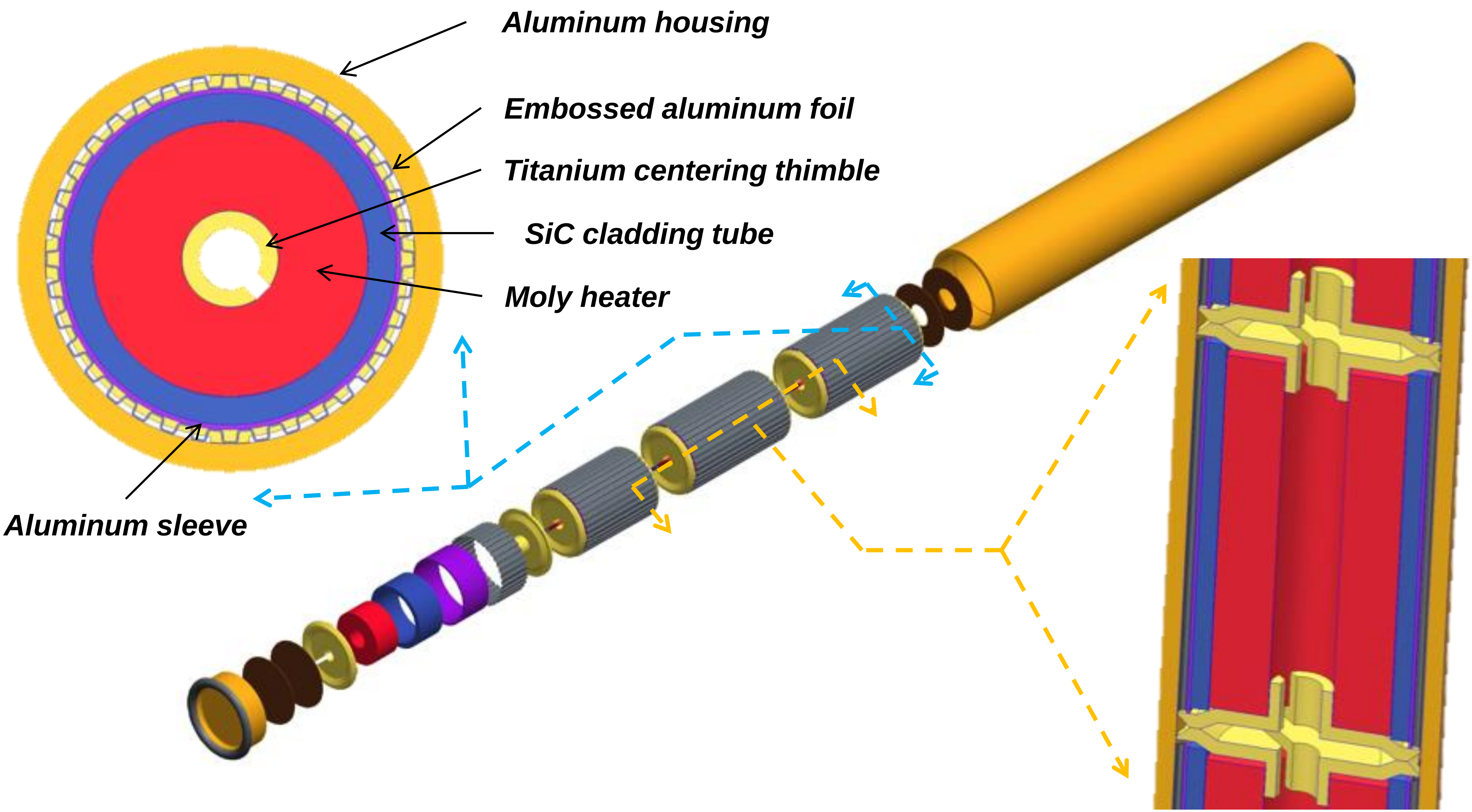
- **Full 2015 Accomplishments Report at:**
  https://nuclearfuel.inl.gov/

- **Major Efforts for FY2016**
  - Complete Technical Review of ATF Concepts
  - Transition to Phase 2 of ATF Industry program
  - 37 new rodlet insertions in ATF-1
  - Initiate Sensor Qualification (SQ) test in the ATF-2 Loop
  - Initiate use of new microstructure instruments in the Irradiated Materials Characterization Lab



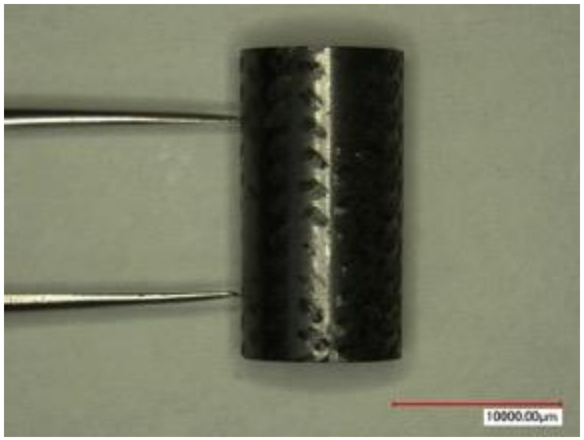
Thank you

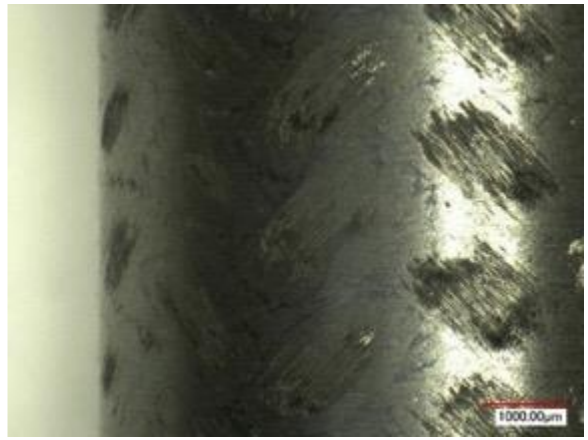
HFIR Irradiation of SiC Cladding under Prototypic High Heat Flux



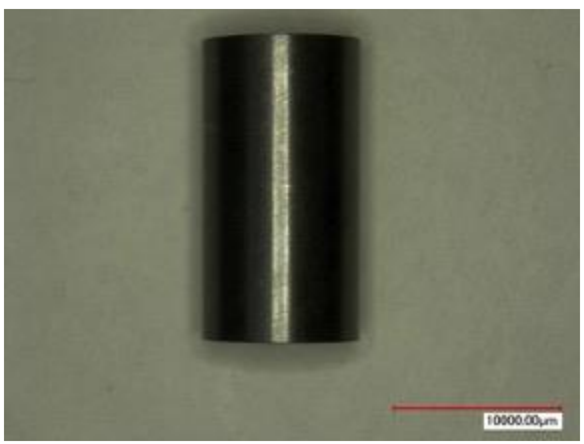
Composite Specimens supplied by General Atomics

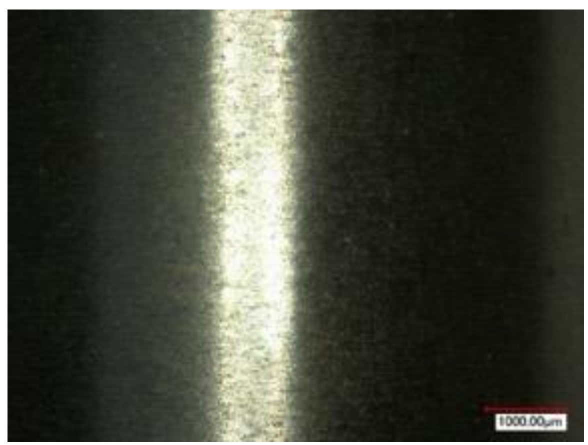
GA-TGI-7-C





GA-TGI-13-ML





U.S. DEPARTMENT OF ENERGY
Nuclear Energy

ATF Irradiation Testing and Qualification Test Series – ATF-1 Initiated Irradiation Feb. 10, 2015

Test Series	ATF-1	ATF-2	ATF-H-x	ATF-3	CM-ATF-x	ATF-y
Test Reactor	ATR	ATR	Halden	TREAT	Commercial Power Plant	TREAT
Test Type	Drop-in	Loop	Loop	Loop	LTR/LTA	Loop
Test Strategy	Scoping – Many Compositions	Scoping – Focused Compositions	Focused	Focused Compositions	Focused Composition	Focused Compositions
	Nominal conditions	Nominal conditions	Nominal	Accident conditions	Nominal conditions	Accident conditions
Fuel	UO_2, U_3Si_2, UN	Down-selected concepts	Selected	Fuel rodlets from ATF-1 and test rods from ATF-2 irradiations	Concepts selected in 2016	Test rods from LTR/LTA irradiations
Cladding	Zr w/coatings, stainless steels, advanced alloys, SiC					
Key Features	Fuel-cladding interactions	PWR Conditions	BWR Conditions	Integral testing	Steady State Irradiation	Integral testing
Timeframe	FY14 – FY18+	FY16 – FY22	FY15-FY22	FY18 – FY25	FY22 – ?	FY – ?

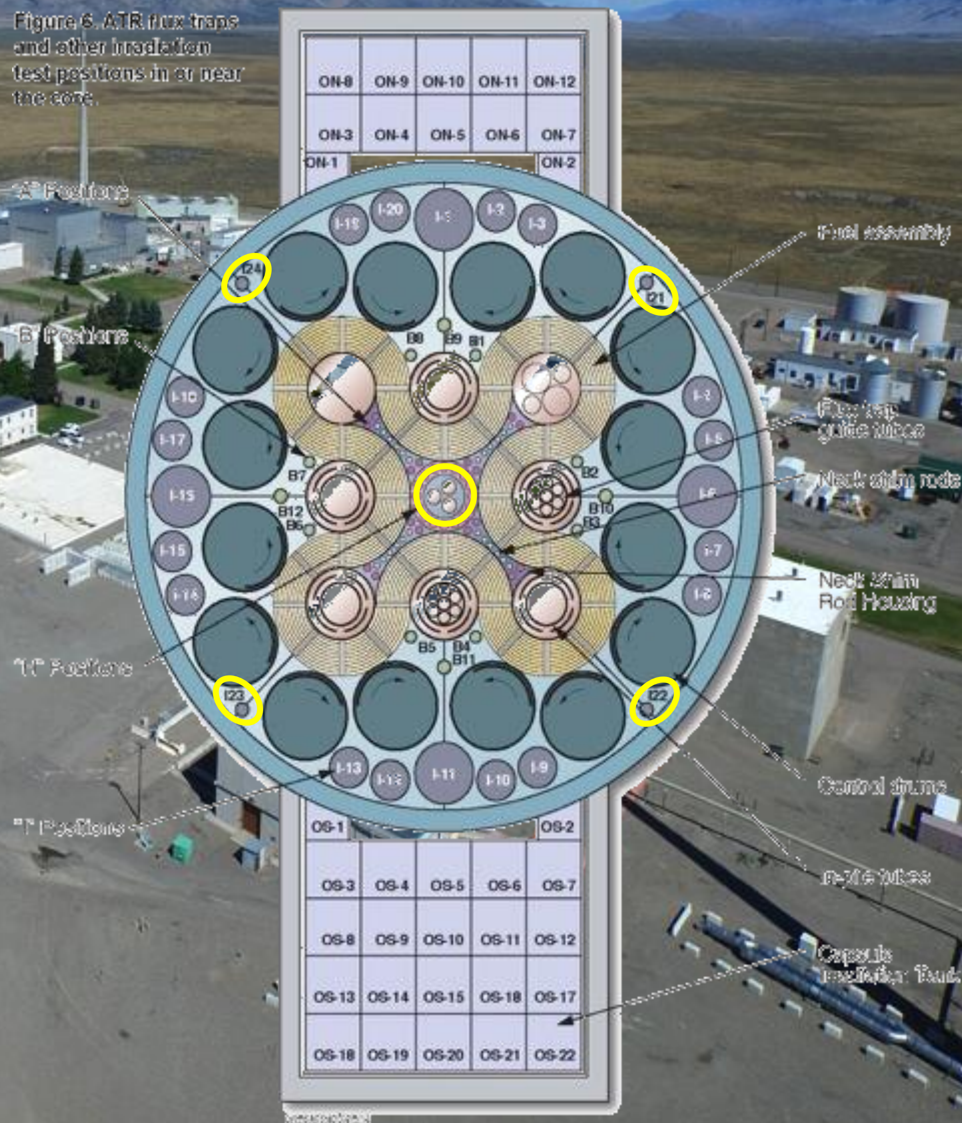
ATF in the Advanced Test Reactor

Phase 1

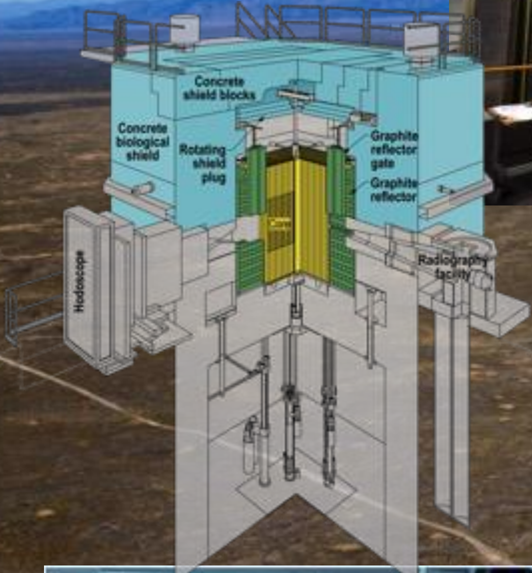
- *Drop-in capsules*
- *Scoping tests*

Phase 2

- *Loop test train*
- *Prototypic irradiation conditions*



Arial View of the Transient Reactor Test (TREAT) Facility



- 100 kW Steady-state power with 19 GW Peak Transient Power
- Core: ~1.2 m high x 2 m. dia.; surrounded by 0.25 m graphite reflector
- 19 x 19 array of 10 x 10-cm. fuel and reflector assemblies
- Fuel: 0.2 wt.% high enriched UO_2 dispersed in graphite
- 12 steady-state and 8 transient control rods
- Instantaneous, large negative temperature coefficient (self protecting driver core)

TREAT Refurbishment activities initiated with FONSI Signature on Feb 27, 2014.