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Update on Development of Enhanced Accident Tolerant Fuel for Light Water Reactors in the United States

Shannon Bragg-Sitton, Ph.D.

Idaho National Laboratory, United States

U.S. DOE Advanced Fuels Campaign

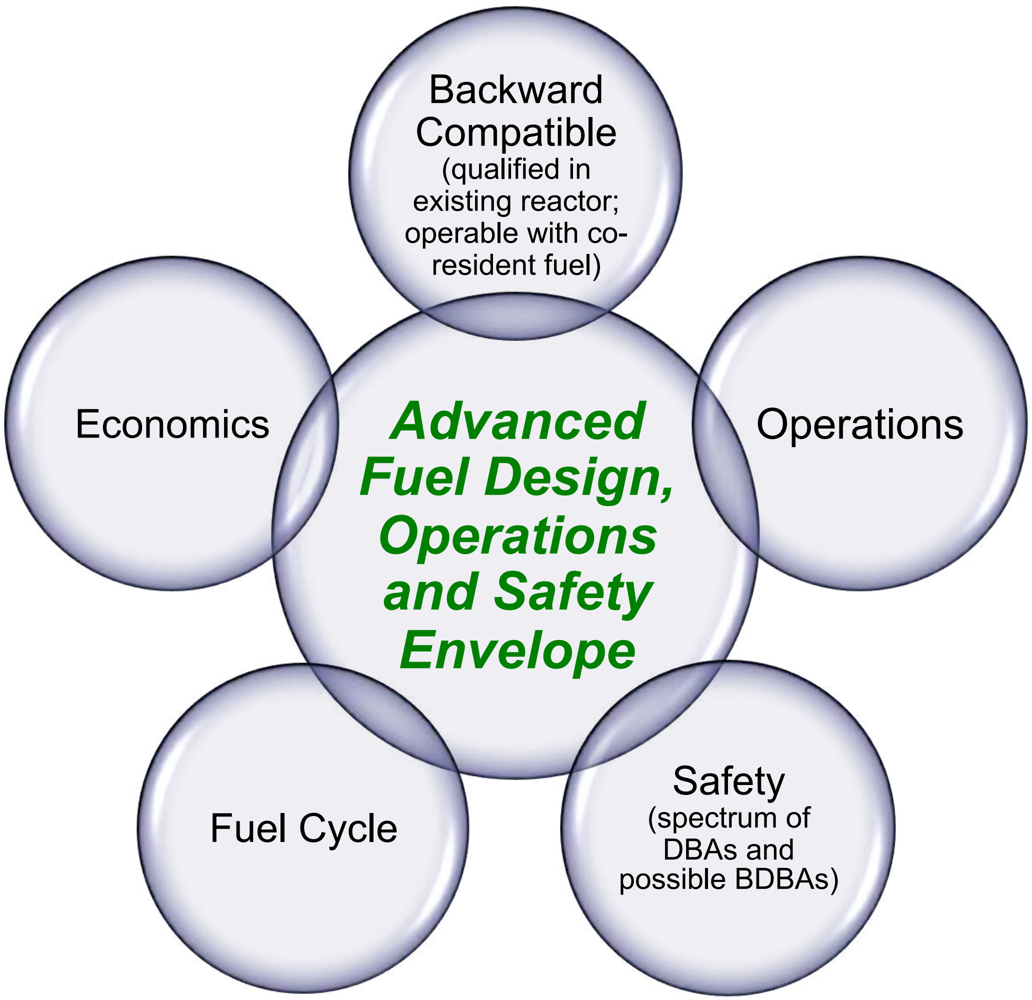
April 28, 2014

OECD / NEA, Start-up Meeting of the Expert Group on Accident Tolerant Fuels for Light Water Reactors (LWRs)

Presentation Overview

- **Status of Evaluation Metrics**
- **U.S. DOE Program Snapshot**
  - Overview of research teams
  - Recent publications
- **Experimental Infrastructure**
  - Out-of-pile testing: Behavior under accident conditions
  - Irradiation testing: HFIR rabbit, ATR capsules, ATR loop
- **Key Updates and Accomplishments**

New ATF Designs Must Meet the LWR Operations, Safety and Fuel Cycle Constraints



ATF will be evaluated over all potential "performance regimes"

- Fabrication / Manufacturability (to include Licensibility)
- Normal operations and anticipated operational occurrences (AOOs)
- Postulated accidents (Design Basis)
- Severe accidents (Beyond Design Basis)
- Used fuel storage / transport / disposition (to include potential for future reprocessing)

See: U.S. DOE LWR ATF Performance Metrics Report, February 2014

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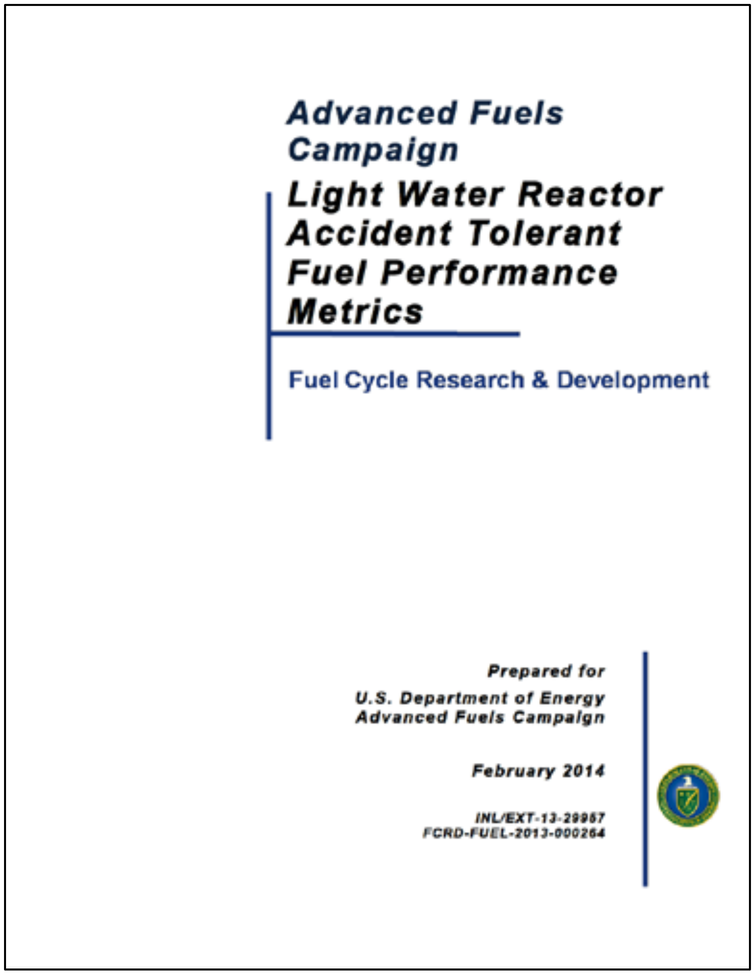
New ATF Designs Must Meet the LWR Operations, Safety and Fuel Cycle Constraints



Advanced Fuels Campaign

Light Water Reactor Accident Tolerant Fuel Performance Metrics

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign

February 2014

INL/EXT-13-29957
FCRD-FUEL-2013-000264

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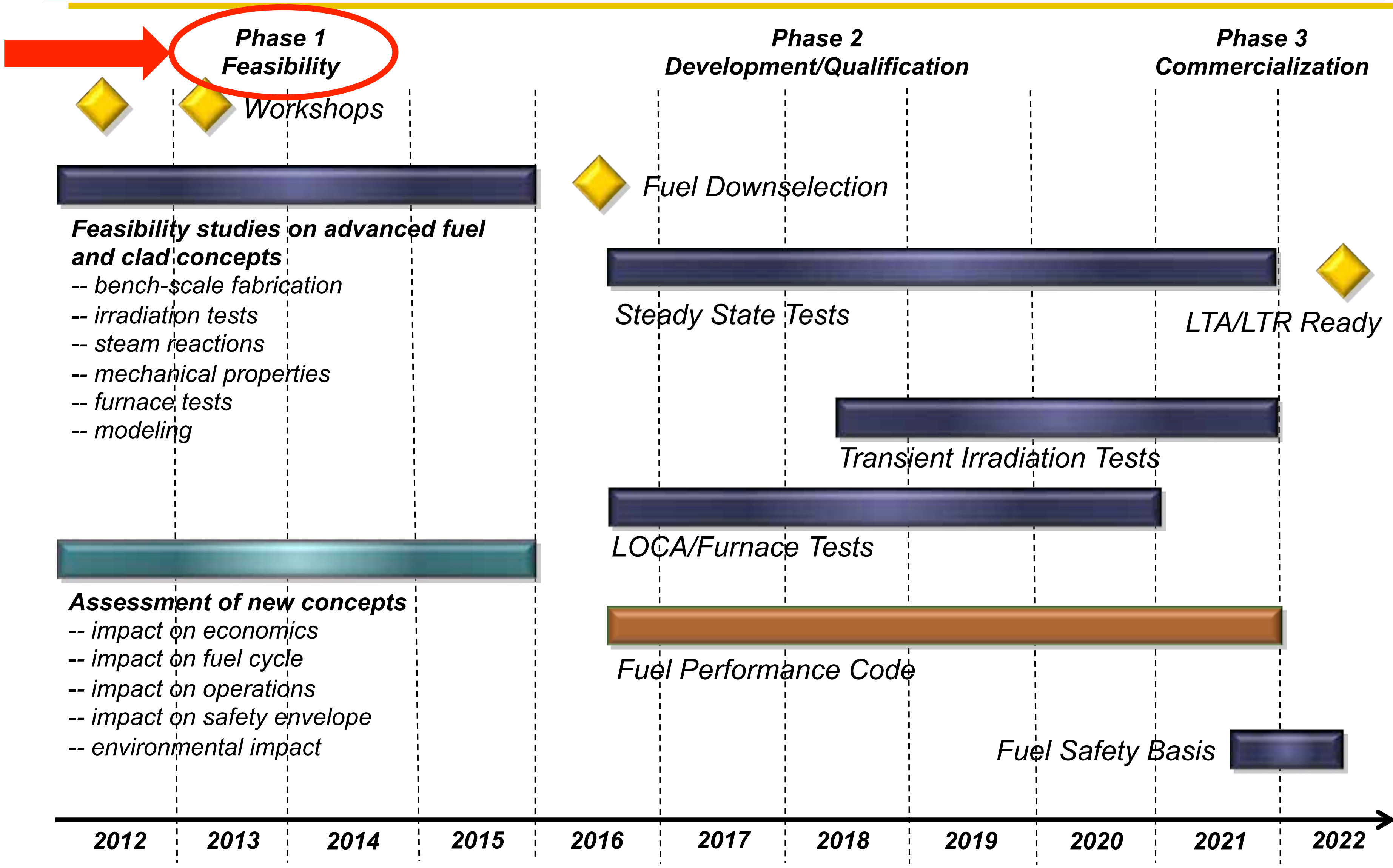
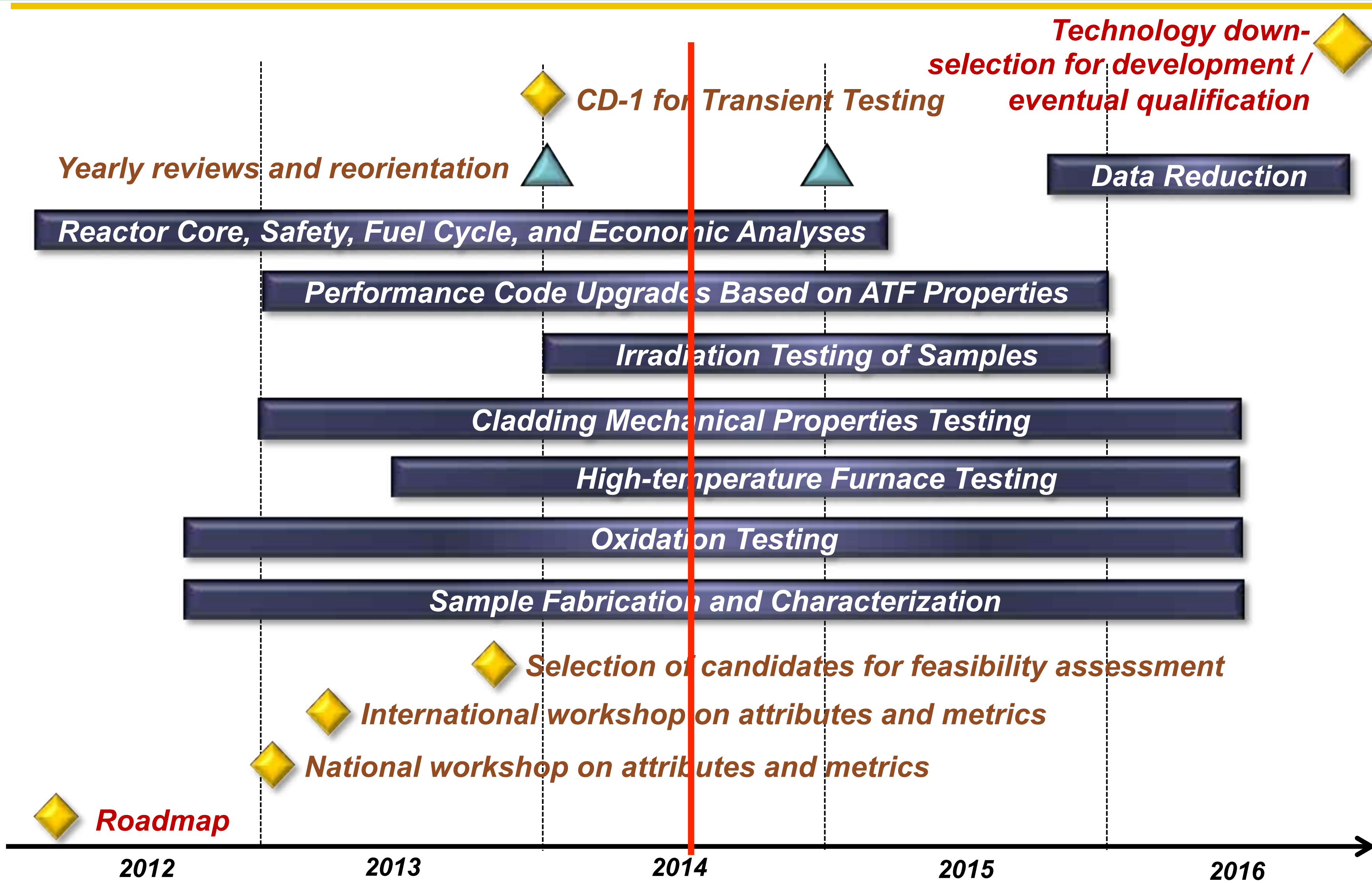
U.S. RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



U.S. Near-term ATF Activities Aimed at Completing the Feasibility Assessment



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The U.S. Accident Tolerant Fuel development is supported by a large part of the U.S. nuclear complex

National Laboratories

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

The University of Tennessee — Knoxville, Chattanooga, Martin, Tullahoma, Memphis

Texas A&M University

Georgia Tech

MIT

Nuclear Industry

GE imagination at work

Westinghouse

AREVA

EPRI Electric Power Research Institute

Summary of Major U.S. DOE Funded ATF Projects

Lead Organization	Category – Major Technology Area	Additional Team Members
Oak Ridge National Laboratory	Fuel: Fully Ceramic Microencapsulated (FCM)-UO_2, UN FeCrAl cladding, SiC cladding	*Initial irradiation of all concepts at Idaho National Laboratory*
Los Alamos Nat. Lab. EPRI + LANL	Fuel: Enhanced UO_2, Composite Fuels Cladding: Molybdenum	
AREVA *(FOA, NEUP)*	High conductivity fuel (UO_2+Cr_2O_3, +SiC) Cladding: Protective materials, MAX phase	U. Wisconsin, U. Florida, SRNL,TVA, Duke **Includes work with AREVA France
Westinghouse *(FOA, NEUP)*	Fuel: U_3Si_2, and UN+U_3Si_2 fuel Cladding: Coated Zr and SiC	General Atomics, MIT, EWI, INL, LANL,TAMU, Southern Nuclear Operating Company **Includes work with WEC Sweden
GE Global Research *(FOA)*	Advanced Steel (Ferritic / Martensitic) Cladding	Global Nuclear Fuels, LANL, U. Michigan
University of Illinois *(IRP)*	Modified Zr-based Cladding (coating or modification of bulk cladding composition)	U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang **UK contributions
University of Tennessee *(IRP)*	Ceramic Coatings for Cladding (MAX phase and multilayer ceramic coatings)	Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO **UK and Australia contributions
Georgia Institute of Technology *(IRP, accident tolerant reactor design)*	Fuel: U_3Si_2 Cladding: FeCrAl Details TBD for fuel component – likely to adopt fuel developed under an above program	U. Michigan, Virginia Tech, U. Tennessee, U. Idaho, Morehouse College, INL, Westinghouse Electric, Southern Nuclear, Polytechnic U. Milan, U. Cambridge

Recent Publications on ATF Projects

*Summary of U.S. ATF research provided in the March 2014 edition of **Nuclear News**, the monthly publication from the American Nuclear Society.*

Journal of Nuclear Materials Special issue on accident tolerant fuels now available.

EXPERIMENTAL INFRASTRUCTURE

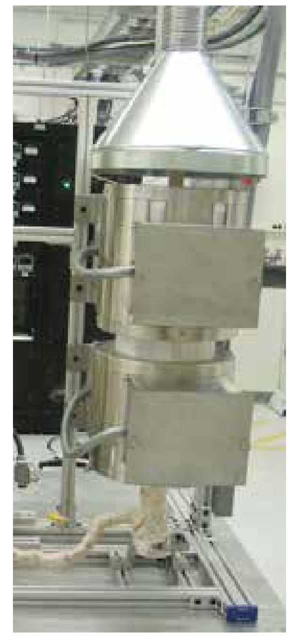
Out-of-Pile Testing: Severe Accident Test Station at ORNL

- **National facility for testing new cladding concepts**
  - Multiple “modules”
  - Steam to 1700°C, typically 1-10 cm/s
  - Pressure to 30 bar

Rubotherm TGA

“Keiser rig” high P/T ~1500°C

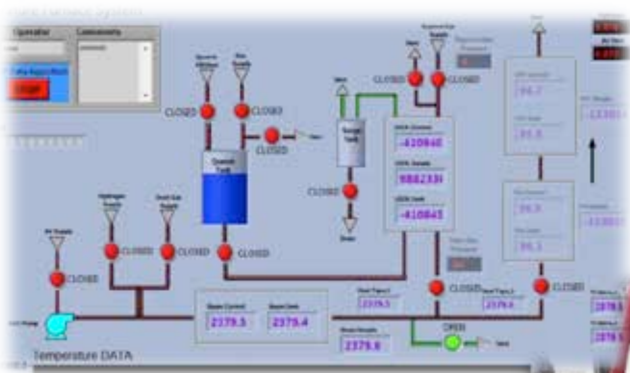
standard LOCA

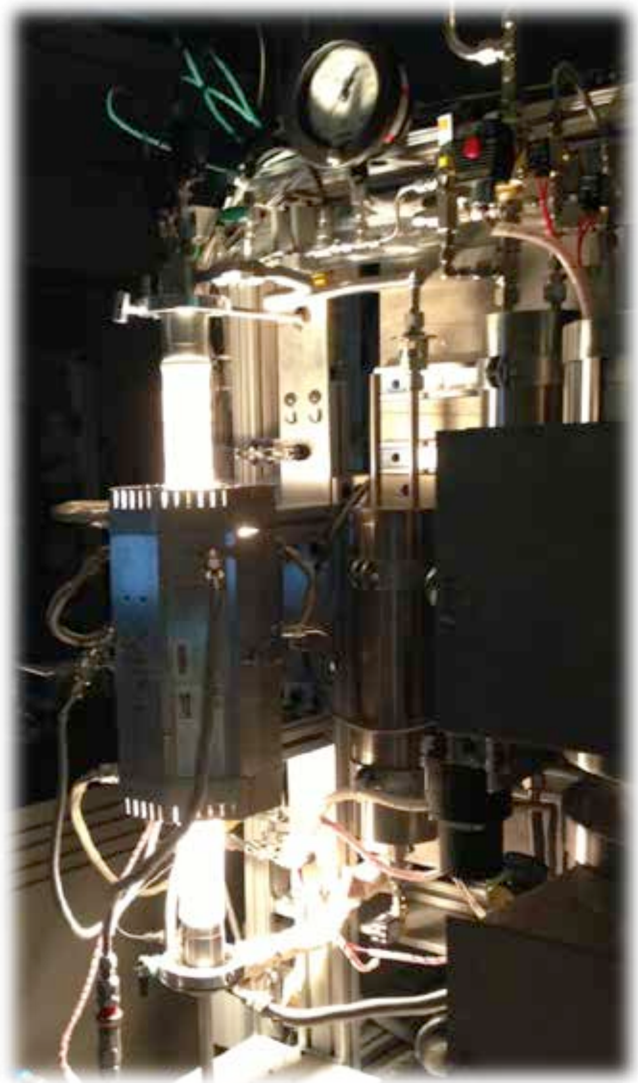


high T ~1700°C

in- & ex-cell units

Integral LOCA Test Module

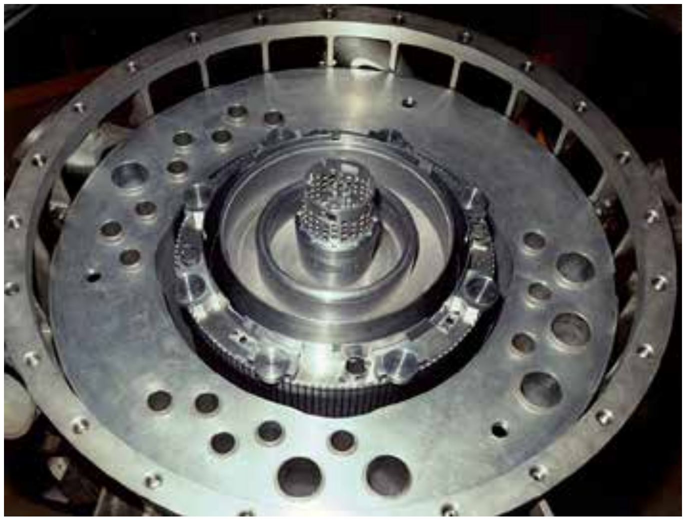




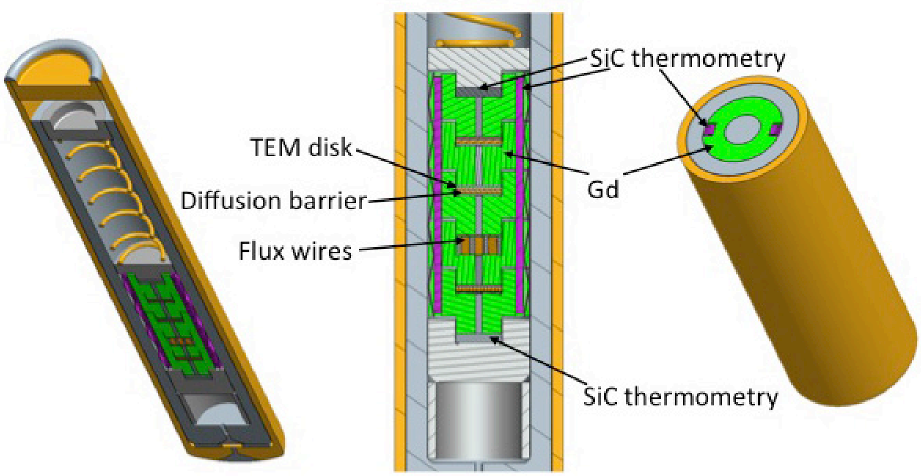
Includes:

Quartz lamp furnace
1200°C steam
- shared generator
Quartz tube
305mm long tube
- internal pressure
Water quench
5°/sec heating
Burst test

The ORNL High Flux Isotope Reactor, Preliminary Irradiation Testing



- Pressurized, light-water-cooled and –moderated, flux-trap-type reactor
- HEU fuel — U_3O_8 dispersed in aluminum
- Two annular fuel elements
- Center cylindrical flux trap, 12.70 cm diameter
- Nominally 7 cycles/year, with a 23 day cycle length
- Hydraulic rabbit testing for small material samples – **preparing SiC joints for irradiation**



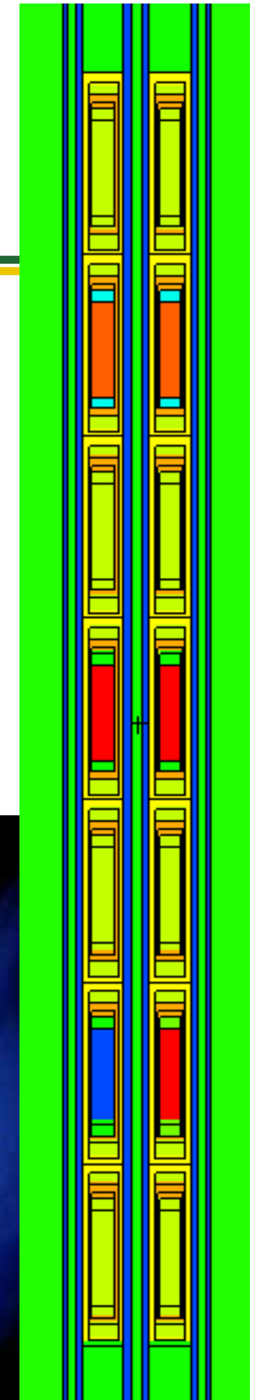
Flux Trap Rabbits for High-Dose Materials Irradiations

ATF Irradiation Testing and Qualification Test Series

ATR: Advanced Test Reactor @ INL

Test Series	**ATF-1**	**ATF-2**	**ATF-3**	**CM-ATF-x**	**ATF-4**
Test Reactor	ATR	ATR	TREAT	Commercial Power Plant	TREAT
Test Type	Drop-in	Loop	Loop	LTR/LTA	Loop
Test Strategy	Scoping — Many Compositions	Scoping — Focused Compositions	Focused Compositions	Focused Composition	Focused Compositions
	Nominal conditions	Nominal conditions	Accident conditions	Nominal conditions	Accident conditions
Fuel	UO_2, U_3Si_2, UN	Down-selected concepts	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	Fuel-cladding-coolant interactions	Integral testing	Steady State Irradiation	Integral testing
Timeframe	FY14 — FY18+	FY16 — FY22	FY18 — FY25	FY2022 - ?	FY26 — ?

ATF-1 Irradiation Test Series (begin mid-2014)



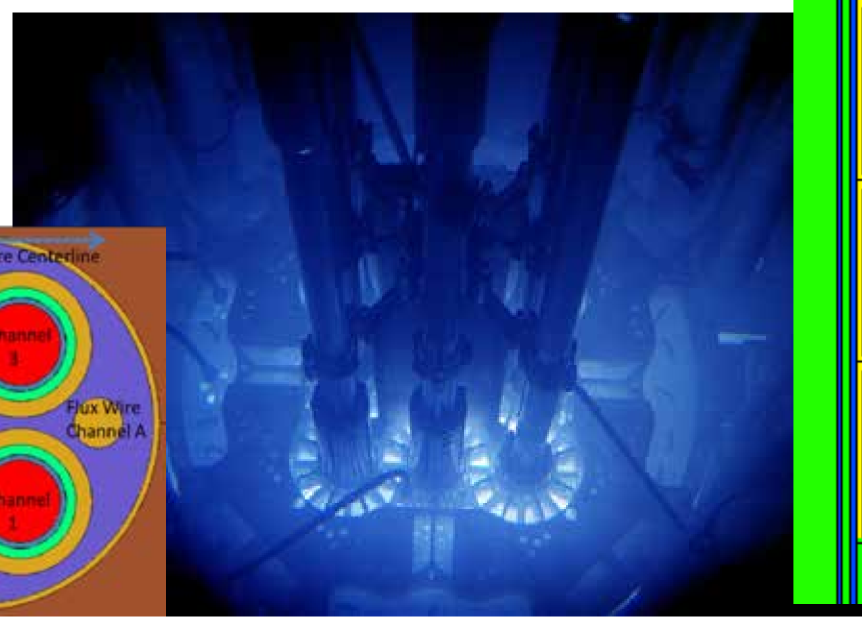
- **Objective:**

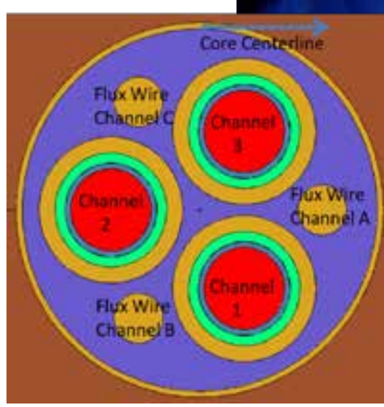
  Assess the performance of proposed Accident Tolerant Fuel concepts under <u>normal</u> operating conditions common to existing LWRs.

  – ATF-1 test series is appropriate for testing irradiation behavior of new fuels and their interaction with cladding

  – Test rodlets are isolated from ATR primary coolant, so ATF-1 test series is <u>not</u> appropriate for testing interaction of cladding (or coatings) with coolant

  – All post-irradiation examination work for ATF-1 planned to be conducted at INL – preliminary plan currently being discussed

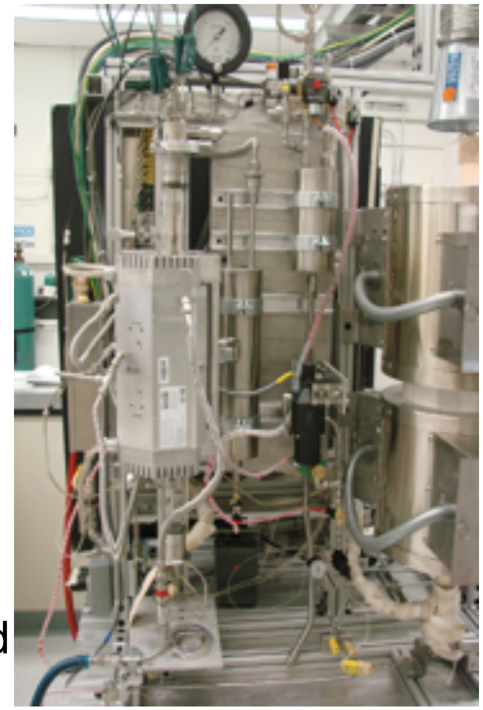


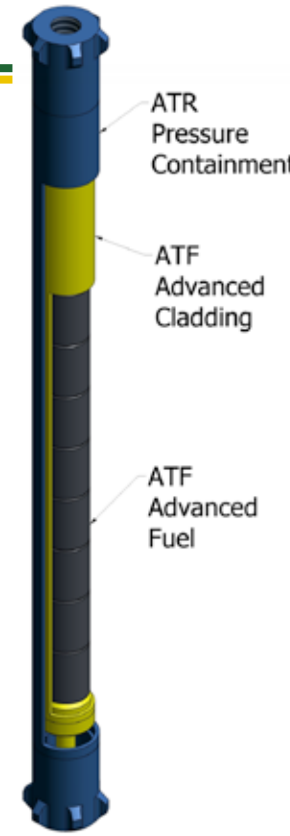


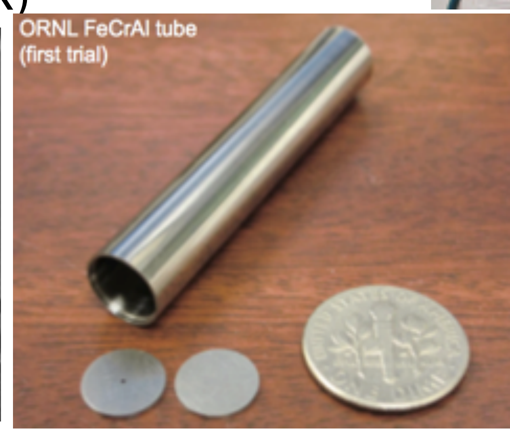
KEY UPDATES AND ACCOMPLISHMENTS

2013 Major Accomplishments

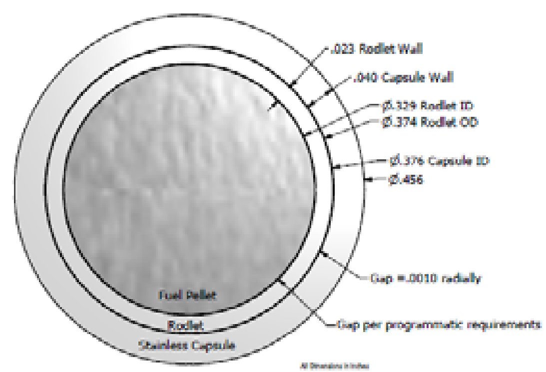
- Conducted Domestic and International Metrics workshops
- Industry teams are well underway
- Oxidation and Steam testing capabilities have been built and deployed across the laboratories
- FeCrAl, Mo, SiC cladding development and testing
- High density ceramic fuel fabrication
- Planning and Design of ATF-1 irradiation experiment @ INL Advanced Test Reactor (ATR)







U_3Si_2

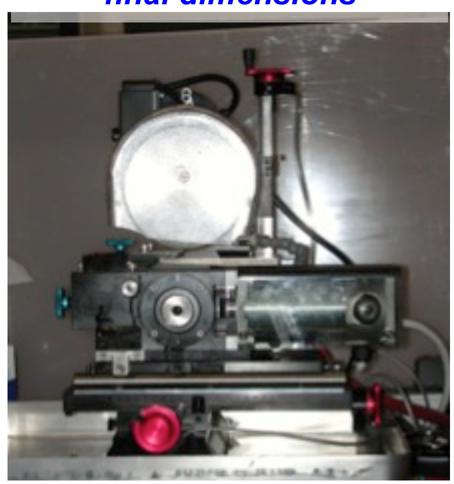


Preparation for Enriched Ceramic Fuel Fabrication for ATF Testing in ATR (LANL)

- **Prepared for fabrication of Accident Tolerant Fuel test articles for ATR insertion**
- **Enriched ceramic fuel fabrication line authorized for production**
  - Custom enrichment
  - Custom dimensions
- **UO_2 feedstock synthesis from UF_6 by integrated dry route process in development**
  - Potential for high uranium density non-oxide ceramic fuel

Glovebox with pressing and sintering capabilities

Centerless grinding to final dimensions



Reactor (in hood) and humidifier (front) for UO_2 synthesis by IDR route

Table 1. ATF-1 Test Matrix. The parameters noted as "critical" are the top priority in design and analysis of the experiments.

ATF Development Lead	Fuel	Anticipated Fuel Enrichment	Cladding	Coating	PICT	Desired Irradiation Conditions: LHGR	Fuel CL Temp	Burnup	No. of Rodlets
					(°C)	(W/cm)	(°C)	(GWd/MT)	
	FCM- UO_2, UN	19.70%	Zircaloy						6
	UO_2	4.96%	FeCrAl						12
ORNL	UO_2	4.96%	SiC	n/a	350-420 *critical for FeCrAl*	~250	<1700	10, 30, 50	6
	U-10Mo								
PNNL	U-7Mo	3-6%	MA-956	n/a	300-400	200-350	~550 *critical*	15, 30	6
EPRI/LANL	UO_2	<5%	Mo	n/a	300-360	350-500	<1700	25, 50	6
	UN/U3Si5	3-5%	SS, FeCrAl	n/a	350 *critical*	~240 (TBD)	<1650	10, 20, 50	6 low BU 6 high BU
LANL	UO2/UB2	3-5%	Zr-alloy	n/a	400 *critical*	~350 (TBD)	<1700	10, 20, 50	6 low BU 6 high BU
	U_3Si_2	~5% for 5 - 10 kW/ft	Zirlo, SiC	n/a	300-400	180-500	~50, 800, 1200 *critical*	20, 40, 70	6 FY14 6 FY15-16
Westinghouse	UN + U_3Si_2	~5% for5 - 10 kW/ft	Zirlo, SiC	Ti_2AlC and/or Nanosteel	300-400	180-500	~50, 800, 1200 *critical*	20, 40, 70	6 FY15-16
AREVA	UO_2 UO_2+Cr_2O_3 UO_2 +SiC UO_2 +diam	4.95%	Zircaloy	n/a	300-400 *critical*	300-400	<1600 *critical*	25, 50	6

Table 1. (continued).

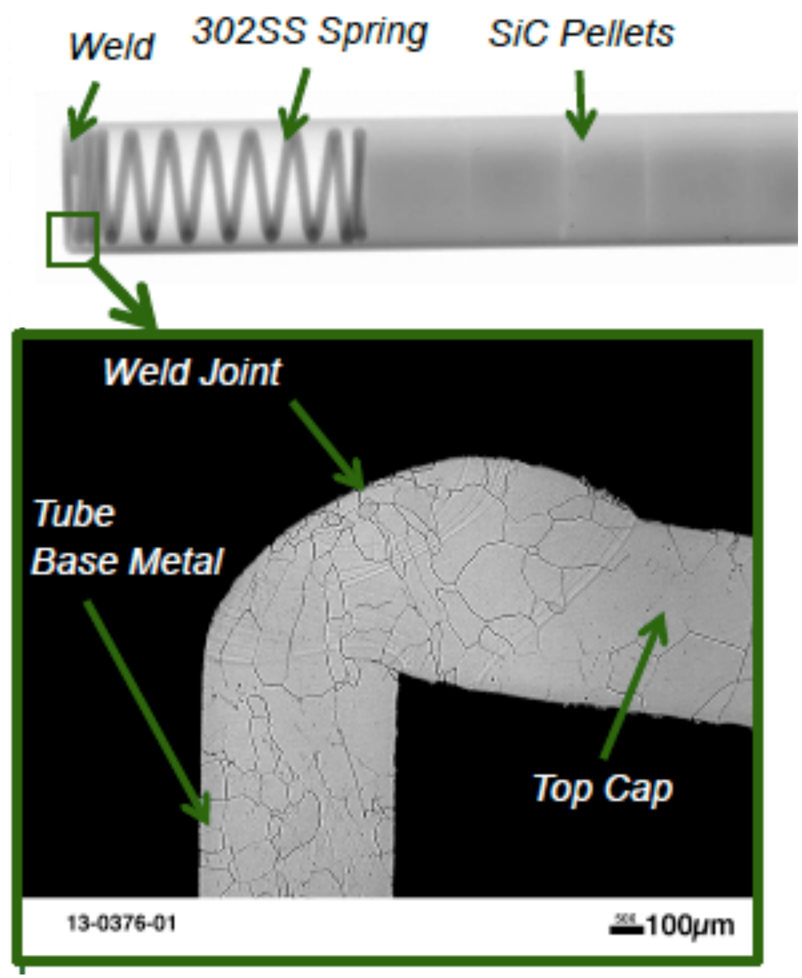
ATF Development Lead	Fuel	Anticipated Fuel Enrichment	Cladding	Coating	PICT (°C)	Desired Irradiation Conditions: LHGR (W/cm)	Fuel CL Temp (°C)	Burnup (GWd/MT)	No. of Rodlets
General Electric	UO_2	4.9% (from GNF)	3 Different Advanced Steels	None	300-450 *critical*	~350	< ~1600 *critical*	20, 80	4 FY14 *(2 alloys, 2 BU levels)* 2 FY15 *(1 alloy, 2 BU levels)*
U. Illinois	UO_2	<5%	Mod. Zr	n/a	TBD	TBD	TBD	TBD	TBD
U. Tennessee	UO_2	<5%	Zircaloy	Ceramics	TBD	TBD	TBD	TBD	TBD
Georgia Tech	U_3Si_2	5-10%	FeCrAl	n/a	TBD	TBD	TBD	TBD	TBD
	Test Nat-U, 5%, 8% enriched								
Ceramic Tubular Products	UO_2	not specified; assume <5%	SiC TRIPLEX	none	300 – 400 *critical*	TBD	<1700	20, 50	TBD

- *Critical testing parameter for most concepts is peak internal clad temperature (PICT)*
- *Nominal LHGR and gas gap TBD to achieve PICT*

Fabrication line to support the fabrication and assembly of ATF-1 experiments at INL

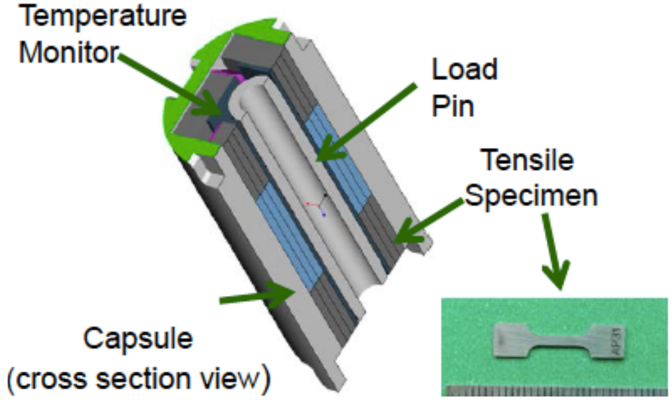
FeCrAl Development Progress

- Engineering grade materials being produced with excellent properties
- Alloy heats now fabricated by a commercial vendor
- Thin tube fabrication pursued by 3 labs with good results (LANL, ORNL, GE)
- Welding of FeCrAl demonstrated by multiple methods; results submitted for publication
- Effect of irradiation at LWR-relevant conditions on embrittlement being evaluated; initial results encouraging
- Design of in-reactor creep capsule underway
- System built, demonstrated to measure H_2 permeation
- Steam attack being evaluated
- Testing of thin-walled tube underway for technique validation

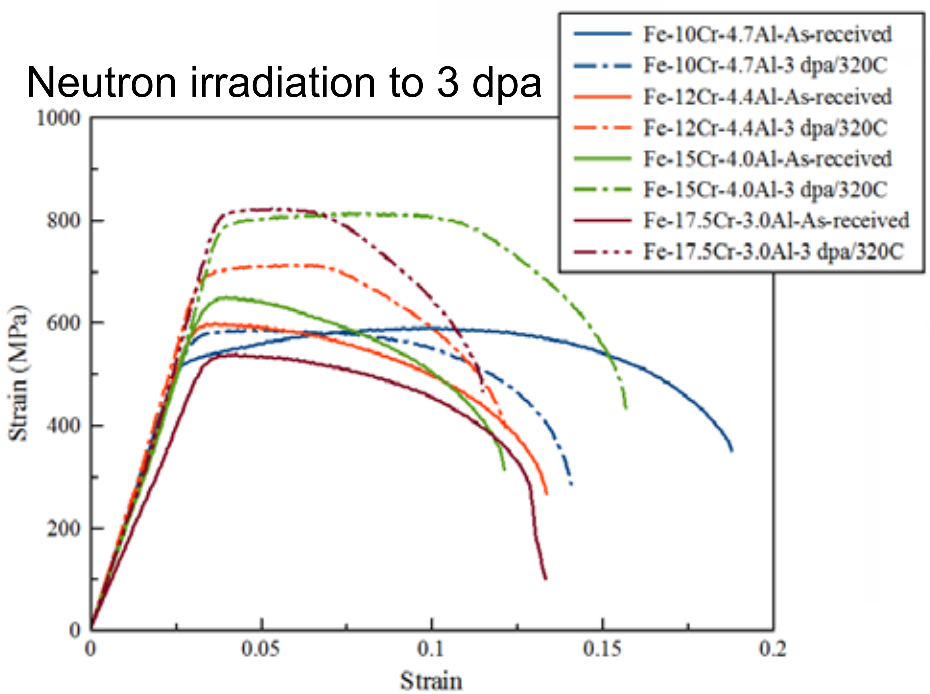


ORNL

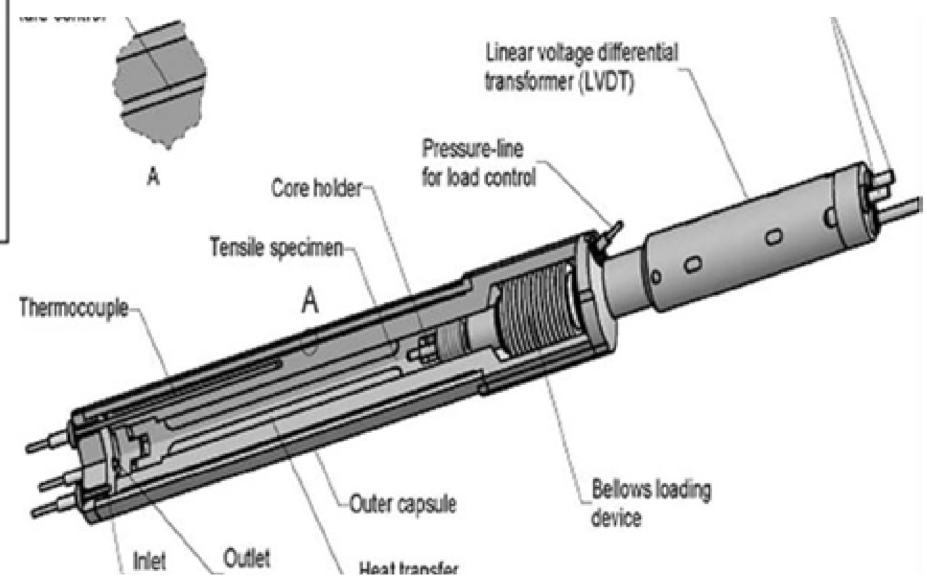
Selected FeCrAl Development Work



Neutron Irradiation Capsule and Specimen

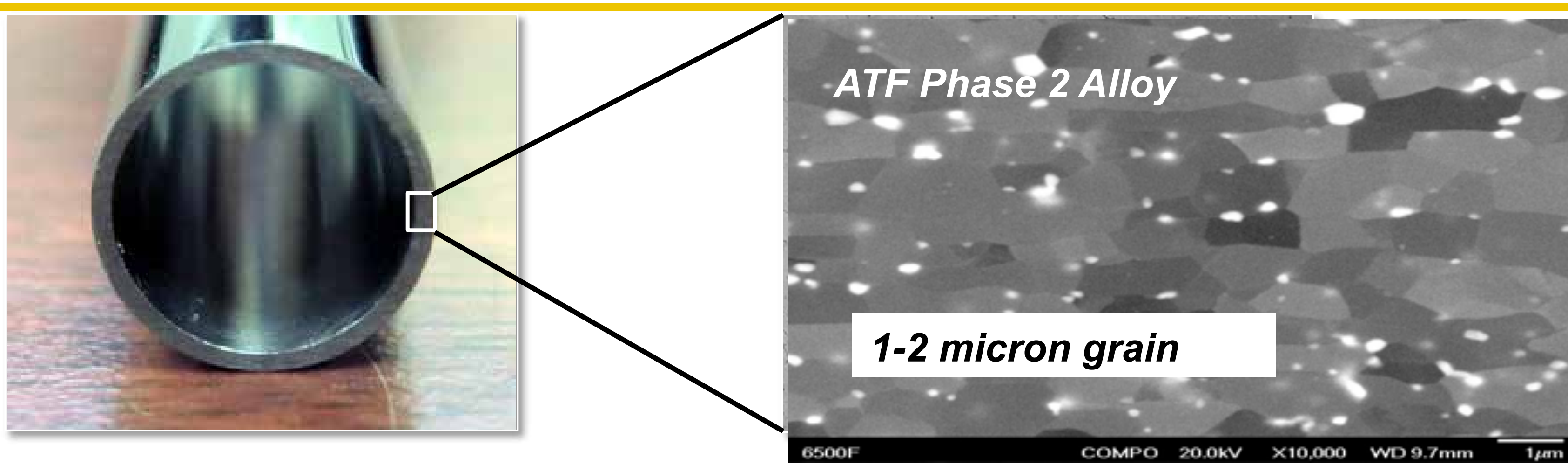


Creep Capsule Design



Development of ATF FeCrAl Alloys

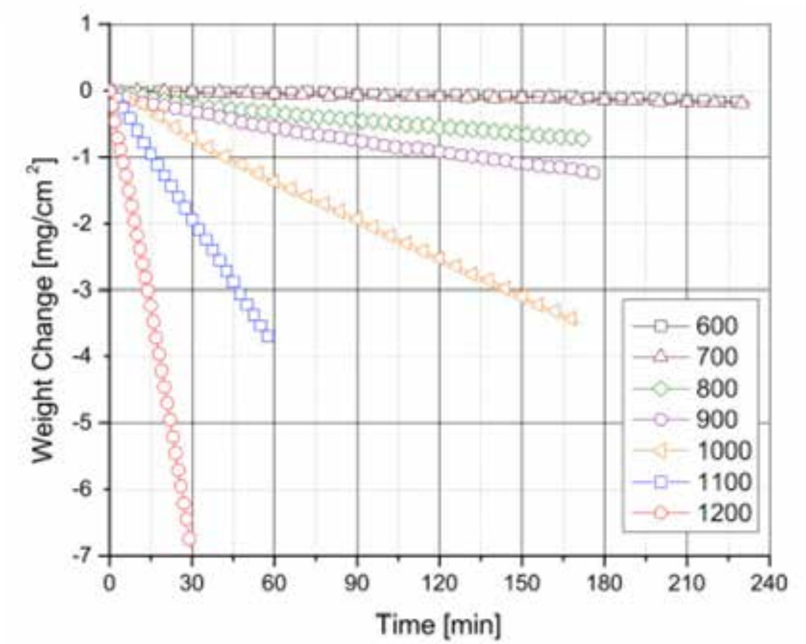
Engineering alloys have been fabricated at ORNL specifically for ATF application.



Alloy	Tested at	YS, MPa	UTS, MPa	Uniform EL, %
ORNL FeCrAl (Phase I) >30-50 micron grain	**RT**	**389 ± 38**	**483 ± 33**	**15 ± 3**
	300°C	**262 ± 8**	**399 ± 29**	**12 ± 2**
ORNL FeCrAl (Phase II) ~1 micron grain	**RT**	**629**	**811**	**12**
APMT (Fw-22Cr-5Al base)	RT	576	608	0.7
	300°C	379	680	20
Min. requirements for Zircaloy 2 or 4	RT	240	415	14
	316°C	105	215	24

Updates on Molybdenum Cladding Development

- **Initial research shows promise for production of Mo tubing by Fluidized Bed-CVD Process being optimized for production with $MoCl_5$ precursor**
- **Analysis shows that very fine grained and high purity material is produced**
- **Mo material loss governed by MoO_3 volatilization in air is greatly reduced under steam and steam plus hydrogen conditions**
  - Same mechanism as for exposure to air, but slower kinetics
- **Test results suggest strong thermochemical gradients may develop as a function of steam velocity and, potentially, test geometry**
- **Work is ongoing to quantify hydrogen production as a function of oxidation**



- *Measurements in water vapor reveal significantly degraded kinetics*
- *10,000 ppm H_2 slows volatilization rate even more*

Summary of Recent SiC Test Results

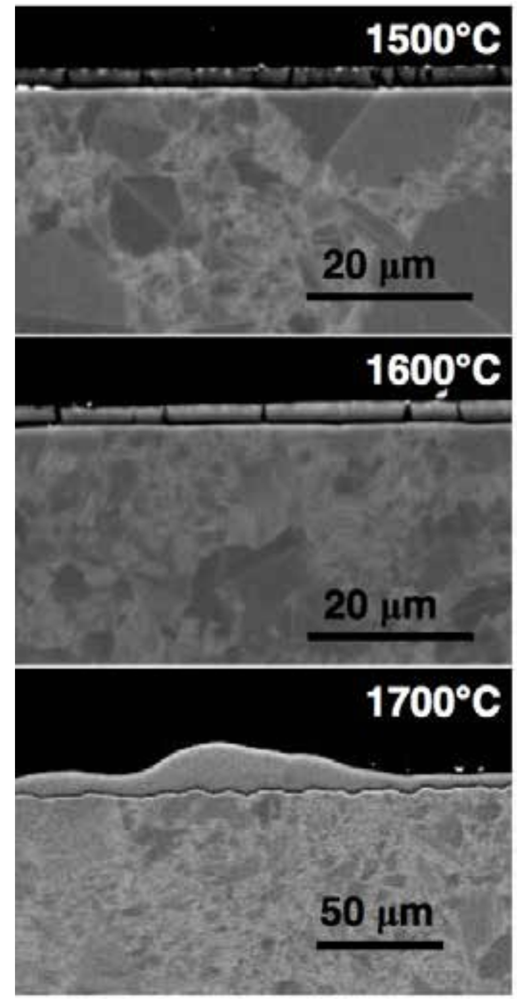
Steam Reactions:

- SiC oxidation and recession due to steam oxidation is **dependent on steam pressure and flow conditions**, yet the overall magnitude is exceptionally low.
- **SiC** materials (CVD/CVI composite) exhibit slow kinetics of reaction with high-temperature steam; at least **2-3 orders of magnitude slower parabolic oxidation rate** when compared to Zr alloys.
- The oxidation kinetics remain exceptionally **low up to ~1700ºC (< 1 mg/cm^2-h)**.
- The presence of a small extent of **microcracks** in SiC/SiC composite **does not** appear to significantly alter steam oxidation kinetics under atmospheric pressures and in an unstressed state.

Water Reactions:

- Likely limited by SiO_2 formation kinetics
- Inside the core, rapid flow is guaranteed to deplete any bulk $Si(OH)_4$
- Silica will deposit in the colder parts of the loop (T-dep dissolution)
- Oxygen activity affects recession rate
- Irradiation induced defects and stresses greatly affect material corrosion rate

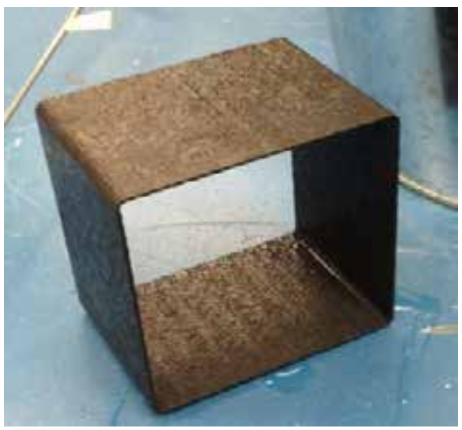
Measurement of Steam Volatilization Rate

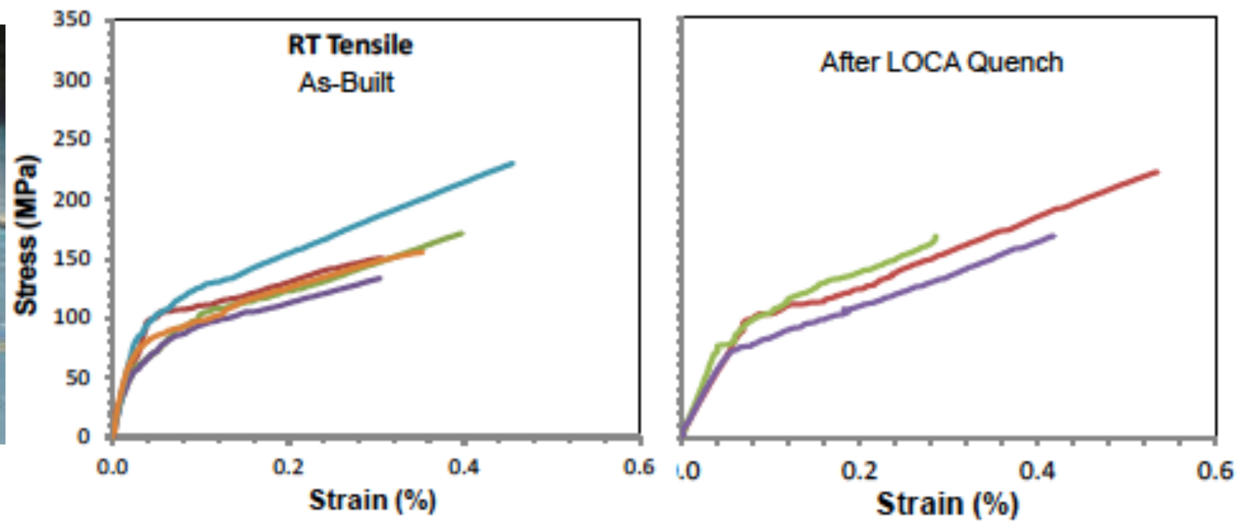


Reference: K. Terrani, ORNL, Mar 2014 AFC Integration Meeting

SiC Channel Box Development (EPRI)

Post Quench tensile tests showed no strength degradation





- SiC CMC shows excellent high temperature performance
- Irradiation of SiC CMC samples at BWR conditions in MIT Reactor:
  Creep and corrosion samples
  - No measurable coupon creep
  - Notable edge and surface degradation
    – detailed examination ongoing

Update on U.S. DOE-Supported Industry Teams – All will supply samples for ATF-1 irradiation

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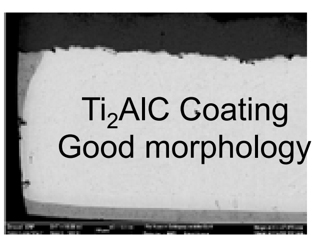
AREVA

- **Coated Zr-alloy cladding** for improved accident performance
- Increased **fuel** pellet conductivity: Fuel with reduced stored energy that must be accommodated during DBE
- Additives achieved:
  - SiC powder or whiskers
  - Diamond
  - Chromia dopant
- Initial LOCA testing of coatings (1100 °C, 4 min)

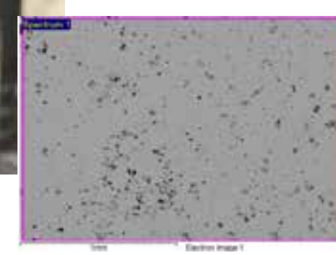


GE

- Advanced **ferritic/ martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding** to improve behavior under severe accident scenarios
- Objectives/Ongoing Tasks:
  - 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 (APMT and Alloy 33)

Westinghouse

- **Cladding** concepts: **SiC** and SiC ceramic matrix composites; **coated Zr alloys**
- **High density / high thermal conductivity fuel pellets** (e.g., uranium nitride/silicides)
- First batch of U_3Si_2 pellets were sintered using finely ground powder
- Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures

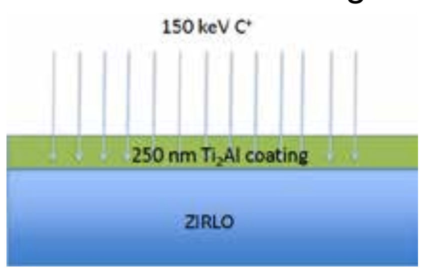


University-Led ATF Development Updates

University of Tennessee

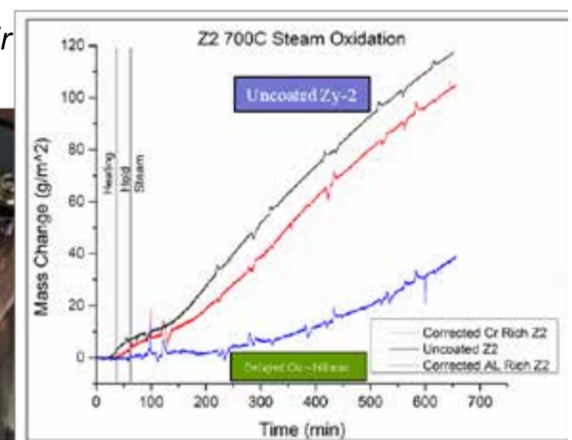
- Ceramic coatings for cladding: MAX phase and multi-layer ceramics
- Autoclave testing (300-360^{o}C, saturation P, ASTM G2)
- High temperature steam testing (1500 psi; 400, 415, 427, 500^{o}C)
- TiAlN appears to adhere well to ZIRLO but reacted with steam; thin layer of TiN may serve as a barrier
- Developing functionally graded interlayer between ZIRLO and TiAlN
- Developing MAX Phase sputtering
- Ion-beam mixing for sub-surface modification of ZIRLO – implanting *into* material vs. coating it

Autoclave Tree



University of Illinois

- Engineered Zr alloy cladding
  (i) application of a coating layer or
  (ii) modification of the bulk cladding composition to promote precipitation of minor phase(s) during fabrication
- FeCrAl coating deposition via magnetron sputtering; tested at T under steam, pre- and post-steam exposure analysis under way
- Proton irradiation at 360^{o}C to 2.2 dpa
- Supporting computational work ongoing
  - *Neutronics (various coatings)*
  - *Fuel performance – neutronics – TH code coupling*
  - *Diffusion in Zr*
  - *Deformation of Zr*



THANK YOU