Characteristics of Accident Tolerant Fuel (ATF) for LWR Applications

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Nuclear Waste Technical Review Board (NWTRB)
Web meeting, May 12-13, 2021

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U.S. DEPARTMENT OF ENERGY

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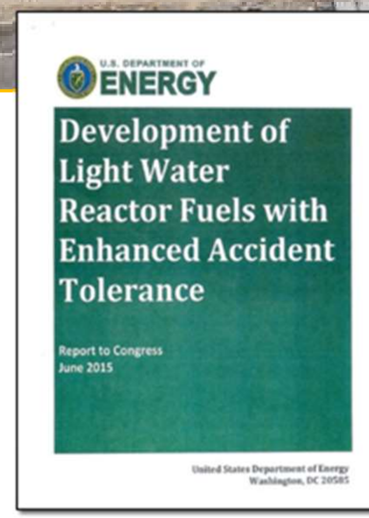
Congressional Direction to DOE and Development Plan on ATF

Following the accident at Fukushima, Congress directed the Department of Energy to begin developing fuels with enhanced accident tolerance that can be used in existing light water reactors.

The Development Plan:

- Identified attributes of accident tolerant fuels
- Laid out a 10-year schedule starting in 2012
- Established the goal of inserting Lead Test Rods/Assemblies in an operating commercial light water reactor by 2022

March 11, 2011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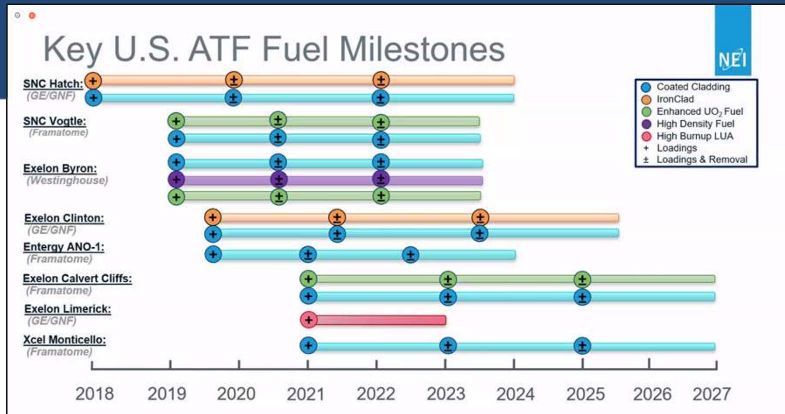
Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
June 2015

United States Department of Energy
Washington, DC 20585

Development and Qualification Progression



Lead Test Rods inserted in commercial facilities in 2019, ~3 years ahead of schedule!

Development

(2012 - 2018)

- Concept identification
- Performance evaluation (Irradiation testing)
- Manufacturing technology development

Licensing

(2019 - 2024)

- Performance demonstration (steady state and transient)
- Industry topical reports
- Regulatory approval

Deployment

(2025 -)

- Full scale fabrication
- Routine Utilization
- Economic considerations

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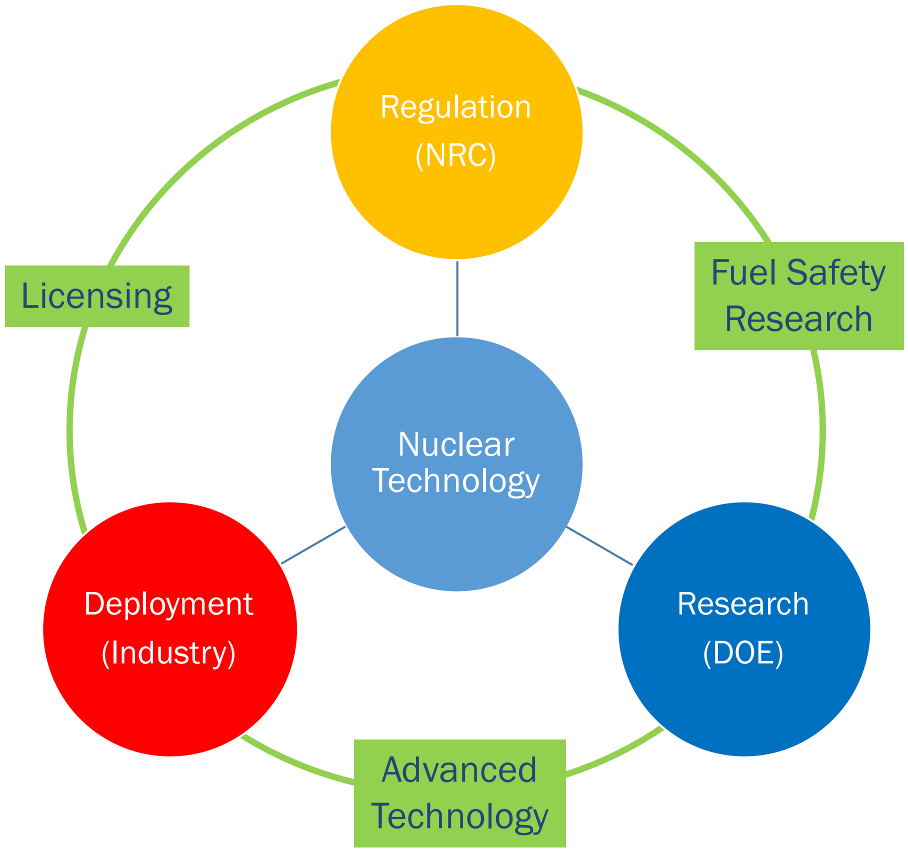
Complementary Roles in U.S. Nuclear Technology Enterprise



Complementary Roles in U.S. Nuclear Technology Enterprise

21 ATF-related Licensing Actions to date
https://www.nrc.gov/reactors/atf/licensing-actions.html

Lead Test Rods currently inserted in 8 commercial reactors

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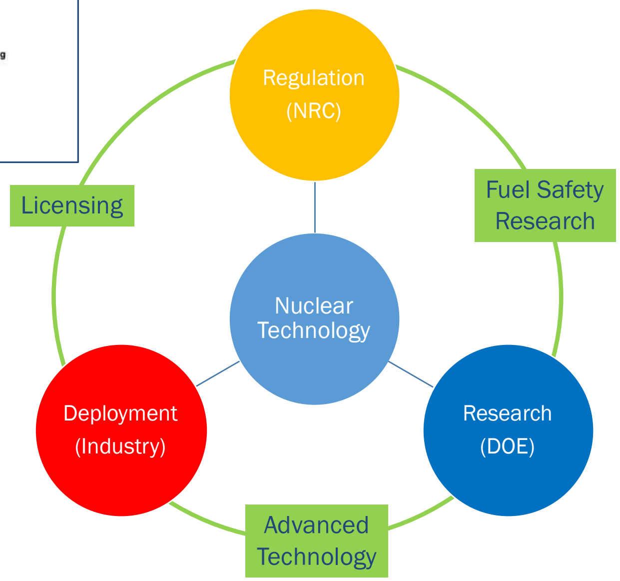
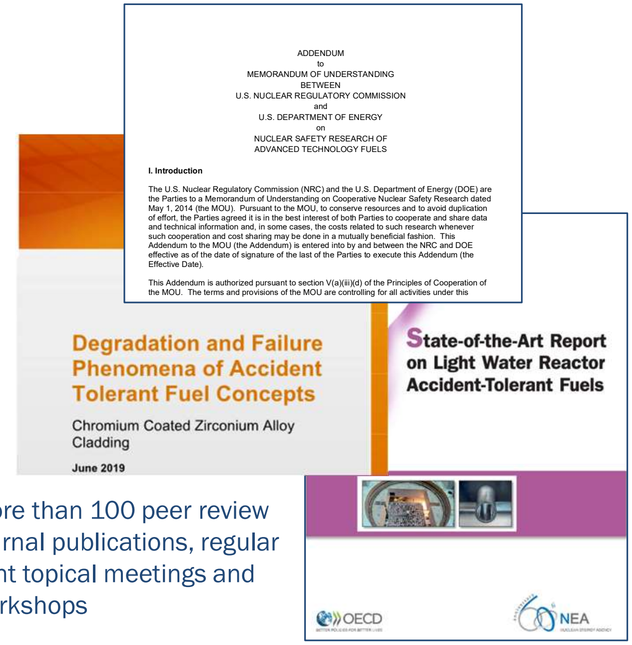




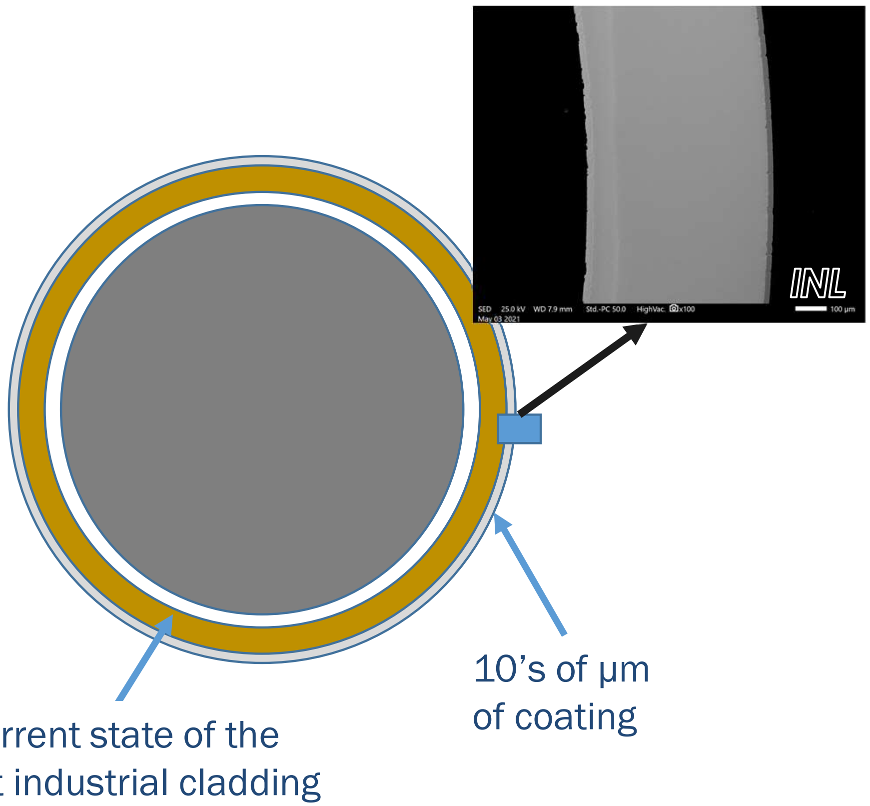
More than 100 peer review journal publications, regular joint topical meetings and workshops

DOE has established a national testbed for LWR fuel studies at the U.S. national laboratories

100's of technical milestone reports emphasizing fuel performance assessment, characterization, and modeling

Near Term Technology Descriptions (1/2)

Coated Zr Cladding



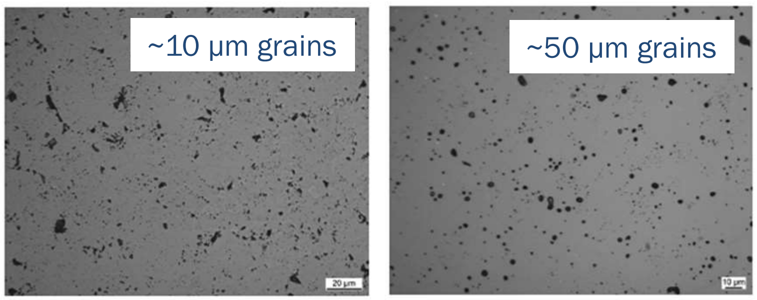
- Coated cladding is intended to
  - Reduced oxidation and hydrogen release when exposed to steam under LOCA or severe accident conditions
  - Minimize in-service oxidation
    - Lower cladding wastage
    - Reduced hydrogen pickup in cladding
    - Improved mechanical properties (primarily ductility)
  - Improved resistance to fretting

- R&D Needs
  - Demonstration of diffusion barrier function (oxygen and hydrogen)
  - Development of manufacturing processes
  - Demonstration of adhesion/stability throughout lifecycle
  - Understanding impact of coating defects
  - Demonstrate enhanced integral performance under DBA (and Severe accident) transients

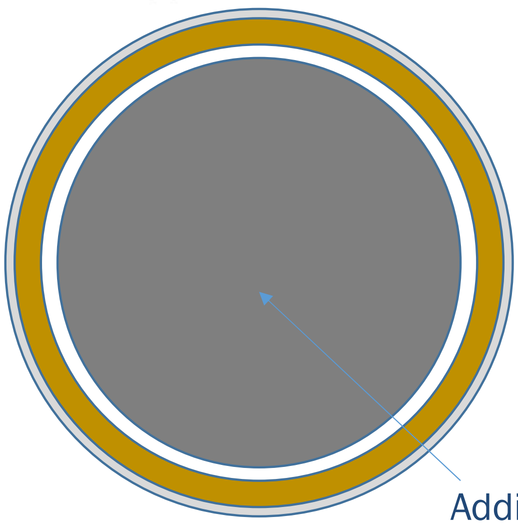
*Image from independently produced PVD coated Zr-4

Near Term Technology Descriptions (2/2)

Enhanced Pellet



(a) Std Opt2 pellets (b) ADOPT pellets



Additives or fabrication process history increased grain size

- Enhanced pellets are intended to
  - Increase pellet density
    - Greater U content
    - Less densification
  - Earlier pellet-cladding gap closure
    - Lower integrated centerline temperature and fission gas release
    - Earlier pellet-clad bonding and onset of 2-sided oxidation
  - Minimal change in thermo-physical properties (although thermal conductivity can be mildly reduced)
  - Improved PCI performance due to increased pellet plasticity
  - Higher resistance to post-failure degradation (reduced oxidation in water)

- R&D Needs
  - Enhancing microstructure-based fuel performance models to account for irradiation history effects on HBu properties
  - Demonstration of integral DBA behavior and relative FFRD phenomena

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*Images from ARBORELIUS, J, et al. (2006) Advanced Doped UO2 Pellets in LWR Applications, Journal of Nuclear Science and Technology, 43:9, 967-976, DOI: 10.1080/18811248.2006.9711184

WEC Concepts (PWR)

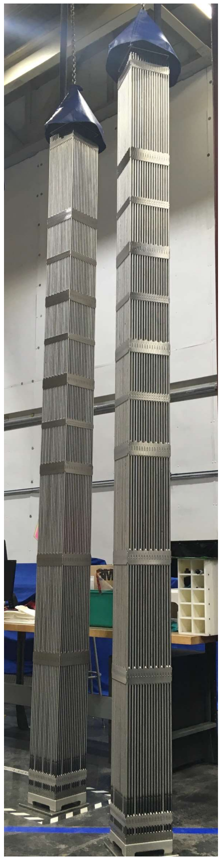
- Near-term ATF Concept (EnCore ® Fuel Program)
  - Cr-coated Zirlo cladding
    - Cr layer Applied by cold spray technique followed by polishing
    - New failure mode possible due to Zr-Cr eutectic that forms at ~1300ºC.
  - Doped-UO_2 pellet design (ADOPT™)
    - Cr_2O_3+Al_2O_3 doped UO_2 pellet
    - Product deployed in Europe for ~15 years. The strategy for the licensing of ADOPT fuel in the US includes two topical reports:
      - (1) A near-term topical report submittal seeking approval for the use while crediting minimal material performance enhancements
      - (2) a longer-term topical report submittal that will seek to fully credit all the performance enhancements.

- Long Term ATF Concept
  - Development of high density pellets (UN)
    - Very high uranium density provide improved fuel cycle economics
    - Increased thermal conductivity result in lower operating temperatures and should result in reduced fission gas release
    - Evaluating fuel performance and stability in high temperature water

Chromium-Coated Zr Cladding

ADOPT™ Pellets

Spring 2019 Byron Unit 2: Cr Coated Cladding with ADOPT



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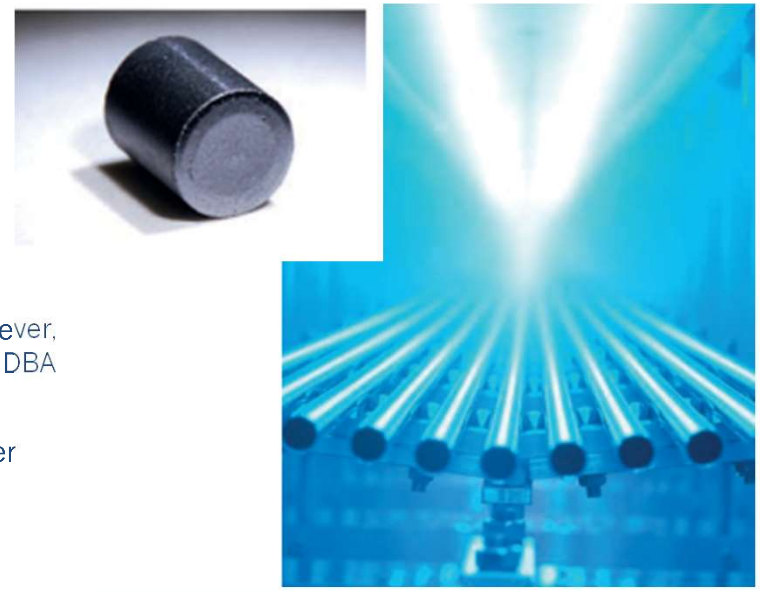
Framatome Concepts (PWR and BWR)

- Near Term ATF Concept ("PROtect")
  - Cr-coated M5 alloy
    - 8-22 μm thick Cr coating applied using physical vapor deposition (PVD)
    - Demonstration testing underway
      - Lead Test rods are in commercial plants
      - Test rodlets are in ATR
    - New failure mode possible due to Zr-Cr eutectic that forms at ~1300ºC. However, this is higher than the current cladding temperature limit of 1200ºC during a DBA
  - Chromia-enhanced Fuel Pellets
    - Doping the UO_2 pellet with small amounts of Cr_2O_3 leads to formation of larger grains in the microstructure
    - Commercially deployed LTAs in the US. Topical report submitted to NRC for licensing.



- Long Term ATF Concept
  - SiC composite cladding for PWRs
    - 3 layer system (Zr liner, SiC-SiC composite, Cr coating)
    - Very low oxidation under high temperature steam, high mechanical strength at high temperature, high melting temperature
  - SiC channel boxes for BWRs

Metallographic cross-section of Cr-coated M5 Cladding tube before irradiation

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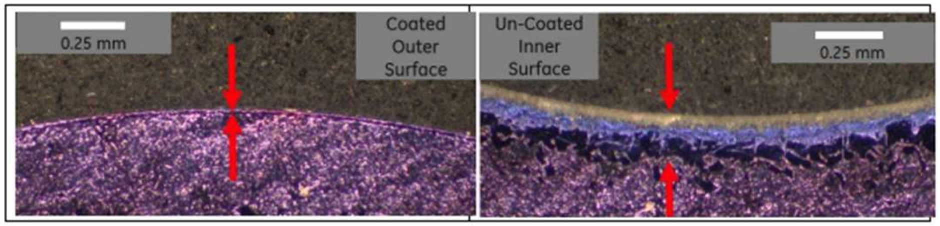
GE/GNF Concepts (BWR)

- Near-term ATF Concept ("ARMOR")
  - Coated Zr-2 cladding
    - Specific attributes of coating (composition, thickness, manufacturing process) are proprietary
    - Demonstration testing underway
      - Lead Test rods of Gen-1 design are in commercial plants
      - Test rodlets are in ATR (PWR loop)



Comparison of ARMOR-coated and and un-coated surface after exposure to steam at 1000°C for 5000 sec

- Long Term ATF Concept ("IRONCLAD")
  - FeCrAl alloy cladding
    - Evaluating multiple compositions
    - Ferritic alloys offer resistance to stress corrosion cracking from the coolant side, high thermal conductivity and low coefficient of thermal expansion.
    - Ferritic steels also exhibit higher strength than current zirconium alloys at reactor temperatures, allowing for thinner tube wall thickness, to diminish the neutron penalty.
    - Significantly improved materials properties over Zr at temperature greater than 1200°C (thus enhanced severe accident performance)
  - CMC channel boxes for BWR
  - Advanced ceramic fuels (next generation dopants)

Note: Irradiation performance of coating in BWR coolant chemistry still under evaluation

TABLE 1. Nominal Compositions of FeCrAl (in mass percent, balance is Fe).

Alloy	Cr	Al	Others
APMT	21	5	3Mo
C26M	12	6	2Mo + 0.05Y

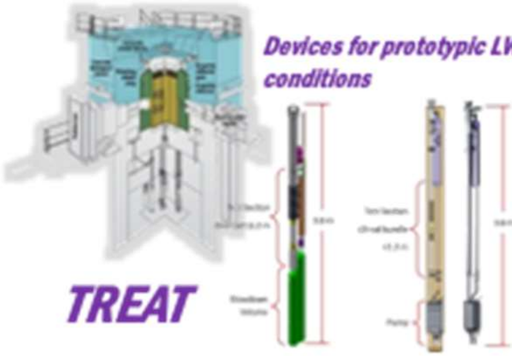
ATF Irradiation Testing Program

Test Series	ATF-1	ATF-2	ATF-3	ATF-H-x	CM-ATF-x	ATF-y
Test Reactor	ATR	ATR	TREAT	~~Halden~~	Commercial Reactors	TREAT
Test Type	Drop-in	Loop	Static/Loop	Loop	LTR/LTA	Loop
Test Strategy	Scoping Many Compositions	Prototypic Cladding and Integral Fuel Concepts	Focused	Focused	Mature concepts	Mature concepts
	Nominal conditions	Nominal conditions	Off-normal conditions	**Limiting Conditions**	Nominal conditions	Off-normal conditions
Fuel	UO_2*, U_3Si_2					
Cladding	Zr w/coatings, Fe-based alloys, advanced alloys, SiC	Promising concepts	Fresh fuel and rodlets conditioned in ATF-1 and ATF-2 irradiations	Promising concepts	Promising near-term concepts	Rods conditioned in LTR/LTA irradiations
Key Features	Fuel and fuel-cladding interactions	PWR conditions	RIA, LOCA	**BWR conditions, ramp testing, run to failure**	Prototypic testing	RIA, LOCA
Timeframe	FY15 – FY20+	FY18 – FY22+	FY19 – FY25+	FY20 – ?	FY18/19 – ?	FY22 – ?

Recommendations from
Halden Gap Assessment

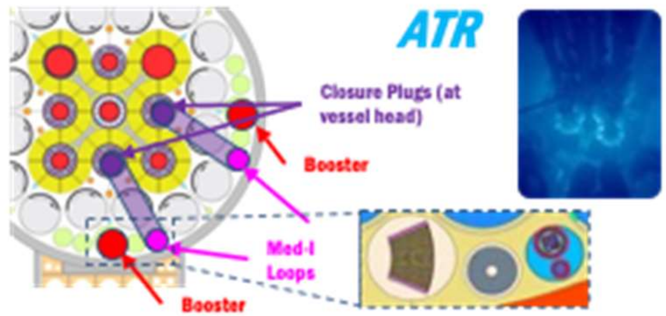
Halden Gap Assessment with Recommendations

1) Accelerate LOCA testing capability at TREAT



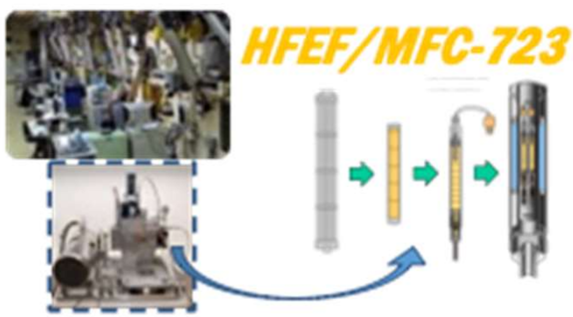
Devices for prototypic LWR design basis accident conditions

2) Expand water loop capacity with ramp testing capability at ATR



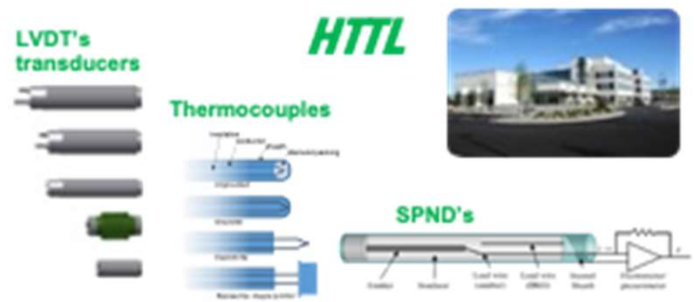
Prototypic environments for operational transient experiments to failure and BWR conditions

3) Establish re-fabrication/ instrumentation capability



Refabrication and reinstrumentation of fuel irradiated in nuclear power plants

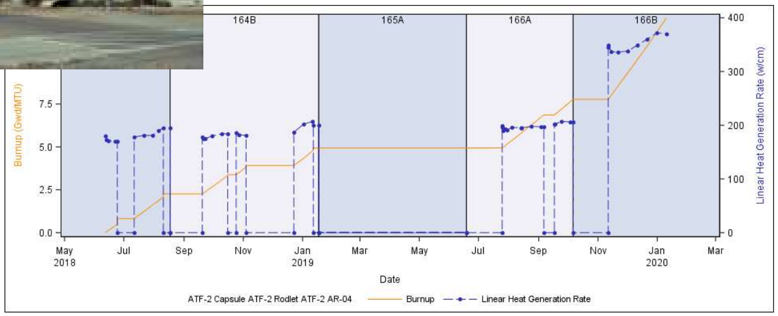
4) Deploy reliable advanced in-pile instrumentation



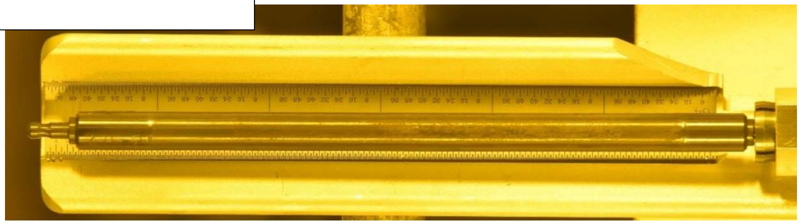
Dedicated instrumentation development with specific focus on in-pile test reactor deployment

Status of Irradiations in ATR and TREAT

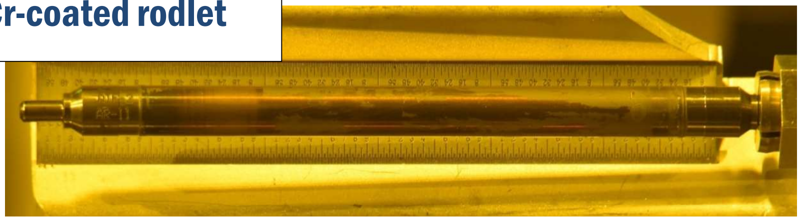
- ATF-1 Dry Capsule Tests
  - Continuing for low TRL technologies
- ATF-2 PWR Loop Tests
  - 19 Cr-Coated rods and 14 reference Zircaloy rods have been irradiated
    - 14 low burnup rods (9-14 MWd/kgU) sent to INL hotcells for PIE in 2020
    - 10 more medium burnup rods (14-30 MWd/kgU) being shipped in fall of 2021
- Core-Internals-Changeout (CIC)
  - Began in March 2021 (scheduled for 274 days, ~9 months)
- Development of additional PWR/BWR loops underway ('i-loops')



Uncoated rodlet



Cr-coated rodlet



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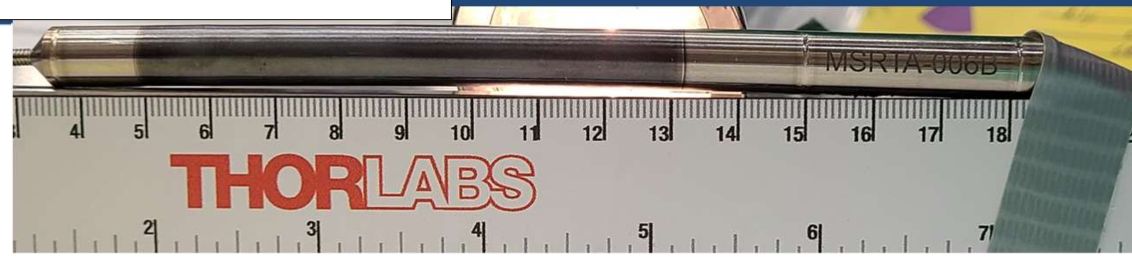
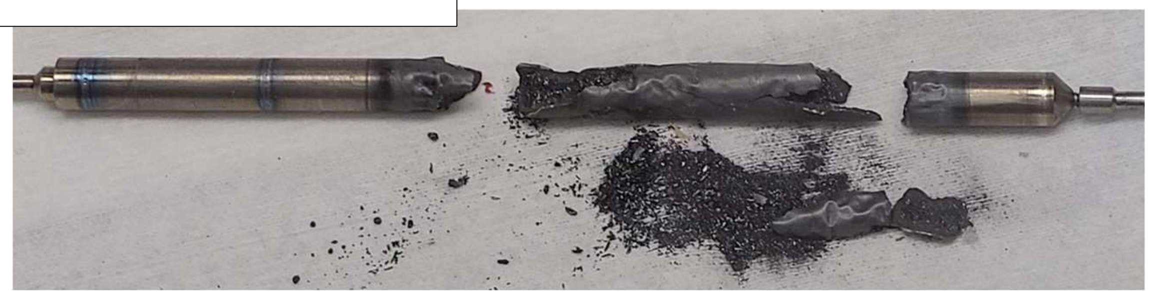
Transient Testing

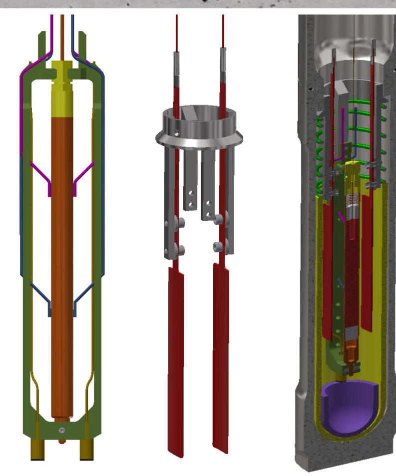
- TREAT
  - First RIA tests on ATF performed in FY19
  - Preparations for LOCA testing underway (FY22)
- Testing with baseline rods completed last fall (UO_2-Zr4)
- Testing with Irradiated ATF-2 rod (UO_2-Zr4) planned for Summer 2021
- Testing with Cr-Coated Cladding (UW-NSUF Project) in an improved capsule planned for early 2022

Energy Deposition ~870 J/g



Energy Deposition ~1108 J/g





Rendering of TREAT RIA Test Capsule

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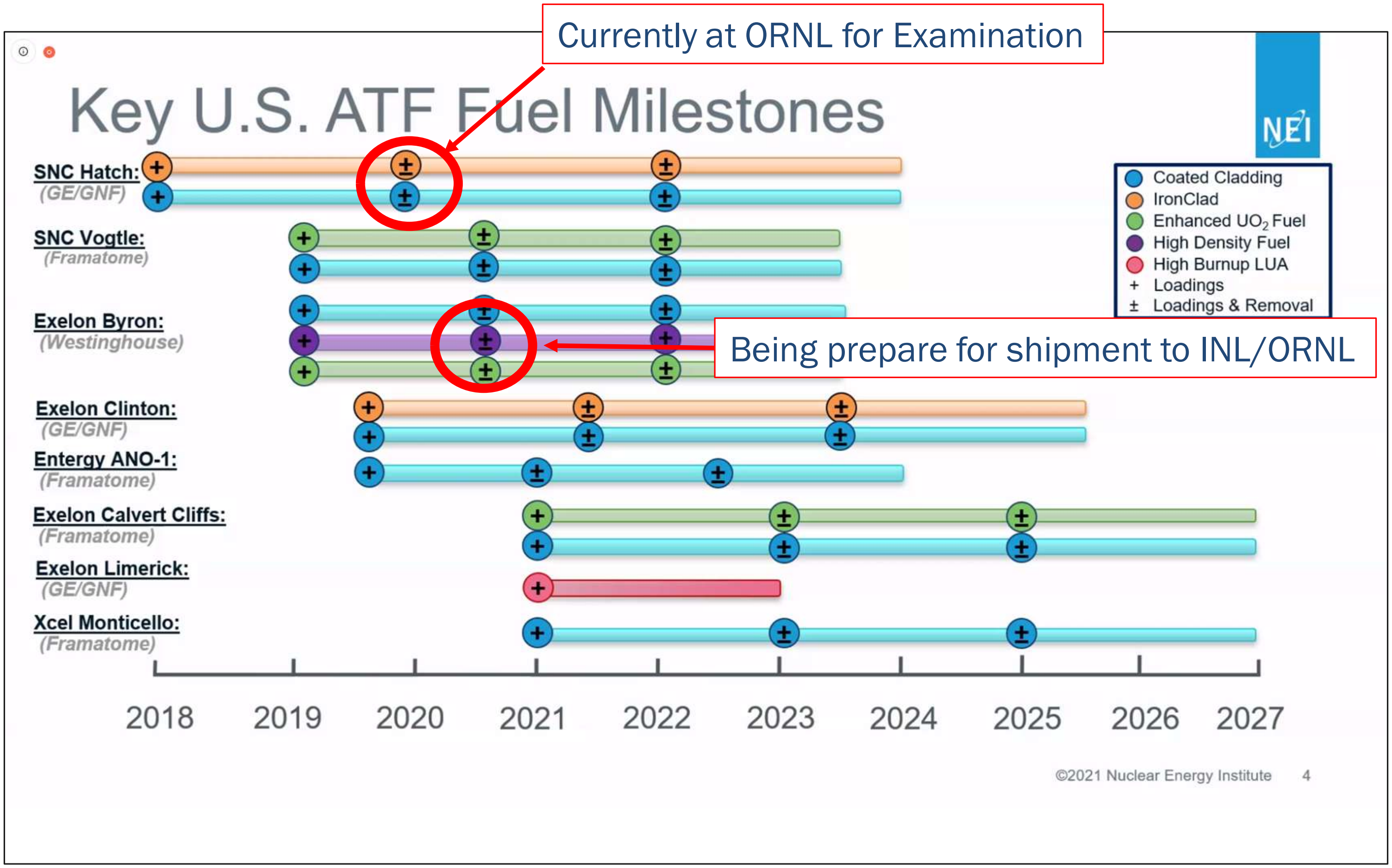
LTA/R Insertion Status

- Lead Test Rods (LTRs) for each near term concept are currently under irradiation in commercial reactor facilities
- Rods will be sent to hot cells at INL and ORNL for examination
- Subsequent R&D to support disposition and storage is possible



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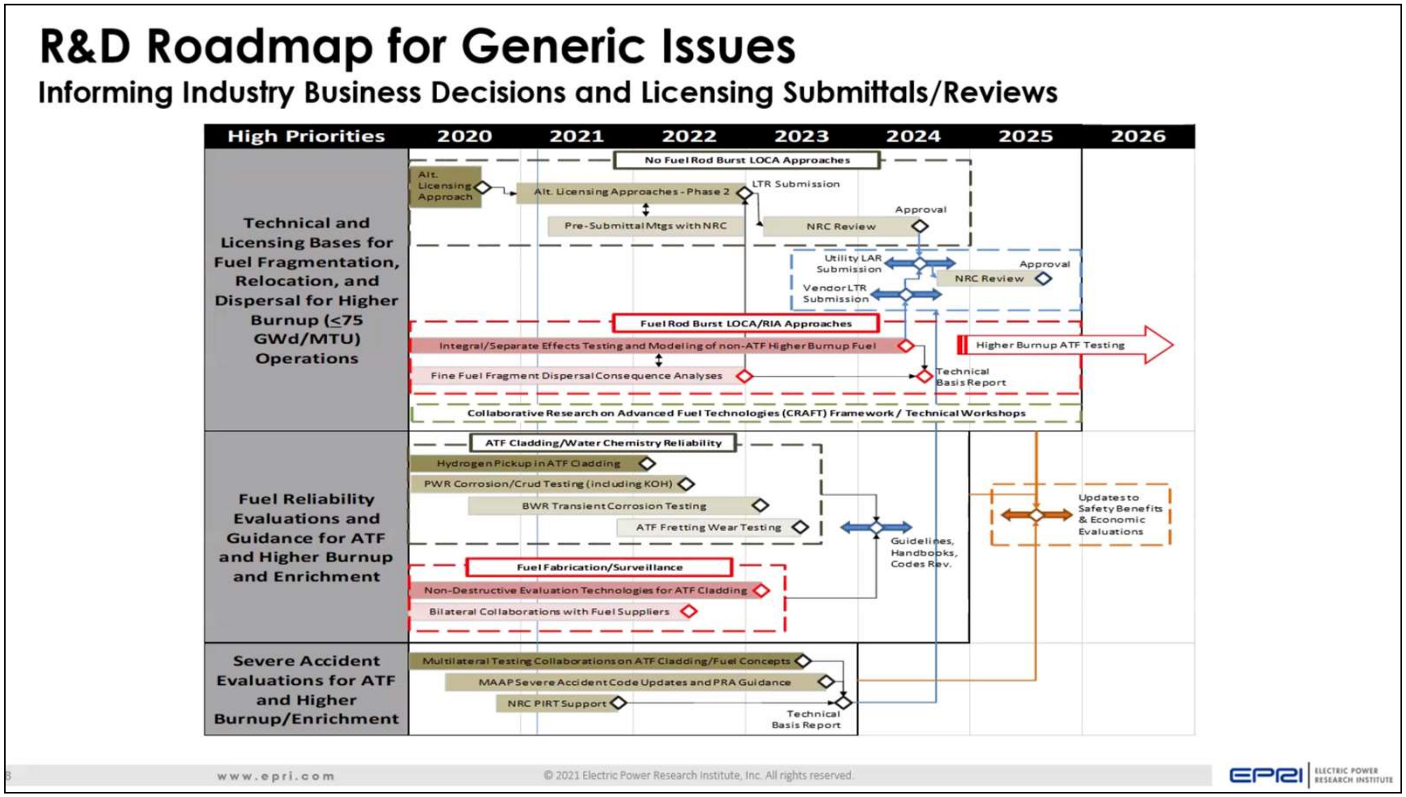
Burnup Extension

- Economic considerations associated with adopting ATF technology are expected to be offset by burnup extension & enrichment increase
- Vendors are already submitting topical reports to extend burnup to 65-68 GWD/MTU
- Request for extension to ~75 GWD/MTU expected in 2020's
  - Pending resolution of HBu LOCA performance questions



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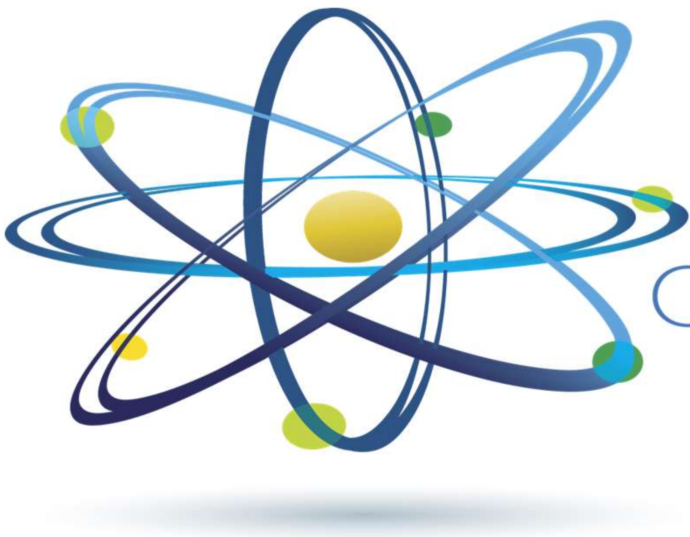
International Collaborations

- Commercial fuel vendor teams are utilizing their extensive international network to support development and licensing activities.
- The DOE ATF program collaborates with many international partners
  - NEA organized committees including the Working Group for Fuel Safety and the Nuclear Science Committee. These interactions have supported development of several ATF assessments and reports.
  - Fuel safety testing collaborations with IRSN (TREAT-CABRI) and JAEA (TREAT-NSRR)
  - Preparing for joint irradiation campaign in ATR with JAEA
  - Participation in international joint projects including Halden Reactor Project, FIDES, SCIP, SPARE, QUENCH

Conclusions

- Key nuclear fuel technology stakeholders are collaborating on the development and deployment of ATF including the research, industrial, and regulatory sectors.
- Key milestone to deploy ATF LTRs by 2022 exceeded by 3 years
- Significant irradiation testing ongoing using both research reactors and commercial lead test rods
- Batch reloads of near term concepts to be deployed by mid-2020's
  - Focus on coated claddings and enhanced UO_2 pellet concepts
  - Long term concepts still in development phase
- Burnup extension and increased enrichment progressing in parallel to enhance economics of ATF utilization



Clean. **Reliable. Nuclear.**

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DOE-sponsored, Industry-led Development of ATF Concepts

Framatome

- ‘PROtect’
  - *Cr-coated M5 cladding*
  - *Cr Doped UO_2*
- ‘Long term’
  - *SiC cladding*

General Electric

- ‘ARMOR’
  - *Coated Zr cladding*
- ‘Long term’
  - *Iron-based cladding (FeCrAl)*
  - *ODS variants for improved strength*

GE imagination at work

Westinghouse

- ‘EnCore’
  - *Cr-coated Zirlo/AXIOM cladding*
  - *ADOPT Fuel Pellet*
- ‘Long term’
  - *SiC cladding*
  - *High density fuel pellets*