



Characteristics of Accident Tolerant Fuel (ATF) for LWR Applications

Dr. Daniel Wachs
National Technical Director, Advanced Fuels Campaign
Idaho National Laboratory

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



Congressional Direction to DOE and Development Plan on ATF

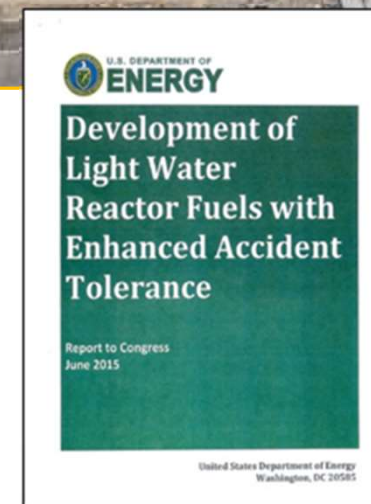
Following the accident at Fukushima, Congress directed the Department of Energy to begin developing fuels with enhanced accident tolerance that can be used in existing light water reactors.

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**



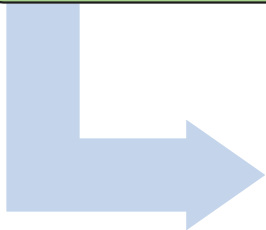
March 11, 2011



Development and Qualification Progression

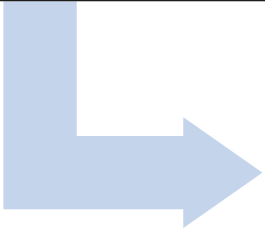
Development
(2012 - 2018)

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



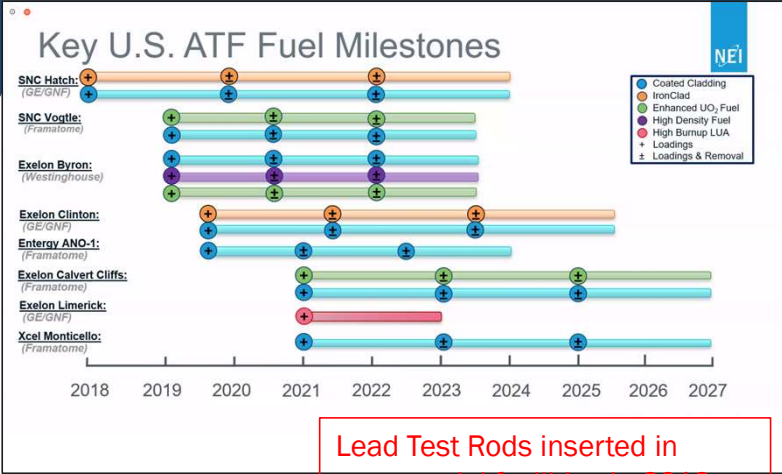
Licensing
(2019 - 2024)

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



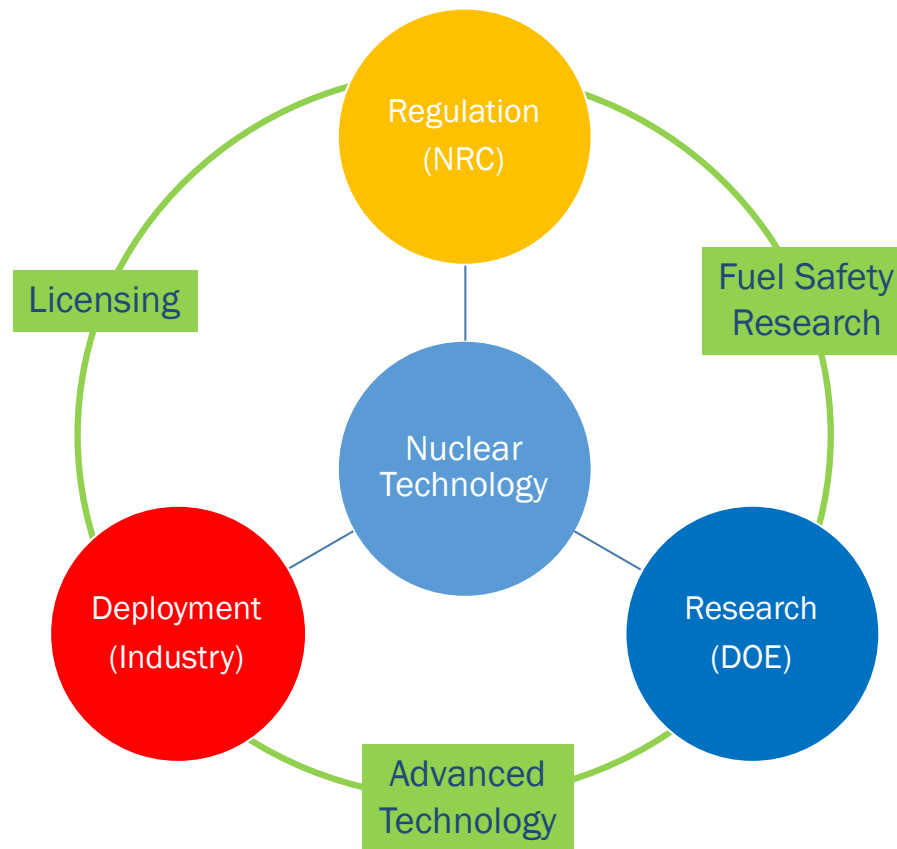
Deployment
(2025 -)

- Full scale fabrication
- Routine Utilization
- Economic considerations




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

Complementary Roles in U.S. Nuclear Technology Enterprise



Complementary Roles in U.S. Nuclear Technology Enterprise




ATF-ISG-2020-01
 Supplemental Guidance Regarding the
 Chromium-Coated Zirconium Alloy Fuel Cladding
 Accident Tolerant Fuel Concept
 Interim Staff Guidance
 January 2020



**PROJECT PLAN TO PREPARE
 U.S. NUCLEAR REGULATORY
 COMMISSION FOR EFFICIENT
 LICENSING OF
 ACCIDENT TOLERANT FUEL**
 Version 1.0



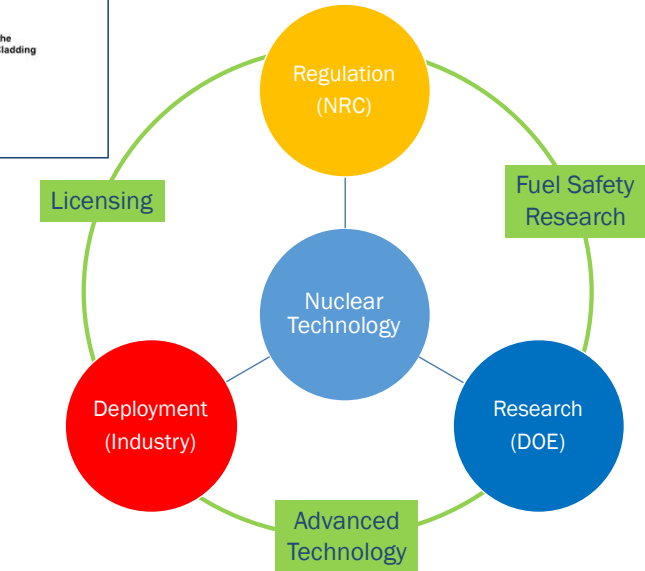
**Licensing Topical Report
 Additive Fuel Pellets for**



Proprietary Information - Withheld Under 10 CFR 2.306.
 December 12, 2019
 U.S. Nuclear Regulatory Commission
 ATTN: Document Control Desk
 Washington, DC 20555-0001



June 15, 2020
 TJT-20-016
 U.S. Nuclear Regulatory Commission
 Attn: Document Control Desk
 Director, Division of Spent Fuel Management
 Office of Nuclear Material Safety and Safeguards
 11555 Rockville Pike
 One White Flint North
 Rockville, MD 20852
Subject: Letter Authorization Application Utilizing Certificate USA/9372/B(UF-96 for Model No. TN-B1 Transport Package
 References: (1) U.S. Nuclear Regulatory Commission, Certificate of Compliance No. 9372, Revision No. 2, for the Model No. TN-B1 Package
 (2) Framatome TN-B1 Safety Analysis Report, FS1-0014159, Revision B, Docket No. 71-9372
 Framatome Inc. (Framatome), is submitting a letter authorization request utilizing Certificate of Compliance No. 9372 for the TN-B1 packaging. This request is to provide for the safe transport of a small number of Framatome boiling water reactor ATRUM 10XM (FANP 10x10) fresh fuel assemblies equipped with inert test rods supporting the development of Enhanced Accident Tolerant Fuels (eATF).




ADDENDUM
 to
 MEMORANDUM OF UNDERSTANDING
 BETWEEN
 U.S. NUCLEAR REGULATORY COMMISSION
 and
 U.S. DEPARTMENT OF ENERGY
 on
 NUCLEAR SAFETY RESEARCH OF
 ADVANCED TECHNOLOGY FUELS

I. Introduction
 The U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) are the Parties to a Memorandum of Understanding on Cooperative Nuclear Safety Research dated May 1, 2014 (the MOU). Pursuant to the MOU, to conserve resources and to avoid duplication of effort, the Parties agreed it is in the best interest of both Parties to cooperate and share data and technical information and, in some cases, the costs related to such research whenever such cooperation and cost sharing may be done in a mutually beneficial fashion. This Addendum to the MOU (the Addendum) is entered into by and between the NRC and DOE effective as of the date of signature of the last of the Parties to execute this Addendum (the Effective Date).
 This Addendum is authorized pursuant to section VI(a)(1)(6) of the Principles of Cooperation of the MOU. The terms and provisions of the MOU are controlling for all activities under this

**Degradation and Failure
 Phenomena of Accident
 Tolerant Fuel Concepts**
 Chromium Coated Zirconium Alloy
 Cladding
 June 2019

**State-of-the-Art Report
 on Light Water Reactor
 Accident-Tolerant Fuels**



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



DOE Awards \$111 Million to U.S. Vendors to Develop Accident Tolerant Nuclear Fuels
 JANUARY 21, 2019

WASHINGTON, D.C. – The U.S. Department of Energy's (DOE) Office of Nuclear Energy (NE) has awarded \$111 million to three industry partners to develop Accident Tolerant Fuels (ATF) General Electric (GE), Westinghouse (WGL) and Framatome received the financial assistance awards in late 2018 with FY18 and FY19 funding. The period of performance for these awards goes through January 31, 2020 with DOE and NE planning additional funding of \$554 million in FY20 and \$30 million in FY21, contingent upon Congressional approval.

Accident Tolerant Fuels are intended to directly and substantially further enhance nuclear fuel reliability and safety, as well as the economics of nuclear reactor operations. The improved heat tolerance of ATF contributes to significantly improved reactor safety and security. ATF also improves economics due to improved heat tolerances and increased ability to power reactors up and down while staying within safety margins.

"Nuclear energy remains a critical component of our 'all-of-the-above' energy strategy and is imperative to our country's energy and national security," said U.S. Secretary of Energy Rick Perry. "The successful development of Accident Tolerant Fuels will enhance the safety and efficiency of our nuclear fleet, which will, in turn, enhance the overall reliability of our energy system."

"We are very pleased with the success of the accident tolerant fuel program to date and its

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

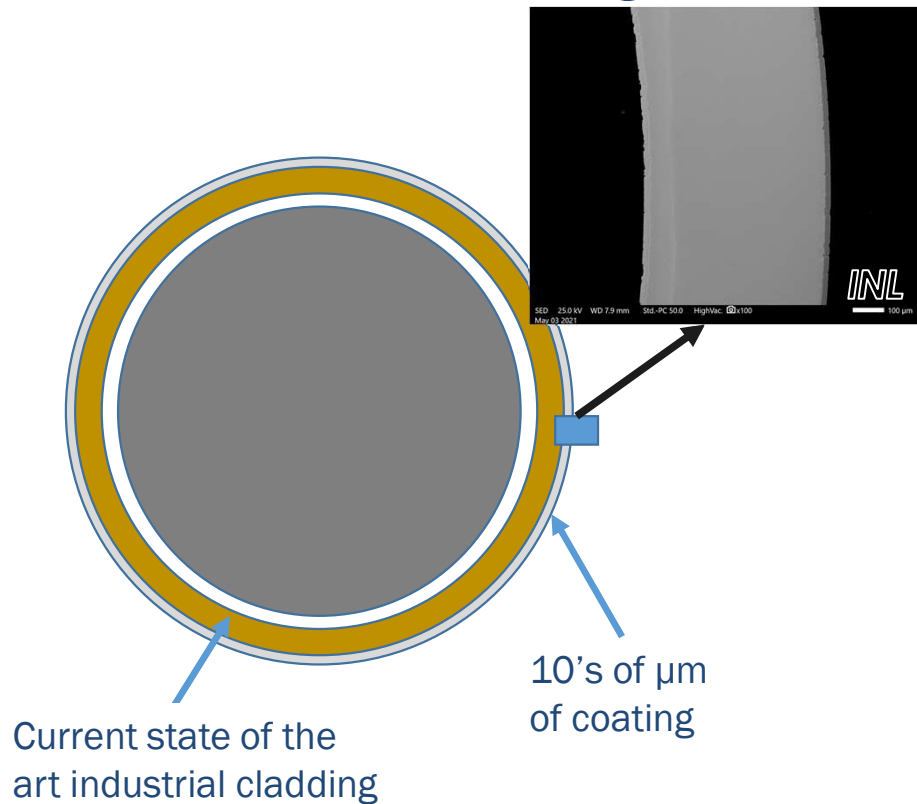
21 ATF-related Licensing Actions to date
<https://www.nrc.gov/reactors/atf/licensing-actions.html>

Lead Test Rods currently inserted in 8 commercial reactors



Near Term Technology Descriptions (1/2)

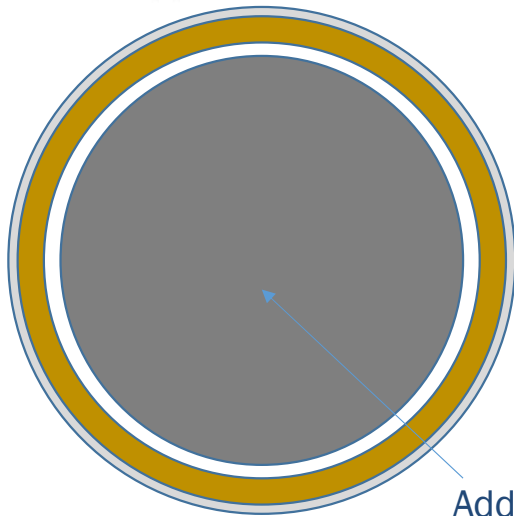
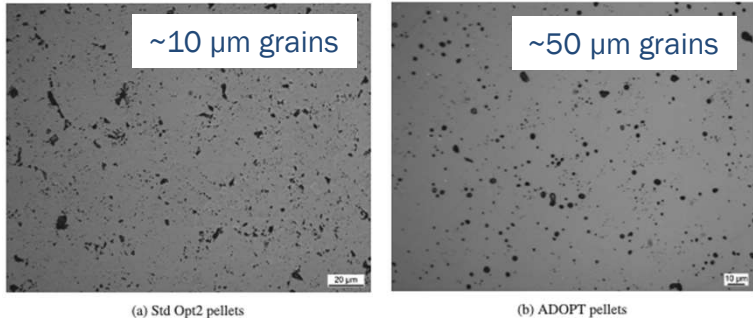
Coated Zr Cladding



- 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

Near Term Technology Descriptions (2/2)

Enhanced Pellet



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

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 ~1300°C.
 - Doped-UO₂ pellet design (ADOPT[™])
 - Cr₂O₃+Al₂O₃ doped UO₂ 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

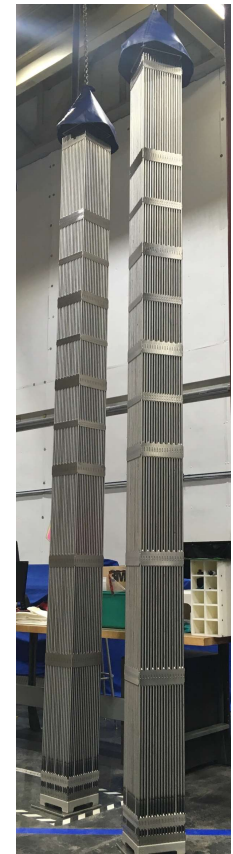
Chromium-Coated Zr Cladding



ADOPT[™] Pellets



Spring 2019 Byron Unit 2:
Cr Coated Cladding with
ADOPT



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 $\sim 1300^\circ\text{C}$. However, this is higher than the current cladding temperature limit of 1200°C 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

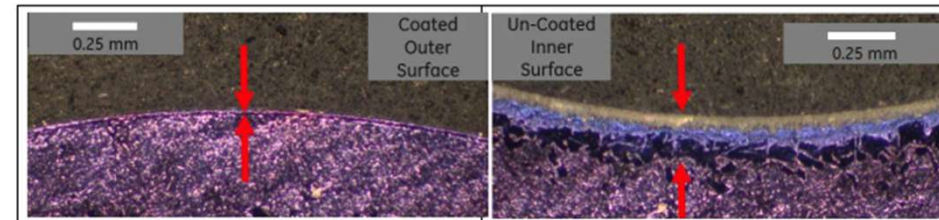
GE/GNF Concepts (BWR)

- 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)

- 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)



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

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 ₃ Si 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 - ?

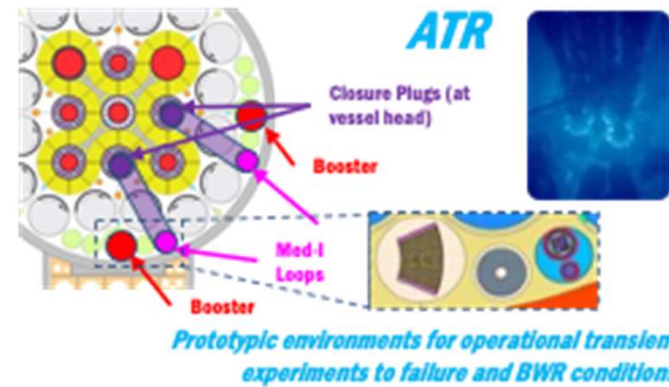
Halden Gap Assessment with **Recommendations**



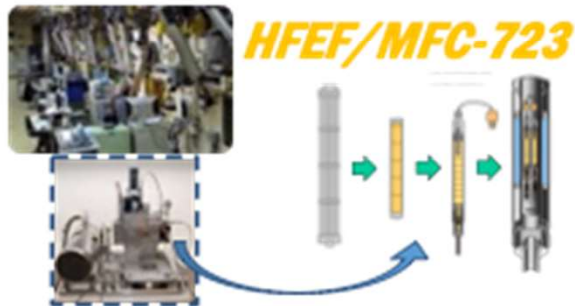
1) Accelerate LOCA testing capability at TREAT



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

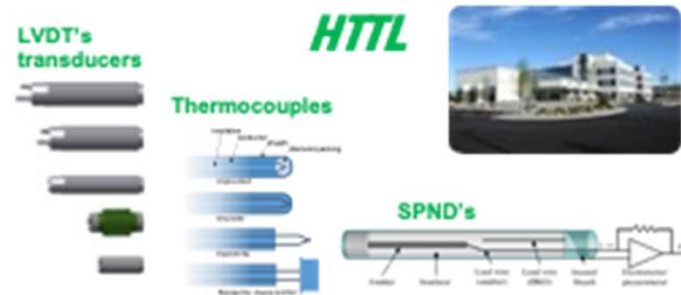


3) Establish re-fabrication/ instrumentation capability



Refabrication and re-instrumentation of fuel irradiated in nuclear power plants

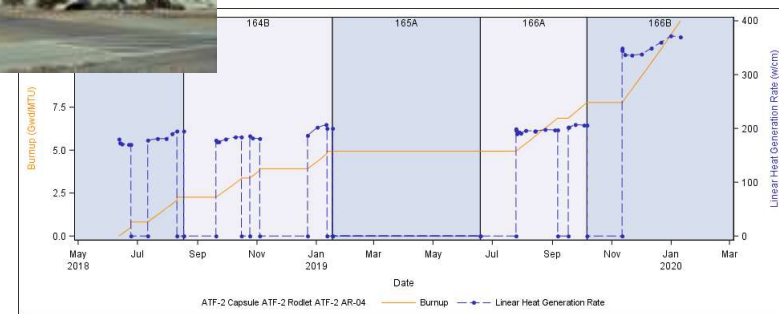
4) Deploy reliable advanced in-pile instrumentation



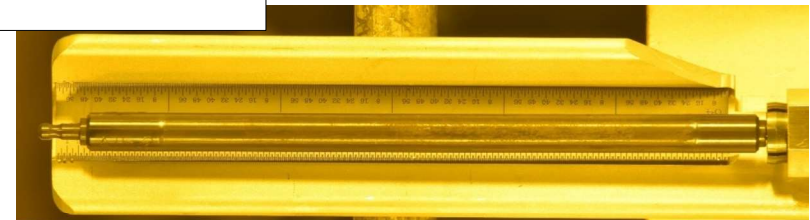
Dedicated instrumentation development with specific focus on in-pile test reactor deployment

Status of Irradiations in ATR and TREAT

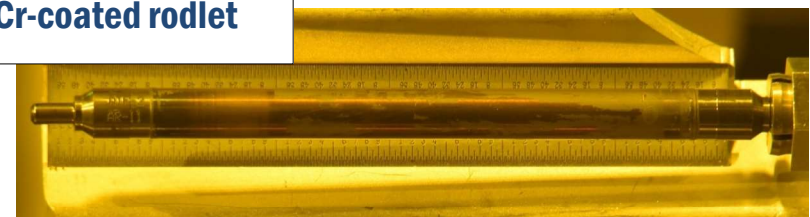
- ATF-1 Dry Capsule Tests
 - Continuing for low TRL technologies
- ATF-2 PWR Loop Tests
 - 19 Cr-Coated rods and 14 reference Zircaloy rods have been irradiated
 - 14 low burnup rods (9-14 MWd/kgU) sent to INL hotcells for PIE in 2020
 - 10 more medium burnup rods (14-30 MWd/kgU) being shipped in fall 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



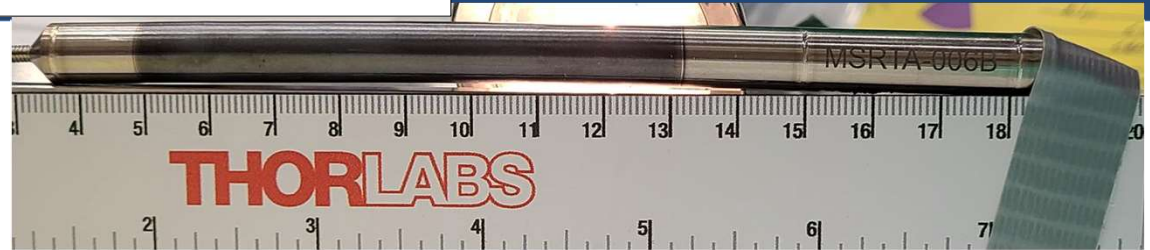
Cr-coated rodlet



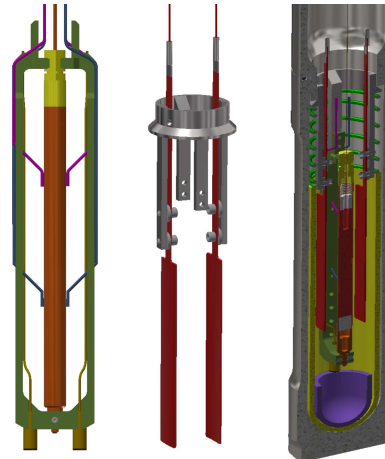
Transient Testing

- TREAT
 - First RIA tests on ATF performed in FY19
 - Preparations for LOCA testing underway (FY22)
- Testing with baseline rods completed last fall ($\text{UO}_2\text{-Zr4}$)
- Testing with Irradiated ATF-2 rod ($\text{UO}_2\text{-Zr4}$) 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



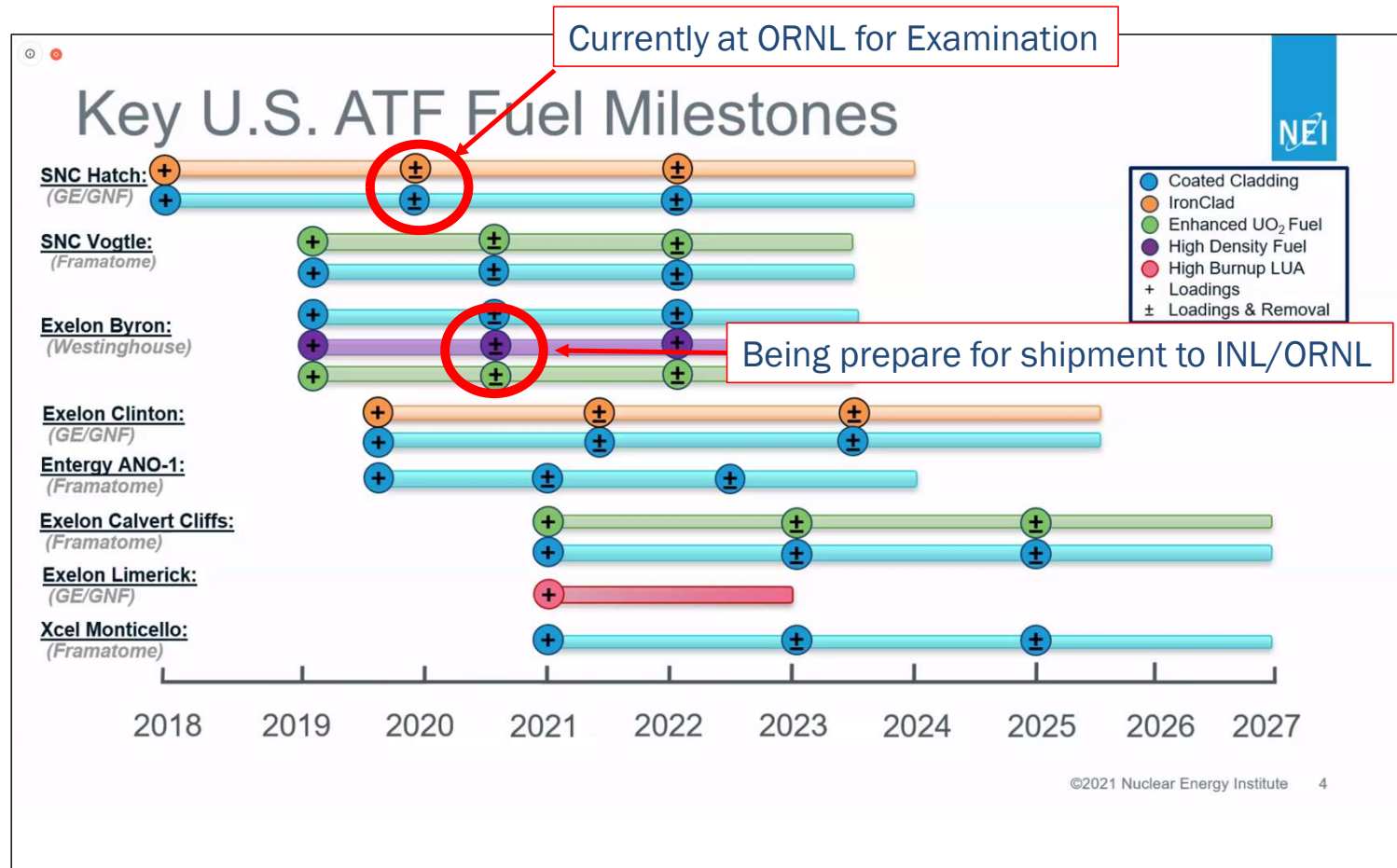
Energy Deposition ~ 1108 J/g



Rendering of TREAT RIA Test Capsule

LTA/R Insertion Status

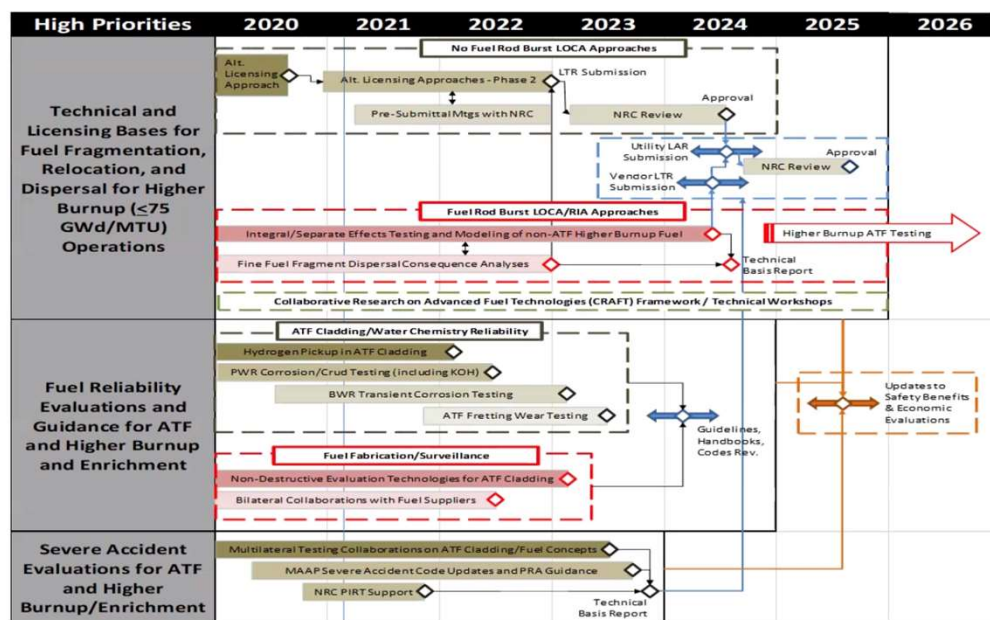
- Lead Test Rods (LTRs) for each near term concept are currently under irradiation in commercial reactor facilities
- Rods will be sent to hot cells at INL and ORNL for examination
- Subsequent R&D to support disposition and storage is possible



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

R&D Roadmap for Generic Issues Informing Industry Business Decisions and Licensing Submittals/Reviews



www.eprl.com

© 2021 Electric Power Research Institute, Inc. All rights reserved.

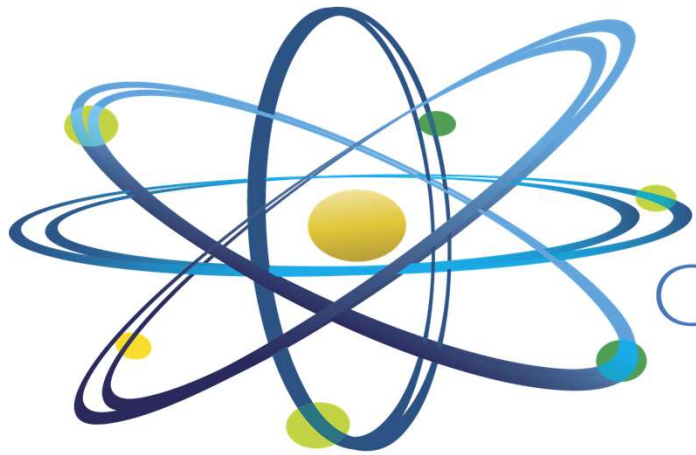
EPRl ELECTRIC POWER RESEARCH INSTITUTE

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.**

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



Westinghouse

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

