Characteristics of Accident Tolerant Fuel (ATF) for LWR Applications

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

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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
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

- Regulation (NRC)
- Fuel Safety Research
- Advanced Technology
- Deployment (Industry)
- Research (DOE)
- Licensing

Nuclear Technology
Complementary Roles in U.S. Nuclear Technology Enterprise

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 the last of the Parties to execute this Addendum (the Effective Date). The Addendum is authorized pursuant to section V(a)(iii)(d) of the Principles of Cooperation of the MOU. The terms and provisions of the MOU are controlling for all activities under this Addendum.

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

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

DOE Awards $111 Million to U.S. Vendors to Develop Accident Tolerant Nuclear Fuels

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

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Non-Proprietary Information – Class I (Public)
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*
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

• 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
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 ~1300°C. However, this is higher than the current cladding temperature limit of 1200°C during a DBA
  • Chromia-enhanced Fuel Pellets
    • Doping the UO₃ pellet with small amounts of Cr₂O₃ 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)

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

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

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

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cr</th>
<th>Al</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>APMT</td>
<td>21</td>
<td>5</td>
<td>3Mo</td>
</tr>
<tr>
<td>C26M</td>
<td>12</td>
<td>6</td>
<td>2Mo + 0.05Y</td>
</tr>
</tbody>
</table>
## ATF Irradiation Testing Program

<table>
<thead>
<tr>
<th>Test Series</th>
<th>ATF-1</th>
<th>ATF-2</th>
<th>ATF-3</th>
<th>ATF-H-x</th>
<th>CM-ATF-x</th>
<th>ATF-y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Reactor</td>
<td>ATR</td>
<td>ATR</td>
<td>TREAT</td>
<td>Halden</td>
<td>Commercial Reactors</td>
<td>TREAT</td>
</tr>
<tr>
<td>Test Type</td>
<td>Drop-in</td>
<td>Loop</td>
<td>Static/Loop</td>
<td>Loop</td>
<td>LTR/LTA</td>
<td>Loop</td>
</tr>
<tr>
<td>Test Strategy</td>
<td>Scoping Many Compositions</td>
<td>Prototypic Cladding and Integral Fuel Concepts</td>
<td>Focused</td>
<td>Focused</td>
<td>Mature concepts</td>
<td>Mature concepts</td>
</tr>
<tr>
<td>Test Type</td>
<td>Nominal conditions</td>
<td>Nominal conditions</td>
<td>Off-normal conditions</td>
<td>Limiting Conditions</td>
<td>Nominal conditions</td>
<td>Off-normal conditions</td>
</tr>
<tr>
<td>Fuel</td>
<td>UO$_2^*$, U$_3$Si$_2$</td>
<td>Zr w/coatings, Fe-based alloys, advanced alloys, SiC</td>
<td>Promising concepts</td>
<td>Promising concepts</td>
<td>Promising near-term concepts</td>
<td>Rods conditioned in LTR/LTA irradiations</td>
</tr>
<tr>
<td>Cladding</td>
<td>Fuel and fuel-cladding interactions</td>
<td>PWR conditions</td>
<td>RIA, LOCA</td>
<td><strong>BWR conditions, ramp testing, run to failure</strong></td>
<td>Prototypic testing</td>
<td>RIA, LOCA</td>
</tr>
</tbody>
</table>

### 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

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

3) Establish re-fabrication/instrumentation capability

4) Deploy reliable advanced in-pile instrumentation
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’)**
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
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
• 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
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
DOE-sponsored, Industry-led Development of ATF Concepts

**Framatome**
- ‘PROtect’
  - Cr-coated M5 cladding
  - Cr Doped UO₂
- ‘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