Nuclear Technology Research and Development

Postirradiation Examination on Innovative Advance Reactor Metallic Fuel Concepts

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Nufuel-MMSNF 2019 Workshop
PSI Auditorium, Switzerland
November 4-7, 2019

INL/CON-19-56301
Contents

Introduction
- Advance Fuel Campaign
- PIE strategy
- Metallic fuel background

Advance fuel form / High burnup concepts test
- Recent engineering PIE results & comparison
- SEM preliminary results

Summary & Prospective
NTRD Advanced Fuels Campaign

- Enhance the performance and safety of the USA current and future reactors
- Enhance proliferation resistance of nuclear fuel
- Effectively utilize nuclear energy resources
- Address the longer-term waste management challenges
History of the AFC Irradiations

- **AFC-1**
  - 36 rodlets
  - non- or low-fertile compositions for accelerators and fast reactors
  - metallic and nitride fuels
  - Am, Np for transmutation
  - sister experiments for low and high burnup comparison
  - FUTURIX-FTA: Phénix fast reactor experiment with select AFC-1 compositions

- **AFC-2**
  - 29 rodlets
  - low-fertile compositions for fast reactors
  - metallic and oxide fuels
  - Am, Np for transmutation
  - Assume batch extraction of TRU
  - RE additions to simulate recycling carry-over
  - sister experiments for low and high burnup comparison

- **AFC-OA**
  - ~30 rodlets
  - low-fertile compositions for fast reactors
  - metallic fuels
  - innovative design features for ultra-high burnup
  - smear density, geometry, alloy, additives, …
  - short and long term tests
PIE Strategy –
Moving towards a mechanistic understanding of nuclear fuel performance

Scale of Exam
Macro

Visual Exams
Dimensional Exams
Neutron Radiography
Gamma Spectrometry
Fission Gas Release
Optical Microscopy
Chemistry Analysis

Did it Fail Catastrophically
How much did the geometry change
Fission Product Migration
Microstructure,
Restructuring, FCCI
Burnup, Actinide Balance

Fuel Performance

Baseline

Relative Activity

Z Position in PGS

A few pins

Beyond Baseline

Electron Microscopy
SEM, TEM, EPMA
Focused Ion Beam
Atom Probe

Elemental distribution
3D microstructure

FIB Sample Preparation

Number of Samples

Select samples to EM
Available PIE

Baseline Nondestructive PIE
- visual
- neutron radiography (thermal, epi-thermal)
- gamma scan (axial isotopic data)
- metrology (radial swelling)

Baseline Destructive PIE
- fission gas analysis
- optical microscopy / metallography
- microhardness
- analytical chemistry / burnup analysis
- mechanical properties

Advanced PIE
- Microstructural analysis (SEM)
- Microchemical analysis (EPMA, SEM)
- Phase analysis (pending deployment)
- Thermal properties (laser flash, TCM)
- XRD, Micro XT
- 3D Microstructure (FIB, PFIB)
- Lower scales (TEM, APT)
History of Metallic Fuels in Fast Reactors

- **EBR-I** (1951)
  - Unalloyed U
  - U-2Zr
  - Pu-1.25Al

- **UK Dounreay Fast Reactor** (1963)
  - U-0.1Cr
  - U-7Mo
  - U-9Mo

- **Enrico Fermi FBR** (1963)
  - U-10Mo

- **EBR-II** (1964)
  - U-5Fs
  - U-10Zr
  - U-20Pu-10Zr

- **FFTF** (1982)
  - Qualification of U-10Zr
  - Assembly testing of U-20Pu-10Zr
Key Features & benefits of Metallic Fuels

- **Historic benefits**
  - Higher breeding ratio (fissile and fertile)
  - Benign response to accident condition
  - Hard neutronic spectrum
  - Outstanding fuel reliability to high burnup (~20 at.%)
  - Compatibility with proliferation-resistant electrochemical recycle
  - Simple, compact (demonstrated remote) fabrication processes
  - Synergistic with passive approach to reactor safety

- **Metal fuel characteristics**
  - U-Pu-Zr alloy base (good irradiation stability)
  - 75% smeared density (accommodate fuel swelling, mitigate FCMI)
  - Large fission gas plenum (accommodate high gas release)
  - Na bond in fuel-cladding gap (keep fuel temperatures low)
  - Low-swelling FMS cladding (minimize cladding/duct dimensional changes)

Schematic of a metallic, Na bonded, fast reactor element

Historical Fuel Performance Issues

- Swelling - limited burnup to 3 at. %, Solved early in EBR-II testing with lowering Smeared Density to 75% to allow for interconnected porosity releasing fission gas, solid fission product build-up limits fuel to 15-20 at.% burnup
- Alloying elements to raise the fuel melting temperature and tailor the phase of U or U+Pu in the fuel (Zr, Fs, Mo, Ti)
- Fuel Cladding Chemical Interaction (FCCI)
  - FCCI occurs at nominal operating conditions in U and U-Mo fuels and limits burnup to 10at. % (U-Fe, U-Ni interaction typically)
  - FCCI occurs at nominal operation conditions in U-Zr and U-Pu-Zr fuels beyond 10at.% burnup (Lanthanide – Fe interaction typically)
- Fuel Constituent Redistribution – an effect of phase transitions
  - U, U-5Fs, and U-10Mo do not redistribute
  - U-10Zr does redistributes where Zr migrates to the center of the fuel
  - U-Pu-10Zr redistributes with Zr migrating to the central region and the periphery

New concepts

- Annular / low smear density
- New alloys
- Additives
- New alloys

Fs – 49.8Mo-38Ru-6Rh-4Pd-2Zr-0.2Nb
Testing Fast Reactor Fuels in a thermal reactor

- Rodlet – capsule – Cd basket system
- Comparison between true fast spectrum vs ATR irradiations: proper temperature profile is created in ATR irradiations
- This allows for the study of fuel performance phenomena that are primarily dependent upon temp. / temp. gradient

Typical AFC-3 Rodlet cross section

![Graph showing power factor vs r/r0 for Unshrouded, SFR, and Cd-shrouded rods.](image-url)
AFC-3 A/B/C/D and AFC-4A series

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- **AFC-3A/B/C/D and AFC-4A is an alloy exploration test**
  - Alternate alloys and forms to U-10Zr, Sodium Bonded, 75% SD
  - Pd additive to mitigate FCCI
  - Annular Forms to eliminate Na treatment issues
- **Meant to test early alloy performance against the historical experience**
- **Irradiation Issues**
  - Capsule Fabrication 3A/B
  - Reactor Uncertainty

<table>
<thead>
<tr>
<th>Rodlet ID</th>
<th>Alloy</th>
<th>Fuel Form</th>
<th>Bond Material</th>
<th>Nominal Smear Density</th>
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<td>U-10Mo</td>
<td>Solid</td>
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AFC-3C had irradiation temperature
- Peak Inner Cladding Temperature (PICT) exceeded 600°C for 3 or 4 rodlets
- PICT in R1 and R5 likely exceeded 650°C
- Experiment removed from ATR early after 3 cycles

AFC-3D had reasonable PICT temperatures and appears to have better performance

Rodlet Diameter 0.230 inch
Capsule Inner Diameter .234±.001 in
Most Capsules are near 0.235 inches
AFC-3C/3D – NDE highlights

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- **Profilometry**
  - AFC-3C presents some degree of diametrical strain (max 0.7% strain)
  - AFC-3D no measurable change in diameter

- **Thermal neutron radiography**
  - Annular fuel pins (e.g. 3C-R4) maintained their annuli
  - Visible change in grey scales shows variation in density
AFC 3C/D - Fission Product Distribution

Axial Gamma spectrometry – RhRu-106 flat distribution – Annular fuel: Cs migrates towards cooler axial ends – Ce-144 some axial migration

Relative Activity vs. Distance from bottom of Rodlet (cm)

- Cs-137
- RuRh-106
- CePr-144
- Mn-54
- Eu-154
Gamma Emission Tomography reveals the transverse distribution of fission products

Signals exist for most major types of fission products
The EBR-II data suggests that FGR is 70±10% after $1.5 \times 10^{21}$ fiss/cc (~4 at.%).

Other AFC tests and transmutation fuel (FUTURIX) tests also follow this general trend.

The AFC-3 tests often also follow this trend:
- There is some evidence that low smear density, annular fuel, and U-Mo fuel release fission gas earlier.
AFC 3C / 3D U-Mo Metallography

Nuclear Energy

AFC-3C R1 (U-10Mo, 75% SD, solid, Na, 2.3% FIMA, 650° C)

AFC-3C R2 (U-10Mo, 55% SD, annular, He, 3.3% FIMA, 625° C)

AFC-3D R3 (U-10Mo, 55% SD, solid, Na, 2.1% FIMA, 625° C)

AFC-3D R4 (U-10Mo, 55% SD, annular, He, 4.5% FIMA, 600° C)
AFC 3C / 3D U-Zr solid Metallography

AFC-3C R3 (U-10Zr, 65% SD, solid, Na, 2.9%FIMA, 630° C)

AFC-3D R2 (U-4Pd-13Zr, 55% SD, solid, Na, 2.8%FIMA, 630° C)

AFC-3C R5A (U-1Pd-13Zr, 75% SD, solid, Na, 2.6%FIMA, 680° C)

AFC-3C R5B (U-2Pd-13Zr, 75% SD, solid, Na, 2.6%FIMA, 660° C)

Fuel Mid-plane

Fuel Top
AFC 3C / 3D U-Zr annular Metallography

AFC-3C R4 (U-10Zr, 55% SD, annular, He, 3.0%FIMA, 620° C)

AFC-3D R5 (U-4Pd-13Zr, 55% SD, annular, He, 2.9%FIMA, 610° C)

AFC-3D R1 (U-10Zr, 55% SD, annular, He, 4.3%FIMA, 600° C)
Two of the Annular U-Zr variants performed exceptionally well

Two contributing factors
- Appropriate PICT at all times during irradiation
- Well machined fuel slugs
U-10Zr prelim. comparison between AFC-series

- **U-10Zr annular: AFC-3D behaves better compare to -3A-3C**
  - Machining, gap ~50µm AFC-3A R4 vs 17µm AFC-3C R4 → 177°C vs 60°C
  - Periphery temperature maintained below the critical temperature for Zr migration (Beta phase)

*AFC-3A: U-10Zr, bu 3.2 at.%, PICT 530°C / U-1/2Pd-10Zr, bu 2.5 at.%, PICT 585°C
# SEM preliminary results

## AFC-3A/B/C/D electron microscopy examination
- Challenges to prepare samples (high dose)
- A more quantitative understanding of the different phases and feature is required
  - New additives work?
  - FCCI
  - Temp / gap effect

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The behavior of Zr and Pd are important for this fuel to well perform
- Zr needs to stay alloyed with U for fuel performance
- Zr and Pd intermetallics need to be avoided
- Pd needs to form intermetallics with Lanthanides (LnPd and Ln₇Pd₃)
- Alloy addition steps are important
FCCI occurred in this sample similar to the same levels observed in U-Mo

Too much Pd can be detrimental to fuel performance
- Pd and Zr will form high temperature intermetallics leaving U unalloyed (PdZr₂)
- Pd alloying addition order can significantly change as-cast intermetallic behavior (understood after this irradiation was fabricated)

Cast annular fuel without a Na bond is susceptible to local overheating
AFC-3A R4 SEM (U-10Zr annular) – FCCI - Helium gap effect

AFC-3A R4 (U-10Zr, 55% SD, annular, He, 3.3%FIMA, 540-600° C)
Advanced metallic fuel form
- Raise from the needs to elevate utilization and reach higher burnup
- Improve historical issue of metallic fuel

AFC-3 and -4 experiments
- Alloys exploration test (annular, alternative alloys, additives)
- Some promising design and value data are examined for the first time
- U-Mo performance are quite below U-Zr
- Annual fuel (well machined) and Pd additives fuel form are somehow promising

Future and Prospective
- Extended examination are needed (also supported by modelling and simulation)
- Extended burnup / experiment on some promising fuel form are needed
- Safety / transient test on promising fuel form are the natural next step
Irradiated Material Characterization Laboratory (2019-2020)

SSPA – Shielded Sample Preparation Area
SEM – Scanning Electron Microscope
TCM – Thermal Conductivity Microscope
EPMA – Electron Probe MicroAnalyzer
XRD – X-Ray Diffraction

TGA/MS – Thermogravimetric Analyzer/ Mass-Spectrometer
APT – Atom Probe Tomography
FIB – Focused Ion Beam
XRM – X-Ray Microscope

P-FIB – Plasma Focused Ion Beam
TEM – Transmission Electron Microscope
PPMS – Physical Property Measurement System
LFA – Laser Flash Analyzer

Come work with us!
Contributors

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