HISTORY OF LEU FUEL DEVELOPMENT AND SELECTION OF USHPRR FUEL SYSTEM

FEBRUARY 2015
High Density LEU Fuel

- Maintaining USHPRR performance with LEU fuel requires an increase in $^{235}$U density
  - Enrichment decreases 4.65 times (93% -> 20%)
  - Uranium density must increase more than 4.65 times
  - Fuel meat uranium density must increase from 1.7 to 8+ g-U/cm$^3$
- Only a few alloys and compounds meet density requirement
- $U_6$Me intermetallic phases
  - Known poor performance (breakaway swelling)
- Uranium Alloys
  - No irradiation performance data at HPRR conditions

Irradiation behavior of $U_6$Mn dispersion fuel
Scoping Irradiation Tests

- Ten (10) fuel alloys were tested in the RERTR-1 and RERTR-2 irradiation test beginning in 1997
- Results indicate the U-xMo ($x \geq 6$ wt.%) alloys exhibit better fuel behavior than U-Nb-Zr

U-5Nb-3Zr at 41% $^{235}$U burnup

U-10Mo at 69% $^{235}$U burnup
Positive Results and Global Interest in U-Mo Fuel

- Fuel testing and out-of-pile programs were initiated worldwide
  - Argentina
  - Canada
  - France
  - Republic of Korea
  - Russia

- Several fuel failures occurred at higher power density and/or high temperature in 2001 - 2003
U-Mo Dispersion Fuel Failures

- U-Mo is a stable fuel under research reactor conditions
- Failures were related to formation of an unstable U-Mo/Al reaction product
Testing Timeline

**U-Mo fuel alloy selected**

**U-Mo/Al dispersion fuel failures**

1. RERTR-1
2. RERTR-2
3. RERTR-3
4. RERTR-4
5. RERTR-5

Miniplate tests
Alternative LEU Fuel Technology

- U-Mo is the only viable solution for the fuel phase
- Potential fixes to breakaway swelling
  - Modify the composition of matrix and U-Mo fuel
  - Change the matrix material (Mg matrix fuel)
  - Remove the matrix (Al and Zr clad ‘monolithic’ fuel)
  - Coated particles (density concern)
- Strategy (2003)
  - Pursue multiple paths until data permits a down-selection
U-Mo Monolithic Fuel

- Crude test plate fabricated for RERTR-4 test
  - Prior to dispersion fuel failures
  - Roll bonding process used for fabrication
  - Fuel foil torn during rolling process
- New fabrication technology required
- Irradiation behavior acceptable in RERTR-4 test

First U-Mo monolithic fuel after irradiation to > 70% burnup
U-Mo Monolithic Fuel Fabrication

- Program intent was to make technology available globally at low cost
- Simple foil fabrication processes developed
- Several fuel plate fabrication processes were pursued
  - Hot Isostatic Press (HIP)
  - Friction Stir Welding (FSW)
  - Transient Phase Liquid Bonding (TPLB)
• Initial low power testing in RERTR-6 irradiation was promising
  - L1F100 U-10Mo (FSW), 46.3% burn-up, peak heat flux 123 W/cm²
• First ‘real’ data on monolithic fuel acquired in 2006
Monolithic Fuel – RERTR-6

L1F100 U-10Mo (FSW)
46.3% burn-up
Reaction ~18 µm (left image)
Reaction ~3µm (right image)
Peak Heat Flux 123 W/cm²
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>1997</td>
<td>RERTR-1</td>
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<td>RERTR-5</td>
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<td>2002</td>
<td>RERTR-6</td>
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- **U-Mo fuel Alloy selected**
- **U-Mo/Al Fuel dispersion fuel failures**
- **U-Mo/Al-Si dispersion and monolithic fuel designs proposed**
- **Monolithic fuel proof of concept**
- **Miniplate tests**

**Testing Timeline**
Irradiation Test Results

- U-xMo alloy (x=7, 10, or 12), Al-6061 cladding, no interlayer in RERTR-7 & RERTR-8
- U-Mo exhibits stable fuel behavior - small, finely dispersed bubble morphology and moderate swelling
- Onset of ‘large’ porosity in fuel/clad interaction layer (higher Mo content more resistant to bubble formation)
Preliminary Conclusions (2007)

• Porosity seen at fuel/clad interface assumed to be similar to porosity seen in U-Mo/Al dispersion fuel
  – Historically led to breakaway swelling
  – Increased tendency for interface failures
  – Delamination of fuel plates not acceptable

• U-Mo fuel continues to behaves well
  – Interface modifications required to meet USHPRR performance criteria

• RERTR-9 and RERTR-10 irradiations tested modified interfaces
  – Silicon and silicon enriched (ex. Al 4043) layers
  – Diffusion barrier layers (Zr, Mo, Nb)
U-Mo fuel alloy selected

U-Mo/Al dispersion failures

U-Mo/Al-Si dispersion and monolithic fuel designs proposed

Monolithic fuel proof of concept

Zr and Si barrier monolithic fuel proposed
Zr and Si Interlayers

- Fabrication/irradiation testing in RERTR-9 & RERTR-10 included:
  - HIP bond Zr, Nb, Mo to U-Mo foil
  - Hot co-roll bond Zr, Nb, Mo to U-Mo foil
  - Si application by thermal spray
  - Si rich Al alloy interfaces
Zr Barrier Layer Fuel

- Complete bonding after irradiation
- No cracking of the fuel foil prior to sectioning
- Some porosity seen inside Zr layer
Selection of Fuel System (2009)

- **U-10Mo** selected as a good balance between irradiation stability and foil fabrication
- **Zr barrier** layer provides a stable interface between fuel and cladding
- **Co-rolling** U-Mo/Zr produced an acceptable product at laboratory scale
- **HIP bonding** selected over friction bonding or transient liquid phase bonding based on preliminary fuel performance and bond strength assessments and repeatability in fabrication
Testing Timeline

- **1997**
  - RERTR-1
  - Full-size plate tests

- **1998**
  - RERTR-2
  - RERTR-3
  - Miniplate tests

- **1999**
  - U-Mo fuel alloy selected
  - RERTR-4

- **2000**
  - U-Mo/Al dispersion fuel failures
  - RERTR-5

- **2001**
  - U-Mo/Al-Si dispersion and monolithic fuel designs proposed

- **2002**
  - Monolithic fuel proof of concept

- **2003**
  - Zr and Si barrier monolithic fuel proposed

- **2004**
  - Creation of FFC Pillar

- **2005**
  - U-Mo/Zr monolithic fuel down-select

- **2006**
  - RERTR-6

- **2007**
  - RERTR-7

- **2008**
  - RERTR-8

- **2009**
  - RERTR-9

- **2010**
  - RERTR-10

- **2011**
  - AFIP-1

- **2012**
  - AFIP-2
  - AFIP-3

- **2013**
  - AFIP-4
RERTR-12 Experiment

- Miniplate test of prototypic zirconium barrier monolithic fuel over a wide range of fission rate and fission density
- Designed to explore fuel operating envelope from 100 – 500+ W/cm²
- Provides excellent data on fuel swelling
- Experiment consists of 56 plates in 7 capsules
  - 3 identical X-type capsules (thin meat)
  - 3 identical Y-type capsules (thick meat)
  - 1 Z-type capsule (mix)
- Fuel meat thickness is the only design variable
  - Thin – 0.25 mm (0.010”)
  - Thick – 0.50 mm (0.020”)
Fuel Swelling Data from RERTR-12

Miniplates are stable to burnups not attainable with LEU
Optical images of 4 RERTR-12 fuel plates with highest fission density.
Neutron radiographs of the four RERTR-12 plates with highest fission density

- **L1P7A0**: 7.7E+21 Ave FD; XE+22 Peak FD
- **L1P754**: 8.1E+21 Ave FD; XE+22 Peak FD
- **L1P759**: 8.7E+21 Ave FD; 1.1E+22 Peak FD
- **L1P785**: 9.2E+21 Ave FD; 1.1E+22 Peak FD
Gamma Scans of L1P7A0 & L1P754

L1P7A0: 7.7E+21 Ave FD; XE+22 Peak FD

L1P754: 8.1E+21 Ave FD; XE+22 Peak FD

- Cs-137 and Ce/Pr-144 distributions track calculated plate power profile
- Both Cs-137 and Ce/Pr-144 redistribute when fuel redistributes
Gamma Scans of L1P759 & L1P785

L1P759: 8.7E+21 Ave FD; 1.1E+22 Peak FD

L1P785: 9.2E+21 Ave FD; 1.1E+22 Peak FD

- Cs-137 distribution is generally flattened with respect to Ce/Pr-144 distribution
- Anomalies in the Cs-137 profile near the high burnup regions of the plates
Microstructure of L1P754 at mid-plane

- Fission density approximately $8 \times 10^{21}$ f/cm$^3$
- Porosity at interface
- Bulge at edges results from creep
- Bubbles small and uniform throughout the fuel
Microstructure of L1P754 at high burnup end of plate

- Pillow type failure of plate
  L1P754 observed on removal from reactor
  - Avg. FD - $8.1 \times 10^{21} \text{ f/cm}^3$
  - Peak FD approximately $1.2 \times 10^{22} \text{ f/cm}^3$
- Failure at peak FD end of plate
- Growth of surface oxide appears to be normal on both fuel plate surfaces
- Fission product release did not occur in reactor
- Fuel is approaching or exceeding threshold for fission gas bubble interconnection
- Irradiation conditions were not prototypic. High end-of-life power at high fission density cannot be achieved in LEU fueled reactors
- Mechanical strength of the U-Mo fuel decreases with increasing fission density
- Calculated shutdown stress in fuel meat approaches or exceeds strength of U-Mo
AFIP-6 Irradiation Test

- **Experiment Design**
  - 2 fuel plates fabricated at B&W by HIP
  - Irradiated in the irradiation hardware utilized for AFIP 1-4
- **Irradiation Conditions (ATR Cycle 146B)**
  - Cycle length - 39.3 EFPD
  - Peak operating power ~ 500 W/cm²
  - Peak fission density $3.4 \times 10^{21}$ f/cc (~44% LEU equivalent burnup)
AFIP-6 Fission Product Release

- Advanced Test Reactor (ATR) stack activity plot during final 11 days of AFIP-6 test
- Peak FD $3.4 \times 10^{21}$ f/cm$^3$ (44% LEU)
- Plate blistered, periodic fission gas release over 11 days
• Test design resulted in a power/cooling mismatch
• Peak fuel meat temperature estimated to be ~500°C
AFIP-6 Blisters

Blisters
AFIP-6 Oxide Layer
Metallography of AFIP-6 Blister Regions
In-reactor Blister Threshold Temperature

- Blistering is expected at the estimated fuel operating conditions
• Same test design as AFIP-6 with no flow restricting orifice
AFIP-6 MkII Exams

- Top: Optical image
- Center: Neutron radiograph
- Bottom: Ultrasonic scan
AFIP-6 MkII Microstructure

AFIP-6 MkII fresh fuel microstructure (SEM)  AFIP-6 MkII microstructure (optical) after irradiation to $3.7 \times 10^{21} \text{ f/cm}^3$
AFIP-6 MkII Microstructure

AFIP-6 MkII microstructure (optical) after irradiation to $4.1 \times 10^{21}$ f/cm$^3$

AFIP-6 MkII microstructure (optical) after irradiation to $4.4 \times 10^{21}$ f/cm$^3$
AFIP-7

- Miniature fuel element (curved and constrained)
- Four (4) full-size (98 cm fuel zone) fuel plates
- Swaged into side plates
• In-canal visual examination shows no abnormalities
AFIP-7 Channel Gap Measurement

- Geometry is maintained during *normal operation* and anticipated transients

- Channel gap probe used to verify coolant channel gap dimensions in fuel elements between irradiation cycles
  - AFIP-7 element assembly (4 plates)
  - Postirradiation examination will begin in 2015 and be completed in 2016
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RERTR Fuel Element Fabrication (2011)

- Fabrication of two full-size hybrid test elements was planned in 2011 and 2012
  - Required foils are 121.9 cm (48 in.) long
  - 11 different foil widths are required
  - Finished U-Mo plates must meet ATR driver fuel specifications
    - Minimum/maximum fuel zone
    - Homogeneity (high/low density regions)
- Scale up of fabrication process did not result in fuel plates that consistently met specifications
Summary

• Monolithic U-Mo fuel has been demonstrated to meet basic fuel performance requirements necessary for qualification
  - Mechanical Integrity
  - Geometric Stability
  - Stable and Predictable Behavior
• Qualification program based on previous successful campaigns
• Monolithic Preliminary Qualification Report report to NRC in 2017
• Fabrication process will be selected based on MP-1 irradiation test results: 2017 – 2020
• Qualification testing: 2020 - 2023
• Monolithic Fuel Qualification report to NRC: 2023