INTERNATIONAL LOW ENRICHED URANIUM FUEL DEVELOPMENT AND NNSA/M3 ROLE

PRESENTATION TO THE NATIONAL ACADEMY OF SCIENCE PANEL
APRIL 16, 2015

PRESENTED BY:
ABDELLATIF YACOUT, MMM EUROPEAN FUEL DEVELOPMENT TECHNICAL LEAD
ARGONNE NATIONAL LABORATORY
High-density U-Mo fuel development is an international effort in cooperation with Russia, Europe (France, Belgium and Germany), and Korea.

European Fuel Development is focused on U-Mo dispersion fuel for the RHF, BR2, RJH and ORPHEE reactors; Germany’s FRM2 reactor will need the U-Mo monolithic fuel for conversion. Fuel qualification to meet the performance requirements is a challenge just as it is for the USHPRRs.

Europe advanced the U-Mo dispersion fuel development through the LEONIDAS program. The program highlighted need for diffusion barriers on the U-Mo powder particles.

Belgium’s SELENIUM program demonstrated beneficial effects of diffusion barrier coatings on U-Mo powder and highlighted focus areas for further demonstration and fuel performance validation.

Europe launched the HERACLES program in 2013 and developed a detailed roadmap focused on U-Mo dispersion fuel qualification and EU HPRR conversions. The U.S is a co-sponsor in the HERACLES program.
International Dispersion U-Mo Fuel Qualification Efforts

- **Europe:**
  - BR2 (Belgium), RHF and ORPHEE (France)
  - JHR (France) - Plans to start with U3Si2 and move to LEU U-Mo fuel in the future as the fuel is qualified

- **Russia:**
  - IRT-3M Lead Test Assembly (LEU U-9Mo) were fabricated and will be irradiated in MIR reactor in support of fuel qualification
  - Fuel will be qualified in 2017
  - Qualified fuel will be used to convert IRT type reactors (IRT-MEPhl, IRT-Tomsk, IR-8), which operate at conditions lower than the EUHFR

- **Korea:**
  - KAERI is collaborating with DOE-NNSA/M3 in
    - irradiation testing of LEU U-7Mo KJRR
    - Lead Test Assemblies during 2015
  - LEU U-7Mo Mini-plates irradiation in HANARO reactor
DOE/EU Collaboration for EU HPRR Conversion

- Focus in Europe is on the conversions and support for Heracles Initiative on LEU U-Mo Dispersion Fuel Development

- EU reactors to use LEU fuel:
  - France - RHF, ORPHEE, JHR (LEU dispersion fuel)
  - Belgium - BR-2 (LEU U-7Mo dispersion fuel)
  - Germany - FRM II (LEU U-10Mo monolithic fuel)

- The US support to the EU (Heracles) Dispersion LEU Fuel Development
  - Provides research on backup (risk mitigation) for the monolithic fuel since dispersion fuel could meet the needs for the conversion of some US-HPRR reactors
  - Provides potential supporting technical data to assist future Russian LEU Dispersion Fuel Development programs
Historical Background
Research and Test Reactor Fuel Development Timeline

Before 1978

HEU Fuel
- U enrichment > 20%
- UAlx-Al, UO2-Al, U3O8-Al, and UZrHx

1980s

LEU Fuel
- U enrichment < 20%; early types – UAlx-Al and U3O8-Al
- Qualified U3Si2-Al with 4.8 gU/cm³ and also UZrHx

1996 - Present

Advanced LEU Fuel
- 235U enrichment < 20%
- U density up to 8-9 gU/cm³ in dispersion, or ~15 gU/cm³ monolithic
- Most promising candidate: U-Mo alloy
Positive Results and Global Interest in U-Mo Fuel

- U-Mo (7-10 wt.% Mo) dispersion and monolithic fuel forms are being developed for conversion of higher performance research and test reactors.
  - Good irradiation performance of its cubic $\gamma$-phase.
  - Alloying Mo is to stabilize uranium in the bcc-structured $\gamma$-phase.
  - High uranium density can be achieved.

- Fuel testing and out-of-pile programs were initiated worldwide
  - Argentina, Canada, France, Republic of Korea, Russia
<table>
<thead>
<tr>
<th><strong>Dispersion Fuel</strong></th>
<th><strong>Monolithic Base Fuel</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance at bounding conditions remains major issue (BR2 and JHR both very high power + high burnup)</td>
<td>Performance of Zr co-rolled fuel in US HPRR envelope is considered acceptable</td>
</tr>
<tr>
<td>Focus on solving fuel performance issues</td>
<td>Bounding operating conditions of USHPRR do not have high power + high burnup combination</td>
</tr>
<tr>
<td>Some fabrication processes must be commercialized, but evolutionary</td>
<td>Focus on improving fabrication process</td>
</tr>
<tr>
<td>Further understanding of fuel performance at extreme conditions needed</td>
<td>Base fuel (Zr co-rolled) qualification report to NRC is in progress</td>
</tr>
<tr>
<td></td>
<td>Fuel performance within USHPRR functional envelope is well understood</td>
</tr>
</tbody>
</table>
EUHFR vs. USHPRR Operating Envelope

EUHFR have most challenging combination of high burnup and moderate power level.

Note that BR2 and RHF designs for LEU assemblies are well-defined and vetted by collaboration between reactor operators and ANL. The CEA and ANL have only recently begun sharing model detail for LEU designs of ORPHEE, and have not yet shared models of JHR.
European/US Irradiation Experiments

- RERTR-1
- RERTR-2
- RERTR-3
- RERTR-4
- RERTR-5
- RERTR-6
- RERTR-7
- RERTR-8
- RERTR-9
- RERTR-10
- RERTR-11
- RERTR-12
- RERTR-13

- AFIP-1
- AFIP-2
- AFIP-3
- AFIP-4
- AFIP-6
- AFIP-7
- AFIP-8
- AFIP-9
- AFIP-10
- AFIP-11
- AFIP-12
- AFIP-13

- IRIS-1
- IRIS-2
- IRIS-3
- IRIS-TUM
- IRIS-4
- IRIS-5
- IRIS-6
- IRIS-7
- IRIS-8
- IRIS-9
- IRIS-10
- IRIS-11
- IRIS-12
- IRIS-13

- FUTURE
- FUTURE II
- SELENIUM

- Miniplate tests
- Full-size plate tests
- Element test

- LEONIDAS GROUP
- HERACLES GROUP
Fuel Performance
U-Mo/Al Dispersion Fuel

- U-Mo/Al dispersion fuel elements are plates/rods with U-Mo fuel particles distributed in aluminum matrix.

(Y.S. Kim, G.L. Hofman, JNM 419, 2011)
Irradiation-Induced Microstructural Changes

Fission gas bubbles
- Appear within fuel grains and on grain boundaries
- Cause fuel phase swelling

Interaction layer
- Form around fuel particles
- Composition: UMoAlx (amorphous)
- Degrade fuel meat thermal conductivity

Porosity
- Between the matrix and IL
- Filled with fission gases
- Can cause fuel plate failure

(Y.S. Kim, et.al, JNM 436, 2013)
(YS Kim et al., JNM, 430, 2012)
(A. Robinson, INL, 2008)
LEU U-Mo Dispersion Fuel Performance

- U-Mo is a stable fuel under research reactor conditions
- Abnormal fuel plate swelling were related to formation of an unstable U-Mo/Al reaction product leading to failure

(F. Huet, RRFM Meeting, 2005)

(M.K. Meyer, INL, 2005)
LEU U-Mo Dispersion Fuel Performance

- U-Mo is only viable solution for the fuel phase due to high density
- Potential fixes to breakaway swelling
  - Modify the composition of matrix and U-Mo fuel (Si addition)
  - Change the matrix
  - Remove the matrix (Al and Zr clad ‘monolithic’ fuel)
  - Coated particles to reduce/eliminate interaction layer
  - Heat treatment to alter grain size and delay breakaway swelling

U-Mo magnesium matrix: RERTR-8 R9R010 irradiated to ~ 91% peak $^{235}\text{U}$ burnup

U-Mo with Si addition (left) and without Si addition (right) under similar operating conditions
Methods for Reducing Interaction Layer Growth

Matrix Modifications

- Adding a small amount of Si in Al matrix

Interaction layer progressively reduces with Si concentration in Al.

Methods for Reducing Interaction Layer Growth

Coating

A. Leenaers, PhD Thesis,
UGENT/SCKCEN, 2014
Failure Criteria U-Mo/Al-Si, Dispersion Fuel
(filled symbols: pillowed and/or large porosity)

Burnup (%) vs. Fission rate (10^{14} \text{ fission/cm}^3\text{-s})

Threshold curve for fuels with Si
Threshold curve for fuels without Si

(G.L. Hofman, ANL, 2015)
Negligible reaction between the fuel particles and matrix in SELENIUM plates.
  - The fuel swelling is dictated by the solid state swelling due to fission product accumulation.
  - Slower linear growth at the beginning, and acceleration of swelling from $4.5 \times 10^{21}$ f/cm$^3$. 

(Van den Berghe, JNM 442, 2013)
The recrystallization process

- Recrystallization or grain subdivision is induced by accumulation of irradiation damage.
- The recrystallization process starts along the preexisting grain boundaries, then moves toward the grain center eventually consuming the entire grain.

(Kim et al, JNM 436, 2013)
The recrystallized volume fractions were measured using SEM images of atomized U-Mo/Al dispersion fuel.

U-Mo fuels show full recrystallization at $4.5-5 \times 10^{21}$ f/cm³ (U-7Mo w/o heat treatment).

References:
EU-US/HERACLES Collaborations

Fuel Development and Qualification
<table>
<thead>
<tr>
<th>Year</th>
<th>AFIP-1</th>
<th>AFIP-2</th>
<th>AFIP-3</th>
<th>AFIP-4</th>
<th>AFIP-5</th>
<th>AFIP-6</th>
<th>AFIP-7</th>
<th>AFIP-6 Mk2</th>
<th>IRIS-1</th>
<th>IRIS-2</th>
<th>IRIS-3</th>
<th>IRIS-TUM</th>
<th>IRIS-4</th>
<th>E-FUTURE</th>
<th>E-FUTURE II</th>
<th>SELENIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
European High Density LEU Fuel Development

Main Components of HERACLES Roadmap

- Comprehension Phase
- Industrialization
- Irradiation Experiments

Parallel Activities

- Modeling
- Manufacturing
- Back-end & Cost Assessment

Key Dates

- Comprehension Phase: to 2018
- Irradiation experiments and fuel qualification: CY2024-2026 depending on schedule, possible elimination of one experiment, degree of overlap with fabrication scheme.
- The first qualified use of U-Mo Dispersion fuel would be in BR-2 mid CY2026 to late 2029

Expert Groups (HERACLES/US)

- Fuel Development Expert Group (FDEG)
- Fuel Manufacturing Expert Group (FMEG)
European High Density LEU Fuel Development

Comprehension Phase

Dispersion Fuel

- SEMPER FIDELIS
- SELENIUM 2
- E-FUTURE 3
- MIXED ELEMENT

FRMII Monolithic Fuel

- FUTURE-MONO-1
- FUTURE-MONO-2
- MIXED ELEMENT

Industrialization

- CERCA Powder Atomization Development
- CERCA Powder Coating Development
- CERCA Dispersed Plates Manufacturing Development
- CERCA Monolithic Plates Manufacturing Development
- TUM Mono coating

CERCA safety analysis / cost assessment / transport …

… BACK-END!
Comprehension Phase Questions

- What mechanisms lead to:
  - accelerated swelling of UMo fuel alloy at high BU?
  - loss of fuel meat integrity? (e.g., IL growth, interconnected pores)?
- What mitigations can be applied to address those mechanisms?

Hypotheses

- Completion of fuel recrystallization near \(-4.5 \times 10^{21}\) fissions/cc in U7Mo w/o heat treatment: allow gas pores to interconnect & release gas to matrix
  - Possible mitigation: change alloy (e.g., U-7Mo to U-10Mo) or apply heat treatment
- Interface failure due to weak interaction layer consuming matrix, e.g.:
# Comprehension Phase Activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State of the Art Assessment</strong></td>
<td>Identify and Prioritize Gaps</td>
</tr>
<tr>
<td>• Theory &amp; Data</td>
<td></td>
</tr>
<tr>
<td><strong>Modeling</strong></td>
<td></td>
</tr>
<tr>
<td>• Phenomenological (particle, IL, microstructure, swelling)</td>
<td></td>
</tr>
<tr>
<td>• Thermo-Mechanical (Plate)</td>
<td></td>
</tr>
<tr>
<td>• Materials Properties</td>
<td></td>
</tr>
<tr>
<td>• Thermodynamics (coating efficacy)</td>
<td></td>
</tr>
<tr>
<td><strong>Advanced PIE on existing materials (fresh &amp; irradiated)</strong></td>
<td>Fill data gaps</td>
</tr>
<tr>
<td>• Additional samples for clean comparisons (e.g., U10Mo vs U10Mo)</td>
<td></td>
</tr>
<tr>
<td>• Advanced PIE to inform theories (e.g., EPMA or microhardness)</td>
<td></td>
</tr>
<tr>
<td><strong>Physical Properties</strong></td>
<td>Process and Irradiation Impact on Hardening, Lattice Parameter, Thermal conductivity...</td>
</tr>
<tr>
<td><strong>Heavy Ion Irradiation</strong></td>
<td>Accelerated investigation of irradiation damage and mitigations</td>
</tr>
<tr>
<td><strong>UMo Dispersion Feasibility Assessment</strong></td>
<td>Assess credibility of fuel system stability for the required operating conditions</td>
</tr>
<tr>
<td><strong>Design of Subsequent Irradiation Experiments</strong></td>
<td>• Design and construct a sub-size plate device</td>
</tr>
<tr>
<td></td>
<td>• Design sample matrix and test conditions</td>
</tr>
</tbody>
</table>
Industrialization Activities

- Scalable/Reliable Processes
- Deployable within French Safety Regulations
- Deployed in stages: Prototype → Pilot → Commercial
- Industrialization may define requirements of irradiation tests - and will constrain it

<table>
<thead>
<tr>
<th>Activity</th>
<th>Objectives/Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomization</td>
<td>• KAERI process has not yet met French regulatory requirements</td>
</tr>
<tr>
<td></td>
<td>• Rotating electrode should scale in flexible manner</td>
</tr>
<tr>
<td>Particle Coating</td>
<td>Process with scalability and required coating characteristics not yet defined</td>
</tr>
<tr>
<td></td>
<td>• Coating method not fully defined</td>
</tr>
<tr>
<td></td>
<td>• Also maturity issue for coating of actinide powders</td>
</tr>
<tr>
<td>Coated Particle Quality Inspection</td>
<td>Method to measure particle characteristics, coating quality, and homogeneity must be developed</td>
</tr>
<tr>
<td>Plate Industrialization</td>
<td>Mature the high density dispersion plate fabrication process for acceptable yields</td>
</tr>
</tbody>
</table>
Summary

- **Current status of U-Mo fuel development**
  - Fuel performance improvements in relation to high power European research reactors have been made particularly by use of coated powder.
  - On-going comprehension phase and planned experiments are expected to provide key understanding and additional improvements in fuel performance to achieve fuel qualification goals.
  - Existing HERACLES roadmap provides the path for dispersion fuel qualification for conversion of BR2, RHF, JHF, ORPHEE, and a possible monolithic fuel qualification path for FRMII.

- **US Collaboration**
  - Technical meetings and exchanges with HERACLES group members and participation in experts groups.
  - PIE and characterization activities in Europe which are associated with the comprehension phase and fabrication of mini-plates.
  - NNSA M³ activities at US national labs support fuel development and qualification:
    - Modeling and simulation, experiment data analysis, coating studies, powder heat treatment.
    - EMPIRE experiment will investigate potential variations in fabrication parameters (coating, heat treatment, powder distribution, ..) that can provide the needed improvements in fuel performance.
### Irradiation Experiment

- **Must inform/demonstrate:**
  - Fundamental fuel system performance (comprehension, predictability)
  - Industrialization selection and maturity
  - Qualification for required irradiation conditions

<table>
<thead>
<tr>
<th>Activity</th>
<th>Objectives/Motivation</th>
<th>Next Steps</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EMPIRE</strong></td>
<td>Mini-Plate Test in ATR with alternatives beyond SEMPER-Fi - input from gap analysis</td>
<td>Experiment design and matrix definition</td>
<td>Some fabrication alternatives might not be available by start of irradiation</td>
</tr>
<tr>
<td></td>
<td>• Coated Particle Fab Alternatives Compare</td>
<td>Particle coatings</td>
<td>CERCA fabricated plates</td>
</tr>
<tr>
<td></td>
<td>• Powder heat treatment</td>
<td>Plate fabrications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Particle size &amp; distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEMPER FIDELIS</strong></td>
<td>Selection Phase. Key HERACLES response to Comprehension Phase 4 full size plates per cycle for 4 cycles Confirm mitigation and predictability of high burnup issues</td>
<td>HERACLES defining best set of low and high burnup plates</td>
<td>Coated Particles could be R&amp;D (e.g., KAERI powder with SCK PVD coating)</td>
</tr>
<tr>
<td><strong>SELENIUM II</strong></td>
<td>Selection Phase Validation Full-size plates &amp; Final down-select</td>
<td>Scope can only be clear after comprehension phase</td>
<td>Coated particles by R&amp;D</td>
</tr>
<tr>
<td><strong>E-FUTURE-III</strong></td>
<td>Full-Size Fuel Plate Qualification Down-select fabrication parameters</td>
<td></td>
<td>Pilot Scale Fab</td>
</tr>
<tr>
<td><strong>Mixed Element</strong></td>
<td>Fuel System Qualification Curved, constrained plates.</td>
<td></td>
<td>Pilot Scale Fab (?)</td>
</tr>
</tbody>
</table>
Status of Comprehension Phase (from FDEG)

- Based on several meetings of HERACLES/US fuels experts it is confirmed that the two key issues that need to be addressed:
  - High burnup swelling rate of UMo (recrystallization)
  - UMo-matrix interaction layer (IL) formation

- Mitigation strategies:
  - Swelling (recrystallization): annealing for Mo homogenization + grain growth (limiting GB)
  - IL formation: Si addition, ZrN coating

- Models provide acceptable prediction of total swelling
  - Further benchmarking required for qualification

- Existing correlations for interaction layer formation and fission rate, temperature and time (fission density) can be considered adequate
  - Basis: UMo-Al(Si) irradiations performed in the past.
  - Coating expected to eliminate IL formation

- KOMO-5 and RERTR-3 data provide support to heat treatment as mitigation for recrystallization
  - Effect on recrystallisation can only be studied by high burnup irradiation, no alternatives

- Coating: Limited irradiation results available
  - Advanced PIE on SELENIUM samples done and more to be done (FIB samples)
Status of Manufacturing Activities (from FMEG)

- Powder Atomization:
  - Prototype at CERCA is successful in producing atomized powder using rotating electrode method
  - Electrodes (pins) for atomization have been successfully manufactured at CERCA

- Powder Coating:
  - PVD coating at SCK and ALD coating at ANL are the two key choices for coating
  - Selection of preferred coating methods and needed tech transfer after irradiation experiments and cost assessments

- Powder Heat Treatment
  - ANL, INL, SCK-CEN have the capability (under development at CERCA/TUM)
  - Heat treatment studies at ANL and SCK show consistent grain growth
  - Further studies to determine heat treatment optimum conditions and Mo homogenization

- EMPIRE Experiment Manufacturing
  - Most of the plates are to be manufactured by CERCA for irradiation at the ATR
  - Limited plates are to be fabricated by ANL (with varying Mo content)
  - Monolithic plates by TUM/CERCA with C2TWP process will be included in EMPIRE
    - Plates with co-rolled Zr coated foil
    - Plates with PVD application of Zr on bare foil

- Materials Supply and Transfer
  - KAERI powder vs. CERCA powder
  - Logistics of coating and heating treating powder for the experiment at ANL and transfer to CERCA
  - CERCA produced powder inclusion in the experiment?
  - Monolithic foil supply for TUM plates
ANL heat treatment: recent study

(a) As-atomized U-7Mo powder
(Darker lines are GB.)
Grain size = 2 – 6 \( \mu m \)

(b) Heat treated U-7Mo at 900 \( ^\circ \)C for 1 h
Grain size = 23 \( \mu m \)

Area Mapping of ALD Coated UMo Powder
U-Mo Atomization - INL Support

- Production of U-Mo atomization pins for HERACLES - atomization pins were produced for demonstration testing using the TUM atomizer
- Characterization: DU, alloy, cast-pins, powder
- Atomizer installed at CERCA
Key Irradiation Experiments

Comprehension phase experiments
- EMPIRE experiment at the ATR
- SEMPER-FIDELIS at BR2

What is expected from the two experiments (from FDEG)
- Engineering
  - Effect of the heat treatment?
    - HT delays recrystallization sufficiently to reduce swelling at high BU?
  - Coating or Al-Si?
    - Eliminate IL formation? Coating required!
    - Reduction of swelling rate allows fuel system to accommodate IL formation in Al-Si matrix?
      - Cheaper fuel system, better for back-end.
  - Deposition method for coating?
    - Differences between ALD and PVD? Effect of AlN interlayer?
- Qualification and modeling
  - Fission rate versus fission density dependences
  - Parameterization of recrystallization (with/without HT)
  - Benchmark effect of variables (kernel size distribution, Mo content, loading, ...)

CERCA powder
European High Density LEU Fuel Development

Dispersion Fuel

SEMPER FIDELIS

SELENIUM 2

E-FUTURE 3

MIXED ELEMENT

FRMII Monolithic Fuel

FUTURE-MONO- 1

FUTURE-MONO- 2

MIXED ELEMENT

Industrialization

CERCA Powder Atomization Development

CERCA Powder Coating Development

CERCA Dispersed Plates Manufacturing Development

CERCA Monolithic Plates Manufacturing Development

TUM Mono coating

CERCA safety analysis / cost assessment / transport …

... BACK-END!
<table>
<thead>
<tr>
<th><strong>EMPIRE (ATR)</strong></th>
<th><strong>SEMPER FIDELIS (BR2)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Separate Effects Tests at two complimentary facilities</strong></td>
<td><strong>Cross-over testing to better connect existing databases</strong> (RERTR, AFIP, E-Future, Selenium)</td>
</tr>
<tr>
<td><strong>Goal to reach BR-2 target conditions (high power, high burnup)</strong></td>
<td><strong>Irradiation of both dispersion and monolithic fuels (TBD for SEMPER FI)</strong></td>
</tr>
<tr>
<td><strong>Plates have European AG3NE or AlFeNi cladding</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Mini-plate Scale - More variables, more sensitive to scale effect</strong></td>
<td><strong>Sub-size or Full (TBD) - Fewer variables, more prototypic for full size</strong></td>
</tr>
<tr>
<td><strong>Better variability of power/burnup</strong></td>
<td><strong>Limited variability of power/burnup, current peak is 470 W/cm²</strong></td>
</tr>
<tr>
<td><strong>Higher coolant pressure (2×BR2)</strong></td>
<td><strong>Lower coolant pressure</strong></td>
</tr>
<tr>
<td><strong>PIE at MFC (split the workload)</strong></td>
<td><strong>PIE at LHMA (split the workload)</strong></td>
</tr>
<tr>
<td><strong>Unique (complementary) PIE capabilities: FIB (key to coating studies)</strong></td>
<td><strong>Unique (complementary) PIE capability: EPMA (TEM for fuel, not coating)</strong></td>
</tr>
</tbody>
</table>
### EMPIRE (ATR)

<table>
<thead>
<tr>
<th>Focus</th>
<th>Coatings, with/without heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating method</td>
<td>PVD vs ALD</td>
</tr>
<tr>
<td>Type of coating</td>
<td>ZrN vs ZrN/AlN</td>
</tr>
<tr>
<td>Mo content</td>
<td>U-10Mo (&gt;^5U)</td>
</tr>
</tbody>
</table>

### SEMPER FIDELIS (BR2)

<table>
<thead>
<tr>
<th>Focus</th>
<th>Heat treatment at distinct fission rate vs. fission density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Si Matrix</td>
<td>(with heat treatment)</td>
</tr>
<tr>
<td>ZrN/PVD coating</td>
<td>with and without heat treatment to high burnup (beyond SELENIUM)</td>
</tr>
</tbody>
</table>

- **Heat treatment of U-7Mo**: with and without → *single optimised procedure*
- **U-7Mo particle size distribution**: standard and modified
- **Variable fission rate and burnup**

### Additional Information

- **KAERI and CERCA powder**
- **Plates made by CERCA and ANL**
- **Earlier insertion, September 2016**: Data for comprehension phase available earlier
- **Monolithic**: C2TWP, co-rolled & PVD Coated

- **CERCA powder**
- **Plates made by CERCA**
- **Later insertion, second half 2016**, after EMPIRE:
  Data for comprehension phase available later
Specific US Activities
# US Dispersion Fuel Activities in Support of HERACLES Comprehension Phase

## E-FUTURE and SELENIUM PIE Support
- Analysis and interpretation of test data
- Comparison with other relevant test results.
- Support of cutting plans and samples selections

## Microstructural Characterization
- Characterization of Fabricated plates & archive samples
- Coating structure
- Thermal properties
- Ion irradiation experiments

## Fabrication Support
- Alternate coating activities in the US (e.g., ALD)
- Ion irradiation (test coating)
- Support EMPIRE fabrication needs
- Fabrication and atomization studies

## EMPIRE Experiment
- Experiment Design and Analysis and matrix definition
- Conceptual design based on output from working groups
- Fabricate materials/plates as needed

---

**Dispersion Fuel Modeling and Simulation**

- DART code mechanistic modeling
- Modeling of fundamental U-Mo fuel properties
- CFD Simulation of SELENIUM experiment and EMPIRE support

- ABAQUS/Multiphysics models of full size plates
- Modeling of coating-fuel and coating-matrix interactions
- Dispersion Fuel Plates Modeling
Failure Criteria U-Mo/Al, Dispersion Fuel
(filled symbols: pillowed and/or large porosity)

Threshold curve for fuels without Si

(G.L. Hofman, ANL, 2015)
How the acceleration of fuel swelling occurs?
- Increased fission gas bubble swelling during fuel recrystallization

**Fuel swelling vs. Fission density**
(SELENIUM and E-FUTURE plates)

**Fission gas bubble swelling vs. Fission density**

(Van den Berghe, JNM 442, 2013)

(G.L. Hofman, ANL, 2015)
Increased gas bubble swelling during recrystallization

Subdivision of fuel grains results in an increased number of grain boundaries and triple points where large intergranular gas bubbles nucleate.

Reduction of fuel grain size results in shortened gas atom diffusion distance from the center of a fuel grain to its boundary, which accelerates intergranular bubble growth.

These changes lead to a significant increase of gas bubble swelling.
The recrystallization kinetics is a function of burnup (JMAK plot).

- Mo content and initial grain size are important factors impacting the recrystallization kinetics.