USHPRR Reactor Conversion

Outline

- Philosophy of Core Conversion
- Principle of Fuel Acceptability for Conversion
- Overview of the 5 USHPRR and 4 EUHFR
  - Require very high density fuels able to withstand
    - High to very high heat flux (fission rate)
    - High burnup (fission density)
    - High to very high coolant flows (potential for hydrodynamic challenges)
- Pillars of the USHPRR Conversion Program to Address Fuel Acceptability
  Analogous expert groups in Europe, but no single integrating organization
- Working Group Approach to Conversions
PHILOSOPHY OF CORE CONVERSION

- Simply Stated: Change as little as possible
- Fuel will be changed (by definition)
- Burnable Absorber should be tuned to fuel composition
- Reflector changes highly effective, if cost acceptable
Leveraging the 30+ Year History of RERTR

Why Do We Need Analyses?

- **Analysis** entails much more than calculation

- The need for analysis: **Demonstrate**
  - **Performance** with new fuel
  - **Safety** with new fuel
  - **Economics** with new fuel

- Nearly every research reactor is unique, so specific analyses are required
  Experience allows the GTRI Convert team to:
  - Use as many established procedures and tools as possible
  - Extend efficiently when necessary, with the benefit of broad perspective

- A series of tools must be applied by experts:
  - Appropriate analyses of performance and safety margins
  - Communicated effectively to operators, regulators, public
PRINCIPLE OF FUEL ACCEPTABILITY FOR CONVERSION

- **QUALIFIED** Fuel Assembly
  - Fuel assembly that has been successfully irradiation tested and is licensable from the point of view of fuel irradiation behavior

- **COMMERCIALY AVAILABLE** Fuel Assembly
  - Fuel assembly that is available from a commercial manufacturer

- **SUITABLE** Fuel Assembly
  - Safety criteria are satisfied
  - Fuel Service Lifetime comparable to current HEU fuel (e.g., Number of FA used per year is the same as or less than with HEU fuel)
  - Performance of experiments is not significantly lower than with HEU fuel

To be **ACCEPTABLE** for LEU conversion of a specific reactor, a fuel assembly must be qualified, commercially available, and suitable for use in that reactor, then reactor operator & regulator must agree to ACCEPT fuel assembly for conversion
# U.S. High Performance Research Reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>HEU Core Power</th>
<th>Primary Uses</th>
<th>Regulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITR</td>
<td>6 MW</td>
<td>Mixed</td>
<td>NRC Regulated</td>
</tr>
<tr>
<td>MURR</td>
<td>10 MW</td>
<td>Isotope Production, Activation</td>
<td></td>
</tr>
<tr>
<td>NBSR</td>
<td>20 MW</td>
<td>Beam Science</td>
<td></td>
</tr>
<tr>
<td>ATR (ATRC)</td>
<td>100-250 MW (ATRC 600 W)</td>
<td>Fuel &amp; Material Irradiation</td>
<td>DOE Regulated</td>
</tr>
<tr>
<td>HFIR</td>
<td>85 MW</td>
<td>Beam Science &amp; Isotope Production</td>
<td></td>
</tr>
<tr>
<td>Reactor</td>
<td>HEU Assemblies Per Year (Plates Per Year)</td>
<td>LEU Needed</td>
<td>LEU U-Mo Assemblies Per Year (Plates Per Year)</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------</td>
<td>------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>MITR</td>
<td>9 (135 plates)</td>
<td></td>
<td>7 (133 plates)</td>
</tr>
<tr>
<td>MURR</td>
<td>23 (552 plates)</td>
<td></td>
<td>22 (506 plates)</td>
</tr>
<tr>
<td>NBSR</td>
<td>30 (1020 plates)</td>
<td></td>
<td>30 (1020 plates)</td>
</tr>
<tr>
<td>ATR (ATRC)</td>
<td>110 (2090 plates)</td>
<td></td>
<td>100 (preliminary) (1900 plates)</td>
</tr>
<tr>
<td>HFIR</td>
<td>7 Cores (3780 plates)</td>
<td>Complex Monolithic, Graded foil, Burnable Absorber?</td>
<td>7 Cores (3780 plates)</td>
</tr>
</tbody>
</table>

USHPRR cannot be converted with existing qualified, commercially available fuels.
## USHPRR

### Mitigation of conversion performance penalties

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Pre-Mitigated Performance Penalty</th>
<th>Key Mitigation</th>
<th>Post-Mitigated Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITR</td>
<td>5-10%</td>
<td>Power Increase (6 MW $\rightarrow$ 7 MW)</td>
<td>None</td>
</tr>
<tr>
<td>MURR</td>
<td>15%</td>
<td>Power Increase (10 MW $\rightarrow$ 12 MW)</td>
<td>None, Potential Slight Gains</td>
</tr>
<tr>
<td>NBSR</td>
<td>10%</td>
<td>Cold Source Upgrade</td>
<td>None, Thermal Small Losses, Cold Small Gains</td>
</tr>
<tr>
<td>ATR (ATRC)</td>
<td>5-10% Preliminary</td>
<td>Minimal Fuel Utilization Changes</td>
<td>Minimal</td>
</tr>
<tr>
<td>HFIR</td>
<td>10-15%</td>
<td>Power Increase (85 MW $\rightarrow$ 100 MW)</td>
<td>None, Potential Small Gains</td>
</tr>
</tbody>
</table>
Key Fuel Performance Issues: Combination of Density, Fission Rate, Burnup

Note foil thicknesses vary widely, so peak heat fluxes not consistently related to peak power density. The very high power densities indicated are in thin foils.
Key Fuel Fabrication Issues for U-Mo Monolithic with Diffusion Barrier: Combination of Density, Waviness, and Clad Thickness

MURR Tolerance Assumption Example for 10 mil clad that had been proposed (redesign was performed for 12 mil clad)
### USHPRR: Fuel Challenges Prior to LEU Refinements

<table>
<thead>
<tr>
<th>Reactor</th>
<th>LEU Needed</th>
<th>Key Fuel Challenges for U-Mo Monolithic LEU Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITR</td>
<td>Base Monolithic Fuel</td>
<td>Finned plates (HEU and LEU) Thinner clad in LEU than HEU</td>
</tr>
<tr>
<td>NBSR</td>
<td></td>
<td>Unfueled region leads to very high local burnup peak</td>
</tr>
<tr>
<td>MURR</td>
<td></td>
<td>Fewer thinner plates with thinner clad in LEU with respect to HEU 5 distinct fuel foil thicknesses</td>
</tr>
<tr>
<td>ATR/ ATRC</td>
<td>Complex Monolithic? Absorber?</td>
<td>48 inch Foils (~2 x length) Some foils 8 mil (0.2 mm) thick Burnable absorber in plates?</td>
</tr>
<tr>
<td>HFIR</td>
<td>Complex Monolithic, Graded foil. Absorber(s)?</td>
<td>Contoured LEU fuel: Radial &amp; axial thickness shape Burnable absorber: $^{10}$B in fuel region of HEU-LEU plates</td>
</tr>
</tbody>
</table>
## USHPRR: Fuel Challenges and Recent Progress

<table>
<thead>
<tr>
<th>Reactor</th>
<th>LEU Fuel Required</th>
<th>Fuel Element Design Features – U-Mo Monolithic LEU Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITR</td>
<td>Base Monolithic Fuel</td>
<td>HEU 15 finned plates; complex fuel management&lt;br&gt;LEU 19 un-finned plates</td>
</tr>
<tr>
<td>NBSR</td>
<td></td>
<td>Unfueled region leads to high local burnup peak</td>
</tr>
<tr>
<td>MURR</td>
<td></td>
<td>Fewer thinner plates in LEU with respect to HEU</td>
</tr>
<tr>
<td>ATR/ATRC</td>
<td></td>
<td>Feasible for LEU to remove absorber used in HEU&lt;br&gt;Fuel foil 1.2 meters in length, 0.2 mm to 0.5 mm thick</td>
</tr>
<tr>
<td>HFIR</td>
<td>Complex Monolithic Fuel</td>
<td>540 involute plates per core&lt;br&gt;Contoured fuel in plates&lt;br&gt;Neutron absorbers relocated?</td>
</tr>
</tbody>
</table>
## European High Flux Research Reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>HEU Core Power</th>
<th>Typical Elements/Core</th>
<th>Primary Uses</th>
<th>LEU Fuel Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR-2 (SCK, Belgium)</td>
<td>50-80 MW</td>
<td>32 Typical each 6 plates</td>
<td>Fuel &amp; Material Irradiation Isotope Production</td>
<td>U7Mo Dispersion</td>
</tr>
<tr>
<td>RHF (ILL, France)</td>
<td>53-58 MW</td>
<td>1 Involute 280 plates</td>
<td>Beam Science</td>
<td></td>
</tr>
<tr>
<td>JHR (CEA, France)</td>
<td>100 MW</td>
<td>38-46 each 8 plates</td>
<td>Fuel &amp; Material Irradiation Isotope Production</td>
<td></td>
</tr>
<tr>
<td>FRM-II (TUM, Germany)</td>
<td>20 MW</td>
<td>1 Involute Graded 113 Plates</td>
<td>Beam Science</td>
<td>U10Mo Monolithic</td>
</tr>
</tbody>
</table>

**ORPHEE (CEA, France)** uses HEU but may shutdown before an LEU fuel could be qualified 14 MW, 8 fresh elements in each core (168 plates/core) for Beam Science
Active GTRI/EU Conversion Analysis Collaborations

Both reactors preparing for decennial review. Updated HEU SAR prepared to explicitly support LEU conversion once fuel is qualified.
BR-2 Burnable Absorber Relocation

- High volume fraction of UMo in LEU dispersion makes integral burnable absorber unattractive

- SCK-CEN has pursued use of Cd wires in swage joints of assembly stiffeners (qualified for use in HEU elements to support LEU Conversion)
RHF Overview of HEU and Proposed LEU Cores

Direct fuel replacement

Problems:
- Incompatibility LEU/boron
- Neutron flux drops by ~10%
- Cycle length drops by ~25%

Solutions:
- Remove the boron from plate
- Increase the power
- Increase the fuel volume
Proposed poison belt for RHF LEU Core

- Schematic of the top poison belt to control power peaking at leading plate edge:
Proposed RHF poison belt would control peaking

Peak too high without burnable absorber

Peak < BR-2 with burnable absorber (Poison Belt)
Experimental Performance

Relative weighted brightness

RHF Conversion Impact for Altered Height of Core

- RHF Choice to maintain the 50 days cycles

HEU 57MW to LEU 55MW
- Cycle length: +9 ± 1%
- Brightness: -16 ± 3%
- Factor of Merit (FOM) ~ -7 ± 4%

HEU 52MW to LEU 55MW
- Cycle length: 0 ± 1%
- Brightness: -7 ± 3%
- FOM ~ -7 ± 4%

Proposed LEU at 55MW:
- between 5 and 10% of losses with respect to the current HEU configuration
Organization to Deploy an Acceptable LEU Fuel

Pillars of the USHPRR Conversion Program

- QUALIFIED Fuel Assembly
  - Fuel Development Pillar

- COMMERCIALLY AVAILABLE Fuel Assembly
  - Fuel Fabrication Capability Pillar

- SUITABLE Fuel Assembly
  - Reactor Conversion Pillar

To be ACCEPTABLE for LEU conversion of a specific reactor, a fuel assembly must be qualified, commercially available, and suitable for use in that reactor, then reactor operator & regulator must agree to ACCEPT fuel assembly for conversion

- Convert Integration Pillar: Cross-Cutting, Systems Engineering & Backend

**Integration** of Facilities, DOE Lab Complex, Regulators
Specific Reactor Conversion Collaboration Structures All Unique

- **MITR**
  - Joint analyses at MITR & Argonne
  - PM Lead by GTRI, at request of MITR (and with active participation)

- **MURR**
  - Joint analyses at MURR & Argonne
  - PM Lead by MURR with active GTRI participation

- **NBSR**
  - Joint analyses at NIST & Brookhaven
  - PM Lead by NBSR staff at NIST

- **ATR**
  - Analysis at INL, with Argonne independent reviews since 2013
  - PM Lead by INL

- **HFIR**
  - Analysis at ORNL – but Argonne will perform independent reviews since 2011
  - PM Lead by HFIR
Organization to Deploy an Acceptable LEU Fuel
HERACLES/GTRI Collaboration

- QUALIFIED Fuel Assembly
  - Fuel Development Expert Group

- COMMERCIALY AVAILABLE Fuel Assembly
  - Fuel Manufacturing Expert Group

- SUITABLE Fuel Assembly
  - Reactor Conversion at each facility with bilateral collaborations

To be ACCEPTABLE for LEU conversion of a specific reactor, a fuel assembly must be qualified, commercially available, and suitable for use in that reactor, then reactor operator & regulator must agree to ACCEPT fuel assembly for conversion

- Integration more complex without a single conversion organization
  - Technical Committee
  - Strategic Committee
WORKING GROUP APPROACH TO CONVERSIONS

- GTRI is successful due to collaboration, not unilateral action

- All research reactors are unique in some attributes, but there are groups of reactors that require similar fuel and/or share fuel supply

- US High Performance Research Reactor Program (USHPRR)
  - LEU UMo Monolithic fuel is expected to meet the needs of the reactors

- EU High Flux Reactor Collaborations (EUHFR) (BR2, RHF, JHR) (FRM-II)
  - LEU UMo Dispersion fuel is expected to meet the needs of the reactors with evolutionary changes to supply chain. FRM-II will need revolutionary monolithic fuel.

- MNSR Working Group in coordination with the IAEA
  - Chinese supplied Miniature Neutron Source Reactors in China and 5 other nations

- Russian/US Collaborative Conversion Feasibility Studies for Russian Domestic Reactors

- International Fuel Development Working Group
USHPRR Working Group Approach to Conversions

Communication for Collaborative Success

USHPRR Working Group

- Key Stakeholders all involved
  - USHPRR Facility Operators
  - DOE Complex for 4 Pillars of Program (Fuel Development, Fuel Fabrication Capability, Reactor Conversion, and Convert Integration)
  - Regulators as observers

- 2-3 Meetings per Year since 2006 to have each of the five reactors and the program pillars exchange information on progress and challenges

- Experts Meetings for more focused topics:
  Thermal Hydraulics, Fabrication, Verification & Validation

USHPRR Project Web Site

- Presentations on the secure project web site shortly after the meetings
- Key reports from the USHPRR Conversion Program pillars and the facilities archived for common access
Conclusions

- **Common Current barriers to conversion of High Performance RRs**
  Fuel must be Qualified, Commercially Available, and Suitable

- **GTRI remains fully committed to**
  High Performance Research Reactor Conversions

- **GTRI enhancing process rigor to address fuel challenges**
  - Design Review Cycles will be more rigorous for all phases of future work
  - Future samples fabricated with commercial emphasis rather than lab scale
  - Redesigns to reduce fabrication challenges
  - New downselects will include both fabrication and irradiation performance

- **Integration through Working Groups Key to Success**
Thank you for your attention

Acknowledgements

- Many thanks to the team efforts of staff at NBSR, MURR, MIT, BNL, ORNL, INL, SCK, ILL, CEA, Areva-CERCA, TUM, and ANL
Supporting Material
Specific Discussion of Challenges for Conversion of the USHPRR
MITR

- MITR fuel assembly
  - Rhomboid
  - Finned Clad on each fuel plate surface to increase heat transfer

- Flexible Number
  - Fuel Elements and
  - Dummy/Experiment Assemblies

- Number of plates increased from 15 HEU to 19 LEU to preserve cycle length & improve thermal margin

- Power Increase
  - 6 MW HEU to 7 MW LEU to preserve operational flexibility

Mitigations will not require significant system modification

Pre-Mitigated Penalty 5-10%
No Post-Mitigated Penalty
MURR

- Very Compact Core Design
  - Core Volume 33 liters
  - Fuel Meat 4.3 liters

- MURR fuel assembly
  - 24 curved plates
  - 45 degree arc
  - No grid flexibility

- Weekly refueling for > 90% capacity factor for > 20 years
- Weekly cycle and initial control blade position key to efficient isotope production

- LEU fuel assembly:
  - 23 plates (for moderation)
  - Plate thicknesses reduced
  - Variable fuel meat thickness for power peaking control
  - Thinner clad for better moderation (fuel utilization)

- Power Increase
  10 MW HEU to 12 MW LEU to preserve Production Rates
NBSR

- **NBSR fuel assembly**
  - Unfueled region at core axial centerline provides flux peak for experiments
  - 34 slightly curved plates per assembly

- No grid flexibility, Compact LEU core design would not preserve sufficient range and flexibility of experiments

- Pre-Mitigated Penalty $\sim$10%

- **No Post-Mitigated Penalty**
  - Thermal loss to be overcome by improved instruments
  - Cold losses completely overcome by upgrade of cold source – potential for small gains in cold neutron performance

- Key Challenge will be timing
  i.e., planning and execution have little margin for problems or adjustments
**ATR**

- **ATR fuel assembly**
  - 19 curved plates
  - 45 degree arc
  - No grid flexibility
  - Integral burnable absorber used to control power peaking within inner and outer plates of HEU
  - 48 Inch plate length (others <24”)

- 5 Lobes of reactor operated at distinct powers, so operational flexibility a key

- Detailed performance penalties still being determined, but preliminary estimates are 5-10%

- Burnable Absorber was key challenge, but was designed out FY13 by selecting distinct foil thickness in plates. FY13 Conceptual Design now in Preliminary Design rigor.
HFIR

- HFIR fuel assembly
  - Involute plates maintain constant water gap between concentric cylinders
  - Graded fuel meat within plates to control power peaking at radial edges of fuel
  - Burnable Absorber in inner element “filler” of HEU to further control radial peaking

- Single-Use Core
- Original Power Rating 100 MW
  - was reduced to 85 MW due to vessel pressure concern coupled with 60s safety basis
  - Plan to return to 100 MW with LEU via modern safety basis

- Pre-Mitigated Penalty 15% BOC
- No Post-Mitigated Penalty
HFIR Key Challenges

- **Onset of Nucleate Boiling (ONB) at Core Exit** is the active thermal constraint

- **Definitive Complex Fuel**
  - Radial grading of fuel must be maintained for LEU
  - Burnable absorber apparently still necessary in inner element
  - Axial grading of last several cm at exit apparently necessary to avoid ONB
  - **Key current design efforts aim to:**
    1. Get rid of axial “toe” in earlier LEU design to keep grading one dimensional
    2. Get absorber out of plate and into structure, like BR2 has done

- **Power Increase** from 85 MW HEU to 100 MW LEU presents additional challenges
  - Computational Fluid Dynamics (CFD) Safety Basis will be required to show that sufficient thermal margin exists at current system pressure