LEU Fuel Studies at the MIT Research Reactor

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Outline

• MIT Reactor
  • Fuel and reactor design
• Analysis models
  • Neutronic
  • Thermal-hydraulic
• LEU fuel design and analyses
• Current status
• Projects completed and future plans
MIT Reactor Fuel

Licensed power: 6 MW
Aluminide fuel
15 plates/element, 60 mils thick
93% enriched
15 mil Al clad with 10 mil longitudinal fins
MIT Reactor Core

- Because of the compactness of the core, MIT is one of five civilian research reactors that cannot convert to LEU using existing qualified fuels.
- Studies have shown that we will need LEU densities exceeding 10 gU/cm³ to maintain criticality and mission.
  - Monolithic U-10Mo fuel (15.5 gU/cm³) is the principal fuel being proposed for conversion.
MIT Reactor

Graphite Reflector
D2O Reflector
Beam Port
Re-entrant Thimble

MITR-II Core
M11 Thermal Beam Line
Thermal Beam Medical Room

Fission Converter
In-Core Experiments

MITR flux and spectrum are roughly equivalent to that of an LWR. In-core experiments design and operation support advanced reactor fuel, materials, instrumentation, and LWR chemistry (PWR or BWR) development.

High temperature irradiation facility has been demonstrated up to 1400 °C.

Versatile irradiation capsule up to 850 °C.

Hot cell and hot box facilities are available for Post Irradiation Examination.

The MITR has been a partner facility of the Advanced Test Reactor National Scientific User Facility (ATR-NSUF) since 2008.
Neutronic Analysis Codes

- MCNP
  - Models of HEU core configurations made based on initial model (MITR core no. 2) by Redmond, et al.
  - Discrete modeling of fuel plates, explicit modeling of structures
  - Modified for experiment evaluation and LEU conversion analysis

- MCODE
  - MCNP-ORIGEN linkage code developed at MIT
  - Graphical User Interface developed for MITR
  - Modified for fuel management and LEU analyses

- Others previously used
  - REBUS-DIF3D
  - CITATION
MCODE-FM

- Used for burnup analysis and fuel management
- User specified axial and radial burnup nodes
- Handles and burns HEU, LEU, and mixed geometries
- Can model all fuel movements, flipping, rotating, and fuel storage
- Optional criticality blade position search
- Can track and plot:
  - All relevant isotopes, including fission products and actinides
  - Power distribution and peaking
Extensive benchmarking has been done comparing measured and calculated values of reactivity worth (\(m_\beta\)) and time (EFPD) for MITR start-up and shutdown.

### In-core Experiments

<table>
<thead>
<tr>
<th>Cycle Nr.</th>
<th>In-core Experiments</th>
<th>Calculation</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>211B</td>
<td>A1: Dummy, A3: Dummy, B3: Dummy</td>
<td>9.46&quot;</td>
<td>9.64&quot;</td>
</tr>
<tr>
<td>211C</td>
<td>A1: Dummy, A3: ULTRA, B3: Dummy</td>
<td>10.65&quot;</td>
<td>10.76&quot;</td>
</tr>
</tbody>
</table>
Thermal-Hydraulics

- Safety limits derived from fuel design geometry and materials, power distributions from MCODE, and flow distributions
- Steady-state codes used:
  - RELAP5
  - Stat7 (statistical propagation of Engineering Hot Channel Factors)
- Accident analyses
  - RELAP5 (Loss of Flow)
  - PARET (reactivity insertion)
LEU Design

• Criteria:
  • Equivalent in-core fast flux and ex-core thermal flux as 6 MW HEU
  • Sufficient margin to Onset of Nucleate Boiling
  • Fuel to fit within existing fuel element geometry
  • No major infrastructure changes

• Original Design:
  • Monolithic U-10Mo
  • 18 plates/element
  • 10 mil Al clad with fins
  • Operation at 7 MW
Concerns about fins

- Thinner cladding design (10 mils) was seen to be possibly problematic in manufacturing, particularly given concerns about monolithic fuel with interlayer.
- HEU fuel burnup limited to $1.8 \times 10^{21}$ fissions/cm$^3$, primarily because of NRC concerns about reduction of fin effectiveness with oxide buildup.
- There will likely be no limit LEU fuel burnup (tests have shown adequate performance beyond 100% burnup of LEU), thus oxide buildup effect becomes primary concern.
Updated Design

- ANL and MIT did optimization study of unfinned fuel with reduction of outer plate fuel meat to reduce power peaking.
- Target was equivalent fuel cycle length and experiment fluxes at 7 MW with adequate margin to ONB.
- Primary flow rate to increase 20% over HEU
  - Possible without major primary system changes as we have some margin.
### HEU and LEU Fuel Designs

<table>
<thead>
<tr>
<th></th>
<th>UAl$_x$ (HEU)</th>
<th>Monolithic U-10Mo (LEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enrichment</strong></td>
<td>93%</td>
<td>19.75%</td>
</tr>
<tr>
<td><strong>Fuel Density (gU/cm$^3$)</strong></td>
<td>1.54</td>
<td>15.5</td>
</tr>
<tr>
<td><strong>Number of plates per assembly</strong></td>
<td>15</td>
<td>19 (unfinned)</td>
</tr>
<tr>
<td><strong>Fuel thickness (mils)</strong></td>
<td>30</td>
<td>25 (center 14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 (plates 2,3,17,18)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 (outer)</td>
</tr>
<tr>
<td><strong>Cladding Thickness</strong></td>
<td>15 mils + 10 mil fins</td>
<td>12-19 mils</td>
</tr>
<tr>
<td><strong>Operating Power</strong></td>
<td>6 MW</td>
<td>7 MW</td>
</tr>
<tr>
<td><strong>Cycle length</strong></td>
<td>40-50 days</td>
<td>60-70 days</td>
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</table>
Heated flow loop

A heated flow loop simulating proposed MITR fuel geometry was built to determine pressure drop and verify ONB correlations.
Accident Analyses of Updated Design

- Loss of Flow
  - RELAP5
  - Design basis shows no concerns with LEU fuel

- Reactivity Insertion
  - PARET
  - LEU easily meets HEU design basis

- Other analyses in progress, but no show-stoppers anticipated.

Loss of flow at 7 MW with scram after 1 s

1.8% ΔK/K insertion in 0.5 s

Note: The End Plate Is Limiting
Status

- U-Mo fuel manufacturing is under development and testing.
- MITR Preliminary Safety Analysis Report for the updated LEU design is being prepared for submittal to NRC in 2015.
  - NRC review is expected to be on adequacy of analyses and methodology.
  - Final SAR and approval will await qualification of U-Mo fuel, expected about 2024.
- Transition from HEU to unfinned LEU to be studied.
TRIGA Study

MIT is working with ANL and General Atomics to explore the possibility of using 45/20 UZrH fuel in the MITR.
- 45 w/o U, 20% enriched
- Used in 14 MW TRIGA in Pitesti, Romania (ICN)
- Not (yet) qualified for use in US

MITR design:
- Shortened to fit into reactor grid space
- Higher erbium content (0.27%)
- Smaller diameter rods (0.54”)

Necessary MITR changes:
- Solid $B_4C$ control blades to meet shutdown margin
- Power increase to 8-9 MW to meet flux requirements
MITR Conversion Reports – Original Design

“Comparison and Validation of HEU and LEU Modeling Results to HEU Experimental Benchmark Data for the MIT Reactor,” ANL/RERTR/TM-10-41

“Neutronic Analyses for HEU to LEU Fuel Conversion of the MIT Reactor,” ANL/RERTR/TM-10-40


“Power Distributions in Fresh and Depleted LEU and HEU Cores of the MIT Reactor,” ANL/RERTR/TM-12-3

“Preliminary Accident Analyses for Conversion of the MITR from Highly Enriched to Low Enriched Uranium,” ANL/GTRI/TM-13-5
MITR Conversion Reports – Revised design

“Low Enriched Uranium Core Design for the MITR with Un-finned 12 mil-thick Clad UMo Monolithic Fuel,” ANL/GTRI/TM-13/15

“Modeled Irradiation Plate History for Conversion of the MITR from Highly Enriched to Low Enriched Uranium,” ANL/GTRI/TM-14/4 (draft)

“Experimental Investigation of a Single-Phase Heat Transfer and Onset of Nucleate Boiling in a Prototypic Materials Test Reactor Coolant Channel to Support the MITR LEU Conversion,” MITNRL-14-01

“Evaluations of LEU Conversion Impact on the In-Core Experiment Performance at the MIT Research Reactor,” MITNRL-14-02
“Design of a Low Enrichment, Enhanced Fast Flux Core for the MIT Research Reactor,” Ellis 2008 (Ph.D.)

“Developing Fuel Management Capabilities Based on Coupled Monte Carlo Depletion in Support of the MIT Research Reactor Conversion,” Romano, 2009

“Estimate of Radiation Release from MIT Reactor with Low Enriched Uranium Core During Maximum Hypothetical Accident,” Plumer 2011


“Study of Turbulent Single-Phase Heat Transfer and Onset of Nucleate Boiling in High Aspect Ratio Mini-Channels to Support the MITR LEU Conversion,” Forrest, 2014 (Ph.D.)

Conclusions

• We believe monolithic U-10Mo to be technically viable for use in the conversion of the MITR to LEU fuel.
  • Revised design of LEU unfinned fuel with thinner outer plates appears to be feasible.
• MIT will continue to work with GTRI program to complete analyses and design revisions, if necessary.
Acknowledgements

• MITR conversion work is supported by the GTRI program
• MIT conversion personnel:
  • Lin-wen Hu
  • Kaichao Sun
  • More than a dozen MIT undergraduate and graduate students
• ANL:
  • Erik Wilson
  • Floyd Dunn
  • Several others
• INL, PNNL, LANL personnel
Questions?

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Backup slides
LEU Core Steady State Analysis

- MCODE used for BOL, MOL and EOL power profiles
- Power profiles then input into RELAP5 to get temperature profiles and to determine margin to ONB.
- The fresh core has the highest peak heat fluxes and lowest margin to ONB.
- The peak heat fluxes and peak temperatures still occur in an edge plate, despite lower fuel loading.
End Coolant Channel Gap

End coolant channel ratio (ECR; ratio of end to interior channel dimension) has been shown to be important parameter for fuel design. Additional 10% power gain with ECR increase to 88% and no significant impact on other parameters was observed.

ECR v.s. minimum ONB Power
6 Fuel Designs Selected

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<tbody>
<tr>
<td>$^{235}$U mass per element (g)</td>
<td>831</td>
<td>910</td>
<td>1058</td>
<td>767</td>
<td>940</td>
<td>968</td>
<td>1169</td>
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<tr>
<td>plates per assembly</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>fins</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>plate thickness (mm)</td>
<td>1.02</td>
<td>1.24</td>
<td>1.37</td>
<td>1.12</td>
<td>1.24</td>
<td>1.24</td>
<td>1.37</td>
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<tr>
<td>1st fuel plates (mm)</td>
<td>0.33</td>
<td>0.33</td>
<td>0.30</td>
<td>0.28</td>
<td>0.33</td>
<td>0.41</td>
<td></td>
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<tr>
<td>2nd fuel plates (mm)</td>
<td>0.43</td>
<td>0.46</td>
<td>0.30</td>
<td>0.38</td>
<td>0.43</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>3rd fuel plates (mm)</td>
<td>0.43</td>
<td>0.46</td>
<td>0.41</td>
<td>0.38</td>
<td>0.43</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>4th fuel plates (mm)</td>
<td>0.64</td>
<td>0.76</td>
<td>0.41</td>
<td>0.64</td>
<td>0.64</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>other fuel plates (mm)</td>
<td>0.64</td>
<td>0.76</td>
<td>0.51</td>
<td>0.64</td>
<td>0.64</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

**Limiting power to ONB** for flow = 2200gpm (MW)
(where >8.4 MW is required based on 20% margin to 7 MW LEU operating power)

| 22 element fresh core | 11.75 | 9.12 | 9.54 | 9.32 | 9.98 | 9.28 | 8.84 |

- All of the above cores showed comparable performance at 7 MW to reference 6 MW HEU core.
Heated Flow Loop