High Flux Isotope Reactor Low-Enriched Uranium Conversion Activities – 2022 Status Update
2022 Reduced Enrichment Research and Test Reactor (RERTR) Meeting
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Oak Ridge National Laboratory
Outline

- HFIR Overview, Mission and Conversion Strategy
- LEU Fuel Designs
- Reactor Physics Modeling and Simulation
- RELAP Model Development
- COMSOL Benchmark Status
- Conversion Pillar Collaboration
**HFIR is a versatile, multi-mission research reactor**

HFIR’s neutron science capabilities serve a variety of high-impact missions located at Oak Ridge National Laboratory.

<table>
<thead>
<tr>
<th>Neutron scattering</th>
<th>Radioisotope production</th>
<th>Materials irradiation</th>
<th>Activation analysis</th>
<th>Gamma irradiation</th>
<th>Neutrino research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold/thermal neutrons to study structure and dynamics of materials</td>
<td>For use in energy, industry, security, medicine</td>
<td>≤14 dpa/year</td>
<td>2 pneumatic tubes</td>
<td></td>
<td>Pure $^{235}$U spectrum</td>
</tr>
<tr>
<td>• Physics</td>
<td>• $^{252}$Cf</td>
<td>• Accident tolerant fuels</td>
<td></td>
<td></td>
<td>Neutrino spectrum and oscillations</td>
</tr>
<tr>
<td>• Chemistry</td>
<td>• $^{238}$Pu</td>
<td>• Fuel cladding</td>
<td></td>
<td></td>
<td>Short baseline</td>
</tr>
<tr>
<td>• Materials science</td>
<td>• $^{225}$Ac</td>
<td>• Advanced alloys</td>
<td></td>
<td></td>
<td>Reactor monitoring</td>
</tr>
<tr>
<td>• Engineering</td>
<td>• $^{188}$W</td>
<td>• Fusion reactor materials</td>
<td></td>
<td></td>
<td>Nuclear safeguards</td>
</tr>
<tr>
<td>• Biology</td>
<td>• $^{75}$Se</td>
<td>• Tensile testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• $^{63}$Ni</td>
<td>• Post-irradiation examinations</td>
<td></td>
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</tbody>
</table>

- **Gamma irradiation**
  - Used fuel
  - Up to $10^8$ rad/h
  - Radiological damage studies
  - NASA material tolerance
  - Resin for $^{137}$Cs removal in waste
  - Insulators
  - Wear resistance

- **Neutrino research**
  - Pure $^{235}$U spectrum
  - Neutrino spectrum and oscillations
  - Short baseline
  - Reactor monitoring
  - Nuclear safeguards
HFIR has a unique geometry for experiment flexibility

**Flux trap target region**
- 37 vertical target positions
- Isotope production
- Materials irradiation
- Hydraulic tube

**Control element region**
- 2 concentric cylinders
- Outer control element (OCE) for safety and regulation
- Inner control element (ICE) for regulation
- Eu, Ta, Al

**Beryllium reflectors**
- 4 beam tubes for scattering
- 42 vertical experiment facilities
- 2 pneumatic tubes for NAA

**Fuel assembly:**
- Inner fuel element (IFE) Outer fuel element (OFE)
  - Involute-shaped Al clad plates
  - 171 IFE plates
  - 369 OFE plates
  - HEU$_3$O$_8$-Al dispersion fuel
  - 9.4 kg $^{235}$U and 2.7 g $^{10}$B

**Light water cooled and moderated**
**16,000 GPM primary coolant flow (120°F 468 psig)**

**85 MW (1.7 MW/L average)**
- $2.5 \times 10^{15} \text{ n/cm}^2\text{-s}$ peak thermal
- 23-26-day cycle lengths

**US DOE User Facility**
**Oak Ridge National Lab**
HFIR Conversion History

- ORNL has been evaluating conversion to an LEU fuel product since 2005.

- Initial studies explored U-10Mo monolithic alloy fuel, but as the U-10Mo designs to meet HFIR performance and safety metrics are complex, it was not clear they could be economically manufactured.

- HFIR re-baselined to a uranium-silicide dispersion fuel ($U_3Si_2$-Al) in 2019.

- HFIR conversion currently scheduled for 2030s

U-10Mo “utilization” design had borated side plates and an axial contour
HFIR Conversion Strategy

HFIR conversion currently scheduled for mid-2030s

1. Develop analytical tools, propose fuel designs, and demonstrate feasibility of HFIR conversion

2. Demonstrate operation of HFIR at increased power with HEU fuel

3. Conduct low-power testing of LEU lead test core in vessel

4. Conduct high-power testing of LEU lead test core in vessel with PIE

5. Demonstrate operation of HFIR with production LEU fuel at increased power

- Five-phase approach is in M³ schedule with summary-level activities
Maintaining HFIR performance and mission capabilities

Key performance metrics have been established for design studies

<table>
<thead>
<tr>
<th>Key performance metrics, defined as a means of capturing data essential for primary missions</th>
</tr>
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<tbody>
<tr>
<td>Cold and thermal neutron flux at cold source moderator vessel</td>
</tr>
<tr>
<td>$^{252}$Cf production</td>
</tr>
<tr>
<td>Thermal neutron flux in $^{252}$Cf targets in flux trap</td>
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<tr>
<td>Fast neutron flux in flux trap targets</td>
</tr>
<tr>
<td>Fast neutron flux in reflector</td>
</tr>
<tr>
<td>Cycle length</td>
</tr>
<tr>
<td>Margin to burnout</td>
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</table>

**X-Y thermal flux distribution on core midplane**

- Cold and thermal neutron flux at cold source moderator vessel
- $^{252}$Cf production
- Thermal neutron flux in $^{252}$Cf targets in flux trap
- Fast neutron flux in flux trap targets
- Fast neutron flux in reflector
- Cycle length
- Margin to burnout

More detailed performance and safety assessments are performed on promising design(s)
Fuel Designs
Fuel Specification and Drawings
LEU Fuel Specification

  - New specification comparable in scope to existing HEU fuel specification.
  - Technical content based on most recent LEU design reports (ORNL/TM-2020/1798, ORNL/TM-2020/1799, and ORNL/TM-2021/1964) and ad hoc input from stakeholders.
  - Structured as a working document to be incrementally refined as the LEU fuel design and fabrication process mature.
LEU Fuel Drawings

  - Provides detailed dimensions of flat fuel plates including fuel core and filler geometry.
  - Drawings will be revised in tandem with fuel specification.
  - Drawings contain three concept inner fuel element fuel plate details representing the principal variations under consideration
Reactor Physics
Modeling and Simulation
Python HFIR Analysis and Measurement Engine (PHAME) for generation and analysis of potential fuel designs

- Allows for analyses of several designs further along in the process

User input:
- Reactor power
- Fuel shape
- Fuel characteristics
- Fuel form
- Design options

Tools:
- Shift (reactor physics)
- MCNP5 (heating)
- HSSHTC (heat transfer)
- SCALE (source term)

Output:
- Reactor performance metrics
- Thermal hydraulic margins
- Reactor physics metrics
Continuously expanded the PHAME simulation toolset to include physics metrics for many follow-on analyses

- Reactor performance metrics
- Thermal hydraulic safety metrics
- Shutdown decay heat data
- Transient physics data
- Sensitivity metrics*
- Safety basis metrics*
- Improved reactor performance metrics*

*capability to generate these metrics are still being incorporated in PHAME

- Design feasibility and performance assessment
- Fuel fabrication/qualification feedback
- RELAP transient simulations
- Sensitivity and uncertainty assessments
- Safety analysis documentation
Silicide Fuel Design Overview
Design Variables and Challenges

*Fuel shape dictates mass, cycle length, fission rate distribution*

- Fuel system
- Reactor power
- Fuel shape
  - Mass and mass split between IFE and OFE
  - Radial contouring profile (across plate)
  - Centered & symmetric (eliminated off-centered & asymmetric)
  - Fuel zone length (50.80–55.88 cm)
  - Axial contouring (bottom 1–3 cm)
- Burnable poison
  - Type (e.g., B, Gd)
  - Amount
  - Location (e.g., filler, clad, side plates)
Design features for candidate low-density silicide fuel designs with 10 mil cladding

- **Axial contoured fuel zone**: yes → no
- **Gd$_2$O$_3$ in addition to B$_4$C in IFE filler**: no → yes → no
- **Centered and symmetric fuel zone**: yes → no
- **Gd$_2$O$_3$ in addition to B$_4$C in IFE filler**: yes → yes → yes
- **Boron strip underneath fuel zone**: yes → no
- **Centered and symmetric fuel zone**: yes
- **Uppermost 54.88 cm of fuel zone**: no
- **Bottommost edge of fuel zone**: yes → no
- **Optimized Design**: yes
Design features for candidate high-density silicide fuel designs with 10 mil cladding

- Design options listed in order of preference
  1. Optimized Design* (radial contour, axial contour, centered and symmetric, B poison in IFE filler)
  2. Alternate 1 Design (radial contour, axial contour, asymmetric, B + Gd in IFE filler)
  3. Alternate 2 Design (radial contour, axially flat, centered and symmetric, B + Gd in IFE filler)
  4. Short Design (radial contour, axial contour, asymmetric, B + Gd in IFE filler, shorter length)

*newest design is a thick cladding variant of this optimized design
Higher U densities in LEU silicide dispersion fuel provide for less complex and higher performing designs

- Continuous filler
- Possible elimination of other complex design features
- Possible reduction of fuel zone length (20” < L < 22”)
- Potential increase in performance metrics
- Maintain or exceed HEU thermal safety margin
- More flexibility in fuel shape
- Enables thicker cladding

Minimum allowable filler thickness has an impact on mass loading and therefore cycle length. Additionally, reducing the “continuous” filler thickness pushes power into the radial flux peaks and therefore reduces thermal safety margin.
Continuously generated design performance metrics for low- and high-density silicide designs

- Low-density silicide fuel (ORNL/TM-2020/1798)
- High-density silicide fuel (ORNL/TM-2020/1799)
- High-density silicide fuel with thick cladding (ORNL/TM-2021/1964)
- U-10Mo fuel for completeness (ORNL/TM-2021/2315)

High-density silicide fuel with thick cladding
Improving the understanding of the sensitivities of proposed designs relative to current fuel design

- While waiting for design feedback from fuel fabrication, assess the robustness of designs to fabrication constraints
  - Determine if the design subject to large changes in performance given small changes in design parameters
  - This assesses impacts of uncertainties in reactor simulations and allows for more rapid response to fabrication feedback

Continuous toolset development to support design and safety analyses

Sensitivity analyses → Validation → Refinement of candidate design(s) → Down-selection to final designs → Safety analyses & documentation
Reactor Physics
Sensitivity Analysis and Uncertainty Quantification of Fuel Designs
Silicide fuel designs have more similar sensitivities to more known experiments than alternate fuel systems (U-10Mo)

- **$\text{U}_3\text{Si}_2$ low density (LD) core:**
  - $c_k \geq 0.8$: 1511
  - Highest $c_k$ value: $0.9273 \pm 0.0131$

- **$\text{U}_3\text{Si}_2$ thick clad (TC) core**
  - $c_k \geq 0.8$: 1516
  - Highest $c_k$ value: $0.9306 \pm 0.0129$

- Most similar critical experiments:
  - LEU-COMP-THERM-066
  - LEU-COMP-THERM-029

- Important isotopes affecting the uncertainty of k-eff:
  - HEU core: U-235, Al-27, H-1
  - LEU core: U-235, Al-27, U-238, H-1
Silicide fuel designs are no more sensitive to effective fuel inhomogeneity than the current HEU fuel design

- Generated sets of measurement-informed effective inhomogeneity profiles (hump and edge profiles)
- The relative changes in the flux at several target locations between the HEU and LEU cores are negligible
In-practice modeling and simulation suites confirm key calculated parameters for LEU fuel designs

- Verification of results from VESTA (former safety basis depletion code), HFIRCON (current safety basis depletion code), and Shift (current scalable design tool)
Filler extensions in silicide fuel designs encompass edges with burnable poisons, reducing localized power peaks

- Generated explicit models of extended filler regions in the inner fuel element plates
  - Conserving boron concentration (increasing loading)
  - Reducing boron concentration (conserving loading)

- Expecting reduced peaking at edges without fuel design changes
  - Fuel shape changes likely required to maintain consistent performance
These recent activities build a basis for validation studies on key performance metrics with uncertainties

- Continue incorporating design feedback in targeted studies to build capabilities to analyze geometries and constraints
- Leverage existing activities to improve our understanding of performance predictions of LEU fuel designs with uncertainties
- Incorporate improved calculation approaches at the appropriate level of fidelity for fuel design assessments
  - Multicycle irradiation of key isotopes
  - Improved metrics for materials irradiation
RELAP Model Status
Transient Analysis with RELAP HFIR Model

• Chapter 15 of the HFIR Safety Analysis Report (SAR) presents consequences for various accident scenarios modeled in RELAP, which will be evaluated to prove LEU fuel design acceptability.

• Current SAR transients use various base plant models. All transients will be standardized to the HFIR Consolidated Model Version 14 and use HFIR-specific RELAP5/Mod3.3-Patch04.

• Near-term goals: Establish a baseline HEU core configuration (HEU Representative Model) and directly compare to LEU Silicide designs for bounding events that challenge the relevant safety margins:
  – Loss of Off-Site Power (LOOP) and Small Break Loss of Coolant Accident (SBLOCA) - cases without kinetics (i.e. decay heat cases)
  – Control Cylinder Ejection (CCE) and Optimum Void in Target Region - active kinetics cases
  – Any additional cases to be added as needed
Status of LEU conversion RELAP model development

- HEU Representative Model: Provides comparison to proposed LEU core designs
  - Safety calculations (2+) in draft or review
  - Internal ORNL TM and publication to follow

- LEU LD optimized $U_3Si_2$-Al Model
  - Draft publication (ORNL/TM-2021/2204) complete, currently in ORNL's publication approval process
  - Inputs (see misc. table right), model, and therefore all model results are preliminary
  - Parametric analysis shows limiting axial location (example figure right, SBLOCA @OFE)

- LEU HD optimized $U_3Si_2$-Al Model
  - Preliminary reactor physics inputs are available for incorporation
  - Publication (ORNL/TM-2022/2396) to be submitted in 2022

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time</th>
<th>LEU</th>
<th>HEU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot channel gap (mil)</td>
<td>BOC</td>
<td>39.3</td>
<td>38.72</td>
</tr>
<tr>
<td></td>
<td>EOC</td>
<td>38.02</td>
<td>36.95</td>
</tr>
<tr>
<td>$U_{25}$ factor extension length (in)</td>
<td></td>
<td>0.265</td>
<td>0.530</td>
</tr>
</tbody>
</table>
LEU LD Optimized U$_3$Si$_2$-Al vs HEU: Heat Deposition

- BOC (left, fuel power densities) limiting radial locations near radial inner edge
- EOC (right) limiting radial locations differ: max. heating near outer edge, max. exit heat flux near inner edge
- Increase in LEU BOC IFE heat deposition fraction appears notable

### Percent of Total Power

<table>
<thead>
<tr>
<th>Region</th>
<th>HEU</th>
<th>LEU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Fuel Element</td>
<td>36.0%</td>
<td>38.7%</td>
</tr>
<tr>
<td>Outer Fuel Element</td>
<td>58.2%</td>
<td>61.9%</td>
</tr>
<tr>
<td>Fuel</td>
<td>94.2%</td>
<td>95.5%</td>
</tr>
<tr>
<td>Non-Fuel</td>
<td>5.6%</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
LEU LD Optimized $U_3\text{Si}_2$-Al vs HEU: **Worst-case SBLOCA**

- Small-break LOCA defined as break size that does not result in fuel damage
- Parameter: Incipient Boiling (IB) ratio, applicable low vel. (e.g. pony motor flow)
- IFE (left) LEU values at BOC at IB>1.0
- OFE and IFE EOC bounded by HEU results and above channel exit
LEU LD Optimized U$_3$Si$_2$-Al vs HEU: Control Cylinder Ejection

- Control cylinder ejection is the bounding limiting frequency event in the reactivity-initiation accident transient category

- Parameters: Peak Power & Excess Energy

- LEU design shows significant improvement, as driven primarily by $^{238}$U Doppler broadening
LEU LD Optimized U₃Si₂-Al vs HEU: Results Summary

- Comparison cases generated for 5 accident transients
  - Three primary coolant accidents (SBLOCA, LOOP, and ATWS LOOP)
  - Two reactivity-initiated accidents (RIA) (CCE & Optimum Void)

- RIA results show LEU silicide designs provide improvement in safety margins

- BOC IFE: there is a notable loss in minimum thermal margin in hot channels

- Overall nominal channels lose thermal margin

### Power excursion parameters

<table>
<thead>
<tr>
<th>Time</th>
<th>Peak Power (MW)</th>
<th>Excess Energy (MW-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCE</td>
<td>Optimum Void</td>
</tr>
<tr>
<td>HEU</td>
<td>BOC</td>
<td>213.031</td>
</tr>
<tr>
<td></td>
<td>EOC</td>
<td>198.878</td>
</tr>
<tr>
<td>LEU</td>
<td>BOC</td>
<td>113.340</td>
</tr>
<tr>
<td></td>
<td>EOC</td>
<td>124.162</td>
</tr>
<tr>
<td>Δ%</td>
<td>BOC</td>
<td>-47%</td>
</tr>
<tr>
<td>(L-H)/H</td>
<td>EOC</td>
<td>-38%</td>
</tr>
</tbody>
</table>

### Nominal channel heat flux ratios

<table>
<thead>
<tr>
<th>Time</th>
<th>IFE</th>
<th>ATWS LOOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOOP</td>
<td>BOC</td>
<td>0.539</td>
</tr>
<tr>
<td>EOC</td>
<td>0.413</td>
<td>0.717</td>
</tr>
<tr>
<td>LOOP</td>
<td>BOC</td>
<td>0.483</td>
</tr>
<tr>
<td>EOC</td>
<td>0.385</td>
<td>0.545</td>
</tr>
</tbody>
</table>

### Hot channel heat flux ratios

<table>
<thead>
<tr>
<th>Time</th>
<th>IFE</th>
<th>OFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATWS LOOP</td>
<td>LOOP</td>
<td>SBLOCA</td>
</tr>
<tr>
<td>BOC</td>
<td>0.140</td>
<td>0.203</td>
</tr>
<tr>
<td>EOC</td>
<td>0.113</td>
<td>0.163</td>
</tr>
</tbody>
</table>

1 Heat flux ratio for LOOP and SBLOCA is the MFIBHF during pony motor flow
2 Heat flux ratio for ATWS LOOP is the maximum Costa flow excursion heat flux ratio
COMSOL V&V Status
Purpose of V&V COMSOL for use in LEU conversion

- The Steady State Heat Transfer Code (SSHTC) evaluates steady state thermal hydraulic core conditions to define TSR safety limits and limiting control settings.
- COMSOL for the same purpose can reduce unnecessary analysis conservatisms and increase reported safety margins.
  - Provides detailed solutions.
  - Allows for the simulation of additional physics that the SSHTC does not.
  - Increases design space with the potential to reduce design complexity.
- Verification and Validation (V&V) of COMSOL provides the regulator with assurance that the code can accurately predict HFIR Safety Basis Conditions.
V&V Results for the Cheverton-Kelley Benchmark

Case 2 results: normal displacements at the mid-length of the fuel plate.

Case 5 results: normal displacements at the mid-length of the plate.

Case 6-7 results: normal displacements at the ends, and the mid-length of the plate mounted in (a) solid, and (b) split base.

Journal manuscript in preparation to elevate the C-K problem as an international benchmark
V&V Results for the Gambill-Bundy Benchmark

COMSOL results are in an excellent agreement with the other CFD codes and the experimental data.
DNS Results for the HFIR Flow Central Subchannel

- Stable solution was produced during several (>20) flow residence times
- Mesh size: 3.2 billion elements
- Runs on HPC platform CORI on 16,384 processes
- Right: entire flow domain, flow from top to bottom
- Left: vertical central cross section

8,694 probes were seeded for instantaneous data collection

### Aggregate mean velocity plot

Groups 1, 2, and 3 are at the lower curvature side, and groups 8, 9, and 10 are on the high curvature side of domain. Central groups are 4, 5, 6, and 7.

### Velocity profiles in wall units

### Normalized Turbulent KE
COMSOL Hot Spot Modeling for the HEU and LEU Silicide Fuel

COMSOL produced U-bar factors are in excellent agreement with the legacy HEATING-6 results.

Hot-Spot models for the LEU Silicide fuel are currently being developed in COMSOL Multiphysics.
Summary
Technical Papers issued in FY22
PHYSOR Reactor Physics, ANS/ATH DNS paper, DNS Letter Report
Technical Papers co-authored in FY22
HFIR Silicide Fuel Qualification Plan, Updates from the Involute Working Group
HFIR LEU Fuel Type and Design Down-Selection

*Must be a balanced, multivariate, quantitative process*

- Performance – ORNL calculates performance metrics
- Safety – ORNL calculates safety metrics
- Cost
  - FF estimates cost of manufacturing
    - Initial
      - R&D (e.g., contoured fuel zone, borated filler, Gd in filler, and centered-symmetric fuel zones)
      - Process equipment
    - Unit
  - FQ estimates cost of qualification
- Uranium utilization
  - ORNL calculates for fuel cycle
  - FF estimates yields for fuel manufacturing
- Time
  - For each fuel type, RC, FQ, FF, and CC create activities and ensure linkages to estimate time

LEU fuel design process is complex
Next Steps in Design Process

ORNL and pillars need to continue to work together to move forward

1. **ORNL/RC/FQ/FF feedback on proposed fuel types and designs to inform design down-select**

   - Higher density (5.3 gU/cm³) U₃Si₂ fuel design study

2. **Design documents for selected designs (performance metrics, safety metrics, and operating parameters)**

3. **For selected designs, confirm SSTH with COMSOL and perform RELAP transient analyses of key accidents**

4. **Rev. 0 COMSOL V&V report**

5. **Fulfill software quality assurance requirements (as necessary)**

6. **Neutronics, SSTH, and RELAP calculations for selected LEU fuel design(s)**

7. **Reference Safety Basis and Safety Design Strategy**

- **ORNL/RC/FQ confirm fuel properties and correlations or identify “unverified assumptions” for later confirmation**
- **ORNL/RC/FF confirm fabrication tolerances and inspection uncertainties for fuel types/designs**
Interfaces Between RC Analyses and FQ Qualification Testing

Key for successful conversion of HFIR

- RC/FQ interface methodology document should be developed to capture definitions, application of margins, meshes, process steps, and information control and account for uncertainties in
  - fuel properties and correlations,
  - fuel manufacturing and inspection (interface with FF),
  - reactor performance and safety analyses,
  - experiment (fuel and conditions) design,
  - experiment conduct (planned vs. as-run), and
  - experiment PIE

in a well-defined, integrated, and consistent manner for both down-select and qualification testing for all five USHPRRs to support successful reactor conversions
ORNL, M$^3$, and Pillars Need to Continue to Work Together

*Collaboration and communication are key for successful conversion of HFIR*

- Complex fuel fabrication R&D and irradiation testing must be conducted to support down-selection
- Fuel down-selection process must be balanced, multivariate, and quantitative
- Cost of fuel must be understood and managed
- Quality of fuel, fuel qualification report, and SAR inputs must be assured to meet reactor operator and regulator requirements
- Code benchmarking data, fuel fabrication data, material properties data and correlations for LEU fuel types must be provided to support performance and safety analyses
- Program and technical documents need integration and control
- Research reactor operators and sponsors are stakeholders and end users
• The High Flux Isotope Reactor is located on the Oak Ridge National Laboratory campus.
• Oak Ridge National Laboratory is managed by UT-Battelle for the US DOE.
• The High Flux Isotope Reactor is a US DOE Office of Science User Facility.