## COMMITTEE Membership

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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</thead>
<tbody>
<tr>
<td>Julia M. Phillips</td>
<td>chair, Sandia National Laboratories (retired)</td>
</tr>
<tr>
<td>Pablo Adelfang</td>
<td>International Atomic Energy Agency (retired)</td>
</tr>
<tr>
<td>Gerald Gabrielse</td>
<td>Harvard University</td>
</tr>
<tr>
<td>Alexander Glaser</td>
<td>Princeton University</td>
</tr>
<tr>
<td>David W. Johnson, Jr.</td>
<td>Journal of the American Ceramic Society</td>
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<tr>
<td>Patrick Lemoine</td>
<td>Commissariat à l'Energie Atomique (retired)</td>
</tr>
<tr>
<td>William R. Martin</td>
<td>University of Michigan</td>
</tr>
<tr>
<td>Roger Pynn</td>
<td>Indiana University-Bloomington</td>
</tr>
<tr>
<td>William H. Tobey</td>
<td>Harvard University</td>
</tr>
<tr>
<td>Paul P. H. Wilson</td>
<td>University of Wisconsin-Madison</td>
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<tr>
<td>Pavel Podvig</td>
<td>technical consultant, Princeton University and Russian Nuclear Forces Project</td>
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**STAFF:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
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<tbody>
<tr>
<td>Jennifer Heimberg</td>
<td>study director</td>
</tr>
<tr>
<td>Darlene Gros</td>
<td>senior program assistant</td>
</tr>
</tbody>
</table>
Reviewers

Nikolay V. Arkhangelsky
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Joanie Dix
Richard L. Garwin
Carol M. Jantzen
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Dana A. Powers
J. Michael Rowe
Sven Van den Berghe

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Sandia National Laboratories
National Institute of Standards and Technology
SCK·CEN, Mol, Belgium
Statement of Task

The committee will review the current status of and progress toward eliminating highly enriched uranium (HEU) use in fuel for civilian research and test reactors. This study will provide:

1. A list of civilian research and test reactors that operate using HEU fuel.
2. A review of civilian research and test reactor conversion status over the past five years.
3. An assessment of the progress being made by the Department of Energy and others to eliminate worldwide use of HEU in fuel for civilian research and test reactors.

This assessment should identify key technical and nontechnical factors and obstacles to conversion; and steps that could be taken to overcome the identified obstacles.
Progress in HEU Minimization since 2009

• 74 civilian research reactors operate or plan to operate with HEU fuel
  – 8 in the U.S.
  – 28 converted or shut down since 2009
  – Periodic reviews by international experts are needed to keep this list up-to-date

• Since 2009, more research reactors have shut down than have converted.
  – Reduced rate of conversions is due to technical and nontechnical challenges:

Progress in reactor conversion and shutdown

Source: modified from Waud, 2015
Timelines for conversion have expanded

• Since 2009 the projected end of the conversion program has moved from 2018 to 2035
  – The report offers recommendations to reduce the use of weapon-grade uranium over this timeframe
  – Management of the program requires risk and systems analysis and independent review of all technical pillars of the program

SOURCE: Committee report
Data Gathering and Site Visits

Full committee meetings:
- Meeting #1: DC
- Meeting #2: Idaho Falls, ID
- Meeting #3: Columbia, MO
- Meeting #4: DC
- Meeting #5: Oak Ridge, TN
- Meeting #6: Vienna, Austria
- Meeting #7: Woods Hole, MA

Site visits with subset of committee to:
- Idaho: ATR, ATR-C, TREAT
- Gaithersburg, MD: NBSR
- Lynchburg, VA: BWXT Fabrication Plant,
- Columbia, MO: MURR
- Oak Ridge, TN: HFIR, SNS, Y12 Fuel Fabrication
- Poland: MARIA reactor
- Netherlands: High Flux Reactor
- Belgium: BR-2, SCK-CEN
- Germany: FRM-II
- France: RHF-Grenoble; CEA and CERCA, Paris
- Russia: Moscow, Dmitrovgrad (NIIAR/RIAR)
Recommendation 1: The continuing need for neutrons

- Research reactors uniquely meet key scientific and industrial needs
- U.S. reactors will be 60-65 years old when conversion is scheduled
- Reactor aging issues, relicensing, and conversion converge in ~15 to 20 years
- A DOE NE/ NNSA study recommended no change to the current plans for conversion
  - DOE does not manage all U.S. research reactors

OSTP should lead the development of a 50-year strategy that enumerates and evaluates U.S. civilian needs for neutrons and how to meet these needs without the use of HEU.
Recommendations 2 and 3: LEU fuel development

- The highest performance research reactors require new LEU fuels to maintain performance.
- Development of the new fuels has taken longer than expected.

Despite longer timescales, the United States should continue to develop monolithic LEU fuel to convert the existing and to use the future generation of U.S. high performance research reactors. The United States should closely monitor the development of LEU dispersion fuels and consider their use as possible backup options if there are unexpected delays in the development of the U.S. monolithic fuel.

**SOURCE:** Office of Material Management and Minimization Office of Conversion
Recommendation 4: Continuing on the current path will result in similar levels of HEU for many years

Since 2009 the scope of the HEU minimization effort and the timeline for its completion have expanded significantly.

SOURCE: Committee report

SOURCE: Modified from USHPRR Road Map_07292015.pdf, Landers, 2015
Recommendation 4: Reducing the enrichment of fuel is possible

All reactors can convert to non-weapon-grade fuel using silicide at 45 percent or less enrichment without performance loss

<table>
<thead>
<tr>
<th>HPRR</th>
<th>U₃Si₂ 4.8 gU/cm³ (percent)</th>
<th>U₃Si₂ 5.8gU/cm³ (percent)</th>
<th>UMo (Dispersion) (percent)</th>
<th>UMo (Monolithic)</th>
<th>Years to Conversion using UMo (Monolithic) Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR</td>
<td>35–40</td>
<td>~30</td>
<td>25–30</td>
<td>LEU</td>
<td>14 years</td>
</tr>
<tr>
<td>HFIR</td>
<td>35–40</td>
<td>~30</td>
<td>25–30</td>
<td>LEU</td>
<td>17 years</td>
</tr>
<tr>
<td>NBSR</td>
<td>~25</td>
<td>LEU</td>
<td>LEU</td>
<td>LEU</td>
<td>12 years</td>
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<tr>
<td>MURR</td>
<td>~45</td>
<td>~40</td>
<td>~35</td>
<td>LEU</td>
<td>12 years</td>
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<tr>
<td>MITR-II</td>
<td>~35</td>
<td>~30</td>
<td>20–25</td>
<td>LEU</td>
<td>12 years</td>
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<tr>
<td>FRM-II</td>
<td>50–60</td>
<td>35</td>
<td>30</td>
<td>LEU</td>
<td>N/A</td>
</tr>
<tr>
<td>BR2</td>
<td>~27</td>
<td>~22</td>
<td>LEU</td>
<td>LEU</td>
<td>N/A</td>
</tr>
<tr>
<td>JHR</td>
<td>27</td>
<td>22</td>
<td>LEU</td>
<td>LEU</td>
<td>N/A</td>
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<tr>
<td>RHF</td>
<td>~27</td>
<td>~22</td>
<td>LEU</td>
<td>LEU</td>
<td>N/A</td>
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SOURCE: Committee-generated table
Recommendation 4: Interim reduction in the enrichment of fuel significantly reduces W-HEU

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Years to Conversion with High-Density LEU Fuel</th>
<th>Years without W-HEU Shipments</th>
<th>W-HEU (kg) Shipped/year</th>
<th>Total W-HEU (kg) Usage Avoided</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR</td>
<td>14</td>
<td>9</td>
<td>120</td>
<td>1080</td>
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<tr>
<td>HFIR</td>
<td>17</td>
<td>12</td>
<td>80</td>
<td>960</td>
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<tr>
<td>NBSR</td>
<td>12</td>
<td>7</td>
<td>13</td>
<td>91</td>
</tr>
<tr>
<td>MURR</td>
<td>12</td>
<td>7</td>
<td>24</td>
<td>168</td>
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<tr>
<td>MIT</td>
<td>12</td>
<td>7</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>FRM-II</td>
<td>17</td>
<td>12</td>
<td>38</td>
<td>456</td>
</tr>
<tr>
<td>BR2</td>
<td>12</td>
<td>7</td>
<td>29</td>
<td>203</td>
</tr>
<tr>
<td>JHR</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RHF</td>
<td>12</td>
<td>7</td>
<td>55</td>
<td>382</td>
</tr>
<tr>
<td><strong>Total W-HEU Usage Avoided (kg)</strong></td>
<td><strong>3399</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SOURCE: Committee-generated table
Recommendation 4: Interim reduction in enrichment and downblending

To achieve the goal of using as little highly enriched uranium as possible during the many years that it will take to design and qualify appropriate low enriched uranium (LEU) fuel, the United States should pursue an interim solution that reduces the civilian use of weapon-grade material.

a. During this interim period, high performance research reactors should use dispersion silicide fuel enriched to the lowest practical level, which can be produced with technologies already known to be reliable. The precise enrichment level can be quickly determined by a focused, small-scale study.

b. The United States should downblend the remaining 20 metric tons of highly enriched uranium (HEU) designated for civilian research reactor use to this lowest practical enrichment level as soon as it has been determined.

c. The interim solution should be pursued in a way that does not compromise the long-term goal of eliminating HEU usage in civilian applications.
Recommendation 5: Engaging with Russia

- Russia has more than 40% of the remaining HEU-fueled research reactors
  - Critical assemblies pose an increased proliferation threat
- Russia has converted all Russian-supplied research reactors outside the Former Soviet Union to LEU fuel
  - Converting its domestic fleet is not a high national priority
  - Conversion of most Russian research reactors is technically feasible
- U.S./Russian collaboration and additional funding to support Russian domestic conversions has ceased
  - The United States and others have little influence on Russian prioritization of domestic reactor conversion

The United States should encourage and facilitate periodic workshops and meetings to continue scientific exchanges and interactions that formed the basis for previous progress in highly enriched uranium (HEU) minimization. These interactions should also seek areas of mutual interest that would result in HEU minimization, jointly study the risks and benefits of LEU conversion, and identify possible collaborations.
Recommendation 6: Reporting on progress

- Reports of progress in converting research reactors include in the conversion totals:
  - Reactors that have shut down
  - Reactors that have introduced as little as a single LEU assembly

- Not counted:
  - Reactors that have moved from “in progress” to “complete” conversion
  - The amount of HEU remaining on site
  - Reduction in annual HEU consumption

- Reports do not adequately capture the reduction in threat

Progress reports should include the following:

- the number of conversions in progress;
- the number of conversions completed, including HEU removal (fresh and spent fuel) from the site;
- separate reporting of conversions and shutdowns;
- reduction of HEU and weapon-grade HEU inventory
Recommendation 7: Program management

• Challenges in program planning and technical execution emphasize the need for robust program management.
  – Independent review teams have focused on strategic review, cost, and fuel development
  – Previous technical review limited to fuel development pillar, performed by ex-fuel developers

In-depth independent technical review of each aspect of the fuel life-cycle (from fuel development, fabrication, recycling, and spent fuel management), as well as integration of the technical components, should be conducted to ensure that the newly instituted risk and systems analysis capabilities within the Material Management and Minimization Office of Conversion develop into robust project and risk management. These reviews should be conducted by qualified, independent, and diverse external experts.
Conclusions and Next Steps (1)

• Stakeholders, from reactor operators to those supporting nonproliferation goals, can find common ground in supporting a 50-year neutron capability strategy and consideration of step-wise conversions

• While U.S. conversion programs can be proud of past accomplishments, the most difficult conversions remain:
  – Technical challenges of new fuel development
  – Challenges of changing international relationships and differing political priorities require novel and flexible solutions
Conclusions and Next Steps (2)

• The conversion program needs stable and effective management and long-term political support to be successful including:
  – A systems-level view of the program
  – Regular, independent technical reviews of all technical aspects of the program
  – Explicit recognition of the span of control of M³ Office of Conversion
    • Align expectations accordingly

The committee saw indications that the Office of Conversion is recognizing and acting on these needs, which is laudable. The committee hopes that this report will help the M³ Office of Conversion be successful in its most important mission.
Statement of Task

An ad hoc committee will conduct a study and prepare a report with findings and recommendations on the current status of and progress toward eliminating highly enriched uranium (HEU) use in fuel for civilian research and test reactors. This study will provide

1. A list of civilian research and test reactors that operate using HEU fuel.

2. A review of civilian research and test reactor status over the past five years, including new HEU-fueled reactors that were planned, under construction, or commissioned; HEU-fueled reactors that were shut down and/or decommissioned; and HEU-fueled reactors that were converted to low enriched uranium (LEU).

3. An assessment of the progress being made by the Department of Energy and others to eliminate worldwide use of HEU in fuel for civilian research and test reactors. This assessment should identify key technical and nontechnical factors responsible for the successful conversion of reactors from HEU to LEU fuel; key obstacles to converting the remaining HEU-fueled reactors; and steps that could be taken to overcome the identified obstacles.