Space Nuclear Power Systems – LEU vs HEU Tradeoffs

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Nuclear Energy in Space: Nonproliferation Risks and Solutions
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Space Nuclear Power Options

- Access to near-Earth space is possible with chemical rockets and solar panels
- However, deep space missions require a nuclear power source
  - Radioisotope Thermoelectric Generators (RTGs) can get small robots past Pluto
  - Nuclear reactor power sources are needed for manned missions, and where we need more power

Multi-Mission RTG

SNAP-10A
Past and Future Space Nuclear Reactors

The Past

• Space Nuclear Reactors developed by governments in primarily nuclear-armed nations
  • HEU was a logical choice
    • Smaller, more compact reactors

The Emerging Future

• Space Nuclear Reactors development by private companies and non-weapon nations
  • Issues with HEU and proliferation
  • LEU may be enabling
    • Space commercialization
    • International collaboration
Space Reactor Schematics

(not to scale)
Kilowatt-class (1-10 kW\textsubscript{e}) space nuclear reactors represent an “entry-level” reactor, intended to bridge the gap between RTGs and larger space nuclear power systems (100’s of kW\textsubscript{e} to 100’s of MW\textsubscript{e}), where RTGs aren’t an option.

Reference LEU Reactor

In the homogeneously moderated core (Fig. 2), the core consists of a uniform and isotropic mixture of fuel (U-10Mo) and moderator (ZrH_{1.5}). In the heterogeneously moderated cores, the first geometry (Fig. 3) consists of spheres of fuel, arranged in a cubic lattice surrounded by moderator. Varying the sphere diameter and spacing provides a specific moderator/fuel ratio. For example, a fuel sphere radius of 0.7 cm, with a square lattice pitch equal to 1.327 cm, provides an 80 wt% moderator/fuel ratio. The second geometry (Fig. 4) considers the fuel and moderator as alternating discs stacked orthogonal to the axis of the control rod. The moderator/fuel ratio is determined by the ratio of the thickness of the fuel and moderator discs. This work considers fuel disk ranging from 0.1 cm to 1.0 cm, in steps of 0.1 cm, while the moderator disc thicknesses vary to provide moderator weight fractions of 30 wt%, 60 wt%, 80 wt% and 90 wt%

The third geometry (Fig. 5) places the fuel inside the core cylinder as a helix structure. In this geometry, the angle subtended by the fuel sector in each vertical step controls the fuel/moderator ratio. To create the helix, the element disc (fuel plus moderator) in each step is rotated relative to the previous step by an amount equal to the fuel angle (Fig. 5). The fuel sector angle (α in Fig. 5) is defined according the moderator-fuel weight percentage. For example, in a 90 wt% helical moderated system, the fuel sector angle is equal to 6.42° degrees.

Table 1 presents the materials and densities used in each region in the model. The LEU reactor is fueled with 19.75 wt% enriched uranium-10 wt% molybdenum alloy and the zirconium hydride (ZrH_{1.5}) acts as a moderator in the system. The choice of zirconium hydride as the moderator in the system is based on the moderator used in the U-ZrH fueled reactors of the Systems for Nuclear Auxiliary Power (SNAP) program (Buden, 2011b); and the present study uses a hydrogen to zirconium ratio of 1.5 for conservatism (Lee et al., 2015). Beryllium oxide serves as the reflector material and a cylindrical boron carbide (B_{4}C) control rod in center of the core provides shutdown control (see Figs. 2–5). The control rod is 22 cm long and 4.4 cm in diameter. All of the computational simulations assume that the boron carbide is enriched to 100% boron-10.

In all cases, the H/D ratio of the core is 1.81, the same as that in the KRUSTY reactor (Poston et al., 2013). The MCNP6™ computational

The multiplication factor \((k_{\text{eff}})\) is a key reactor physics parameter.

In order for a reactor to produce power, \(k_{\text{eff}}\) must be greater than unity (often \(\sim 1.035\)).

So,

\[
k_{\text{eff}} \approx P_{\text{fission}} \cdot P_{\text{not-capture}} \cdot P_{\text{not-escape}} \approx 1.035
\]

\(P_{\text{fission}} \approx \text{enrichment}\)

\(P_{\text{not-capture}} \approx \text{enrichment}\)

\(P_{\text{not-escape}} \approx \text{size}\)

\textit{nota bene} – This is a huge simplification. Entire textbooks exist on this topic, with thousands of lines of legacy computer code representing thousands of man-hours of work devoted to producing accurate estimates of reactor behavior; but, for purposes of this discussion the approximation is adequate.
If enrichment goes down, so does $P_{\text{fission}}$ and $P_{\text{not-capture}}$.

$$P_{\text{fission}} \approx \text{enrichment} \approx \downarrow$$

$$P_{\text{not-capture}} \approx \text{enrichment} \approx \downarrow$$

Therefore $k_{\text{eff}}$ also goes down.

$$k_{\text{eff}} \approx \downarrow P_{\text{fission}} \cdot \downarrow P_{\text{not-capture}} \cdot P_{\text{not-escape}} \approx \downarrow$$
In the simplest case, LEU means a bigger core or a thicker reflector.

\[ P_{\text{fission}} \approx \text{enrichment} \approx \downarrow \]

\[ P_{\text{not-capture}} \approx \text{enrichment} \approx \downarrow \]

\[ P_{\text{not-escape}} \approx \text{size} \approx \uparrow \]

\[ k_{\text{eff}} \approx \downarrow P_{\text{fission}} \cdot \downarrow P_{\text{not-capture}} \cdot \uparrow P_{\text{not-escape}} \approx \leftrightarrow \]
Fig. 6. Multiplication factor as a function of reflector thickness for an unmoderated LEU reactor core with the same dimensions as KRUSTY.

Core Size, LEU-Fueled Kilowatt-Class Reactor

Fig. 7. Multiplication factor as a function of core diameter for the un-moderated LEU reactor with a H/D ratio of 1.81 and a reflector thickness of 30 cm. From Mencarini, L.d.H., and King, J.C., “Fuel geometry options for a moderated low-enriched uranium kilowatt-class space nuclear reactor,” Nuclear Engineering and Design, 340, 2018, p. 122-132.
Mass Optimization

The optimum mass of a space reactor is a balance between core size and reflector thickness.

This is still very heavy (725 kg) compared to the HEU-fueled kilopower designs (~100 kg)

![Graph](image)

**Fig. 8.** Fuel and reflector mass as a function of reflector thickness for an unmoderated LEU reactor with a multiplication factor of 1.035.

Adding a moderator is one option to reduce the size of an LEU-fueled reactor.

A moderator increases $P_{\text{fission}}$, hopefully more than it decreases $P_{\text{not-capture}}$, allowing size to go down.

$$P_{\text{fission}} \approx \text{enrichment} + \text{moderation} \approx \uparrow \uparrow$$

$$P_{\text{not-capture}} \approx \text{enrichment} + \text{moderation} \approx \downarrow$$

$$P_{\text{not-escape}} \approx \text{size} \approx \downarrow$$

$$k_{\text{eff}} \approx \uparrow \uparrow P_{\text{fission}} \cdot \downarrow P_{\text{not-capture}} \cdot \downarrow P_{\text{not-escape}} \approx \leftrightarrow$$
• Adding moderators to reduce the required mass of fissile uranium is a standard technique (nearly all terrestrial reactors are moderated)

• On Earth, we commonly use water as a moderator as it is cheap, well-known, and effective

• In space, however, water is a poor option
  • Severely limits operating temperatures

• Metal hydrides, mainly zirconium hydride (ZrH), are usually considered for space reactor moderators
  • Good hydrogen density
  • Higher operating temperature than water

• Beryllium and graphite could be options, but they generally aren’t better than ZrH

• Other metal hydrides (e.g. yttrium hydride) are in development
Adding a moderator (ZrH) reduces the mass of the reactor.

This is still heavy compared to the HEU-fueled kilopower designs (~100 kg), but getting better.

Fig. 9. Fuel and reflector mass as a function of reflector thickness for a LEU-fueled, 30 wt% homogeneously moderated reactor, with a multiplication factor of 1.035.

80 wt% moderator/fuel ratio. The second geometry (L.d.H. Mencarini, J.C. King) acts as a helix structure. In this geometry, the angle subtended by the fuel fractions of 30 wt%, 60 wt%, 80 wt% and 90 wt% moderator.

The third geometry (Lee et al., 2015) acts as a fuel sphere radius moderator/fuel ratio. For example, a fuel sphere radius and the cladding between the fuel and the moderator. The computational models in this work consider four cases, a homogeneous mixture and the heterogeneous core models in this work consider core moderator fractions of 30 wt%, 60 wt%, 80 wt% and 90 wt% moderator.

The multiplication factor. This work considers core moderator fractions of 30 wt%, 60 wt%, 80 wt% and 90 wt% moderator. The heterogeneous core models consider three different fuel/moderator geometries inside the core, as described in the previous section. In all cases, the reactor core and the control rod in the LEU reactor study adjusted the reactor models. The LEU reactor is fueled with 19.75 wt% enriched uranium-10 wt% molybdenum alloy fuel to match zirconium ratio of 1.5 for conservatism.

The materials and densities used in each region in the reactor models. The initial core diameter is 22 cm long and 4.4 cm in diameter. All of the computational simulations assume that the boron carbide (B
c

<table>
<thead>
<tr>
<th>Region</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel block U-10Mo</td>
<td>16.82</td>
</tr>
<tr>
<td>Control rod BeO</td>
<td>2.40</td>
</tr>
<tr>
<td>Boron carbide</td>
<td>2.0</td>
</tr>
<tr>
<td>Zircaloy</td>
<td>2.7</td>
</tr>
<tr>
<td>Zirconium hydride</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The moderator in the system is based on the moderator used in the U-ZrH system. The choice of zirconium hydride as the moderator in the system is based on the moderator used in the U-ZrH system. The choice of zirconium hydride as the moderator in the system is based on the moderator used in the U-ZrH system.

The isometric and radial cross-sections of the LEU-fueled reactor with disc fuel geometry. The isometric and radial cross-sections of the LEU-fueled reactor with helical fuel geometry.

Optimizing configuration, moderator ratio, and dimensions results in a much less massive reactor (193 kg).

However, there is now less fissile uranium in the core, which will impact reactor lifetime.

Fig. 10. Fuel and reflector mass as a function of reflector thickness for an LEU-fueled, 80 wt% heterogeneously moderated reactor, with spherical fuel geometry and a multiplication factor of 1.035.

• As a reactor is producing thermal power, it is consuming fissile uranium (effectively reducing enrichment).

\[ P_{fission} \approx enrichment \]

• Fission also increases the amount on non-fissile fission products in the core (decreasing \( P_{not-capture} \))

• Thus, as fissile uranium is consumed, \( k_{eff} \), will go down (more or less linearly)
  • The smaller the amount of fissile material in the core, the faster \( k_{eff} \) will decrease

• Therefore, minimizing mass by increasing moderation will also decrease reactor lifetime
A highly moderated LEU reactor will have a shorter lifetime than a comparable HEU reactor (based on fissile consumption).

However, it is still possible to have an acceptable lifetime with moderate mass.

**Fig. 13.** Multiplication factor as a function of operating time and moderator fraction for the minimum mass homogeneously moderated LEU-fueled reactors operating at 15 kWt.

Important Considerations

• The previous analysis ignores two particularly important considerations (amongst others) – shielding and materials.

  • **Shielding** – The radiation shield is often the dominant mass in the space nuclear reactor power system
    • Increasing the reactor size increases the shield size, often as a function of $r^2$.
    • Recent results indicate that the shielding for a moderated LEU space reactor is unlikely to be significantly thinner than the equivalent shielding for an un-moderated HEU space reactor
      • In fact, it may even be thicker
Important Considerations

- **Materials** – While there is significant experience with ZrH as a reactor moderator, that experience is *not* in the regimes needed for a moderated space reactor.

  - The hydrogen in the ZrH will diffuse at high temperatures
    - Moderator will require some form of cladding or diffusion barrier

  - TRIGA reactors operate at much lower temperatures (<373 K) compared to space reactors (>1000 K)

  - SNAP-10A was ZrH moderated, but relatively low power (~500 W), and the lifetime was short (43 days)
Summary

• There may be compelling arguments for embracing LEU for future space nuclear power systems
  • Especially if we considering international efforts and commercialization

• Switching from HEU to LEU will almost certainly increase reactor mass

• Moving to moderated systems can partially offset the resulting mass penalty

• However, significant research on high temperature moderators is needed
  • Understanding the behavior of metal hydride moderators at high temperatures
  • Moderator claddings/diffusion barriers
  • Moderator integration into high-temperature/high-performance reactor systems

These research areas are the same as those needed to reduce the use of HALEU in terrestrial micro-reactors.
Questions/Comments?