Space Nuclear Power Systems – LEU vs HEU Tradeoffs

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Nuclear Energy in Space:

Nonproliferation Risks and Solutions

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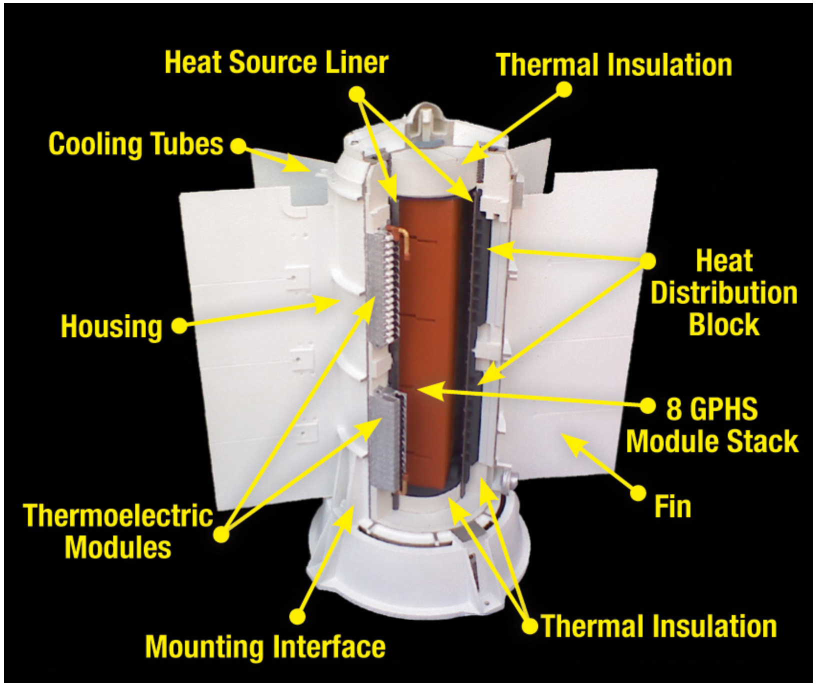
Space Nuclear Power Options

- 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



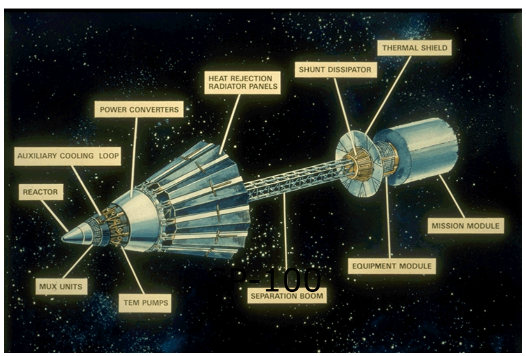
Multi-Mission RTG

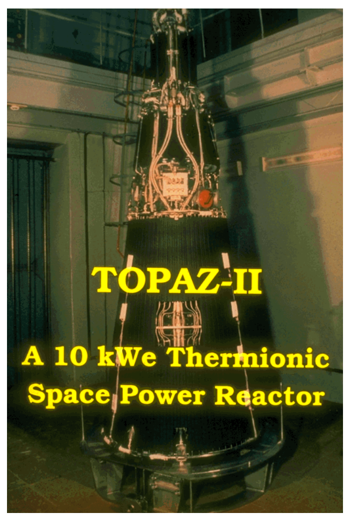
SNAP-10A

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

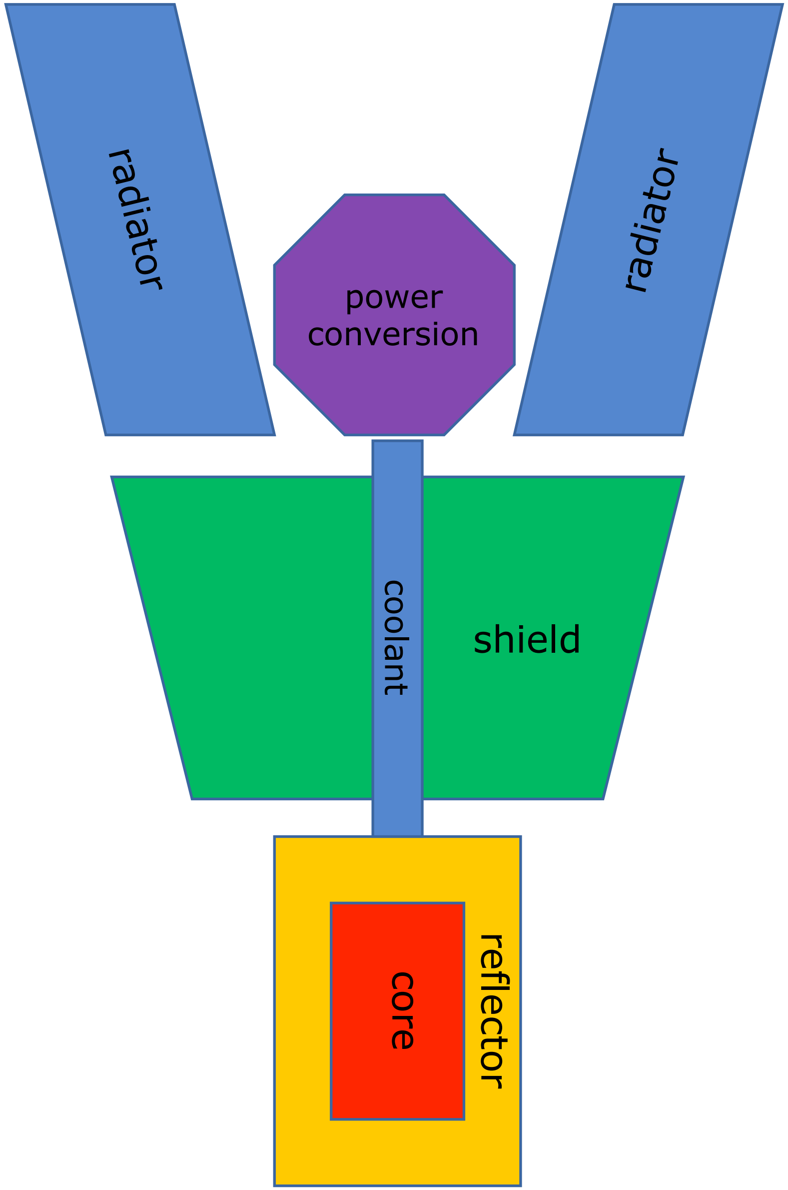




The Emerging Future

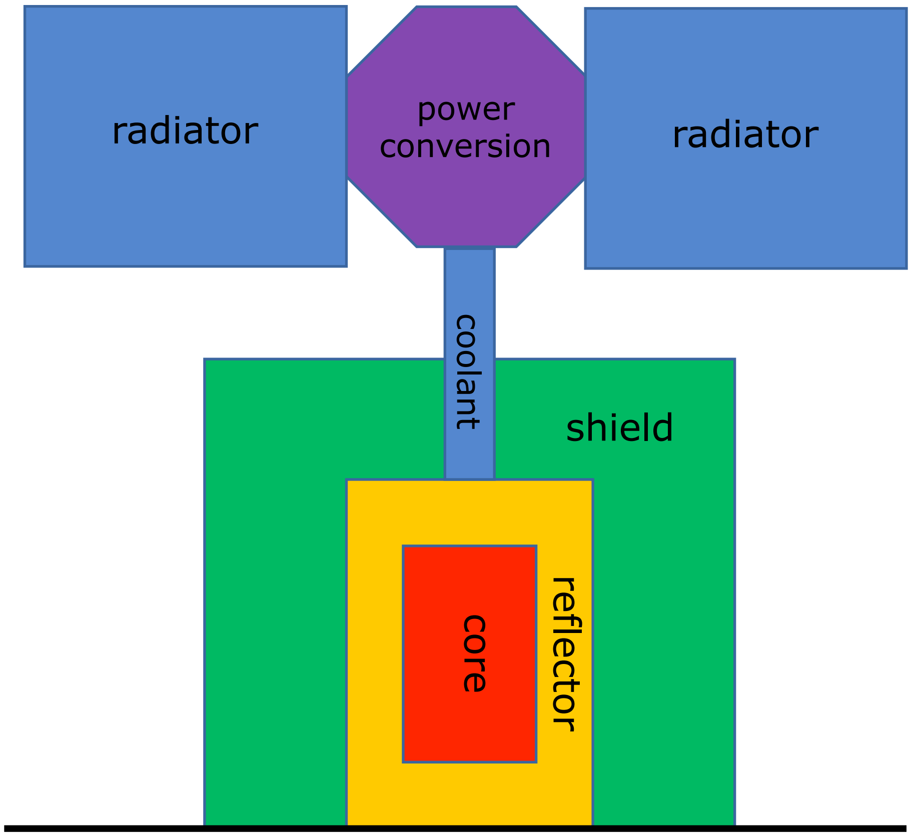
- Space Nuclear Reactors development by private companies and non-weapon nations
- Issues with HEU and proliferation
- LEU may be enabling
  - Space commercialization
  - International collaboration

Space Reactor Schematics



deep space

(not to scale)



surface

Kilowatt-Class Space Nuclear Reactors

Kilowatt-class (1-10 kW_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_e to 100's of MW_e), where RTGs aren't an option.

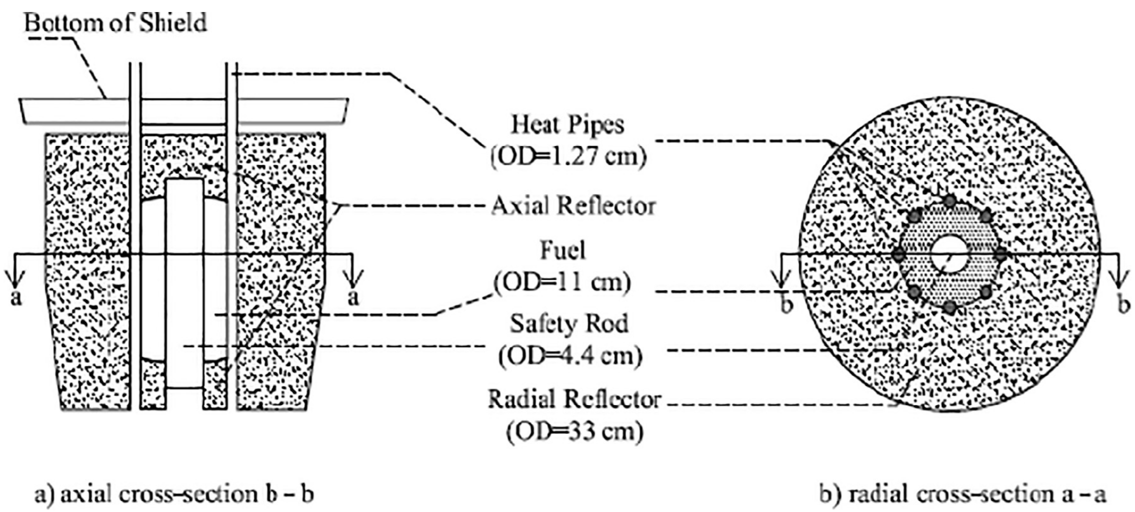
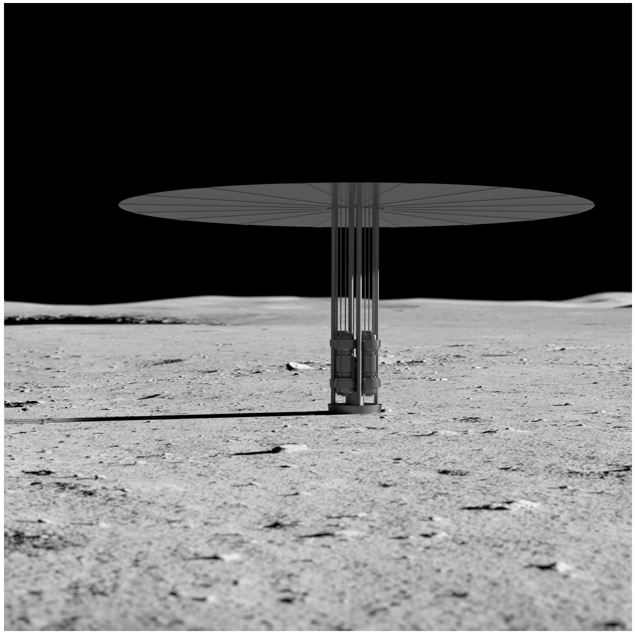


Fig. 1. Axial and radial cross-sections of KRUSTY (adapted from Poston et al., 2013).

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.



Reference LEU Reactor

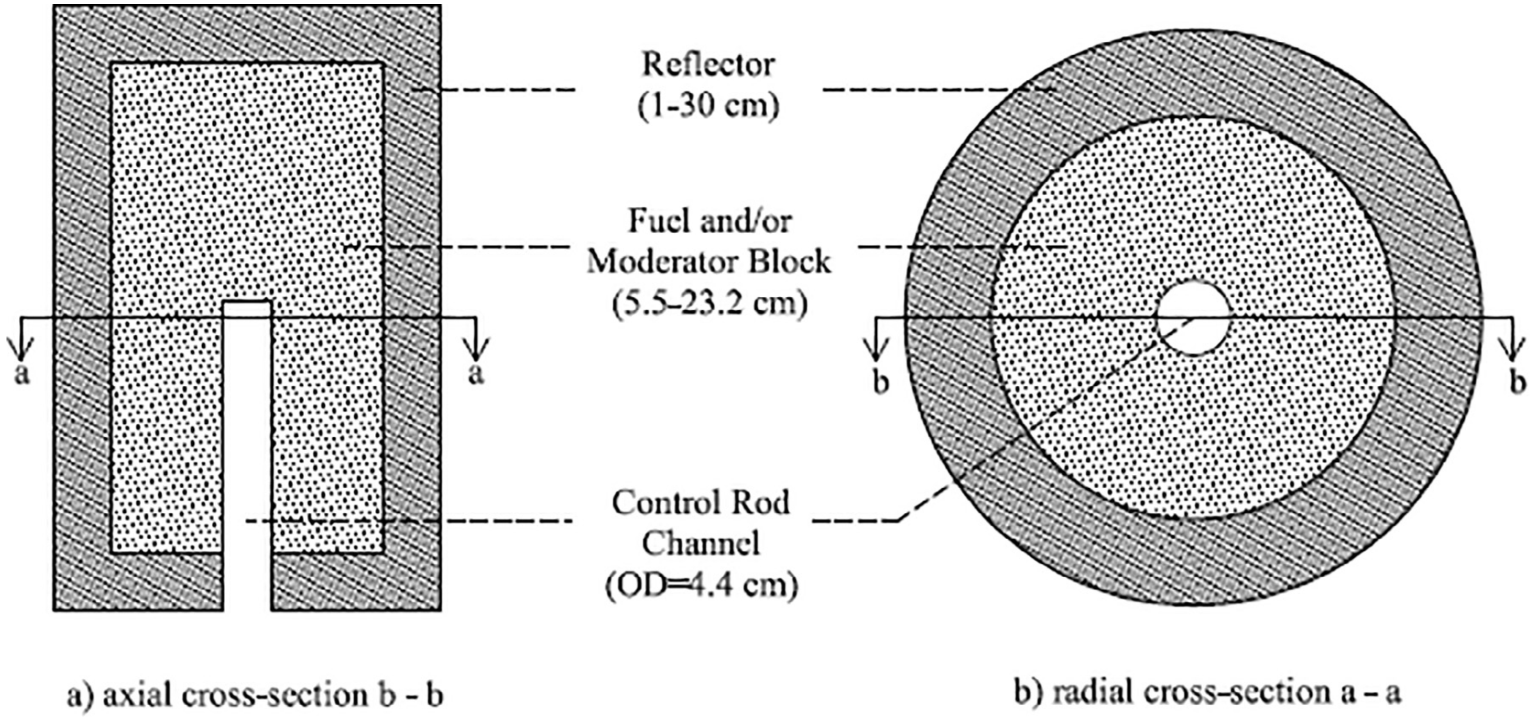


Fig. 2. Axial and radial cross sections of the LEU-fueled reactor.

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.

Criticality

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

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

So,

$$k_{eff} \approx P_{fission} \cdot P_{not-capture} \cdot P_{not-escape} \approx 1.035$$

$$P_{fission} \approx enrichment$$

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

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

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.

Enrichment

If enrichment goes down, so does $P_{fission}$ and $P_{not\text{-}capture}$.

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

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

Therefore k_{eff} also goes down.

$$k_{eff} \approx \downarrow P_{fission} \cdot \downarrow P_{not-capture} \cdot P_{not-escape} \approx \Downarrow$$

Enrichment – Simple Solution

In the simplest case, LEU means a bigger core or a thicker reflector.

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

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

$$P_{not-escape} \approx size \approx \uparrow$$

$$k_{eff} \approx \downarrow P_{fission} \cdot \downarrow P_{not-capture} \cdot \uparrow P_{not-escape} \approx \Leftrightarrow$$

Reflector Thickness, LEU-Fueled Kilowatt-Class Reactor

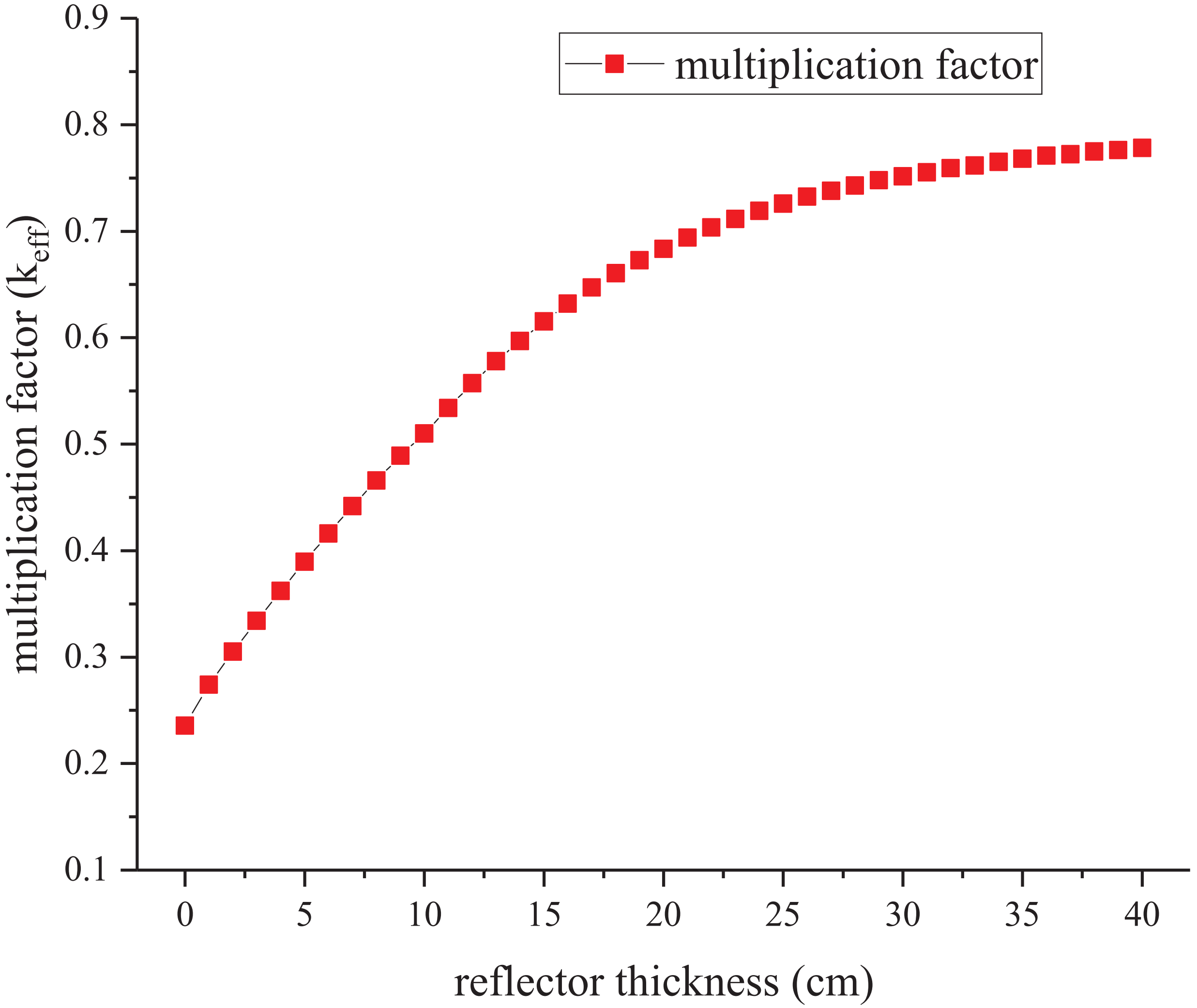


Fig. 6. Multiplication factor as a function of reflector thickness for an un-moderated LEU reactor core with the same dimensions as KRUSTY.

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.

Core Size, LEU-Fueled Kilowatt-Class Reactor

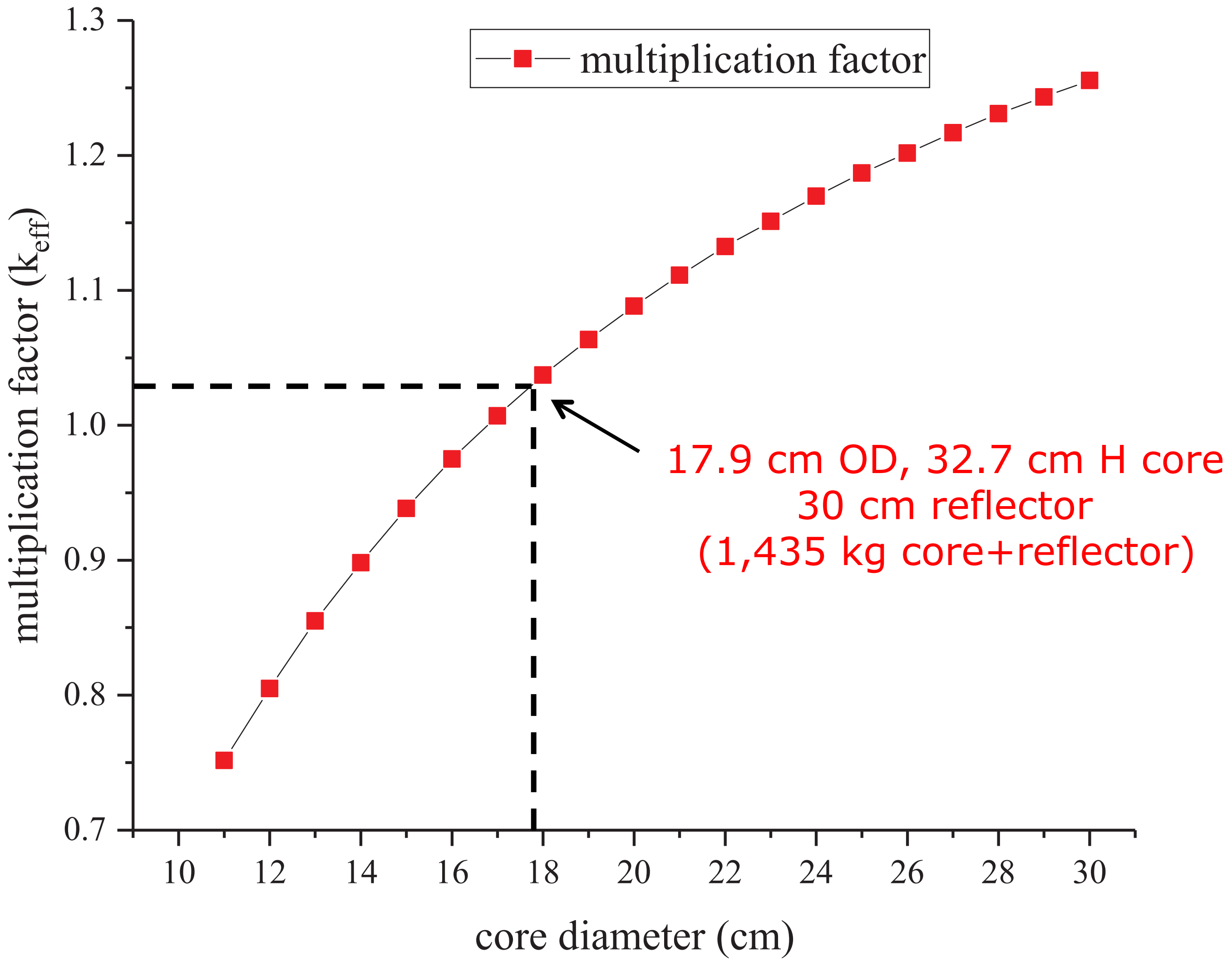


Fig. 7. Multiplication factor as a function of core diameter for the un-moderated LEU reactor with a H/D ratio of 1.81 and a reflector thickness of 30 cm.

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)

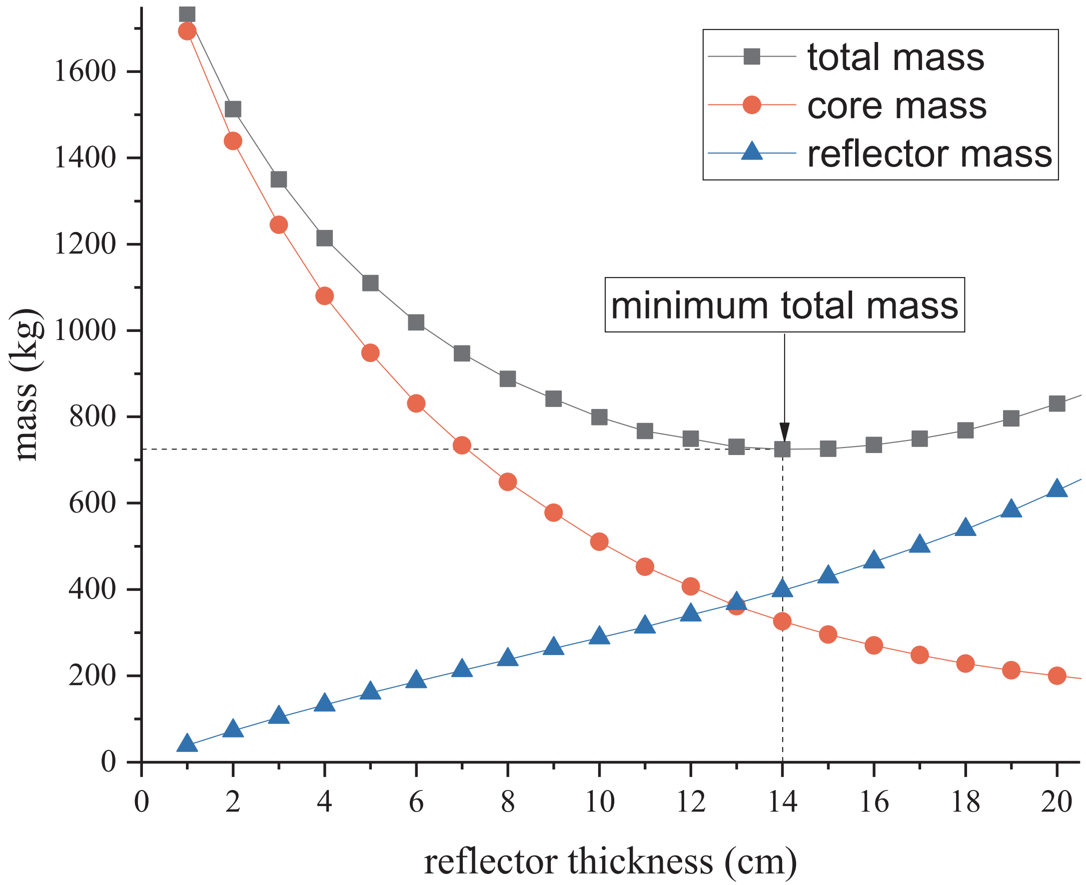


Fig. 8. Fuel and reflector mass as a function of reflector thickness for an un-moderated LEU reactor with a multiplication factor of 1.035.

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.

Moderation

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

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

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

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

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

$$k_{eff} \approx \uparrow\uparrow P_{fission} \cdot \downarrow P_{not-capture} \cdot \downarrow P_{not-escape} \approx \Leftrightarrow$$

Moderator Options

- Adding moderators to reduce the required mass of fissile uranium is a standard technique (nearly all terrestrial reactors are moderated)
- On Earth, we common 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

Homogeneously Moderated Reactor Mass

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.

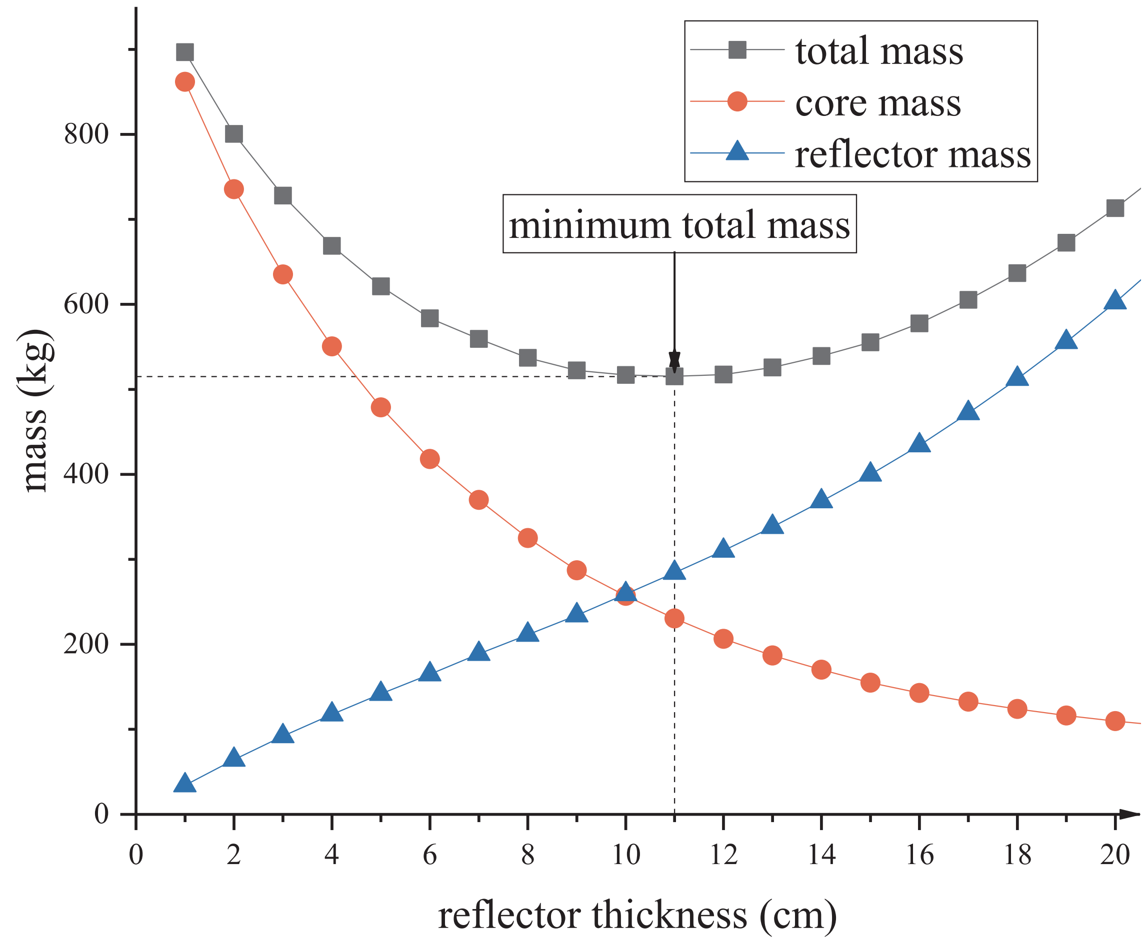


Fig. 9. Fuel and reflector mass as a function of reflector thickness for a LEU-fueled, 30 wt% homogeneously moderated reactor, with a multiplication factor of 1.035.

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.

Moderator Configuration Options

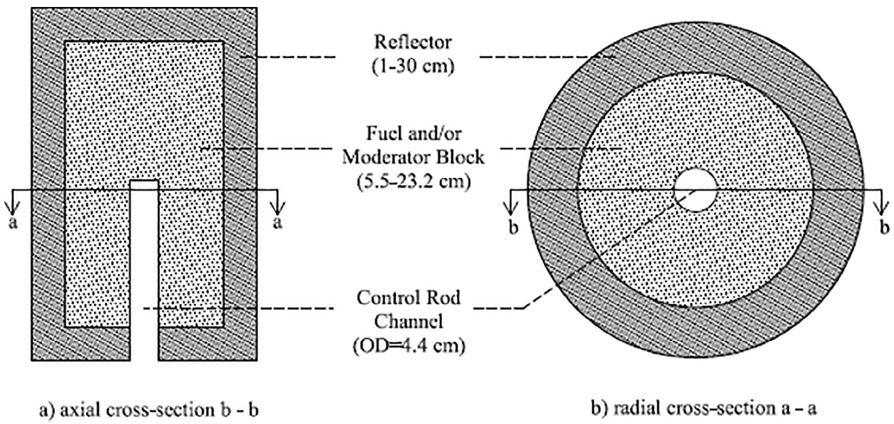


Fig. 2. Axial and radial cross sections of the LEU-fueled reactor.

homogenous

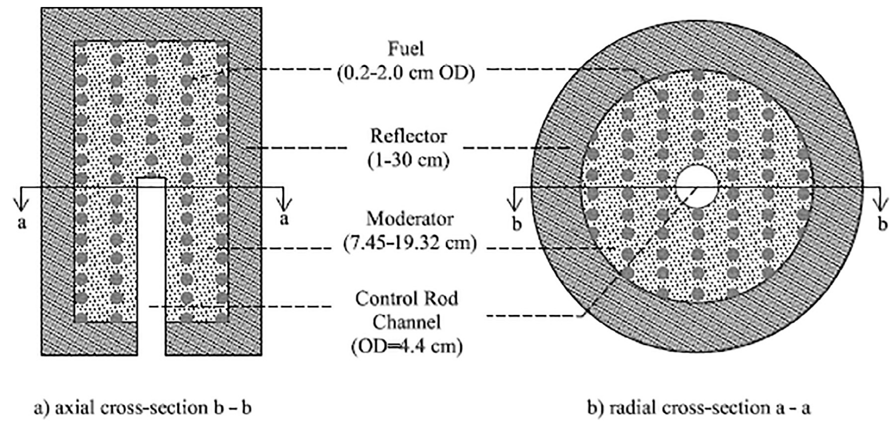


Fig. 3. Axial and radial cross-sections of the LEU-fueled reactor with spherical fuel geometry.

fuel spheres

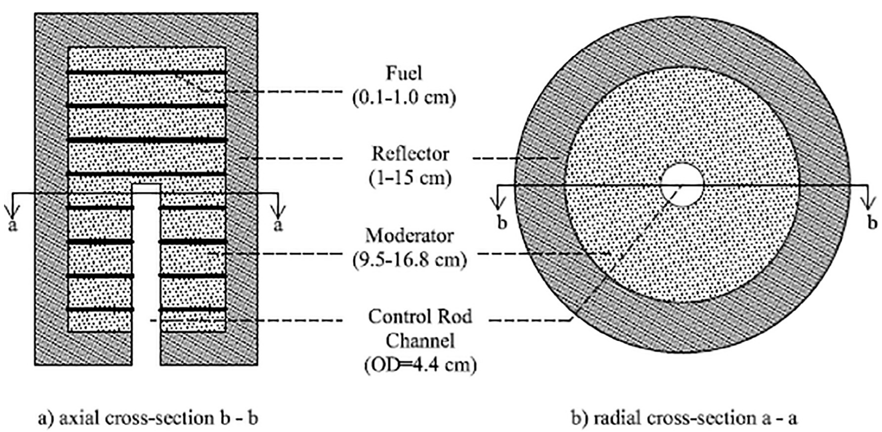


Fig. 4. Axial and radial cross-sections of the LEU-fueled reactor with disc fuel geometry.

fuel plates

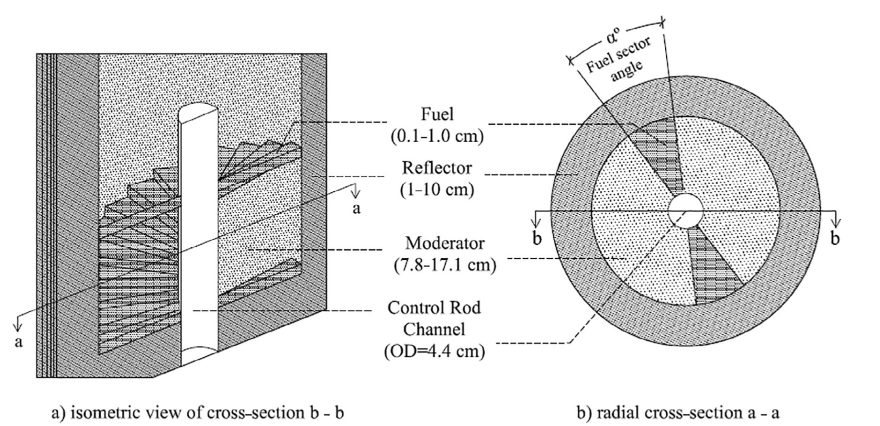


Fig. 5. Isometric and radial cross-sections of the LEU-fueled reactor with helical fuel geometry.

fuel helix

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.

Lowest Mass Moderated Reactor

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.

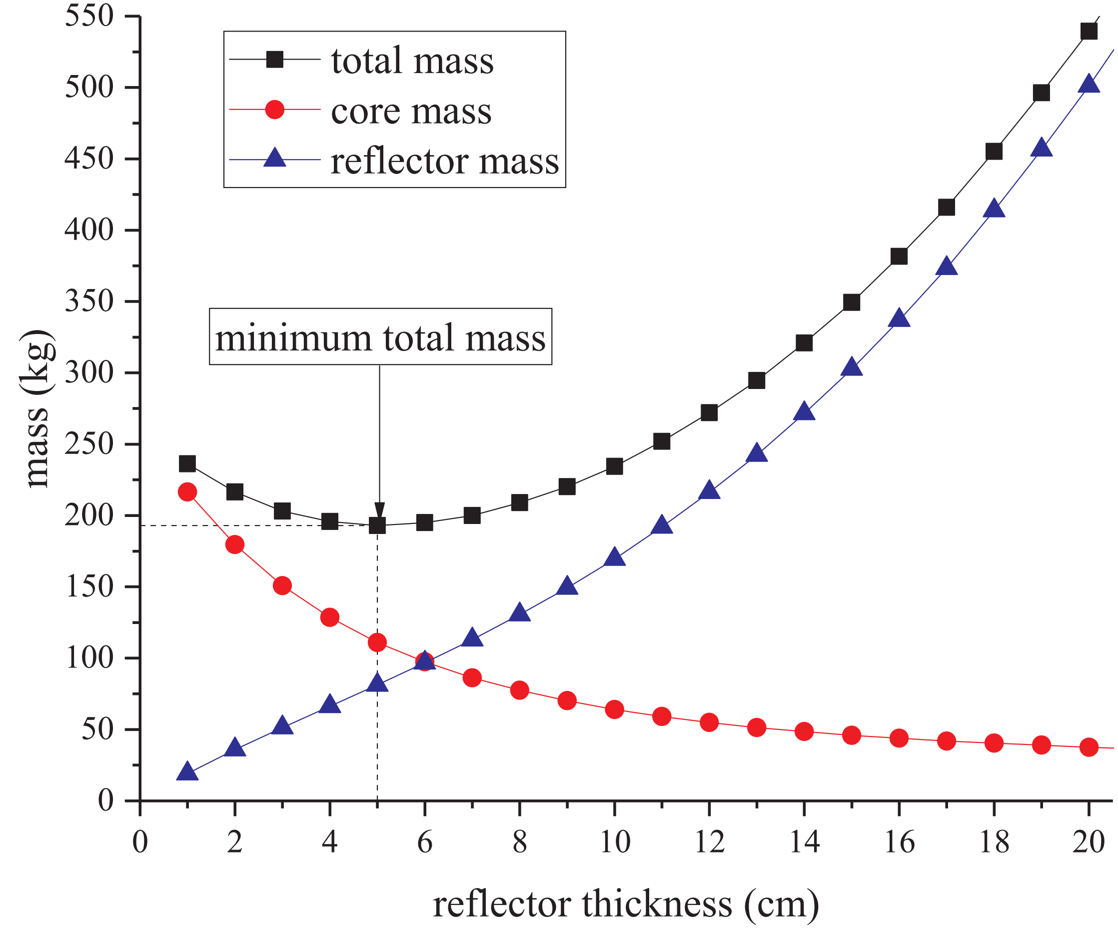


Fig. 10. Fuel and reflector mass as a function of reflector thickness for an LEU-fueled, 80 wt% heterogeneously moderated reactor, with spherical fuel geometry and a multiplication factor of 1.035.

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.

Reactor Lifetime

- 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 $P_{not\text{-}capture}$)

- 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

Impact of Moderation on LEU 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.

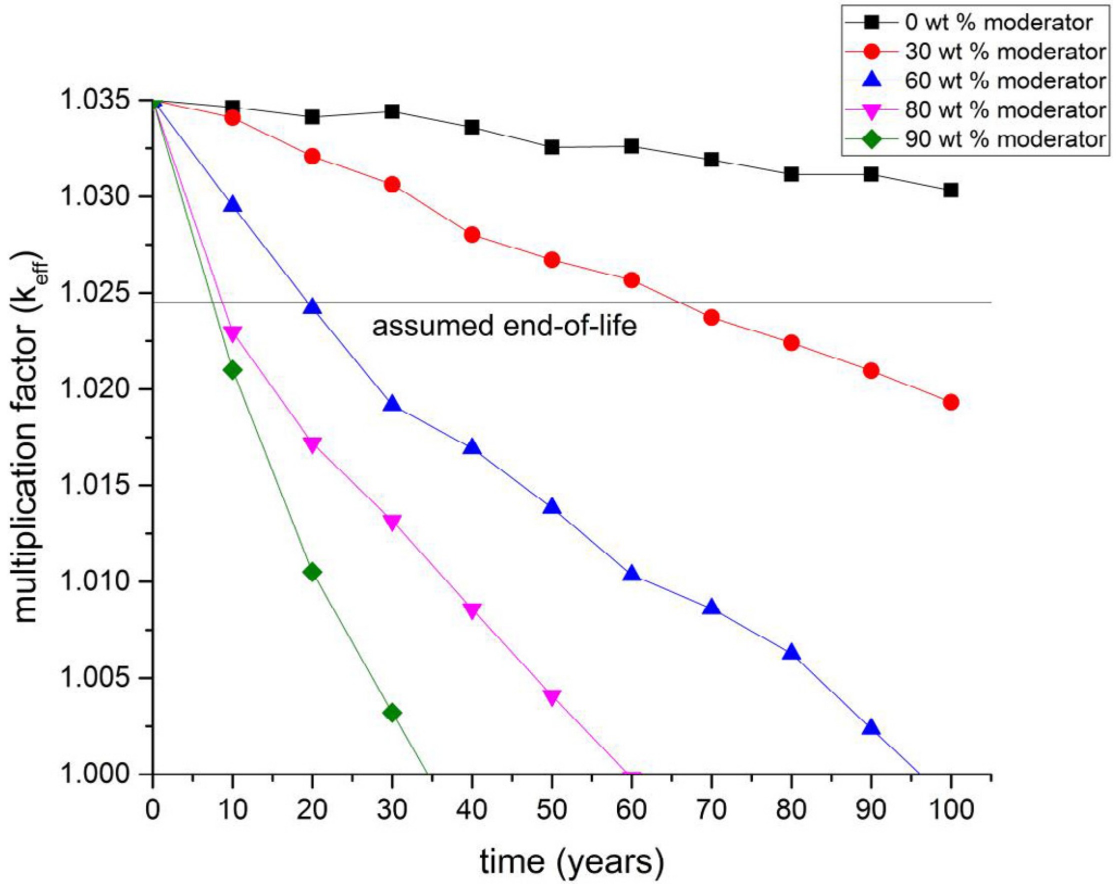


Fig. 13. Multiplication factor as a function of operating time and moderator fraction for the minimum mass homogeneously moderated LEU-fueled reactors operating at 15 kW_t.

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.

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_e), 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?