SpaceX Falcon Heavy Mass Constraints as Design Driver for Practical Heat Pipe Stirling Micro Reactors

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Abstract

Renewed interests in space exploration have resulted in over $3M (FY2022) in awards for conceptual surface fission power (SFP) designs for the latter Artemis missions. Previous SFP designs haven't constrained themselves within the domain of practical power generation or launch capabilities (by commercially-available rocketry). Herein, we propose the SpaceX Falcon Heavy fairing constraints as a design driver for SFP systems. The design has been evaluated within MCNP6.2 and ANSYS to meet the following criteria:

- Launch accident tolerance (subcritical throughout accidents)
- Fuel capabilities of 350kWt operations over 10+ years
- Deployment to Lunar surface on a single Falcon Heavy (<10E3kg)
- Low standoff at 5mRem-yr^{-1} for 1km from reactor system

Fuel Analysis & Core Design

From the INL "Special Purpose Microreactor Design A", generic hexagonal fuel elements around the INL-proposed SS heat pipes. A materials study (MCNP) revealed excellent performance with UC at 900K, from which fuel pitch and enrichments were ultimately determined. Finally, the bulk core design (elements, reflectors, and control drums) concluded a design capable of meeting the reactor core design criteria.

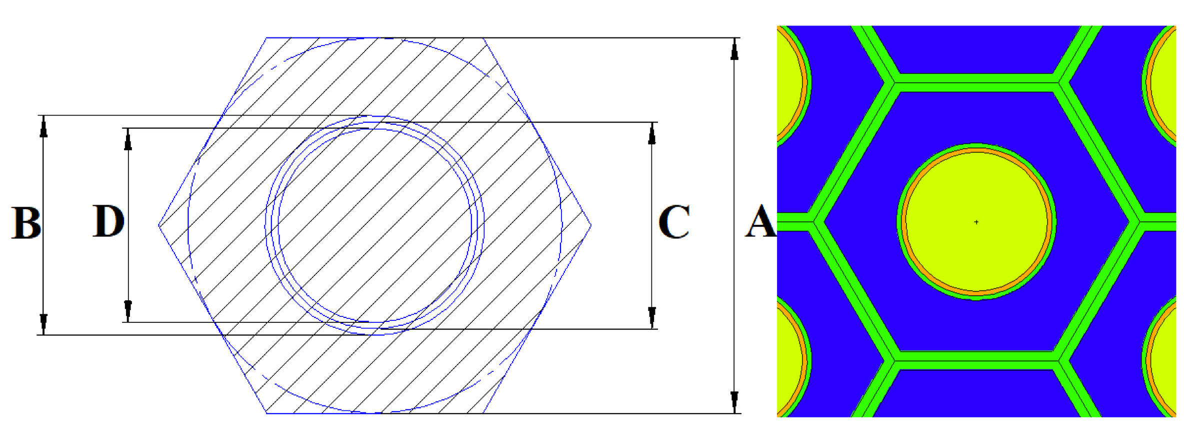

Fig 1-2. Prismatic hexagonal fuel element with heat pipe casing and homogeneously approximated wetted wick dimensions, evaluated at 1200K and purposed from the INL heat pipe microreactor. Dimensions A-D depict the fuel pin pitch, heat pipe exterior diameter, heat pipe interior diameter, and inner wick diameter, respectively. A-D:

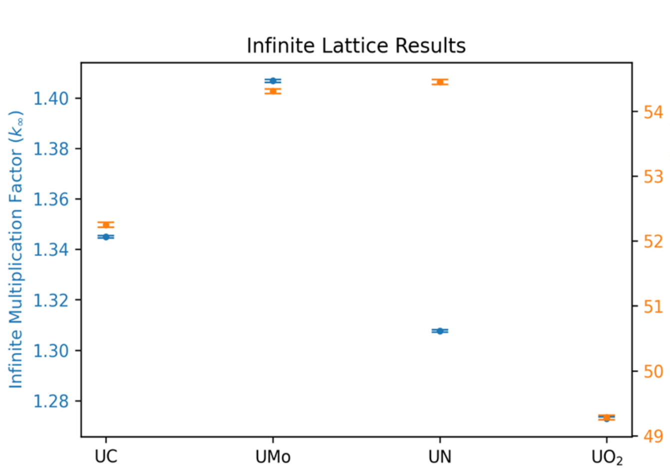

Fig 3. k_∞ and average neutron energy calculations, utilizing periodic boundary condition with matching specifications reported in Fig. 2.

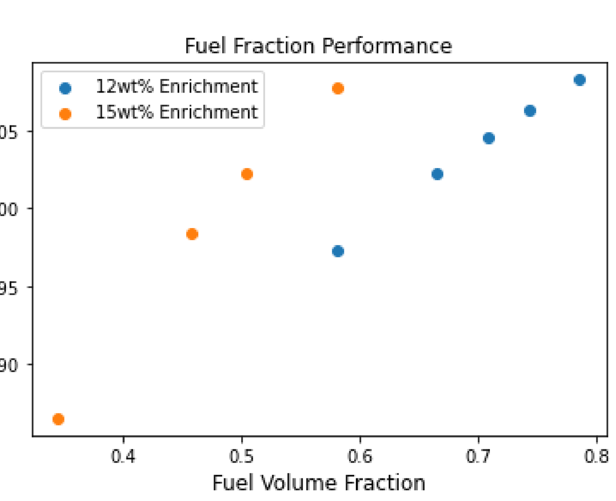

Fig 4. Fuel volume effects on k∞ for the fuel elements, with the fixed heat pipe dimensions and materials.

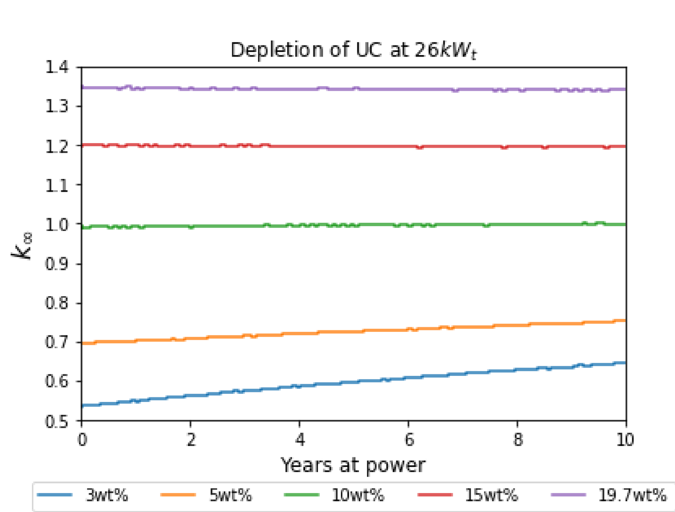

Fig 5. Depletion of the UC fuel pin at varying enrichment levels utilizing periodic boundary condition with matching specifications reported in Fig. 2.

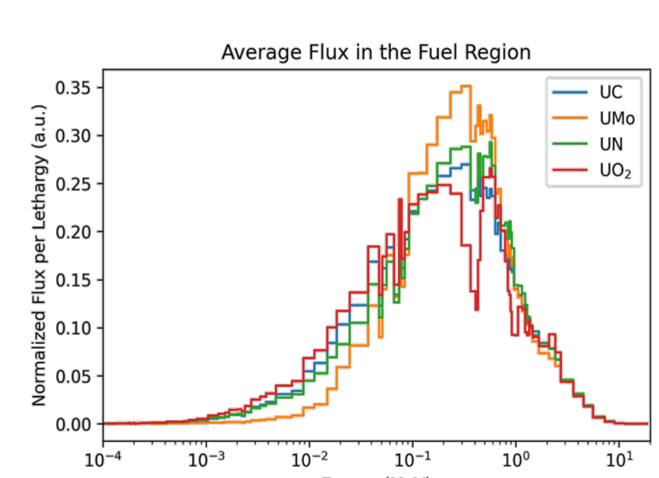

Fig 6. Normalized flux spectra within the simulated fuel. Evaluations were performed for elements (dimensions A-D: 5cm, 3.4cm, 3.2cm, 3cm of Fig. 1), 100cm in height. Axial reflectors of 15 cm BeO were placed on both the top and bottom of the fuel elements.

Table 1. Evaluated core configurations and corresponding details.

Core Layout	K_{eff}	σ (pcm)	Design Remarks
A	1.03659	0.00060	Drums offset 37.13cm
B	1.05508	0.00073	Drums offset 37.13cm , 4 rings, 43 fuel elements
C	1.05067	0.00074	Drums offset 37.13cm , 3 rings, 31 fuel elements
D	1.02214	0.00078	Drums offset 34.53cm
Final Selection	1.01774	0.00068	Drums offset 37.13cm , 4 rings, 43 fuel elements, thicker absorbers

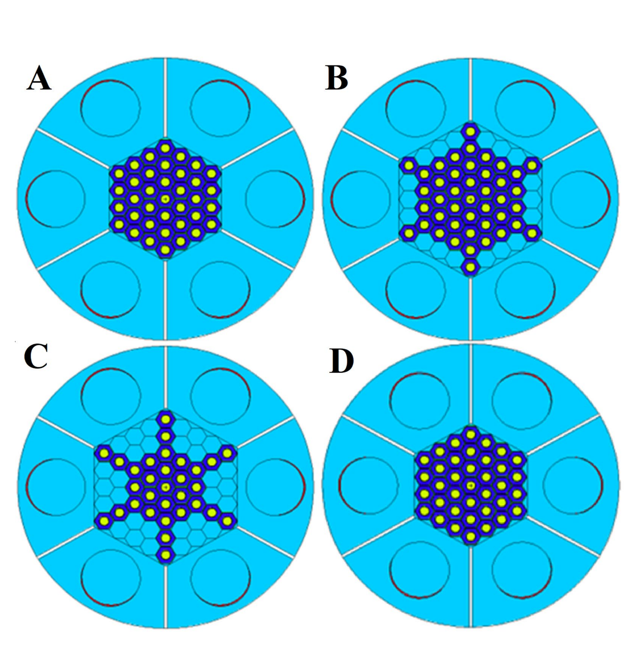

Fig 7. Evaluated core configurations and corresponding details.

Accident and Shielding Analyses:

Launch accidents were considered and evaluated in MCNP, determining that the core remained subcritical. The sequence/pattern in which control drums were affected was investigated, showing no significance upon the results.

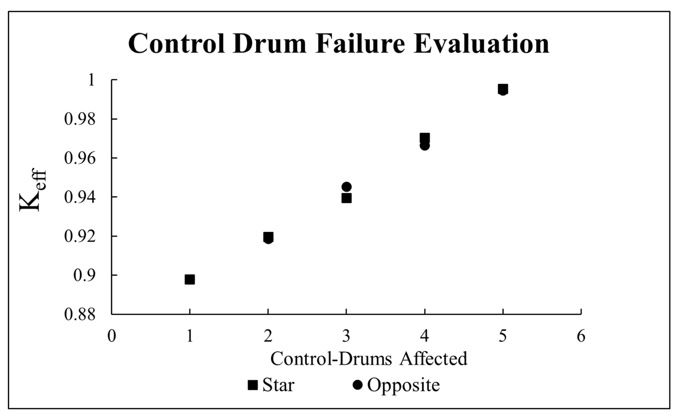

Fig 8. Criticality analysis of reactor with control drums failed in the "on" position with the highest positive reactivity.

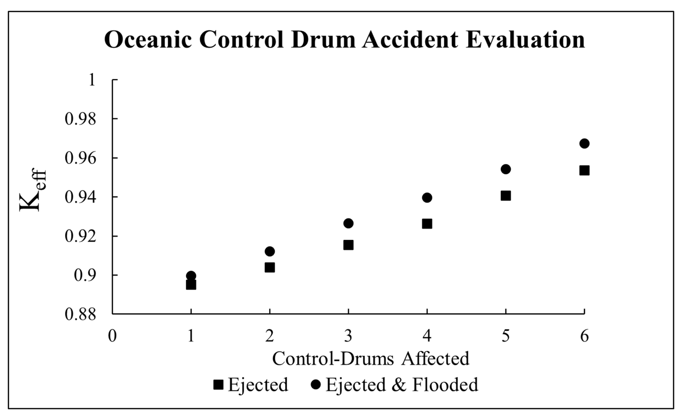

Fig 9. Criticality analysis of reactor with control drums ejected and/or flooded with water while the core is submerged in water.

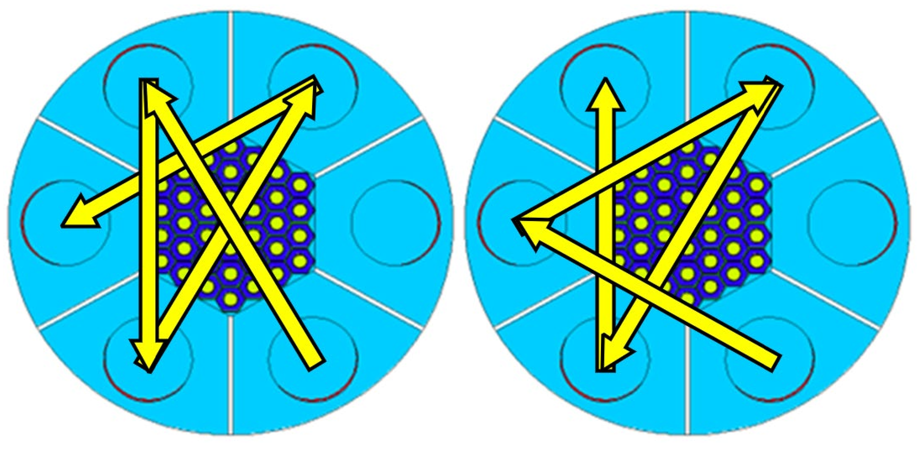

Fig 10. "Opposite" and "star" evaluation patterns that were examined as a source of evaluation bias.

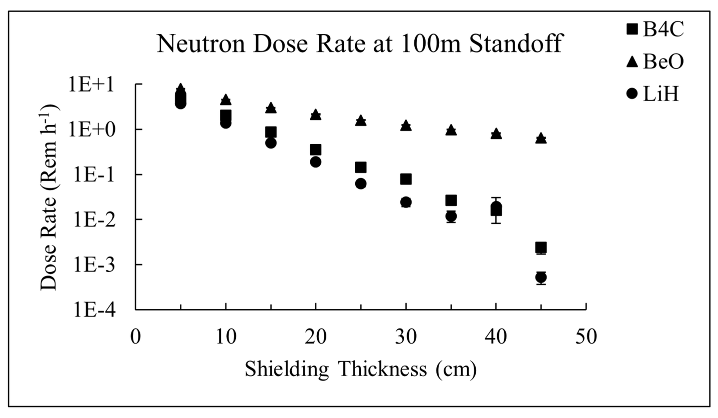

Fig 11. Neutron dose component materials study for 100m standoff.

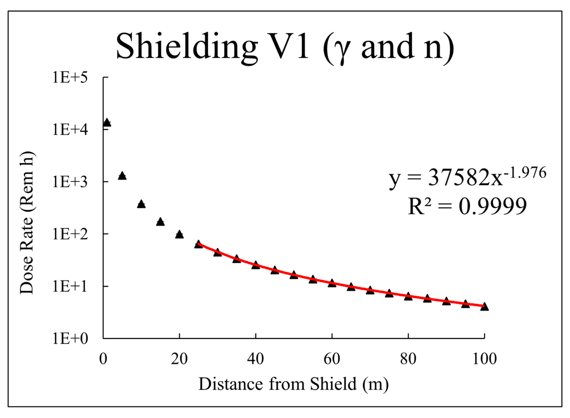

Fig 12. The first permutation of the shielding consisting of 40cm LiH 1cm B_4C, and 1.5cm SS316. Shielding mass: 2000kg. 385 Rem-yr^{-1} at 1km.

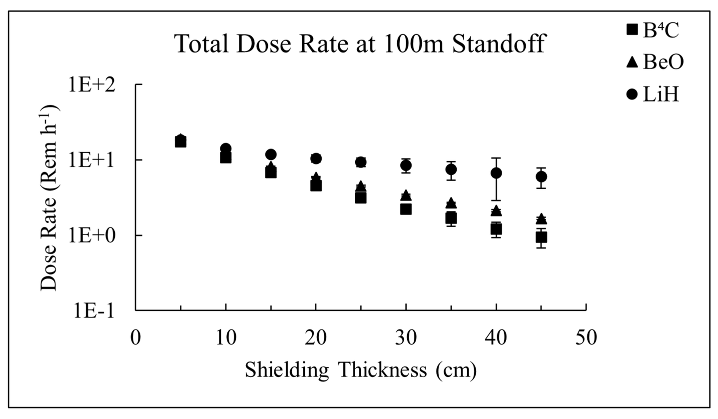

Fig 13. Total dose rate for selected materials without a strong gamma shield.

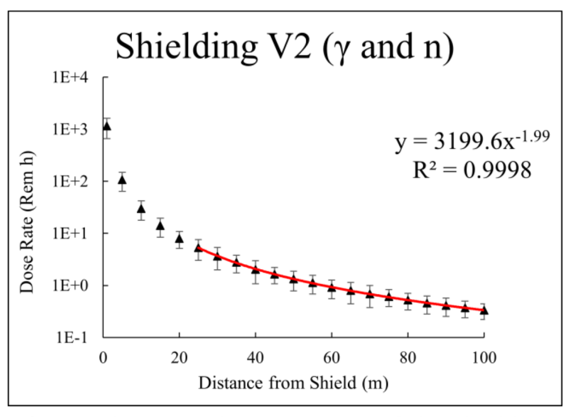

Fig 14. The second permutation of the shielding consisting of 40cm LiH 1cm B_4C, and 12.5cm SS316. Shielding mass: 7100kg. 30 Rem-yr^{-1} at 1km.

Conclusions

A reactor has been designed using a mass/size design driver and demonstrating practical power, longevity, and safety through the scope of evaluations. Further consideration into gamma shielding should purpose the native lunar regolith or small craters (<100m in diameter) to maintain strict payload limitations.

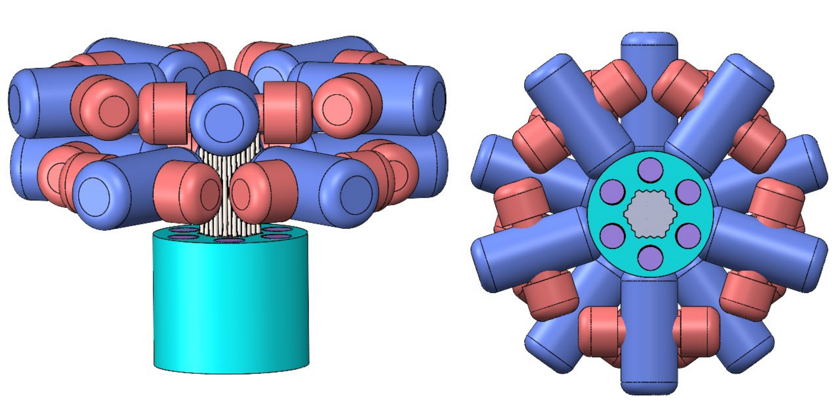

Fig 15. A conceptual rendering of the reactor with 10 free-piston stirling engines, lacking shielding or visible coupling from the straight heat pipes to the stirling engines.

Acknowledgements

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