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Feasibility of Low-Enriched Uranium Fueled Nuclear Thermal Propulsion in the Low-Thrust Region Below 16klbf

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ABSTRACT

This paper establishes the feasibility of Low-Enriched Uranium fueled Nuclear Thermal Propulsion (LEU-NTP) reactors in the low-thrust region below 16klbf (71kN). A reference, 7.5klbf, High-Enriched Uranium (HEU) design is converted to 19.75% enriched LEU and shown to be capable of reaching criticality and meeting other performance requirements with a minimal mass increase. At this smaller scale, historical LEU-NTP conversion techniques that focus on maximizing neutron moderation or minimizing leakage within the active core are insufficient. Thus, the 7.5klbf preliminary design requires several unique modifications, including a reduction in the number of control drums and adjustments to selected materials. To verify the design's feasibility, several key neutronic and thermal-hydraulic performance parameters including burnup, Xenon worth, and submersion criticality are characterized with Serpent 2.0 and the Space Propulsion Optimization Code. The methods applied in this work reveal an opportunity for further LEU-NTP optimization that may directly translate to increased scalability and efficiency for future designs.

1. Introduction

Nuclear thermal propulsion (NTP) is unchallenged as the technologically superior transportation method for near-term, crewed missions to Mars. Its fundamental performance capabilities are double that of current, state-of-the-art technologies, making it an optimal solution for the high mass, long distance architectures necessary for human spaceflight beyond cislunar space. NTP is the only currently viable option that delivers six astronauts to Mars within three months, reduces the total required number of launches, enables mission profiles with either short-term or extended stays on the Martian surface, and offers abort scenarios at any point during transit (Sager, 1992; Durante and Bruno, 2010; Drake, 2013; Joyner, 2017).

Fortunately, nuclear thermal propulsion already possesses significant historical data from the original research conducted during the Rover/Nuclear Engine for Rocket Vehicle Application (NERVA) program from 1955 to 1972. Most of today's design work involves improving upon the program's final design iteration, the 16.4klbf Small Nuclear Rocket Engine (SNRE) (Fig. 1).

Several attempts to launch this technology into space took place in the decades following the NERVA program, yet none progressed beyond laboratory experiments. In January 1994, a preliminary proposal was submitted to the Department of Energy presenting a space nuclear system utilizing low enriched uranium (LEU) instead of high-enriched (HEU). Such a system might generate the public support, reduce the security costs, and ease the regulatory burdens enough to finally achieve a sustained source of funding. The proposal was rejected on the basis that the additional mass necessary to achieve criticality with anything less than HEU would be prohibitive (USDOE ASSISTANT SECRETARY FOR NUCLEAR ENERGY, 1994).

Almost twenty years later the first LEU-NTP reactor design was published, a low-enriched version of the SNRE, with initial findings suggesting the change in reactor mass would be negligible (Venneri and Kim, 2016). A surge of independent reviews verified this work, and by 2015 NASA had redirected its NTP program to experimentally proving LEU-NTP's feasibility. Since then, almost all NTP publications either assume the use of LEU for mission analysis or seek to further understand the full range of LEU-NTP's potential and limitations.

These studies have repeatedly shown that LEU-NTP systems are equivalent to their HEU counterparts in both single-mission performance and total mass at both the standard NTP thrust levels for crewed Mars missions, 16-25klbf, and the higher thrusts considered for upper stage orbit transfer maneuvers, greater than35kblf (Patel et al., 2016a; Joyner, 2016; JOYNER, 2018; Eades et al., 2015). This equivalence is

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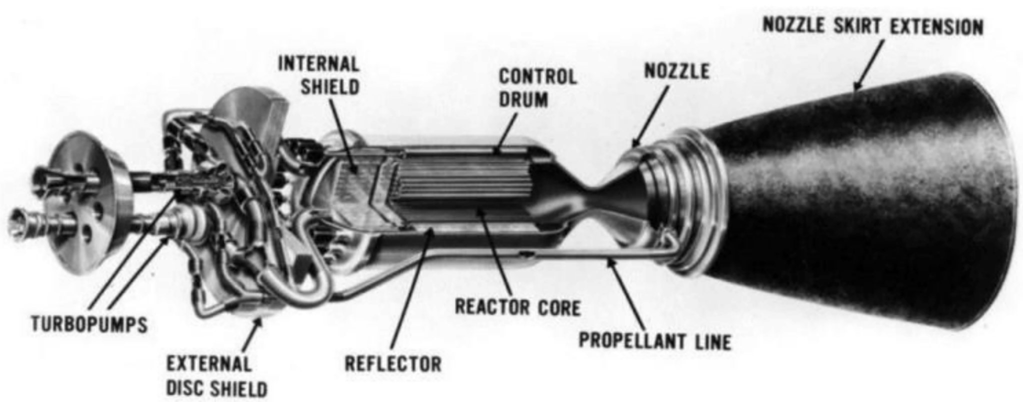
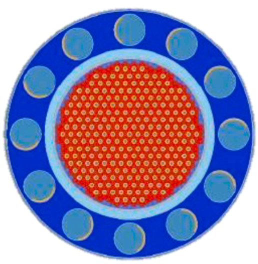
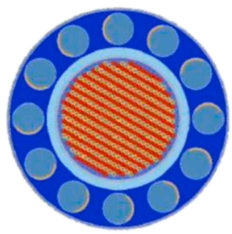
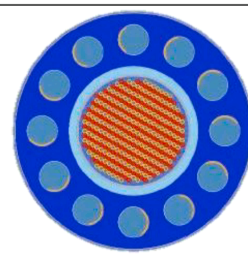
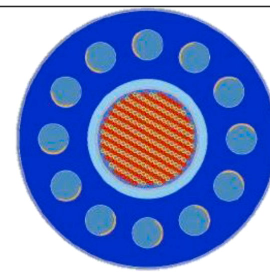


Fig. 1. Schematic of the NERVA Program's Small Nuclear Rocket Engine (SNRE). (Humble et al., 2007).

Table 1
Specific Impulse (I_{sp}) and T/W ratios of small-scale SNRE-based designs. (Schnitzler et al., 2011; Schnitzler and Borowski, 2007).

16 klb$_f$ – SNRE	7.5 klb$_f$	6.0 klb$_f$	5.3 klb$_f$
			
I_{sp}: 875s **T/W Ratio:** 3.91 **Diameter:** 98.5cm	**I_{sp}:** 894s **T/W Ratio:** 2.35 **Diameter:** 87.7cm	**I_{sp}:** 894s **T/W Ratio:** 1.71 **Diameter:** 97.6cm	**I_{sp}:** 893s **T/W Ratio:** 1.27 **Diameter:** 106.5cm

primarily because, at thrusts greater than 16klbf, reactor size is driven by cooling requirements rather than criticality (Patel et al., 2016a). Thus, both LEU and HEU-NTP reactors at these larger thrusts are volumetrically constrained by thermal-hydraulics rather than the nuclear physics.

At smaller sizes, however, LEU reactors are more constrained by their neutronics than HEU (Kim et al., 2013; Licht, et al., 2016). Thus, for engines smaller than 16klbf, which would be most useful for missions such as small-scale qualification testing, robotic interplanetary missions, or proposed as a faster means to achieve first-flight, the LEU-NTP reactor configuration was once again assumed to require an unacceptable mass increase.

The actual transition point between nuclear physics and thermal-hydraulics as the primary driver for NTP reactor size is understood to occur at some thrust level below 16klbf. Rather than immediately attempting to derive this value, this work extends the baseline for the minimum feasible LEU-NTP engine by successfully converting the smallest accepted HEU-NTP design, a SNRE-based, 7.5klbf reactor

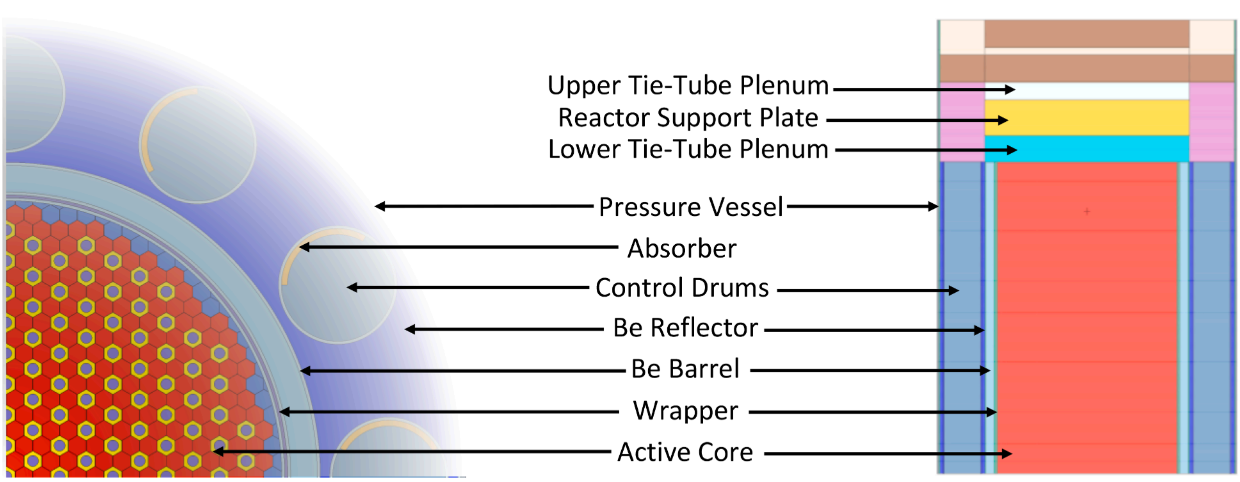


Fig. 2. Key components of Schnitzler's generic SNRE model.

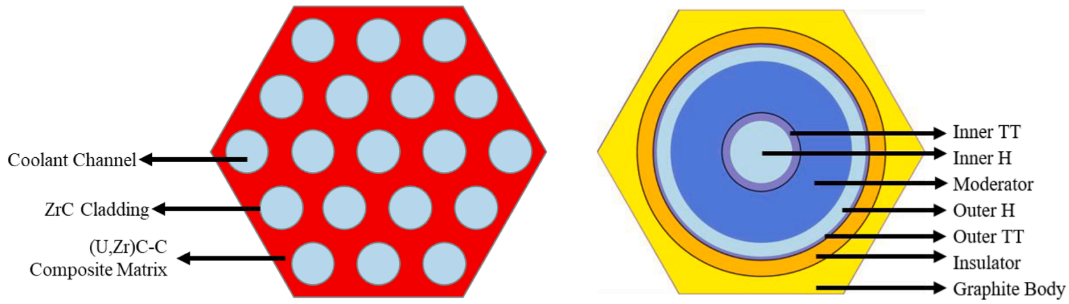


Fig. 3. SNRE-based Fuel and Moderator Elements.

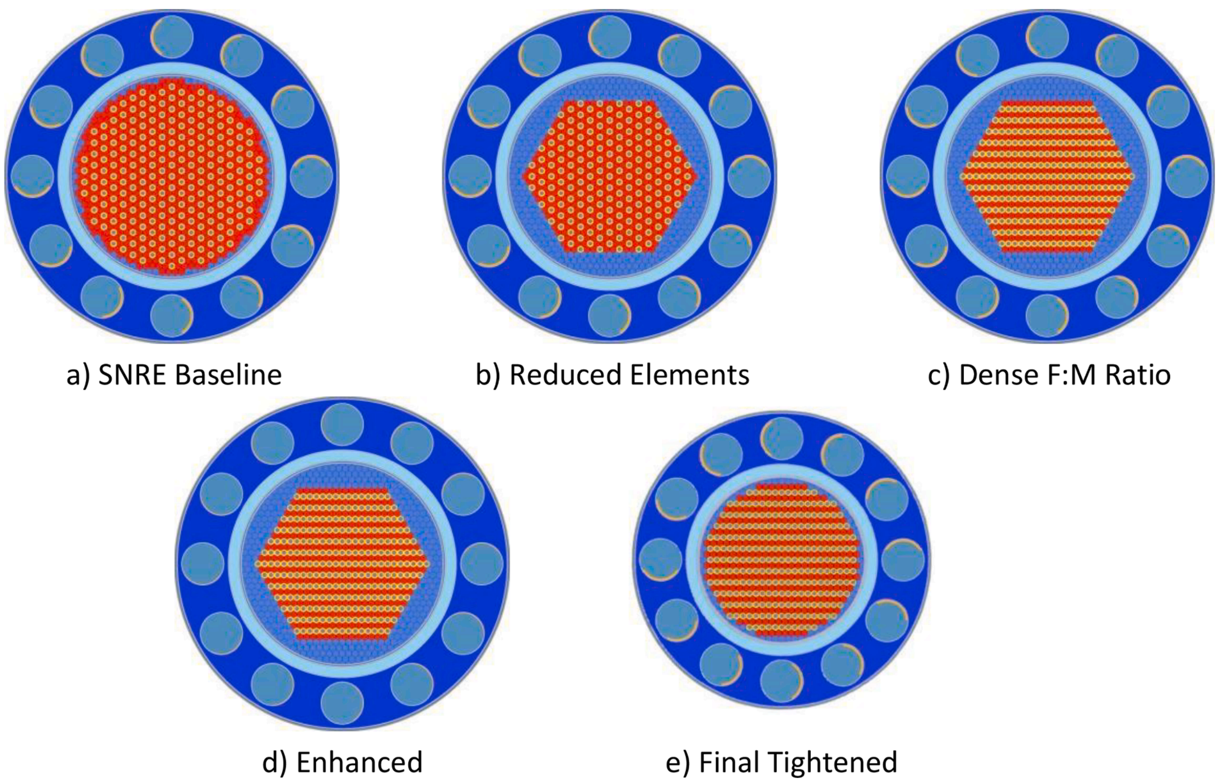


Fig. 4. Visual Progression of 16klbf to 7.5klbf Engine Modifications.

model, to its LEU equivalent (Schnitzler et al., 2011).

The following work begins with a description of the standard and small-scale HEU-NTP SNRE-based reactor configurations and their major similarities and differences. Following this background, the Methodology section details the three-phase approach of recreating Schnitzler's 7.5klbf HEU-NTP model, converting it to LEU, and then performing various thermal-hydraulic and neutronic analyses to verify the design's feasibility. The numerical outputs from this process are then presented in the Results and further summarized in the Conclusion section. Additional parametric considerations that were not implemented in the final 7.5klbf LEU-NTP design are discussed in the Appendix A.

2. Background

Dr. Bruce Schnitzler from the Oak Ridge National Laboratory first investigated smaller scale NTP engines in 2011 (Schnitzler et al., 2011). Through applying systematic modifications to his previously published model of the SNRE, Schnitzler concluded that the smallest reasonable (HEU) NTP thrust size was 7.5klbf. It was possible to achieve criticality at thrusts below 7.5klbf; however, the necessary design modifications would more than halve the engine's thrust-to-reactor-weight (T/W) ratio, from the SNRE's value of 3.91 to 1.71 or lower. Thus, these smaller engines were judged too heavy to be considered useful (Table 1).

Though not identical to the actual SNRE, Schnitzler's SNRE-based model and his reduced thrust designs follow the same general design configuration (Fig. 2). Radially surrounding each active core is a thin, metallic wrapper for structural support, a beryllium barrel, beryllium reflector housing twelve control drums with absorber plates, and an outer aluminum pressure vessel. Axially, the Schnitzler models contain the same general components as the original NERVA design, but each region has been homogenized to simplify the neutronic analysis. Directly above the active core is the lower tie-tube plenum, the reactor support plate, and the upper tie-tube plenum.

The active cores are composed of alternating hexagonal fuel and tie-tube/moderator elements that are rounded out with pure beryllium filler. The fuel elements are a 93% enriched UZrC-C uranium carbide-composite matrix with nineteen hydrogen cooling channels, while the tie-tube elements (TT) are made up of a series of annular rings (Fig. 3). The inner and outer tie tubes offset the axial loads on the core, the two-pass hydrogen loop both cools the element and assists in pre-heating the propellant, the moderator region slows neutrons to increase the fission

Table 2
Geometric Differences between Schnitzler's SNRE Model and his Reduced Thrust Design.

	SNRE Baseline	7.5klb$_f$ Design
Number of Hexagonal Rings	17	14
Number of Fuel Elements	564	260
Number of Tie Tube Elements	241	251
F:M Ratio	2:1	1:1
Moderator Thickness (cm)	0.31750	0.34036
Absorber Thickness (cm)	0.6350	0.1905
Reactor Diameter (cm)	98.5	87.7

probability, and the insulator and graphite body prevent the inner materials from melting. Both the fuel elements' inner coolant channels and every outer prism is coated with zirconium carbide cladding to prevent fission product release.

Schnitzler deliberately designed the smaller engines to have minimal differences with the SNRE. In total, only four changes were made to the original model (Fig. 4a): the number of fuel and tie tube/moderator elements (Fig. 4b), the configuration and therefore ratio between the fuel and moderator elements (Fig. 4c), the thickness of the moderator material in the elements and of the absorber pads on the control drums (Fig. 4d), and the overall reactor diameter (Fig. 4e). Table 2 details the initial SNRE and final 7.5klbf design.

3. Methodology

This analysis follows the same general approach as previous NTP conversion and scaling studies (Joyner, 2016; Benensky, 2016; Patel, 2016). It begins with creation and validation of a baseline HEU model, in this case Schnitzler's 7.5klbf reactor. The model is then converted to LEU and systematically modified until it achieves criticality. Thermal-hydraulic analysis further refines the configuration by identifying unmet key engine performance parameters. Finally, after confirming both neutronic and thermal-hydraulic feasibility, burnup, Xenon buildup, and water submersion simulations evaluate the preliminary design's safety and operational margins.

Schnitzler's reference 7.5klbf HEU-NTP reactor was recreated using information provided in Schnitzler's publications and original NERVA reports (Section 4.1) (Schnitzler and Borowski, 2007; Durham, 1972; Schnitzler et al., 2009). All geometric representations and neutronics calculations were performed in Serpent 2 version 1.27 with ENDF/B VII.1 cross section data. As Schnitzler's work does not include a k-effective value for the final 7.5klbf configuration, the baseline model was validated by following Schnitzler's detailed scaling procedure from the original, 16.4klbf SNRE to 7.5klbf and comparing the k-effective values at each step. After model validation, the reactor's HEU fuel was immediately substituted with a 19.75% enriched uranium carbide equivalent and the drop in reactivity noted.

The LEU conversion process (Section 4.2) utilized the One-Factor-At-a-Time (OFAT) method to incrementally return the core to a feasible design. The OFAT method "is a method of designing experiments involving the testing of factors, or causes, one at a time instead of all simultaneously." It is most useful when the "number of runs is limited, [the] primary goal is to attain improvements in the system, and experimental error is not large compared to factor effects, which must be additive and independent of each other" (Daniel, 1973). As this report is intended as proof-of-concept rather than optimization, the OFAT method is acceptable for this effort. Multivariable analysis would be recommended for future optimization studies.

The order in which individual adjustments were made to the core can be divided into three general phases. The first (Section 4.2.1) focused on applying the same modifications to the 7.5klbf SNRE core that had successfully been used on the historical, larger-thrust designs. After these adjustments were shown to be insufficient for reaching criticality, the second phase (Section 4.2.2) was solely dedicated towards finding a

Table 3
Comparison of k-eff and other relevant information with Schnitzler's 7.5klbf HEU scaling process. (Schnitzler et al., 2011; Schnitzler and Borowski, 2007).

	Schnitzler	Rawlins*	Δ (pcm)
K-eff resulting from Fig. 4a-d			
SNRE Baseline	1.001605	0.99949	−211.5
Reduced Elements	0.9987	0.99947	+77
Dense F:M Ratio	1.0512	1.06025	+905
Enhanced	1.0802	1.08078	+58
Final Tightened Properties (Fig. 4e) (87.7 cm active core dia.)			
K-effective	–	1.00411	
Reactor Mass (kg)	1432.45	1453.32	
Control Drum Worth ($)	10.3	9.94	

* Serpent modeling uncertainty ~70pcm. Control drum rotation angle 90°.

critical reactor configuration through a detailed exploration of the full parameter space. Once a critical configuration had been found, this result was analyzed with a simplified version of the Space Propulsion Optimization Code (SPOC) to quantify its thermal-hydraulic feasibility and key engine performance parameters. The core was then readjusted to reflect a more realistic core design that remained below the desired weight (Section 4.2.3)[1].

SPOC is a one-dimensional, hot-channel analysis tool in MATLAB that implicitly calculates a full-system engine power balance, created by Dr. Peter Husemeyer and the Ultra-Safe Nuclear Corporation (Husemeyer, 2015). This code was successfully peer-reviewed by experts within the nuclear thermal propulsion community and its accuracy was specifically compared to a baseline SNRE design, called the SNRE-The Next Generation (SNRE-TNG) (Patel et al., 2016b). Some of its major assumptions include a constant heat transfer coefficient independent of the ZrC cladding density or carbide fuel composition, vacuum specific impulse assuming a nozzle efficiency of 97%, and the calculation of reactor power rather than whole system power.

Once a reactor proved operational, the core's 10-zone axial power distribution and active-core radial peaking factor were input into a simplified version of SPOC along with the relevant geometric properties, desired thrust, and maximum average fuel element temperature. SPOC then utilized an iterative solver to converge on and output various parameters including the vacuum specific impulse, maximum pressure drops through an average and peaked element, average mass flow rate, maximum peaked fuel element temperature, and reactor total power. Schnitzler did also utilize thermal-hydraulic analysis to verify the engine's performance (Stewart and Schnitzler, 2008); however, not enough information was provided to successfully compare performance values.

The final core design was then evaluated for safety and operational feasibility (Section 4.3). Burnup and Xenon buildup calculations verified whether the reactor could operate for the total duration of a sample mission including required startup and shutdown times. Finally, water submersion simulations modeled the core's ability to remain subcritical in the extremely unlikely event that a launch failure causes the reactor to fall into the ocean completely intact except for the control drums.

[1] As a by-product of the OFAT method, several modifications were tested that either resulted in a negligible or negative impact to total reactivity and thus were not included in the final design. In the spirit of thoroughness and increasing the academic knowledgebase, these negative results are included in Appendix A.

Table 4
Material assumptions used in the Serpent Model. (TT = tie-tube element).

Hydrogen TT First Pass Density (g/cm^3)	0.45642
Hydrogen TT Second Pass Density (g/cm^3)	0.01289
Hydrogen Fuel Element Density (g/cm^3)	0.00115
Zirconium Carbide Density (g/cm^3)	3.54
Stainless Steel Wrapper Material	Inc-718
Zirconium Hydride Ratio	1:1.64
Aluminum Density (g/cm^3)	2.70
Core Uniform Temperature (K)	1200*

* Within available cross sections, 1200 K represents the closest effective flat fuel temperature. While the actual axial and radial temperature profiles will affect the total reactivity of the core, modeling with uniform fuel temperature has been shown to be an acceptable method for first-order reactor feasibility modeling. (Valtavirta and Leppänen, 2017; Greifenkamp et al., 2008).

Table 5
Growth in k-eff following several modifications.

	k-eff	Δ (pcm)*	Mass
Small 7.5klbf HEU (87 cm active core dia.)	0.99915	–	1434.23
Small 7.5klbf LEU (87 cm active core dia.)	0.69902	−29,888	1434.23
ZrH Ratio = 1.8	0.71623	+1721	1432.98
ZrH Ratio = 2.0	0.73762	+2139	1432.15
ZrH Thickness = 0.44199	0.79534	+5772	1463.57
Structural Material = Zircaloy-4	0.93144	+13,610	1450.07

* Serpent modeling uncertainty ~75pcm.

4. Results

4.1. 7.5klbf model creation and validation

Table 3 compares k-effective values for each step in Schnitzler's 7.5klbf HEU-NTP reactor scaling process (as previously described in Fig. 4) with this work's baseline 7.5klbf HEU Serpent reproduction. Most design specifications were pulled from either Schnitzler's previous publications or the official SNRE Final Design Report. Any additional assumptions used to generate the initial model are listed in Table 4. Note that Schnitzler did not provide a k-eff value for the Final Tightened 7.5klbf core configuration.

The relatively large pcm disparity in the "Dense F:M Ratio" step (Fig. 4c), where the fuel to moderator element configuration changes from 2:1 to 1:1, compared to the extreme closeness of the other values, implies that some discrepancy may exist in the moderator material assumption. This and any additional deltas may also be attributed to a difference in computational tools and cross section data, with Schnitzler utilizing MCNP and a combination of ENDF/B VI and VII.0 and this work using Serpent 2.0 with ENDF/B VII.1, respectively. As this difference is corrected in the Enhanced step, the total average variation in k-effective of a few hundred pcm is acceptable and the Serpent model can therefore be baselined for further neutronic calculations.

4.2. LEU conversion process

The first step in the conversion of any SNRE-based HEU-NTP reactor design to LEU is to replace the 93% enriched uranium in the UZrC-C graphite composite fuel with 19.75% enriched high-assay low-enriched uranium (HALEU). All U, Zr, and C relative ratios and densities remained the same consistent with NERVA and Schnitzler documentation, and both versions were modeled in Serpent 2 as homogenous. The effects of heterogeneity in graphite composite fuels are believed to have never been addressed in public literature; however, the discrete phases in the standard graphite composite fuel should be sufficiently small, on the order of ~10 μm, to have a negligible impact (Stewart and Schnitzler, 2015). Similarly, the conversion from HEU to HALEU does thermalize the neutron spectrum. It is assumed that Serpent 2 can address any effects from changes to the neutron spectrum within the limits of available nuclear data. For the Schnitzler design, this reduces the k-eff by almost 30,000 pcm (included in Table 5). To get a feasible reactor, therefore, the following design changes must reverse this decrease in reactivity. Note that this process begins with an undersized core diameter of 87.0 cm as opposed to 87.7 cm, due to a miscalculation in the active core diameter. This size discrepancy is corrected by Approach 3, and the total impact to core k-effective of this geometric error is shown to be small (~300pcm).

Table 6
Cumulative list of modifications made in the 7.5klbf LEU-NTP design.

	k-eff	Δ (pcm)	Mass (kg)
Structural Mat. = Zircaloy-4	0.93144	+13,610	1450.07
Total Iron Removal	0.94337	+1193	1410.30
Absorber = 0.1 cm B_4C	0.93574	−763	1381.94
Number of Control Drums = 6	0.96752	+3178	1392.07
ZrC Density = 6.61 g/cm^3	0.97930	+1178	1426.20
Uranium Loading = 0.64 g/cm^3	0.99128	+1198	1426.69
Control drums at 180°.	1.02142		1426.69

4.3. LEU conversion approach 1: Active core thermalization

Following previous NTP conversion publications, this work began with thermalizing the reactor by maximizing the moderator design and replacing the tie-tube structural material within the active core region (described in Table 6) (Joyner, 2016; Benensky, 2016; Patel, 2016). To increase the moderator, the ratio of Hydrogen in the ZrH moderator was increased from 1.64 to the more commonly utilized 1.8 (1.8H atoms for every 1 Zr atom) and then finally to the theoretical maximum of 2.0. This increased k-eff to 0.71623 and 0.73762, respectively. While $ZrH_{2.0}$ is both more difficult to manufacture and structurally weaker, the priority of this first approach was proving neutronic feasibility, and thus theoretical maximums were allowed (PULS, 2012). Next, the moderator thickness was expanded to 0.44199 cm, the maximum size without impacting the total element diameter, which increased the k-eff to 0.79534. Lastly, the structural material in the tie tubes changed from high-neutron absorbing Inconel-718 to Zircaloy-4. This increased k-eff to 0.93144. While much higher than the k-eff after the change to LEU, the core is still subcritical. Therefore, it is not enough to just modify the design in the active core region; we must change the design outside the active core region as well.

4.4. LEU conversion approach 2: Outer core region

The most common historical adjustment to the outer core region is increasing the reflector region, either by expanding the radial reflector or including an axial plate. While effective for increasing k-eff, this approach significantly increases the total reactor mass and thus was not considered a viable solution for this work. Initially, all iron except that in the control drum actuators was excluded from the preliminary 7.5 klbf LEU model, in essence removing the upper and lower tie-tube plenums, core support plate, and the U-seals in the barrel. While highly theoretical, this helped minimize the total number of neutron absorption losses and increased the total k-eff to 0.94337.

To match better with the original SNRE design, and to decrease the system mass, the control drum absorber material was changed from Schnitzler's original Hafnium to B_4C and the thickness was reduced from 0.1905 cm to 0.1 cm. While the rationale for Schnitzler's use of Hafnium is unknown, possible reasons may include its generally higher absorption cross section starting at resonance energies around 1–10 eV, its relatively high absorption cross section regardless of isotope, and the fact that Hafnium transmutes to Tantalum, another high neutron absorber. Nevertheless, B_4C is both a much stronger neutron absorber than Hafnium at the thermal energies necessary for LEU-NTP cores, which creates the opportunity for thinner absorber plates, and a

Table 7
Thermal-Hydraulic Performance of the initial critical 7.5klbf LEU-NTP configuration.

	7.5klbf HEU Design	7.5klbf LEU Design
Thrust to Reactor Weight Ratio	2.35	2.36
Coolant Inlet Temp (K)	370	370.1†
Max Average Fuel Temp (K)	2860	2860†
Nozzle Expansion Ratio	300:1	300:1†
Nominal Thrust (klbf) [kN]	7.42 [33.0]	7.42 [33.0] †
Vacuum Isp (s)	914.67	918.76
Reactor Power (MWth)	145.78	147.00
Max Peaked Channel Temp (K)	2870.92	2865.40
Average Core Pressure Drop (MPa)	0.26	0.48*
Total Mass Flow Rate (kg/s)	3.68	3.66

* The difference in pressure drop is due to a decrease in inlet pressure from 7 MPa in the HEU design to 3.962 MPa in the LEU design. While the rationale for Schnitzler's 7 MPa is unclear, 3.962 MPa more accurately reflects the NERVA-era SNRE inlet pressure.

Table 8
Cumulative list of modifications made in the 7.5klbf LEU-NTP design. Control drums at 180°.

	k-eff	Δ (pcm)	Mass (kg)
Uranium Loading = 0.64 g/cm^3	1.02142 ± 90	–	1426.69
Active Core Diameter = 87.7 cm	1.02442 ± 69	+300	1444.73
Upper Region Fe/Al Inclusion	1.02659 ± 80	+217	1467.49
ZrH Ratio = 1.88	1.01358 ± 75	−1301	1468.39
Structural Material = E635	1.01424 ± 73	+66	1468.82

significantly lighter material. Thus, these adjustments to absorber plate material and thickness decrease the total reactor mass by almost 30 kg, but also reduce the k-eff by more than 750 pcm. After considering these changes to the absorber, the smaller size of this design and highly thermalized configuration allowed for a reduction in the total number of control drums without severely impacting the control drum worth. Reducing the total number of control drums, and therefore number of absorber pads, from 12 to 6 increased the k-eff to 0.96752. The NTP control drums are generally designed to rotate synchronously with margin for one or two control drum failures. Exact transient effects and control schemes for the control drums is an area of current study for both LEU and HEU-NTP designs and is more thoroughly discussed in published literature. (Goode, 2015; HASSE, 2017) Additional studies into the impact of fewer control drums on the controllability may be discussed in future work.

Finally, a series of changes were made to better match the design with the SNRE. Initially, this work had assumed a ZrC density of 3.54 g/cm^3 (approximately 50% of theoretical) throughout the reactor. However, in the SNRE only the tie-tube insulator region utilized this lighter density while the remainder of the core returned to the standard density of 6.61 g/cm^3. In addition, the total Uranium loading in Schnitzler's work was reported as 0.6 g/cm^3, whereas the SNRE reports the volumetric concentration of Uranium in the fuel as 0.64 g/cm^3. Thus, this number was increased to match the SNRE. These adjustments ultimately brought the core to a k-eff of 0.99128 with the control drums at 90° or 1.02142 when rotated fully out at 180°. Table 6 presents a summary of design changes and their effects on k-eff and the total reactor mass.

Now that the core is critical, this design can be run through the SPOC thermal-hydraulic code to evaluate engine performance. For reference, the 7.5 klbf LEU-NTP reactor design with all design changes up to this point is included in Table 7, along with Schnitzler's 7.5 klbf HEU-NTP reactor design. Also in the table is the output from SPOC for the LEU-NTP design. SPOC was not used for the HEU-NTP design, those numbers are found from Ref. (Schnitzler and Borowski, 2012). As shown in the table below, the LEU-NTP design offers similar performance as the HEU-NTP design, while being of similar mass. This is quite advantageous because the LEU-NTP design does not have the same regulatory/proliferation concerns as the HEU design.

Table 9
Final design thermal-hydraulic comparison.

Geometry	7.5klbf HEU Design		7.5klbf LEU Design	
Moderator Thickness (cm)	0.34036		0.44199	
Moderator Material	ZrH-1.64		ZrH-2.0	
Absorber Plate Thickness (cm)	0.1905		0.1	
Absorber Plate Material	Hf		B_4C	
Primary Structural Material	Inc-718		Zircaloy-4	
Number of Control Drums	12		6	
Zirconium Carbide Density (g/cc)	3.54		6.61	
Uranium Loading (g/cc)	0.60		0.64	
Mass				
Reactor Mass (kg)	1453.32		1468.82	
Fuel Mass (kg)	179.21		179.70	
U-235 Mass (kg)	27.47		6.22	
Neutronics				
Calculated k-eff w CDs @ 180°, 1200 K	1.03824	± 95	1.01424	± 73
Calculated k-eff w CDs @ 0°, 298 K	0.97090	± 92	0.98971	± 64
Control Drum Worth ($), 1200 K *	9.94267		9.08	
Cold to Hot Worth ($)*	0.44400 (decrease)		5.80933 (decrease)	
Thermal-Hydraulics**				
Thrust to Reactor Weight Ratio	2.31		2.29	
Vacuum Isp (s)	914.67		911.78	
Reactor Power (MWth)	145.78		145.53	
Coolant Inlet Temp (K)	370		370.1†	
Max Average Fuel Temp (K)	2860		2860†	
Max Peaked Channel Temp (K)	2870.92		2867.57	
Nozzle Expansion Ratio	300:1		300:1†	
Nominal Thrust (klbf) [kN]	7.42 [33.0]		7.42 [33.0] †	
Average Core Pressure Drop (MPa)	0.26		0.36	
Total Mass Flow Rate (kg/s)	3.68		3.69	

* Assuming an effective decay constant of 0.0075.
** The radial and axial peak power profile between the HEU and selected LEU configurations remained within a margin of a few percent. For additional information on effects on the radial and axial power profiles, please refer to Appendix A.
† SPOC Input Parameter.

4.5. LEU conversion approach 3: Refinement

The final set of design changes aimed to make the reactor more realistic and manufacturable (Table 8). This involved first adjusting the active core diameter to match Schnitzler's design. In addition to minimizing differences between the LEU core and its HEU benchmark, the additional fuel in the active core diameter increases the k-eff to 1.02442 with the control drums at 180°. Next, further analysis revealed that only the Iron in the barrel region significantly impacted the neutron economy, therefore the Iron in the upper core regions was restored. Note that the core support plate's Iron was replaced with Aluminum to better match the SNRE's original design intention. Next, the ratio of H in ZrH was decreased to a more reasonable 1.88 from the theoretical maximum 2.0. This yielded a k-eff of 1.01358. Lastly, the tie-tube structural material was changed from Zircaloy-4 to E635. While potentially more difficult to obtain, the Russian manufactured E635, also a zirconium-based material, is significantly stronger than Zircaloy-4 while generating a negligible neutronic impact. The material consequences of having a zirconium-based moderator in direct contact with the outer hydrogen loop and the possibility for delayed hydride cracking will need to be evaluated in future work. (Puls, 2012) Other options including introduction of an outer coating resistant to hydrogen may be considered in future work.

Table 9 compares the configuration, mass, neutronic and thermal-

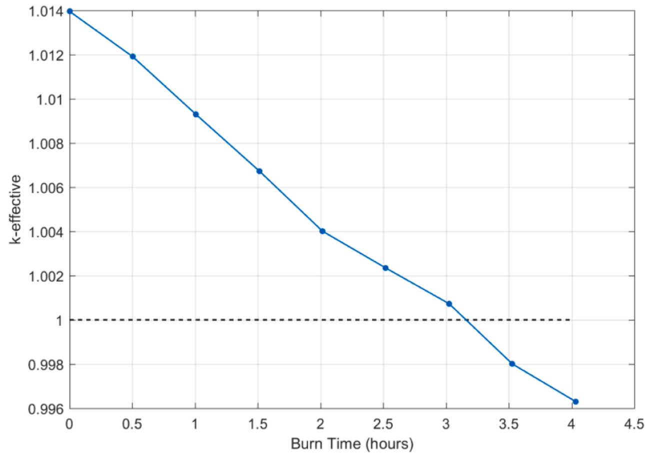


Fig. 5. Decrease in 7.5klbf LEU-NTP core k-effective after 4 h of operation.

hydraulic performance parameters of the final 7.5klbf LEU-NTP design with Schnitzler's HEU counterpart. These results confirm that a 7.5klbf LEU-NTP reactor can reach criticality (k-eff of 1.01424), has sufficient control drum worth ($9.08), and meets thermal-hydraulic requirements. In addition, this final 7.5klbf LEU-NTP core has a specific impulse within 3 sec of the initial HEU configuration, and a total mass within 15 kg of the initial HEU configuration. This total mass allows for comparable thrust-to-reactor-weight ratios.

4.6. Final configuration analysis and feasibility

To further validate the feasibility of a 7.5klbf LEU-NTP engine, this work includes analysis on burnup, Xenon equilibrium, and submersion criticality. For a Lunar architecture utilizing a 7.5klbf NTP design, the entire mission could require as little as 30 min of engine operation with each burn lasting less than 15 min (Borowski, 2016). These working conditions are relatively short, even for an NTP engine. For comparison, the average total burn time of a 16klbf NTP engine for a crewed Mars mission is between 2 and 4 h depending on the architecture (Venneri and Kim, 2016). Thus, Fig. 5 shows the decrease in k-effective of the improved 7.5klbf LEU-NTP core for a single burn up to 4 h and verifies that the engine has enough excess reactivity to last through a single Lunar mission. Note that, while 4 h is sufficient for a Lunar mission architecture, the 7.5klbf HEU-NTP design has a total excess reactivity 2,000pcm larger than the LEU-NTP counterpart. This means that the HEU-NTP equivalent should have a significantly longer burnup time and thus be more applicable for longer-length missions.

Similarly, due to the short operating time of the reactor, Xenon buildup is not a concern during each individual burn. In fact, over the course of the 4-hour continuous burn shown above Xenon has a negligible effect on the k-effective. This was verified by setting the fission product concentration cut-off at zero, running the burnup sequence for the four hours, and then comparing the final k-effectives with and without fission products.

Finally, water submersion analysis is crucial for proving reactor safety. This test ensures that, should the reactor unexpectedly re-enter and fall into the ocean, under no circumstances will the core reach critical. This is reflected in the model by bringing the entire core below room temperature and filling the coolant channels, gaps between components, and core surroundings with water. Unfortunately, similar to most initial LEU-NTP designs, surrounding the reactor with cold water does bring the current core configuration supercritical, up to a k-effective value of over 1.22. Submersion criticality prevention remains an area of study for LEU-NTP reactor cores and is more extensively investigated in other publications (Venneri and Kim, 2016). While this concern does not negate the previous findings, and Schnitzler did not perform submersion analysis on his 7.5klbf HEU-NTP designs for comparison, a realistic LEU-NTP core design would need to resolve this issue. Therefore, resolving this issue with submersion criticality is left to future work; this current configuration is close, but still not quite entirely feasible in that it will not meet the water submersion requirement.

Additional future work includes performing multi-factor design of experiments (DOE). The OFAT approach was sufficient for getting an LEU design that would be close to and meet the same performance requirements as the HEU design. However, for better optimization of the LEU design, using a multi-factor approach would be more effective. Using this multi-factor approach would generate a response surface and allow for scaling to be determined. The farthest extension of this work would be to determine the exact transition point to where using an LEU design is more massive than using an HEU design, for the same engine performance. This work suggests that this transition point is somewhere below 7.5 klbf, but future work would determine this exact transition point. Similarly, analysis could be performed to identify the smallest possible LEU-NTP reactor size, regardless of thrust-to-weight comparability.

5. Conclusion

In conclusion, NTP is the only technologically feasible solution for near-term crewed missions to Mars. It offers superior trip times, abort capability, reduced system masses, and increased performance. Traditional NTP designs, such as the SNRE, have used HEU, but there has been increasing interest in converting these HEU designs to LEU for the reduced regulatory burdens and security considerations an LEU design offers. LEU designs have been proven feasible for flight reactors (16–25 klbf) and upper-stage transfer vehicle reactors (>35 klbf) but have not been proven feasible for technology demonstration size reactors (<16 klbf). This work shows that, for a technology demonstration reactor rated for 7.5 klbf, the LEU design does not markedly differ in terms of performance (specific impulse of 914 sec for the HEU design, 911 sec for the LEU design) or mass (1468 kg for HEU-NTP, 1469 kg for LEU-NTP). These data indicate that LEU-NTP is feasible even in low-thrust regimes. To get this LEU-NTP design, the initial effort applied conventional design techniques in the active core region (increasing moderator effectiveness by increasing moderator thickness and H ratio in ZrH) but found these to be insufficient. Therefore, the design required changes to the outside the active core region as well (reduce the number of control drums from 12 to 6). Thus, in addition to furnishing the feasibility of LEU-NTP, this work suggests that converting an existing HEU design to LEU at lower thrust levels requires additional design changes outside the active core region. However, these analyses do not produce a design that passes the submersion criticality test, is not optimized (using a multi-factor design approach), and does not stipulate the exact transition point where HEU-NTP is less massive than LEU NTP for the same performance levels. These are left to future work. Nevertheless, employing these design changes on smaller-scale designs make technology demonstration mission of LEU-NTP more feasible, reducing the technical risk for NTP and bringing Mars colonization closer within the grasp of humanity.

CRediT authorship contribution statement

Samantha B. Rawlins: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **L. Dale Thomas:** Resources, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Samantha Rawlins reports financial support was provided by the Korea

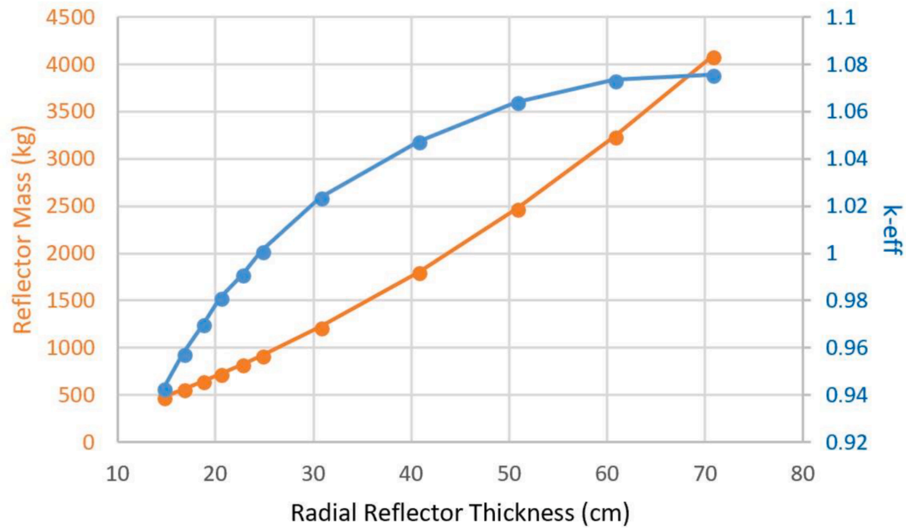


Fig. A1. Reactor k-effective as a function of reflector thickness.

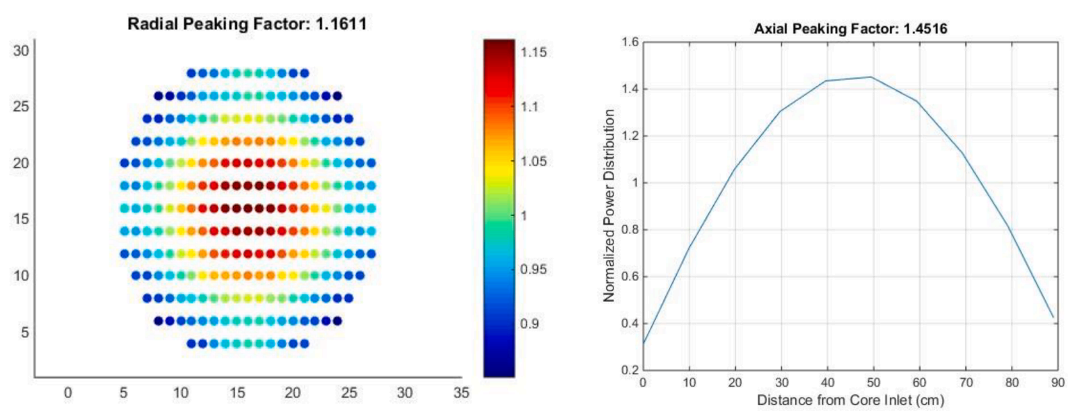


Fig. A2. Radial and axial peaking factor of the 7.5klbf LEU core with flipped fuel and moderator element positions.

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Appendix A

The following parameters were also investigated as a part of the OFAT method but did not contribute to the final 7.5klbf LEU-NTP design.

Radial reflector thickness

Increasing the radial reflector thickness significantly improves the neutron leakage rate, but at a cost to total reactor mass. As such, the sensitivity analysis shown in Fig. A1 demonstrates the relationship between reflector diameter, mass, and total k-effective.

Though reaching criticality purely through reflector growth is

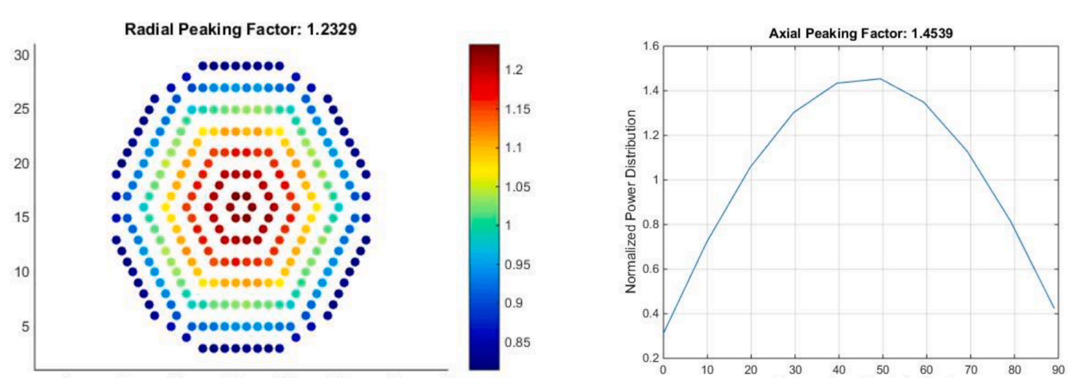

Fig. A3. Radial and axial Power Profile of the 7.5klbf LEU Core with a Ringed Configuration.

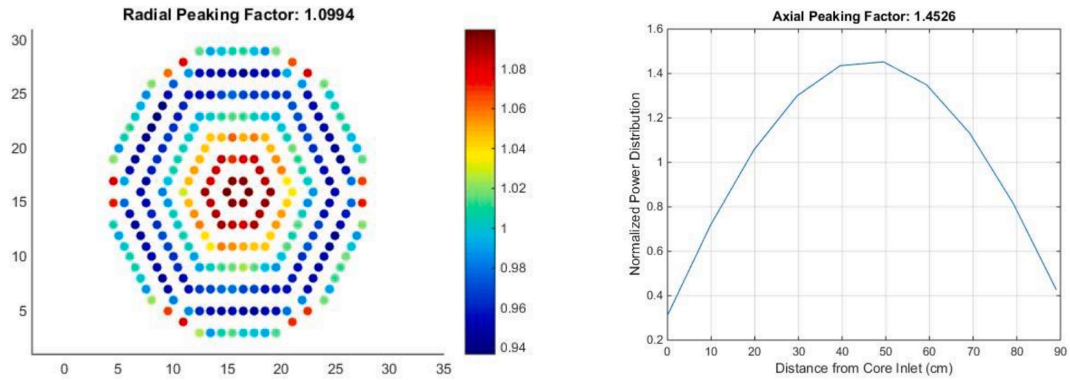

Fig. A4. Radial and Axial Power Profile for the core with $ZrH_{2.0}$ filler elements.

theoretically possible, the required mass gain and total engine size makes such a design infeasible. Still an increase in reflector thickness from 14.732 cm to 20.447 cm, such that the entire engine diameter matches that of the original SNRE's only increases the reflector's mass by ~240 kg while increasing the core's k-eff by ~4000pcm. Thus, while not ideal, should an increase in reflector thickness be necessary to reach criticality, minor adjustments would be acceptable. Additional analysis will also need to be performed on the required shielding thickness, which, due to the LEU conversion, can likely be reduced a considerable amount, thereby balancing an increase in reflector mass.

Element configuration

Once again, one of the most reliable ways to improve the criticality of a core is to increase its moderation. Schnitzler accomplished this by adjusting the amount of zirconium hydride in each tie tube element and modifying the fuel to moderator element ratio from 2:1 to 1:1. Other, larger, LEU-NTP designs have followed in this trend and successfully increased the ratio to 1:2. However, Schnitzler estimated that a minimum of 260 fuel elements would be required for a 7.5klbf HEU core to reach criticality, and the current LEU design is already at this limit. While this number was an approximation, attempting to increase even slightly the ratio by switching the positions of the fuel and moderator elements in the core, such that there were 251 fuel elements and 260 moderators, only decreased the criticality (Fig. A2).

Still, the radial and axial reflector sensitivity analyses showed that it was possible to increase further the total number of fissions in the core. As such, it was hypothesized that changing the core's pattern distribution from Schnitzler's lines to a ringed configuration may assist in flattening the power profile (Fig. A3). This ringed configuration consisted of 270 fuel elements and 241 moderator elements.

Interestingly, the ringed pattern only exaggerated the radial power profile. This result is likely due to each ring of moderating material scattering the neutrons back towards the center of the core rather than outwards. Still, the change did produce a slight increase in k-effective despite the reduction in moderator elements, meaning that another, similar, configuration could have a larger impact.

Periphery material

A fourth hypothesis for flattening the power profiles was changing the material of the beryllium filler elements that round out the active core. Switching from a highly reflective material to a highly moderating material, such as zirconium hydride, could assist in slowing down any neutrons that do escape to the reflector region so that when they return to the active core they are more likely to fission. Fortunately, this modification had the predicted effect of flattening the radial power profile, but the total increase in k-effective was less than 200pcm (Fig. A4).

Nevertheless, such a change may not be reasonable. Zirconium hydride, as discussed in Section 4.1.1, is a very brittle material with a relatively low melting temperature. Further analysis would need to be performed on the exact structural significance and expected temperatures in the peripheral region, but current intuition suggests that a different material will need to be used or the region should remain beryllium filled.

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