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Consideration of Low Enriched Uranium Space Reactors

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The Federal Government (NASA, DOE) has recently shown interest in low enrichment uranium (LEU) reactors for space power and propulsion through its studies at national laboratories and a contract with private industry. Several non-governmental organizations have strongly encouraged this approach for nuclear non-proliferation and safety reasons. All previous efforts have been with highly enriched uranium (HEU) reactors. This study evaluates and compares the effects of changing from HEU reactors with greater than 90% U-235 to LEU with less than 20% U-235. A simple analytic approach was used, the validity of which has been established by comparison with existing test data for graphite fuel only. This study did not include cermet fuel. Four configurations were analyzed: NERVA NRX, LANL's SNRE, LEU, and generic critical HEU and LEU reactors without a reflector. The nuclear criticality multiplication factor, size, weight and system thermodynamic performance were compared, showing the strong dependence on moderator-to-fuel ratio in the reactor. The conclusions are that LEU reactors can be designed to meet mission requirements of lifetime and operability. It will be larger and heavier by about 4000 lbs than a highly enriched uranium reactor to meet the same requirements. Mission planners should determine the penalty of the added weight on payload. The amount of U-235 in an HEU core is not significantly greater in an LEU design with equal nuclear requirements. The politics of nuclear non-proliferation and safety will determine the final decision.

I. Nomenclature

B^2 = buckling, first eigenvalue of the nuclear criticality wave equation, cm^{-2}
D = core diameter, cm
D_f = fast neutron diffusion coefficient, cm
k_{eff} = effective criticality coefficient, dimensionless
k_{inf} = criticality coefficient for infinite dimension reactor (no neutron leakage), dimensionless
L = core length, cm
M/F = moderator-to-fuel atom number density ratio, dimensionless
N_d = core atom number density, moderator + fuel, atoms/cm^3
R = radius, cm
V = minimum core critical volume, cm^3
z = core length-to-diameter ratio, L/D, dimensionless
σ_a = microscopic neutron absorption cross section, barn x 10^{-24} cm^2
τ = core age, cm^2

II. Introduction

Low enriched uranium (LEU) reactors, for use in thermal propulsion or electric power applications, have not been given serious consideration in the past. LEU is defined as having less than or equal to 20% uranium 235 (U-235) in the uranium fuel. Previous space reactors, whether in orbit (SNAP-10A) or being developed for space application (e.g. NERVA E-1, SP-100, PBR) were all highly enriched uranium (HEU) reactors, having U-235 concentration in excess of 90%. Recently, LEU reactors have been endorsed by several non-governmental organizations for non-proliferation and nuclear safety reasons. The Federal Government (NASA, DOE) is funding a program to BWXT Nuclear Energy for evaluating LEU reactors for space applications [Ref. 1], concentrating on nuclear fuel in the form of "Cermet" (ceramic metallic) rods, not graphite. The object of this paper is to evaluate and compare size and weight of LEU and HEU reactors in a fundamentally and relatively simple analytic manner for graphite-based fuel only. No cermet fuel analysis is included.

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Investigations of nuclear reactors for propulsion began as early as 1948, with designs for submarines, aircraft, rockets, ram jets , and even train locomotives. In 1955, Project Rover began the study of nuclear rockets for space and ICBM propulsion, the work being done primarily at Los Alamos Scientific Laboratory (LASL), now Los Alamos National Laboratory (LANL). Other studies on nuclear related space activities took place at a plethora of vendors. The number of industrial contractors was voluminous, and interest high. Over the past 70 years, similar programs for nuclear space propulsion and power have been started, cancelled, and restarted nearly every decade. Today the number of interested vendors is miniscule by comparison. The prior industrial base and its personnel have all but disappeared.

Reactor excess reactivity requirement is set by reactor/engine thrusting lifetime and control requirements. Thus for any mission, system weight comparisons should be made for systems with the same reactivity. For this same mission requirement and a similar bill of materials, an LEU reactor will have a larger critical volume than an HEU reactor because enriched fuel has a higher probability of fissioning than LEU in a similar configuration. A larger volume means a larger, heavier reactor and thus a larger, heavier nuclear propulsion engine. A secondary effect of a larger reactor diameter is that it would require a shadow radiation shield that is larger than an HEU reactor for the same power.

To study the reactivity, weight, size, and performance of LEU and HEU reactors, several computer codes, previously written by the author for NERVA style reactors, were adapted to the Small Nuclear Rocket Engine (SNRE), designed by LASL near the end of the Rover/NERVA program. These codes were written in QBASIC (upgraded to a 64 bit compiler). The nuclear code addressed primarily reactor criticality and power distribution as a function of materials, fuel element loading, and size. The reactor and rocket system thermodynamic performance and weight were evaluated by a code which duplicated those characteristics of the NERVA E-1 proposed flight engine. Studies (Ref. [2-4]) of a similar nature were recently completed and are used as a basis for comparison.

III. Nuclear Considerations

A. Code Validation

Six coupled partial differential equations were derived and solved for three-region (center island, core, reflector), two-group (fast, thermal) reactor, using Fermi age neutron diffusion theory, closely following the method of Ref. [5]. It was modified to include a fast fission term directly. The two-group three-region (2G3R) code was originally designed to analyze a flux trap reactor with the island being a moderator (e.g. beryllium), to reduce significantly the critical mass. The accuracy of the code was checked by comparison with NRX-A2 (NERVA Reactor Experiment A-2) data, and by comparison with an established nuclear code (ANISN) for flux trap calculations.

Nuclear properties (cross section, diffusion coefficient, age, etc.) and physical properties (density, thermal expansion, etc.) for ambient conditions were taken from various standard source textbooks and handbooks for fast and thermal neutron groups. A two-region model of a cold, clean NRX was used to calculate the radial fission distribution, which compared favorably with the PAX critical facility measured distribution. HEU loading was adjusted to give a carbon/uranium (C/U) atom ratio of 116 for the 1610.5 elements of NRX. Calculated core average reactivity coefficients (0.0071 reactivity units/$) for C, U, niobium (Nb) and tantalum (Ta) again compared very favorably with measured data. The calculated average core hydrogen reactivity coefficient is $6.4/kg (hot) versus $6.1 measured in PAX (cold).

After including 90 kg NbC anti-corrosion coating and 8.8 kg TaC shim rods, the resultant multiplication factor was 1.001 (control drums simulated at 90 degrees). Cold-to-hot reactivity changes were programmed to account for addition of hydrogen coolant and temperature change from ambient to hot operating conditions. Dimensional changes of core expansion and reflector contraction were used in criticality equations. Fast cross sections were not adjusted for temperature effects. Thermal neutron absorption cross sections were adjusted by the square root of the ambient-to-operating absolute temperature ratio. Transport and slowing down cross sections were corrected by the temperature ratio raised to the 0.055 power in order to agree with the observed temperature effects in the NRX-A2 hot tests. Age was also corrected for the higher thermal energy cutoff. Cumulative cold-to-hot changes were -$0.527 calculated versus -$0.439 measured in NRX-A2.

A final comparison of 2G3R calculations was made with 12 data points from the established ANISN nuclear code calculation for a flux trap model of an NRX type reactor, having a beryllium island, an annular core with NERVA type fuel elements, and beryllium reflector. This advanced design was proposed as a method for not only reducing the size and weight of the reactor, but also significantly reducing the amount of HEU. For 250 to 750 fuel elements, various island and reflector radius combinations, the average absolute deviation of the 2G3R code in the calculation of k_{eff} was 2.8% in comparison with ANISN.

B. NERVA-NRX with LEU

When public disclosure was made by the Federal Government of interest in LEU reactors for space power and propulsion, the existing 2G3R NRX model, cold and clean, was changed from 93% to 20% U-235 enrichment. For the original fuel loading of 0.382 gm U/cm^3, 1610.5 elements, tie rods (not tie tubes), and reflector, the k_{eff} was reduced from 1.037 to 0.778 by reducing the enrichment and keeping the same total uranium mass, 187.4 kg. Thus, by only lowering the enrichment to that of LEU, the reactor became very sub-critical. To determine what changes are necessary to make the NRX critical with low enrichment, the following study was done.

Using the same characteristic fuel dimensions, the same mass of NbC coolant channel coating and TaC shim rods per fuel element, tie rods, and reflector thickness, a limited three-dimensional parametric study was performed by 1) varying the number of fuel elements (changing core diameter) from 2000 to 14000, 2) changing the core length-to-diameter (L/D) ratio from 0.75 to 2.0, and 3) the loading (amount of uranium per element) from 0.1 to 0.8 gm U/cm^3. Increasing loading did not increase k_{eff}, but increasing the moderator-to-fuel ratio (M/F) by reducing the loading did increase reactivity. For example, Fig. 1 shows that for 0.2 gm U/cm^3 loading, the same criticality as NRX was reached at 8670 fuel elements for L/D = 1, 7230 fuel elements for L/D = 1.25, and 6420 elements for L/D = 1.5. This increases the core weight by as much as 5.4 times heavier. These configurations have 155 to 163 kg U-235, or about 85% of the U-235 in NRX, an insignificant reduction. If a smaller LEU NRX-type reactor is required, the conclusion is that different moderator and/or a significant increase in the moderator-to-fuel ratio is needed to increase the k_{eff}.

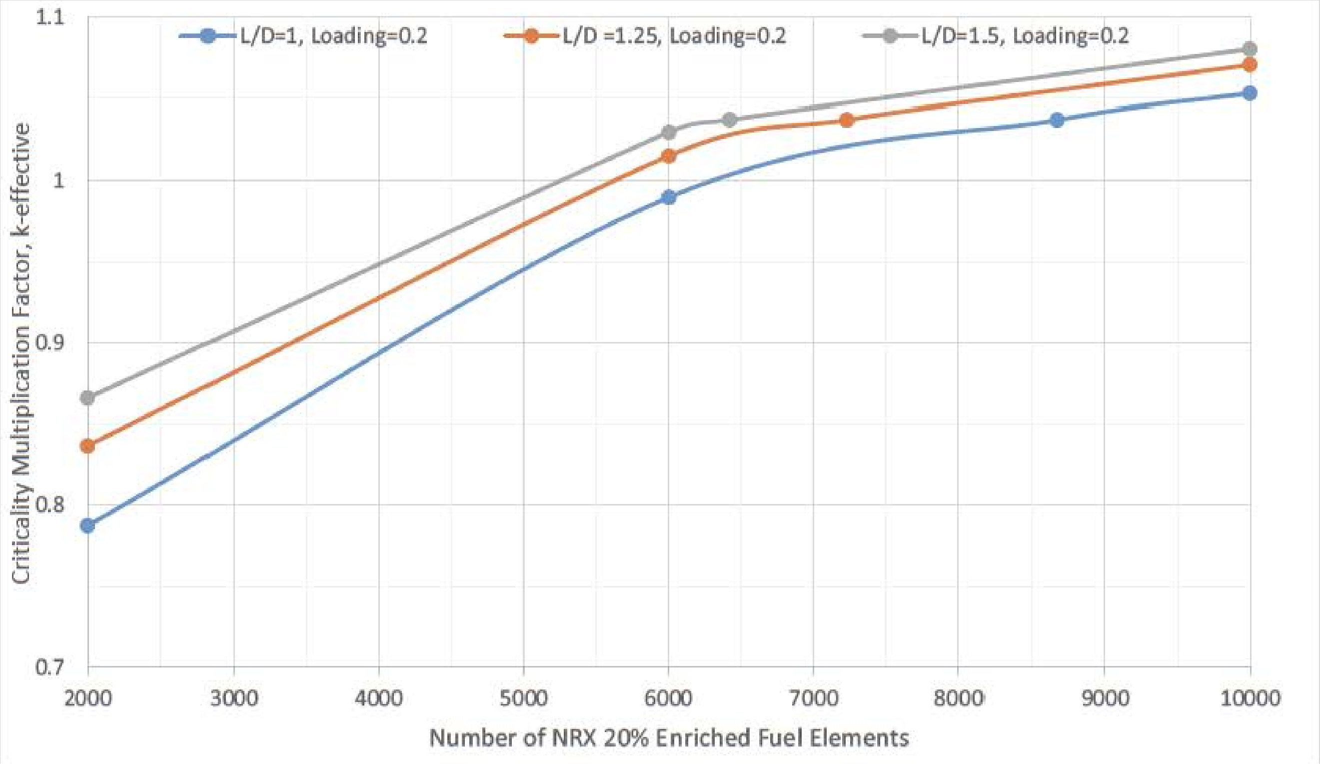

Fig. 1 Criticality Factor (k_{eff}) using 20% Enriched NRX Fuel Elements.

C. HEU Model Analysis (SNRE and C-HEU)

Ref. [4] proposes two different core configurations for the composite HEU and LEU reactors, labeled C-HEU and C-LEU. The C-HEU design is essentially the same as the SNRE, while the C-LEU has decreased the ratio of the fuel elements to the tie tube elements, thus increasing the M/F ratio for the low enrichment design. The fuel elements and the tie tube elements are the same design, differing only in the number of each.

For the SNRE (C-HEU), using the same neutron diffusion code as above, the dimensions and nuclear data were updated to the 93% enriched original LASL design. The baseline dimensions and materials data, as given in Table 1, were taken from Ref. [3]. The fuel form is the uranium-zirconium-carbon (U,ZrC) composite developed by LASL late in the Rover program. It is 35 volume per cent (v/o) composite. The melting point of the chosen fuel (Ref. [2]) is 2900 K (5220 R). From a quasi-binary phase diagram at 2900 K, the atomic composition is 35 a/o U, 17.5 a/o Zr, and 47.5

a/o C. The remaining volume of the fuel is carbon (graphite). The calculated nuclear cross sections and masses were based on fuel loading of 0.6 gm U/cm^3 and not the atom percentages at melting temperature. The calculated primary constituent masses in the core were: uranium - 67.1 kg, zirconium carbide (ZrC) - 149.0 kg, zirconium hydride ($ZrH_{1.8}$) - 103.6 kg, Inconel - 35.1 kg, and carbon - 227.8 kg. U-235 mass of 62 kg compared favorably with 60 kg of Ref. [1]. The resultant cold core diameter is 57.36 cm and 89 cm core length (L/D = 1.55).

The cold, clean criticality calculation resulted in a k_{eff} of 1.059, remarkably close to that of SNRE (1.058, Ref. [3]). A calculation of hot critical was made using the same average temperatures of NERVA (slightly lower than SNRE), and the same hydrogen coolant mass distribution. Temperature-based corrections were made to nuclear cross sections, age, core expansion, and the addition of hydrogen. The resultant k_{eff} was 1.052.

Table 1 Baseline Fuel Element and Tie Tube Characteristics.

Fuel element length, cm	89
Number of fuel elements	564
Distance across flats, cm	1.915
Coolant channels per element	19
Reamed channel diameter, cm	0.2565
ZrC channel coating, cm	0.01
ZrC element exterior coating, cm	0.005
Fuel element loading, gm U/cm^3	0.60
Number of tie tubes	241
Tie tube ID (Inconel), cm	0.4191
Tie tube OD, cm	0.5207
$ZrH_{1.8}$ sleeve OD, cm	1.1694
Tie tube liner ID (Inconel), cm	1.3559
Tie tube liner OD, cm	1.4102

Two variations of the base SNRE style design were further examined to enable direct comparison with C-LEU. Table 1 of Ref. [4] contains characteristics of composite fuel LEU and HEU designs (labeled C-HEU and C-LEU). The cermet fuel reactors of Ref. [4] are not included herein. The C-HEU reactor is dimensionally very similar to the SNRE. The C-LEU (19.75% enriched) design contains 348 fuel elements and 325 tie tube elements. As in SNRE, the tie tube elements contain $ZrH_{1.8}$, which effectively increases the M/F ratio. The first variation of C-HEU changed the number of fuel and tie tube elements in the original SNRE model to that of C-LEU, retaining the same mass of ZrC, $ZrH_{1.8}$, and Inconel per element. This core configuration change decreased k_{eff} to 1.037 from the SNRE of 1.059, showing the combined effect of increasing the M/F ratio while decreasing the number of fuel elements. This change decreases the U-235 mass to 36 kg from 62 kg. The core diameter also decreased by 5 cm.

The second variation examined the effect of core length on criticality. In a later section labeled "Back to Basics", the theoretical optimal L/D ratio is 0.9237 for the minimum critical volume core of a bare circular cylinder having a k_{eff} of exactly 1.000. Using the original SNRE number of fuel and tie tube elements, the core length was reduced to 53 cm from 89 cm. The resultant k_{eff} decreased from 1.059 to 0.983 for the theoretical optimal L/D ratio, showing the effect of the absence of a reflector on reactivity. The total uranium mass decreased to 40 kg. On the negative side, this shorter core has higher heat flux for the same reactor power and thus has higher material temperatures, as shown later in the section on system performance. Further optimization of the SNRE design to reduce overall weight and U-235 mass may be achieved with various tradeoffs.

D. LEU Model Analysis

The configuration of the LEU model is taken from Ref. [4], labeled C-LEU. It has 348 19.75% enriched fuel elements and 325 tie tube elements with a core radius of 2.3 cm less than SNRE. The fuel loading was increased slightly to 0.64 gm U/cm^3 and the composite fuel was increased to 50 v/o from 35 v/o. The calculated uranium mass is 45 kg with 9 kg U-235. The remaining constituent material masses are: ZrC - 220 kg, $ZrH_{1.8}$ - 140 kg, Inconel - 47 kg, and carbon - 155 kg. Core diameter is 52.2 cm. Neutron cross sections for the LEU composite fuel were recalculated. Neutronically, the biggest differences between the C-HEU and C-LEU designs of Ref. [4] are the increase in the M/F number density ratio (mainly the addition of $ZrH_{1.8}$) of 19% and the reduction in enrichment. The calculated cold, clean k_{eff} was only 0.987, as compared to the 1.059 for the SNRE. The hot k_{eff} is 0.956. Ref. [4] states only that k_{eff} is desired to be greater than 0.99 for a suitable design. No absolute value is given for comparison.

Since the calculated value of criticality was less than 1.0, three variations were examined to increase k_{eff}. Doubling the number of fuel elements and tie tubes increased k_{eff} to 1.020, critical but still not the equivalent of C-HEU, despite the increase in core diameter to 73.8 cm with a corresponding increase in core weight. Tripling the number of fuel elements to 1044 and tie tube elements to 975 resulted in a k_{eff} of 1.034, nearly the equivalent of the C-HEU at one third the core size. The U-235 mass is 26 kg with a core diameter of 90.4 cm. This is only 10 kg less than the modified C-HEU design with a much smaller core. The last variation reduced the core length, keeping the original number of elements. At the theoretical optimal L/D of 0.9237 (without reflector), the k_{eff} decreased further to 0.907 from 0.983.

E. Back to Basics

In order to compare HEU and LEU sizes in a more fundamental way, a bare right circular cylinder without reflector was chosen. The objective was to calculate and compare the critical mass and radius (defined as $k_{eff} \equiv 1$) for the same moderator-to-fuel ratios as above. Starting with the buckling equation for criticality from Ref. [5],

$$B^2 = (2.405/R)^2 + (\pi/L)^2$$

the corresponding minimum critical volume,

$$V = \pi R^2 L = 148.24/B^3$$

letting $z = L/D$, and substituting into the above two equations, the solution for z is 0.9237. This reduces the buckling equation to $B^2 = 8.676/R^2$ for minimum critical volume as a function of the core radius.

The equation for criticality from Ref. [5] is

$$k_{inf}\exp(-B^2\tau) = 1 + D_f B^2/N_d\sigma_a$$

The principal difference in the calculation of k_{inf} for HEU and LEU is in the resonance escape probability. The absorption cross section as a function of neutron velocity for U-238 has multiple peaks resulting in a higher probability for non-fission absorption than for U-235. For the M/F ratio of SNRE (78.8), the resonance escape probability is 0.848 for 93% enriched. If C-LEU has this same M/F ratio, the resonance escape probability is only 0.504 (19.75% enriched). For the M/F ratio of C-LEU (93.2), the resonance escape probability is 0.909 for 93% enriched C-HEU and 0.672 for 19.75% enriched C-LEU.

Using these equations for a bare circular cylinder (no reflector) with $k_{eff} \equiv 1$, the two designs (C-HEU and C-LEU) from Ref. [4] were investigated for both number density M/F ratio combinations. With the atomic/molecular number densities of the designs, critical length and critical mass were calculated as a function of critical core radius. These are shown in Fig. 2 and Fig. 3, respectively. For the same core length, the critical radius of the 93% enriched core is always smaller than the 19.75% enriched core. Similarly, the U-235 mass in the HEU reactor is also always equal to or smaller, regardless of the M/F number density.

For comparison purposes, consider the inflection point in the Fig. 3, which is the minimum volume core of all minimums, and thus the lowest weight. This point on each curve has an L/D of 0.9237. If both C-HEU and C-LEU have the same M/F ratio as the original SNRE of 78,8, the U-235 masses are 32.5 and 118 kg, respectively. The core diameters are 57.4 and 140.8 cm. If both C-HEU and C-LEU have the M/F ratio (93.2) as the C-LEU of Ref. [4], the U-235 masses are 12.6 and 12.5 kg, respectively. The core diameters are 43.4 and 72.2 cm. These four examples of U-235 mass and core size each have exactly $k_{eff} \equiv 1$without a reflector.

For all things being equal, this basic calculation of criticality conclusively shows that the U-235 masses of the HEU design are less than or not significantly greater than LEU, but that the LEU design is significantly larger and heavier than a comparable HEU design. It also suggests that further optimization of the M/F ratio may reduce U-235 mass and size of both designs.

F. Enrichment

The U.S. advanced gas centrifuge program is designed for a cascade of 11,500 unit centrifuges with a production capacity of 3.8 million separative work units (SWU). A QBASIC program was written to conform to these basic requirements, with physical sizes estimated from published architectural sketches. The plant output is full enrichment of 93% and tails of 0.3% U-235. Within the cascade, there are 63 stages (6934 units) in the enriching section, a feed stage (819 units), and 7 stages (3747 units) in the stripping section.

Within the enriching section, the 20% enrichment is reached in the 35th stage after processing through 6550 units. To reach 93% from 20%, only 384 unit centrifuges are necessary from the 35th to the 1st stage. From a nuclear non-proliferation standpoint, if one has the capability to produce 20% enrichment, it is a relatively simple addition to enlarge to plant production to 93%. Thus, the 20% enrichment limit is a weak argument for approving of 20% enrichment and prohibiting 93%.

Limiting the enrichment of space reactors to 20% is not the panacea it may seem. It has been speculated by the media (and probably calculated) that 250 kg of 20% can be weaponized, albeit an inefficient low yield one. Again, this minimizes the apparent non-proliferation/safety gain that one might achieve by switching to low enriched uranium for use in space reactors.

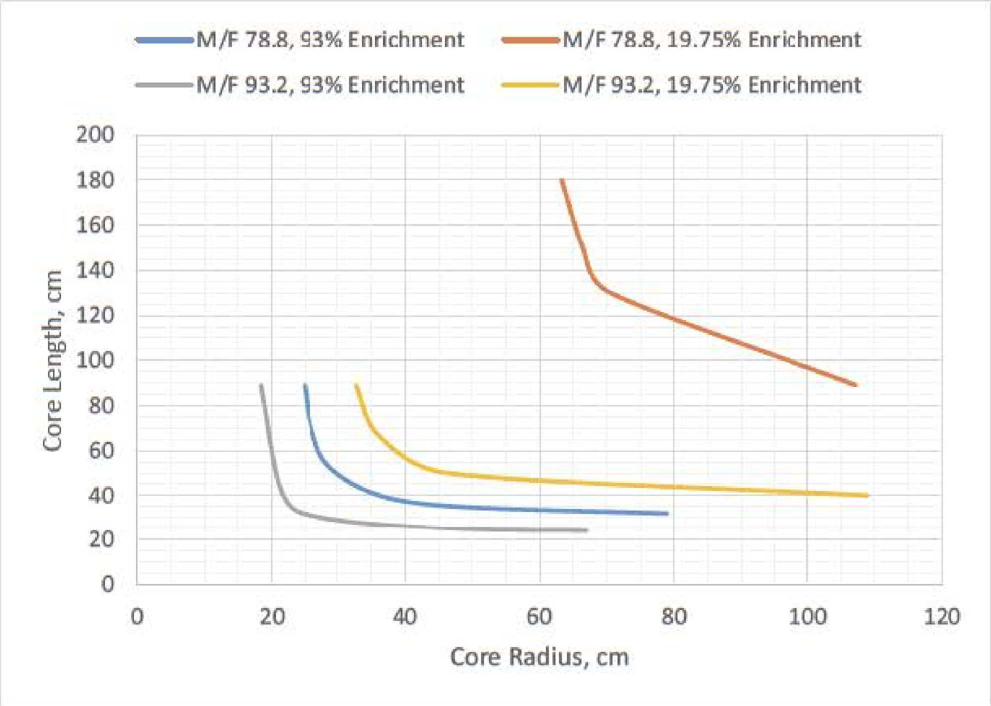

Fig. 2 Core Length as a function of Core Radius for $k_{eff} = 1$.

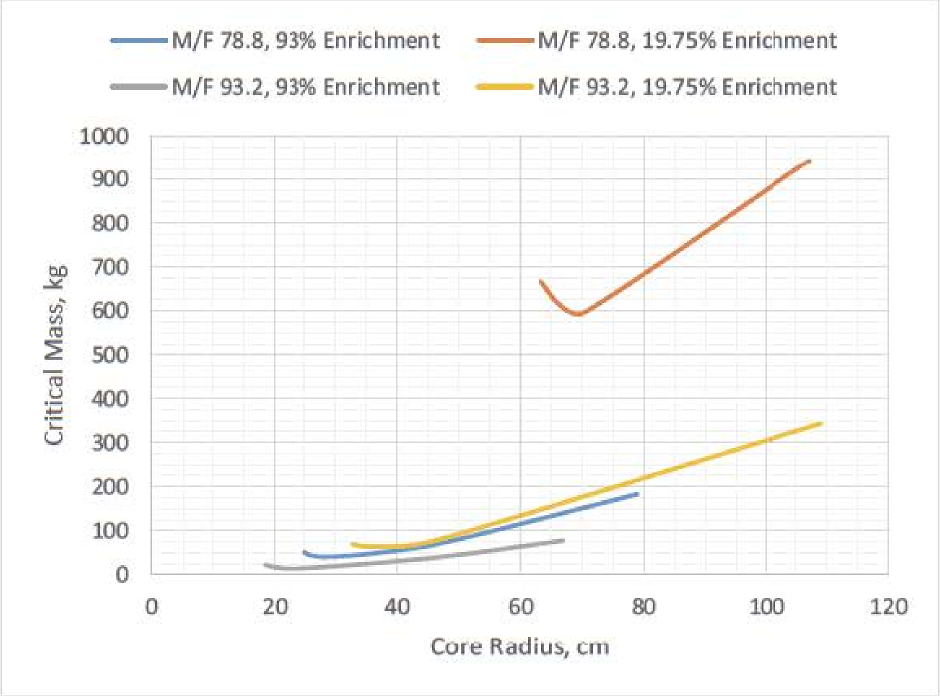

Fig. 3 Critical Mass as a function of Core Radius for $k_{eff} = 1$.

G. Nuclear Conclusions

A comparison summary of the results of the nuclear calculations is given in Table 2 and is discussed in the following paragraphs.

The direct use of the NERVA NRX reactors with 20% enriched fuel is not feasible. The k_{eff} is reduced to 0.778. To achieve the original NRX k_{eff} of 1.037, the fuel loading must be reduced to 0.2 gm U/cm^3, and the number of fuel elements must be increased from 1610.5 to 6420, adding over 9000 kg weight.

Direct comparisons of data from all previous sections are difficult principally because of different core configurations. For the original SNRE with a core length of 89 cm, core radius of 28.68 cm, and k_{eff} of 1.059, the U-235 mass is 62.4 kg. This high k_{eff} may be necessary for long operating times. The Jupiter Icy Moons Orbiter (JIMO) had a 10-year transit time using 100 kW electric thrusters. The closed Brayton cycle power system design of Ref. [6] has a clean cold reactivity requirement of 1.068 for this mission. For lesser missions, a lower k_{eff} is acceptable, but design comparisons can only be made for reactors with the same mission reactivity requirement.

The original SNRE design with k_{eff} of 1.059 (labeled C-HEU in Ref. [4]) is under-moderated and cannot be directly compared with the C-LEU design with $k_{eff} = 0.987$. By changing SNRE to the same core design as C-LEU, its k_{eff} is reduced to 1.037. To increase the k_{eff} of C-LEU to this value, the core size must be increased by a factor of three, adding 1386 kg to the core mass. The U-235 masses are 36 and 26, respectively, not a significant difference.

The theoretical minimum volumes of bare cylindrical reactors without reflectors were examined for two M/F ratios, that of the original SNRE and the C-LEU of Ref. [4]. It shows conclusively that in all cases, the HEU design is significantly smaller in core diameter and is less than or insignificantly larger in the mass of U-235.

It is believed that the objective of considering low enriched uranium reactors for space power and propulsion is to reduce the amount of U-235 used in the design. This can always be achieved, as shown above, but at the cost of additional weight and size. On the basis of the amount of U-235, there does not appear to be a significant difference between the two designs from the standpoint of nuclear non-proliferation and safety. It is for the mission planners to say how much additional weight of the LEU reactor can be tolerated for the same mission. The ratio of the lost-payload-to-increased-reactor weight must be calculated to determine to penalty to the mission.

IV. System Performance Considerations

The objective of this section is to evaluate and compare the system performance (thermodynamic and weight) of both the SNRE (C-HEU) and C-LEU rocket engine systems. For an exact comparison of the same mission, the two designs should have the same neutronic performance, that is, the same k_{eff}. Of the several variations studied in the HEU and LEU sections, none had the same neutronics. The closest comparison is between the HEU with k_{eff} of 1.037 and the LEU with k_{eff} of 1.034. The physical differences between the two are given in the next section.

The computer code used in these evaluations was developed in the post-NERVA period for further system studies. It is also written for the QBASIC 64 bit compiler, and techniques verified by comparison with NRX full-scale test data and the NERVA E-1 proposed flight engine. The in-vessel radiation shadow shield was removed from the model to be consistent with Ref. [4].

A. System Description

The system flow schematic, shown in Fig. 4 and taken from Ref. [3], was modified by the addition of two valves which allow for variable tie tube flow during operation (reactivity control by stored hydrogen mass in tie tubes), with a constant nozzle bypass flow fraction. The flow diagram is a typical full-flow (also called expander or topping) cycle because the turbine is in-line, using power added to the tie tubes, nozzle and reflector components before entering the reactor core. The flow leaving the pump is split 65/35, nozzle/tie tubes. The 35% to the tie tubes is further split for reactivity flow control. Calculations of fluid state points were made for 90% of the total tie tube flow. Pump and turbine assumed efficiencies are 0.8 and 0.85, respectively. Nozzle area expansion ratio is 100, with exit plane Mach number of 6.2 at the chamber temperature of 4851 R (2695 K).

Table 2 Nuclear Results Summary.

REACTOR STYLE	DESCRIPTION	CORE LENGTH/ DIAMETER	ENRICHMENT %	No. FUEL ELEMENTS	FUEL LOADING gm U/cm^3	No. TIE TUBES	CORE RADIUS cm	U-235 MASS kg	CORE MASS kg	ENGINE MASS kg	k-effective
NERVA	NRX	1.5	93	1610.5	0.382	Tie Rods	43.8	174	1391	NA	1.037
	NRX	1.5	20	1610.5	0.382	Tie Rods	43.8	37.5	1391	NA	0.778
	NRX	1.5	20	6420	0.2	Tie Rods	87.5	156	10793	NA	1.037
	NRX	1.25	20	7230	0.2	Tie Rods	92.9	155	10749	NA	1.037
	NRX	1.0	20	8670	0.2	Tie Rods	101.7	163	11292	NA	1.037
SNRE	SNRE	1.55	93	564	0.6	241	28.5	62.4	678	1951	1.059
	C-HEU	1.76	93	348	0.6	325	26.1	36	693	2087	1.037
	SNRE	0.9237	93	564	0.6	241	28.5	37.1	401	1652	0.983
LEU	C-LEU	1.76	19.75	348	0.64	325	26.1	8.8	604	1897	0.987
	C-LEU	1.19	19.75	696	0.64	650	36.9	17.7	1209	2668	1.02
	C-LEU	0.975	19.75	1044	0.64	975	45.2	26.2	2079	3858	1.034
	C-LEU	0.9237	19.75	348	0.64	325	26.1	4.8	328	1557	0.907
BARE CYL.	MIN. VOL.	0.9237	93	N/A	N/A	N/A	28.7	32.5	N/A	N/A	1
	MIN. VOL.	0.9237	19.75	N/A	N/A	N/A	70.4	118	N/A	N/A	1
	MIN. VOL.	0.9237	93	N/A	N/A	N/A	21.7	12.6	N/A	N/A	1
	MIN. VOL.	0.9237	19.75	N/A	N/A	N/A	36.1	12.5	N/A	N/A	1

B. System Fluid State Points

Two nearly equivalent neutronic systems were evaluated, both different from Ref. [4]. The HEU configuration used the same number of fuel and tie tube elements as the original C-LEU system, 348 and 325, respectively. The LEU configuration tripled the number of fuel and tie tube elements, so that the two systems have nearly the same k_{eff}. The chamber temperature and pressure are 4851 R (2695 K) and 450 psia (3.1 MPa), the same as the SNRE. Reactor power is 356 MW, compared to 343 MW from Ref. [4]. Total flow rate is 18.3 lbm/s (8.3 kg/s), compared to 17.9 lbm/s (8.1 kg/s) for Ref. [4]. The specified thrust is 16406 lbf (72.2 kN) and a calculated specific impulse of 898 s. These are the same for both configurations.

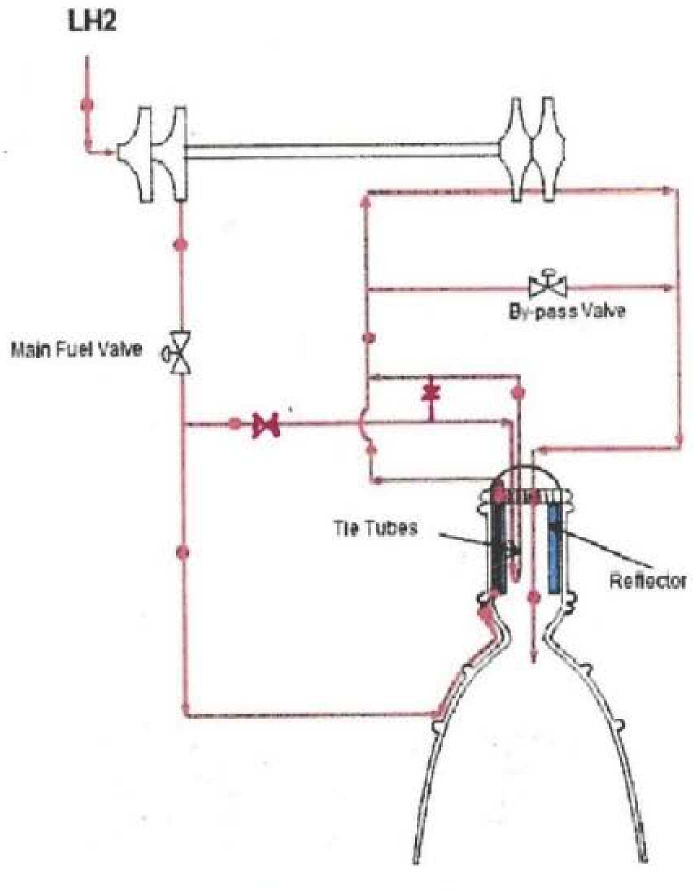

Fig. 4 System Flow Schematic.

Table 3 contains the fluid state points for the C-HEU system of 348 fuel elements and 325 tie tube elements, with a core diameter of 20.5 in. It also has the calculated tie tube fluid and Inconel liner surface temperature axial distribution. The average maximum fuel temperature is 4959 R (2755 K). Power density based on total core volume is 1.78 MW/L.

The C-LEU system state points are the same as C-HEU, except for pressure. Because it has triple the number of core elements for nearly neutronic parity with the C-HEU system, the core diameter is 35.6 in, operating at one-third the power density. The pressure differences between the two systems state points result from the lower pressure drop in the larger diameter core, as this effect propagates through the system. The pump outlet pressure for this system is reduced to 866 psia form 1144 psia for C-HEU. The maximum average fuel element temperature is reduced by 20 R (11K) because of the larger surface heat transfer area. Both cores were orificed with the same size average orifice. Depending on the radial power distribution in the core, the pressure drop could change considerably.

C. System Weights

The calculated weights of the engine/reactor components for both systems are given in Table 4. The C-LEU engine is 3895 lbm (1770 kg) heavier than the C-HEU engine, principally because it has three times as many fuel and tie tube elements. The weight and size calculations for components like the pressure vessel and support plate are based on structural equations from Ref. [7]. Weight and pressure force calculations were made on the core and reflector. The reflector weight includes the graphite slats necessary to round the core, pyrographite insulation, graphite lateral support, beryllium reflector, and a 0.125 inch thick boron-titanium cylinder on the outer diameter. Both the titanium core support plate and pressure vessel with hemispherical heads were sized based on an allowable yield strength of 50000 psi at 1250 R (687 K). The turbopump and nozzle weights are based on correlations used in Ref. [6].

These weights do not include radiation shielding. At the end of the NERVA program, the E-1 flight design contained an internal radiation shadow shield of lead/boron aluminum-titanium-hydride material, to reduce intensity on the turbopump and propellant heating in the tank (Ref. [8]). Because the C-LEU reactor diameter is 15.1 inches larger, its shield will necessarily be larger.

The remaining question is how much does an extra 3895 lbm cost in terms of reduced mission payload, not counting the additional shield weight. That answer is for mission planners to provide.

Table 3 Fluid State Points for HEU Engine.

	PSIA	DEG R	LBM/S	MW	
Propellant tank out	30	36	18.3		
Pump out	1144	57	18.3	1.6	
Nozzle in	1144	57	11.9		
Reflector in	1102	283	11.9	10.8	
Reflector out	1094	369	11.9	4.2	
Tie Tube in	1102	57	5.8		
Tie tube out	1094	571	5.8	11.8	
Turbine in	1094	420	16.3		
Turbine out	688	397	16.3	-1.6	
Support plate in	655	400	18.3		
Support plate out	649	408	18.3	0.6	
Core in	649	408	18.3		
Core out	450	4851	18.3	340	
Tie Tube X/L	0	0.25	0.5	0.75	1
Downcomer fluid temperature	57	90	114	126	129
Upcomer fluid temperature	571	513	371	217	129
Liner surface temperature	659	977	1019	737	240

Table 4 Engine System Weights.

Component	HEU lbm	LEU lbm
Fuel elements	575	1726
Tie Tube elements	950	2848
Reflector	1161	1782
Support plate	337	471
Pressure vessel	287	512
Turbopump, valves, piping	893	759
Nozzle	389	389
Total Engine	**4592**	**8487**

V. Conclusions

The concise, simple conclusions of this study are:

1) A low enriched uranium reactor with composite fuel can be designed to meet mission requirements of lifetime and operability.
2) The resultant LEU-based engine will be larger and heavier by about 4000 lbm (1818 kg) than an HEU-based engine to meet the same requirements. This weight does not include the added radiation shield weight of the LEU reactor from a larger diameter core. Mission planners will determine the penalty of the added weight on payload.
3) The amount of U-235 in an HEU core will not be significantly greater in an LEU design.
4) The politics of nuclear non-proliferation and safety will determine the final decision.

VI. References

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