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IMPACT OF THE USE OF LOW OR MEDIUM ENRICHED URANIUM ON THE MASSES OF SPACE NUCLEAR REACTOR POWER SYSTEMS

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

DECEMBER 1994

Prepared by the

United States Department of Energy
Office of Nuclear Energy

Foreword

The design process for determining the mass increase for the substitution of low-enriched uranium (LEU) for high-enriched uranium (HEU) in space nuclear reactor systems is an optimization process which must simultaneously consider several variables. This process becomes more complex whenever the reactor core operates on an in-core thermionic power conversion, in which the fissioning of the nuclear fuel is used to directly heat thermionic emitters, with the subsequent elimination of external power conversion equipment.

The increased complexity of the optimization process for this type of system is reflected in the work reported herein, where considerably more information has been developed for the moderated in-core thermionic reactors.

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EXECUTIVE SUMMARY:

At the request of the Presidential Office of Science and Technology Policy (OSTP), a brief study was done by the Department of Energy's Space Reactor Power Systems Division of the impact of using other than highly enriched uranium (HEU) in the design of space nuclear reactor power systems. A presentation of the preliminary results was made to OSTP on February 10, 1994 (Ref. 1). Subsequent to that presentation, more detailed calculations have been performed by contractor personnel to confirm those results. This report outlines the methodology and reports the findings, which support the conclusions of the earlier presentation.

The findings can be generally stated as follows:

- Use of Uranium enriched to significantly less than 93% U-235 (medium-enriched uranium [MEU], defined as approximately 35% U-235, or low-enriched uranium [LEU], defined as <20% U-235), always results in a mass penalty for the reactor core for a given power.

- The amount of the reactor core mass penalty depends on the reactor thermal power, and on whether the reactor operates with a fast or thermal spectrum.

- Payload shielding mass increases because the reactor becomes larger in volume and requires a larger diameter shield for a given spacecraft configuration.

- The total system mass, which is composed of the reactor core, shield, power conversion and radiator masses, will also increase by the same amount (approximately) as the core and shield, assuming that the power conversion system and the radiator heat rejection temperature and heat rate remain the same.

- System re-optimization for minimum system mass for MEU and LEU reactors, particularly for thermionic reactors, generally results in different system operating parameters than for HEU systems.

HISTORICAL BACKGROUND OF HEU USAGE:

The Use of HEU In Space Nuclear Reactors

Since the early 1960s it has been realized that the application of nuclear reactors as space power sources provides the greatest potential for lowest mass energy sources at high power levels. The first U.S. space nuclear reactor system to be designed, built, and launched into earth orbit was the SNAP-10A nuclear power source, a highly-enriched uranium-fueled (93% U-235) reactor which was launched on April 3, 1965. The reactor was coupled to a thermoelectric conversion unit and achieved a nominal 500 We output with a thermal conversion efficiency of ~5%. It operated successfully and as designed until a spacecraft voltage regulator component failed after 43 days of operation; this malfunction resulted in reactor shutdown. Following the shutdown, the nuclear power system and spacecraft were boosted to a high earth orbit, where they remain today.

Russian activity in space nuclear reactor power has been extensive. From December 1967 through March 1988 the Former Soviet Union is known to have launched 37 space nuclear reactors utilizing highly-enriched uranium fuel. Of these, two are believed to have been launch failures and two others have re-entered the earth's atmosphere. The remaining 33 were boosted into higher earth orbits, where they also remain today.

The U.S. and Russian designs have always assumed the use of HEU for space reactor power sources because the energy cost of launching a spacecraft with a given payload is so great that HEU has been a clear fuel of choice for a minimum launch weight configuration.

The Use of HEU in Naval Reactors

Highly-enriched uranium has been chosen for other applications where size and weight are of great importance, e.g., as in Naval submarines and, to a lesser degree, Naval surface vessels. Indeed, the advantages accruing to HEU in this application are so great that Naval reactor fuel has typically utilized enrichments in excess of the usual 93%. This use of HEU (or better) has been true not only for U. S. Naval vessels, but for nuclear reactor powered vessels of foreign navies as well.

The Evolving U. S. Nuclear Non-proliferation Policy

With the formulation of national policies dedicated to non-proliferation of weapons-grade fissile fuel, and the use of low-enriched uranium fuel in U.S. commercial nuclear power reactors and low-powered research reactors, the Executive Branch, through the President's Office of Science and Technology Policy (OSTP), is reviewing the effect of mandating the use of LEU for non-proliferation reasons in U.S. test and research reactors, and in space nuclear reactor power systems. (Civilian power reactors, which have no stringent constraints on reactor size or mass, are typically thermal-spectrum reactors with about 4% enriched uranium fuel).

Accordingly, the OSTP has requested reviews of the effect of replacing the HEU in the design of a proposed new research reactor (the Advanced Neutron Source), and in the design of future U.S. space nuclear reactor power systems. In response to the latter request, a short study has been undertaken by the DOE of the neutronic effects and of the impact on the power system masses which result from using LEU or MEU in nuclear reactors designed for electrical power production in space.

As introduction to this study, it is instructive to understand the enabling role of space nuclear reactors in space missions, and the corollary process of system design and mass minimization which leads to the selection of system parameters for those power systems. An understanding of the optimization process will help to illustrate the effects of replacing the fissile fuel isotopes of U-235 with non-fissile isotopes of U-238.

INTRODUCTION

Space Missions Enabled by Space Nuclear Reactors

Certain classes of space missions can only be enabled by nuclear reactor power systems. They are characterized by:

- o High power requirements, usually above the 10-40 kWe range, for relatively long times (a power requirement characteristic of high-power communication satellites).

- o Power requirements typically above 1-10 kWe which cannot be met by solar power devices, either because the required solar collector panel area is too large for launch vehicle transport or because the insolation is too low (e.g., beyond Mars orbit or in planetary shadow).

Power requirements for below ~1 kWe can typically be met either with radioisotope thermoelectric generators (RTGs) in the case of deep space missions, or with solar panels for orbits nearer the sun. Figure 1 illustrates the approximate (and overlapping) regimes of applicability for reactor, solar, and RTG power systems.

The Design Process

The design of a space nuclear reactor power system is a complex process which must consider several competing effects in the evolution of a system with minimum weight to meet mission requirements for power, lifetime, and safety. It is possible, in a very general way, to generate curves of specific weight vs. power level (kg/kWe vs. kWe) when approximate analytical expressions can be derived for the system components and to then choose the mimimum point of the summed curves for the composite system design. An alternative, and more exact, way for any given design is to generate a series of individually mass-optimized design points around the power level requirement and choose the minimum mass point from such a derived point-wise curve. Frequently, the total system mass minima are broad and relatively flat curves, and are not overly sensitive to slightly off-minimum design point selection. References 2 and 3 are examples of codes for such uses.

A number of specific reactor designs have been proposed for space nuclear-electric power. They are generally characterized as either fast-spectrum reactors (e.g., the SP-100 design) or as moderated, thermal- to epithermal-spectrum reactors (e.g., SNAP, TOPAZ, STAR-C, or Nerva

REGIMES OF POSSIBLE SPACE POWER APPLICABILITY

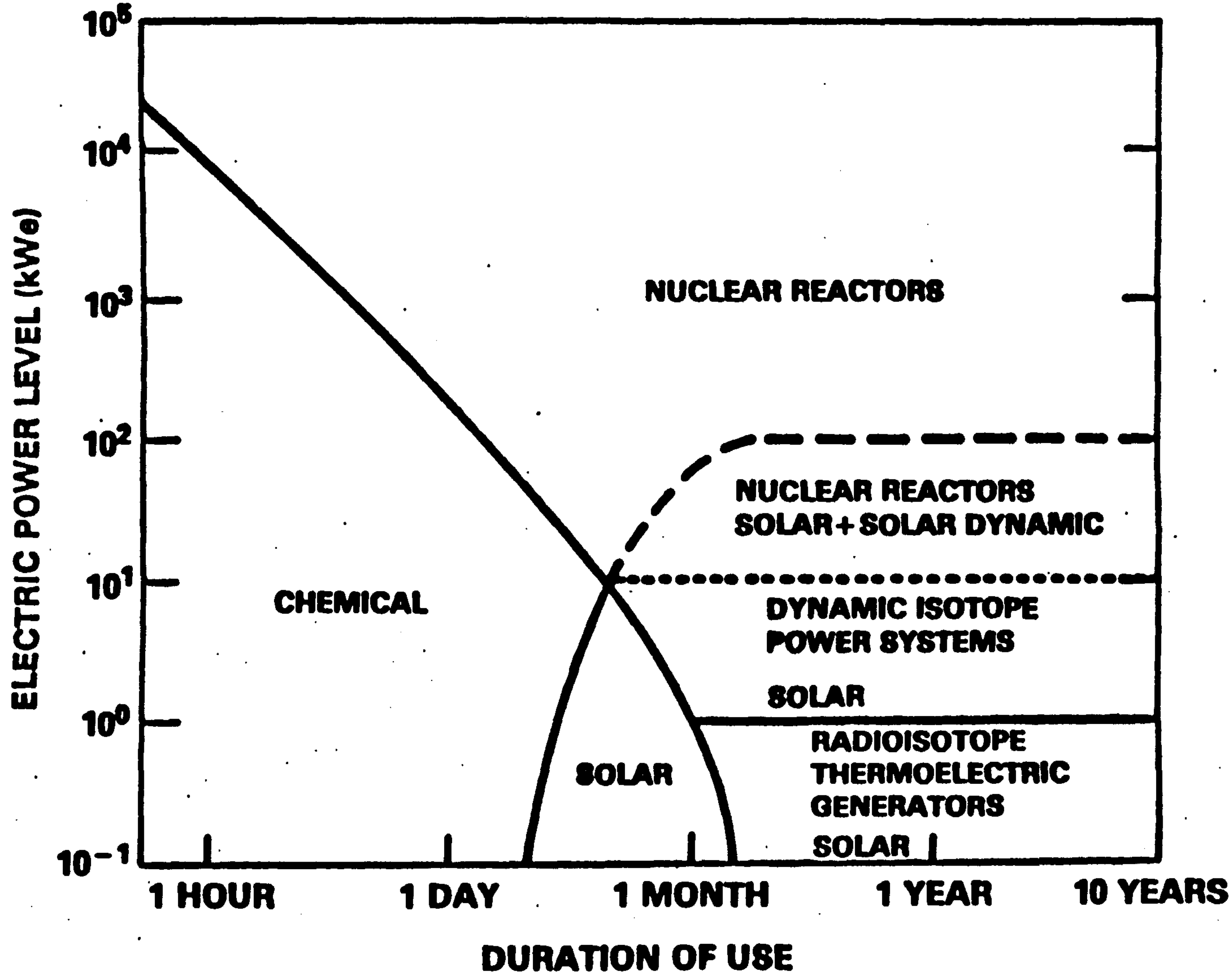

FIGURE 1

designs). The reactor power systems can be further characterized by whether they use static thermoelectric or thermionic power conversion systems or whether they use dynamic power conversion systems (e.g., Brayton or Rankine cycles). The substitution of LEU for HEU in the different systems increases the masses by different percentage amounts and usually requires a reoptimization process of the system operating parameters in order to minimize the increase. For example, in the case of a moderated in-core thermionic reactor, the diameter of the fueled emitters will change with the substitution of LEU for HEU in order to minimize neutron resonance absorption in the U-238.

General relationships can sometimes be deduced concerning reactor mass and shield mass and their relation to total system mass. A 1988 study by an Air Force/DOE evaluation panel for small space reactor systems (Ref. 4) examined a number of HEU-fueled reactor designs. The mass trends for reactors in the 10-30 kWe power range, shown in Appendix A, indicated that in this power range the radiation shield mass was ~166% of the reactor core mass, and that together they made up about ~59% of the total system mass.

The Selection of Fast vs. Moderated Reactors for a Space Power System

In the design process, the selection of whether a fast reactor or a thermal system will best satisfy the power system designer's needs is generally determined by the electrical power required. For higher power levels (above 100 kWe) the high specific power (kWt/l) of fast reactors makes them the only type that can be considered. The crossover point from a fast reactor to a thermal reactor occurs over a range of output power typically at or below the 40 kWe level, as determined by DOE-funded studies at Rocketdyne (RD) and other contractors. The RD studies (Ref. 5) indicate that at 40 kWe, a fast spectrum thermionic element reactor is smaller and lighter than a moderated design. Table 1 below illustrates the comparisons of a 40-kWe fast core with thermionic fuel elements (TFEs) vs. a 40-kWe moderated core also using TFEs.

TABLE 1

MASS COMPARISONS FOR AN HEU-FUELED THERMIONIC 40-kWe REACTOR

	Fast Spectrum	Moderated Spectrum
Reactor Core		
Diameter, cm	47.5	57
Height, cm	48	54
No. of TFEs	72	134
Core Mass, kg	894	1266
Shield Mass, kg	1445	1700
Radiator Mass, kg	388	335

Other conclusions drawn by RD are that control is simpler (lower burnup, no burnable poisons needed, in-core control rods are not needed) and that the benefits of a moderated core increases with decreasing power. At powers ≥40 kWe, the optimum moderation ratio (ratio of H/U-235 atoms in the core) decreases (i.e., the spectrum hardens); and the thermionic converter geometry changes to reduce internal electrical resistance (I^2R) losses in the thermionic cells.

MASS IMPACTS ON FAST REACTORS

When fueled with HEU, advantages of either reactor spectrum type depend upon the power level and the conversion equipment. As earlier mentioned, fast reactors, because of their high power density (kWt/liter) in the reactor core, are the only type that can be considered for higher power levels. Control of fast reactors in the ranges up to several hundred kWe can be accomplished by reflector control drums, or by relatively few control rods, because the large neutron mean free path of fast reactors increases the effectivity of external control drums. Higher-power moderated reactors, on the other hand, have a relatively short mean free path for neutrons and so the individual effect of control rods is less, and more are needed for reactivity control. The multiplicity of control rods for the moderated systems increases system mass and complexity.

Scaling Factors for HEU to LEU Fast Reactors

The effect of replacing U-235 with U-238, on an atom-for-atom basis, can be estimated from first principles. For a just-critical reactor, the loss of one fissile U-235 atom to an exchange with a U-238 atom means that the core mass must be increased by, in the case of an LEU reactor, the re-insertion of a fissile atom now accompanied by four or more non-fissile U-238 atoms.

This simple model will not hold correct for the replacement of all the fissile atoms in a given fast reactor. If it did, the answer to the mass increase from HEU to LEU, for a fast reactor, would be a factor of four. However, the atoms of U-238 themselves capture neutrons parasitically at their resonance absorption energies. (The effect of fast fission is small relative to the absorption). Further, as the size of the reactor increases with the mass, the neutron leakage changes significantly. The net effect, which can be calculated for a simple model from one-group reactor theory (Ref. 6), is much greater as shown below.

The reactor physics effects from adding the extra U-238 diluent to the reactor core can be derived from the Boltzmann equation for a critical reactor:

Production = Absorption + Leakage

$$\mathcal{P} = A + \mathcal{L}$$

where Production ≈ $\nu\Sigma_{fiss}$

Leakage ≈ Reactor Size and Σ_{scat}

Absorption ≈ $\Sigma_{abs} = \Sigma_{fiss} + \Sigma_{capt}$

Σ_{fiss} varies with fuel burnup and fast fission effect

Σ_{capt} includes control allowance, reactivity temperature defect, and parasitic absorption in U-238

From this, the increased parasitic resonance capture in U-238 from LEU can be seen to cause a redistribution of the neutron balance between fissile absorption and parasitic capture absorption for a just-critical reactor, with the net effect that the critical mass required (the amount of fissile U-235) will increase.

Some general conclusions for the effect of substituting LEU for HEU can be derived from the one-group steady-state Boltzmann diffusion equation for the reactor core:

$$D\nabla^2\Phi - \Sigma_a\Phi + k_\infty\Sigma_a\Phi = 0$$

from which can be derived an approximate critical radius R_c for a fast reactor core with a thick reflector:

$$R_c \approx \frac{\pi}{B_c} - \left(\frac{\Sigma_{tr}}{3\Sigma_a}\right)_r^{1/2} \frac{1}{(\Sigma_{tr})} \qquad \text{(Ref. 6)}$$

From this approximation it is possible to plot parametric curves of the calculated critical masses of fast reflected reactors with various volume percentages of fuel, coolant, and structural material, with enrichment as a variable. These parametric curves are shown in Fig. 2 (Ref. 6). For a fuel volume of 50% (curve B of Fig. 2) the ratios of the core masses relative to HEU are interpolated in Table 2 below. The table also indicates a rough idea of the increase in relative shield masses on the assumption that while the core mass is proportional to the cube of the radius, the shield mass is proportional to the square of the radius of the increased size core.

TABLE 2

Core and Shield Mass Ratios for Fast Reactors

Enrichment	Core Mass Ratio	Shield Mass Ratio
93%	1	1
35%	~8	~4
20%	~16	~6

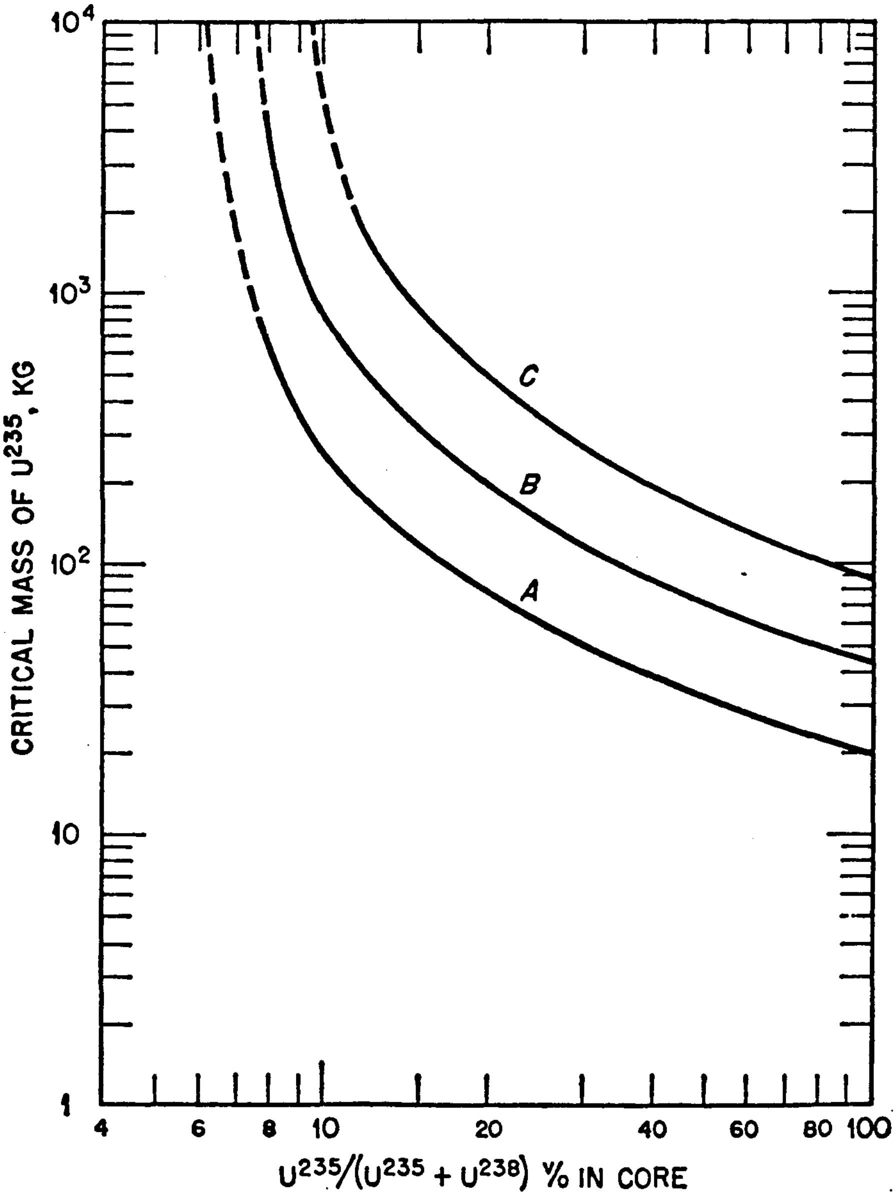

FIGURE 2. Critical Mass vs. Enrichment for U-235

Curve A: 100% Fuel Material Only
Curve B: 50% Fuel, 33% Coolant, 17% Structure
Curve C: 25% Fuel, 50% Coolant, 25% Structure

Case Studies for Fast Reactor Designs

The SP-100 Derivative

At the request of the Space Reactor Power Systems Division of DOE, the Martin Marietta Astrospace Division performed a study of the impact of using low enrichment fuel for the SP-100 design (a fast reactor using UN as fuel) at power levels of 20 kWe and 100 kWe for U-235 fuel enrichments of 35% and 20%, for comparison with the reference design cases of ~93% HEU (Ref. 7).

The study was conducted using the COROPT-S optimization code, and nuclear calculations were verified with the TWODANT code. COROPT is a code that is used on the SP-100 design to perform conceptual design optimization studies. It is usually used to optimize on minumum mass with HEU fuel, and hence required some modification to be applicable for the larger, low enrichment cores. The COROPT code does not have the capability to perform mass scaling for all the subsystem components of the reactor power system mass, and such masses were estimated.

TWODANT nuclear calculations were completed for the 35% MEU enrichment cores for 100 kWe and for 20 kWe. Preliminary results were obtained for the 20% LEU enrichment cases, and are so reported.

Finally, it should be noted that, as in any design point comparisons, the reference HEU cases for the 20 kWe and the 100 kWe designs are not exactly comparable since the fuel pin diameter on the higher power design is allowed to be variable to minimize system mass. Other technology assumptions, such as completion of system qualification programs, will cause minor differences. Table 3 is a listing of the component masses for the 20 kWe SP-100 design at ~93% HEU enrichment, at ~35% MEU enrichment, and (non-optimized) 20% LEU enrichment. The total system mass is seen to more than double, from ~2500 kg to ~6000 kg for the 35% MEU case, and to quintuple to ~15,000 kg for the 20% MEU enrichment. The major increases are in the core and shield, as expected, while the power conversion and heat rejection system masses for the 20 kWe designs remain the same.

Table 4 is a listing of component masses for a 100 kWe design, comparing as before a reference design using ~93% HEU enrichment with ~35% MEU and with ~20% LEU. For this higher power system design, the total system mass at the 35% MEU enrichment is increased by 67%, while at the 20% LEU enrichment the system mass doubles. Again, the power conversion and heat rejection system masses are the same for the three 100 kWe cases, and the major increases are in the reactor core and shield.

Such mass increases have profound implications on the launch vehicle selection and configuration. The higher power level systems are beyond the capability of any but the most powerful launch vehicles, and then can only attain a low earth orbit (LEO). This will be examined more completely later.

TABLE 3

Comparison of Low-Enriched Fuel With SP-100 Reference Case
20 kWe System

Feature	HEU	MEU	LEU
Inner/Outer Zone Enrichment (%)	97/97	35/35	20/20
Reactor Dimensions			
Diameter (in)	19	29	40
Length (in)	39	58	93
Total No. Fuel Pins	882	3534	8430
Mass Summary (kg)			
Reactor Subsystem	533	2632	9957
(Fuel)	(126)	(1018)	(4426)
Shield	662	1433	3204
Reactor I & C	193	249	442
Balance of System	1100	1100	1100
Primary Heat Transport SS Power Converter SS Heat Rejection SS Power Conditioning SS Mechanical SS			
Total	2488	5414 -2488	14703 -2488
Δ Mass		2926 kg	12215 kg

TABLE 4

Comparison of Low-Enriched Fuel With SP-100 Reference Case
100 kWe System

Feature	HEU	MEU	LEU
Inner/Outer Zone Enrichment (%)	86/97	34/35	20
Reactor Dimensions			
Diameter (in)	20	31.5	----
Length (in)	49	68	----
Total No. Fuel Pins	858	3006	----
Mass Summary (kg)			
Reactor Subsystem	696	2938	8774
(Fuel)	(153)	(977)	(3448)
Shield	1089	1693	3932
Reactor I & C	380	518	758
Balance of System	2517	2517	2517
Primary Heat Transport SS Power Converter SS Heat Rejection SS Power Conditioning SS Mechanical SS			
Total	4682	7666 -4682	15981 -4682
Δ Mass		2984 kg	11299 kg

MASS IMPACTS ON MODERATED REACTORS

Moderated reactors typically will have a much more thermal neutron flux spectrum than fast reactors. Figure 3 illustrates the difference between a TOPAZ-II moderated in-core thermionic reactor with an epithermal spectrum and an SP-100 reactor with a fast spectrum. In the epithermal spectrum there is significant flux in the resonance absorption energy region in the 0.10 to 10 kev range and therefore the design of the fuel pin diameter for MEU and LEU cases becomes very important (and variable with power level) to minimize the probability of resonance capture.

Additionally, a different complication enters the design optimization for moderated, lower power thermionic reactors, and that is the necessity to maintain sufficient thermionic fuel element emitting area to provide the required electrical power. If the emitting area of the fuel elements is sufficient to provide the design power, but the amount of fissile fuel in those elements is not sufficient to maintain criticality and allow for burnup, the design is "criticality-limited". In this case more fissile material is needed, and the extra emitting area which comes with the additional fuel means that either the emitting surface must be run at a lower temperature, or the unneeded extra power generated must be rejected (an inefficent process).

If, on the other hand, the reactor is critical with a given number of fuel elements, but the emitter area of those fuel elements is not sufficient to provide the required power, the reactor is "power-limited" and additional emitter area--in the form of more fuel pins--must be added.

Both of these design situations require additional fuel--and thus additional mass--for resolution. An understanding of this distinction will help in evaluating the mass tables for moderated in-core thermionic systems, and in realizing why system operating parameters will change with power level as well as enrichment.

Case Studies for Moderated Reactor Designs

The LEU Derivative of the SNAP-8 Reactor

Early (1984) scoping studies were carried out on a SNAP-8 moderated reactor by Rockwell International (ref. 8) to assess the substitution of LEU for HEU. The reactor core was cooled by liquid metal to transport heat to out-of-core thermoelectric power conversion elements. Very preliminary studies on the reactor core, sized for a remotely located nuclear-electric power supply,

Comparative Neutron Flux Spectra

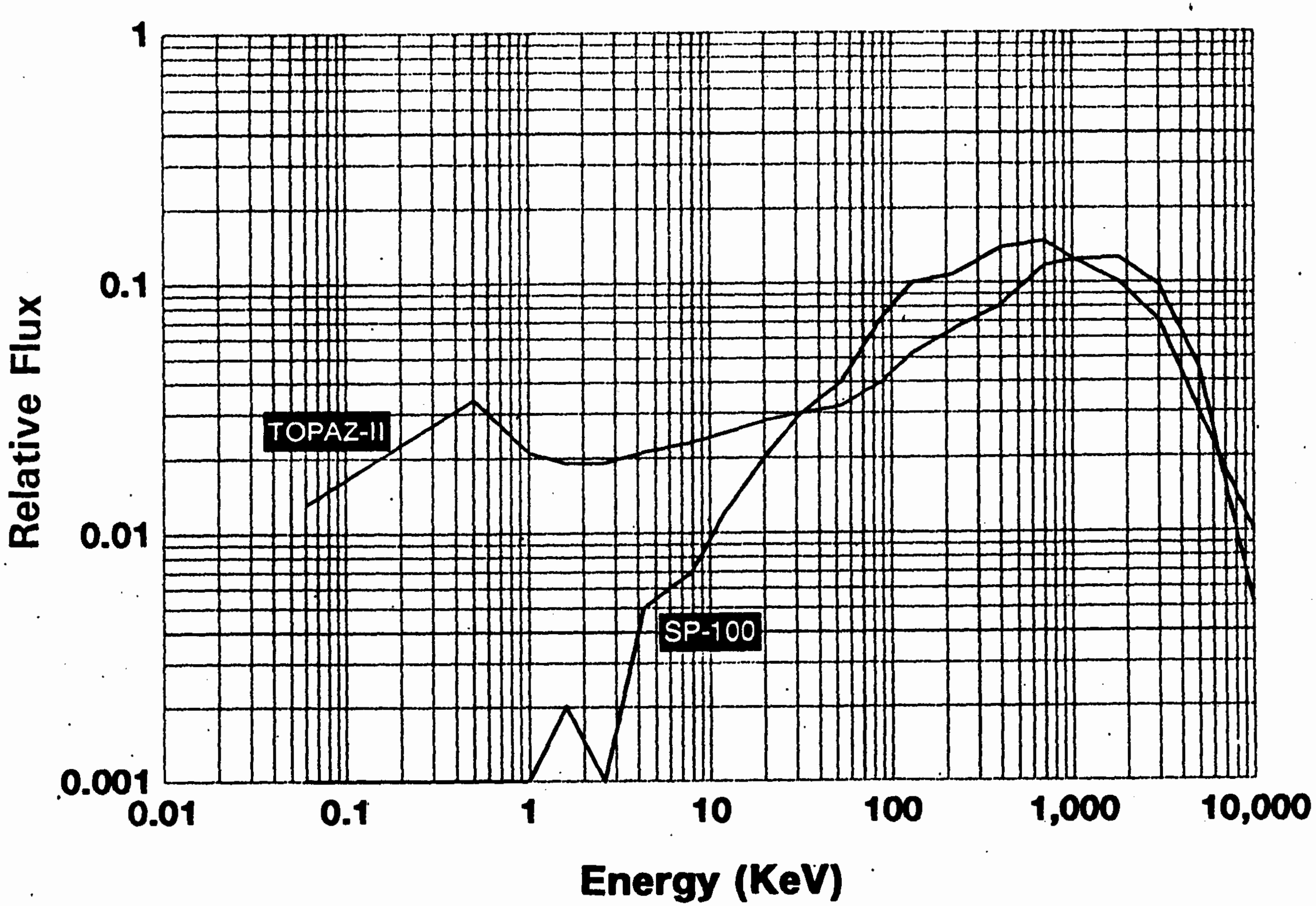

FIGURE 3

utilized a 20% U-235 enrichment limitation on the fuel fabrication design. The fuel form was a uranium-zirconium alloy hydrided to an H/Zr ratio of 1.80. The SNAP-8 reactor used fuel pins with a 5/8" diameter; the LEU design used a ~1.0" diameter fuel pin to maintain a reasonable L/D ratio for the longer core of the LEU design. The resultant parameters are shown below in Table 5.

TABLE 5

COMPARISON OF HEU\LEU DESIGNS FOR SNAP-8 TYPE REACTOR

Core Parameters	SNAP-8 Reactor	LEU Design
Power (kWt)	600	500
No. of Fuel Pins	211	200
Core Height (in.)	16.0	29.5
Core Diameter (in.)	9.0	14.8
Fuel Form	$UZrH_{1.8}$	$UZrH_{1.8}$
Uranium (wt. %)	10.35	10.35-18.0
U-235 Enrichment	93%	20%
Relative Core Volume	1.0	5.0

Thus, for this system the mass increase for the core only (excluding the reflector or the shield) is a factor of ~5.

The S-PRIME Thermionic Reactor Baseline Design

More detailed data on the effect of LEU replacement of HEU is available from scoping studies carried out on moderated thermionic reactor systems which are representative of recent design efforts in the development of the S-PRIME concept for the Thermionic Space Nuclear Power System (TI-SNPS) program. This design effort had the goal of developing a moderated in-core thermionic system with a 5- to 40-kWe scalability to meet Air Force space power system requirements.

The objective of the scoping studies (Ref. 9) was to assess the impacts of using an MEU or LEU fuel in the current S-PRIME design in place of HEU. Estimates for system impacts were made at the 20 kWe and the 40 kWe power levels. The study included evaluation of the subsystem and system size and mass impacts as well as a review of the technical issues associated with these system designs.

The 40-kWe baseline design uses multicell (flashlight battery arrangement) thermionic fuel elements in a Be/ZrH moderated reactor to achieve a specific mass of 15 We/kg and an end-of-mission efficiency of 7.0%. The reactor is cooled with a NaK pumped loop which rejects waste heat through a 27 m^2 heat pipe space radiator. The lifetime requirements are for 18 months continuous operation with a near-term goal of 5 years and a long-term goal of 10 years.

The reactor design uses 84 TFEs arranged into a 12-series by 7-parallel circuits electrical network to provide 31.5 volts at 1430 amperes. Core thermal power is limited to 570 kWt.

The internal structure of the core is composed of modular elements consisting of TFE power-producing pins and Be/ZrH moderator pins with Hastelloy clad. Structural support and core vessel are stainless steel. The reactor power output is scaled from 5 kWe to 40 kWe by adjusting the ratio of fuel/moderator pins without the need for changes in component technology.

Scope of the Study

Since a major portion of the total power system mass is composed of the reactor and shield masses in these power ranges (see Appendix A) it was necessary to develop reasonably accurate algorithms to estimate the size and mass of these subsystems. These algorithms were modeled upon those developed in the 40 kWe baseline design study. In a similar manner, the reactor controls, heat rejection system, and structural masses were modeled from the baseline design. New estimates were generated for the 20 kWe system.

Simplifications which were made to allow this study to proceed within time and budget constraints included:

- Use of a one-dimensional nuclear model. Criticality calculations were performed with MICROX cross-sections and ONEDANT2, a 1-dimensional transport code, with a constant core length. The critical size was established by adding unit cells to the core pattern to achieve a given criticality.

- Controls and safety analyses not performed. A conservative (i.e., lower mass) calculation has been performed which does not examine the need for in-core control mechanisms. Water immersion criticality and temperature coefficients were not calculated.

- Scaling of TFEs and power subsystems. The number of TFEs and the thermionic performance were established by simple scaling with the given constraints on the electrical series-parallel constraints. Mass estimates for the power subsystems (i.e., the balance-of-plant) were scaled from the 40 kWe baseline design.

Parametric Investigations

An important parameter in thermionic reactor design is the diameter of the TFE emitter. Initial surveys were made to establish whether the emitter diameter of 1.8 cm selected for the S-PRIME baseline HEU design (called the "J-series") would be appropriate for the MEU and LEU cases. The results of the early parametric studies showed that the optimal emitter diameter is larger for the MEU and LEU cases. Accordingly, emitter diameters of 2.79 cm (the "F-series") and of 3.56 cm were also considered in the parametric surveys. The 3.56 cm emitter was not carried into the point designs since it is outside the data base. Also, the parametric surveys indicated that the use of fueled moderator pins with additional uranium could help decrease the reactor diameter, and this design change was investigated.

Reactor Impacts

Table 6 summarizes the impacts of using LEU or MEU on the design of the S-PRIME reactor for the 20 kWe and 40 kWe output power cases. The baseline HEU design is included for comparison. At 40 kWe the reactor mass penalties for going to MEU and LEU are 505 kg (59%) and 954 kg (111%) respectively, and the corresponding core diameter increases are 31% and 46%. At the 20 kWe power level, the comparisons worsen because the TFE requirement is dominated by criticality, rather than thermionic, considerations.

The use of a fueled moderator ($UZrH_{1.8}$) was briefly investigated and shown to give a modest reduction in core size and mass at the 20 kWe power level. However, this marginal improvement is more than offset by the mass increases in the subsystems associated with the parasitic heat rejection requirement.

Heat Rejection Subsystem Impacts

Table 7 shows the estimated increases in the various heat rejection subsystem masses for the 20 kWe and 40 kWe power systems using MEU and LEU. A mass impact can occur in the heat rejection subsystem if the core layout does not permit the TFE operating parameters to be optimized for the MEU/LEU designs (i.e., if the thermionic elements are not operating at peak efficiency, more of the thermal heat of the reactor core will have to be rejected, and the radiator size and mass will increase). This is dramatically illustrated with the use of the fueled moderator pins, where the additional heat generated in the moderator must be transported and radiated away, making for a much higher heat rejection system mass (first column of Table 7).

Total System Mass Impacts

The summary tables 8 and 9 illustrate the combined effects of the MEU/LEU impacts on the total power system mass for the 20 kWe and 40 kWe power levels. For the 40 kWe design, the use of MEU increases the total system mass by 33%, and the use of LEU increases the total system mass by 57% relative to the HEU baseline design. At the 20 kWe power level, the comparable numbers for MEU and LEU usage are increases of 16% and 95%, respectively. Because of the fact that these point designs are not individually optimized for thermionic performance, the impact of the MEU and LEU usage in this power range of from 20 to 40 kWe is simply quoted as:

The total MEU system mass increase is from 16-33% (25±9%)
The total LEU system mass increase is from 57-95% (75±20%)

TABLE 6

S-PRIME LEU/MEU Fuels Reactor Design Impact

Power (KWe)	20	20	20	20	40	40	40
Fuel Type	LEU	LEU	MEU	(Baseline) HEU	LEU	MEU	(Baseline) HEU
Moderator Type	$UZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$
TFE Size	F	F	F	J	F	F	J
No. of TFEs	60	90	36	48	84	60	84
No. of Mod Pins	120	180	72	156	168	120	168
Electrical (SxP) Arrangement	10 x 6	10 x 9	12 x 3	12 x 4	12 x 7	12 x 5	12 x 7
No. of Rods	5	7	5	1	7	5	1
Current/TFE (A)	119	89.3	238	179	204	286	204
Current Density (A/cm²)	1.70	1.27	3.39	3.95	2.91	4.07	4.51
Avg Emitter Temp (K)	1712	1680	1736	1742	1716	1763	1760
Critical Mass (U-235 Kg)	59	30.5	21.4	30.7	28.5	35.6	53.8
H/U-235 No. Density Ratio*	27	79	45	19	79	45	12
EOM Core Power (KWt)	1190	506	343	310	719	655	570
TFE Power (KWt)	410	506	343	310	719	655	570
Driver Power (KWt)	780	0	0	0	0	0	0
Heat Rejection Power (KWt)	1150	479	317	285	668	604	522
Core Diameter (cm)	54.5	62.7	43.2	37.9	60.7	54.5	41.5
Core Height (cm)	61.3	61.3	61.3	61.3	61.3	61.3	61.3
Reactor Component Masses (Kg)							
TFEs	328	492	197	138	459	328	241
Moderator Pins	602	500	200	218	466	333	226
Grid Plates	31	36	15	12	34	28	14
Core Filler Pieces	57	65	45	28	63	57	31
Radial Reflector	317	420	199	154	394	317	184
Safety/Control Rods	16	23	16	9	23	16	9
Reactor Vessel	63	83	39	30	78	63	36
Electrical Interconnects	16	22	10	8	21	16	13
NaK Coolant	27	36	17	13	34	27	16
Reactor Subtotal	1457	1677	738	610	1572	1185	770
Reactor Controls	110	154	110	50	154	110	50
Full Reentry Shield	72	96	45	35	90	72	42
Total Reactor Mass	1639	1927	893	695	1816	1367	862

* Assumes no beryllium in moderator pins

TABLE 7

LEU/MEU Mass Heat Rejection Subsystem Mass Summary

Power Level	20	20	20	20	40	40	40
Fuel Type	LEU	LEU	MEU	Baseline HEU	LEU	MEU	Baseline HEU
Moderator Type	$UZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$	$ZrH_{1.8}$
Heat Load KWt	1150.0	479.0	317.0	285.0	668.0	604.0	522
Radiator Area (sqM)	59.4	26.9	18.2	19.0	38.0	32.8	27
Total # Heat Pipes	150.0	100.0	90.0	80.0	130.0	130.0	100
Manifold Ht (Cm)	45.0	30.0	25.0	20.0	30.0	30.0	35.0
Heat Pipe Condenser Length (M)	6.85	3.89	3.17	3.36	4.98	4.60	4.42
Mass Element (Kg)							
1. Piping	31.0	31.0	31.0	31.0	31.0	31.0	31.0
2. Main Manifold	70.9	44.7	32.1	25.2	47.7	45.9	49.3
3. EM Pump	263.4	44.3	28.4	26.6	79.9	65.9	66.0
4. Vacuum Unit	27.0	26.7	23.8	22.1	25.4	54.4	27.3
5. Getters	29.7	22.3	14.9	14.9	22.3	22.3	22.3
6. Heat Pipes/Fins	329.7	138.0	100.8	105.4	205.2	184.5	142.9
7. ID Insulation	48.0	21.9	14.6	15.3	30.7	26.5	22.3
8. Ground Heater	3.5	2.5	2.0	2.0	2.5	2.5	2.5
9. NaK Inventory	58.6	57.3	45.5	40.3	52.0	49.7	57.5
MASS SUBTOTAL	861.8	388.7	293.1	282.8	496.7	482.7	421.1
Natural Threat Protection Subsystem Mass	144.2	133.3	92.4	80.2	131.5	120.7	62.1
TOTAL SUBSYSTEM MASS	1006.0	522.0	385.5	363.0	628.2	603.4	483.2

TABLE 8

Comparison of Low and Medium Enrichment Fuels with S-PRIME High Enrichment Fuel Baseline Design - 40 KWe System

Fuel Enrichment	HEU	MEU	LEU
Reactor Height (cm)	111.5	111.5	111.5
Reactor Diameter (cm)	59.0	72.0	78.2
No. of TFEs - Series	84J	60F	84F
No. of $ZrH_{1.8}$ Pins	168	120	168
UO_2 Mass/U-235 Mass (Kg)	65.7/53.8	115/35.6	162/28.5
MASS SUMMARY (Kg)			
Reactor Subsystem	770	1185	1572
Reactor Controls	50	110	154
Reentry Shield	42	72	90
Radiation Shield	587	799	919
Heat Rejection	421	483	497
Natural Threat Protection	62	121	131
Power Conditioning, Control and Distribution	563	563	563
Boom/Structure	170	213	250
TOTAL	2665	3546	4176
Delta Mass Increase	Baseline	881 (33%)	1511 (57%)

TABLE 9

Comparison of Low and Medium Enrichment Fuels with S-PRIME High Enrichment Fuel Baseline Design - 20 KWe System

Fuel Enrichment	HEU	MEU	LEU	LEU
Reactor Height (cm)	111.5	111.5	111.5	111.5
Reactor Diameter (cm)	55.4	60.7	80.2	72.0
No. of TFEs - Series	48J	36F	90F	60F
No. of $ZrH_{1.8}$ Pins	156	72	180	120*
UO_2 Mass/U-235 Mass (Kg)	37.6/30.7	69.3/21.4	173/30.5	115/59
MASS SUMMARY (Kg)				
Reactor Subsystem	610	738	1677	1457
Reactor Controls	50	110	154	110
Reentry Shield	35	45	96	72
Radiation Shield	452	526	869	924
Heat Rejection	282	293	389	862
Natural Threat Protection	80	92	133	144
Power Conditioning, Control and Distribution	392	392	392	392
Boom/Structure	121	140	237	253
TOTAL	2022	2336	3947	4214
Delta Mass Increase	Baseline	314 (16%)	1925 (95%)	2192 (108%)

- $UZrH_{1.8}$ moderator pins with 15% enrichment

Technology and Developmental Impacts

For thermionic space power reactors, the preferred reactor control scheme has been to use radial reflector control to maintain a constant power output. However, the MEU and LEU systems examined here do not have sufficient neutron radial leakage to allow use of reflector control, and an alternate control technology such as in-core devices (which require active cooling and variable positioning hardware devices which are maintenance-free for years) or such as an adaptation of burnable poisons would have to be investigated.

Minimizing the mass increases through a reoptimization of the TFE emitter diameter could have significant benefit, and this could pose technology issues that require a development and test program to resolve. For example, the fuel centerline temperature of an increased-diameter emitter could exceed the current capabilities of the UO_2 pellet technology and require redesign and requalification of the fuel.

TOPAZ-I Thermionic Reactor

Some preliminary studies of a TOPAZ-I type of space nuclear reactor have been reported where MEU and LEU have been substituted for the baseline HEU and the fuel content adjusted for criticality (Ref. 10). These preliminary, unoptimized studies which were done independently of those reported above, indicated that it may be possible to design an MEU thermionic system with a mass less than 40% greater than a corresponding HEU system, and to design an LEU thermionic system with a mass penalty less than 75% greater than that of the HEU system. These numbers are consistent with the more extensive mass impact studies reported above.

TYPICAL PAYLOAD CAPABILITIES OF SPACE LAUNCH VEHICLES

While it is outside the scope of this paper to examine potential launch vehicles for suitability for the launch of space nuclear power systems, it is useful to look at some of the performance parameters for current world launch vehicles (see Appendix B). When these capabilities are applied to the launching of LEU or MEU systems, it becomes apparent that only the larger vehicles are capable of lifting the power system and the satellite/ soacecraft to be powered. Table 10 below exhibits the reduction in launch vehicle payloads for the case studies evaluated earlier in this report.

TABLE 10

LEU/MEU ENRICHMENT IMPACT ON LAUNCH VEHICLE PAYLOAD MARGINS FOR GEOSYNCHRONOUS TRANSFER ORBITS (TITAN IV/CENTAUR ASSUMED)

	U-235 Enrich.	Fast Reactor Power Level 20 kWe	100 kWe	Moderated Reactor Power Level 20 kWe	40 kWe
Power System Mass (kg)	93%	2488	4682	2022	2665
	35%	5414	7666	2336	3546
	20%	14703	15981	3947	4176
Payload Margin*	93%	3772	1578	4238	3595
	35%	846	----	3924	2714
	20%	----	----	2313	2084

*assumes launch vehicle performance of 6260 kg to GTO

The comparisons made above utilized a Titan IV/Centaur launch vehicle capability for injection into at least a geosynchronous transfer orbit (the orbiting of nuclear power sources into a low-Earth orbit has not been considered as a potential mission). From the table, it is clear that the use of LEU or MEU severely restricts--or eliminates altogether--the payload margins.

CONCLUSIONS

The results of the studies reported here indicate that replacing HEU fuel with LEU in either fast spectrum or moderated spectrum reactors significantly reduces launch vehicle payload margins at lower power levels, and that LEU is not a viable alternative for fast-spectrum systems, which tend to be favored at higher power levels.

The mass and size impacts associated with the MEU option also result in unattractive weight penalties, and, if a constant payload margin is assumed, require larger launch vehicle capabilities than are required with HEU systems. This is believed to be at odds with the Air Force policy to use a "smaller, cheaper, faster" approach to their launch programs. Other space programs are vigorously pursuing a "step-down" approach which utilizes less-expensive launch platforms than those currently used--or those that would be needed for launching MEU systems.

APPENDIX A

Air Force/DOE 1988 Study

	Concept	Organizations Providing Information
1.	SP-100 Reactor Scaled-Down	General Electric Company
2.	SP-100 Innovative	General Electric Company
3.	Particle Bed Reactor	Babcock and Wilcox, Lookheed Missiles and Space, Garrett Fluid Systems, Brookhaven National Laboratory
4.	Fast Reactor Derivative	Rockwell International, Argonne National Laboratory
5.	SNAP Reactor Derivative	Rockwell International
6.	STAR-C Reactor	GA Technologies
7.	Moderated In-Core Thermionic Reactors	GA Technologies Space Power Inc.
8.	NERVA Derivative	Westinghouse Electric Corporation
9.	SCOR/AMTEC	Westinghouse Electric Corporation
10.	Heat Pipe Reactors	
	Out-of-Core Thermionic	Space Power Inc.
	Out-of-Core Thermoelectric	Los Alamos National Laboratory

Mass Trends 10-30 kWe

Reactor + shield mass/total system mass	=	0.59
Shield mass/reactor mass	=	1.66

Performance Parameters for Launch Systems. The table shows the capability of various systems to launch boosted weight to low-Earth orbit (LEO), geosynchronous transfer orbit (GTO), and Sun-synchronous orbit (SSO).

Launch System	LEO (kg)	GTO (kg)	SSO (kg)
SCOUT I	250	---	---
SCOUT II[6]	500	---	---
DELTA II 6920/6925	3850	1460	2940
7920/7925	4855	1820	2850
ATLAS I	5765	2240	---
ATLAS II[6]	6500	2680	---
ATLAS IIAS[6]	8560	3460	---
TITAN II	2150	---	1650
TITAN IIA, PAM D-2	4200	---	3600
TITAN III	14400		---
TITAN IV	17450	8500	13400
TITAN IV/CENTAUR[1]	---	(6260)[4]	---
SHUTTLE	22765		
IUS		(2300)[4]	
TOS		5800	
PAM-D		1225	
PAM-D-2		1850	
PEGASUS	455		310
TAURUS[6]	1725	377	1340
PROTON	20000	5500 (2200)[4]	2800
LONG MARCH 2E	8800	---	
ARIANE 40	4850	1900	3620
42P[1]	6050	2600	
42L[2]	6800	3000	5400
44P	7300	3200	
44LP[3]	8250	3700	
44L	9600	4200	6900

1 with solid rocket motor upgrade
2 with 2 liquid rocket boosters
3 with 2 liquid and 2 solid rocket boosters
4 delivered to geosynchronous orbit
6 under development

NUS = No Upper Stage
IUS = Inertial Upper Stage
TOS = Transfer Orbit Stage
PAM = Payload Assist Module

APPENDIX C

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