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White Paper – Use of LEU for a Space Reactor

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Introduction

Historically space reactors flown or designed for the U.S. and Russia used Highly Enriched Uranium (HEU) for fuel. HEU almost always produces a small and lighter reactor. Since mass increases launch costs or decreases science payloads, HEU was the natural choice. However in today's environment, the proliferation of HEU has become a major concern for the U.S. government and hence a policy issue. In addition, launch costs are being reduced as the space community moves toward commercial launch vehicles. HEU also carries a heavy security cost to process, test, transport and launch. Together these issues have called for a re-investigation into space reactors the use Low Enriched Uranium (LEU) fuel.

HEU Advantages

HEU is highly concentrated in U-235 (a fissile isotope) and largely devoid of U-238 (primarily a neutron absorber). The relative lack of U-238 allows a much higher fraction of neutrons to cause fission, and thus a smaller volume/mass of uranium is required to sustain a chain reaction (i.e. criticality). As a result, HEU allows a much lower volume/mass reactor than LEU. This is especially true for lower power reactors (<~100 kW); higher power reactors are more limited by heat transfer than by criticality. The large inventory of U-235 also gives HEU reactors long "nuclear lifetime" (low burnup reactivity), because each fission burns a smaller fraction of the U-235 inventory. From the criticality perspective, the lifetime of HEU NASA KiloPower designs is many decades. HEU fueled reactors can also be very simple. In the current NASA KiloPower design, the reactor is a simple block of metal fuel. This allows for a simple to test and simple to build system with low complexity. Also, the nuclear properties of U-235 have been studied extensively (probably more than any other isotope on the periodic table), which reduces nuclear uncertainty. Overall, the mass benefit of HEU is by far the most important advantage for a space reactor.

Reasons to Use LEU instead of HEU

The primary reasons to use LEU are political and economic. Recently there have been calls by policy makers in and outside of the U.S. government for a ban on the use of HEU in nonmilitary applications. The goal is to reduce the proliferation of HEU in non-weapon states. To achieve this goal there is already a program to eliminate the use of HEU in research reactors worldwide. In addition, even the U.S. Navy has been asked by the President to examine the elimination of HEU in naval reactors (although this would take potentially decades to implement.)

HEU can be expensive to process, test, transport and/or launch. Data is available on the cost of security at Y-12 plant (storage and processing of HEU), the security at the Nevada National Security Site (nuclear testing of HEU) and on the transport of HEU (Safe Secure Transport or SSTs). This data indicates annual security costs in the ten's of millions and facility infrastructure costs that can range from ten's to hundred's of millions. However as of today, many of the costs are borne by the U.S. DOE weapons program and the cost to use facilities currently involves the user (example is NASA) only paying "marginal" cost (cost above that already paid by the NNSA/DOE) for the use of the facility. So, currently it can be argued that the cost for HEU is minimal, however that could change in the future. For a commercial space reactor effort, given the "marginal" cost model, the cost of using DOE facilities is increased more by the level of bureaucracy than the cost of security.

Recent NASA studies on the launching of HEU indicate a cost on the order of ten million per month at the launch site. But, the cost for security at launch may be completely offset by the increased launch costs for more weight. This will be examined in more detail later.

The potential savings for an LEU space reactor may be that the design, processing, transport and launching of a space reactor done outside of the NASA/DOE/government paradigm. The very bureaucratic nature of the government process can greatly exaggerate costs and these could be greatly reduced by a commercial company in a fashion similar to that for commercial rocket costs.

Design Paths for an LEU Reactor and Examples

There are three primary design paths for an LEU space reactor; 1) use the same simple fast neutron spectrum reactor solid-block fuel with no moderator (like KiloPower), except use LEU fuel instead of HEU fuel; 2) use a fuel that combines the fuel and moderator into a single material, much like the UZrH fuel used in TRIGA research reactors; or 3) design a reactor with fuel and moderator as separate layers/elements. All 3 of these reactor types have been studied recently at Los Alamos National Laboratory.

The fast-spectrum single-block fuel is the simplest reactor to design and build. From a development perspective it is virtually identical to its HEU counterpart, and in fact slightly easier to develop due to lower fuel burnup and lower linear heat rate. It is simply a bigger and heavier version of the same reactor.

A moderated reactor can often look attractive because of the potential to reduce fuel mass. However, it is complicated by the need to retain hydrogen in the metal hydride moderator. The partial pressure of the hydrogen in a moderated system increases significantly with reactor temperature, which leads to hydrogen loss via diffusion. This is problematic for space reactors because they need to operate at high temperature in order to thermally radiate power to space. At low reactor temperatures (<~600 C), low thermal efficiency can cause the mass of the power conversion and heat rejection systems to become prohibitively large. The need to for high temperature makes it difficult to prevent the hydrogen from diffusing out of the system over time; more so, the ability to prove/qualify hydrogen retention for 10+ years. Research has been performed on methods to greatly slow down the diffusion by using coatings on the moderator/fuel, but these only slow down the diffusion and do not entirely stop it.

In a system that combines fuel and moderator, e.g. UZrH fuel, the ability to hold hydrogen becomes even more difficult than for a simple moderator (e.g. ZrH). Additionally, hydrogen migration in UZrH (generally from hot to cold regions) causes changes in criticality and can lead to control issues. UZrH is also known to have significant swelling, and the rate can be highly sensitive to the temperature windows in which it operates. At the temperatures required for Kilopower all of these issues will make reactor design complex, operation unpredictable and qualification difficult.

Some of the issues with UZrH can be mitigated by separating out the fuel and moderator; for example LANL evaluated a concept with alternating layers of metal fuel and YH moderator (note: YH holds hydrogen better than ZrH at elevated temperature). This type of concept could be attractive if the moderator could operate at a much lower temperature than the fuel, thus decreasing hydrogen loss. The engineering difficulty arises in separately cooling the fuel and moderator while not incurring neutronic penalties in the system given the need for insulators, separate cladding/structure, and separate cooling paths. For a KiloPower-type system, LANL found that this type of system did not offer a practical solution.

Another potential issue with a moderated reactor is associated with reactor physics. The neutronic behavior of fast-spectrum reactors is extremely simple and predictable. Moderated reactors introduce complexity and uncertainty in how neutrons interact with the system, and how that translates into dynamic reactor operation. The physics of a moderated system also generally make it harder to meet launch safety requirements. Therefore, the performance benefits (e.g. lower fuel mass) of a moderated system must be enough to overcome both the technology, reliability, and surety risks.

Mass Comparison of HEU and LEU KiloPower Systems

LANL has examined several reactor design options to evaluate their impact on system mass. Three applications are considered: a 1-kWe space reactor, a 10-kWe space reactor, and a 10-kWe Mars surface reactor. Four designs were generated for each application: HEU-U7Mo, LEU-U7Mo, LEU-U(unalloyed), and LEU-UZrH. There were other cases evaluated, which assumed different shielding requirements, but those are left out of this summary.

The unalloyed uranium case is included because of lower mass, although it has a slightly higher development risk than U7Mo, because of an increased susceptibility for phase change and slightly lower creep strength. The UZrH cases presented are highly idealistic. The fuel is assumed to be formed homogenously in a large can/tub of 1-mm thick Mo, with no internal structure. The assumed hydrogen loss rate from the fuel is 10-times less than what General Atomics has previously said was reasonable for clad fuel pins with a specialized glass coating. These assumptions were made to put the moderated system in as good of light as possible, to determine if it might be worth pursuing.

Schematics of 1-kWe space concepts are shown in Figure 1, and a mass comparison is provided in Figure 2. A mass comparison for a 10–kWe space concept is shown in Figure 3.

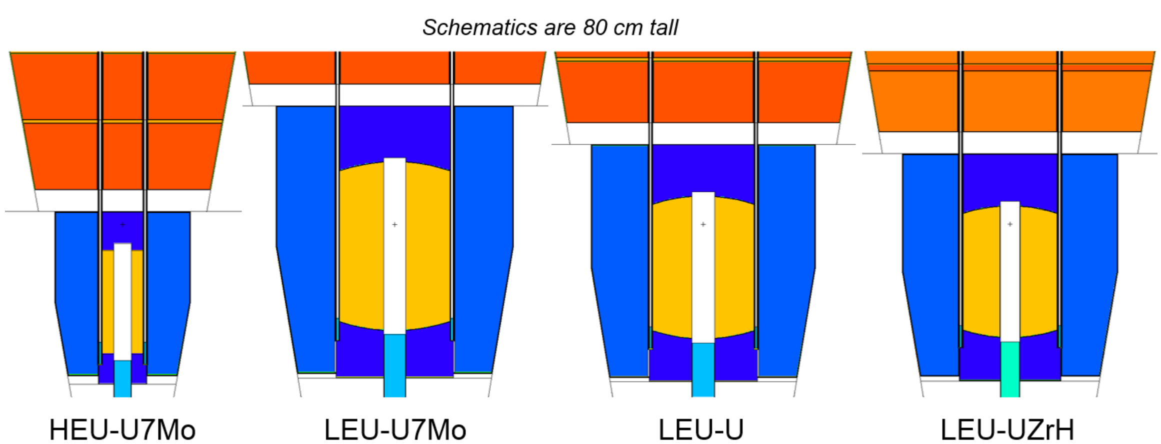

Figure 1. – Relative sizes of LEU systems compared to 1-kWe HEU KiloPower space system

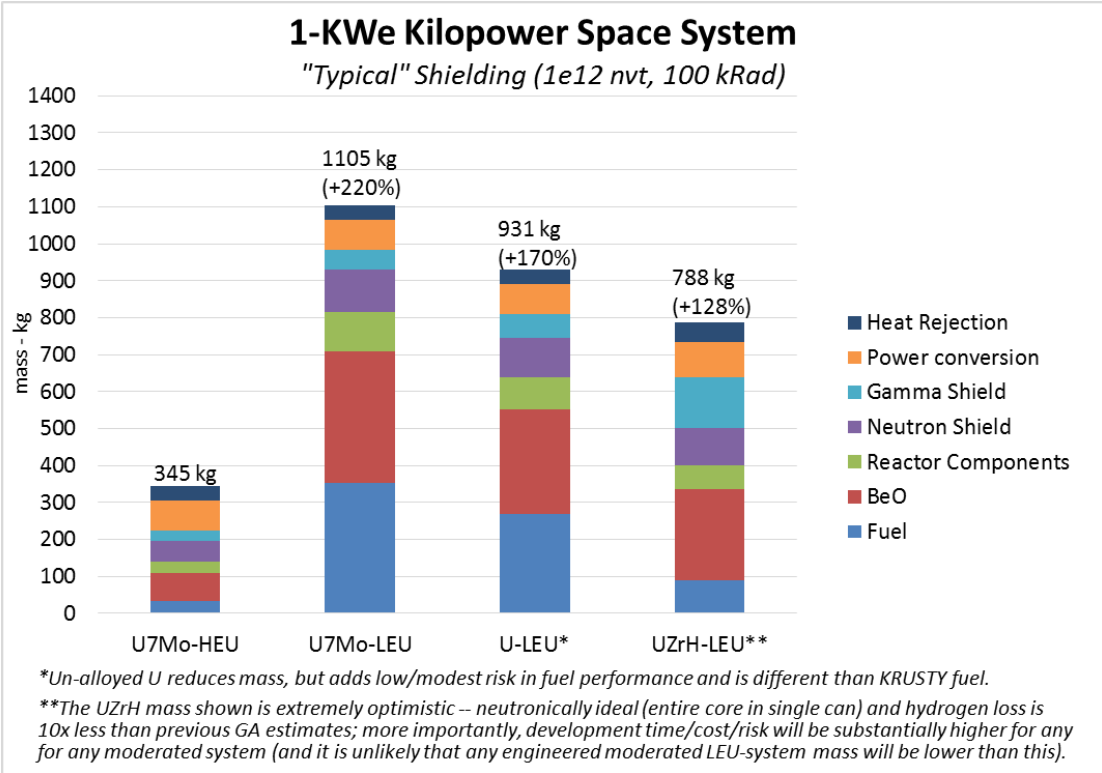

Figure 2. – Mass of LEU systems compared to 1-kWe HEU KiloPower space system

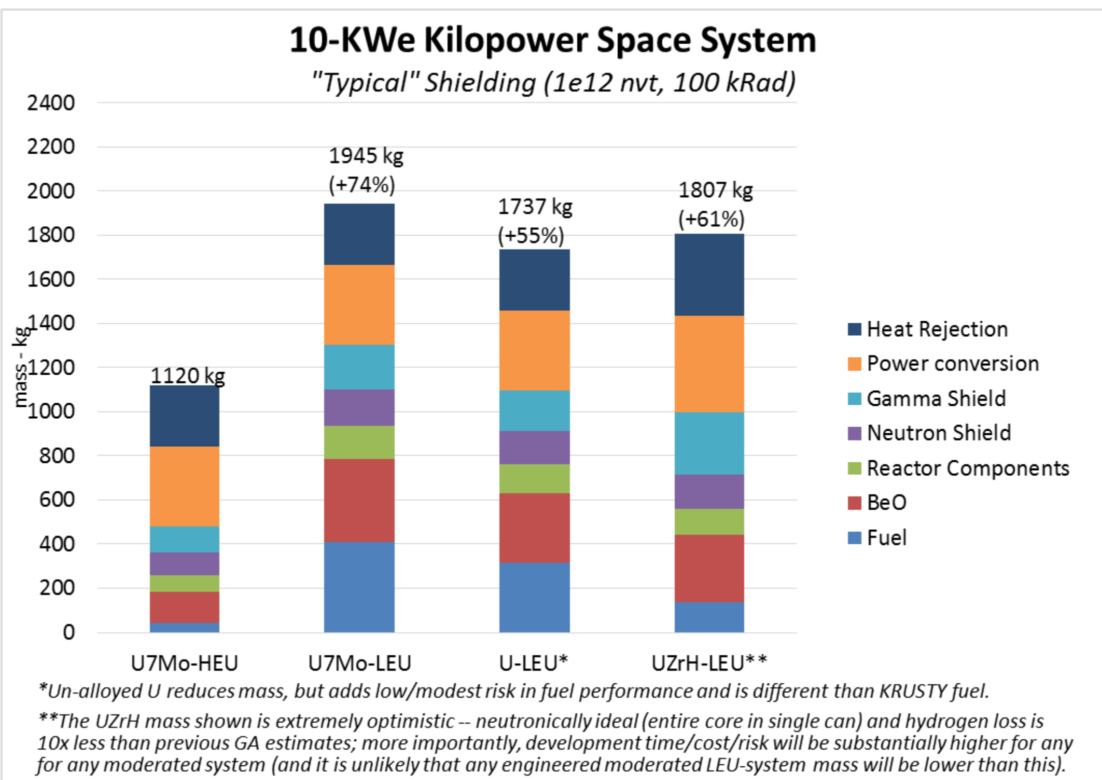

Figure 3. – Mass of LEU systems compared to 10-kWe HEU KiloPower space system

Schematics of 10-kWe Mars surface concepts are shown in Figure 4, and a mass comparison is provided in Figure 5.

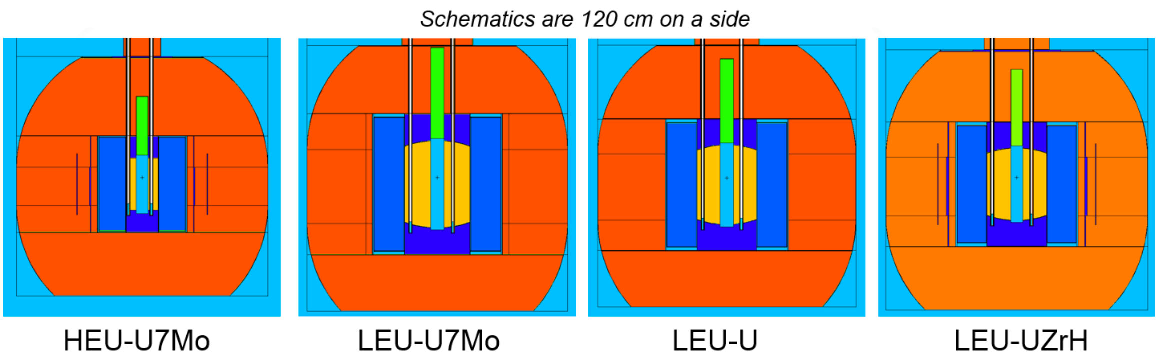

Figure 4. – Schematics of LEU systems compared to 10-kWe HEU Mars surface system

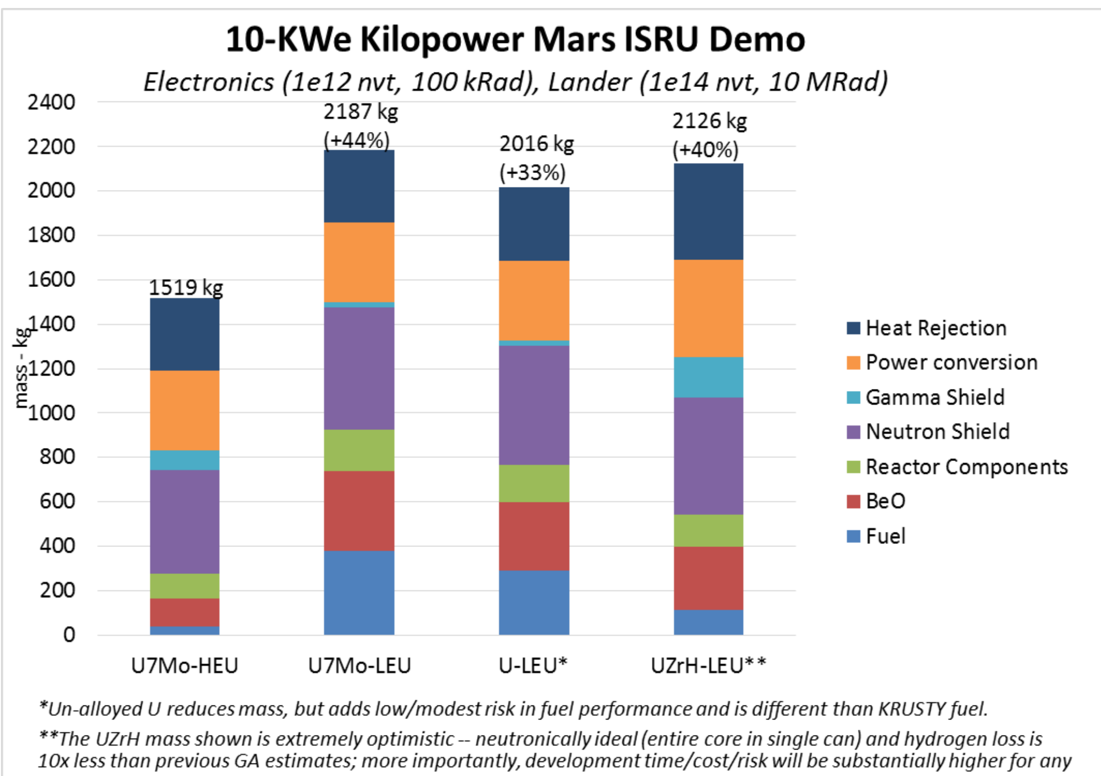

Figure 5. – Mass of LEU systems compared to 10-kWe HEU KiloPower Mars surface system

Figures 2, 3 and 5 compare a HEU system to three variants of an LEU system (two metal block and one combined moderator/fuel), each for a different KiloPower application. The masses of an LEU system with separate moderator and fuel are not shown because they showed no mass benefit over the UZrH concepts, while they are also much more complex.

These figures show that LEU systems result in ~500 to 800 kg mass increase over an HEU system. On a percentage basis, this is a much larger penalty for a 1-kWe space system (>100%), than for a 10-kWe space system (~60%) or a 10-kWe Mars surface system (~40%). If the electric power was increased to 100 kWe, the percent increase in mass would become even smaller, and so on, because the reactors become heat transfer and/or burnup limited, instead of criticality limited. It is the low power of the Kilopower reactors (especially 1-kWe) that makes the mass impact of using LEU so significant.

Disadvantages of an LEU Space Reactor System

The downside to using LEU is the increased mass. For the metal-block fast reactor, higher mass is the only significant negative of using LEU – in fact, the LEU system may be slightly easier to develop. Moderated LEU systems will have mass penalties similar to fast LEU systems. Lower mass LEU systems can be created on paper, but they are unlikely to be significantly lighter than the fast system (if they could indeed by successfully engineered and qualified.) Regardless, any moderated options will require substantially more development cost, time, and risk, as well as have lower lifetimes and reliabilities. A moderated space reactor is at best a research and development effort and not simply an engineering effort.

Advantages of an LEU Space Reactor System

The primary advantages of developing an LEU system are political and economic.

Using LEU would comply better with potential U.S. policy to eliminate the uses of HEU. LEU would also lessen concerns about a system falling into the wrong hands due to an aborted or failed launch. An HEU launch might require a large specialized force on standby in case retrieval is needed; more so that for an LEU system.

The cost of launching an LEU reactor is probably about equal to the cost of launching an HEU reactor for a 1 kWe reactor and maybe more for a large reactor. The assumption is that the HEU reactor would require about 2 months at the launch site costing about $10 million per month or $20 million extra dollars (note NASA used $70 million in its Nuclear Power Assessment Study.) The LEU reactor would have a mass increase of about 600 kg for most Kilopower applications. At a launch cost of approximately $50,000 dollars per kg to Geosynchronous Orbit, this translates to about $30 million of added cost. There would also be a penalty to achieve the remaining delta-V of the mission, i.e. the extra spacecraft/lander mass and propellant that would be required for the heavier system. While no definitive conclusion can be made, the launch costs for LEU are probably about equal or only a few 10's millions more expensive than HEU – a lot might depend on how successful NASA and industry are at reducing Earth-to-orbit costs.

For a government space reactor project, the development costs of an HEU system would not be substantially higher for HEU versus LEU, so the choice becomes more of a policy decision. This is largely because of security costs could be shouldered by the U.S. weapons program.

For a commercial space reactor effort, LEU is probably the only option and could prove to be much cheaper. Based on the cost reductions for rockets developed privately versus those developed by government, it can be assumed that development costs of a commercial space reactor could be anywhere from 10% to 50% of the cost of a government developed space reactor. For a reactor concept like KiloPower this could mean a cost in the 10's of millions instead of 100's of millions.

Conclusions

An LEU space reactor in the 1 kWe to 10 kWe range will have a mass ~600 kg higher than its HEU counterpart. The higher mass of the LEU will increase the cost of launch and obtaining mission delta-V, but can offset by the programmatic advantages and decreased security costs for an HEU system.

Moderated LEU systems have many technical issues that would only resolved by an R&D effort, which would likely remove any potential cost advantages of LEU. A fast-spectrum, solid-block LEU system is much simpler to engineer and build, and evolves directly from the 2017 KRUSTY reactor test. Therefore, given that realistic moderated systems offer no clear mass advantage over the fast systems, the simple fast-reactor is the obvious choice for an LEU system of this size.

The potential reasons for choosing an LEU system are both political and economic. An LEU system would be better from policy position and perhaps reduce public opposition. An LEU system might also be more affordable, by better allowing commercial development and production and avoiding the high security costs (fabrication, testing, transport, launch, recovery, etc.) of HEU. These advantages of LEU systems must be ultimately be balanced against the costs associated with the significantly higher mass.

There may also be cases where the optimal path would be to initially develop an LEU system, due to decreased development cost and risk, and later evolve to a higher performing HEU system once the technology is established (assuming the reactor technologies are similar between the two systems). The presence of a working system on the shelf might make the benefit/cost trade clearer, and make the pursuit of a higher performance HEU system easier to justify.

Overall, the HEU-vs-LEU issue will essentially be the same for all classes of space reactor: e.g. space, surface, NTP and NEP; however, in addition to a mass penalty, some concepts might require additional complexity and development risk to allow the use of LEU. First order, HEU will generally offer substantially lower mass with significantly increased cost/risk, and vice-versa.