Title: White Paper - Comparison of LEU and HEU Fuel for the Kilopower Reactor

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Intended for: Report

Issued: 2018-10-10

White Paper

Comparison of LEU and HEU Fuel For the Kilopower Reactor

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EXECUTIVE SUMMARY

This white paper presents a comparison of Low Enriched Uranium (LEU) versus Highly Enriched Uranium (HEU) as fuel for the Kilopower space reactor. It draws upon a previously published white paper[1] by the LANL authors, which was written in order to explore synergistic programmatic objectives with the current NASA Nuclear Thermal Propulsion (NTP) program. In that white paper no recommendations or conclusions were drawn on the appropriate choice of fuel for Kilopower. However, recent news articles, congressional remarks and conference papers have suggested the use of HEU for Kilopower may need to be reconsidered. This white paper explores in more detail the pros and cons of both fuel choices and presents a conclusion on why the use of HEU is the preferred choice as fuel for Kilopower.

In summary, the pros for an HEU for space reactors are:

- A LEU Kilopower will be 600 to 800 kg heavier than an HEU system. On a percentage basis, a 1-kWe space and lander system has a 200% increase in mass. For 10-kWe space system, the increase is 70%. For a 10-kWe Mars surface system, the increase is 40%. Overall, the mass benefit of HEU is by far the most important advantage for a space reactor.
- Mass is one of the major discriminators in the types of missions that can be performed. Many planetary surface and deep space missions will either have reduced science payloads or will not be possible without the mass savings of HEU.
- HEU is highly concentrated in U^{235} (93%). The increase in U^{235} will mean a much longer "nuclear lifetime", because each fission burns a smaller fraction of the U^{235} inventory.
- HEU reactors often provide a simpler engineering approach to ensuring safety for launch criticality accidents, depending on safety requirements.
- HEU reactors are generally a simpler and more straightforward design solution for space reactors. The reactors are compact which simplifies many neutronic and heat transfer issues. Increased design margins allow simpler development and adaptation to potential changes in requirements. Also, smaller components (fuel, reflector, shield, etc.) are generally easier to manufacture. Lower mass and volume allow a broader range of mission applications and spacecraft integration options.

The cons of using HEU for space reactors are:

- The use of HEU for civilian purposes is not in line with non-proliferation policy objectives of the U.S. government.
- There may be increased security costs for testing, transport and launching a reactor. Although many of these costs are already covered by existing capability on the U.S nuclear weapons program. These assets are already paid for and are not going away in the near future. This means cost may not be a major discriminator in any decision.
- The urgency of recovering a reactor that falls back to Earth after launch is significantly higher if the fuel is HEU as opposed to LEU. The U.S. government may require additional forces be ready to mobilize for recovery.
- Performing work in a Security Category 1 facilities can be cumbersome and takes more time and effort, but it is manageable and done every day.
- The use of HEU will make it more difficult for commercial companies to develop and manufacture similar space reactors.

KILOPOWER DESIGN AS A REFERENCE POINT

The focus of this white paper is the Kilopower reactor. Kilopower is a scalable 1 to 10 kW electric space reactor. The baseline design uses HEU alloyed with molybdenum metal as a fuel, Stirling engines as the power conversion and sodium heat pipes to transfer heat to the Stirling engines. Kilopower is shown in its notional flight configuration in Figure 1.

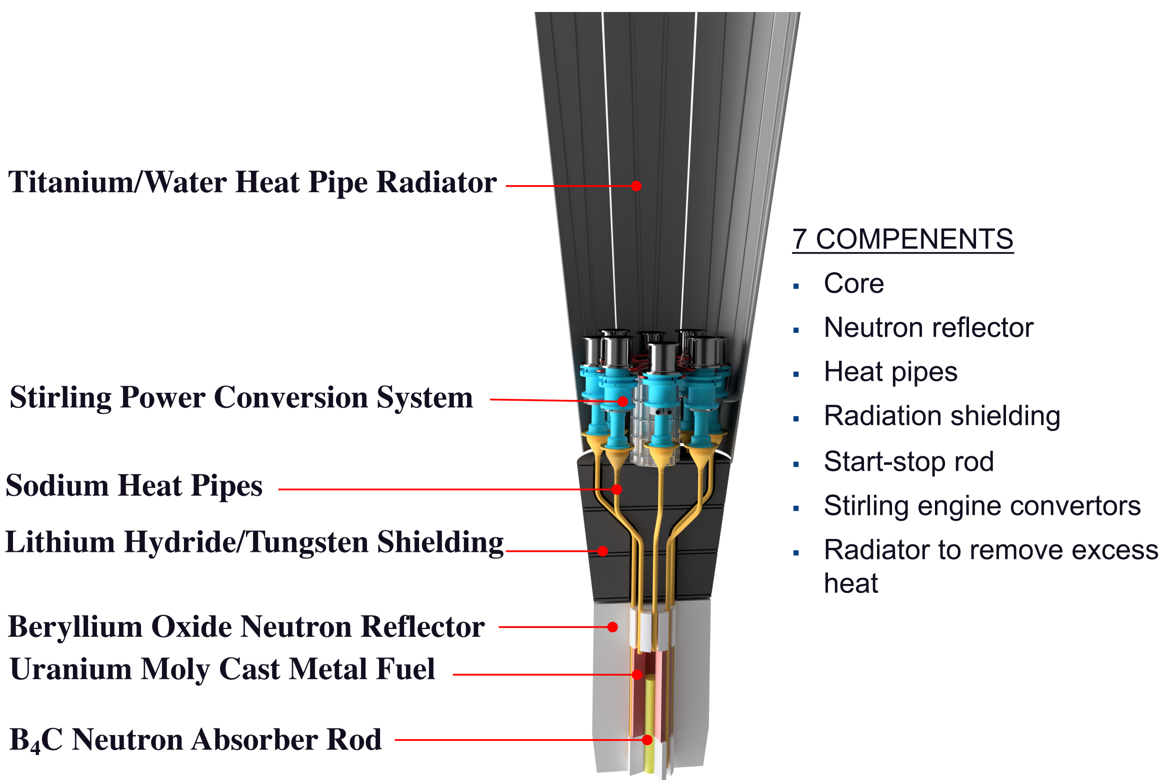

Figure 1. – Kilopower 1 kW Space Reactor In-Space Configuration

In March 2018, the Kilopower reactor was tested. The test, called KRUSTY (Kilopower Reactor using Stirling Technology), demonstrated the system's ability to self-regulate using well characterized physics. The test also showed the ability to manufacture, transport, assemble and operate the reactor under the current regulatory framework. Given that Kilopower is NASA's near-term option for either planetary surface power or in-space missions it has become a focus for the LEU versus HEU conversations and the basis for this white paper.

Kilopower is a very low mass reactor that benefits significantly from HEU. But, as reactors grow larger in size, the mass differences between LEU and HEU fuel loading become less significant. The reasons vary, but in general low power reactors are "criticality limited", meaning that the mass of fuel is determined by the amount necessary to achieve a critical mass. The critical mass of HEU (93% enriched) is ~52 kg, the critical mass of LEU (20% enriched) is over 400 kgs. As the reactor get larger in power, other issues such as thermal issues, radiation damage to components, and fuel performance start to increase the complexity and/or mass of the reactor. There is no clear cut off as to where these effects become dominate over the issue of critical mass. LANL experience for space reactors using standard materials and designs would indicate that at level below 100 kW the use of LEU has a large mass penalty and the penalty is driven by the criticality limitation. At levels between 100 kW and several megawatts other factors begin to impact the reactor mass. At levels above several megawatts the consequences of LEU are less pronounced, unless very long lifetime is desired. Note that the generalities above apply to reactors that retain the design characteristics of Kilopower, while for very-high temperature reactors that require refractory metals (like cermet fueled thermal nuclear rocket concepts), HEU has many significant advantages regardless of power level.

MASS COMPARISONS FOR KILOPOWER

The fast-neutron-spectrum, single-block fuel being pursued for Kilopower is the simplest reactor to design and build. From a development perspective, the LEU concept is very similar to its HEU counterpart. It is largely a bigger and heavier version of the same reactor (albeit with slightly more difficult engineering and manufacturing issues.)

LANL has examined several reactor design options to evaluate their impact on system mass. Four applications are considered: a 1-kWe space reactor, a 10-kWe space reactor, a 1-kWe Moon surface reactor and a 10-kWe Mars surface reactor.

A previous version of this white paper[1] compared 4 concepts for each application: 1) HEU-7% Molybdenum (Mo), 2) LEU-7%Mo, 3) LEU (no molybdenum) and 4) LEU-Uranium Zirconium Hydride, (UZrH). Cases 3 and 4 were included to demonstrate the mass of the reactor if the Kilopower fuel choice was abandoned in favor of a moderated fuel approach. Moderating the reactor is addressed after the section on mass comparisons below.

In this white paper, only 2 concepts are compared: 1) HEU-8%Mo and 2) LEU-U8%Mo. These concepts are of higher fidelity than those in the previous white paper, because they use the benchmarked codes and actual material specifications from the KRUSTY experiment performed in 2018. Note that the actual Mo composition of the KRUSTY fuel was 7.65 weight percent but is referred to here as U-8%Mo for simplicity.

The masses of LEU and HEU designs are compared below. The first comparison of designs is for typical deep space missions. For these hypothetical missions, a dose requirement to a 4-m diameter payload region on a 15-year mission was chosen as representative. The shielding requirement utilize a 15-m boom with a fast neutron fluence (>100 keV) of 1e12 n/cm2 and a gamma dose (Rad Si) of 100 kRad.

Schematics and mass comparison of the 1-kWe space concepts and the 10 kWe space concepts are shown in Figures 2 and 3.

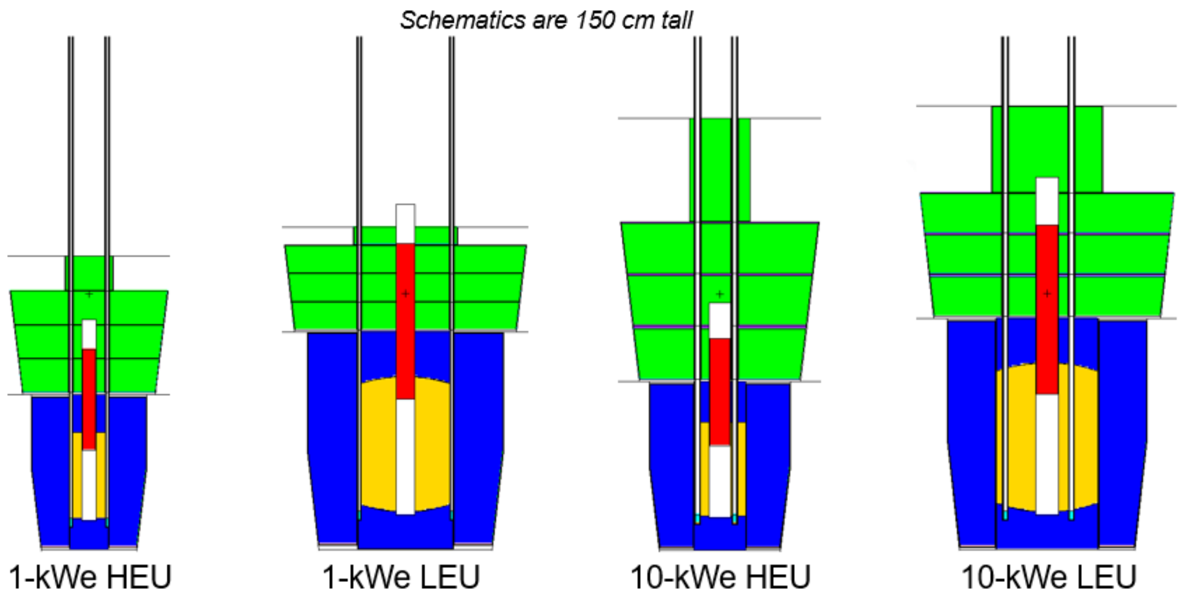

Figure 2. Relative sizes of HEU/LEU Kilopower space reactors (Fuel - Yellow, Neutron Reflector - Blue, Shielding – Green, Control Rod – Red)

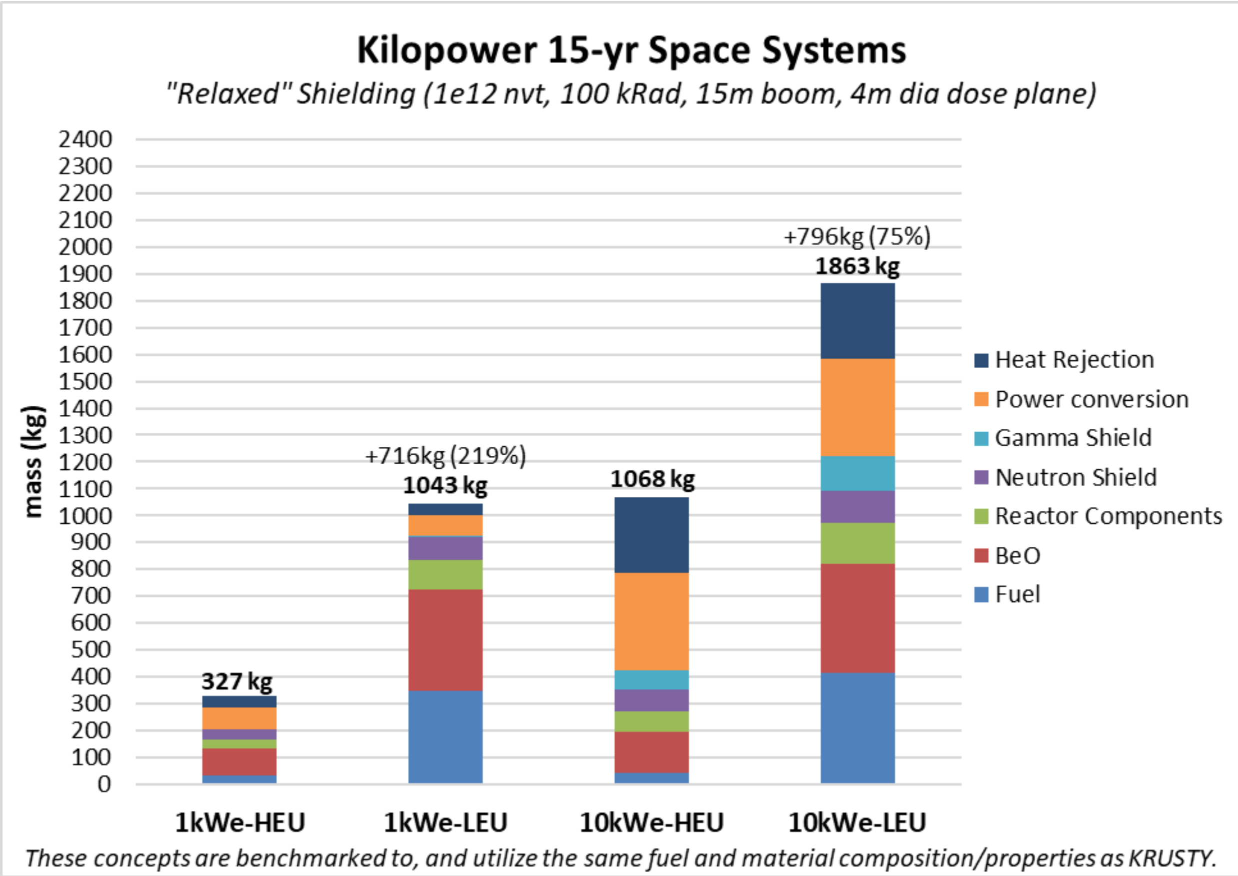

Figure 3. Mass Comparison of HEU/LEU Kilopower space reactors

These figures show that LEU systems result in ~700 to 800 kg mass increase over an HEU system. On a percentage basis, this is a much larger penalty for a 1-kWe (~200%), than for a 10-kWe space system (~70%). 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.

The second comparison of LEU and HEU designs is for surface missions including a 1 kWe Moon surface reactor and a 10 kWe Mars surface reactor. The Moon surface reactor has mission-specific requirements based on a short-lived demonstration mission where the reactor operates for ~1 year "as landed" on the lander. Future missions will likely have decades of operation but will utilize some in-situ shielding or burial. All of the surface cases limit the dose to reactor non-electronic components (e.g. Stirling engines, control motors) of 1e14 n/cm2 (>100 keV) and 10 MRad gamma (Rad Si). Schematics and mass comparison of the surface lander concepts are shown in Figures 4 and 5.

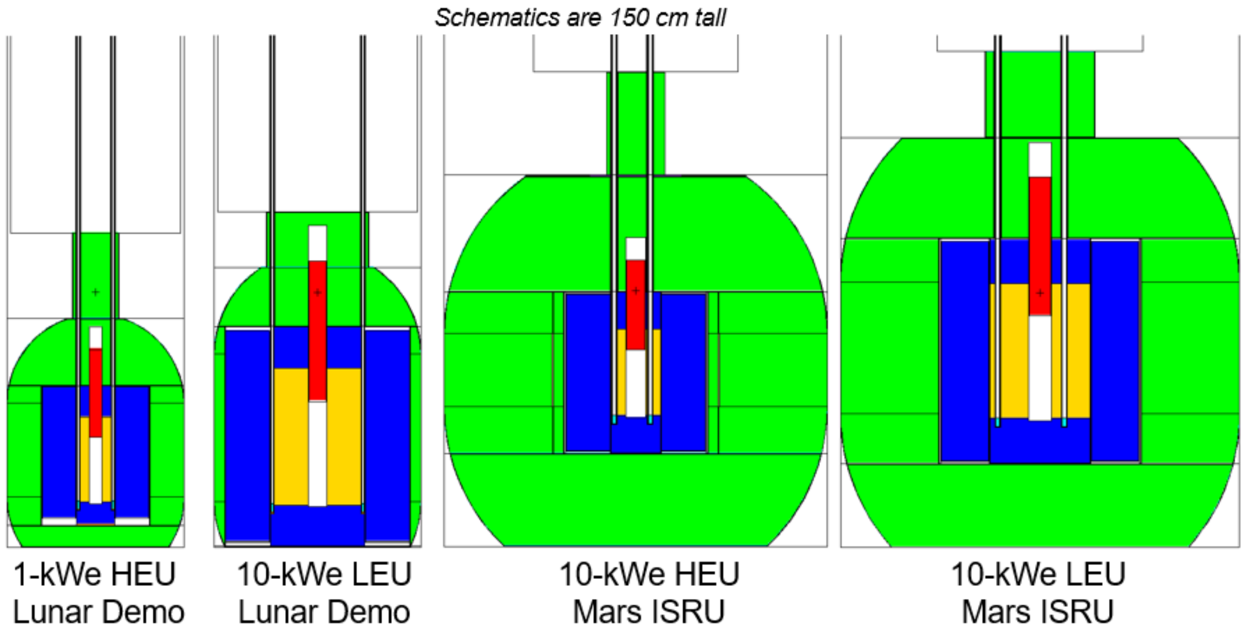

Figure 4. Relative sizes HEU/LEU KiloPower surface lander demonstration systems(Fuel - Yellow, Neutron Reflector - Blue, Shielding – Green, Control Rod – Red)

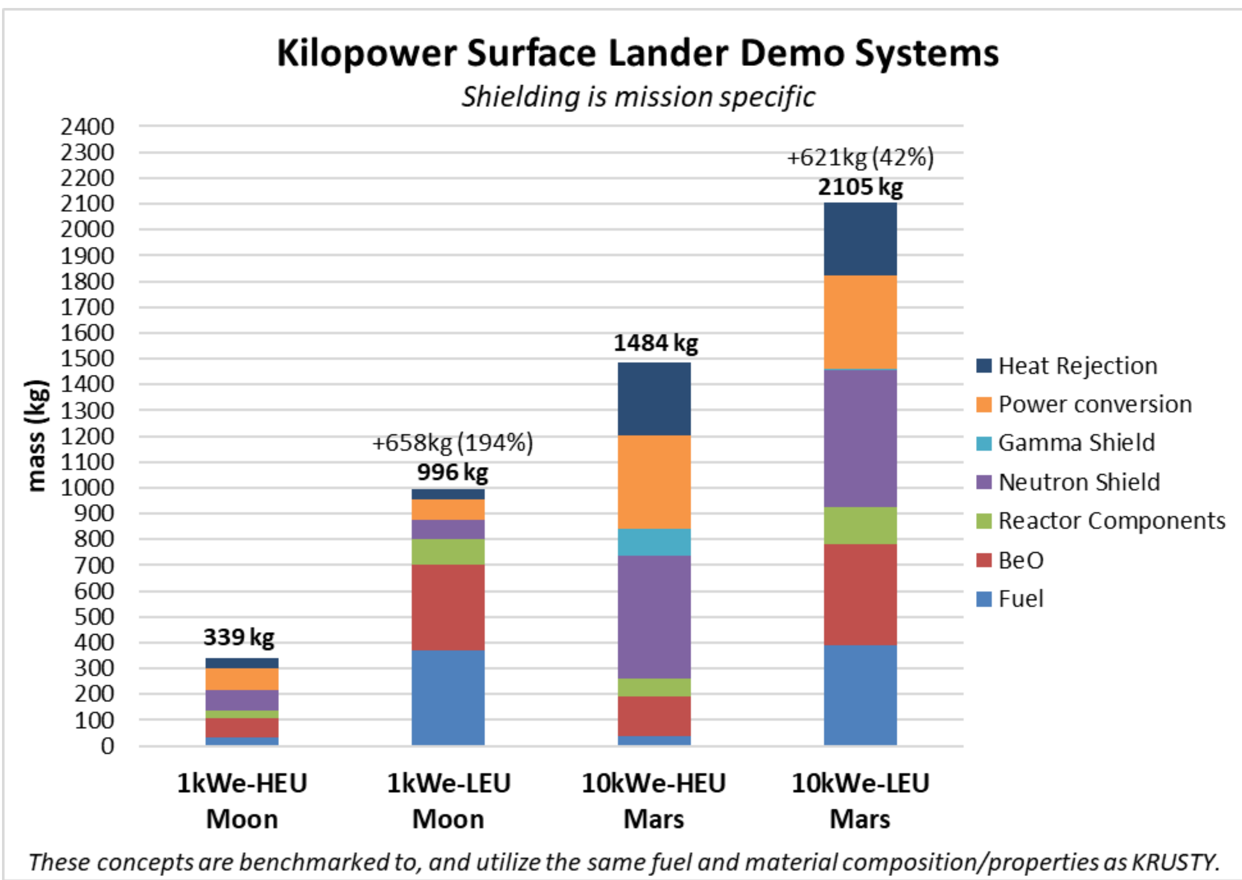

Figure 5. Mass Comparison sizes HEU/LEU Kilopower surface lander demonstration systems

These figures show that LEU systems result in ~650 mass increase over an HEU system. On a percentage basis, this is a much larger penalty for a 1-kWe Moon surface systems (~190%), than for a 10-kWe Mars surface system (~40%).

Design considerations for reducing mass - moderation

There are three primary design paths for an LEU space reactor; 1) use a simple fast neutron spectrum 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 the SNAP-10A space reactor; 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 (example see Fallgren[2]).

Moderators reduce the speed of a neutron and this can increase the efficiency of fission. By increasing the efficiency, either the mass of the fuel can be reduced or the enrichment of the fuel can be lowered. Water is the primary means of moderating a reactor for terrestrial applications. Water is not a practical option in space due to freezing/thaw issues and excessive pressure at high temperature. The best design option for space reactors appears to be a metal hydride moderator; however, this approach involves considerable development risk. Hydrogen loss in a moderated system increases significantly with reactor temperature, which is problematic for space reactors because they need to operate at high temperature in order to thermally radiate power to space. In addition, moderated systems have more complex and uncertain reactivity feedback and reactor dynamics. There is also uncertainty on how the reactivity and dynamics of the system will change with fuel burnup/lifetime. Finally, moderated systems are generally more difficult to engineer to meet launch accident safety requirements (due to lack of intrinsic neutron poisons and lower reflector worth), and they usually require larger excess reactivity, which can complicate safety as well.

In a system that combines fuel and moderator, (e.g. UZrH fuel), the ability to hold hydrogen at high temperature[3] (>600 C) has been demonstrated to be very difficult. 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. LANL has evaluated UZrH reactors for Kilopower applications, and the mass savings (versus current HEU unmoderated reactors) were ~25% at 1-kWe and only ~5% at 10-kWe – not enough to justify the high technical risk.

Some of the issues with UZrH can be mitigated by separating out the fuel and moderator, and cooling the moderator to lower temperature. LANL evaluated a concept with alternating layers of metal fuel and YH moderator[3] (note: YH holds hydrogen better than ZrH at elevated temperature). These concepts look promising on paper, but would be very difficult to engineer without adding significant mass, complexity, cost and development risk. Therefore, for a Kilopower-type system, LANL found that this type of system did not offer a practical near-term solution.

Design considerations for reducing mass – high temperature fuel system

Another design choice than can reduce mass is to use a fuel and structure that can go to higher temperature. Higher temperature allows for a more efficient power conversion system (thereby lowering the power of the reactor and thus size). It also means that the radiator that is the ultimate heat sink can radiate at a higher temperature, thus reducing size and mass.

Most high temperature fuels and structural/cladding materials have several development concerns. The first is that most are at a low level of technical maturity (very low technical readiness level or TRL) and lack the irradiation data needed for a robust design. Second for these fuels, the required infrastructure to make 10's of kg's quantities of fuel does not exist. Most of these fuels are done in lab scale quantities (100s of grams.) Even if these issues can be overcome, none of these fuels will have the uranium atom density (U^{235} atoms per cc) that HEU will have (high temperature fuels have uranium dispersed in a matrix.) Also, higher temperature structural materials in the reactor core generally absorb more neutrons (making criticality more difficult to achieve) and are harder to fabricate. Overall, the gains from lower power conversion/radiator mass will likely be negated by the increased core mass, while the higher temperature design will be substantially harder to develop.

SAFETY CONSIDERATIONS

Reactors that have not undergone fission will be limited to the small amount of naturally occurring radioactivity in the uranium (i.e. radioactively benign at Launch). The isotope U^{234} provides over 97% of the total radioactivity in the reactor core. It is naturally present in the Uranium but becomes more concentrated because in the process of enriching the U^{235}, U^{234} comes along. U^{235} represents the remaining radioactivity in the core.

The safety implications between LEU and HEU are almost indistinguishable from each other. This is because the total mass of U^{234} and U^{235} in both cores will be comparable, with LEU typically having slightly more of the two isotopes than HEU. This is because, although LEU has about 4.5 times less U^{234} and U^{235} on a percentage basis then HEU (assuming 20% enriched LEU and 93 percent HEU), the amount of LEU needed to make a Kilopower reactor critical is about eight times higher than HEU. In either case the total amount of reactivity for a LEU or HEU Kilopower reactor is still only a few curies and far below any level of concern given an accidental release.

For many space reactor concepts the use of LEU makes it more difficult to preclude inadvertent criticality during various accident conditions, but for Kilopower, LEU presents only a small disadvantage.

SECRUITY CONSIDERATIONS

The security differences between LEU and HEU will be significant. LEU, a Security Category 4 material, will require little protection during any phase of manufacturing, testing, transportation and launch. HEU, a Security Category 1 material, will require extensive protection during manufacturing, testing, transportation and launch.

During the testing of Kilopower, the KRUSTY experiment, the manufacturing, testing and transportation were performed using DOE assets. The manufacturing of the reactor core was performed at the Y-12 National Security Complex, testing was performed at the Nevada National Security Site, and transportation was provided by the DOE Secure Transport organization. Each of the assets already has adequate security for Category 1 material provided by and paid for by the DOE. For the KRUSTY test (which consisted of short-term activities), DOE did not required NASA to pay for infrastructure and security. For this 3 ½ year development NASA payed a marginal cost of personnel and materials for these activities

Launching a reactor into space would require extensive security measures at the launch site, (e.g Kennedy Space Center.) These costs would be borne by NASA. Estimates for these services varies. The Nuclear Power Assessment[4] study estimated a cost of ~$70M ($40M non-recurring, $30M recurring). The Nuclear Power Assessment study used 9 months at Kennedy Space Center for their estimate. Recent, studies by the Y-12 security experts puts the cost estimate at a much lower value, but the time at the cape at was lowered to 1 to 2 months.

POLICY CONSIDERATIONS

The U.S. government has had a policy of minimizing the use of HEU. This policy was articulated by the Global Threat Reduction Initiative[5] based upon policy speeches by President Barack Obama. One example is the NNSA Research Reactor Convert Program which is tasked with phasing out HEU in many civilian (i.e. university) test reactors.

Although the reduction of HEU is a goal of the U.S. government, many government reactors are still using HEU. These reactors include the reactors used in the Nuclear Navy and two DOE test reactors. In these instances, national needs have been deemed higher than the need to reduce HEU, since for these applications the use of LEU impacts reactor performance.

The use of HEU for civilian purposes is not in line with non-proliferation policy objectives of the U.S. government. However, there exists clear precedence for using HEU when national priorities are impacted. The use of HEU is well established by both the U.S. and Russia governments for all space reactors used to date. HEU is the only approved material listed in the U.N. "Principles Relevant to the Use of Nuclear Power Sources in Outer Space[6]."

POTENTIAL COST IMPACTS

The cost impacts between LEU and HEU for Kilopower can be estimated from the KRUSTY project completed in March 2018. The reactor core tested during KRUSTY was built at the Y-12 plant in Oak Ridge, TN. The core was transported to the Nevada Test Site by DOE secure transport. The reactor was assembled and tested at the Device Assembly Facility. All of these assets are at Security Category Level 1. During the KRUSTY project the DOE did not charge NASA for the short-term use of the facilities. NASA only paid the marginal cost above the normal operating costs of the facilities. As an example, NASA paid for the manufacturing and processing, to cast the KRUSTY core. The actual HEU raw material was free and the building costs were paid for by the DOE weapons program.

It is anticipated that if a NASA reactor program were to go ahead for the future, the need for DOE support would continue to be short-term. Several reactor cores would be manufactured at one time. Testing would be on an as needed basis. Transport would occur only during assembly and transport. Therefore, the cost between LEU and HEU for Kilopower for these activities is likely the same.

Security at KSC has already been discussed, but the additional security costs for launching HEU compared to LEU is less than 70 million dollars (and probably much less.)

LEU could be more expensive to manufacture. LEU material would have to be down-blended from HEU which would be a cost. An LEU core would require larger fuel and reflector pieces which would increase manufacturing costs. Although, all of these costs are probably on the order of a few millions of dollars.

In summary, cost is probably not a deciding factor in choosing either HEU or LEU, given the total cost of a space reactor in the of the order of a few 100's of millions of dollars.

POTENTIAL MISSION IMPACTS

A recent conceptual design for a Lunar Kilopower demonstrator was performed by the NASA Glenn Research Center COMPASS team. The design aimed to not only land and operate a 1 kW electric fission power system on the moon but also to use that power for valuable science. It was found that an SLS or Falcon Heavy launched lander (with 2000 kg of landed payload capability) can land not only the reactor but also two 400 kg class science rovers. One rover performs stationary science and also serves as a recharging/survival node. The other is a prospecting rover and a mobile asset during periods of darkness that returns to the recharging node for power. Each of these elements could be provided with 250W of power through the service rover. The demonstrator would provide continuous science for at least one year. For redundancy, the reactor could be controlled by the service rover or a small shielded controller on the lander itself. The key design aspect to keeping the reactor shielding mass low was separating the science rovers from the reactor by 60 m using a fixed power cable. This design used HEU which kept the complete power system mass under 700 kg (includes structure and 30% growth.). The reactor fuel and reflectors weighed just over 100kg using HEU.

A trade was performed using LEU fuel for the same mission. Unfortunately, the use of LEU fuel significantly increases the fuel and reflector mass to provide the same 1 kW of power. The same fuel and reflector system using LEU weighs in at 700 kg alone, roughly the same mass as the complete HEU power system. This extra 700 kg takes up almost a 1/3 of the assumed 2000 kg payload mass. In order to keep the same lander and fit the 2000 kg payload limit several changes were performed to the design which notably reduced its science return and reliability. First the prospecting rover was removed along with one half of the cargo box. This was not enough to make up the 2000 kg mass penalty, so the on-board reactor control, communications, and shielding was removed; necessitating a zero-fault tolerant control from the service rover. So, while the LEU option can still provide power for follow-on vehicles (which will require another launch) the LEU option reduces the science return by approximately 50% and forces the mission to depend on single string, zero-fault tolerant control.

The COMPASS team has performed several Kilopower design reference missions to other targets including, a Titan, Chiron and Kuiper belt object orbiters. Fission reactors enable many orbiter missions. Thus, a big question is how LEU would impact these orbiter missions.

The Titan orbiter utilized the HEU 1 kW electric version of the power system. Being heavier the HEU design added 2-3 years trip time compared to a radioisotope system but preserved the ~100 kg of science payload and doubled the science data return using its higher power. Launched with an Atlas 551 class launcher (medium class) the Titan orbiter mission used solar electric propulsion (SEP) and chemical propulsion to reach Titan orbit. With a launch mass of over 8 metric tons, the HEU mission carried over 4 metric tons of chemical and SEP propellant. Ignoring growth and integration, the addition of 700 kg for the LEU power system would require about an additional ~1200 kg of propellants. So, the launch mass could easily grow by more than 2000-2500 kg to over 10 tons necessitating a heavy lift launcher. Since the whole vehicle is heavier the SEP system would be undersized to complete the mission in the same period, so either an additional couple of years would be needed or the SEP power level would need to be increased - again increasing mass.

The last two studies used the 10 kW Kilopower to utilize the increased power for electric propulsion. Focusing only on the Kuiper belt object (KBO) mission, the HEU system delivered a 130 kg science payload to the KBO in 16 years using a Delta IV heavy lift launcher with solid upper stage to provide a C3 of about 50 km^2/s^2 and a quick trip out of the inner solar system. The dry mass of the system was ~ 2500 kg and the xenon propellant mass was ~1200 kg for a launch mass of ~ 3700 kg. It is important to note that when growing a power system to 10 kW from 1 kW the HEU reactor portion of the mass only increases by approximately 100 kg.

Assuming a 700 kg system increase for the LEU option, (with growth to 800 kg) for a 10 kWe system the LEU system would increase the spacecraft dry mass by 800 kg (ignoring growth and integration), necessitating an additional 400 kg of propellant. So, the additional 1200 kg increases the launch mass to 5000 kg (if growth and integration were added this number would probably grow over 30%.) This would require use of the Falcon Heavy (expendable). The added mass would have one more very important impact: the heavier mass would reduce the acceleration level of the NEP vehicle - which could add trip time to the already long 16 years. The actual mission would need to be evaluated.

The estimates above are not conservative. If the actual LEU mission design were fully studied it is expected that the impacts would be worse. For these three missions, the use of LEU would either greatly reduce the science payload, necessitate the move to a larger launch vehicle, and/or add significantly increase the trip time.

CONCLUSIONS

The Kilopower development team recommends the use of HEU as the fuel for the Kilopower reactor concept. HEU provides a significant mass benefit over LEU. A design without HEU fuel will greatly diminish NASA mission science, increase mission time or prevent the missions altogether. Cost and safety will probably not be factors in the decision to use HEU. Security costs during launch and the policy issues of using HEU of great concern, but these issues are manageable.

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