Technical Advantages of HEU vs LEU for Special Purpose Reactors (SPRs)

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Summary of Key Points

- Reactors that require low mass and/or small size generally benefit technically by using Highly Enriched Uranium (HEU); this benefit is remarkably dependent on the specifics of the application, and the multitude of design constraints that complicate design and development.
- For most reactors, the penalty of using of LEU or HALEU (High Assay Low Enriched Uranium) can be accepted as either added mass and/or additional neutron moderation.
- Additional neutron moderation can add significant risk in development, operation, and reliability; this risk is highly dependent on the how the moderator is integrated into the reactor system. Given the current lack of US capability to design, develop, and deploy novel reactors, the added complexity of increased moderation could make the difference between success and failure.
- There is no simple answer regarding the benefits of using HEU for SPRs; for some applications (e.g. surface reactors with high uranium-density fuel) the penalty of HALEU can be small, but others (e.g. NTP, low-power space reactors, TRISO-fueled SPRs) the penalty can be large.

This white paper addresses the "technical" advantages of using HEU as compared to LEU (or High Assay LEU – HALEU) for special purpose reactors (SPR) applications; i.e. reactors that don't power the grid. This is intended to provide more context to the issue than provided in a white paper from 2018.[1] The 2018 paper focused on small surface power systems (especially Kilopower), in which case HEU vs LEU is essentially a trade between lower mass and higher programmatic risk of HEU. Since then, many people have turned to moderated concepts to remove the mass penalty (on paper) of LEU, which presents an entirely different discussion than what was presented in the previous white paper. A broader look at HEU vs LEU trades can be found in an upcoming publication by Lal.[2]

In almost every special-purpose reactor application, HEU has technical advantages, while LEU has programmatic advantages. The key point of this paper is that the advantages of HEU are remarkably different depending on concept requirements and technologies, and it is unwise to make any blanket statements to the contrary.

There are numerous examples of how the benefits of HEU are dependent on technology. If a reactor uses U-metal fuel (currently the most available, easiest to produce) and requires long life, fuel swelling can quickly become an issue as power increases; for a reactor where fuel swelling might present a major concern (e.g. Kilopower), the penalty of using HALEU becomes minimal above 100 kWt. In stainless-steel reactors, the high flux of an HEU core can limit the structural performance of the reactor, so that the advantage of HEU diminishes with higher power and lifetime. In UO2 or UN fueled heat-pipe or gas-cooled reactors, the design can become thermally challenged with increasing power, and at power levels of ~1 MWt the advantage of HEU starts to disappear. Whereas TRISO fueled systems (or other low-uranium density fuels) generally require a lot of fuel to go critical, and in some cases, HEU can have strong advantage up to 100s of MWt. Or, if you are going to ultimately develop a high-performance SP-100 class reactor (Li-cooled with UN fuel), HEU will provide a benefit to much higher powers than Kilopower, because the heat transfer of pumped-lithium-cooled UN pins is fantastic and UN can go to much higher burnup than UMo without complications. In some cases, depending on power level, HEU can allow external reactivity control vs more complicated internal control and/or allow a higher reflector worth to simplify safety. I could list dozens of examples. In almost every case, HEU has some type of technical advantage, it's just important to understand where it is a game changer versus a small advantage that might not outweigh the programmatic/cost challenges of HEU.

First order, the advantage of using HEU comes down to how "criticality limited" the system is, versus being limited by other design issues like heat transfer, swelling, strain, complexity, irradiation damage, mass transfer, etc. A criticality limited reactor generally has much more fuel than it otherwise would need to complete its mission, other than it requires "excessive" fuel to sustain a fission chain reaction (i.e. go "critical"). When a reactor is severely criticality limited beyond acceptable mass or fuel limits, the fallback option is usually to moderate the reactor. A moderator slows down (thermalizes) neutrons, which increases the probability of individual uranium atoms undergoing fission, and therefore reduces the amount of fuel to achieve criticality. The crux of the issue is that in many cases the addition of moderation significantly complicates reactor design, technology, and performance. However, just as when comparing HEU vs LEU, the complications introduced by moderation are highly dependent on requirements and technology; e.g. for some low temperature or short-lived applications, moderation can simplify reactor development and performance (e.g. a UZrH-fueled reactor). Water-cooled reactors use moderation and can be complex, but they benefitted from several dozens of reactor tests prior to the 1980s, plus the water "cools" itself, which is a major simplification. In general, the biggest complication of incorporating a moderator is for reactors with high outlet temperature (>700 C) and/or long lifetime (>>1 year).

Although a blanket statement cannot be made about moderation, several potential risks can be introduced by "adding" moderation to reduce critical mass; i.e. where the preferred option is too heavy and additional moderator is used to reduce size/mass. This discussion does not necessarily apply to cases where the preferred coolant (e.g. water), reflector (e.g. Be), and/or core block (e.g. graphite) also provide moderation. Some of the complications caused by adding moderation to lower critical mass are:

1) An additional material/technology is used in the reactor, which must be developed and qualified for the specific application. 2) The core geometry must allow the inclusion of the moderator and allow mechanical integration. 3) The nominal neutron spectrum of a moderated reactor does not generally allow the use of intrinsic "spectral shift" neutron absorbers. A moderated reactor often requires an additional safety system to prevent water immersion criticality; a system that must be integrated into the reactor, be proven to stay embedded during impact, and be reliably withdrawn for operation). 4) The smaller neutronic radial reflector worth of a moderated reactor can make ground, transport, and launch safety harder to address; i.e. for KRUSTY the fuel/core could not go critical in any configuration unless surrounded by the reflector. 5) Thermal management of the moderator becomes an added system design constraint, plus other design constraints specific to the moderator. 6) In most cases, the moderator will have a lower maximum temperature than the rest of the core, which will increase the potential for irrecoverable core damage during decay heat removal scenarios. 7) In some cases, a separate coolant flow stream or heat sink must be provided if the moderator is intended to operate below the primary coolant temperature. 8) A moderated reactor is generally much more sensitive to impurities or as-built material specs, as well as unknown or uncertain reactivity effects. 9) The reactivity of a hydride-moderated system can be very sensitive to the hydrogen ratio maintained by the material, with detrimental operational effects if hydrogen deviates a few percent from the design value, or hydrogen is lost or redistributed during operation. 10) Moderation will almost always substantially increase the magnitude of feedback

coefficients, which makes operation and transient response more uncertain. 11) The use of low-enriched (<20% ^{235}U) fuel exacerbates the moderator effect because of very large ^{238}U resonance absorption, and requires significantly more excess reactivity. 12) Moderation (in SPRs) will almost always move the reactor neutron spectrum into regimes where nuclear data less certain, plus the added neutronic uncertainty of the moderator itself. 13) The moderator temperature can be very uncertain because of less certain internal heating, potential heat transfer from hotter regions, and less certain heat rejection path, in particular, if a high level of insulation is required. 14) If compact, high-temperature insulation is required, the effectiveness/robustness of the insulation itself can be a major risk. 15) A moderated SPR can often result in more than one strong feedback component, which can conflict with each other to create various possible zero-reactivity state points, and create instabilities. 16) The higher magnitude and uncertainty of feedback (as well as more uncertain thermal performance) will require more reliance on robust instrumentation and a flexible, fast-acting autonomous control system. 17) The combination of #7 through #16 makes steady/dynamic performance extremely hard to predict and control, and overall makes the moderated option more reliant on nuclear-powered ground testing than a similar, higher-mass system with no moderation (or a smaller amount of moderation).

Bullet #17 can easily become a showstopper without a ground test infrastructure to perform design, build, and test iterations. This issue is discussed in detail in a paper that describes a potential early-flight NTR demo mission, referred to as FD-1[3], and also in a separate white paper.[4] The difficulty of bullet #17 depends largely on 2 design features. A) Is the moderator internal to the fuel (UZrH) or external (ZrH, YH, Be); with the latter introducing added dynamic complexity. B) Is the moderator cooled by the same heat sink, flow path as the fuel (SNAP, TOPAZ, PEWEE, LWRs) or cooled by a separate heat sink, flow path; with the latter adding an even greater layer of dynamic complexity. In all cases, the difficulties of using moderation cannot be reduced to a sound bite or a simple explanation.

Apart from moderation, another option to shift a reactor away from being too heavy due to criticality limits is to use isotopes like U-233, Pu-239, Am-242m as the fissile material, but in most cases that will likely introduce more issues than it would solve (at least for early generation systems). Alternatively, if applications can benefit from higher power or longer lifetime, then the mass penalty of being criticality limited can be mitigated by shifting requirements in that direction.

In my experience an "effective" reactor design (providing the most power-lifetime-reliability for the least mass-complexity-risk-cost) will generally balance many of the key engineering issues to a comfortable level, i.e. finding sweet spot within respective knees in the curve for each technology/phenomena. Of course, if requirements drive you to one extreme this approach goes out the window, but I think decision-makers will usually find that shifting requirements away from one extreme might give them a better solution in the end. Requirements should never be set in a vacuum (enter space reactor pun here); an understanding of technologies/limits will help the end-user achieve a more useful (successful) outcome.

There are two examples of what I consider poorly conceived requirements being pursued today. The first is for a HALEU 25-klb, 850-sec NTR[5,6]. An NTR requires an extremely high-temperature fuel, so it must either utilize a refractory metal for structure (with high neutron absorption, or highly problematic enriched isotopes) or utilize a fuel form with a low uranium density. The criticality limit of an unmoderated 25-klb HALEU concept with sufficient structure and flow area might be ~6 mT (depending on a lot of variables), while it is generally considered that a 25-klb reactor must have a mass <<~6 mT to be practical. To bring the critical mass down, significant moderation is required, which introduces a plethora of complications in technology, physics, and operation. These complications drive the NTR concept far away from any reactor that has ever been built or operated. The use of HEU would not only simplify reactor dynamics and launch safety but also allow some operational heritage to the reactor performance experience of the Rover/NERVA program. Another possible solution is that an unmoderated 6 mT reactor might be attractive for a 75-klb engine; this was the target thrust level of the Rover/NERVA program. Regardless of power level, Rover/NERVA used HEU because it allowed a rather low uranium-density fuel, simple physics, and HEU was more off-the-shelf than HALEU (which is actually still true today). Anyway, a practical 75-klb NTR could probably be pursued with HALEU. Noting that practical is still a long way from reality; an NTR is a Herculean engineering task, which is why it must be as simple as possible to have a reasonable chance for success. The test-articles of NERVA were indeed very simple relative to today's prevailing ideas, but even they did not get close to flight after ground testing 19 different reactors.

Similarly, a current US program for transportable reactors has also created a set of requirements that I believe are unlikely to produce a successful product. A 1-to-3 MWe transportable reactor can be comfortably designed using HALEU with a high-uranium density fuel (e.g. UO2, UN, UMo). Alternatively, a TRISO-fueled 1 to 3 MWe reactor could be comfortably developed using HEU. Furthermore, HALEU and TRISO might provide the best design option for Small Modular Reactors (SMRs), with powers in the several 10s of MWe or higher. Unfortunately, the combination of transportable, >1 MWe, HALEU, and TRISO create a poor set of requirements, i.e. one that is unlikely to produce a successful outcome.

In my opinion, in both of the cases above the government agencies involved did not get the proper recommendations from the people they relied upon for technical advice, whether it came internally or from academic and/or commercial partners. The disconnect may be that past reactors have been developed with repeated nuclear-powered ground testing, but today we no longer have the ability to test >100 reactors as we did in the '60 and '70s. If the US decides to go all-in on creating a high-cadence ground-testing infrastructure (10s of $B investment plus consistent stout political fortitude), then the pursuit of complex new reactor types for first-generation systems might make sense. Otherwise, only reactors that are similar to past experience and/or utilize simple and predictable thermal-neutronic physics have a decent shot a success, and more advanced concepts should evolve via future generations. I think this is true across the board, i.e. surface power, space power, NTP, NEP, Microreactors will probably only get to the ultimate desired performance with an evolutionary approach. The good news is that ANY success in ANY of these areas benefits everyone greatly. KRUSTY was the first step in that direction and hopefully, a Kilopower flight demo could be next, although other options might be possible including a low power demo of the original Megapower[7] design for Microreactors or the NASA FD-1[3] for NTP.

Even for a reactor as simple as KRUSTY, there were dozens of design issues/margins to balance;[8] criticality was of course one them, and it was only the simple nature of the system and the large, predictable design margin that allowed it to succeed (and perhaps more importantly, the streamlined programmatic approach). The goal was never to find the best performance (a combination of mass and power). The goal was to create a real reactor with acceptable performance, and as KRUSTY was envisioned and developed, the requirements were adapted to best achieve that goal. HEU provided major advantages for KRUSTY (most notably fuel availability and a compact size that was easier and safer to transport, assemble and test), and resulted in the first test of a new reactor concept in the US in over 40 years. It is important to note that the decision to use HEU in KRUSTY was not primarily based on performance; if a HALEU KRUSTY would have significantly increased the possibility of success it would have been selected. HALEU Kilopower designs are potentially practical for many applications, provided that a ~600 kg mass penalty is acceptable for the end-user. This mass penalty is similar regardless of whether the system is 1 kWe or 30 kWe (actually, a 30-kWe system is only advisable with HALEU, because fuel swelling may become a problem with HEU – 10 kWe is considered the low-risk limit for an HEU concept). For Kilopower, the reactor (sans power system) performance and development risk are largely independent of power level, or the use HEU vs LEU,[9] except that the 1 kWe HEU reactor has a leg up because has already been demonstrated. Ultimately, there is little doubt that if HALEU had been prescribed for KRUSTY it would have taken longer, cost more, and overall been far less likely to succeed.

The bottom line is that it is unwise to make blanket statements about the benefits of using HEU versus LEU for special purpose reactors. In some cases, the use of HALEU can achieve acceptable performance and could be the best option because of programmatic advantages. In other cases, the use of HALEU could likely be the difference between program success and program failure.

References:

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