KILOPOWER REACTORS FOR POTENTIAL SPACE EXPLORATION MISSIONS

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Fission systems can expand our capability to explore space by orders of magnitude. This paper presents variations of the Kilopower concept, which could provide robust, long-lived power from 1 to 10 kWe for space exploration missions. The small, simple reactor design uses existing technology and lends itself to quick and affordable development. The simplicity in design, operation and development led to the success of the Demonstration Using Flattop Fissions (DUFF) and Kilowatt Reactor Using Stirling Technology (KRUSTY) tests. Conceptual designs and masses are presented for 1-kWe space science mission, 10-kWe NEP missions, a 1-kWe lunar demo mission and a 10-kWe Mars ISRU demo mission.

I. INTRODUCTION

Space fission power development in the US has been a failure since the SNAP program in the 1960s, with billions of dollars spent and no tangible results. The key contributing factor to these failures was that programs tried to take too large of a first step; i.e. the path to success was not sufficiently simple. Simplicity is essential to any first-of-a-kind engineering project – not necessarily the simplest design, but finding the simplest path through design, development, fabrication, safety, and testing.

The Demonstration Using Flattop Fissions (DUFF) experiment was envisioned as a simple step to prove that a positive step, no matter how small, could be taken to move space fission power forward. DUFF used an existing reactor, a simple heat pipe, a rudimentary heat exchanger, and existing Stirling converters to produce electricity. The DUFF experiment was completed for <$1M in less the 6 months after it was first envisioned.

The Kilowatt Reactor Using Stirling Technology (KRUSTY) was envisioned as the next step towards successful deployment of a space reactor. KRUSTY was a prototypic nuclear-powered test of a 5-kWt Kilopower space reactor. Kilopower reactor concepts utilize heat pipes to transfer fission energy from a solid block of fuel, and are intended for simple, low-power (1 to 10 kWe) space and surface power systems. KRUSTY was designed to be as prototypic as possible within the cost constraints of a 3-year <$20M program.

II. KILOPOWER REACTORS

Figure 1 shows the basic layout of a Kilopower system. Note that there is an intentional distinction in this paper between “reactor” and “system”; the latter includes the power conversion system (PCS), which includes the converters, heat rejection, control, and overarching structure.

![Fig. 1. 1-kWe Kilpower system layout.](image-url)
e.g. at low powers (<100 kWt) thermal management and irradiation damage of components do not complicate system design. The simplicity of the system also leads to high reliability. The reactor is essentially solid-state, with the control rod being the only moving part. Actually, at low powers (~10 kW) the burnup reactivity is so small that long lifetime (10+ yr) could be achieved without any control movement after startup; higher power systems would require occasional movement to maintain reactor temperature. At all power levels, Kilopower systems can survive worst case transients (e.g. loss of power conversion heat removal) without any control action. The lack of need for real-time reactor control greatly simplifies system control. The Stirling controller can independently control the system, without potential interference and interactions caused by a separate control feature associated with the reactor. The “reactor” control system only needs to move the rod at startup, and whenever a boost reactor temperature is desired – this could possibly be done remotely when deemed necessary by a ground engineer, and thus not require any automated control software.

Another system attribute that leads to high reliability is inherent redundancy in heat transport. Each heat pipe is an independent, highly reliable mechanism. In all proposed Kilopower systems, full power can be delivered even with several heat pipes or Stirling engines failed. If three heat pipes fail that are directly adjacent to each other, then power level may need to be reduced to avoid exceeding the fuel temperature limit (assuming that heat pipe failures can be diagnosed). The baseline Kilopower power conversion approach is to attach a single Stirling engine to a single heat pipe – referred to as the 1-for-1 approach. This was the configuration used in KRUSTY, which provides the simplest suite of technologies, the simplest system dynamics, and the highest efficiency (i.e. smallest temperature drop). The 1-for-1 configuration requires a large number of small engines, which may or may not be optimal from a cost and development perspective. One negative of this approach is that if a Stirling engine fails it effectively fails a heat pipe in the core, whereas an intermediate heat transfer mechanism would eliminate this problem. However, the 1-for-1 approach provides a reliable diagnostic of heat pipe failure, which will allow mitigation of worst case failure patterns if they indeed occur (noting that the probability of heat pipe failure will likely be much lower than that of a Stirling converter).

Kilopower reactors should also be very reliable with respect to launch and landing loads. A solid block of fuel eliminates potential fuel-pin, grid plate, movements. Heat pipes should also be less fragile than the alternative – coolant piping to and from the reactor, including connections to other loop components; plus, the piping and connections will likely provide a single point failure. The Kilopower project has started to evaluate launch loads, and the system appears robust.

Finally, the compact reactor size allows for a simple approach to launch safety, transport, and nuclear and non-nuclear system testing. Kilopower reactors are essentially non-radioactive at launch. The only condition that can create a nuclear hazard is an inadvertent movement of the control rod that causes criticality. There is no conceivable launch or transport accident (including water, wet-sand, etc.) that can cause criticality unless the rod is removed. More so, the system will only go critical if the rod is removed AND the radial neutron reflector is geometrically intact. It is unlikely that any impact strong enough to remove the rod will not also remove, or least significantly crack/deform the radial reflector, and system design can help ensure this. Therefore, the only significant nuclear safety engineering required for Kilopower is to ensure the rod does not move unless it is properly commanded to do so (a feature that any reactor must have by definition).

III. REACTOR CONCEPTS

Kilopower designs have focused on two power levels, 5 kWt and 50 kWt, to be utilized in 1 kWe to 10 kWe power systems. Reactor thermal power is largely dictated by two design requirements, heat pipe throughput and the peak fuel temperature, including the margin required to tolerate various failure scenarios. To meet these requirements at a specified “rated” power, the number and diameter of the heat pipes can be optimized.

More recently, Kilopower concepts have been considered for two different 235U enrichments; 93% enriched (HEU) and 19.75% enriched (LEU). There are several pros and cons between these concepts, but overall, the HEU concepts are superior from a performance and technology perspective, and the only significant reason to consider LEU is rooted in anti-proliferation policy. Current US law and regulations allow a path for a NASA missions use HEU; in fact the KRUSTY test was fueled by HEU. Both options are provided in this paper to allow high-level decision makers to make an informed decision on the issue.

Figure 2 shows MCNP schematics of four concepts, combining the two aforementioned power levels and enrichments: fuel is depicted in gold and BeO reflector in blue. The reactor concepts use the identical material specifications as those actually used in KRUSTY. The tools used to create these concepts, MRPLOW, MONTEBURNS and FRINK, are also the same as for KRUSTY, with slight improvements based on benchmarking of the results. Therefore, the reactor mass estimates should be very accurate.
The heat pipe diameter for the concepts above were initially chosen to best accommodate their specified power level, although KRUSTY results are indicating that 50 kWt should be possible with ½” heat pipes (the size used in KRUSTY). This provides the option to design all Kilopower concepts with the same ½” heat pipe, which would reduce development cost and allow future work to focus on the performance and reliability of one size of heat pipe. This approach will also lower the mass 50-kWt core, and actually transform the 5-kWt to a 10 kWt core (with a small mass increase). The negatives of this approach are a slightly higher mass for systems that don’t require a full 10 kWt (e.g. a 1-kWe system), and a less easy transition to power levels >50 kWt. Kilopower will likely adopt the one-heat-pipe-size-for-all-reactors approach, unless there is a strong indicated demand for systems at or below 1-kWe.

IV. POTENTIAL SPACE APPLICATIONS

The ultimate goal is to use the same Kilopower for a wide range of space exploration missions. The “guts” of the Kilopower system, the reactor and power conversion are intended to be accommodate any possible launch and spacecraft configuration; the primary differences will be in shielding, heat rejection and interface structure.

IV.A Space Power: Tight Dose Requirements

Figure 3 shows the MCNP schematic of Kilopower systems that utilize the reactors shown in Fig. 2. The shielding consists of 3 layers of LiH (depicted in green) and W, and a LiH “top hat”. These concepts are designed to “tight” shielding requirements to a 4-m diameter dose plan over 15-full-power years: 1e11 nvt (neutron fluence of energy >100 keV) and 25 kRad (dose to Si), with 10 m of separation from the shield to the dose plane. All of the concepts presented in this report use the same dose requirement for the Stirling convertors: 2e14 nvt and 10 MRad.

IV.B Space Power: Relaxed Dose Requirements

Figure 5 shows the MCNP schematic of Kilopower systems designed to more “relaxed” shielding requirements to a 4-m diameter dose plan over 15-full-power years: 1e12 nvt and 100 kRad, with 15 m of separation from the shield to the dose plane.
Fig. 5. Kilopower space concepts – relaxed dose.

Visual comparison of the shielding in Fig. 3 and Fig. 5 shows the impact of the change in dose requirements. The masses are the relaxed-dose concepts are shown in Fig. 6.

Fig. 6. Space Kilopower masses – relaxed dose.

V. SURFACE POWER APPLICATIONS

Surface power applications provide three primary differences from space applications: gravity, landing loads, and in some cases an atmosphere. The intent of the Kilopower project is to use the same reactor power system for space and surface applications, with the only difference being in shielding (perhaps with simple “snap-on” modules) and a different radiator configuration.

Shielding is significantly different because of potential scattering off the surface and perhaps the atmosphere. This requires some type of 4-pi (omnidirectional) shielding, as opposed to space where everything can “hide” behind a shadow shield. However, surface missions can benefit from the ability to use in-situ materials as shields themselves: e.g. berms, sandbags, geologic features, or burying the reactor in a hole.

Two near-term surface applications are presented here; both are demonstration missions that would precede surface power for human missions. To simplify the demonstrations, the reactors are left in-place on the lander. The lifetime of the mission is made rather short (a year or two) to allow a lighter shield and simplify the overall demonstration. The lunar demo uses the 1-kWe reactor (with same reactor core as KRUSTY), and is also intended to carry a lunar science payload. The Mars demo uses the 50-kWt reactor and is landed with an ISRU (In-Situ Resource Utilization) package to demonstrate the ability to extract oxygen and potentially produce methane propellant from Martian CO2. The schematics and masses of these concepts are shown in Fig. 7 and 8.

Fig. 7. Space Kilopower masses – relaxed dose.

Fig. 8. Space Kilopower masses – relaxed dose.

Note that all of the concepts presented in the paper use the low-mass neutron shielding option of LiH. Lithium hydride involves some technical risk, including thermal management, potential loss of hydrogen, and perhaps some irradiation induced swelling at higher power levels. The end-user of the system will have to weigh this risk versus the mass savings as compared to using Be or B4C. The Kilopower project is currently investigating this issue.

The shielding of Kilopower reactors for Human missions has been studied previously. Overall, the mass to deliver 40 kWe to an outpost ranged from 5000 kg (buried reactor) to 8000 kg (reactors left on lander), with several other options possible as well.
VI. TECHNICAL CHALLENGES TO FLIGHT

KRUSTY demonstrated the nuclear-powered operation of a Kilopower reactor that was flight prototypic in most key respects. The flight-reactor technologies (fuel, heat pipes, and reflector) were operated in a vacuum at full temperature. KRUSTY power was limited to 5 kWt, but the system performance and operation at a 50 kWt system is very similar. A more detailed discussion of how KRUSTY applies to a flight-reactor is in a companion paper in these proceedings.

The 5-kWt concept, and more so the 50 kWt concepts will require additional engineering to complete a flight-system, in addition to challenges associated with ATLO (Assembly, Transport, Launch and Operations) which are not discussed here.

A 50 kWt reactor will require a different heat-pipe-to-fuel bonding method than was used in KRUSTY. At low powers <~10 kWt, the delta-T across the fuel is small enough that heat pipes can be placed only on the perimeter of the core, which simplifies bonding and assembly options. In KRUSTY, a simple interference-fit created contact pressure that provided adequate gap conductance in a vacuum. At powers >~10 kWt, it is necessary to place heat pipes within the fuel block to keep fuel delta-Ts manageable, which limits the options to force pressurized contact (except perhaps an extreme shrink/expansion fit). Three bonding options are being evaluated within the Kilopower project, a braze, a diffusion bond, and a liquid metal bond (with the core contained within a hermetic can). All of these options must consider chemical compatibility and potential mass transfer; e.g., the diffusion bond includes a layer of material between the fuel and heat pipes. The KRUSTY electrical system testing indicated that a diffusion bond is not too difficult, because the heat pipes and fuel, separated by a thin copper layer, physically bonded very quickly at 800 C in a vacuum. More recent testing is also providing encouraging results with respect to diffusion bonding of heat pipes enclosed in the 50-kWt geometry.

The Kilopower fuel is also sensitive to design power. UMo metal fuel was selected for Kilopower largely because it was the only fuel form that could be produced without substantial upfront cost or effort. Fortunately, UMo has two ideal properties for Kilopower, including high uranium loading and high thermal conductivity. One drawback of UMo is its relatively low melting point compared to its desired operating point (KRUSTY fuel operated as high as 880 C). It is rather easy to engineer the system to prevent melting, but at operating temperature the material will be “soft”, so the design must ensure there is no long-term creep caused by primary loads, or perhaps even gravity. Another issue with UMo is the aforementioned lack of chemical compatibility with most structural materials (e.g. Haynes 230) at elevated temperatures. This issue is also being evaluated and tested within the Kilopower project. Fortunately each of these issues can be mitigated with engineering and testing, and in the worst case a lower temperature (system efficiency) can provide the margin needed.

At higher powers another significant drawback is UMo fuel swelling. In general, the impact of fuel swelling should be manageable and predictable if dimensional changes are kept on the order of thermal expansion. When UMo heats from room temperature to 800 C, it expands ~4% in volume, or ~1.3% in each dimension (with the potential for some anisotropy, which can be tested for with as-cast pieces). The nuclear feedback that occurred in the KRUSTY test indirectly confirmed that there was indeed ~4% of relatively uniform fuel expansion. For a 50-kWt HEU concept the peak burnup is ~0.7 a/o with 15 years of full-power operation. This level of burnup is expected to produce ~3% volumetric swelling, or ~1% increase in each dimensions, which is less than caused by thermal expansion and allows some margin for uncertainty.

Fuel swelling is the root of the proposed 50-kWt limit for HEU Kilopower reactors (although higher powers would complicate other design issues as well). It is certainly possible that more testing on UMo swelling and/or confidence in Kilopower thermomechanical behavior could increase this power limit. LEU concepts will have substantially more swelling margin than HEU concepts. Figure 2 shows that the LEU concept has ~10 times more fuel then the HEU concept, which hurts in terms of mass, but helps in terms of swelling. The LEU system could go to several 100s of kWt before swelling becomes a significant issue. Additionally, power densities of the LEU cores are so low that core heat transfer will allow higher powers, and more heat pipes could be added to increase power further. More work would be needed to quantify the maximum practical power for an LEU system, taking into account the increased complexity of power conversion integration, ex-core component heating, possible radiation damage to non-fuel materials, etc.

Other potential lifetime issues include the ability of the control rod to remain operable (motor and bearing lifetime, and geometric integrity of the passage), heat pipe reliability (possible corrosion, mass transfer effects), component radiation effects, etc. Overall, it does not appear difficult to engineer the 50 kWt reactor to be reliable for 15+ years. It is probably more difficult to ensure the operation of the Stirling convertors for such a long time, and this will be a major consideration for any flight project. The latter will be mitigated as much as possible through redundancy, and fortunately the Kilopower concept allows great flexibility in providing redundancy.
VII. GROWTH TO MUCH HIGHER POWERS

The previous section eludes to the power level limitations of Kilopower systems, which can incorrectly lead to the argument that it is a poor investment because it is a “dead end”. This argument is bogus on many levels. First, the tried and true way to reach a dead end is to embark on a program that cannot make substantial technical progress in the first few years; i.e. every space reactor program in the past 40 years except for Kilopower. Also, history, and common sense, shows that systems that attempt to accommodate a vast suite of power levels and requirements are very likely to reach a dead end. What matters is... can the first development effort be successful, and then what is required to expand that technology beyond its specific limitations.

The key aspect of the Kilopower technology that allows the simplest evolution to higher powers is the simplicity and robustness of system dynamics and control. The underlying physics and technologies allow this attribute to apply to concepts >>1 MWt, as indicated by the same models that designed and successfully predicted the KRUSTY test. Why is this so important? Because nuclear system dynamics and control is the hardest, most expensive, and riskiest part of space reactor development and testing (due to the difficulty of nuclear-powered testing). More so, testing becomes increasingly difficult as the power level rises, so it is a huge advantage if the operation of a system can be tied to, and potential qualified by, the testing of previous lower power systems.

There are three major changes in technology that would be needed for Kilopower to evolve to significantly higher power levels. The first would be a switch from a solid cast core to a core that contains fuel rods/pellets in a monolithic block (to eliminate the aforementioned fuel swelling issue). This approach has actually been the primary focus of the Kilopower reactor design team for decades, but like all other programs it was hitting a dead end; at least until recently. The block-core reactor dynamics will be the same as the Kilopower core, with thermal expansion providing the only significant feedback effect. At powers >50 to 100 kWe, the second technology switch will likely be to change from Stirling to Brayton power conversion. This is a major technology change, but the beauty of the Kilopower load-following approach is that the heat pipes will remove power from the fuel in the same manner. The reactor will still load follow the thermal power draw; the question is how the Brayton control system will be designed best take advantage of this phenomenon.

Finally, for systems that require >1 to 3 MWe of power (a surface colony or high power NEP), the heat pipes in the core can be eliminated and a direct-cycle Brayton can be used, where the coolant flows directly through the holes in the core. The reactor dynamics will still be comparable to Kilopower, including thermal load following, but dynamics will be affected by the changing manner in which power is removed; e.g. the flow velocity, temperature, and pressure. Also, a gas-cooled system does not have the option of redundancy and may have more difficulty with decay power removal. The Kilopower design team has already spent considerable time investigating these evolutionary concepts, and they look very promising.

Regardless, the 1 to 10 kWe Kilopower technology has multiple applications right now: 1-kWe for “traditional” and enabled outer planet missions, 10-kWe to enable NEP missions to orbit out planets, moons and beyond, and 10-kWe as surface power modules for Human outposts.

VIII. CONCLUSIONS

Kilopower offers the first realistic shot in over 40 years that the US could quickly and affordable establish fission power in space. The reactor technology is simple and robust, but more importantly the operation of the technology within a power system has been proven in a nuclear-powered system test: i.e. KRUSTY. More so, Kilopower has many applications that fit within the near and long term goals of NASA, and will enable new paradigm for even more ambitious space exploration.

REFERENCES