NOTIONAL DESIGN OF THE KILOPOWER SPACE REACTOR.

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Introduction: Fission systems can expand our capability to explore space by orders of magnitude. This paper presents a reactor concept that could provide robust, long-lived power to a simple 0.5 kWe to 1 kWe space fission power system[1,2]. 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) experiment[3].

Basic Reactor Concept: The reference reactor core is a casting of alloyed HEU, with an OD of 11 cm and a length of 25 cm. There is a 4 cm B_4C startup rod that inserts into a hole along the axial core centerline. The reference heat pipe vapor temperature is 1050 K, which led to the selection of a sodium working fluid and super-alloy wick and shell. The peak fuel temperature is limited to 1200 K – a somewhat arbitrary limit until detailed thermal-structural design can be performed. The strength of uranium is rather low above 1100 K; however very little stress is expected in the core. Eight heat pipes are positioned on the outer fuel boundary to transport heat to the power conversion system. This particular configuration is limited to ~4 to 5 kWt, depending largely on the assumed conductance between the fuel and heat pipes. Significantly higher powers, 10s of kWt, can be obtained in follow on concepts by positioning the heat pipes within the fuel, and not just along the perimeter.

Each heat pipe is 1.27 cm in diameter and ~4 m long. The heat pipe design has more than a factor of 2 throughput margin – the nominal heat pipe power is ~1 kW, and the peak axial and radial heat fluxes are also well within the established limits. Similar heat pipes have been proven reliable at neutron fluences an order of magnitude higher than produced within the core. The baseline reflector material is BeO, although Be metal or a mix of Be and BeO would produce similar neutronic results.

When the startup rod is in core, it maintains subcriticality during credible operational and launch accident conditions. At startup, the rod is withdrawn to a position that achieves the desired steady-state reactor temperature. Once that condition is achieved, it is planned for the rod never to move again (hence it is referred to as a startup rod instead of control or safety rod). This strategy is allowed by the load following dynamics of the system, coupled with the extremely low fuel burnup (thus negligible burnup reactivity).

Reactor concept schematics and dimensions are shown in Figure 1. The design and analysis of this concept was completed with the design tool MRPLOW[4]. A more detailed discussion of the general concept and design philosophy is provided in a previous paper[5].

Early Design Trades: Some early design trades have been performed to determine the best Kilopower concept, noting that best is simply the concept with the highest probability of being successfully operated in space. In the tables below, the reactor mass estimate includes core, reflector, heat pipes, and startup rod, and reactor module adds the shield, instrumentation, and control.

Fuel Composition. The lowest mass Kilopower system would use straight HEU (perhaps with minor alloying), assuming that Pu, Am, etc. are off the table for an early launch system. The biggest concern with uranium is a phase change between room and operating temperature, especially if the system would need to undergo at least one full thermal-cycle or more (note: the reference flight system will likely be designed to

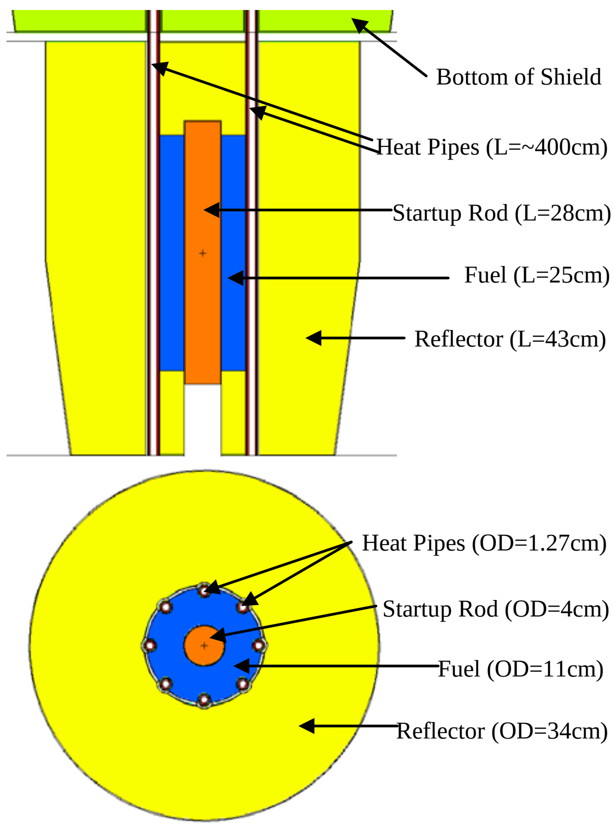

Figure 1. Kilopower Reactor Schematics

stay near operating temperature its entire lifetime).

Fuel Clad/Barrier. At elevated temperatures (>1000 K) a barrier is needed to prevent chemical interaction between the uranium fuel and super-alloy heat pipes (and potentially other structure). In addition, the strength of the candidate fuels is also very low at high temperature. The design question to be addressed is whether a thin coating can be used to provide a chemical barrier, or if structural containment is needed, which would then also serve as the chemical barrier. Currently, Mo is being considered to provide either the thin coating or the cladding. Table 2 shows the mass impact of placing a 1-mm Mo can around the fuel, versus a 20 micron Mo coating.

Table 1. Impact of fuel composition and clad.

Mass Estimate	**Reactor (kg)**	**Reactor Module (kg)**
Fuel with 20-µm Mo coating		
U	126	244
U-7Mo	164	303
U-10Mo	191	341
Fuel clad in 1-mm Mo can		
U	142	268
U-7Mo	186	335
U-10Mo	225	392

Table 1 shows a modest, yet significant increase in mass with the Mo can; however, if tests show that the fuel is too soft to prevent substantial creep over mission lifetime then it should be acceptable. Actually, the more important impact of a fuel clad might be thermal performance – it will probably be harder to promote thermal conductance between the fuel and clad than for the clad/fuel to the heat pipes.

Table 1 also shows a significant increase in mass as the Mo content of the fuel is increased. Until thermal testing of the fuel/system can be performed, it is difficult to quantify the potential risk incurred by using U versus U-7 or U-10Mo, caused primarily by the possible phase change and slightly lower strength.

The current reference is to use U-7Mo with a thin-Mo coating (either on the fuel or the super-alloy components). A detailed discussion of fuel properties and material selection is provided in a companion paper at this conference[6].

Startup Rod Follower. One of the most effective ways to reduce the size/mass of a leakage dominated system is to add a follower to one end of the control rod (i.e. a material that fills the void created by withdrawing the neutron absorber). A fuel follower is most effective, but adds several significant design challenges (including power removal, reactivity sensitivity, safety, etc.). A reflector follower mitigates the major design issues, but is less effective and still has challenges, including system integration. Table 2 shows the mass impact of using a BeO follower with both the U and U-7Mo fuel.

Table 2. Impact of rod BeO follower.

Mass Estimate	**Reactor (kg)**	**Reactor Module (kg)**
U fuel with coating		
Without follower	126	244
BeO follower	106	214
U-7Mo fuel with coating		
Without follower	164	303
BeO follower	135	258

Table 2 shows that a BeO follower reduces reactor module mass by ~20%, which likely corresponds to a ~15% drop in power system mass. The current reference is to not have a follower, because of the potential design and integration complexity.

Scalability to Higher Powers: The reactor concept presented is tailored to the low powers needed for the Kilopower concept and to be as simple as possible to develop. The generic concept of a block-fuel reactor cooled by heat pipes can go to much higher powers (several 10s of kWt) by adding more heat pipes and embedding them within the fuel. As powers increase, the concept will become more and more dependent on high, reliable component conductances (perhaps via braze or diffusion bond). In addition, at powers >~20 kWt a control system will be needed to compensate for burnup reactivity loss during the mission. At powers >~50 kWt the swelling of the fuel may become significant, such that a pin-type reactor, or a concept with robust fuel structure would be needed. In general, reactors of this type up to ~50 kWt are very simple; however several factors in development and testing become more difficult as power increases. The proposed 4-kWt system is perfectly suited for initial development because of low development cost and risk.

References: [1] Mason L., Gibson M.A., and Poston D. (2013) *NASA TM-2013-216541*. [2] Gibson et. al. (2014) NETS-2014. [3] Poston D.I. et al (2013) NETS 2013-6967. [4] Poston D.I. LA-UR-12-20216 [5] Poston D.I. et al (2013) NETS 2013-6965. [6] Creasy J. et. al. (2014) NETS-2014.