REACTOR MODULE DESIGN FOR A KILOWATT-CLASS SPACE REACTOR POWER SYSTEM.

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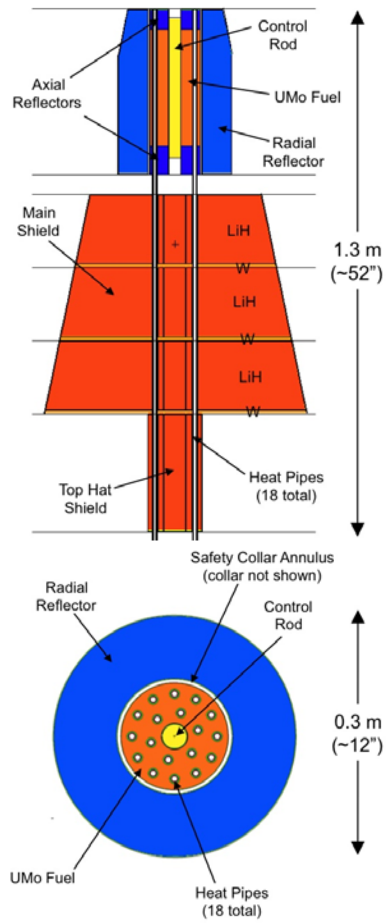
Introduction: NASA has dependably relied on radioisope power systems for many decades. As future space exploration missions become more ambitious, the need for more power could present two issues: 1) the higher mass of >1 kWe radiositope systems might limit exploration capabilities and 2) the supply of ^{238}Pu or alternatives might become limited. Fission power systems can provide a compliment/alternative to radioisotope systems in many scenarios. A simple fission system based on existing technology could provide robust, long-lived power in the range of 1 to 10 kWe.

System Options: The reactor concept for a kilowatt-FSP system will have to be very light/compact, relatively high-temperature, and have a lifetime of ~10 years (for deep space missions). These requirements lead to a fast-spectum reactor, cooled by heat pipes or pumped liquid-metal. Near term power conversion technologies that could meet these requirements are thermoelectrics or Stirling engines. This study examines an 1100 K, 15 kWt heat-pipe cooled reactor that could provide power to a 1-kWe thermoelectric power system or a 3-kWe Stirling power system.

Reactor Concept: The reference reactor concept utilizes a metallic fuel that conducts fission heat to in-core heat pipes, which then transfer the power through the shield to the power conversion system. The reactor is controlled by an in-core control rod. An annular safety collar is used to satisfy launch safety requirements. The figures below show a reactor and shield side view, and the radial core cross section.



Fuel: The fuel selected for the reference reactor is U10Mo (uranium 10 w/o molybdenum). This fuel was selected for its high uranium density, high thermal conductivity and excellent neutronics characteristics (low neutron capture at fast energies, modest capture at moderated energies, and inherent gamma shielding). One of the potential concerns with U10Mo is material swelling at relatively low fuel burnup (~1%), however the burnup in this application is so low (~0.1%) that swelling should not be a significant technical risk. The reference form of the U10Mo is cylindrical plates, with plate thickness defined by manufacturing and assembly considerations. These plates will contain holes for a central control rod and in-core heat pipes. The fueled region is 12.9 cm in diameter and 30 cm tall. For this study, a maximum fuel temperature of 1200 K was imposed on the fuel, which significantly influences the core and heat pipe geometry.

Core Internal Structure: One of the key features of the proposed concept is that the fuel can provide its own structural support. The core assembly would contain a can or a liner to prevent material interactions or perhaps inhibit fission gas release (which may be negligible due to the low burnup), but a structure it is not required to ensure/maintain fuel physical integrity. This feature (or lack thereof) is also enabled by the very low burnup, thus minimizing possible mechanical changes in the fuel. The advantages of this approach are that it minimizes the amount of structural material neutron absorption in the core (keeping the core compact) and the temperature gradient losses through fuel structure. A nickel-based superalloy (e.g. Hasteloy-X) is a good candidate for whatever structural or can material that might be required. Molybdenum is a good candidate material if a liner is required.

Heat Pipes: The reference reactor is cooled by liquid metal heat pipes. The proposed geometry uses 18 heat pipes: 6 in an inner ring and 12 in an outer ring. A “ring” geometry provides symmetry and simplifies power conversion integration. The spacing of the heat pipes minimizes the distance that heat must travel through the fuel; which keeps the fuel temperature below 1200 K, and the temperature gradients and thermal stresses relatively low. The reference heat pipe vapor temperature is 1100 K, which led to the selection of a sodium working fluid and super-alloy wick and shell. Each heat pipe is 1.11 cm in diameter and ~4 m long. The heat pipe design has more than a factor of 2 throughput margin, given the nominal heat pipe power of about 800 W, 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. There are several possible options for thermally coupling the heat pipes to the fuel, including a braze, a HIP (Hot Isostatic Press) or a liquid-metal or gas bond. As the design evolves, each option will be evaluated for technical risk, cost, and reliability.

Neutron Reflectors: A very "high-worth" reflector is needed to keep system size small and also to make launch safety accidents relatively easy to accommodate. The reflector material specified for most space reactors is Be or BeO: all other candidate materials do not have sufficient reactivity worth to meet the currently assumed launch accident criticality requirements. For this application, a compact geometry is highly desirable, thus BeO was chosen because it is a denser, higher worth material per unit thickness than Be. The proposed concept places the BeO in brick form within a stainless-steel (or superalloy) can. The neutron fluence is expected to be low enough that BeO swelling and cracking should not be a significant technical issue. If detailed design and investigation indicates material degradation may be an issue, then a BeO powder may be a better choice (but with a lower density, thus requiring a thicker reflector). The radial reflector surrounding the core is 7.7 cm thick. The upper axial reflector is 5 cm thick and the lower axial reflector is 7 cm thick (the lower reflector optimizes to the thicker geometry because it also provides shielding benefit).

Control Rod: Nominal reactor control is performed with a central boron carbide (B_4C) control rod that is clad with Hasteloy-X. The rod will be moved by a drive mechanism on the back side of the shield, with a drive-shaft penetrating straight through the shield. The control rod contains the required reactivity worth to ensure the reactor can be started from a cold subcritical condition to full-temperature critical operation. One of the significant advantages of this concept is that further reactor control is not required after startup. If there is no control rod movement, the reactor temperature will slowly degrade with time, by approximately 3 K per year or 45 K over the entire 15-year mission. The hot-end temperature drop would cause a small decrease in reactor thermal power over time, although the drop in effective heat sink temperature in the outer solar system may counteract this effect, allowing full power throughout the mission.

Safety Collar: The simplest design approach to meet the assumed launch accident safety requirements was to place an annular B_4C collar between the reactor and the radial reflector. This collar would be removed from the core once the probability of Earth return became negligible. The collar/mechanism design will ensure that the collar remains in place during launch, but is ejected prior to reactor startup.

Radiation Shield: The reference shield utilizes lithium hydride (canned in stainless steel) as the neutron shield material and tungsten as the gamma shield material. The LiH is enriched in ^{6}Li to reduce the gamma source from neutron capture in the stainless-steel and tungsten, and because ^{6}Li is naturally lighter than ^{7}Li. Tungsten or any other high-Z material serves as a better gamma shield because it reduces the thickness and therefore, the geometric expansion of the shield diameter into the shield cone. The reference shield utilizes 3 layers of LiH and W, with each layer of LiH being placed in a stainless-steel can. The shield contains full penetrations for the heat pipes and the control rod shaft. A gap is provided around each heat pipe in which multi-foil insulation will be placed to prevent shield heating and parasitic power loss. Shielding calculations showed that the streaming dose through these penetrations accounted for approximately 50% of the payload dose. Consequently, a "top hat" shield was added behind the main shield that substantially reduced this streaming dose.

Safety Analysis: Fission reactors pose no radiological risk to personnel or the public until they have operated. Therefore, unintentional criticality is the only significant "nuclear" safety issue. Safety during ground operations is covered by existing DOE orders. Safety in the event of launch failure is ensured by evaluating and testing reactor criticality under credible accident configurations and environments. For this study, three accident environments were evaluated: a) internal voids empty, external voids filled with dry sand, b) internal and external voids filled with fresh water, resting on concrete, and c) internal voids filled with sea-water, external voids filled with wet-sand. Two configurations were evaluated: 1) radial reflector and all surrounding material stripped off (i.e. bare reactor core), and 2) radial reflector compacted yet intact, control in. There is no basis to imply that any or all of the evaluated scenarios are credible from a launch safety perspective; rather, they are evaluated to provide confidence that the concept should remain subcritical during what might eventually be deemed a credible accident scenario. The reactor k-eff was <0.985 for all combinations of the above configurations and environments.