LA-UR-14-23402

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Title:	KiloPower Space Reactor Concept - Reactor Materials Study
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Intended for:	NASA Deliverable
Issued:	2014-05-14

KiloPower Space Reactor Concept
Reactor Materials Study

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Introduction

This paper presents the logic and analysis used to produce an initial choice of fuel, reflector material and heat pipe placement for the Kilopower reactor concept. Kilopower is a small 4 kWt (1 kWe) space reactor system that uses a highly enriched uranium core with heat pipes to deliver thermal energy to Stirling engines to produce electricity.

First, the paper presents the logic behind the initial selection of uranium metal as the base starting point for the fuel over a myriad of other fuel choices. Next, a material study was performed that examined the choices of potential alloy materials for uranium, choices for reflector material and choices for the location of the heat pipes.

The results of the material study was a fuel choice of highly enriched uranium alloy with 7% molybdenum, a reflector choice of beryllium oxide, and a choice for the heat pipe placement at the edge of the fuel.

This report is a companion document to heat pipe mechanical design performed by NASA Glenn Research and materials research/manufacturing design work performed by NASA Glenn and Y-12.

Selection of Uranium Metal as Base Fuel

This section presents the logic as to why uranium metal was selected as the base fuel concept and serves as a lead-in to the material study.

The first two sections establish the requirements for the fuel. The next sections present the selection logic for the selection of uranium metal.

Why Commercial/Test Reactor Fuel Qualification is Not Needed

This section addresses what type of fuel data or research is needed for the Kilopower space reactor concept. The type of data needed is based upon the design requirements placed on the fuel. It his therefore helpful to explore the NRC requirements placed on fuel and compare those to the requirements needed for the Kilopower space reactor concept.

A common misperception is that the NRC qualifies fuel for use in commercial nuclear reactors. In reality the NRC qualifies a “fuel system” that includes the fuel, its cladding and its associated temperature/mechanical limits based upon the type of reactor coolant. The guiding principle behind the qualification process is the "Defense-in-Depth" philosophy that mandates a reactor design maintain multiple barriers to the release of radioactive fission products from the reactor (typically the fuel cladding, reactor vessel and reactor containment comprise the traditional barriers.) In pursuit of this principle, the NRC has requirements that are derived from the Code of Federal Regulations (CFRs) that provide performance criteria for the "fuel system". Most criteria are in the form of general design criteria. Other criteria are more specific rules (such as the "emergency core cooling system" rule.)

As nuclear fuel undergoes fission, fission gas is produced. This fission gas can cause fuel swelling or the gas is released from the fuel. Fuel swelling combined with neutron damage to the fuel pellets cause changes in the fuel properties (such as thermal conductivity). The combination of fuel swelling, fission gas release and changes in the fuel properties can cause the fuel cladding to be ruptured from stress or cause changes in the heat transfer at the cladding – reactor coolant boundary. Any or all of these issues can cause fuel cladding failure, thus violating the "Defense-in-Depth" philosophy and the NRC requirements.

Given these issues with commercial reactor fuel, a great deal of effort is put into obtaining data that supports the position of the reactor designer that fuel will be safe under all conditions. A large portion of this data is obtained by putting new reactor fuel into a test reactor to obtain fuel behavior as a function of fuel burn-up (a measure of the number of fissions). Other data for the fuel is obtained from fuel-coolant flow experiments. These experiments can take years to complete.

This process is not appropriate for selecting a fuel for a deep space reactor. The fuel for a deep space reactor is not attempting to comply with the "Defense-in-Depth" philosophy of the NRC by preventing cladding failure. The next section provides the requirements for a space reactor such as the Kilopower reactor concept.

Kilopower Fuel Design Goals and Requirements

The design goal for the Kilopower space reactor fuel is simply <u>to produce the appropriate level of thermal power at the appropriate temperature while keeping the core as small and light as possible</u>.

The required design function of the core is to:

- Work neutronically (i.e. go critical and provide the appropriate excess reactivity to reach the design temperature of the system),
- Maintain geometry (needed for neutronics and mechanical integrity), and
- Transfer heat to the heat pipes (a part of maintaining geometry).

It is not required that the fuel hold in fission products (the fuel has no cladding, given it is not attempting to protect the public while operating. It will not be operated until it is in deep space.) Nor is it required that the fuel maintain some severe mechanical constraint (such as supporting a large mechanical load.)

Fuel Burn-Up, Swelling and Radiation Damage

The fuel for the Kilopower system will have virtually no burn-up. The burn-up over a 15-year life for a 1 kWe (4 kWt) system will be less than 0.1%. The low power of the Kilopower system means very few fissions occur over the life of the reactor. The amount of fuel needed is based on the amount necessary to achieve a critical mass, but almost all of the fuel will be un-used at the end of 15 years.

This is an important fact because no burn-up means no swelling of the fuel due to fission gas generation. A plot of volumetric swelling as a function of burn-up is shown in Figure 1. As can be seen in Figure 1, no burn-up means no fuel swelling.

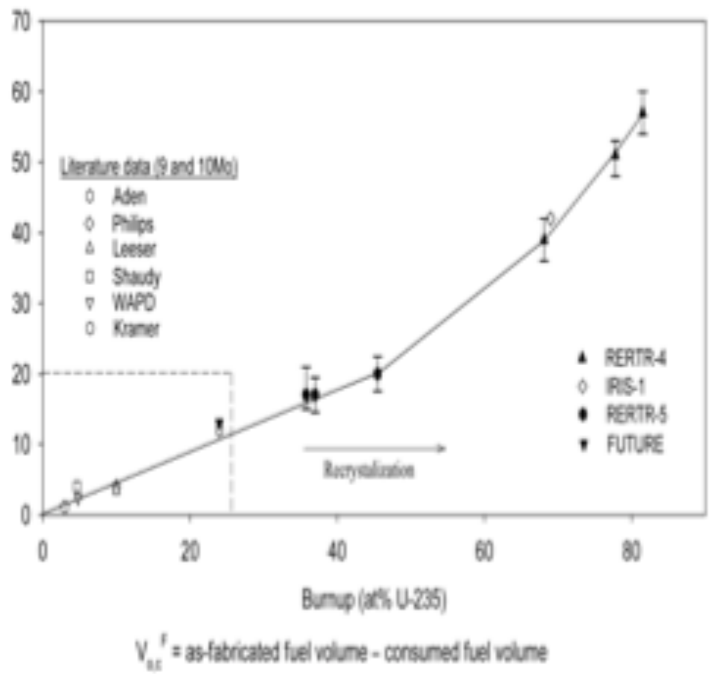

Figure 1. Fuel Swelling as a Function of Fuel Burn-up[1]

The most conservative of calculations based on good data show that fuel swelling can be safely ignored as a phenomena. The volume change percent for Kilopower (based on 0.33e20 fissions/cc) would be 0.12% using the formula from Hofman[2].

$\Delta V/V = 0.356*B$,

where B is in fission density in 10e20 fissions/cc in change in volume is volume percent

$\Delta V/V = 0.356 * 0.33e20$ fissions /cc = 0.12%

This value for fuel swelling, due to irradiation, is ten times less than the fuel volume change due to standard thermal expansion based on temperature and can safely be ignored as a second order effect.

1 U-Mo Fuels Handbook, by J. Rest, Y. S. Kim, G. L. Hofman, Argonne National Laboratory and M. K. Meyer and S. L. Hayes, Idaho National Laboratory, June 2006, Figure 6.1 - Burnup dependence of U-Mo swelling, pg. 31

2 G.L. Hofman and M.K. Meyer, “Progress in Irradiation Performance of Experimental Uranium-molybdenum Dispersion Fuel,” International Meeting on Reduced Enrichment for Research and Test Reactors, 2002.

In addition, the radiation damage to the fuel will be very low. Radiation damage will have no significant impact on material properties of the fuel or the reflector.

Uranium Metal as the Fuel Start Point

If the design goal for the Kilopower space reactor fuel is to produce the appropriate level of thermal power at the appropriate temperature while keeping the core as small and light as possible, then the atom density of uranium 235 is the key parameter. The larger the U-235 atom density the smaller and lighter the reactor will be. Therefore, other fuels forms, such as uranium oxide, uranium nitride or uranium carbide are eliminated. These fuels include oxygen, carbon and nitrogen atoms that take up space needed by uranium atoms. The best choice for a fuel then is a pure uranium metal (the material with the densest concentration of U-235 atoms as possible) because it make for a small and light of reactor core possible. This means a highly enriched U-235 metal is the starting point for fuel selection.

Materials Study for Kilopower

This section presents the materials study for Kilopower. The section is divided into an introduction, background and research objectives, scientific approach, accomplishments and the initial reference reactor concept based upon the results of the study.

Introduction

Y-12, NASA and LANL looked at various combinations of alloys to uranium metal as possible fuel choices. Un-alloyed uranium is the best choice for keeping the core as small and light as possible (given that it produces the highest uranium atom density of any available fuel). As will be shown, un-alloyed uranium could work, but margins in some properties (like creep) were not sufficient to have a high certainty of success. Other trade studies were then performed with various alloys (moly, vanadium, etc.) Most of the alloys with uranium provided sufficient margin in material properties that a core could be produced. In addition, an alternate design method was to “can” the un-alloyed uranium core in a material with the appropriate mechanical properties, thus maintaining the geometry of the core. The drawback to a canned core is that the can will absorb neutrons thus requiring more fuel and increased weight.

Background and Research Objectives of Materials Study

Heat pipe/Stirling engine reactors have been proposed because of their inherent simplicity. The simplicity of these reactor argues for a reliable, safe, easy to operate and easy to manufacture reactor. One of the key features of these types of reactors is the reactivity feedback mechanism that allows for the reactor to be self-controlling. Fast reactors in this size range are controlled by thermal expansion and subsequent negative reactivity feedback. Thermal feedback lowers reactor power if less heat is extracted by the power conversion. In self-regulating cores, therefore, a narrow temperature region exists over which design power can be delivered to the power converter; any change in one parameter will necessarily change the other. Precise understanding of coupled core and heat conversion system physics is essential to accurately designing and/or predicting the operating envelope of self-regulating nuclear reactors. This means that design selections such as the type of uranium alloy and its casting and engineering details such as the fabrication methods used to achieve thermal bonding between various components of the heat conversion system can have huge impacts on the overall performance of the reactor system. The purpose of this research was to investigate a matrix of materials and bonding techniques for the fuel and reflector and run a series of calculations to optimize the choice of materials.

The greatest risk in the proposed design is the uncertainty in material properties and the impact of the bonding technique on heat transfer for the reactor fuel and reflector. The goal was to determine what form of U-metal fuel (U, U-Mo, U-Zr, U-V) and at what mass fractions can the U-metal fuel simultaneously meet the thermal-structural requirements of the system, while at the same time maximizing effective uranium density (to decrease mass of system). Another difficult challenge is to develop a method to thermally and mechanically bond the components; this bond must provide reliable thermal conductance in a vacuum for 15+ years between dissimilar metals at very high temperatures (~1100 K). A reliable bond will preclude fuel melt, while a more resistive bond (such as a radiative heat transfer gap) may not provide reliable operation.

Scientific Approach of Study

This research was performed with the two principle LANL reactor design tools. The first design tool is the radiation transport code, MCNP6. MCNP6 (Monte Carlo Neutron Photon) is the LANL Monte Carlo code for radiation transport. The MCNP code is widely used in studies of advanced reactor concepts, either directly as a main-line design tool or indirectly as part of the verification/validation process. MCNP is routinely used to calculate k-effective and detailed distributions of power and reaction rates. MCNP provides highly accurate results, using continuous-energy physics, ENDF/B-VII nuclear data, and explicit 3D constructive solid geometry.

The second design tool is the systems modeling code FRINK. The systems model is a point kinetics neutronics model coupled to a two-dimensional heat transfer model. The model is based upon a Fortran based code developed at LANL called FRINK7. FRINK models reactivity coefficients individually by component. The system models heat transfer conduction in the core and includes gap conductances. The model includes time dependent thermal properties. The model also includes a heat pipe model (including heat pipe physics), and a representation of the energy removed by the operation of the Stirling engine.

A high-uranium density fuel is needed to design a system that is attractive (i.e. low mass) to NASA. The ideal fuel candidate from a mass perspective is pure uranium HEU; however, pure uranium metal has an anisotropic response to neutrons and becomes very soft at high temperature (>800°C). The following materials were examined in this study as candidates for the fuel.

- Pure Uranium
- U doped with small quantities of Fe or Si
- Uranium with 2.5% Vanadium
- Uranium with 1.5%, 7% and 10% Molybdenum
- Addition of a can (stainless-steel) around the fuel

Material properties for pure Uranium were provided by MST-6. Material properties with the additive materials were provided courtesy of staff at the Y-12 plant.

There are only 2 candidate reflector materials that could meet the anticipated requirements for a NASA flight system: Beryllium (Be) and Beryllium Oxide (BeO). Other materials will not have sufficient neutron reflection to meet launch criticality safety requirements (e.g. the reactor falling in water and/or sand) and also allow compact geometry and low fuel mass. Both were examined as part of the study. The material properties for Be and BeO were provided by MST-6.

The final issue was how to create an acceptable thermal-structural bond between the fuel, heat pipes and reflector. The first concept examined was to embed the heat pipes in the reflector, because this simplifies system development. The second option was to bond the heat pipes to the outside of the fuel (in this configuration, between the fuel and reflector) because this lowers the temperature gradient. This option could include a gap between the reflector and fuel to lower temperatures in the reflector. Also, the heat pipes on the outside of the fuel were examined with a gap and larger heat pipes so as to lower temperature gradients in the fuel.

In order to score a measure of success from modeling, criteria were needed to score each design configuration. The criteria are presented below. The criteria are all weighted equally.

- Lowest system mass;
- Smallest size (radial and axial dimensions of system);
- Smallest delta temperature across reactor fuel and heat pipe;
- Least Impact on reactor neutronic performance (smallest neutron absorption);
- Least impact from off normal performance (least estimated probability for melting, cracking or softening of fuel or reflector);
- Least potential for long-term material interactions (probability of material interactions leading to degraded performance);
- Least impact to launch safety accidents (pass-fail on k-effective greater than 1 for design basis accidents).

The following "matrix of calculations" was performed to evaluate the materials against the success criteria to down-select to the appropriate design for the reactor concept.

Table 1. Matrix of Calculations

		Fuel Composition					
		U	Doped U	U-2.5%V	U+1.5% Mo	U+7% Mo	U+10% Mo
Reflector and Heat Pipe Configuration	BE + HP Refl	●	●		●		
	BeO + HP Refl	●	●		●		
	BeO + HP edge	●	●		●		
	BeO + HP edge + gap	●	●	●	●	●	●
	BeO + HP edge + gap + Big HP	●	●				

Accomplishments of Materials Study

Table 1 formed an initial set of 23 calculations done with MCNP and the systems model, FRINK. The results of these calculations gave the following insights:

- Vanadium performed slightly worse than Molybdenum in impacting neutronics for similar material quantities. Also the data set for Vanadium was less robust than for Molybdenum (potential for adverse thermal issues.) Vanadium was then dropped from further consideration.

- Heat pipes in the reflector did not perform as well as heat pipes at the edge of the fuel with a gap between the fuel and the reflector. The heat pipes in the reflector produced too large of a delta temperature for the power level of the reactor. By placing the heat pipes at the edge of the fuel the delta temperature was lower. Also, a mechanical press fit of the heat pipes to the fuel is possible in this location. Finally, if a gap was introduced between the fuel and the reflector (only with heat pipes at the edge of the fuel), the reflector ran cooler and thus less excess reactivity was needed in the system. <u>For these reasons, the heat pipes at the edge of the fuel were selected for the design</u>.
- Beryllium Oxide and Beryllium both performed well for the system neutronically. <u>BeO has better high temperature properties and was selected as the reflector material.</u>
- Configurations with a higher length to diameter ratio were favored over small ratios for launch safety considerations. This was a discriminator for some of the Molybdenum plus U systems.
- Doped U systems behaved neutronically and thermally identical to pure Uranium systems. It is believed that the dopents will assist in grain refinement, yield strength and ultimate strength. Creep strength was believed to be unaffected. However, both U and doped U have a low creep strength at the desired operating temperature. This issue introduces uncertainty into the performance of the system, as discussed in the next bullet.
- Uranium (or doped U) versus Uranium plus Molybdenum was a hard decision; in fact, so difficult that a sub-matrix of these two options was done that included an additional 22 calculations on small variations within this sub-matrix. Both Uranium fuel and a Molybdenum alloy had positives and negatives. U and doped U make for a smaller, lighter core that has the best neutronics (they have the highest density of uranium). However, material properties are pushed to their limit and the probability of failure is higher than desired (this uncertainty in strength at high temperatures was described in the previous bullet). Molybdenum added to Uranium was acceptable for size, weight and neutronics and eliminates most material limits issues. However, the size and mass was less than ideal for shipping and manufacture. The final selection was 7% Molybdenum added to Uranium because the material properties removed the issue of phase change, low melting temperature and issues with creep strength at high temperature. Mass estimates for 7% Moly ranged from a low of 258 kg to over 300 kg, which was competitive to the pure Uranium systems with a mass range of 226 kg to 255 kg. <u>For this reason, the 7% Moly alloy was chosen as the final material for the reactor design.</u>
- An alternative to the selected design would be to can the pure-uranium system in a stainless-steel or Haynes 320 outer shell. This design choice would be larger and heaver (~300 to 310 kg) than desired for the system with 7% Moly, but is still competitive.

Preliminary Reference Reactor Design

The reactor for a kilowatt space fission power system has to be very light/compact, relatively high-temperature, and have a lifetime of ~10 to 15 years (for deep space missions). These requirements favor a fast- spectrum reactor, cooled by heat pipes. The reference reactor concept utilizes a metallic fuel that conducts fission heat to heat pipes, which then transfer the power through the shield to the power conversion system. The reference reactor concept is very simple. The core is a casting of HEU with 7% Molybdenum as an alloy, with an OD of 11 cm and a length of 25 cm. There is a 3.7 cm B4C control rod that inserts into a hole along the axial core centerline. The reference heat pipes have a super-alloy steel wick and shell. The peak fuel temperature is limited to 1200 K, which limits the core power to ~4 kWt; which depends largely on the assumed gap conductance between the fuel and heat pipes. 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, given the nominal heat pipe power of about 1 kW, and the peak axial and radial heat fluxes are also well within the established limits. The baseline reflector material is BeO, although Be metal or a mix of Be and BeO produce similar neutronic results. The reference power conversion system configuration uses multiple Stirling engines to produce 800 to 1000 Watts of electricity. A schematic of the reference design is shown in Figure 2.

The operations k-eff values, as calculated by MCNP, for the reactor concept are shown in Table 2.

TABLE 2. Operational Criticality Results.

Reactor State	**k-eff**
Cold-BOL-Rod out	1.0352 +/- 0.0005
Cold-BOL-Rod in	0.9590 +/- 0.0005
Warm-BOL-Rod out	1.0118 +/- 0.0005
Warm-EOL-Rod out	1.0102 +/- 0.0005

Fuel Type: The fuel should have established performance/properties in the proposed environment (temperature, burnup and fluence) and an existing production and fabrication infrastructure. A metallic fuel is the best option to meet the aforementioned attributes. The most common metallic fuel forms use an alloying metal. For this reactor design a 7% molybdenum alloy was chosen as the best option for performance and material properties. One of the primary reasons to alloy the fuel is to prevent a phase change over the operating temperature range. A phase change generally causes an abrupt change in density and other properties, and the reactor mechanical design must accommodate this.

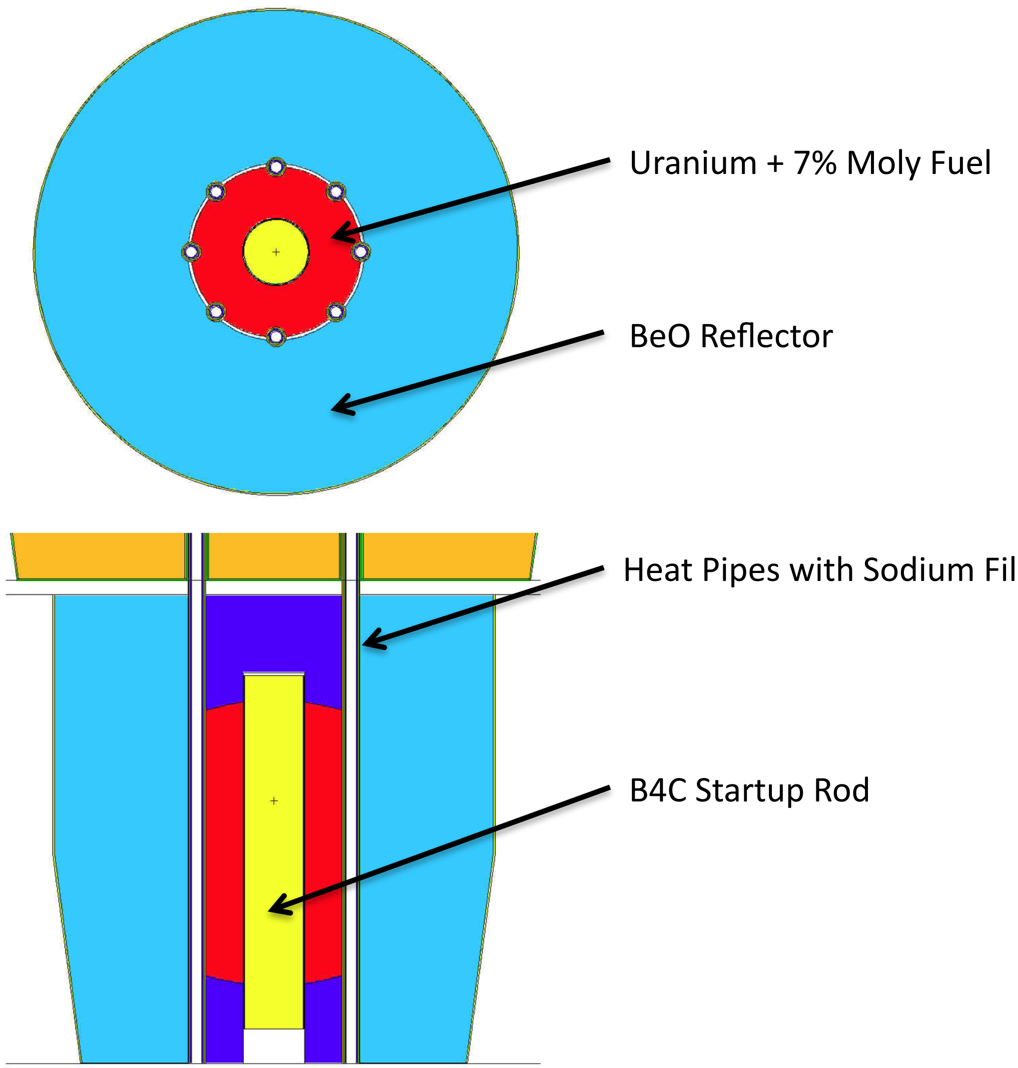

Figure 2. Reference Reactor Concept

Fuel/Reactor Geometry: Although not neutronically optimal, a cylinder with an L/D >1 is generally preferred because it reduces shield size, shortens heat conductions paths, and adds more heat transfer area from the fuel to the cooling mechanism. Perhaps the most compelling reason for a cylinder with a high L/D is to meet criticality control and safety requirements. A control rod has maximum neutronic worth when in the center of a long L/D cylinder, and a control mechanism aligned with the system/launch axis is generally easier to integrate. Criticality safety is also simpler with a very high worth radial reflector (facilitated by a high L/D).

Heat Pipes: The reactor is cooled by liquid metal heat pipes and the proposed geometry uses 8 heat pipes in a circular pattern in the gap between the fuel and radial reflector. The optimal size, number and placement of heat pipes is dependent on a large number of factors; most importantly the temperature drop from the fuel to the power conversion system. The number and location of the heat pipes determines the average distance that heat must flow to reach the heat pipes; the shorter the distance the lower the delta-T. Two different approaches for attaching the heat pipes are shown in Figure 3. The first uses a portion of the core wall and screws to mechanically attach the heat pipes to the core. The second uses non-HEU clamps to mechanically attach the heat pipes to the core. Both would be acceptable solutions for the design.

Neutron Reflector: 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.

Radiation Shield: The reference shield utilizes lithium hydride (canned in stainless steel) as the neutron shield material and depleted uranium as the gamma shield material. The shield contains full penetrations for the heat pipes, plus a gap for multi-foil insulation to prevent shield heating and parasitic power loss.

Reactor Operation and Control: The reactor control of this concept is the simplest imaginable for any fission reactor. There is one neutron absorbing control rod; when it is in the core the reactor remains subcritical under all credible scenarios and when it is out of the core the reactor is supercritical (with the full Be reflector present). The position of this rod sets the average temperature at which the reactor will be critical during steady-state operation; to a first order, this reactor temperature is independent of the reactor power. If more power is removed by the power conversion system, then the reactor power will increase to maintain this temperature, or vice-versa. Except for small second order effects, the reactor power will load follow the power draw demanded by the power conversion system.

Nuclear Safety: 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 testing is covered by existing DOE orders. The configuration of the reference reactor greatly simplifies operational criticality safety. The core cannot go critical in any scenario when the B4C rod is inserted. Furthermore, even with the rod removed the HEU core will not go critical unless surrounded by Be or BeO (even if it is accidently dropped in water).

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) all voids and surroundings filled with pure fresh water, b) all voids and surroundings filled with pure dry sand (64% SiO_2), c) all voids and surroundings filled with wet sand (64% SiO_2, 36% seawater), Two configurations were evaluated: 1) nominal as-launched condition and 2) radial reflector, startup rod, and all surrounding material stripped off (i.e. bare reactor core). 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 bounding credible accident scenario (bounding because the reactor is infinitely reflected on all sides, the materials are free of impurities, and every possible void is flooded. The reactor had k-eff <0.985 for all combinations of the above configurations and environments.

Power System: The reactor could be used to provide power any form of Power Conversion System (PCS), but has been designed with Stirling engines in mind. The baseline technology is to use modified Advanced Stirling Converters (ASC) that have been developed for NASA’s Advanced Stirling Radioisotope Generator (ASRG).

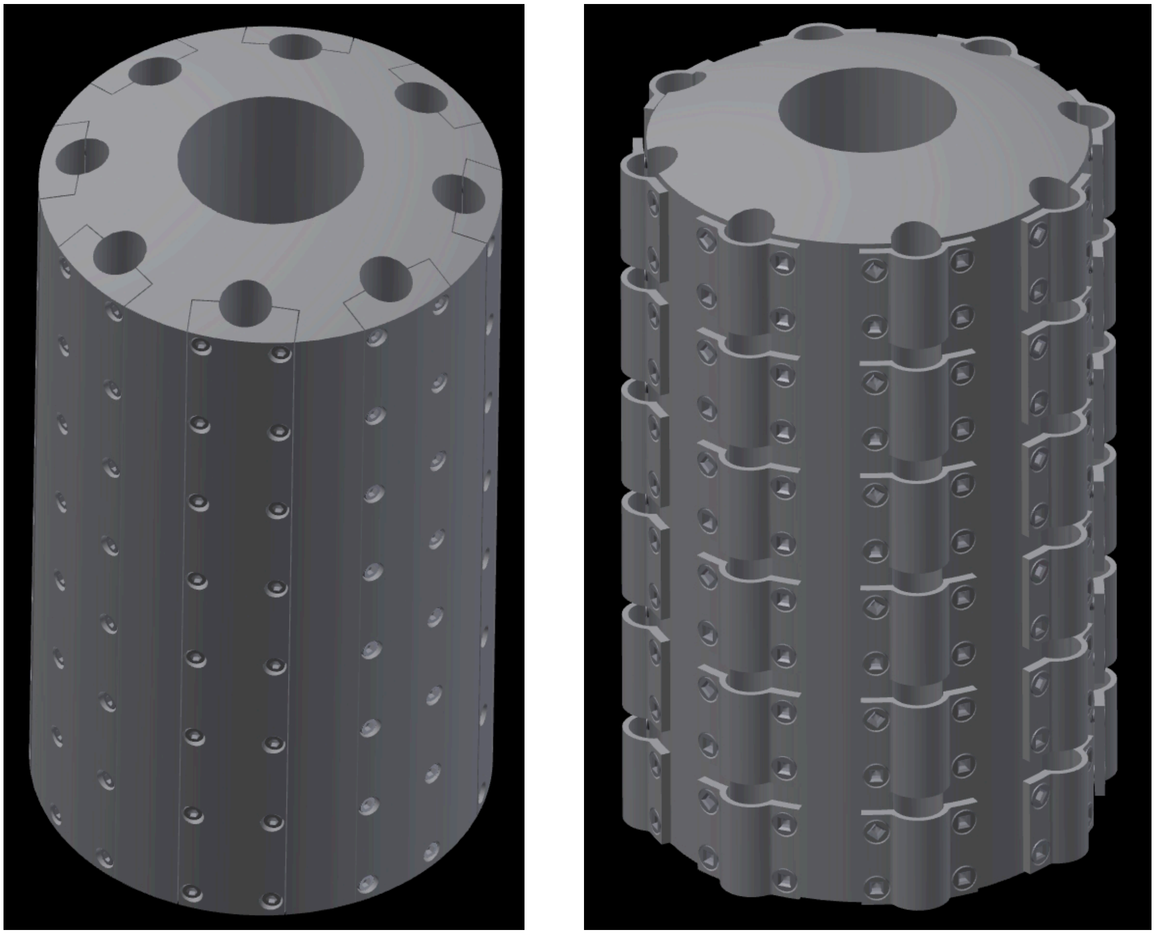

Figure 3. Methods for connecting heat pipes to edge of reactor core.

Path Forward

This design choice of 7% moly alloy will be tested early in the next stages of the project. Y-12 is doing work to understand and validate the existing data base for uranium-moly alloys near the design temperature of the reactor. The next phase of the project will include:

- Y-12 will experimentally validate uranium-molly mechanical/thermal (creep) data.
- A depleted uranium-moly alloy core will be tested at Glenn. An electrically heated core with heat pipes and Stirling engines will be placed in a vacuum chamber at temperature for a period of months.

These tests will provide early data to validate the choice of fuel, reflector and heat pipe location. This is a low cost option to provide the necessary data for the choice of fuel. If this uranium-moly alloy proves to not have sufficient margin, then the alternative choice would be to go back to an unalloyed uranium fuel and “can” the core with stainless-steel or Haynes 230. If this decision were made it would be a minor set back to the program and could be easily overcome.