Development of NASA's Small Fission Power System for Science and Human Exploration

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Exploration of our solar system has brought great knowledge to our nation's scientific and engineering community over the past several decades. As we expand our visions to explore new, more challenging destinations, we must also expand our technology base to support these new missions. NASA's Space Technology Mission Directorate is tasked with developing these technologies for future mission infusion and continues to seek answers to many existing technology gaps. One such technology gap is related to compact power systems (> 1 kWe) that provide abundant power for several years where solar energy is unavailable or inadequate. Below 1 kWe, Radioisotope Power Systems have been the workhorse for NASA and will continue, assuming its availability, to be used for lower power applications similar to the successful missions of Voyager, Ulysses, New Horizons, Cassini, and Curiosity. Above 1 kWe, fission power systems become an attractive technology offering a scalable modular design of the reactor, shield, power conversion, and heat transport subsystems. Near term emphasis has been placed in the 1-10kWe range that lies outside realistic radioisotope power levels and fills a promising technology gap capable of enabling both science and human exploration missions. History has shown that development of space reactors is technically, politically, and financially challenging and requires a new approach to their design and development. A small team of NASA and DOE experts are providing a solution to these enabling FPS technologies starting with the lowest power and most cost effective reactor series named "Kilopower" that is scalable from approximately 1-10 kWe.

Nomenclature

ASC	=	Advanced Stirling Convertor
ASRG	=	Advanced Stirling Radioisotope Generator
ATLO	=	Assembly Test and Launch Operations
BOM	=	Beginning Of Mission
DAF	=	Device Assembly Facility
DOE	=	Department of Energy
DU	=	Depleted Uranium
DUFF	=	Demonstration Using Flattop Fission
ISRU	=	In-Situ Resource Utilization
K	=	Kelvin
KRUSTY	=	Kilopower Reactor Using Stirling TechnologY
k_{eff}	=	Reactivity Coefficient

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kg   =   Kilogram
kWe   =   Kilowatt Electric
kWt   =   Kilowatt Thermal
MLI   =   Multi-Layer Insulation
NRC   =   National Research Council
W   =   Watt
V   =   Volt

I. Introduction

Over the past five decades numerous space reactors have been designed in the U.S. with little success in hardware development and no success in flight. As NASA's budget continues to be stretched over a growing mission portfolio, efficient technology development is crucial to building a healthy U.S. space nuclear program capable of producing flight systems. The Kilopower team is challenging the overly expensive technology development process used in past failures by matching a simple reactor to a smart test program with flight hardware as the end success criteria. The development strategy involves a strong test program utilizing existing facilities that will help reduce high risk components and design assumptions through extensive testing. The program has been carefully planned to match the fidelity of the design to affordable testing capabilities and provide successive steps in the development cycle. The reactor design will advance throughout the test program with a near term goal of a full scale nuclear ground test, nicknamed KRUSTY (Kilopower Reactor Using Stirling TechnologY), using the flight prototypic highly enriched UMo core, heat pipe thermal transport systems, and Stirling power conversion. If successful, the technology demonstration will take approximately 3 years and 10 million dollars to complete. The fidelity of the design at the end of the 3 years is anticipated to address a major portion of the technical risk associated with a flight unit with minimal invested cost. Figure 1 illustrates the flight concept of a 4kWt reactor core coupled to a 1kWe Stirling power conversion system and a 40kWt core coupled to a 10kWe conversion assembly. The 1kWe Kilopower reactor is the baseline design for the nuclear test and will affordably address Kilopower designs ranging from 1-10kWe.
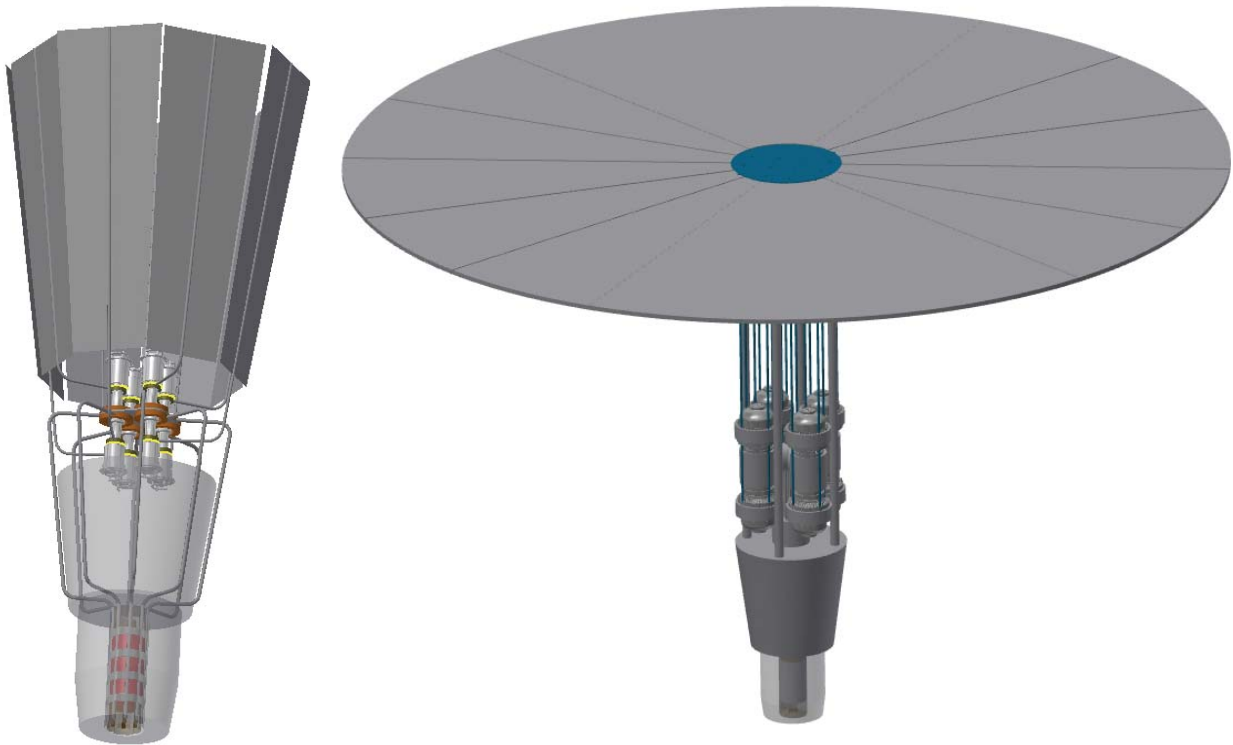

Figure 1. 1 kWe (left) and 10kWe (right) Kilopower Systems

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The basic design approach is derived from a 2010 Small Fission Power System Feasibility Study performed by a joint NASA/DOE team in response to a request from the National Research Council (NRC) Planetary Science Decadal Survey [7]. After reviewing options, the team selected a reference concept and evaluated the feasibility for a 10 year flight system development to support future space science missions that exceed radioisotope power system capabilities or require too much ^{238}Pu fuel. The reference concept defined in the 2010 study is similar to the current Kilopower concept, sharing the cast UMo fuel form, BeO reflector, and Na heat pipes. The baseline reactor thermal power level for the 2010 concept was 13 kWt, allowing a thermoelectric power system option at 1 kWe [8] or a Stirling power system option at 3 kWe [9].

II.   System Design

A. Reactor

The Los Alamos National Laboratory is leading the design of the reactor, reflector, and shield that will be demonstrated in the full scale nuclear test. The Y-12 National Security Complex is leading the material development and manufacturing of the Uranium alloy core and will verify fuel selection through early material testing and manufacturing trials leading up to the full scale fabrication. As part of the development phase, there will be numerous tests to validate the design and material selections with expected iterations leading up the final design. A solid cast uranium molybdenum alloy core has been selected as the fuel because of an existing material database, simple reactor construction and operation, and most importantly, the existing infrastructure and production capabilities at Y-12. The solid core works well with lower power reactors because of negligible fuel burnup and volume swelling issues that can challenge higher power reactors, which would typically incorporate cladded pin-type fuel [2]. The solid core design provides sufficient thermal power while reducing the fuel, radial reflector, and shadow shield geometry and mass, giving the total system a higher specific power (W/kg) than other fuel forms. The baseline material for the core has been chosen to be 93% highly enriched U235 alloyed with 7% Mo by weight, and is expected to produce an optimum balance between neutronic, thermal, and metallurgical properties [3]. Figure 1 shows the current LANL design of a 4kWt flight core, which provides 1kWe with Stirling power conversion.
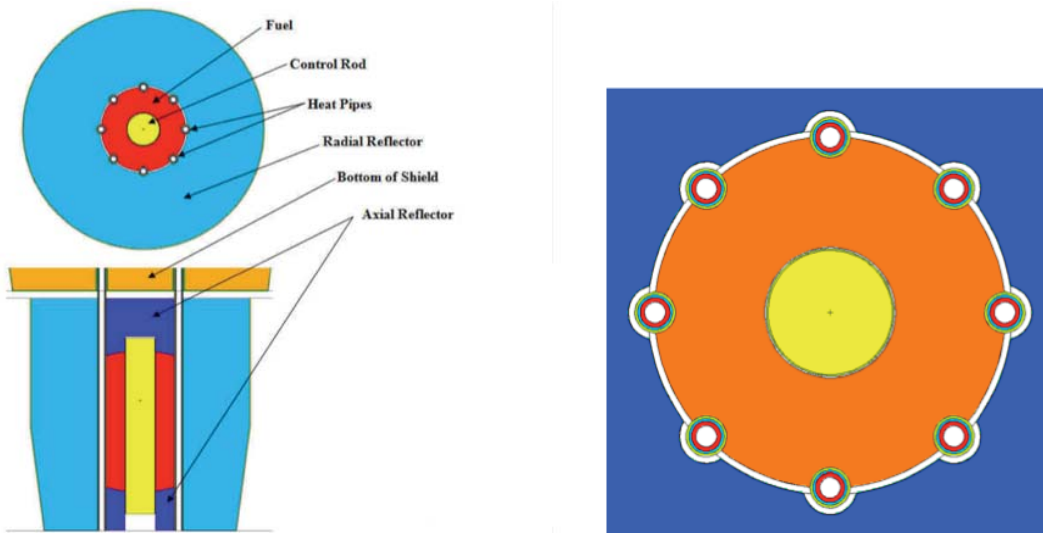

Figure 2. Flight design of the Kilopower 4kWt core and reflector assembly.

Beryllium Oxide has been selected as the radial reflector material for its high neutron reflectance throughout the required temperature and energy spectrum as well as its mechanical and thermal properties. The reflector design is monolithic and does not incorporate control drums typical of higher power reactors, highlighting another significant and simplified design feature. For criticality safety throughout ATLO, only a single control rod of B_4C is needed in

the center of the core to keep k_{eff} at a safe level during all expected operations and hypothetical accidents. When the reactor reaches its startup location in space or on the surface of another planet, a control mechanism will slowly remove the poison control rod and allow the reactor to start up. This benefit of controlled startup at the mission destination allows BOM power levels and overall power system life expectancy to be directly coupled to mission timeline requirements. The flight system could utilize a number of control rod options that could be specifically tailored to mission requirements. For instance, the simplest control rod design, as baselined, would perform only one movement at the beginning of the mission allowing the reactor to start up and load follow the power conversion system. This method allows the natural degradation of the core temperature as fuel is spent and neutronic behavior changes over time. Conservative thermal degradation of the 4kWt core using this method are estimated to be 3 K/yr with 0.1% fuel burnup over 15 years. An alternative approach is to use an active control rod that adds reactivity as needed throughout the mission to keep the reactor temperature and power constant. Using active control, the reactor can provide constant power for several hundred years at the 4kWt level due to very little fuel burnup and needed reactivity insertion. These simple control rod and startup methods are an important design feature needed for missions that may require the reactor to startup under minimum power at a location where solar energy is limited and battery power is necessary. Initial estimates of the required power for startup is 1 amp hour at 28VDC.

B. Heat Transport and Power Conversion

Thermal energy from the core is transported to the power convertors via sodium heat pipes. Heat generated from the fission reactions is conducted through the core, into the heat pipe evaporator and vaporizes the sodium liquid. The sodium vapor travels up the heat pipe where it can be accepted by the Stirling convertors at the condenser interface. As the sodium vapor releases its latent heat and condenses back to the liquid phase, the wick pumps it back to the evaporator where the cycle continues. Alloy 230 is the baseline envelope material for the heat pipes because of its known compatibility and prior experience with sodium as well as its high temperature strength and creep resistance. This passive thermal transport operates solely on thermal energy and requires no electrical power for pumping. This is an important design feature, which reduces the parasitic losses of the power system and simplifies system startup and control.

High efficiency free piston Stirling convertors have been baselined for the initial designs to increase system performance and provide high specific power. Their use benefits from existing flight development of the Sunpower Inc. 80 We Advanced Stirling Convertor (ASC) as well as recent successful technology demonstrations of both 1 and 6 kWe convertors developed by Sunpower Inc. for NASA under the current Nuclear Systems Program. The Stirling engine heat acceptor is conductively coupled to the sodium heat pipe condenser and uses the thermal energy from the reactor to thermodynamically drive the power piston and linear alternator. The Stirling convertors in both the 1 and 10 kWe Kilopower designs are arranged in the vertical dual opposed configuration allowing easy power scaling while minimizing the shield half angle and mass. Thermoelectric conversion has been studied as an alternate power conversion technology that offers simplicity and additional redundancy but requires significantly more thermal power from the reactor due to its lower efficiency[8]. NASA studies are currently looking at these two power conversion options for future development and mission use. The preliminary baseline design (figure 1) uses 8 125We ASC style convertors in a dual opposed configuration with mating hot ends. Coupling the hot ends of all 8 convertors is a conduction plate that allows redundant heat paths in the event of a heat pipe or convertor failure. This hot end assembly increases reliability but also reduces mass using a unified insulation package and fewer components. Future Stirling designs will likely incorporate a shared expansion space between engine pairs similar to the current 6kWe Sunpower Inc. design[13].

The Stirling engines must reject their waste heat to space at the optimum temperature in order to establish a balance between the conversion efficiency and radiator mass. This optimum temperature is not equal for the 1 and 10 kWe systems but does fit well within the operating range for water based heat pipes. Titanium water heat pipes are baselined for the Kilopower systems and have already been through a significant development cycle with numerous successful designs and tests. The Ti/H_2O heat pipes will transfer the waste heat from the Stirling engines to a radiator fin where it can then be rejected to space.

C. Mass and Performance Scaling of Kilopower Systems

Preliminary mass estimates were generated for Kilpower systems from 1 kWe to 10 kWe, assuming the same basic reactor design parameters defined in the 2010 NRC feasibility study. The results are presented in Table 1. The 1

kWe system allows the heat pipes to be clamped to the outside perimeter of the core, while the larger systems will require the heat pipes to be inserted in the core. Increasing power output requires a slightly larger core and more heat pipes, but no major changes to the basic design approach. The radiator area is based on one-sided heat rejection to a 200 K thermal sink with 10% area margin. The systems could employ fixed radiators for planetary spacecraft applications, or deployable radiators for Mars surface applications. The stowed dimensions are provided for both options. The mass breakouts are shown for the reactor, shield, and balance-of-plant. As indicated, the system specific power improves with increasing power level from about 2.5 W/kg at 1 kWe to 6.5 W/kg at 10 kWe.

User Power, kWe	1	3	5	7	10
Power System Characteristics					
Reactor Thermal Power, kWt	4.3	13.0	21.7	30.3	43.3
Radiator Area, m²	3.2	9.6	13.5	17.1	20.0
Stowed Diameter, m	1.1	1.2	1.3	1.4	1.5
Stowed Height (with fixed radiator), m	3.0	4.9	5.9	6.7	7.3
Stowed Height (with deployable radiator), m	N/A	2.2	2.7	3.0	3.3
Mass Summary, kg					
Reactor (UMo core, BeO reflector, Na heat pipes)	136	175	198	215	235
Shield (LiH/W, 25 krad and 10^{11} n/cm² at 10 m separation)	148	272	364	443	547
Balance-of-Plant (Stirling engines, radiator, electric controls, structure)	122	304	449	589	763
Power System, kg	406	751	1011	1246	1544
Specific Power, W/kg	2.5	4.0	4.9	5.6	6.5

Table 1. Kilopower System Options

The system concepts are meant to support both science and human exploration uses. For science, a number of mission concepts were studied during the NRC Planetary Science Decadal Survey with projected power requirements greater than 500 watts [10]. These missions may include orbiters, landers, multiple science targets, expanded instrument suites, in-situ data analysis, high-rate communications, and/or electric propulsion. Human outpost missions to the moon and Mars have generally required tens of kilowatts to accommodate landers, habitats, in-situ resource utilization (ISRU) plants, rover recharging, communication relays, and science packages. Until recently, the preferred approach was to deliver a large, centralized 40 kWe fission power plant that could meet the mission requirements with margin for growth. The drawback was the large landed mass, complex installation, and lack of system-level redundancy. The 1-10kWe fission power option could be used for human precursor missions to demonstrate ISRU production or on human outpost missions where compact packaging, modularity, and redundancy are favored over growth capacity. An additional application for the small fission system that is being considered for Mars surface missions is to provide a portable utility pallet for remote charging of long-distance piloted rovers.

III. The Development Program

Early demonstration of the Kilopower technology was proven with the DUFF (Demonstration Using Flattop Fission) experiment in 2011 [4,5]. This test not only showed that nuclear testing of space reactors and their subcomponents can be affordably tested but that there are existing nuclear facilities that can be utilized for development programs[6]. This proof of concept test successfully showed that reactors could be coupled to Stirling power convertors via heat pipes and produce electricity. Building on the DUFF experiment, the Kilopower team has planned a follow-on three year development program that is designed to reduce the technical risk associated with the flight unit by addressing many first and second order design uncertainties. The three year program is expected to start at the beginning of NASA fiscal year 2015 and end with the KRUSTY test by the start of FY 2018. In order to complete the program, many tests will be performed to determine if the preliminary design will function as expected with the understanding that modifications will be necessary to evolve towards the final design. These tests will include material testing, simple thermal mockup tests, higher fidelity component and system tests, and end with the full scale nuclear test. Using this strategy, early first order design flaws will be exposed with little investment and plenty of time for design modifications. All mechanical, thermal, and power conversion systems will be completely verified before nuclear testing is commenced.

A. Material Testing and Fabrication

Nuetronic worth is a key driver for selecting a reactor fuel. Chemical and structural stability are, however, very important design factors as well. It cannot be over emphasized that the fuel selection trade space is greatly expanded by designing the fission system to a very low fuel burn-up. The gas generation and fuel swelling that result from advanced radiological stages are crucial drivers in most fuel systems but are essentially non-factors in the design trade-space discussed here. Fabricability, structural stability, chemical stability as well as neutronic worth were the discriminators used for fuel selection in this design concept. Uranium oxides or uranium nitrides were not selected since the additional volume stability is not needed in low burn-up applications. The selection of an uranium molybdenum (UMo) alloy over uranium with low alloying additions was made to take advantage of the higher temperature strength, wider range of microstructural stability, and the relatively larger physical property data associated with UMo alloys. Y12, NASA Glenn, and LANL have conducted extensive reviews of data collected for the past 5 decades regarding UMo fuel properties. The 2009 UMo Fuels Handbook [11] provides the thermo-physical and much of the mechanical property data required for conceptual design of the compact fission power system. Absent from the fuels handbook is time-dependent mechanical property data, or creep data, which will be needed for this design but is not relevant in typical fuel pellet systems. Scrutiny of older literature suggests that, although the creep strength of UMo alloys is very low at these temperatures, it will be sufficient for this design [12]. These material selection assumptions will be verified by casting and testing a lot of prototypic depleted uranium molybdenum rods. Samples will be tested for compressive creep strength, tensile creep strength, impact excitation modulus, and diffusion rates relative to pure molybdenum after characterizing the chemistry and grain size of the rod.

B. Thermal Prototypes

Each of the Kilopower components will start with thermal testing to verify analytical models and provide test and assembly knowledge that will be useful leading up to the nuclear demonstration. Starting with the reactor core, the heat transfer mechanisms associated with the thermal coupling and temperature drop from the core to the sodium heat pipe evaporator will be demonstrated using a full scale stainless steel 316L core, a custom graphite heater, 8 alloy 230/sodium heat pipes, 316L core containment can, mock axial reflectors, and several heat pipe clamping designs. This early prototype will address several first order design features that can easily be modified to improve performance and eventually be downselected to carry forward through the test program. The assembly has been specially designed to not only test heat transfer and mechanical coupling but will also verify assembly operations for KRUSTY integration. Figure 3 shows the thermal prototype assembly and the individual components intended for early testing. The 316L stainless steel was chosen as the surrogate material for many of the components as a cost effective way to develop early material creep models that could verify modeling tools and creep behavior of the design. The surrogate material physical properties are very well documented and are similar enough to many of the published UMo alloy properties that results should be useful on numerous first order effects. At the conclusion of the material and thermal prototype tests, a preliminary design review will be held to determine if the design is ready

to move forward to casting a depleted UMo core for further non-nuclear testing. The thermal prototype testing will verify:

1. High temperature creep modeling using known 316L material properties
2. Heater design and thermal behavior at nominal Kilopower operating temperatures and power levels
3. Core to heat pipe contact resistance and thermal performance
4. MLI insulation assembly and thermal performance
5. Sodium heat pipe performance using gas calorimetry
6. Heat pipe to core clamping mechanisms
7. Core containment can geometry and mechanical design
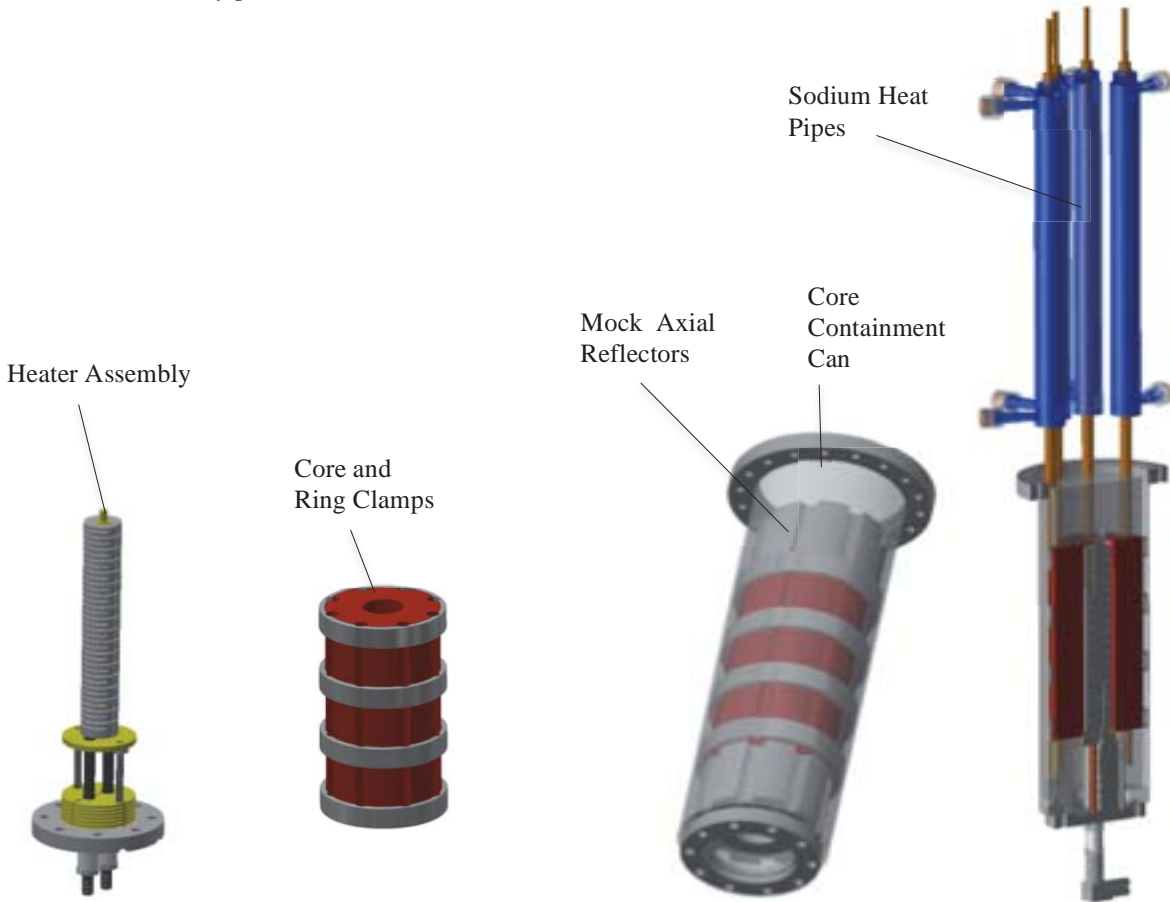8. Assembly processes for KRUSTY and ATLO

Figure 3. Thermal Prototype Assembly and Test Components

C. Stirling Power Conversion and Sodium Heat Pipe Testing

The ASC power conversion units from the ASRG program will be used for initial power conversion testing starting in FY15. Two convertors will first be tested separately to re-verify individual performance followed by coupling them as a pair to the Kilopower hot end conduction plate and sodium heat pipes. Internal modifications to the convertors are expected to boost performance by 20% for Kilopower testing and take advantage of the higher power fission heat source. With 8 sodium heat pipes and only two convertors, the remaining convertor assemblies will be replaced with thermal simulators to mimic the response of the Stirling convertors. The conduction plate will be the coupling mechanism between the eight heat pipes, 6 thermal simulators, and 2 Stirling convertors. The assembly will initially be tested in vacuum with the stainless steel core to verify system performance and thermal integrity. Figure 4 illustrates the sodium heat pipe array, hot end conduction plate and Stirling convertors/simulators. This test will address:

1. System level integration and assembly processes
2. Steady state and transient system performance
3. Total conversion efficiency including thermal losses
4. Flight prototypic sodium heat pipe performance
5. System response and mechanical integrity to induced heat pipe failure
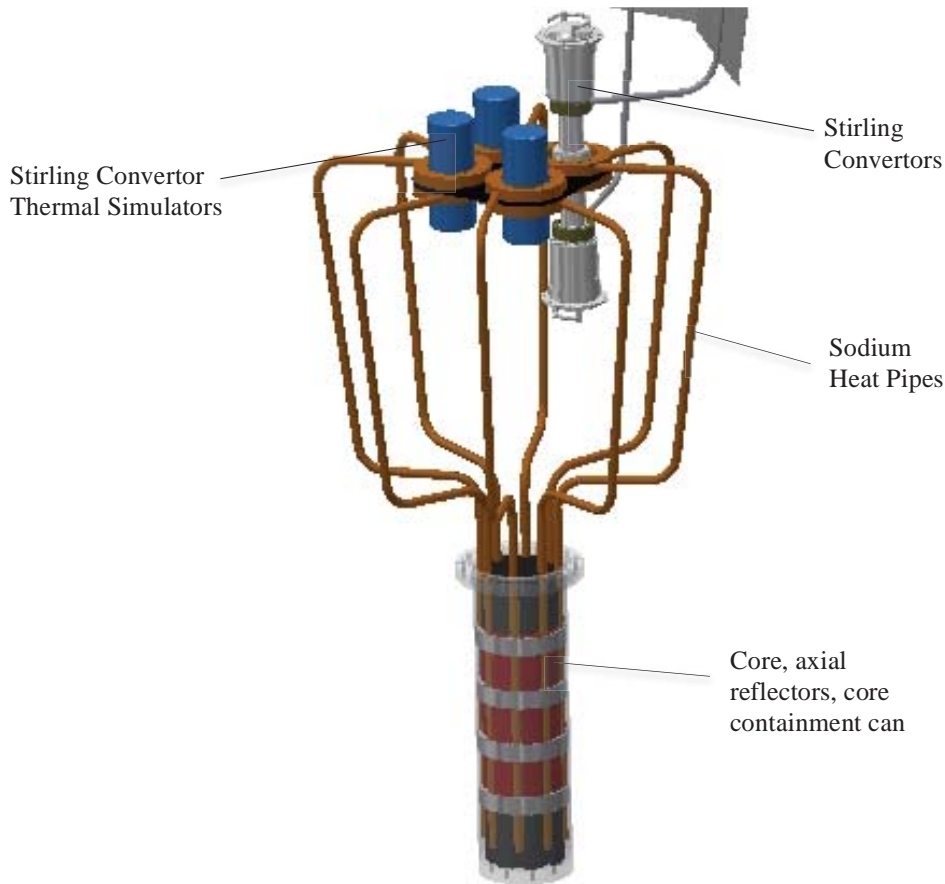6. System response to simulated convertor failure

Figure 4. Kilopower Assembly Test with core, sodium heat pipes, hot end conduction plate, Stirling convertors, and Stirling thermal simulators.

D. Depleted UMo Core

Once the preliminary design review is complete, the engineering drawings will be released to produce a depleted UMo core at the Y-12 National Security Complex. Y-12 will build the core to print and ship to the NASA Glenn Research Center where further testing will take place. At the time of delivery, the Kilopower system will have been fully checked out and ready for integration with the DU core. This test assembly is identical to the Stirling power conversion and sodium heat pipe configuration in figure 4 and will further the design fidelity by verifying:

1. The UMo interface requirements between the heat pipes, insulation, and clamping mechanisms.
2. Mechanical design integrity during multiple thermal cycles and potential core deformation
3. Thermal expansion of the core and its affects on the system
4. Material creep of the UMo core under induced design stresses
5. Diffusion of the UMo with interface materials
6. Thermal vacuum acceptance criteria

E. Highly Enriched UMo Core and the KRUSTY Test

At completion of the NASA thermal vacuum testing of the DU core, a final design review will be held to determine if the HEU core is ready to begin fabrication. This final design review will accumulate all design revisions throughout the testing program and release the final design drawings to Y-12 for fabrication. When complete, the HEU core will be shipped to the DAF facility where it will integrate into the test assembly at the proper time. The full scale nuclear testing will be performed with the Comet criticality machine at the Device Assembly Facility (DAF). The flight prototypic assembly for the KRUSTY test will be identical to the DU core test leaving only the nuclear design to be verified. Figure 5 illustrates the integrated test assembly with Comet depicting the two extreme reflector positions using the lift table. Comet will make the test assembly go critical by raising the radial reflector around the core and provide the necessary reactivity to create the 4kWt steady state thermal power. The test assembly will incorporate a custom vacuum chamber specifically designed to fit on top of Comet and provide the relevant space environment throughout the nuclear testing. The KRUSTY test will verify and/or demonstrate:

1. Reactor Startup Operations
2. Excess reactivity needed to meet Kilopower thermal power and temperature requirements
3. Integral nuclear cross sections and temperature dependence
4. Reactor load following to Stirling convertor demands
5. ATLO assembly procedures
6. Steady state and transient differences between electrical and nuclear heat sources
7. Temperature feedback mechanisms and dynamic response
8. Operational stability for follow-on engineering-unit nuclear tests
9. Nuclear design tools such as FRINK and MRPLOW

IV.   Conclusion

Developing a small fission power system for NASA's science and human exploration is an endeavor worth taking with potential to open up a new class of missions not currently achievable with radioisotope and solar power sources. An affordable approach to addressing many engineering risks of a future flight development program have been proposed to take approximately three years and ten million dollars using a test plan that progresses through increasing levels of hardware fidelity leading up to a full nuclear ground test nicknamed KRUSTY. This development project of Kilopower will provide extensive science and engineering data not attained in the last five decades of U.S. space reactor programs.

Starting with the lower power 4kWt reactor core for the first nuclear demonstration is extremely important to keeping development costs at an affordable level. Nuclear testing costs are directly proportional to reactor thermal power and the 4 kWt design allows the testing to take place at existing facilities under current regulations and licensing at the Nevada Test Site. By design, the lower power demonstration offers a subscale test of a 10 kWe capability, adding considerable value to both science and human exploration needs and paving the way for future higher power systems. Successful nuclear testing of the Kilopower reactor will help fill the existing technology gap of compact power systems in the 1-10 kWe range enabling new higher power NASA science and human exploration missions.
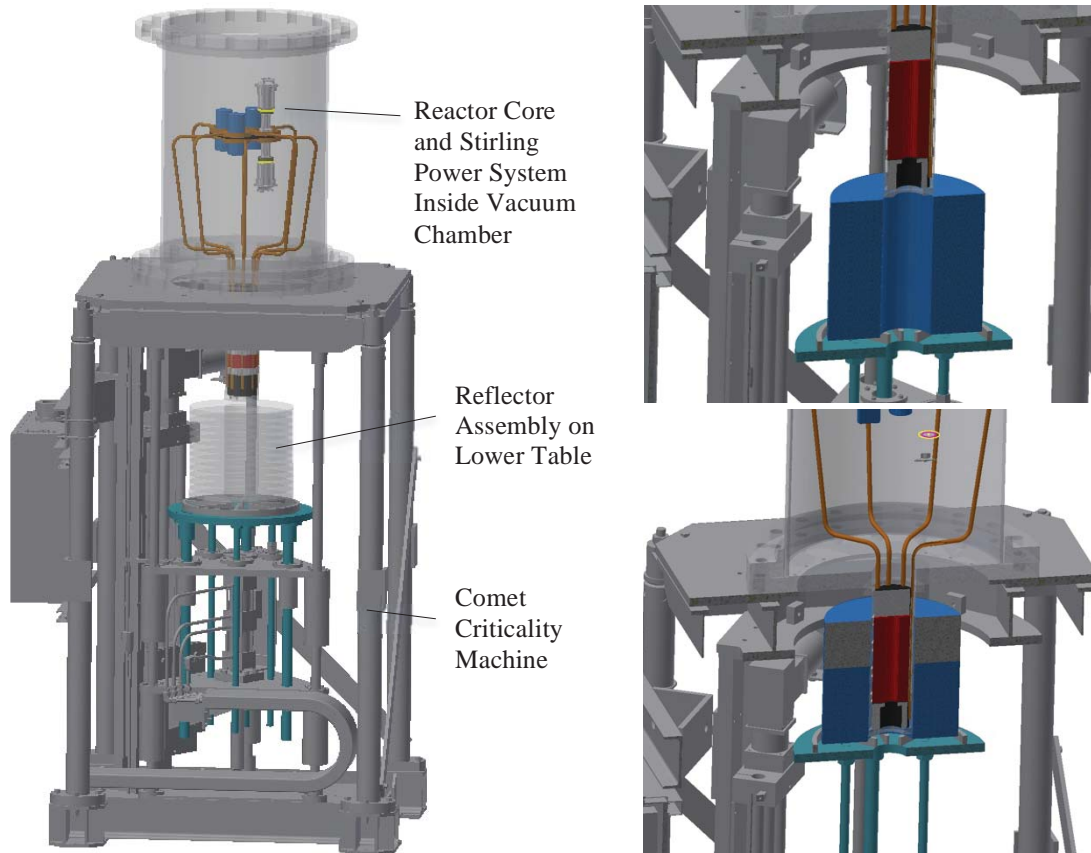
Figure 5. KRUSTY test assembly integrated with the Comet criticality machine.

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