Higher Power Design Concepts for NASA's Kilopower Reactor

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Abstract- **The successful testing of the Kilopower reactor during the KRUSTY (Kilopower Reactor Using Stirling TechnologY) experiment significantly reduced the risk to fly fission power systems by demonstrating stable reactor operation through nominal and severe simulated mission scenarios. The experiment validated the neutronics, heat transfer, and power conversion systems needed for 1 kilowatt of electrical power production from the Kilopower reactor. The need for higher power reactors to support human exploration missions to the moon and Mars has become increasingly important due to the urgency to put boots on the moon by 2024 and have a sustainable presence in the following years. This desire has prompted NASA to continue the development of the Kilopower reactor to extend the power up to 10 kilowatts of electricity in support of a lunar base. These 10 kilowatt units are expected to be used as standalone units or be ganged together to create a modular power grid for propellent production, human habitats, and robotic exploration to name a few. The Kilopower reactor was originally designed to produce electrical power from 1 to 10 kilowatts using the same highly enriched uranium fuel, sodium heat pipes, and Stirling convertors at the proper scale. Consideration has also been given to the use of low enriched uranium fuel for these missions and will be studied along with the other aspects of the reactor. This paper will focus on the design concepts and trades associated with the scale up of the Kilopower power conversion system and heat transfer system to support human exploration of the moon and Mars.**

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1. INTRODUCTION

NASA's Kilopower project has successfully graduated from the Game Changing Development program to the Technology Demonstration Mission program, as a step forward to proving fission power technologies for lunar missions under space policy directive 1. Both programs are managed within the Space Technology Mission Directorate at NASA and are designed to mature technologies from early prototypes to flight hardware. The Kilopower Reactor Using Stirling TechnologY test (KRUSTY) performed in March of 2018 at the Nevada National Security Site provided a short term nuclear demonstration of the 1 kW_e Kilopower reactor[1,2]. This test provided valuable information into the readiness of highly enriched fast spectrum reactors for use in space and planetary power systems[3]. Successful demonstration of the technology has led to further developments of the Kilopower reactors including the scale up to 10 kW_e for a lunar demonstration. A concept of the 10 kW_e reactor and power conversion module is shown in figure 1 to provide some general knowledge of the system.

Increasing the power output by a factor of 10 requires some architecture trades to allow for the additional heat to be extracted from the core to the power conversion system and rejected to the environment. These design architecture trades will include the number of heat pipes mated to the reactor core, the number and size of Stirling convertors, and whether a heat exchanger will be used in between the heat pipes and power convertors. To provide the correct solution requires several approaches that include failure modes and reliability of the system, the technology readiness of each component, assembly and qualification of the system, and manufacturing readiness and reliability for each component and subsystem to name a few. This paper will focus on the reliability of the system using several different architectures to see how the reliability of each component effects the system reliability, Beginning of Mission (BOM), and End of Mission (EOM) power output available to the user.

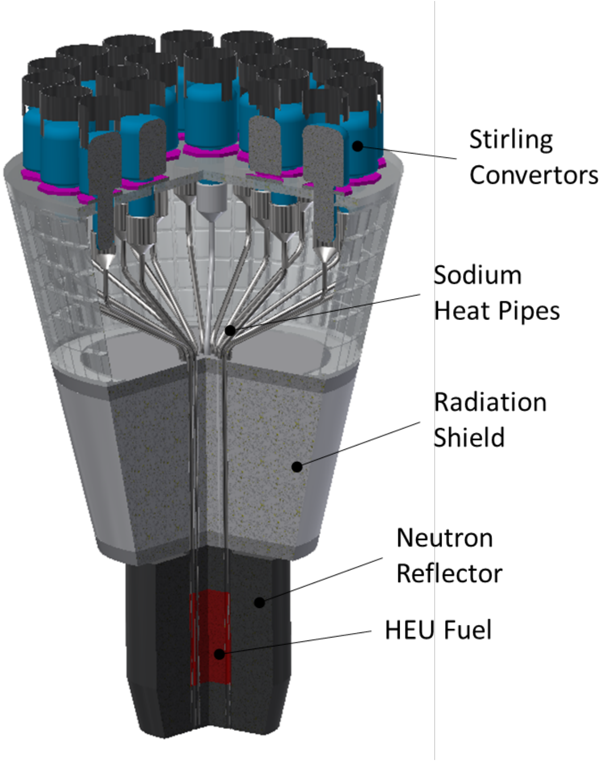


Figure 1. 10 kW$_e$ Kilopower single convertor to heat pipe concept showing reactor core, shielding, and power conversion modules. Heat rejection system not shown.

2. REACTOR CORE AND HEAT PIPE REDUNDANCY

The 10 kW$_e$ (kilowatts electric) core requires approximately 43 kW$_t$ (kilowatts thermal) to be generated by the reactor core. This thermal energy must then be transferred from the core to the power conversion system via the sodium heat pipes. The diameter, quantity, and arrangement of the heat pipes within the core effect the overall size and mass of the uranium core while providing redundancy against multiple heat pipe failures that can surpass fuel temperature limits. More heat pipes embedded within the core provides additional redundancy but displaces fuel which must be added to the outer diameter creating a significant mass penalty. Initial analysis has suggested that the balance between failure redundancy and core size requires approximately 24 heat pipes. Using 8 heat pipes on the inner part of the core and 16 around the outer part provides a symmetrical arrangement that can tolerate several failure modes of the heat pipes or down stream components such as a Stirling engine or heat rejection component.

Core Thermal Analysis

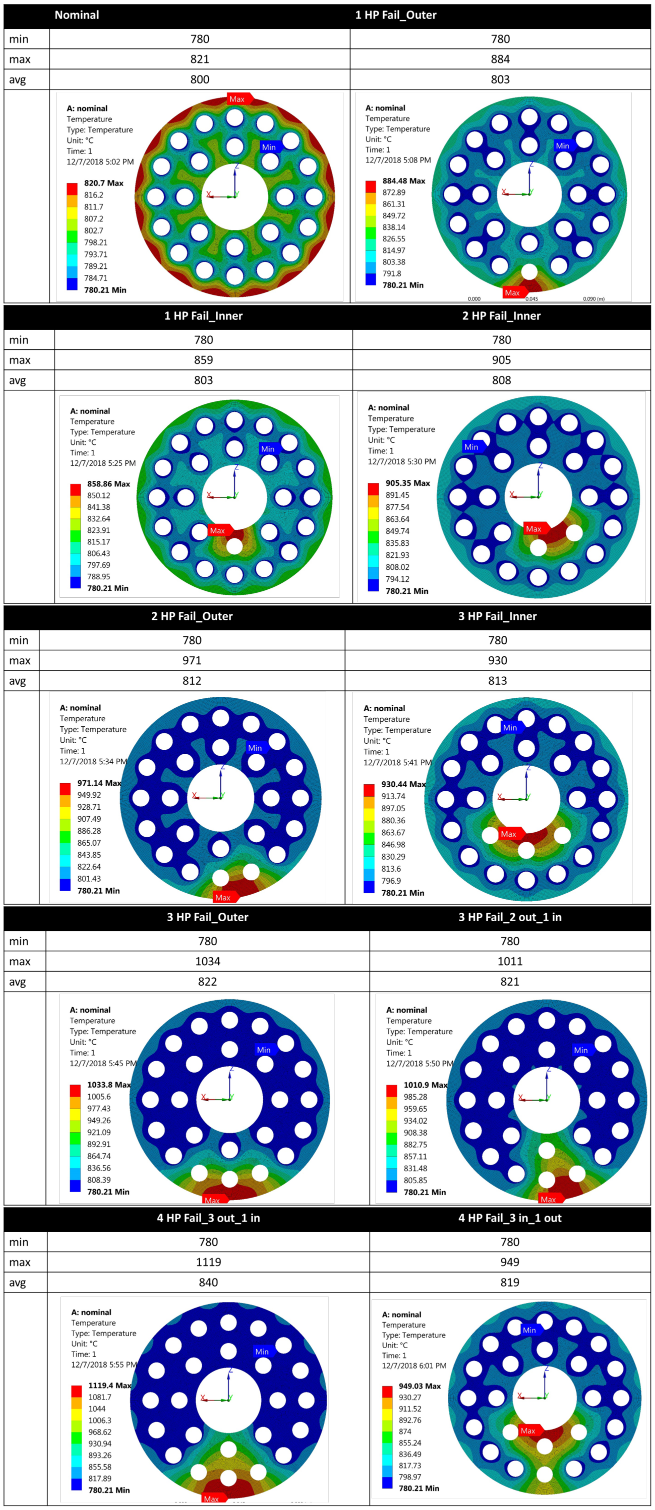
A conservative thermal analysis was completed to understand the worst-case scenarios that could impact the core's material integrity by increasing the fuel temperature to 85% of its melting point (approximately 1000°C) through multiple heat pipe failure scenarios. The kilopower reactor design does not require the core to be a structural component in the system and therefore greatly reduces the impact of reduction of strength at high percentage of melt temperatures of the uranium molybdenum alloy.

The worst-case failure is a heat pipe that loses its working fluid through a leak and has no ability to transfer heat away from the core. A failure of a downstream component such as a Stirling convertor or heat exchanger will generally have less impact given that the primary heat pipe will still be removing some heat from the core through insulation losses. All the failure modes in this analysis were assumed to be heat pipe loss of fluid failures of single and multiple neighboring units to be conservative.

The model assumed perfect insulation of the outside surfaces with 43 kW$_t$ being generated evenly (no power peaking) within the fuel volume and evenly distributed among the 24 heat pipes (-1.8 kW$_t$ per heat pipe). A convective heat flux boundary condition was set at the internal heat pipe boundary that would allow the neighboring heat pipes to absorb the failed heat pipe thermal load as temperatures increased. The remaining working heat pipes would continue to carry all of the generated 43 kW$_t$ for the analysis with no movement of the control rod. This methodology also requires the Stirling convertors to ramp up power production levels to match the additional effort required from each heat pipe.

Figure 2 shows how the location of the heat pipe failure and combined effects of several neighboring heat pipe failures drive the maximum temperatures. Using 1000 °C at the maximum allowable temperature, several failure combinations could be overcome. In general, the inner heat pipes have more tolerance to neighboring failures and can survive 3 neighboring inner failures and one outer as shown in 4 HP Fail_3in_1 out in the bottom right corner of figure 2. The outer heat pipes could suffer at most two neighboring units with a maximum temperature of 971 °C as shown in case 2 HP Fail_Outer. Adding the third outer failure or two outer and one inner takes the maximum core temperature above 1000 °C.

This preliminary analysis provides some valuable information about how many heat pipes could fail assuming the remaining working heat pipes could passively adjust to the higher thermal loads with the Stirling convertors actively following. Realistically, if the core suffered that many unlikely neighboring heat pipe failures, the control rod would be moved to lower the core temperature and reduce overall power output. Additionally, the physics and passive control of the core using negative temperature feedback would self-adjust the average core temperature back to 800°C which hasn't been taken into account for this analysis as seen with the rising core averages. The core reliability analysis will account for the probability of neighboring and non-neighboring failures. A 24 heat pipe architecture that is permanently bonded to the uranium core will be used as the baseline for the remaining discussions to help narrow the focus of the power conversion system.



	Nominal	1 HP Fail_Outer
min	780	780
max	821	884
avg	800	803

	1 HP Fail_Inner	2 HP Fail_Inner
min	780	780
max	859	905
avg	803	808

	2 HP Fail_Outer	3 HP Fail_Inner
min	780	780
max	971	930
avg	812	813

	3 HP Fail_Outer	3 HP Fail_2 out_1 in
min	780	780
max	1034	1011
avg	822	821

	4 HP Fail_3 out_1 in	4 HP Fail_3 in_1 out
min	780	780
max	1119	949
avg	840	819

Figure 2. Thermal analysis of a 43 kW_t Kilopower HEU core at 800 °C nominal average core temperature compared to several heat pipe failure scenarios and their corresponding temperature effects.

3. HEAT PIPE AND POWER CONVERSION ARCHITECTURES

We will graphically look at 3 different design options that help visualize the scale and arrangement of the Stirling power convertors and how redundant each system is. This information will lead into the reliability section where several designs are analyzed based on current knowledge of the probability of failure of each component. Additional components and subsystems are required for the heat rejection of the Stirling power convertors, but these will not be covered in this paper.

Single Convertor to Heat Pipe Architecture

The first system architecture is based on having a highly redundant number of strings by using one Stirling convertor for every sodium heat pipe. This configuration is shown in Figure 3 and requires 24 convertors rated at 500 W_e each with active or passive balancing. This design architecture was the baseline for the 1 kW_e system used in the KRUSTY nuclear test and has several advantages.

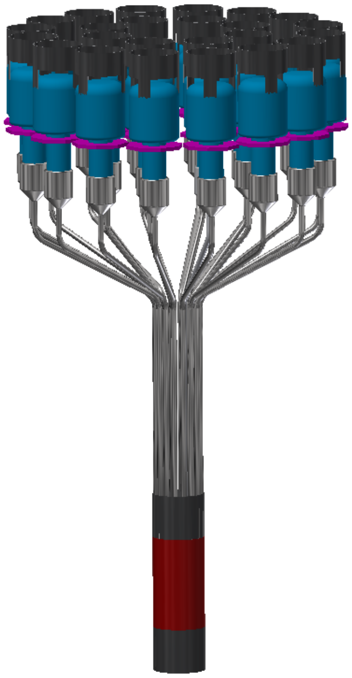


Figure 3. Single convertor to heat pipe concept showing (24) 500 W_e Stirling convertors with balancers and integrated sodium heat pipes

The integrated heat pipe and convertor allow the hot end of the Stirling convertor to be welded into the heat pipe condenser providing superior heat transfer between the heat pipe vapor and the convertor's heat acceptor. This provides a higher temperature hot end for the convertor which ultimately increases the efficiency and electrical power output of each convertor. This architecture also provides a modular system configuration in which each heat pipe and convertor can be fully tested before being assembled and bonded into the reactor core. This modularity provides a lower risk approach to qualification and acceptance testing by allowing each individual unit to be tested independently and in conjunction with manufacturing production rates of both heat pipes and convertors. Another added benefit of this design is the ability to easily determine independent heat pipe and convertor performance using minimum telemetry signals.

The biggest disadvantage of this design is shown in table 2 below which points out that the Stirling convertor and controller probability of failure have a direct impact on the localized core temperature excursions. This effect is reduced at the system reliability by keeping the power conversion string reliability high with 24 redundant strings.

Secondary Heat Exchanger Architecture

The second design architecture incorporates a heat exchanger that separates the primary heat pipes from the Stirling power convertors. This heat exchanger is shown in figure 4 as one sodium vapor chamber that is welded or brazed onto the 24 heat pipes. In this arrangement the evaporator for the secondary heat exchanger is the outside diameter of the condenser section of the primary heat pipes. The hot ends of the 8 convertors arranged in a dual opposed configuration would also be welded into the vapor chamber allowing the sodium vapor to condense directly onto the pressure vessel at the heat acceptor location, similar to the integrated option in the first design case. This secondary vapor chamber is a separate pressure vessel from the 24 primary heat pipes and decouples any one Stirling convertor from effecting any single heat pipe.

The main advantage of this arrangement is that it spreads the thermal effects of any Stirling convertor/controller failures over all 24 heat pipes. This effects the system reliability by not allowing the highest probability of failure component (presumed to be Stirling convertor/controller combination) to be directly tied to neighboring heat pipes. Another advantage of this architecture is that it allows fewer numbers of higher power convertors which may prove to be extensible to higher power systems.

The major disadvantage of this system is the manufacturing complexity of the large welded system. The assembly will require a significant amount of time to process the primary and secondary heat pipe/vapor chamber and assemble all the Stirling convertors. Any one mistake during manufacturing or early test programs will result in major cost and schedule slips. Another obvious disadvantage is the single point failure of the secondary vapor chamber. A leak in the vapor chamber to the outside environment or a leak of the Stirling convertor working fluid into the sodium vapor chamber would result in total system failure. This would not damage the reactor core but the system would not be able to produce electrical power due to the inability of the convertors to receive appreciable heat.

Figure 4. Welded secondary heat exchanger concept with (8) 1.5 kW$_e$ Stirling convertors arranged in a dual opposed configuration

Radiatively Coupled Heat Exchangers

The third design architecture offers a combination of modularity and redundancy using non-contact radiatively coupled heat exchangers. Figure 5 depicts the concept with 3 separate secondary heat exchangers each carrying 4 Stirling convertors that slide over the primary heat pipes and transfer heat via a finned radative design. The male fins are bonded to the 24 primary heat pipes and coated with a highly emissive material. The female fin geometry is bonded to each heat exchanger with a high IR absorption material to effectively transfer the heat from the primary heat pipe to the secondary heat exchanger. In this architecture, the primary heat pipes can be fabricated, processed, and tested individually to allow easier component level qualification and acceptance testing. The same holds true for the secondary heat exchangers that are also sodium vapor chambers and can be assembled and verified through subsystem testing.

The main benefit of this architecture is its modularity in assembly or disassembly as well as the ability to add more power or redundancy by adding additional heat exchangers. Another advantage is the ability of the primary heat pipes to thermally grow without being constrained to the secondary heat exchanger or Stirling convertors. This provides a simplified structural design for both the primary heat pipes and secondary heat exchanger and its attached convertors.

The drawback to this design architecture is the thermal performance hit taken across the radiatively coupled boundary and the additional engineering needed to successfully find the right materials for the finned parts. Early analysis has shown that a temperature delta of approximately 100°C is needed to transfer the required amount of heat within realistic surface area geometries.

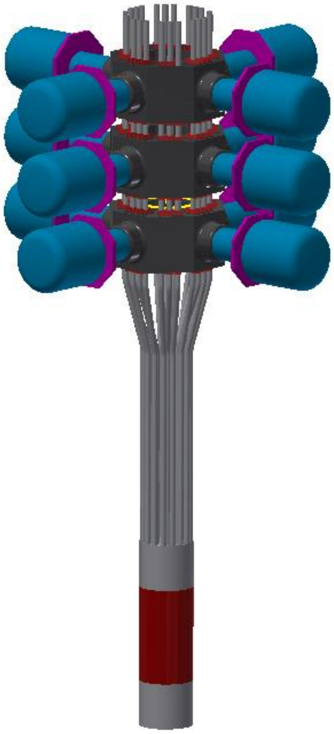


Figure 5. Radiatively coupled heat exchanger concept with (12) 1 kW$_e$ Stirling convertors.

4. RELIABILITY ANALYSIS BACKGROUND

Because of the near term lunar technology demonstration mission of the Kilopower 10 kWe reactor, an early decision is needed on the electrical power output from each Stirling convertor and the associated power conversion system architecture. This is important so that design and development of the higher power convertor and controller can begin. The rapid development timeline of a mid 2020's lunar mission drives the power conversion design towards a highly redundant system. This mitigates overall power system risk and estimates individual Stirling convertor output. In order to complete the reliability of the system, estimates are needed for each of its subcomponents. Putting these subcomponents together in various architectures with various levels of redundancy improves the system reliability[4]. For this study, the subsystems that will be considered are the core heat pipes, the Stirling convertors, balancers for the convertors if they are not operated as dual-opposed pairs, and the controller. Neither the reactor core nor the heat rejection system was included in this analysis.

5. COMPONENT LEVEL RELIABILITY

Core Heat Pipes

The 10 kWe Kilopower core utilizes 24 sodium heat pipes to remove the heat from the reactor core. NASA has for many years developed sodium heat pipes for nuclear power systems. Experience shows that these heat pipes have very long lives (>100, 000 hours) and, when destructively tested at the end of their lives, show no discernable change from when they were assembled.[5] The core thermal analysis in the earlier section showed that three neighboring heat pipe failures create temperature excursions above the prescribed limits. A range of assumed heat pipe reliabilities were considered to understand how their Probability Of Failure (POF) impacted the core POF. Heat pipes, as well as thermosiphons, are expected to be extremely reliable components. To bound the range of heat pipe POF, 0.1%, 0.5%, 1% and 5.0% were considered. A simplified core POF model was used to obtain approximate results of three heat pipes failing next to each other. Table 1 shows the results of this analysis of core failures. For the 5% heat pipe, the probability of three neighboring heat pipes failing in the core was 0.5673% with all others an order of magnitude below that value. For the remainder of this analysis we will assume a 1% POF for the each of core heat pipes.

Table 1. Probability of Heat Pipes Failing in a 24 HP Core

Heat Pipe Probability of Failure (%)	Heat Pipe Reliability (%)	Probability of No Heat Pipe Failures (%)	Probability of a Single Heat Pipe Failure (%)	Probability of Two Heat Pipe Failures (%)	Probability of 3 Heat Pipe Failures	Probability of Three Heat Pipe Failing Next to Each Other(%)
0.10%	99.90%	2.37%	0.03%	0.00%	0.00%	0.0000%
0.50%	99.50%	11.33%	0.64%	0.02%	0.00%	0.0001%
1.00%	99.00%	21.43%	2.39%	0.17%	0.01%	0.0017%
5.00%	95.00%	70.80%	33.92%	11.59%	2.98%	0.5673%

Intermediate Heat Exchanger

In order to decouple the core reliability from the power conversion system, an intermediate heat exchanger is being considered. Both sodium pool boiler concepts and radiative concepts have been discussed above. Both are estimated to have a POF of 1% for this analysis. This intermediate heat exchanger becomes increasingly important to overall system reliability if the reliability of the power conversion string is low. Table 2 shows how the Stirling convertor, controller and balancer string reliability may impact the core reliability when the system architecture directly couples the power convertors to the core and does not use an intermediate heat exchanger.

Table 2. POF as a Function of Power Conversion String Reliability without Intermediate HX

Stirling Convertor String POF (%)	Stirling Convertor String Reliability (%)	Core POF with Three Failed Stirlngs r(%)
1.00%	99.00%	0.0020%
10.00%	90.00%	4.00%
20.00%	80.00%	14.00%

Stirling Convertors and Controllers

Reliability estimates for Stirling convertors and controller are based upon work performed during the Advanced Stirling Radioisotope Generator program. Figure 6 shows the ASRG critical components and layout. During this program, a Failure Mode Effects and Criticality Analysis (FMECA) was performed for all of the components in the ASRG. At the end of this process, estimated reliabilities for the various subcomponents and generator were developed. Table 3 shows the ASRG POF broken into sub-assemblies and included the Generator Housing Assembly (GHA), a pair of Advanced Stirling Convertors (ASC), and Advanced Controller Unit (ACU). The overall reliability for the ASRG was estimated to be 96.9% for its 17 year life. Each of the ASC's had a POF of 0.84% with a combined POF of 1.76% and both are required to operate for a successful mission. Based on the layout of the generator, redundant convertors were not practical.

The ASCs produced about 80 watts each for the radioisotope generator. Stirling convertors that will be used for the 10 kWe fission reactor will need to produce significantly more power. Higher power Stirling convertors will grow in length and diameter but their material selections, operation parameters and overall layout changes are relatively small. As an example, an 80 watt convertor optimizes for a frequency of operation at approximately 100 hz which is also true for a 1 kWe convertor. The materials used for the hot end and cold end of the convertor are the same. Internal structures, both gas bearings, flexures, and many other components are larger, but their designs are well understood and have been demonstrated. In this analysis, we will therefore assume that the POF of a higher power but similar convertor design to the heritage convertors will result in similar POFs.

For the ACU, a single card was required to operate each convertor and each card was estimated to have a POF of 5.4%. This POF dominated the other estimated subsystems by a factor of 3X. Due to this relatively high POF, the decision for the dual opposed ASRG was to add a single backup controller card, giving the ACU 3 separate controller cards with 2 required for operation. While each card was estimated to have a POF of 5.4%, overall POF falls to 1.29% with the additional backup card. For Kilopower, system arrangements can use either a single card controller for a single Stirling or have a backup card (dual card controller) for a single Stirling, or have dual opposed Stirling convertors with a 3 card controller. A POF of 5.4% for each controller card will be the basis for the controller designs. The POF of each arrangement is shown in Table 4.

Stirling convertors require either a balancer or an opposed Stirling convertor to remove unbalanced forces from impacting the spacecraft. Active balancers use a mass and spring that are coupled to a linear motor and controlled by electronics that are very similar to the convertor controller. For this reason, a POF was developed using the similar components found in the ASRG FMECA. Assembling a controller, motor, mass spring assembly, and housing assembly resulted in an estimated POF of 2%. Passive balancers may also be used and would result in a considerably higher reliability, but the vibration force reduction is less than the active balancers. 2% POF will therefore be used as conservative representation of a balancer.

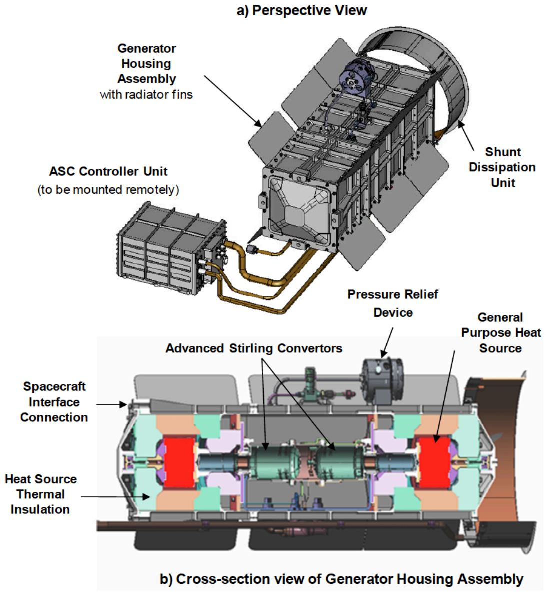


Figure 6. Advanced Stirling Radioisotope Generator.

Table 3. ASRG POF and Reliability Estimates.

ACU	ASCs	GHA	System Probability of Failure	Reliability
1.29%	1.76%	0.07%	3.12%	96.89%

Table 4. POF of Single and Dual Opposed Controllers.

Description	POF with Single Stirling and One Card Controller	POF with Single Stirling and Controller with Backup Card	POF for Dual Opposed Stirling Convertors with 2 Controllers and Single Backup Card
Number of Controller Cards	1	2	3
Minimum Required	1	1	2
Probability of Failure of Cards	5.40%	0.29%	0.84%
Common Cause		0.0045	0.0045
Overall POF	5.40%	0.74%	1.29%

6. SYSTEM RELIABILITY

Overall system reliability is based on the architecture and components one assumes. The power conversion string POF for the systems considered are shown in Table 5. The strings vary from 90.2% for the pool boiler/radiatively coupled designs to 96.4% for the 24 core heat pipes directly connected to a Stirling convertor with a dedicated balancer and dual card controller.

Table 5 POF for Several Power Conversion String Combinations

Case	# core heat pipes	# Stirlings	Intermediate HX	Stirling Convertor	Balancer + Controller	Stirling Controller	Structure	String POF	String Reliability
Core Heat Pipes to Stirlings, Balancers, Single Card Controller	24	24	None	0.83%	2.0%	5.40%	0.07%	8.3%	91.7%
Core Heat Pipes to Stirlings, Balancers, Dual Card Controller	24	24	None	0.83%	2.0%	0.74%	0.07%	3.6%	96.4%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Single Card Controller	24	24,12,8	1.0%	0.83%	2.0%	5.90%	0.07%	9.8%	90.2%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Dual Card Controller	24	24,12,8	1.0%	0.83%	2.0%	0.74%	0.07%	4.6%	95.4%

Figure 7 shows both power output and probability of providing full power as a function of the number of failed convertors for a 91.7% reliable string. As an example, if we wish to have a 99.7% chance of producing full power at end of life, we would need to develop 686 watt convertors. Notice that (24) 686 watt convertors produce a total of 16,464 watts at the beginning of the mission. Subtracting the 6 string failures still produces 12,348 watts. After electrical losses from the controller and power management and distribution system, the electrical power available to the end user is around 10 kW$_e$. As the string reliability goes up, the less redundant the system must be, thus reducing mass.

Figure 8 shows the effects of adding a redundant controller to the 24 heat pipe to 24 convertor system, increasing the string reliability to 96.4%. The power level for the convertor has dropped to 617 watts to achieve a 99.9% reliability. The higher reliability string reduces the extra redundancy in both convertor power level and the number of failed strings. The system need only carry 4 redundant strings instead of 6 from the prior example.

Figure 9 shows the effect of using a total of 12 convertors. This configuration requires the addition of an intermediate heat exchanger. To provide a 99.8% chance of full power operation at the end of mission 1372 watt convertors are required. Finally, Figure 10 shows an 8 convertor configuration with the need for a 2058 watt convertor for an overall 99.5% reliability.

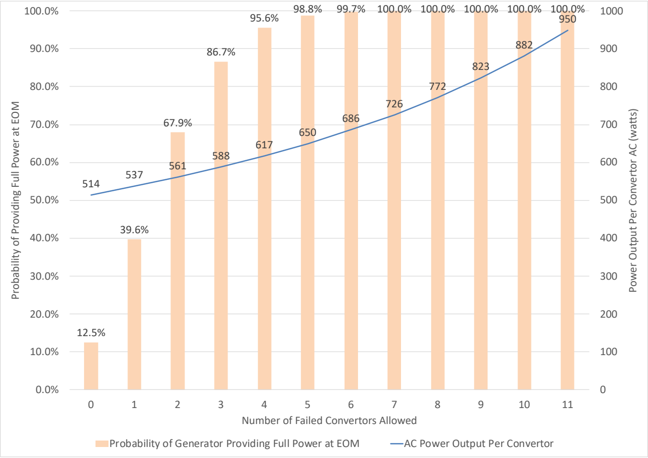


Figure 7. Reliability and single convertor power output of a 24 Stirling 91.7% (single card controller) reliable string as a function of the number of failed convertors.

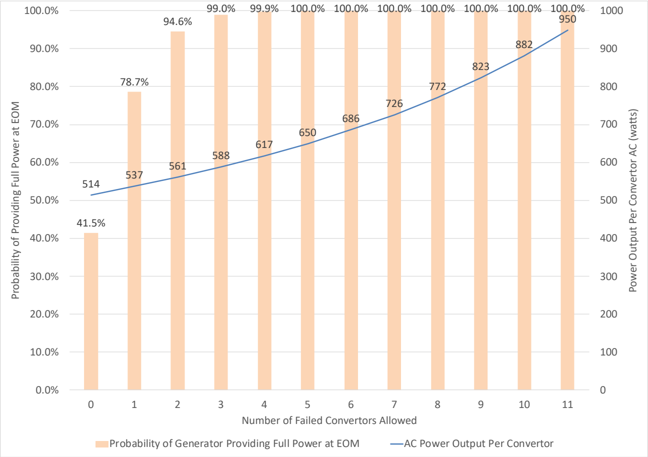


Figure 8. Reliability and single convertor power output of a 24 Stirling 96.4%(dual card controller) reliable string as a function of the number of failed convertors.

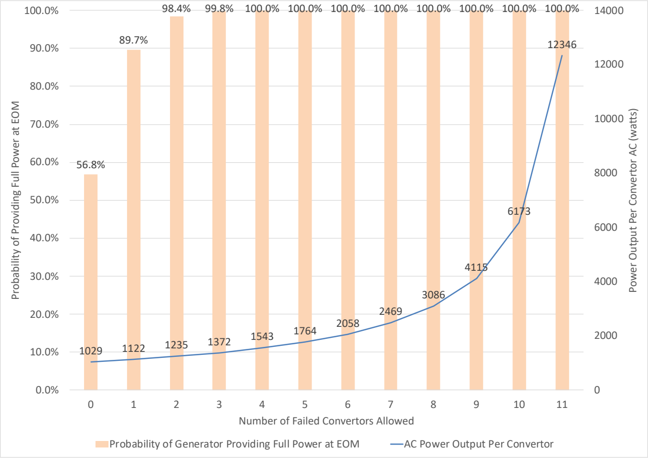


Figure 9. Reliability and single convertor power output of a 12 Stirling 95.4% convertor/dual card controller power system as a function of the number of failed convertors.

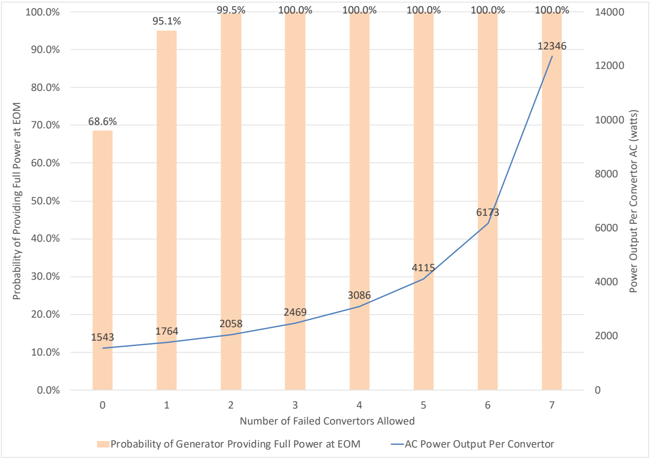


Figure 10. Reliability and single convertor power output of an 8 Stirling 95.4% convertor/dual card controller power system as a function of the number of failed convertors.

For the concepts which directly couple the core heat pipes to the Stirling convertors, the failure of any component in the power conversion string will feed back into the core. The core reliability is therefore not just based upon the heat pipe failing but any of the components in that string. Using the 91.7% string reliability (Table 5) without a backup card raises the chance of failure of 3 neighbor heat pipe strings to 2.5% from the 0.0017% (Table 6) when the core is operated independently from the power system using the intermediate heat exchanger. If we add a backup controller card to the string, string reliability improves significantly from 91.7% to 96.4% and results in a core POF of 0.2%. This propagation of failures lead us to consider the radiative and pool boiler intermediate heat exchanger concepts discussed earlier. The consequence of adding the intermediate heat exchanger is that it defines the minimum POF which we set at 1%. The benefit is that the downstream components, Stirling convertor, controller, and balancer combinations, allow us to vary the total number of convertors which may reduce the overall power system mass and cost.

Table 7 shows a 12 convertor string architecture that can provide full power with 9 working convertors while Table 8 shows a 8 convertor string architecture that requires 6 convertors operational to provide full power. For the 24/18 system with an intermediate heat exchanger little benefit is seen of adding the dual card controller because the POF of the power conversion system is so low. For the 12/9 and 8/6 systems The POF has jumped from 0.26% to 2.4% and 3.61% respectively.

Table 6 Overall POF 24 Convertor Strings with 18 Operating at End of Life

Case	# core heat pipes	# Stirlings / #Opearting EOL	Core POF	Intermediate HX	Power Conversion Subsystem	System POF	System Reliability
Core Heat Pipes to Stirlings, Balancers, Single Card Controller	24	24/18	2.5%	0.0%	0.26%	2.80%	97.20%
Core Heat Pipes to Stirlings, Balancers, Dual Card Controller	24	24/18	0.2%	0.0%	0.00%	0.20%	99.80%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Single Card Controller	24	24/18	0.0017%	1.0%	0.67%	1.67%	98.33%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Dual Card Controller	24	24/18	0.0017%	1.0%	0.01%	1.01%	98.99%

Table 7 Overall POF 12 Convertor Strings with 9 Operating at End of Life

Case	# core heat pipes	# Stirlings / #Opearting EOL	Core POF	Intermediate HX	Power Conversion Subsystem	System POF	System Reliability
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Single Card Controller	24	12/9	0.0017%	1.0%	2.40%	3.40%	96.60%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Dual Card Controller	24	12/9	0.0017%	1.0%	0.17%	1.17%	98.83%

Table 8 Overall POF 8 Convertor Strings with 6 Operating at End of Life

Case	# core heat pipes	# Stirlings / #Opearting EOL	Core POF	Intermediate HX	Power Conversion Subsystem	System POF	System Reliability
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Single Card Controller	24	8/6	0.0017%	1.0%	3.61%	4.62%	95.38%
Heat Pipes to HX, Secondary HP to Stirlings, Balancers, Dual Card Controller	24	8/6	0.0017%	1.0%	0.47%	1.47%	98.53%

7. SUMMARY

Kilopower is a promising new technology that will allow NASA to enhance its exploration of the Moon and Mars. This paper highlights some possible architectures of mating the Kilopower reactor with primary heat pipes, intermediate heat exchangers, and Stirling power convertors. Each architecture presents unique challenges for the Kilopower development team. Redundancy was explored as a way to increase system reliability and mitigate risk for the power conversion subsystem which is still very early in its development cycle. Although the POF and reliability numbers used in this report are early derivatives, the results show how the different architectures can all provide a highly reliable system using redundant units of lower reliable components. NASA and DOE will continue to study the many possible architectures while increasing the confidence levels of the reliability data. Equally important in the decision making will be the technology readiness of nuclear and non-nuclear components and manufacturing methods, assembly test and launch operations, and the extensibility to future missions.

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BIOGRAPHY

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