Stirling Isotope Power Systems for Stationary and Mobile Lunar Applications

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The NASA Exploration Systems Architecture Study (ESAS) places a significant emphasis on the development of a wide range of capabilities on the lunar surface as a stepping-stone to further space exploration. An important aspect of developing these capabilities will be the availability of reliable, efficient, and low-mass power systems to support both stationary and mobile applications. One candidate system to provide electrical power is made by coupling the General Purpose Heat Source (GPHS) with a high-performance Stirling convertor. In this paper we explore the practical power range of GPHS/Stirling convertor systems all with conductively coupled hot-end designs for use on the lunar surface. Design and off-design operations during the life of the convertor are studied in addition to considering these varying conditions on system. Unique issues concerning Stirling convertor configurations, integration of the GPHS with the Stirling convertor, controller operation, waste heat rejection, and thermal protection are explored. Of particular importance in the evaluation process is a thorough understanding of the interactions between the wide range of unique lunar environments and the selection of key systems operating characteristics and the power systems design. Additionally, as power levels rise the interface between the GPHS and Stirling and the Stirling and the radiator begins to dominate system mass and material selection becomes more important.

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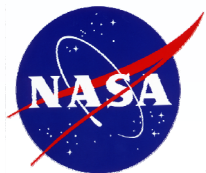
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The work described in this paper was performed for the Exploration Systems Mission Directorate (ESMD), which provided funding for these projects. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of NASA.

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Objective & Requirements

- Explore the practical power range of GPHS/Stirling convertor systems all with a conductively coupled hot end designs for use on the lunar surface
- Design and off-design operation during the life of the convertor
- Varying environmental conditions
  - Of particular importance in the evaluation process is a understanding of the interactions between the Stirling system and the lunar environments
- 14 year life
- Maximum Number of GPHS modules set to 12
- Maximum Heater Head temperature 1123 K
- GPHS Iridium capsule cladding temperature limit of 1608 K which leads to a GPHS surface temperature of 1373 K
- At the design point both of these temperatures are fixed and used to size interface
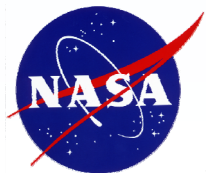
Thermal Environment

- Power operation on the lunar surface is a challenge due to the wide range of temperatures encounter as both latitude and time of day change

- Lunar soil has a high solar absorptivity and low thermal conductivity

- Typical space based systems use Beginning of Life (BOL) emissivity of >0.9 for modern space radiators, surface treatments limit solar absorptance to 0.06

- Due to dust accumulation an emissivity of 0.86 and a solar absorptivity of 0.5 was assumed.

- The sink temperature extreme's used in this study are 340 K and 60 K for a equatorial full sunlight and a pole crater respectively
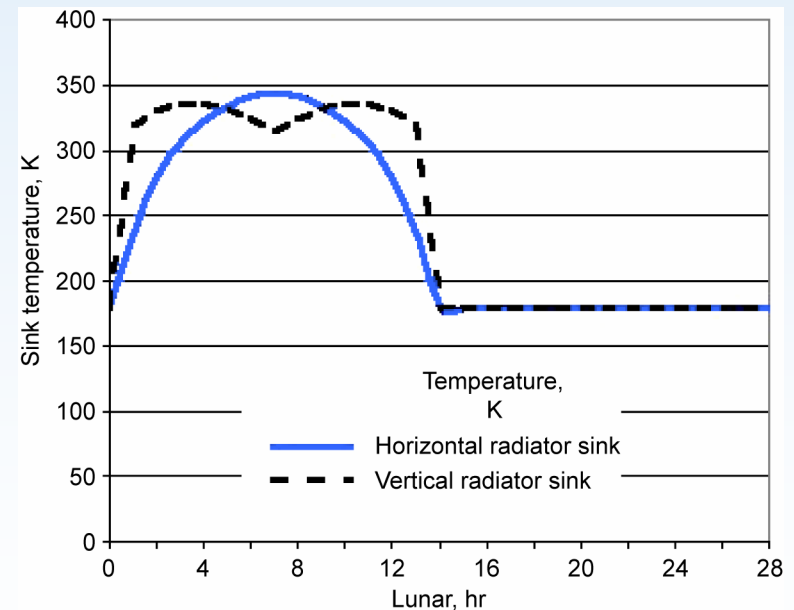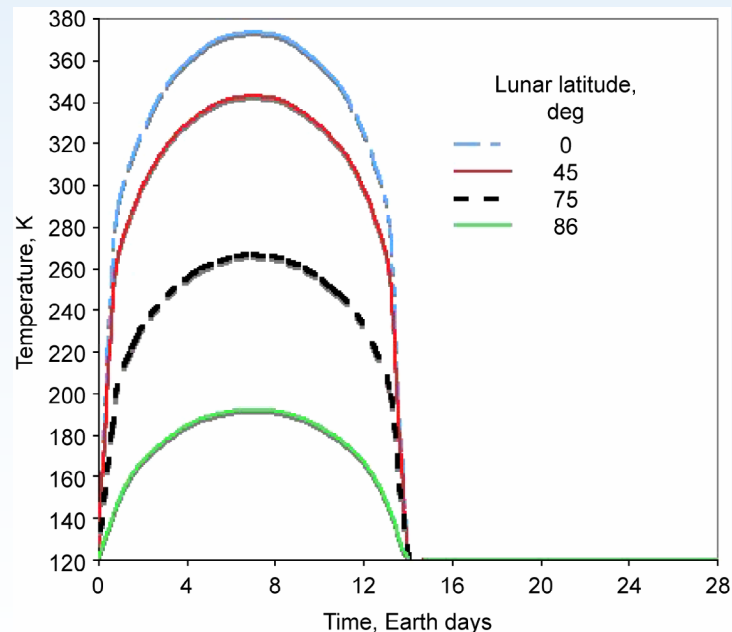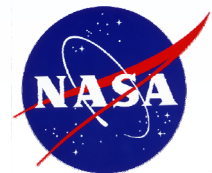
Stirling Convertor

- The convertor technology utilized in this evaluation is derived from that employed in the Advanced Stirling Convertor (ASC) currently under joint development by the industry team of Sunpower Inc. and P&W Rocketdyne and NASA / GRC.

- This convertor emphasizes the use of high heater head temperatures (1123 K (850 C) high specific power levels (75 to 100 We/Kg), and electrical output to thermal input efficiencies of approximately 60% of Carnot

- Current FeNdB magnet / alternator technology limits Stirling cold end temperatures to less than 390 K (115 C). With sink temperatures approaching 340 K, FeNdB are not practical for all lunar conditions

- In order to allow adequate margin and to maintain a reasonable size on radiator area Samarium Cobalt (SmCo) magnets were used for all convertors modeled. SmCo magnet / alternator technology limits rejection temperatures to somewhat less than 550 K (250 C) and in all cases the maximum Stirling cold end temperature was set at 530 K. Current assessment is that there is little or no impact on alternator mass or efficiency if SmCo magnets are used at temperatures between 400 and 550 K when compared with the FeNdB magnets.
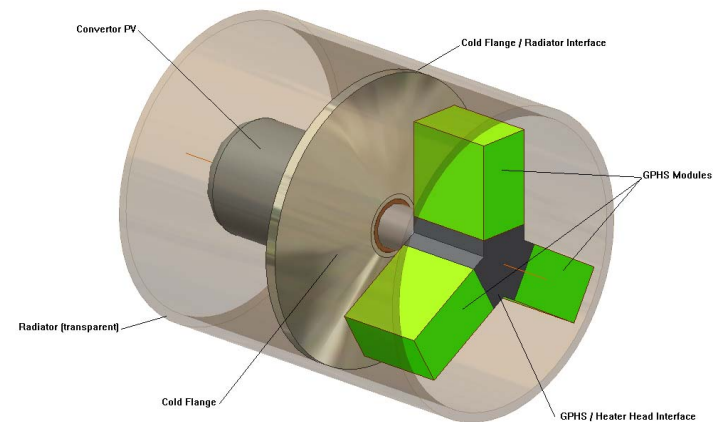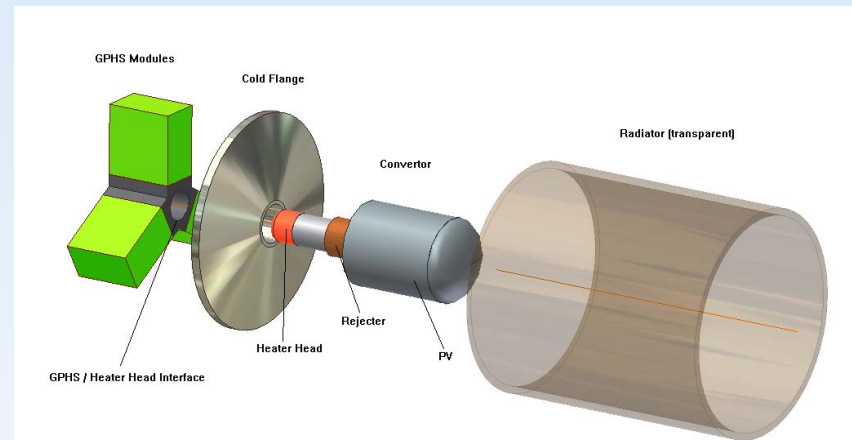
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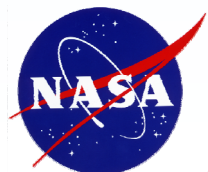
Overview of System

- GPHS Modules are conductively coupled to Stirling Heater Head
- Cold end design is radial conduction path out from cooler to cylindrical radiator which surrounds the assembly.
- Heat Source assembly is surrounded by Multi-layer insulation and the insulation is surrounded by a aluminum shell.
- Various materials were tried for both the hot and cold ends
- When heat pipe are used:
  - heat pipes run out from the cooler and a Stirling cold end interface to the radiator and then towards the ends

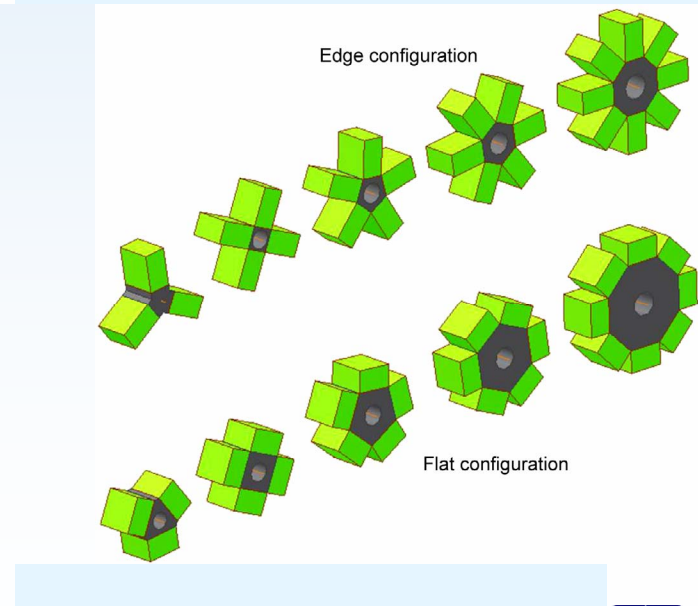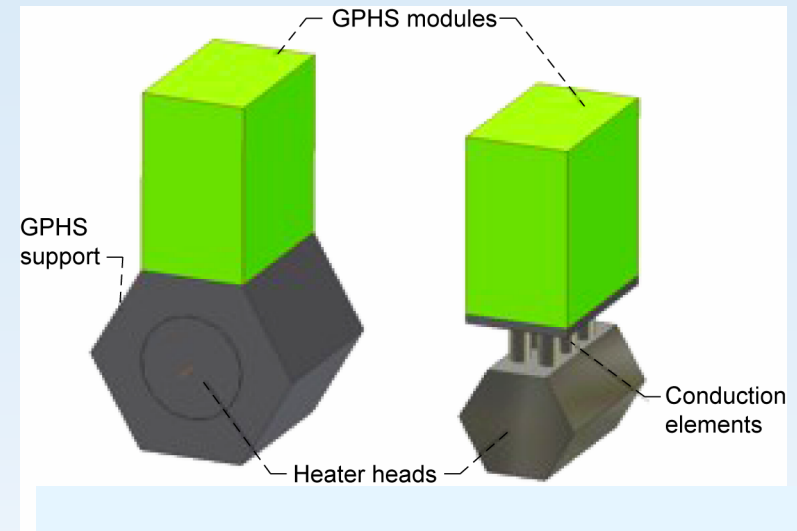**Glenn Research Center**

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GPHS Orientation & Stirling Integration

- GPHS to convertor attachments
  - 2 Options considered, solid block or smaller elements
    - (Ni and Graphite considered, Ni selected as reference)
  - Used allowable ΔT to size the thickness of conduction path into heater head
  - This was done to find the minimum material mass needed
- GPHS have different dimensions on each side
  - Two orientations considered
    - "Small Area - "Edge" configuration
    - Large Area- "Flat" configuration

Height	5.3	cm
Width	9.32	cm
Length	9.72	cm

GPHS modules

GPHS support

Heater heads

Conduction elements

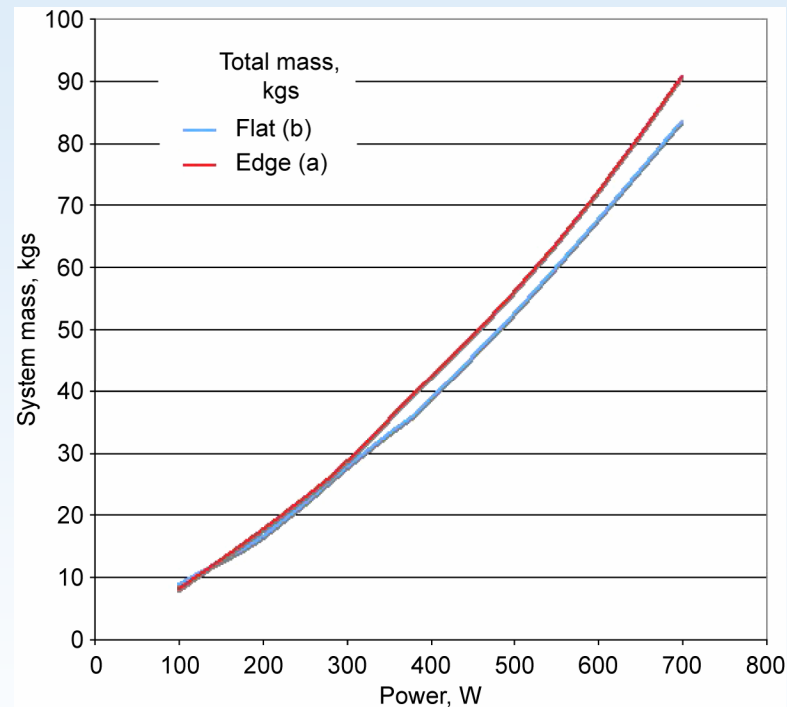Edge configuration

Flat configuration

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GPHS Integration

- Flat or Edge on configurations trade connector mass for enclosure and cold end flange mass
- Little difference seen in total mass seen with either configuration but "flat" provided some small benefit so for future plots we assumed a "flat" orientation
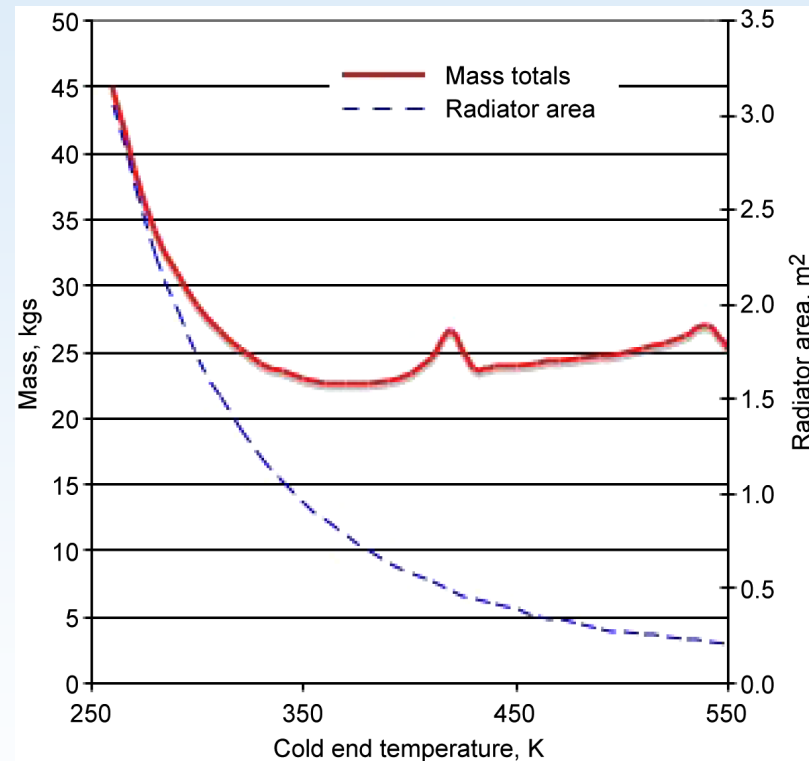

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System Analysis

- System is modeled based on the desired power output, environment and components properties

- Many systems are sized for a variety of Stirling cold end conditions- Off-design is found by fixing the system design and then varying off design environmental or heat input values (decay of Pu-238)

- Example: 200 watt Stirling convertor, Nickel connector on hot-side, Aluminum cold-end flange, Plot of mass and radiator area as a function of Stirling cold-end temperature
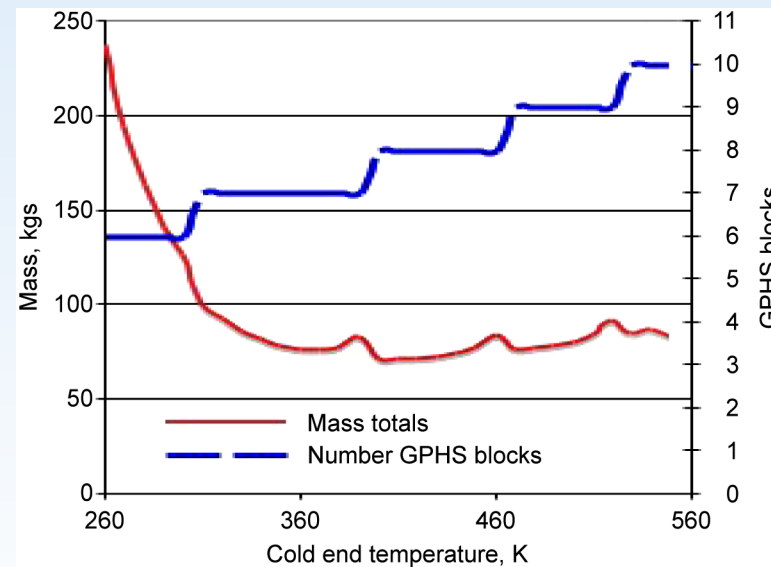
GPHS Module vs. Efficiency

- Typically for space systems mass is minimized, but given limited GPHS modules, Cold end temperature can be dropped to reduce their required number

- Example:500 watt, system, Ni Hot-End, conductive cold end. Plot of system mass and number of GPHS modules vs. convertor cold end temperature

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Sink Temperature

- Sink Temperature affects both system mass and radiator area.
- It also greatly affects both the range and minimum mass points of the Stirling cold-end
- Examples:
- Plot on left is for a 200 watt, 60 K system- Minimum mass system of 20 kgs occurs at a Stirling cold end temperature of 380 K
- Plot on right is the same system except with a 340 K sink. Minimum system mass of 26 kgs occurs at 480 K
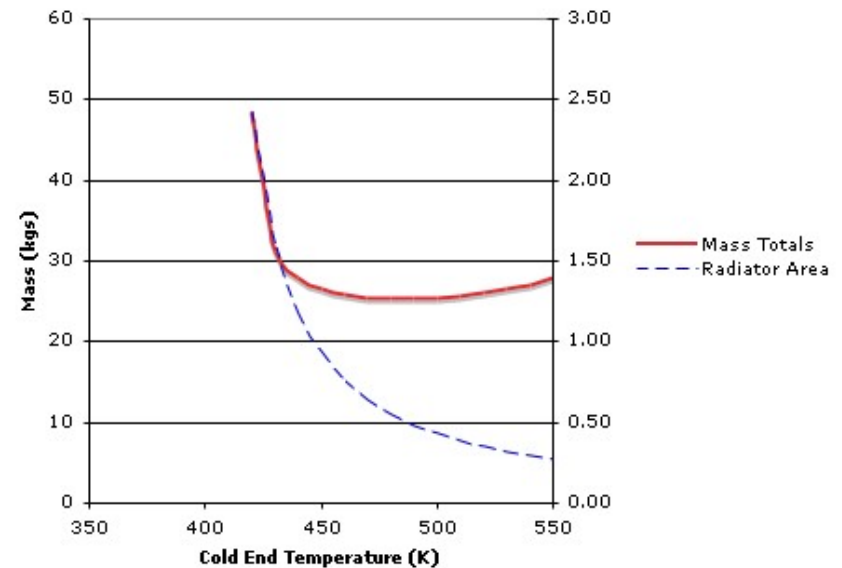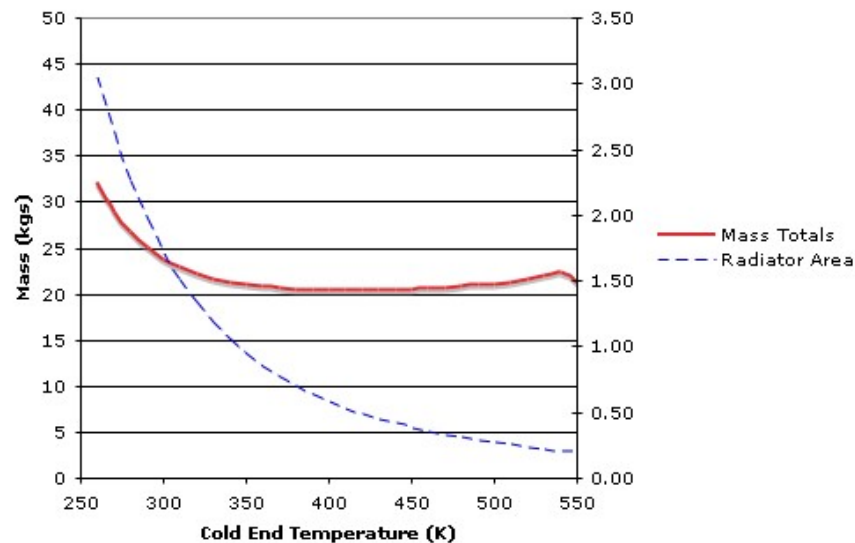
Power Level

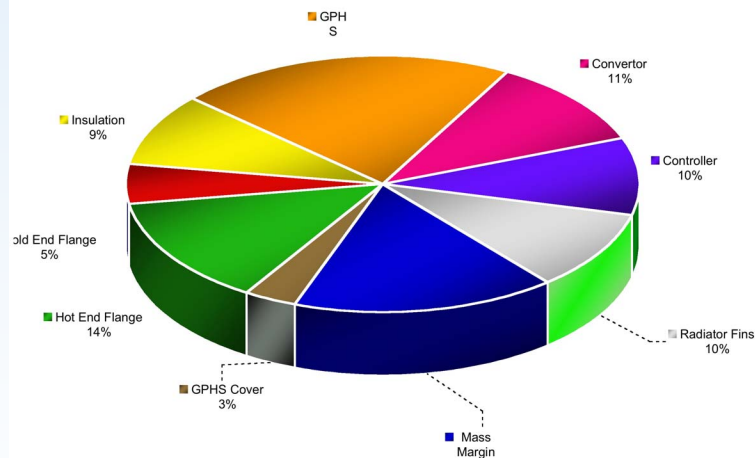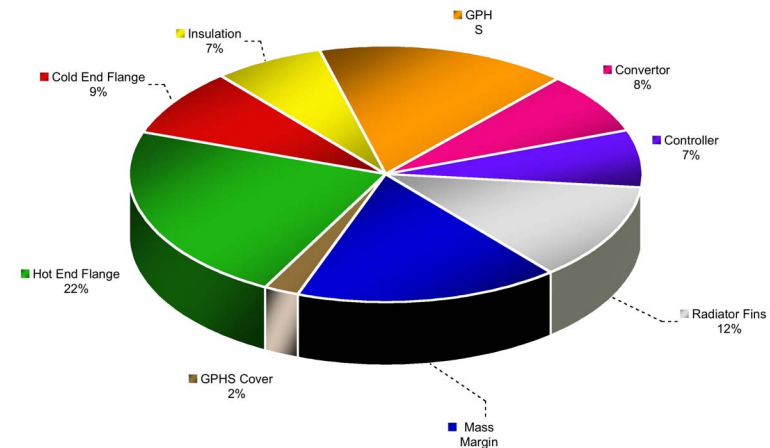- As power levels rise the difficulty in getting heat into and out of the convertor comes to dominate the system mass.
- This can be seen by looking at the mass fraction dedicated to heat addition and heat removal for a 200 and 600 watt dual opposed system.

200 watt system
Heat Addition/Removal Mass Fraction
29%

600 watt system
Heat Addition/Removal Mass Fraction
43%

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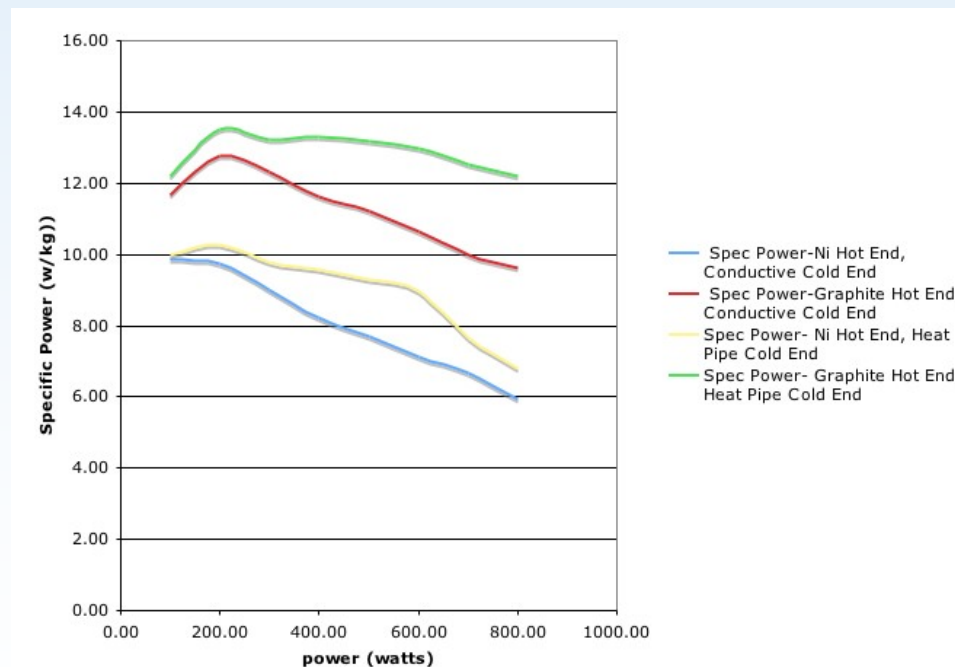
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Power Level (cont.)

- To decrease the mass associated with both heat input and extraction higher conductivity and lighter weight materials can be used.
- Heat pipes can be used to decrease the temperature drop through the flange and decrease the fin length on the radiator
- Heat pipes on the hot-end were not considered

Vibration Isolation System

- Due to the motions of the components within the Stirling convertor a net unbalanced force will be transmitted to the structure supporting the convertor. In most cases these are well above acceptable values thus requiring the use of some form of vibration cancellation or minimization

- The most common approach employed recently in low power RPS is to mount the convertors is opposed pairs

- Even with a dual opposed pair to reduce vibration, the loss of a single convertor of the pair would require the other convertor to be shut down

- A dual opposed pair with a balancer would allow power to be generated if a single convertor fails

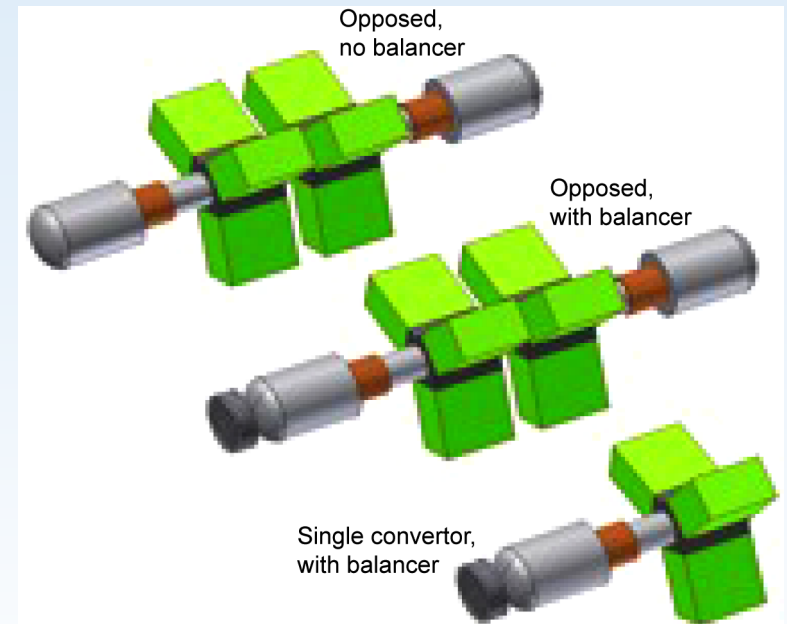- Balancer mass is approximately 20% of the convertor mass

Opposed, no balancer

Opposed, with balancer

Single convertor, with balancer

Figure 11.—LPS configuration.

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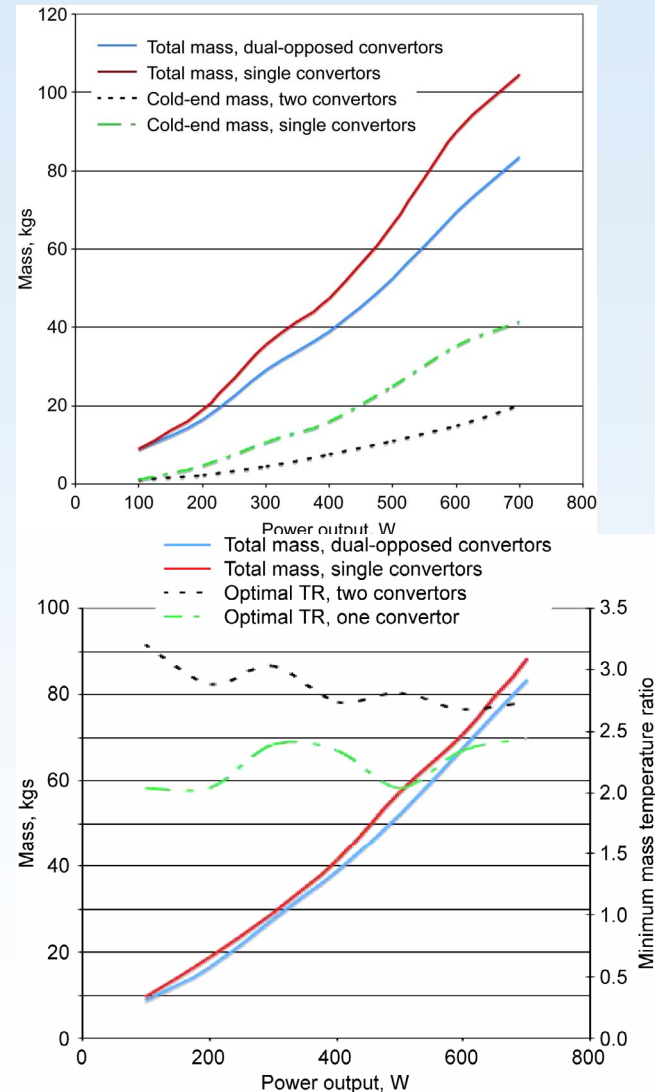## at Lewis Field

Single vs. Dual Opposed Systems

- As Stirling convertors increase in power output their specific power improves but…

- As power levels rise the mass penalty for heat addition and removal increases.

- Two ways to model systems, let temperature vary for best mass or fix cold end temperature

- At all of the power levels considered the dual opposed configuration provided a equivalent or lower system mass as the single convertor system.
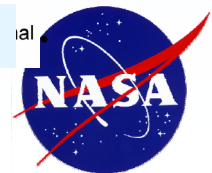
Convertor Failures

- For a dual opposed configuration with a balancer, the failure of a single convertor will still allow some power to be generated
- To keep the system within its temperature limits several things must occur:
  - The heater head temperature must drop to allow twice the amount of heat to flow into the single convertor
  - The second Stirling must be oversized and able to absorb the additional heat that was going to the second convertor
  - The second convertor must reject all of the heat and keep the cold-end within its allowable magnet limits
  - The convertor alternator must be sized to produce about 50% more power
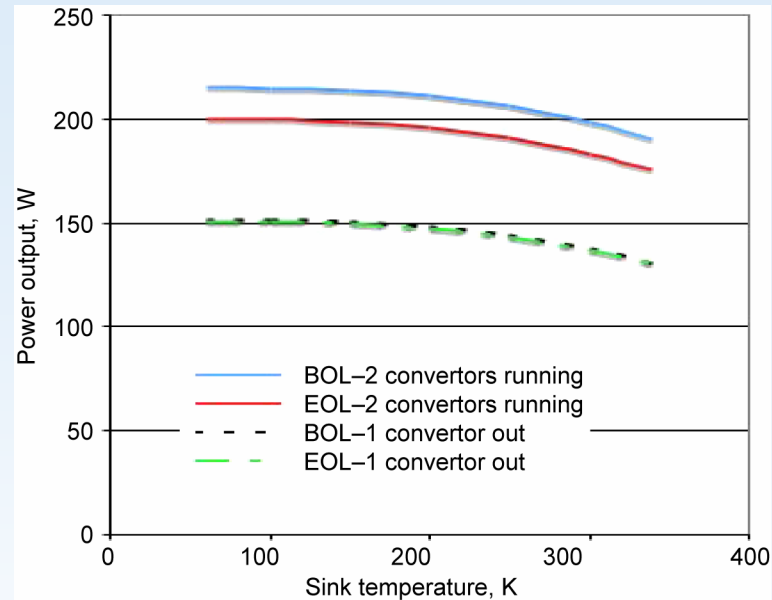
Configuration	BOL-2 convertors running	EOL-2 convertors running	BOL-1 convertor out	EOL-1 convertor out
Heater Head Temperature (K)	1117	1123	924	979

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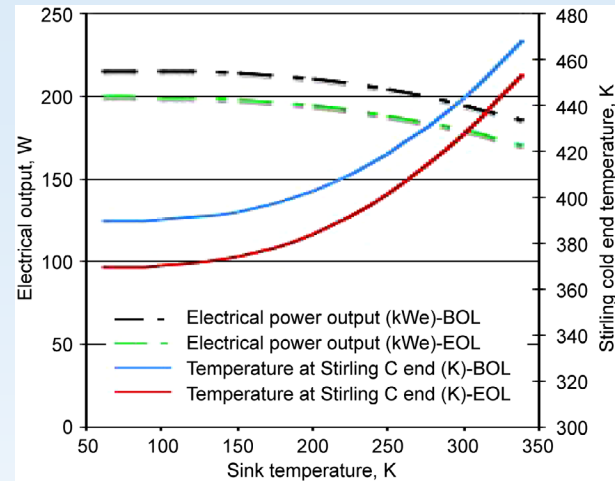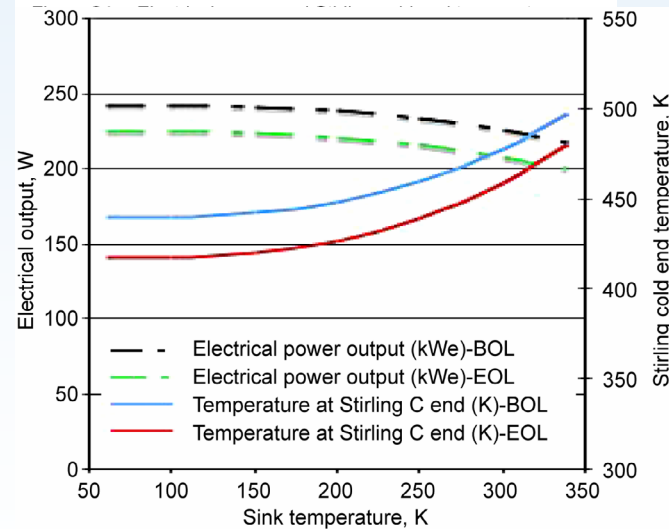
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Off-Design Operation

- BOL and EOL operation changes the operating conditions on the system
- Power variation for the 60 K and 340 K design points over a range of sink temperatures is about 10%
- All systems considered here are designed to produce full power at EOL (14 years)
- Varying Sink temperatures can significantly change cold end operating temperatures - about 100 K for both cases

60 K sink design point

340 K sink design point

Conclusions

1. For the power levels of interest energy transfer based only on thermal conduction between the GPHS modules and convertor heater head should be utilized due to its inherent simplicity. However, the overall integration of GPHS / Stirling convertor system is driven by the heat addition / removal constraints of the Stirling heat exchangers.

2. Environment plays a significant role in the specific power of the system. Systems designed for operation in a 60 K environment but placed in 340 K (max lunar sink environment) potentially can exceed linear alternator allowed temperatures. Convertor and linear alternator operating temperatures must be increased to on the order of 250 C.

3. Various mechanical configurations of the thermal interface between the GPHS / heater head are rejector / radiator available. An important factor in the specific selection will depend on the materials for the interface and in the case of the cold end the heat transfer mechanism. Using a Ni interface on the hot end and an aluminum cold shoe on the cold end maximum specific power (watts/kg) occurs around 200 watts for a dual opposed convertor (100 watts/convertor).

4. The integration of multiple GPHS modules (up to 12 investigated) with the a Stirling convertor can be carried out in a manner that is mutually compatible with the GPHS requirements and the conditions that are needed for high convertor efficiencies.

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