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Stirling Isotope Power Systems for Stationary and Mobile Lunar Applications

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Abstract

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.

Nomenclature

Al/TPG	aluminum/thermal pyrolytic graphite
ASC	advanced Stirling convertor
ASRG	advanced Stirling radioisotope generator
BOL	Beginning-of-Life
EOL	End-of-Life
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
FeNdB	iron neodymium boron
GPHS	General Purpose Heat Source
LPS	Lunar Power System
MLI	multi-layer insulation
RPS	Radioisotope Power Systems
RTG	Radioisotope Thermoelectric Generator
SmCo	samarium cobalt
SRG110	110 watt Stirling radioisotope generator
UV	ultraviolet

I. Introduction

One method of providing power on the lunar surface is by coupling a General Purpose Heat Source (GPHS) to a Stirling convertor. These systems are potentially attractive in that they require fewer GPHS than their Radioisotope Thermoelectric Generator (RTG) counterparts and allow continuous operational capabilities without the need for energy storage systems during the long (14 Earth days) lunar night. In addition, the relatively low amount of emitted radiation allows for placement near human operations with minimal shielding (ref. 1). Although Stirling generators have been proposed numerous times before, as electrical power requirements increase, it becomes more challenging to insert and extract heat into a Stirling convertor without either heat pipes or a pumped liquid loop. Heat insertion/extraction is exacerbated by the use of GPHS because of the relatively low heat flux; a high heat flux is required by the Stirling convertor on the hot-end. Several concepts for integrating multiple GPHS modules to a Stirling convertor were discussed at last year's Intersociety Energy Conversion Engineering Conference (IECEC) (ref. 2). While other types of integration are most likely a requirement for power levels above a few kilowatts, it is interesting to consider what limits may exist for a conductively coupled GPHS/Stirling power systems. This paper will explore the point at which conductive coupling become mass prohibitive for both the hot and the cold-ends. This paper is intended as a guide to help understand the important trades associated with a conceptual Stirling Lunar Power System (LPS) rather than a final power system design.

Several factors were assumed for this analysis. A typical mass margin used for Exploration Systems Mission Directorate (ESMD) preliminary designs is 20 percent (sum of total component mass estimates times 0.2) and is used in this analysis. A power management and distribution and controller efficiency of 91 percent was assumed. System life is 14 years (end-of-life (EOL)) and a maximum heater head temperature of 1123 K. In most of the cases minimum system mass was used as the selection criteria for the "best" system. It was found that by varying the cold-end temperature of the Stirling convertor system mass could be reduced. Maximum number of GPHS units per system was limited to 12.

II. Thermal Environment

Power system operation on the lunar surface is a challenge because of the lack of atmosphere to reject heat and the wide range of heat rejection or sink temperatures, which occur during the lunar diurnal cycle. To maximize the efficiency of the power system, a Stirling convertor prefers a large temperature difference across its hot/cold-ends. The maximum hot-end temperature is set by material concerns while the cold-end temperature is a compromise between getting as close as possible to ambient temperature to increase efficiency and increasing the size of the heat rejection system. While many radiator orientations are possible, horizontal (parallel to the lunar surface) and vertical radiators help bound the trade space. Vertical radiators have the advantage of being able to radiate from two sides, effectively doubling the amount of heat rejected per radiator panel. The downside to the vertical orientation is that the radiator "sees" the very warm (during the lunar day) lunar soil reducing the amount of heat that can be rejected.

This large variation in temperatures is due to the lunar soil's high solar absorptivity and low thermal conductivity and lack of any atmosphere to move heat via conduction. This combination leads to lunar surface temperatures ranging from 120 to 374 K (–153 to 101 °C) (refs. 3 and 4). Figure 1 shows a plot of surface temperature as a function of latitude and time of day. In addition to the location selected for a power system, radiator orientation also plays an important role in the effective sink temperature. For a radiator located near the equator, north-south or east-west alignments of the Sun pass nearly straight overhead and an east-west alignment of the radiator would minimize the Sun incident component of the energy received by the radiator. Figure 2 shows a plot of sink temperature for both a horizontal radiator and a north-south vertical-pointing radiator at the equator. There is no long-term data on the thermal coating degradation in the lunar environment. Degradation is predicted to occur due to both the accumulation of dust on the surface and ultraviolet (UV)/charged particle interaction with the surface treatments on the radiators. Beginning-of-life (BOL) emissivity is >0.9 for modern space radiator surface treatments and solar absorptance is about 0.06. For this analysis a radiator emissivity of 0.86 and solar absorptivity of 0.5 was assumed to reflect dust accumulation on the radiator. For this analysis the range of temperatures considered for sinks ranged from 60 to 340 K (–213 to 67 °C).

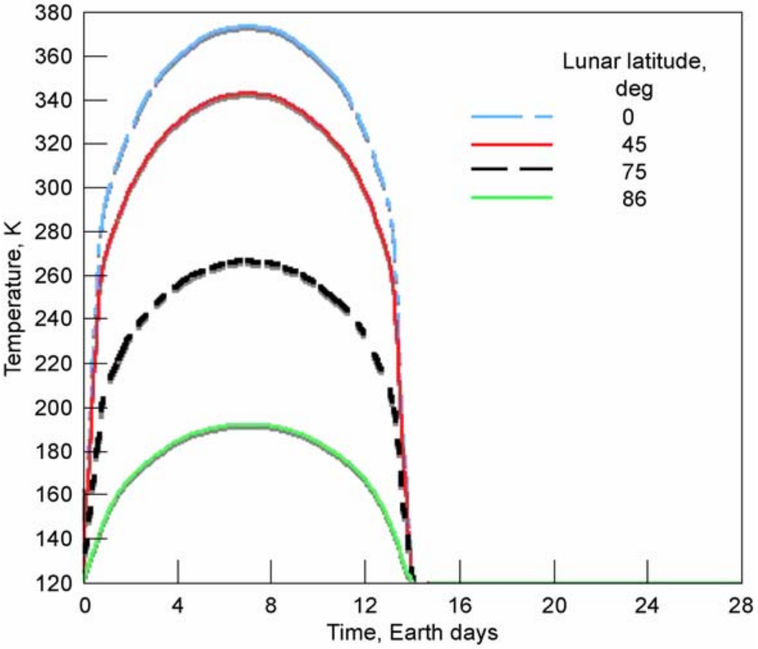

Figure 1.—Lunar surface temperature as a function of time and latitude.

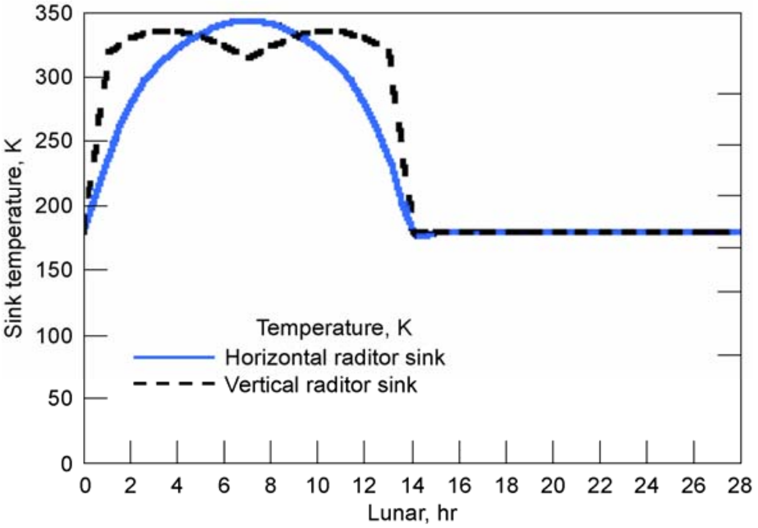

Figure 2.—Sink temperature as a function of Earth days.

III. Stirling Convertor

The convertor technology utilized in the LPS evaluation is derived from that employed in the Advanced Stirling Convertor (ASC) currently under joint development by the industry team of Sunpower, Inc., P&W Rocketdyne, and NASA GRC. This convertor and the associated technology emphasizes the use of high heater head temperatures (1123 K (850 °C) versus the currently widely employed 923 K (650 °C)), (ref. 5) high specific power levels (75 to 100 We/Kg), and electrical output to thermal input efficiencies of approximately 60 percent of Carnot. Unless the temperature of the GPHS exceeds this limit, 1123 K (850 °C) is used for all cases evaluated in this paper. In that case the temperature of the Stirling heater head is reduced to limit the upper temperature of the GPHS. Utilizing the ASC as a starting point, it is a straightforward matter to scale this technology to higher power levels and different waste heat rejection temperatures, which allows the convertors to be evaluated within the overall LPS context. As previously noted the specific power of the Stirling convertor itself improves somewhat with power level. However, this change is relatively small in comparison to the significant mass changes that occur in the convertor-related subsystems involving the multiple GPHS to convertor integration and waste heat radiator (ref. 6). Therefore the focus of the convertor evaluation was in the areas of integration with the GPHS heat source, vibration isolation options, and convertor impact on LPS configurations. Current iron neodymium boron (FeNdB) magnet/alternator technology limits rejection temperatures to less than 390 K (115 °C). In many of the cases considered the worst case lunar sink temperature is 340 K (67 °C) allowing only a 50 K temperature difference between the cold-end and sink temperature to reject heat. 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 K (127 °C) and 550 K (277 °C) when compared with the FeNdB magnets operating at their lower temperature limits.

IV. GPHS/Convertor Hot-End Integration

The GPHS in the form of an RTG has been used for many deep space missions when there is a lack of adequate solar illumination to power solar cells (ref. 7). The GPHS fuel has a half-life of approximately 87 years that leads to relatively constant heat flux out of the GPHS module and each module produces about 250 W BOL. Current GPHS in the form of a STEP 2 GPHS are used for all space missions. Dimensions of this Step 2 GPHS module are shown in table 1 (ref. 8).

TABLE 1.—STEP 2 GPHS DIMENSIONS

Height	5.3 cm
Width	9.32 cm
Length	9.72 cm

Using the largest face (9.32 by 9.72 cm) the maximum heat flux out of a single GPHS module at BOL with insulation on the other sides is 2.69 W/cm^2 (ref. 9). In contrast to the low heat flux from the GPHS modules is that of the Stirling convertor heater head, which requires an input heat flux of about 15 W/cm^2.

Material temperature limits for both the convertor and the GPHS set the upper bounds for both component temperatures. The GPHS module temperature limit is set by the iridium cladding around the Pu-238 fuel whose temperature must be maintained between 1335 °C (1608 K) in normal operation and must not drop below 900 °C (1173 K) on ground impact. The 900 °C (1173 K) minimum temperature set the GPHS module dimensions and materials assuming a dispersal of the modules while the 1335 °C (1608 K) will be set by insulation and Stirling convertor heat flows. In the GPHS the iridium capsule is located inside a graphite shell. The effective maximum surface temperature of the graphite shell is 1100 °C (1373 K) in a vacuum (ref. 10). Fixing temperature of the heater head at 1123 K allows a temperature drop between the outer graphite shell and the heater head of 250 K (–23 °C). By combining this requirement with the distance between the heater head and the GPHS, the material properties and the contact resistance between the thickness of the connector and diameter of the convertor can be found. This connector between the GPHS and Stirling convertor is shown in figure 3. On the outside of the GPHS assembly, multilayer (vacuum foil) insulation is used and then around that, an aluminum housing is used.

Currently small, low-power Radioisotope Power Systems (RPS), such as the ASRG and SRG–110, employ a single GPHS module, which is located forward of the heater head and coupled to it via a “hot shoe” that acts as the thermal interface between the two components (ref. 11). The heat transfer mechanism is soley via conduction through the hot shoe material that is generally an Ni-200 series alloy because of their relatively high-thermal conductivity. Simply stacking the GPHS modules in a “layer cake” manner, see figure 4, has distinct limits due to the increasing temperatures of the GPHS modules as one progresses away from the heater head of the convertor. Current estimates are that the GPHS temperature constraint, when combined with the convertors 850 °C (1123 K) heater head operating temperature, limits the stack to no more than two modules, the equivalent of approximately 170 We output. To overcome this constraint it is necessary to utilize GPHS to heater head thermal couplings which are mounted radially about the heater head, see figure 5, when the GPHS module number required is greater than two. The focus in the LPS is higher convertor power levels so the number of GPHS modules becomes significant and their specific mounting configuration, which is important in both the overall mass and physical size of the LPS package. As can be seen in figure 5, as power increases (as well as the number of GPHS modules), there are two options available for mounting. The conventional “flat” (Orientation B) mounting arrangement utilizes the large face area of the GPHS at the thermal interface while the alternative “edge” (Orientation A) mounting employs one of the narrow faces.

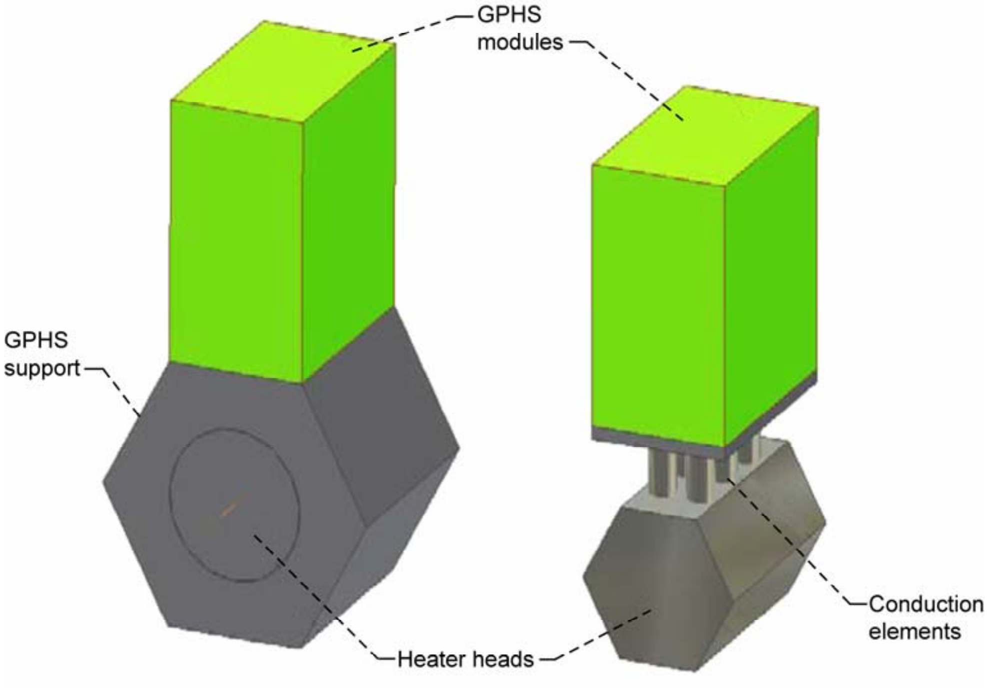

Figure 3.—Configuration options for GPHS support structure.

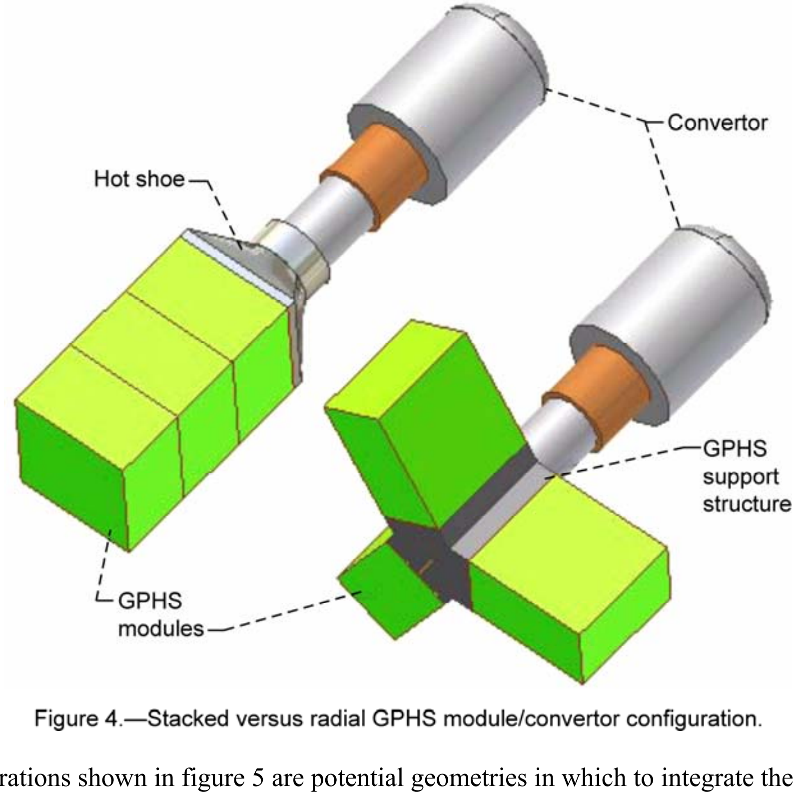

Figure 4.—Stacked versus radial GPHS module/convertor configuration.

The two configurations shown in figure 5 are potential geometries in which to integrate the GPHS to the Stirling convertor. It has been shown that regardless of orientation when all sides are insulated and heat flows out of a GPHS through one face that there is little difference between surface temperatures (ref. 12). This occurs because of the high conductivity of the GPHS graphite. Orientation A (edge) should allow a lighter GPHS to Stirling conductor by having a larger radius and thus a greater insulation and container mass. Orientation B (flat) should have a higher

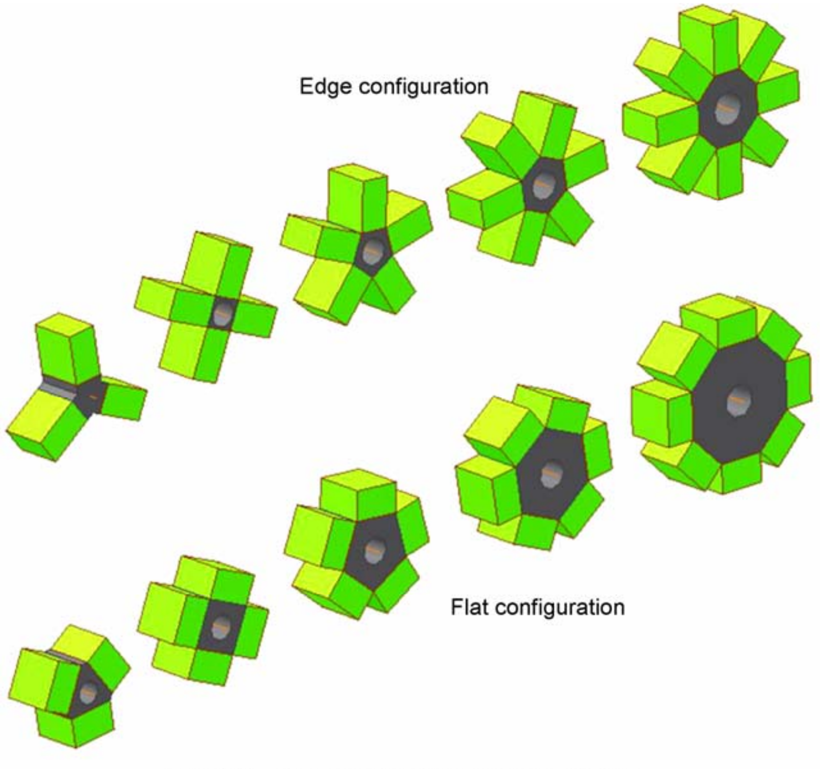

Figure 5.—Radial GPHS module configurations.

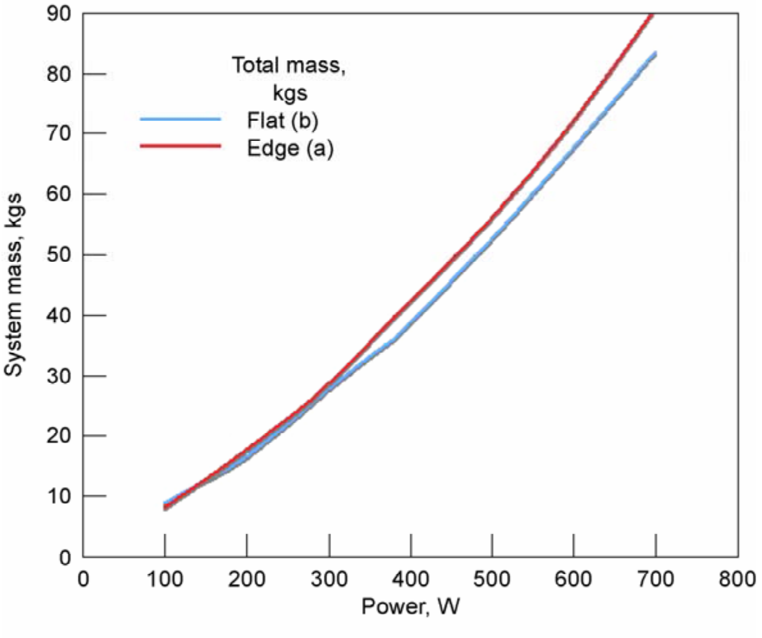

Figure 6.—System mass as a function of GPHS orientation.

GPHS to conductor mass and lower insulation and container mass. Figure 6 shows a system-level trade using both orientation A and B from 100 to 700 W. At each power level the system mass is minimized by a varying temperature of the Stirling convertor. For the entire power range considered flat surface is slightly more mass efficient for the assumptions made in this study and will be used from here forward for the discussed designs.

A concern with the use of GPHS modules for configurations that have two convertors operating in an opposed manner is that if one convertor fails, even if the other convertor continues to operate, the thermal energy produced

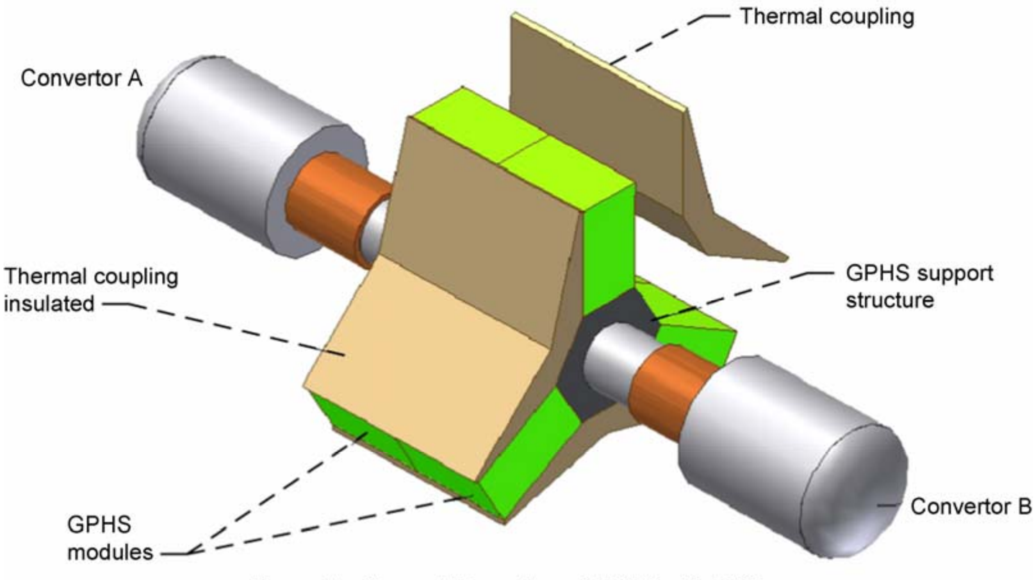

Figure 7.—Thermal integration of GPHS with Stirling.

by the GPHS assembly of the failed unit is lost from the point of view of useful power production. An alternative to thissituation involves taking advantage of the fact that the mass of these high-performance convertors is relatively low in comparison to the overall LPS mass thus allowing the convertor power capability to be oversized without having a significant impact on the overall LPS. For example, if an LPS employed two convertors each employing three GPHS modules the nominal output power would be on the order of 500 We. If one convertor fails the available power is on the order of 250 We. However, if the convertors were each sized for an output power of 500 We, but normally operated at 250 We and one convertor failed, the properly operating convertor could be “throttled up” to 500 We assuming that the thermal input to the convertor is the equivalent of six GPHS modules. A possible technique for carrying out the latter is shown in figure 7 in which thermal “couplings” are employed that act as thermal short circuits between the two GPHS assemblies. During normal operation (both convertors functioning) these components essentially do nothing since the operating convertors are absorbing the thermal energy produced. If one convertor fails then these elements act as thermal conductors transferring energy from the failed side to the operating convertor. As can be seen in figure 7 each convertor has a GPHS support structure designed for six modules but only three are installed. This allows the thermal couplings to be integrated in a thermally effective manner with the GPHS support structure/convertor heater head. If a generator is designed to operate with a failed convertor it will most likely require a “balancer” to remove the vibration imposed by the failure of the single convertor. This is discussed in a later section. Stirling convertor diameters are set by fixing heat flux into the convertor and limiting heater head height to 1.5 cm. As the number of GPHS modules grows, the distance from the surface of the GPHS module to the heater head also grows.

Cold-End Interface

Just as in the hot-end of the convertor, the cold-end design limits the heat flux out of the convertor. For the designs considered here a value of half the heater head heat flux was used (7.5 W/cm^2). A cold flange is attached to the convertor and runs radially out to the surface of the radiator. The radiator is a cylinder whose inner diameter is set by the housing of the GPHS modules and length set by the required area (section V). Temperature drops are calculated from the outer wall of the cold-end, through the cylindrical cold-end to radiator connecting plate, out to the surface of the radiator. The thickness of the flange is set to a specified temperature drop. The greater the temperature drop allowed in the flange, the lighter the mass but the lower the overall effective temperature of the radiator and thus the larger the radiator size and higher mass. The same is true for the fin thickness of the radiator that is set by fixing the temperature drop from the outer cold-end flange to the average radiator surface temperature. Figures 8 and 9 show typical mass and radiator area variations for both cold-end flange ΔT and fin-to-average radiator temperature for a 200 W generator in 60 K (–213 °C) sink environment. Both fin-to-average and cold-end

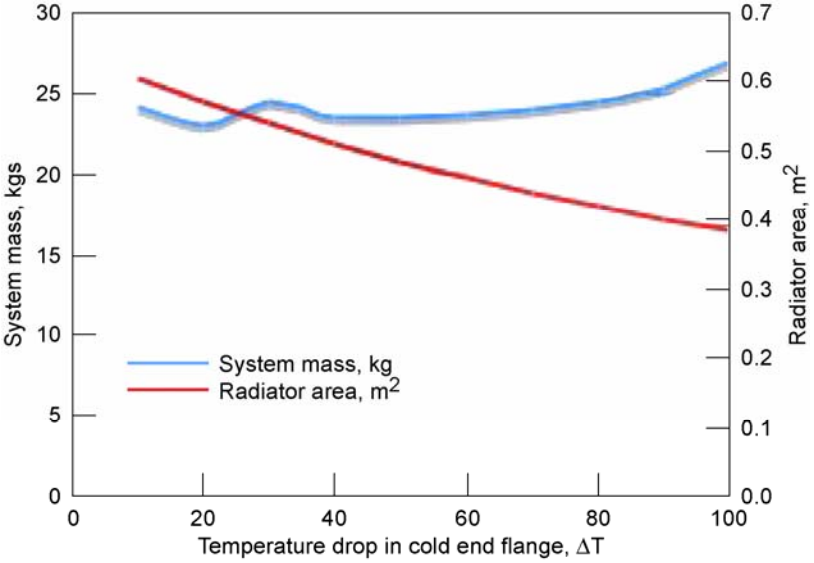

Figure 8.—System mass and radiator area as a function of cold end flange temperature drop.

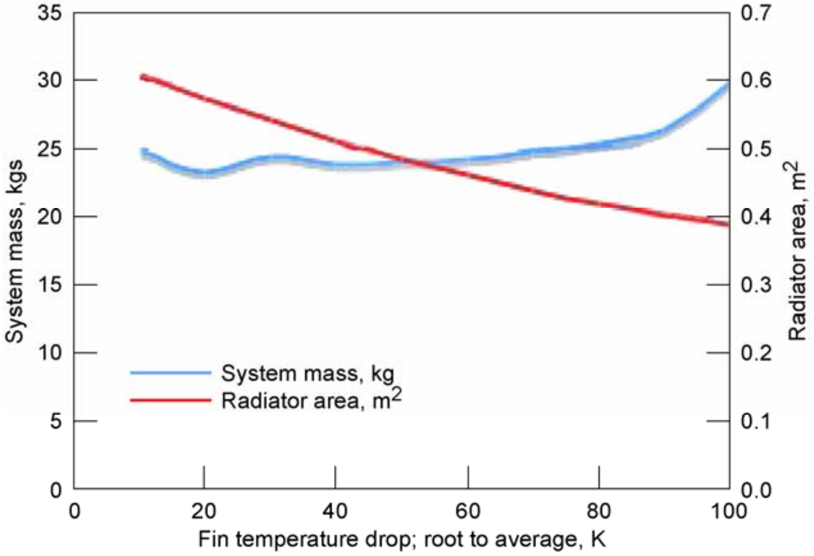

Figure 9.—System mass as a function of radiator fin temperature drop, 60 K sink.

flange optimize to an approximate 30 K ΔT. Figure 10 shows the same 200 W system except now the sink temperature is raised to the lunar worst case 340 K (67 °C). This shows unsurprisingly at a system level it is more advantageous to trade a smaller ΔT (now 10 K) for mass at 340 K than it is at 60 K.

Vibration Isolation Systems

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 assessed recently in low-power RPS is to mount the convertors in opposed pairs, see figure 11, such that the vibrations of the two operating convertors cancel each other (ref. 13). Note that the orientation of the convertors shown in the figure, hot-end to hot-end, is not required and was used for clarity. This can be carried out by use of techniques such as the convertor controller actively synchronizing the two convertors, electrically coupling the alternators, or various combinations of

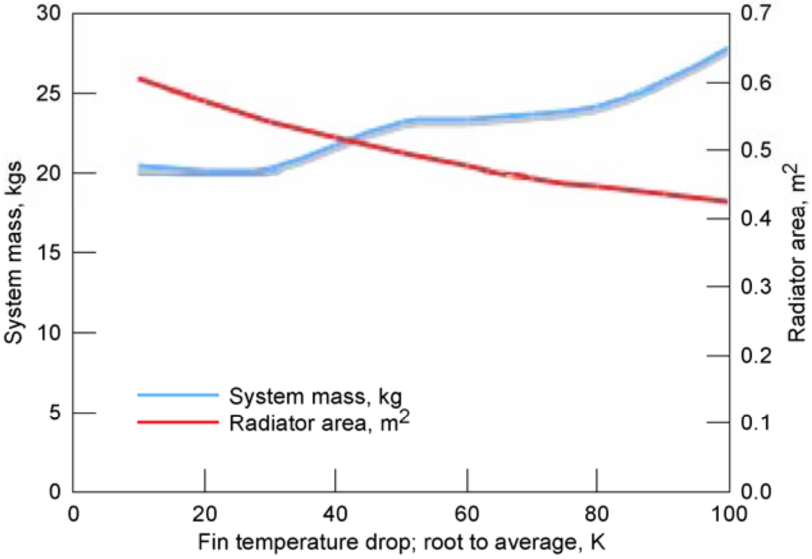

Figure 10.—System mass as a function of radiator fin temperature drop, 340 K sink.

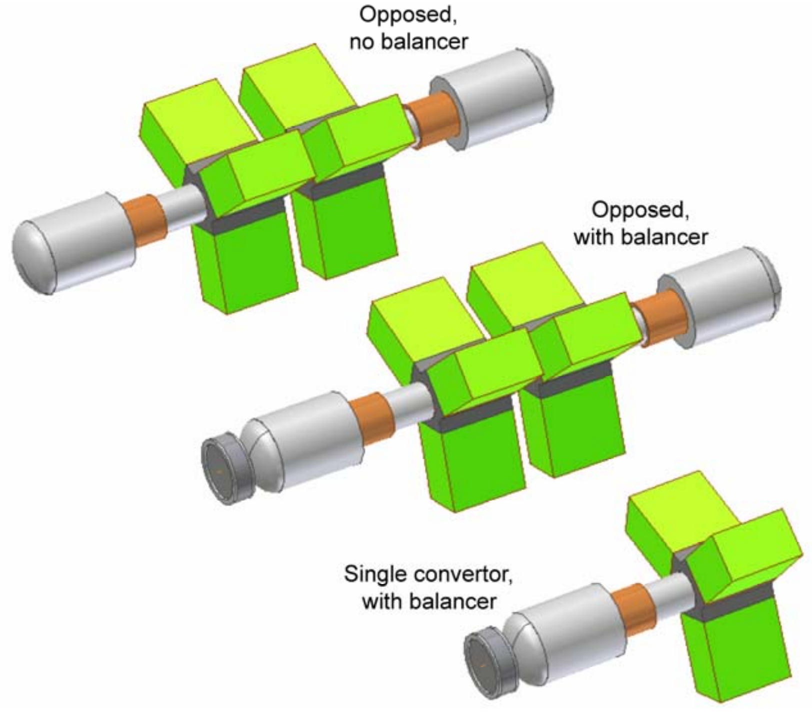

Figure 11.—LPS configuration.

these and other techniques. A disadvantage of this configuration is that if one convertor “fails” then the remaining convertor will be unbalanced and will transmit vibration loads to the supporting structure. This can lead to the situation if one convertor actually fails that the “healthy” convertor must also be shut down, which has a significant impact on overall system reliability and the requirements for backup RPS to ensure mission success (ref. 14). An alternative is to incorporate a mechanical “balancer” with the convertor that will cancel a significant portion of the unbalanced force of a single convertor. This can be used for the case where opposed convertors are employed or where the system is made up of a single convertor, see figure 11. The balancer is fundamentally a spring mass system tuned to resonate close to the operating frequency of the convertor generally made up of planar or flexure springs, a mass, and in the case of an active balancer, a small linear motor. The additional mass increase in convertor caused by the balancer will be on the order of 20 percent of the convertor mass. While there is this mass penalty, the use of balancers does allow a number of LPS configurations to be considered.

V. LPS Configuration Constraints

In the LPS evaluation, the GPHS modules and the associated support structure are assumed enclosed within a high-performance multi-layer insulation (MLI) package. The impact of this is further complicated by the fact that the baseline configuration of the LPS heat rejection radiator is a cylinder that surrounds the entire convertor and the MLI package as shown in figures 12 and 13. Note that the three-GPHS configuration is shown for clarity, all systems employing more GPHS modules are configured in the same manner. As can be seen, the convertor hot-end is coupled to the GPHS module assembly (MLI removed for clarity) while the cold-end (rejecter) of the convertor is attached to the "cold flange," which thermally couples the convertor to the radiator assembly (shown transparent for clarity).

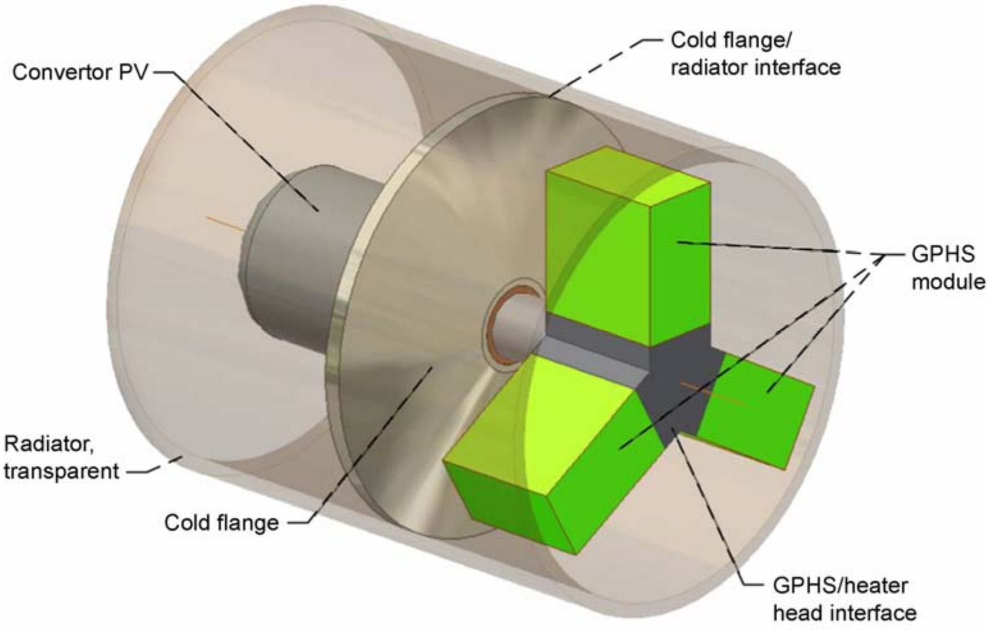

Figure 12.—LPS configuration.

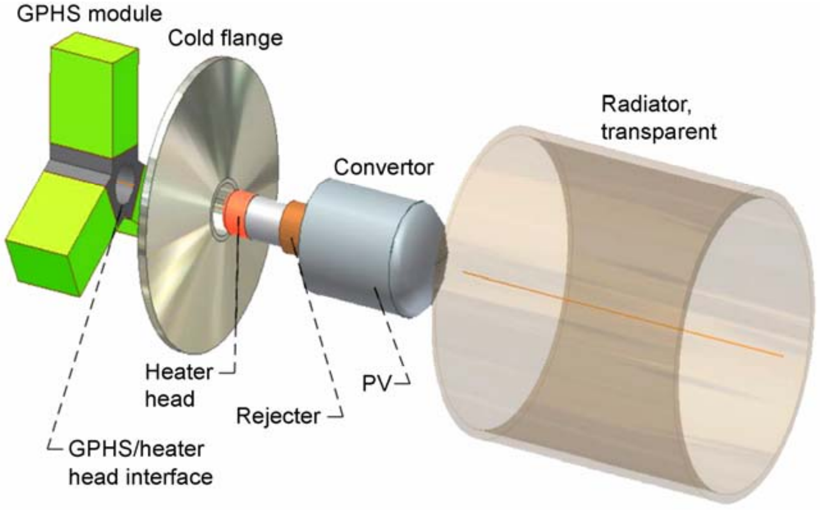

Figure 13.—Expanded view of a three-GPHS module system.

VI. Analysis

A computer simulation was created to model the performance of a GPHS/Stirling system under various thermal, power, and environmental conditions. Each of the major components, which make up the system are accounted for in the mass balance. For each of the configurations, system life is set to 14 years, maximum GPHS temperature is 1373 K (1100 °C), and maximum Stirling temperature is set to 1123 K (850 °C). Power level is set for EOL conditions and insulation is sized such that the GPHS at BOL is within its allowable temperature limits. Unless otherwise noted, cold-end Stirling temperature associated with the minimum mass system was used. In exploring the possible trades in the cold-end (conduction sleeve to radiator), both conductive and heat pipe interfaces were explored looking at various materials, power levels, and environments. Figure 14 shows system mass and radiator area as a function of Stirling cold-end temperature for a 200 W convertor with both a nickel hot-end and an Al cold-end flange.

The radiator fin material selected was an aluminum (Al)/thermal pyrolytic graphite (TPG) combination, and a 60 K sink temperature was selected as representative of the shaded lunar polar region. TPG must be encapsulated in another material for strength and in this example Al was selected. A ΔT of 30 K was set for both the cold-end flange and the root-to-average radiator temperature. Three GPHS modules are required to produce the 200 W and minimize mass by varying cold-end temperature. A total system mass of 23 kgs results with a convertor specific power of 8.7 W/kg. Figure 15 shows a pie chart of this system. The step in figure 14 occurring at 410 K occurs as the system has switched from requiring three GPHS modules to four. The mass rise before the switch is the insulation increasing in thickness in an attempt to extract as much energy as possible into the convertor.

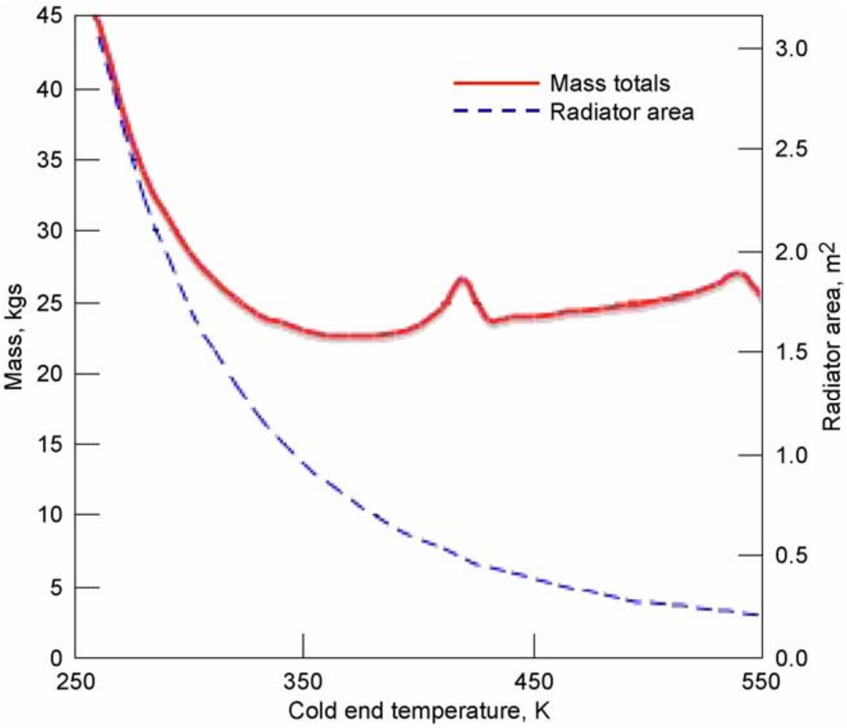

Figure 14.—Mass and radiator area as a function of cold end temperature, 200 watts, 60 K sink.

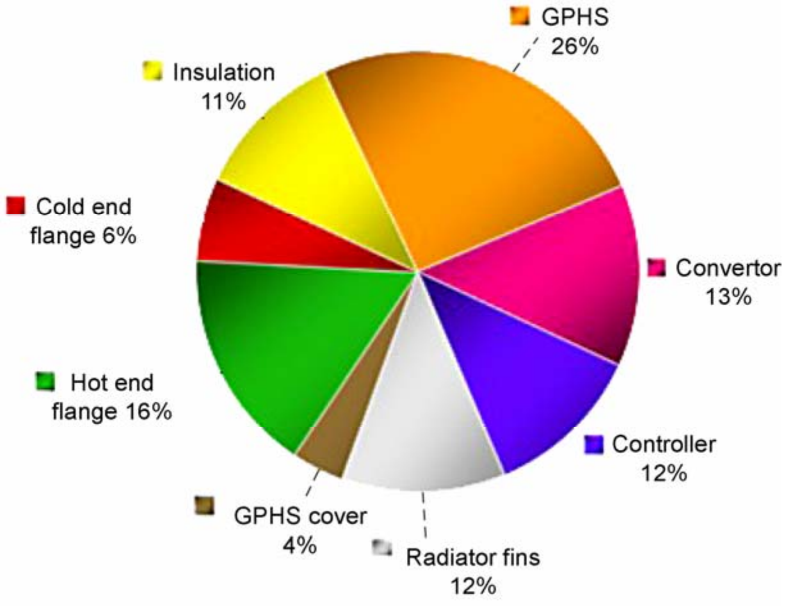

Figure 15.—Mass breakdown of 200 watts, 60 K sink LPS.

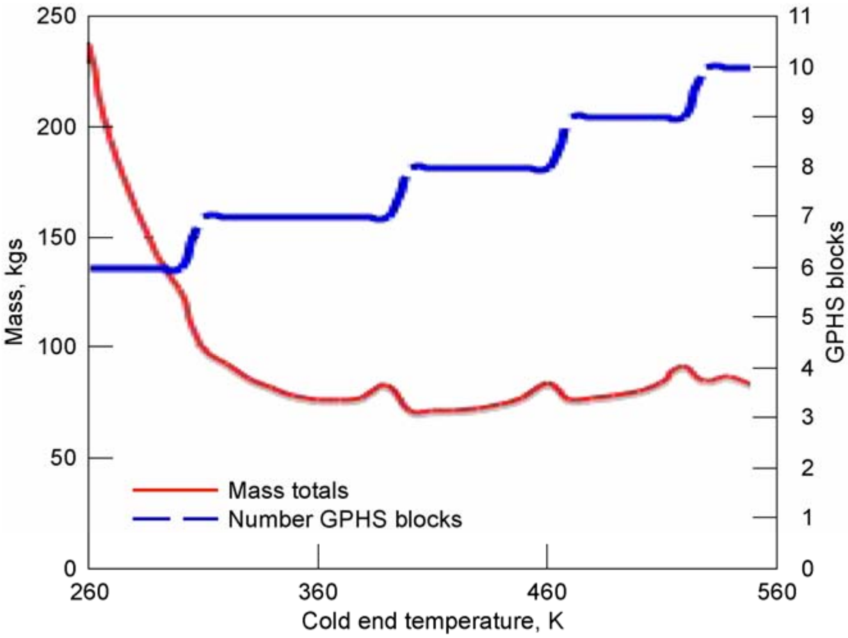

Figure 16.—System mass and number GPHS modules as a function of cold end temperature, 60 K sink, 500 watts.

GPHS Module and Mass Trades

At each power level, the number of GPHS modules required depends upon whether the user desires minimum mass, has limitations on radiator area, or would like to reduce the number of GPHS modules to as few as possible. Figure 16 shows system mass and number of GPHS modules as a function of Stirling cold-end temperature for a 500 W, 60 K sink system using a conductive-only interface on the cold-end. A minimum occurs in system mass resulting in a total mass of 59 kgs at a Stirling cold-end temperature of 410 K (137 °C) and using eight GPHS modules. If it were desired to reduce the GPHS module count to six, the bottom end of the convertor would be dropped to increase system efficiency. The additional mass for both radiator and insulation is about 50 kgs, nearly doubling the total mass of the convertor to 120 kgs and raising the radiator area from 1.35 m^2 to over 4 m^2. As the radiator area grows both the thickness of the cold flange and that of the radiator fin material must grow to maintain

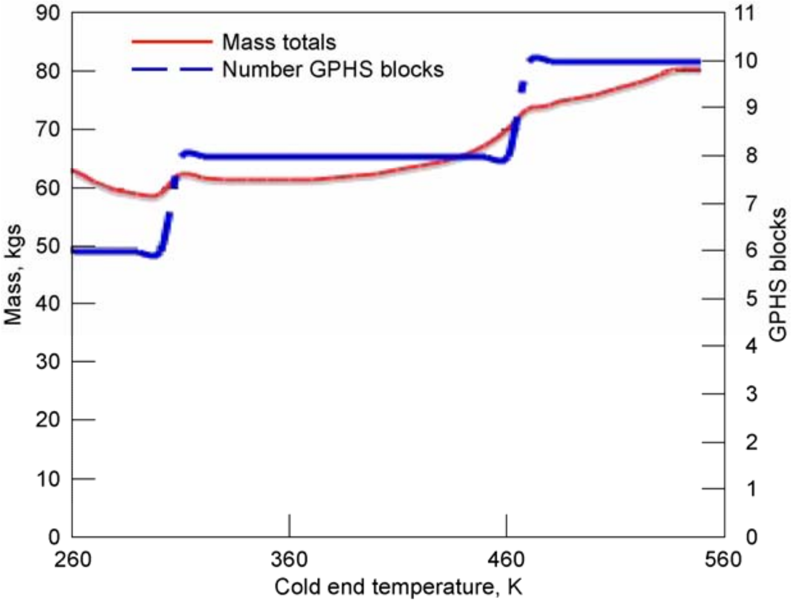

Figure 17.—System mass and number GPHS modules as a function of cold end temperature, 60 K sink, 500 watts, heat pipe.

the ΔT assigned to each piece. One way to effectively reduce the root-to-fin average temperature drop and the mass of the cold flange is with the use of heat pipes. While at low power levels, their mass and additional failure modes/complexity does not lend itself to a compelling mass advantage. At higher powers or if necessary to reduce the number of GPHS modules via their lower ΔT through the radiator the use of heat pipes can become advantageous. This will be discussed in greater detail in another section. Figure 17 shows the same system that was shown in figure 14 except now heat pipes are being used as a heat transport device on the cold-end. Mass effects are dramatic in that now rather than having a mass minimum at 410 K (137 °C) there is a broad minimum mass of just over 60 kgs (slightly higher than the conduction-only mass system) and a wide latitude of cold-end temperatures with comparable system masses. In addition, we can now go to six GPHS modules and pay little, if any, mass penalty.

Sink Temperature

Because sink temperatures can change so dramatically on the lunar surface, it is important to consider the differences in system mass and operation in both environments. Figure 18 shows a plot of mass and radiator area as a function of Stirling cold-end temperature. Minimum mass cold-end temperature has risen significantly over the 60 K (–213 °C) sink temperature discussed earlier. For this system (200 W, Ni hot-end, Al cold-end, Al/TPG radiator), designed for operation at the worst case lunar thermal environment (340 K), significant differences are seen not only in total mass, but also in the distribution of the mass fractions associated with each component and the operational temperatures of the Stirling convertor. Total system mass has risen to 26 kg (8.7 W/kg), and the number of GPHS modules needed for this minimum system mass is now four. Minimum mass occurs at a Stirling cold-end temperature of 480 K. Additionally, this is beyond the allowable magnet temperatures built into the SRG–110 and would require a change to Samarium Cobalt magnets.

Power Level

As power levels increase the relative importance of getting the heat into and out of the convertor becomes a greater fraction of the total mass of the convertor. Figure 19 shows mass and specific power comparisons for a solid Al/TPG radiator and a water heat pipe radiator as a function of power level with a Ni hot-end. For each case the ΔT of the cold-end flange and the radiator fins are set at 30 K. Up to 200 W, both the conductive and heat pipe integrated cold-end systems masses are about the same. Above that power level, the advantages of the shorter conduction distances and reductions in cold-end flange mass make a water heat pipe system more mass attractive. For both heat pipe and conductively coupled cold-ends, the best specific power occurs at about 200 W.

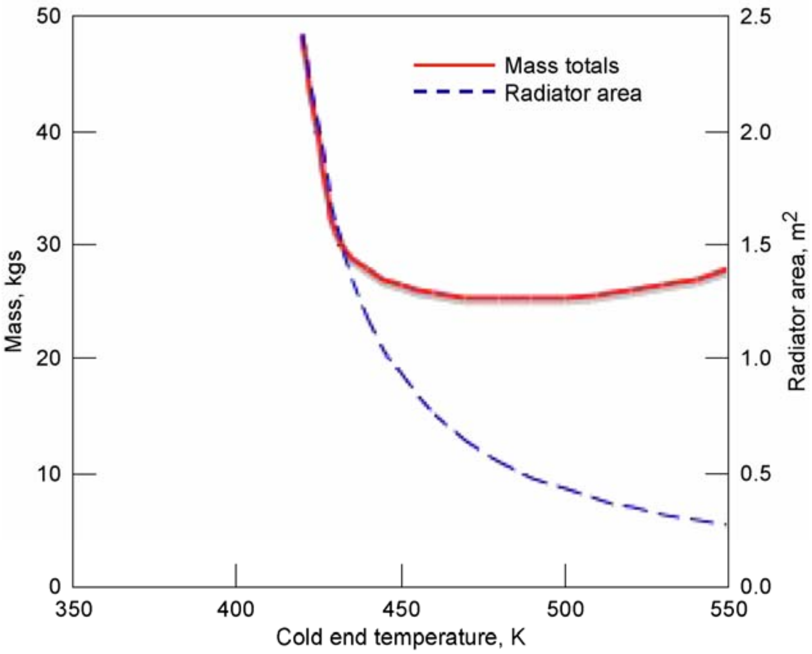

Figure 18.—System mass and radiator area as a function of cold end temperature, 340 K sink, 200 watts.

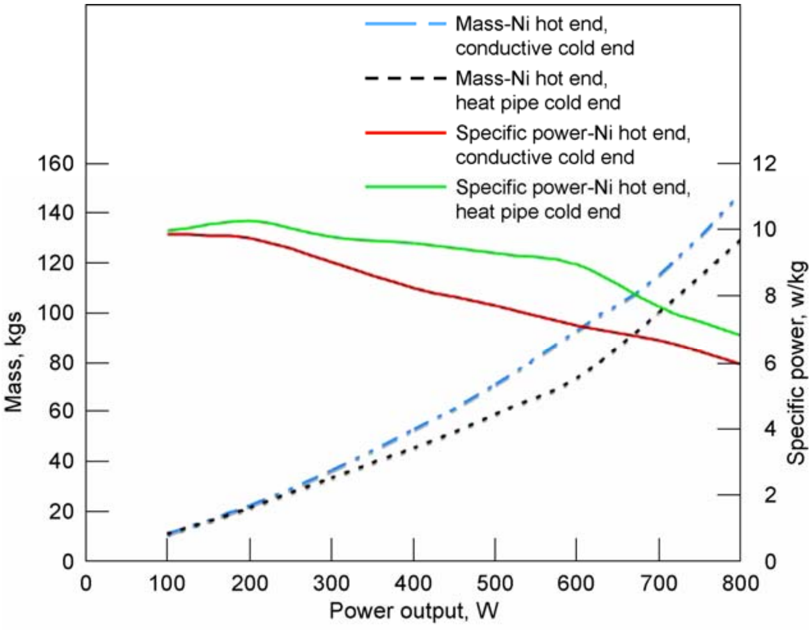

Figure 19.—Mass and specific power as a function of power level with conductive and heat pipe cold and Ni hot end.

Figure 20 shows mass and specific power as a function of power output except the nickel hot-end is now replaced with a high-conductivity graphite hot-end. The combination of the graphite hot-end and the heat pipe cold-end allows the system to scale relatively flat to 800 W (400 W/convertor). This is significant in that it shows that with the use of advanced materials, direct conductive heat input and water heat pipes on the cold-end can allow Stirling/GPHS power systems to grow to significantly higher powers while maintaining a relatively high specific power.

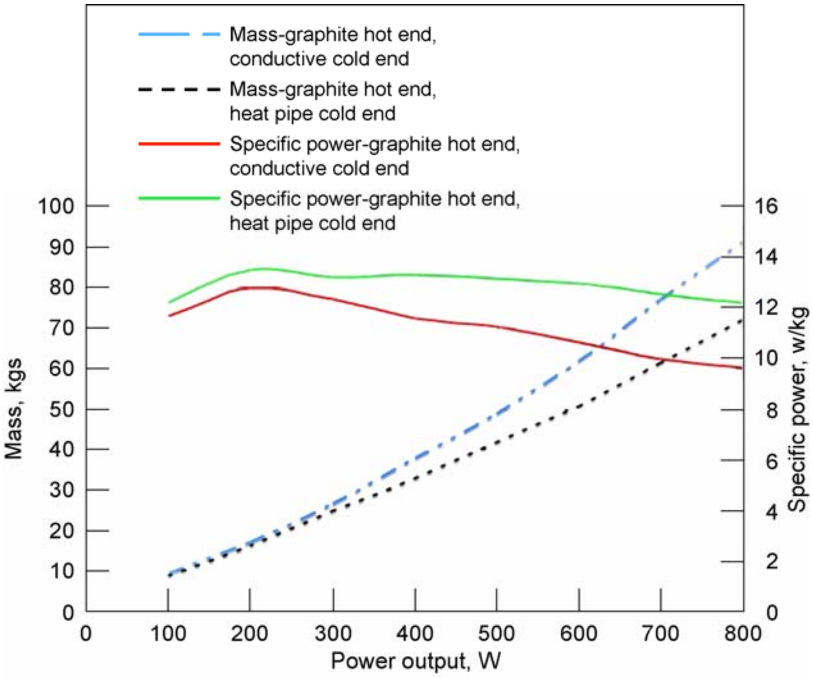

Figure 20.—Mass and specific power as a function of power level with conductive and heat pipe cold and graphite hot end.

Single Convertor

The advantage of using a single convertor over a dual-opposed convertor is both a reduction in part count and the desire to take advantage of the increasing specific power of the convertor with increasing power level. The disadvantage of using a single convertor will be the increase in heat flux into and out of the convertor and the associated increases in masses necessary to meet the temperature constraints set on the system. Figure 21 shows a comparison of a dual-opposed and single-piston system from 100 to 700 W using the minimum mass system over the range of cold-end temperatures considered (260 to 530 K). For the systems considered, little difference was seen in total mass; rather the differences are found in the minimum mass temperature ratios. For the single convertor option, minimum mass occurred at significantly lower temperature ratios (higher Stirling cold-end temperature) than for the dual-opposed system. This was due to the fact that a greater ΔT driving force was needed to keep the mass of the cold-end from growing too rapidly. This lower ΔT across the engine results in a lower Carnot efficiency and at each power point considered required at an additional GPHS module over its dual-opposed counterpart. Figure 22 shows a similar plot except cold-end temperature was held constant (in this case Tcold = 400 K). This plot shows the dramatic rise in cold-end mass due to the increase in radiator and cold-end flange mass increases with increasing power level.

Dual Opposed With Balancer

Operation of a dual-opposed convertor with a balancer allows power to be produced even if one convertor fails. How much power depends upon how the system is designed and where in the operational life of the convertor the failure occurs. The configuration used in this analysis fixes the heat paths at the design point (EOL) with two convertors operating. Both convertors share the heat of the operating convertors. If one convertor fails then the system will continue to operate at reduced power output. This reduction comes from the fact that higher temperature drops occur when nearly double the amount of heat is sent through the same interface (both hot and cold) and the heat rejection path is now longer. In addition to this, given the temperature limits of the iridium cladding of the GPHS, this design sets the upperbound of the system temperature at the material limit of the Stirling convertor. This was done by sizing GPHS to heater head conduction bar such that the GPHS surface temperature was maintained at 1373 K (1100 °C). When a convertor fails, the upper limit on GPHS operation is still a requirement of our design. If we double the heat flow through the same GPHS to heater head conductive path, we increase the ΔT in order to remove all of the heat generated by the modules. This then requires a drop in

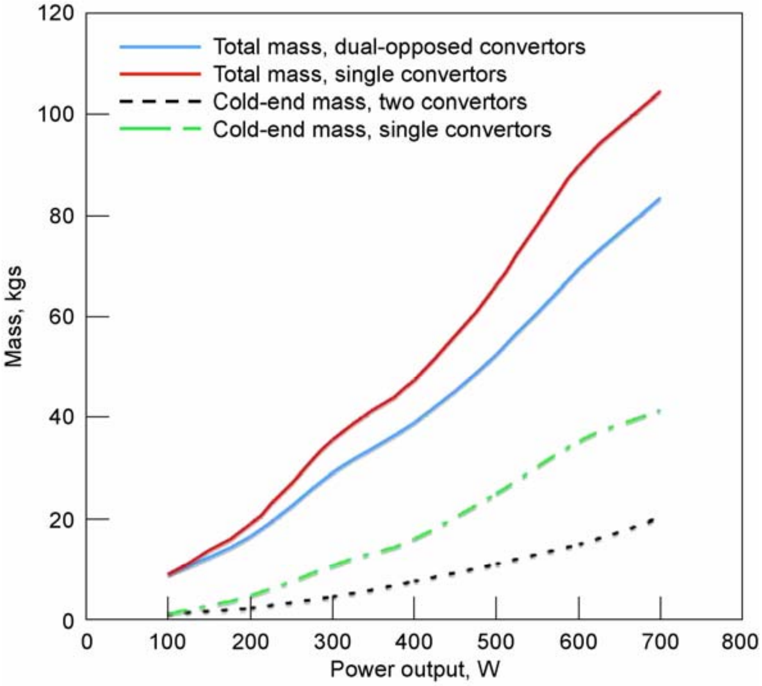

Figure 21.—Dual-opposed versus single-piston configurations minimize mass.

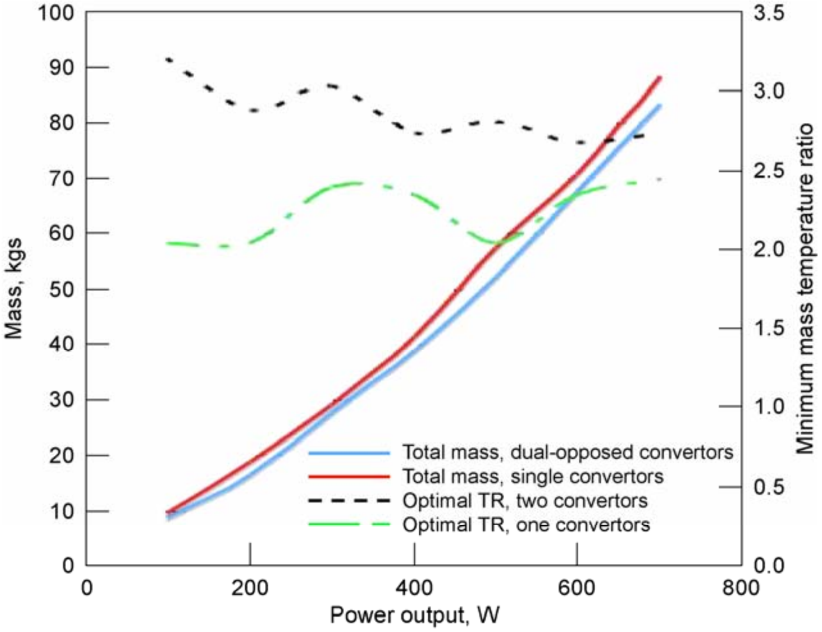

Figure 22.—Power output as a function of sink temperature, operational convertors, and mission time.

the heater head temperature and a rise in the cold-end temperature. Figure 23 shows a plot of BOL and EOL power output as a function of sink temperature for both convertors operating and a single convertor-out configuration. It is interesting to note that the BOL/EOL power output is nearly identical for a single convertor out. At BOL, the heater head temperature must be dropped significantly more than at EOL due to the greater amount of heat the single convertor is required to remove. Even with a convertor capable of the full power load for this configuration, only 150 W was possible out of the design point 200 W system. To keep the GPHS within its temperature limits requires a lower heater head temperature and thus a less efficient system. At EOL, less heat

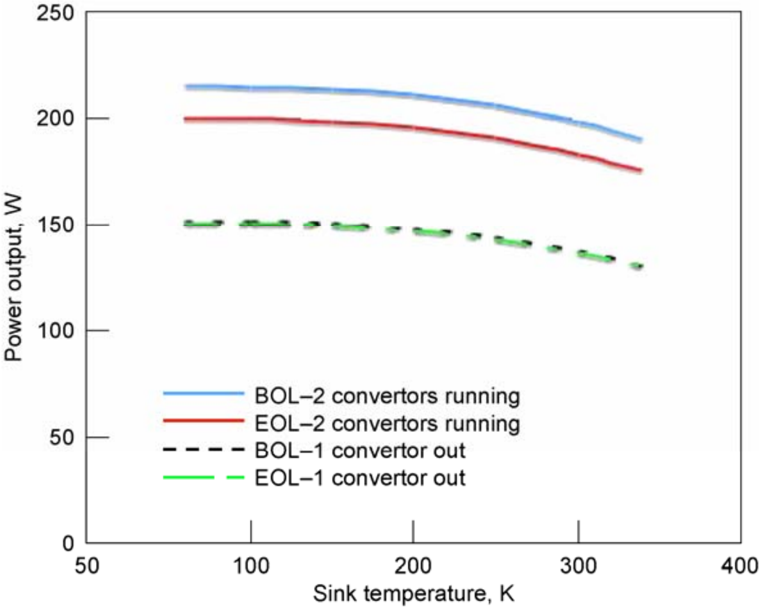

Figure 23.—Electrical power and Stirling cold end temperature as a function of sink temperature, 60 K sink design point.

is going into the convertor allowing the heater head temperatures to rise and resulting in a more efficient system. Table 2 shows the heater head temperatures necessary to ensure that the GPHS surface temperature does not exceed 1373 K (1100 °C). This requires that the engine and control system is able to over-stroke to pull the additional heat out and that it is able to infer the temperature of the GPHS surface.

TABLE 2.—HEATER HEAD TEMPERATURES AS A FUNCTION OF MISSION TIME AND OPERATIONAL CONVERTORS

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

GPHS Temperature Limits

If the LPSs are designed for full-power EOL operation at one of the lunar poles, significant variations in power and cold-end temperatures occur during operation under direct illumination and during BOL. GPHS modules heat production decays over time (about 0.8 percent per year) and over the 14-year life of the assumed mission will drop from an initial 250 W of thermal power per module to about 230 W. Figure 24 shows both cold-end Stirling cold-end temperature and power variation as a function of sink temperature for a system designed for 200 W, full-power operation with a 60 K sink. Stirling cold-end temperature varies from about 390 K (117 °C) with a 60 K sink to almost 480 K (207 °C) with a 340 K sink at BOL. Power ranges from a maximum of 220 to 180 W from BOL to EOL maximum and minimum sink temperatures. Figure 25 shows the same system with the exception of being designed for full-power operation at EOL in a 340 K sink. Power varies from 245 to 200 W, but now Stirling cold-end temperatures vary from 430 to 510 K (157 to 237 °C). Both of these cases demonstrate the need for magnets, which can operate over a wide range of temperatures. In addition, each convertor must be sized to accommodate an approximate 20 percent increase in stroke (i.e., power) to maintain a constant heater head temperature.

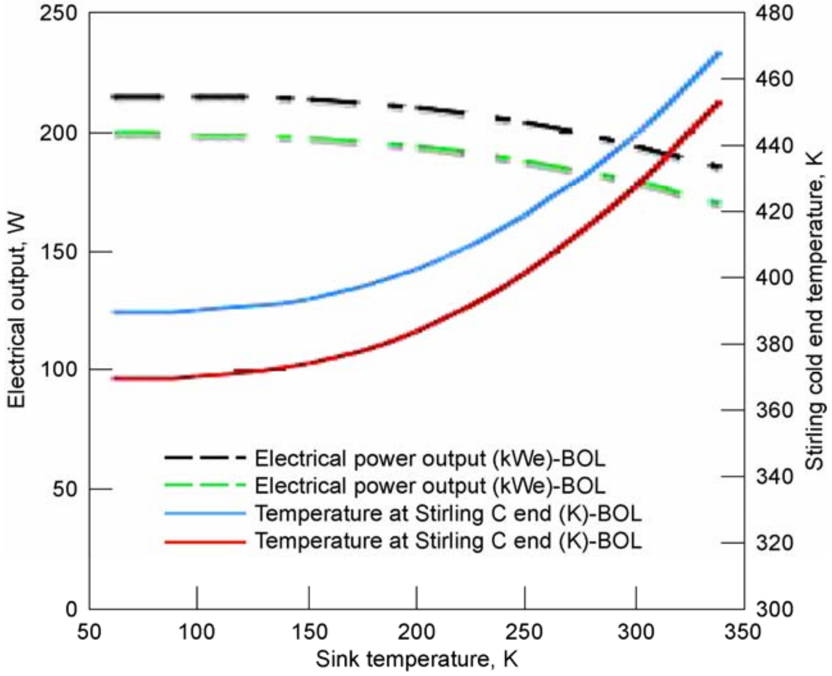

Figure 24.—Electrical power and Stirling cold end temperature as a function of sink temperature, 60 K sink design point.

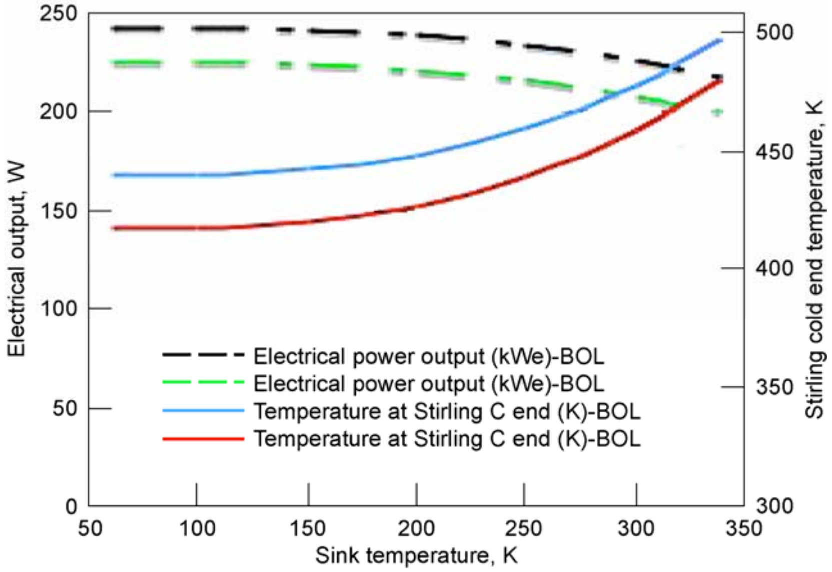

Figure 25.—Electrical power and Stirling cold end temperature as a function of sink temperature, 340 K sink design point.

VII. Conclusions

The integration of the standard GPHS module with Stirling convertors employing technology defined in the current NASA/Sunpower Advanced Stirling Convertor project will allow considerable flexibility in the development of an LPS to support future mission requirements. These LPSs will be characterized by efficient utilization of GPHS resources and high reliability, and they can be employed over in a wide range of lunar environments. However, in the development of such system, a wide number of tradeoffs are possible all of which can lead to LPS configurations that change fundamentally as the desired power levels vary. Based on this evaluation of LPS configurations, the following conclusions and/or recommended areas for further review have been identified:

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 (523 K).
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 (W/kg) occurs around 200 W for a dual-opposed convertor (100 W/convertor). Adding heat pipes on the cold-end and a graphite conductive interface on the hot-end allows specific power to stay relatively constant up to almost 800 W (400 W/convertor).
4. The integration of multiple GPHS modules (up to 12 investigated) with 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. GPHS orientation effects are relatively small.
5. LPS configurations can vary widely from conventional opposed convertors (SRG–110 configuration) to independent convertors, which employ vibration-balancing systems.
6. LPS configuration, in particular that of the radiator, can have considerable impact in the overall LPS mass due to the importance of the rejection temperature on convertor efficiency and the techniques employed to thermally couple the two components.

References

1. Schmitz, P., Penswick, L.B., Shaltens, R., “Modular GPHS-Stirling Power System for Lunar Habitation Module,” 3rd IECEC, San Francisco, CA, 2005.
2. Ibid.
3. Simonsen, Lisa C., et al. “Conceptual Design of a Lunar Base Thermal Control System,” 2nd Conference on Lunar Bases and Space Activities, Houston, TX, April 5–7, 1998.
4. Dallas, D., Diaguila, A.J., Saltsman, J.F., “Design Studies of the Effects of Orientation, Lunation, and Location on the Performance of Lunar Radiators,” NASA TM X–1846, NASA Lewis Research Center, Cleveland, OH, 1971.
5. Wood, G., Carroll, C., Matejczyk, D., Soendker, E., Penswick, L.B., “Advanced Stirling Convertor Update,” STAIF 2006.
6. Schmitz, P., Penswick, L.B., Shaltens, R., “Modular GPHS-Stirling Power System for Lunar Habitation Module,” 3rd IECEC, San Francisco, CA, 2005.
7. Pantano, D.R., Hill, D.H. “Thermal Analysis of Step 2 GPHS for Next Generation Radioisotope Power Source Missions,” STAIF 2005.
8. Or, C.T., Carpenter R.T., “Steady State Temperature Predictions for General Purpose Heat Source in Various Environments,” Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion, IECEC–98–227, Colorado Springs, CO (1998).
9. Ibid.
10. Ibid.
11. Wood, G., Carroll, C., Matejczyk, D., Soendker, E., Penswick, L.B., “Advanced Stirling Convertor Update,” STAIF 2006.
12. Chuen, T. Or, Carpenter, R. “Steady-State Temperature Predictions for General Purpose Heat Source in Various Environments,” 33rd IECEC, August 1998.
13. Wood, G., Carroll, C., Matejczyk, D., Soendker, E., Penswick, L.B., “Advanced Stirling Convertor Update,” STAIF 2006.
14. Que, S., Augenblick, J., Redinger, D., “Low-Mass Stirling Convertor Assembly Progress Update,” STAIF 2006.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

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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