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Preliminary Design of a Mobile Lunar Power Supply

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PRELIMINARY DESIGN OF A MOBILE LUNAR POWER SUPPLY

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ABSTRACT

A preliminary design for a Stirling isotope power system for use as a mobile lunar power supply is presented. Performance and mass of the components required for the system are estimated. These estimates are based on power requirements and the operating environment. Optimizations routines are used to determine minimum mass operational points. Shielding for the isotope system are given as a function of the allowed dose, distance from the source, and the time spent near the source. The technologies used in the power conversion and radiator systems are taken from ongoing research in the Civil Space Technology Initiative (CSTI) program.

INTRODUCTION

NASA's Space Exploration Initiative (SEI) has identified a wide range of surface and orbital systems which require power levels in the range of 100's of watts to 100's of kWe. Included among these power sources are isotope power systems which are candidates for low power (100's of watts to 10's of kWe) missions. This study concerns itself with a Stirling isotope power system for use as a mobile power source on the lunar surface in the power range from .5 to 10 kWe.

Isotope systems, in the form of Radioisotope Thermoelectric Generators (RTG's), have already been used in a variety of missions from Pioneer to Gallileo and are planned on many future missions. One drawback of these systems is their low thermal to electric power conversion efficiency (~ 6%). This results in practical limits to the electrical power output which can be generated because of the expense of the Isotope fuel. Dynamic Isotope Power Systems (DIPS) offer the possibility of reducing isotope fuel mass by taking advantage of their increased thermal to electric power conversion efficiency when compared to RTG's. This study takes technologies developed in the Civil Space Technology Initiative (CSTI) program and applies them to the design of a DIPS. This DIPS is based on free piston Stirling convertor/linear alternator convertor technology and uses a novel thermal integration of its heater head with a General Purpose Heat Source (GPHS) heat source. The GPHS is the energy source that is the DOE standard for space isotope power systems. The free piston Stirling convertor is chosen because of its high thermal to electric conversion efficiency potential, few moving parts, and ability to scale over a wide range of electrical outputs.

ANALYSIS

This system consists of a free piston Stirling convertor/linear alternator (FPSC/LA) whose hot end is coupled to GPHS blocks through heat pipes imbedded in a graphite bar (See Figure 1.). Waste heat from the convertor cold end is removed by a pumped liquid loop and taken to the radiator where it is rejected to space. Two FPSC heater head temperatures are considered. The 1050 K heater head temperature is considered the baseline system while the 1300 K is analyzed to determine the effects of increased heater head temperature on system efficiency and mass. These two temperatures represent the CSTI Stirling technology which was used as the basis for this study. Because of the great cost associated with transporting any type of system to the moon, the mass delivered to the surface is often cited as a key parameter which relates directly to cost. All systems in this study are optimized to provide minimum mass. This is accomplished by allowing the temperature ratio across the Stirling convertor to vary.

Layout of this power system is designed for straightforward operation, with a configuration that can be easily assembled and maintained by the astronauts. No fluid connections need to be made or broken during deployment. The system is characterized by mathematically modeling the components. The component physical characteristics vary according to changes in either the thermal or electrical outputs. The components which are modeled include the heat source assembly (HSA), FPSC/LA, waste heat removal including radiators and power conditioning and controls, and shielding. Detailed discussion of each component is as follows:

Heat Source Assembly (HSA)

The heat source assembly produces heat and and routes it to the Stirling convertor. It consists of the GPHS heat source, high temperature insulation, high temperature heat pipes, a center graphite bar, and structure. The HSA is designed to slide onto and off the Stirling Convertor/heat pipe assembly (See Figure 1.). The holes in the graphite bar are sized to allow the heat pipes to undergo creep expansion while allowing HSA removal during its operational life. Because of this extra space, the heat pipes and the center graphite bar are not in direct contact over its entire surface. This provides both conductive and radiative heat transfer paths at the heat source/power convertor interface.

The HSA is similar in construction to the GPHS RTG in that the GPHS blocks are stacked, one on top of another, and then placed in compression inside an aluminum case. This prevents the blocks from moving. If the system should reenter the atmosphere the aluminum casing heats up, melts and disperses the blocks. The blocks are surrounded by multifoil insulation which is placed inside the aluminum container. The HSA is different from the GPHS RTG in that the case contains four rows of blocks instead of one, which are arranged in a cross configuration around a center, graphite bar.

Previous analysis has shown that radiation coupling of GPHS's with Stirling convertors keeps the GPHS's within their temperature limits while also providing the heat flux necessary for the convertor to operate at 1050 K.[1]t From geometrical considerations it is assumed that conduction/radiation coupling of this new HSA configuration should provide at least this good of a heat transfer path and keep the GPHS's within their temperature limits. A 1300 K convertor is also analyzed to see what effect a higher temperature would have on the mass and efficiency of the system.

The 1050 K system heat pipes are assumed to be niobium with sodium as the working fluid. For the 1300 K case, molybdenum heat pipes would be used with lithium as the working fluid. Both the niobium and molybdenum are coated with rhenium to make them compatible with the graphite blocks.[2] The HSA uses multifoil insulation to decrease heat loss from the heat source assembly directly to space. Insulation values are set to keep the heat loss at 5 % or less.

Stirling Convertors

The power convertors take the heat generated from in the HSA and convert it to electrical power. This FPSC/LA is assumed to be similar to the Stirling space power convertor built by MTI for SP-100 reactor applications under NASA's CSTI High Capacity Power Program

This convertor technology, which can be scaled over a wide range of output power levels, is being considered for lower power applications such as dynamic isotope power systems. Design data relating specific mass and efficiency to temperature ratio for low power (.5 to 10 kWe) free piston Stirling convertors have been published by MTI.[3] These models include optimizations for either minimum convertor specific mass or maximum convertor (percent of Carnot) efficiency. The maximum convertor efficiency scaling relationships are used in this analysis.

Radiators

There are two types of radiators used in this system. The first is the main radiator, which is designed to reject waste heat from the Stirling convertor. The second is the HSA radiator which rejects heat from the heat source assembly if, for any reason, the heat flow through the Stirling convertor is interrupted. This can be caused by either a convertor failure or any time when the convertor is not attached to the heat source.

Main Radiator

The main radiator is made of metal heat pipes which are inserted into carbon-carbon (c-c) composite fins. The choice of metal and the heat pipe working fluid is based on the heat rejection temperature of the system. A horizontal orientation is chosen to minimize sink temperature and to keep the thermal environment the astronauts are exposed to a minimum. This configuration leads to a equivalent sink temperature of 220 K.[4]

Because optimization of this DIPS is performed by varying temperature ratio across the FPSC, the cold end temperatures take on a many values. This can lead to different types of heat pipe working fluids. Water/titanium heat pipe radiators are possible for systems with rejection temperatures below 500 K. Above this temperature the choices for heat pipe working fluids are not so attractive. Mercury heat pipes operate in this temperature range but have safety implications. Because of the desire to have the radiators bolted on to the secondary loop and to remove the need to make fluid connections on the lunar surface a pumped loop system is not practical. Dowtherm A is a candidate at temperatures above 500 K. Dowtherm A has its own problems in that it has a low liquid transport factor (which results in more heat pipes in the radiator) and also decomposes under gamma radiation. Despite these problems Dowtherm A is chosen as the working fluid above 500 K. Because of the increased amount of heat pipes the radiators will likely be heavier. Therefore, a range of radiator specific masses are considered.

The following parameters are used in the system design. The bulk fluid temperature drop from inlet to outlet of the cooler head is 10 K. The temperature drop across the liquid metal to the radiator conduction heat exchanger is 50 K. The emissivity of the one sided radiator is set at .85 while the view factor of the radiator is set at .9. The base line radiator specific mass chosen is 5.0 kg/m^2 which is consistent with the CSTI goals for radiators coupled with Stirling convertors. Radiator specific masses from 3 kg/m^2 to 7 kg/m^2 are also considered to see what effect on overall mass there is if these goals are exceeded or not met.

High Source Assembly Radiator

The heat source assembly radiators reject heat from the GPHS when the Stirling convertor either fails or is not being used. Two heat pipes from inside the center graphite bar are connected to a small finned surface. These heat pipes, based on the Reversible Heat Removal System (RHRS) of Rockwell/Rocketdyne, only begin to operate when the heat source assembly temperature has risen above its design temperature limit.[5] The heat pipes are molybdenum with a rhenium coating and use lithium as the working fluid. For the 1050 K system, these heat pipes operate when the temperature of the graphite bar rises above 1300 K. The heat pipes are heavily insulated along their adiabatic section with multifoil insulation to force the heat loss path through the finned surface. These fins ($\approx$ 10 cm^2) are set so that they radiate from only one side of the vehicle and allow the astronauts to approach the system from the other side to replace or repair the Stirling convertor assembly.

Power Management and Distribution (PMAD)

The PMAD takes the electrical power produced by the Stirling convertor, distributes it, and converts it to other forms. The PMAD includes all electrical components outside the Stirling convertor and includes: shunt regulators, distribution switches, motors, lights, sensors, computers, and wiring. The PMAD mass for a rover is based on the strawman architecture for all the loads, switches, and the source as shown in Figure 2 .

The Stirling engine power supply is assumed to put out 2.5 kW of single phase AC power at approximately 200 volts, 70 Hz ac. This voltage and frequency are put directly on the distribution bus. There is a shunt regulator connected to the bus to dissipate any power not used by the load (since the source is a constant power output). The power conditioning is done at the load interfaces through converters designed for each load.

The motor and associated control mass estimates are based on high frequency AC induction motors from electromechanical actuators (EMA) applications (proposed for use on the Advanced Launch System), scaled down to the power levels required in this case. The switchgear masses are based on Space Station Freedom RPC and RBI (remote power controller and remote bus interrupter, respectively) masses, again scaled down to this application. The converter masses are estimates, and the wiring mass is estimated based on insulated copper wiring with the appropriate power and voltage (200 volts ac) level.

Shielding

Shielding may be required to protect humans in the vicinity of these systems. The shielding configuration used in this study is a shadow shield with a dose plane diameter of 2 meters. The mass of these shield have the potential of dramatically affecting the way power systems optimize. Rockwell preformed a study of dose attenuation as a function of shield thickness produced by the GPHS using lithium hydride for the neutron shield and tungsten for the gamma shield. Their attenuation curves are used in this analysis.[6] A more detailed discussion of the shielding requirements and dose rates is given in Appendix A.

RESULTS

Figures 3 and 4 shows system mass and radiator area as a function of electrical power level for the 1050 K and 1300 K system based on optimization for minimum system mass. All temperatures represent heater head inner wall temperatures. System mass varies smoothly from 50 kg at .5 kWe to 800 kg at 10 kWe for the 1050 K system and radiator area varies from 0.9 m^2 to 16.0 m^2 respectively. The temperature ratio which provides the minimum mass varies from 2.2 at .5 kWe to 2.3 at 10 kWe. For the 1300 K system the mass varies from 46.0 kg at 0.5 kWe to 449.32 kg at 10 kWe and the radiator varies from 0.3 m^2 to 12.0 m^2. The temperature ratios which provide minimum mass span from 2.2 at .5 kWe to 2.7 at 10 kWe. The nonlinearities in the radiator plot are numerical artifacts of the optimization.

Figure 5. shows system mass and radiator area as a function of temperature ratio for a .5 kWe, 1050 K system. This system has a minimum mass of 49.7 kg and a radiator area of 0.9 m^2 at a temperature ratio of 2.2. The discontinuities are due to the discrete number of GPHS blocks used when sizing the heat source. The three spikes shown in Figure. 5 are when the system goes from 5 to 4 to 3 GPHS's. From a temperature ratio of 2.2 to 2.6 the variation in system mass is small. This allows the designer to accept significant temperature drops across various parts of the cold end of the system to facilitate reliability or repairability without greatly affecting system mass. The radiator plot in Figure 5. varies smoothly because the amount of heat rejected is based on the thermal power sent through the convertor.

Figure 6 shows a plot of system mass and radiator area as a function of temperature ratio for a 2.5 kWe system with a minimum system mass of 159 kg and a radiator area of 2.3 m^2 at a temperature ratio of 2.2. Because the thermal power requirements are so much higher the heat source behaves more like a continuous function than when the heat source assembly is smaller. This causes the bumps to diminish in size over the temperature range. The variations in system mass for the 2.5 kWe are small over the temperature ratio range from 2.1 to 2.6.

Because nuclear reactors and isotope heat sources are so different, significant differences occur in the design of the Stirling converters when optimization of isotope systems is done to produce minimum mass. Stirling convertor studies for reactor heat sources indicate that light weight, moderately efficient convertors produce minimum system while isotope/Stirling systems tend to provide minimum mass when the Stirling convertors are more efficient.[7] . The reason for this is that increases in thermal power in reactor systems requires a small change in reactor mass while in isotope systems increases in thermal power, and therefore mass, occurs by volumetric increases in the heat source size. These relatively rapid changes in the heat source mass of isotope systems, when compared to reactor systems, tend to make minimum mass optimization occur at different state points and Stirling convertor designs. Isotope systems tend to optimize at higher efficiencies which can be obtained by both an increase in temperature ratio and more efficient, but heavier, convertors.

Figure 7 shows the effect of variations in radiator specific mass on a 1050 K system. Two radiator area specific masses, 3 kg/m^2 and 7 kg/m^2, are considered in addition to the 5 kg/m^2 baseline radiator area. At .5 kWe the change in system mass from a 7 kg/m^2 radiator specific mass to a 5 kg/m^2 radiator specific mass is from 49.7 kg to 51.9 (4.0% change) and at 10 kWe it goes from 544.8 kg to 585.0 kg (7.0 % change). There is no change in radiator area when going to a 7 kg/m^2 because the systems optimize at the same temperature ratio. For the 3 kg/m^2 radiator the system mass is 47.52 kg at .5 kWe (4.38% change) and 493.0 kg at 10 kWe (9 % change). At .5 kWe there is no change in radiator area for the 3 kg/m^2 radiator, however at 10 kWe the radiator increases from 16.6 m^2 to 23.0 m^2 an increase (38 % increase) due to a increase in temperature ratio which produces minimum mass from 2.3 to 2.4.

Figure 8. shows three surfaces of system mass as a function of time spent, distance from the source, and time spent at the source. It clearly shows that the distance from the source, not the time spent in its proximity, is the main contributor to shield mass. To more clearly see the trade offs between distance, dose, and system mass, four plots are made from the first row of Table A2. From these plots shown in Figure 9 it is clear that, for most system' a distance of 5 meters greatly reduces shield mass.

Table 1 shows a mass breakdown of four 2.5 kWe Stirling isotope power systems. The table has two 1050 K systems, one shielded and one unshielded, a 1300 K system, and a 1300 K Rockwell designed 2.5 kWe Stirling isotope system.[8] The shielded system provides a dose rate of 2.2 REM in 90 days at a separation distance of 5 meters. The mass savings in going from a 1050 K to 1300 K design is 26 kg while the radiator area reduction is about 2.0 m^2. The proposed 1300 K system is about 95 kg lighter than the Rockwell design. This is primarily due to the geometry and reductions in structure and insulation of the heat source assembly.

CONCLUSION

Using the technologies developed in the CSTI program a Stirling isotope power system is modeled. It is found that the Stirling convertors used to provide minimum mass are different than those designed for space reactor applications because of the way in which the heat source mass varies as a function of thermal power output. The convertors used in isotope systems provide higher efficiencies than those found in reactor systems at the expense of higher convertor mass. Because of the high efficiencies at any given temperature ratio attainable with Stirling convertors relative to other dynamic systems, temperature drops which would be unacceptable in other systems can be tolerated to facilitate ease of assembly with a minimum overall impact to the system mass and radiator area.

It is found that separation distance plays the dominant role in determining shielding mass and in also determining the dose received by the astronauts. Simple operational constraints which limit the time spent in close proximity can make the shield mass a small fraction of the total system mass. The PMAD system for a rover power supply appears to have a minimal impact during system optimization while still providing reliability and repairability.

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[1] T. J. McComas, E. T. Dugan, "Thermal Analysis of Conceptual Designs for GPHS/FPSE Power Systems of 250 We and 500 We", NASA Grant No. NAG3-1123 Final Report, March 19, 1991.

[2] R. H. Titran, Personal Communication, NASA Lewis Research Center,June 1, 1991.

[3] G. R. Dochat, "Stirling Engine System Considerations for Various Space Power Applications", Eighth Space Nuclear Power Symposium,January 1991.

[4] "Dynamic Isotope Power Systems (DIPS) for Space Exploration-Technical Information", U.S. Department of Energy Contract No. DE-AC03-88NE32129.Rocketdyne Division, Rockwell International. May, 1990.

[5] "Dynamic Isotope Power Systems (DIPS) for Space Exploration-Technical Information", U.S. Department of Energy Contract No. DE-AC03-88NE32129.Rocketdyne Division, Rockwell International. May, 1990.

[6] "Dynamic Isotope Power Systems (DIPS) for Space Exploration-Technical Information", U.S. Department of Energy Contract No. DE-AC03-88NE32129.Rocketdyne Division, Rockwell International. May, 1990.

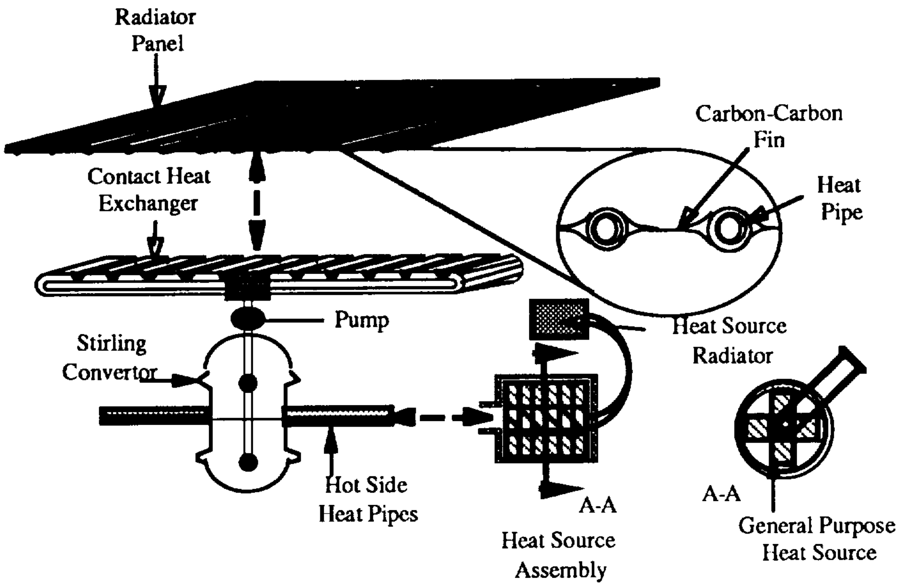
[7] P. C. Schmitz, "Space Reactor/Stirling Cycle Systems for High Power Lunar Applications".NASA Technical Memorandum TM-103698, January, 1991.

[8] R. H. Harty. "A Comparison of Radioisotope Brayton and Stirling Systems For Lunar Surface Mobile Power". Rockwell International, Eight Symposium on Space Nuclear Power Systems, January, 1991.

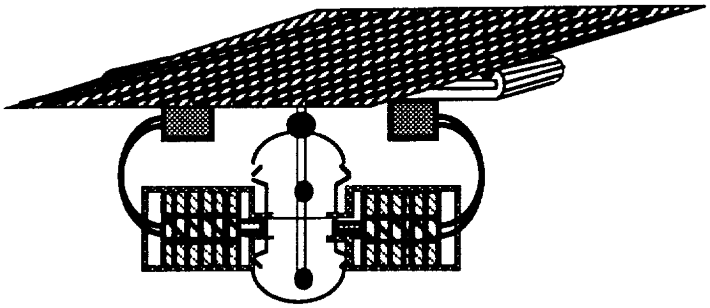
[9] R. J. Fry, Guidance on Radiation Received in Space Activities. National Council on Radiation Protection and Measurements Document 98.,July 31, 1989.

	1050 K System	1300 K System	1050 K with Shielding	Rockwell Stirling System
Electrical Power Output (kWe)	2.5	2.5	2.5	2.5
Mission Life(yrs)	10	10	10	15
Thermal Power at BOL (kWth)	9.2	8.06	7.89	11.7
Efficiency of Stirling Convertor	0.3157	0.3608	0.3403	
Temperature Ratio	2.3	2.7	2.5	2.5
Spec Mass of Stirling (kg/kWe)	7.17	6.36	6.72	
Number of GPHS Blocks	38	33	35	
Distance from Dose Plane (m)	XXX	XXX	5	
Dose Plane Diameter (m)	XXX	XXX	2	
Allowed Dose (REM)	XXX	XXX	2.2	
Time Spent at Site (yrs)	XXX	XXX	0.25	
Thermal Power Rejected (kWth)	5.4	4.42	4.84	
Average Radiator Temp (K)	411	436	375	
Main Radiator Area (m2)	5.19	3.25	7.25	
Sink Temperature (K)	220	220	220	
Component Masses (kg)				
GPHS Blocks	55.138	47.88	50.8	Heat Source
Heat Pipes	12.9	12.1	12.1	73
GPHS Container	24.51	22.4	23.22	Fuel and canister
Insulation	5.17	4.86	4.97	80
Primary Heat Transport	xx	xx	xx	7
Gamma Shield	0	0	41.27	
Neutron Shield	0	0	18.38	
Stirling Convertor	17.9	15.9	16.8	16
Radiator	28.6	17.8	39.88	36
Structure	14.42	12.09	20.74	16
Total Source	158.638	133.03	228.16	228
	PMAD for all Systems (kg)			
Shunt Regulator	2			
Wiring harness	2			
2.5 kW, 200 vac main switches	6 kg, 3.0 each			
Primary Distribution Load Center	switches: 9 + box: 4 = 13			
Communication Converter	0.5			
Data Handling Converter	0.5			
Sensing Convert	0.5			
Motion motor converter & control	.5 each (total 2.0)			
Digging motor converter & control	1			
Motion motor	.5 each (total 2.0)			
Digging motor	1			
Motor gears	1.0 each (total 4.0)			
Total PMAD	**34.5**			
Total System	**193.138**	**167.53**	**262.7**	**262.5**

Table 1. Mass Breakdown for Stirling Isotope Power Systems



a. Before Assembly



b. After Assembly

Figure 1 a.,1 b. Stirling Isotope Power System

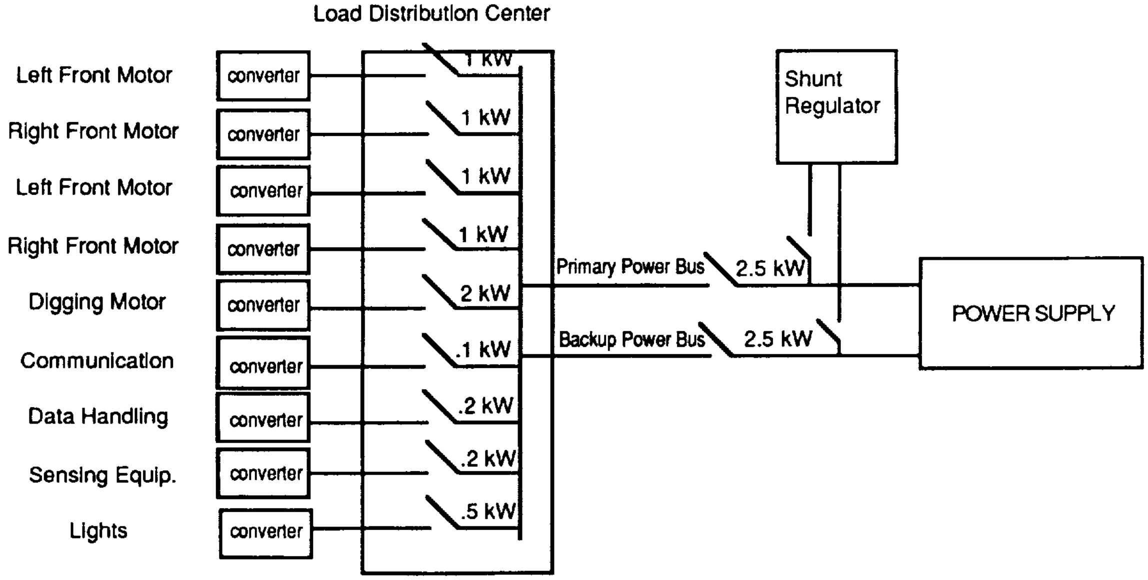


Figure 2. PMAD Strawman Architecture

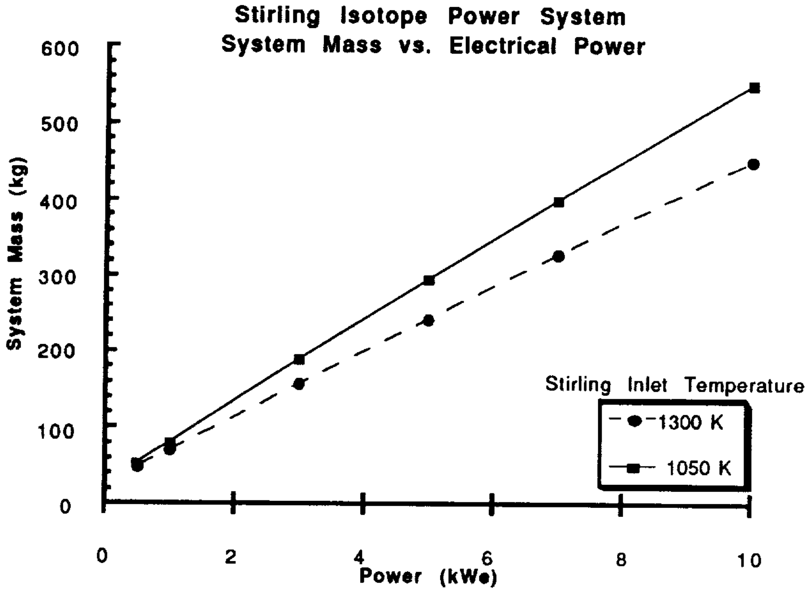


Figure 3. System Mass as a Function of Electrical Power

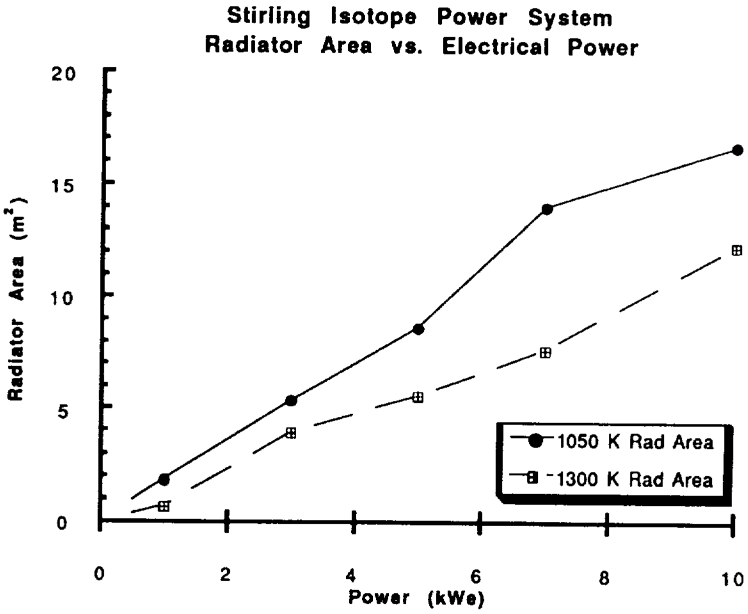


Figure 4. Radiator Area as a Function of Electrical Power

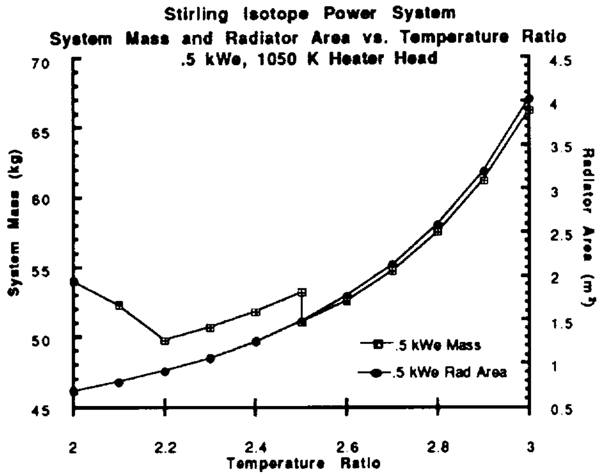


Figure 5. System Mass and Radiator Area as a Function of Temperature Ratio for a .5 kWe System

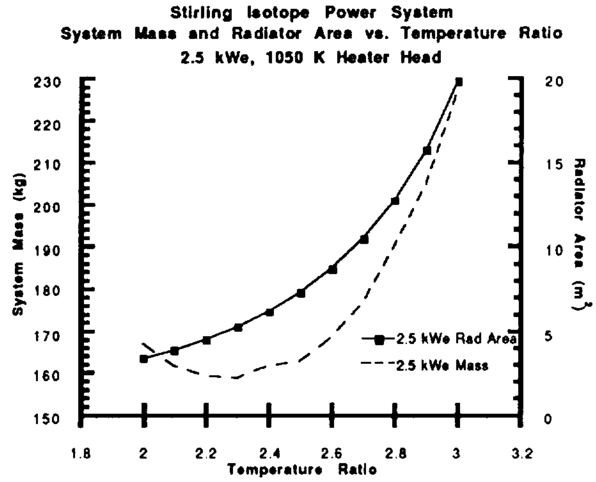


Figure 6. System Mass and Radiator Area as a Function of Temperature Ratio for a 2.5 kWe System

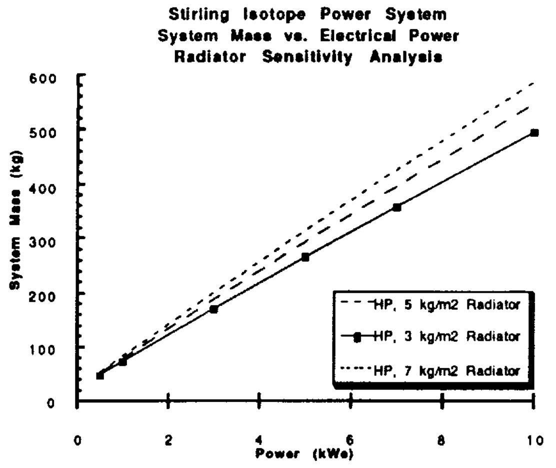
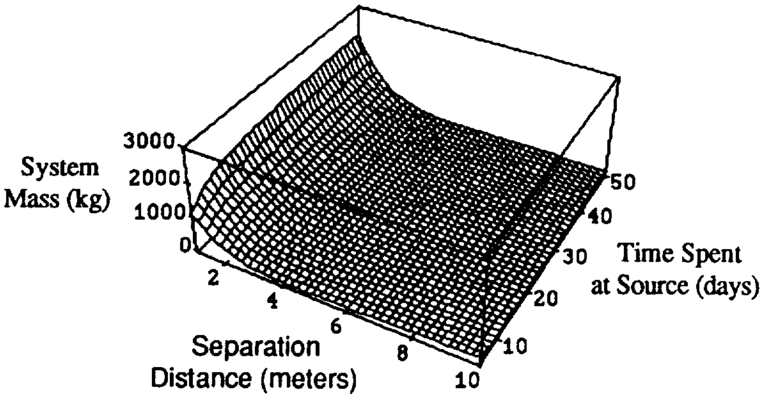
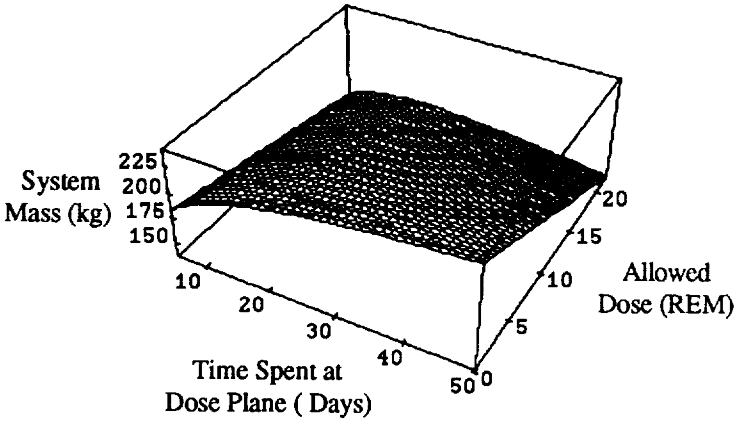


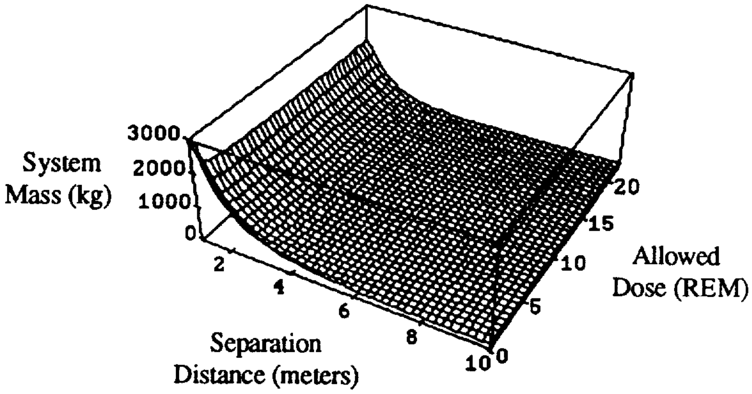
Figure 7. System Mass Sensitivity to Radiator Specific Mass as a Function of Electrical Power



a.) System Mass as a Function of Separation Distance and Time Spent at Source for a 2.2 REM Dose



b.) System Mass as a Function of Time Spent and Allowed Dose at a 5 Meter Separation Distance



c.) System Mass as a Function of Separation Distance and Allowed Dose for a 90 day stay time

Figures 8a, 8b, 8c. Shielding Effects on System Mass

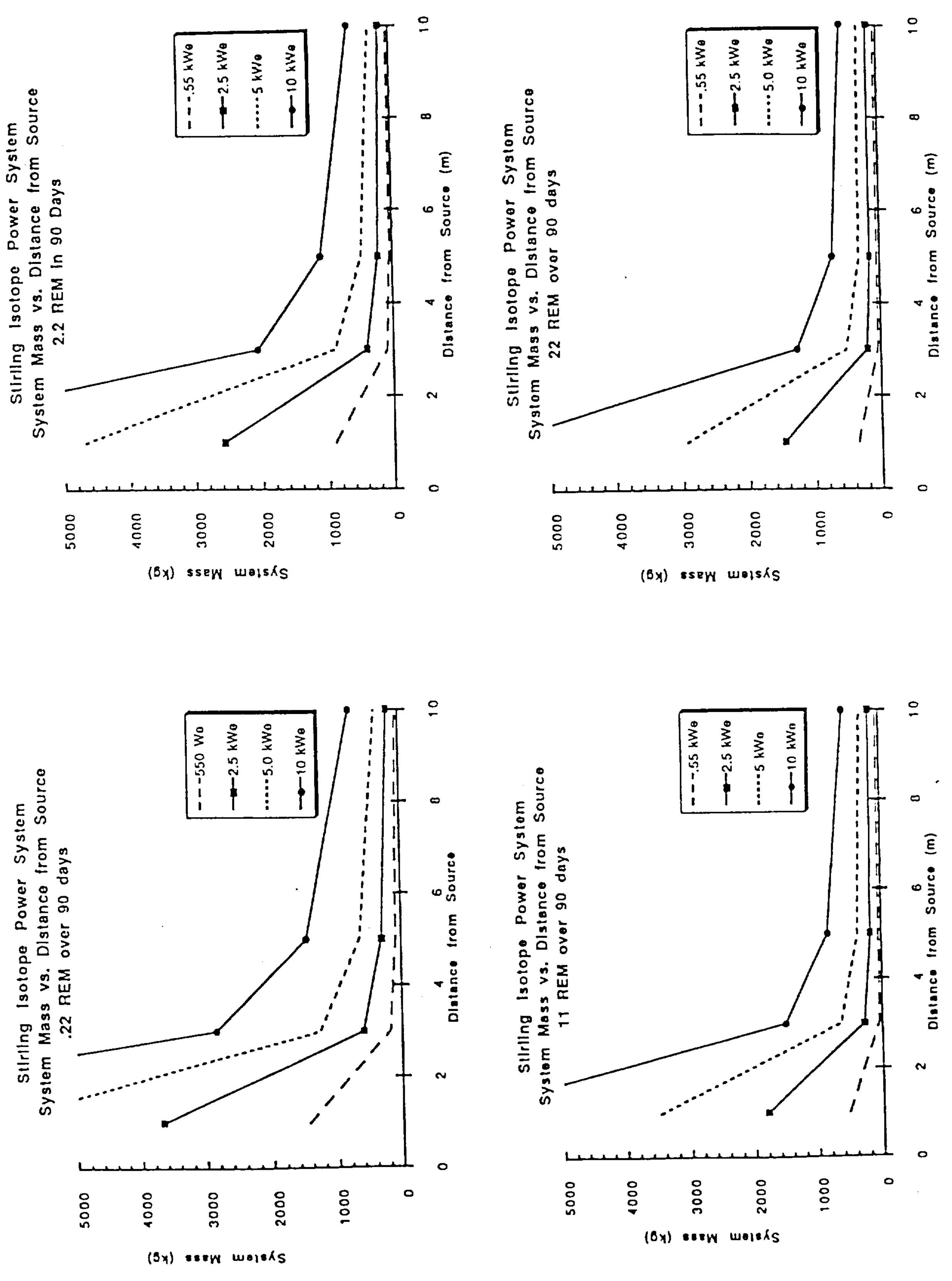


Figure 9. System Mass as a Function of Dose and Separation Distance

Appendix A

Because shielding has the potential of dramatically affecting the mass of isotope systems, an analysis of the parameters which affect these shields is required. The three factors characterized are allowed dose, the distance from the source, and the time spent at the source.

In order to estimate the dose allowed by the astronauts, an inventory of doses received throughout the mission is necessary. The National Council of Radiation Protections document number 98 details recommended dose limits for the astronauts in the following categories: doses received during transit to the lunar surface, dose rates on the lunar surface, and doses received from a variety of Solar Particle Events (SPE's).[9] The methodology used in this study is to sum all of the doses received during the astronauts' mission and compare that with the recommend guidelines set by NCRP-98.

	Mission Duration			
	30 Days	90 Days	6 Months	1 Year
Earth-Moon-Earth Transit	4.3	4.3	4.3	4.3
Lunar Surface	1.1	3.1	6.2	12.4
Solar Particle Event (10gm/cm2 of Shielding)	21.6	21.6	21.6	21.6
Total (REM	26.0	28.0	32.1	38.3
NCRP-98	25	50	50	50
Balance (REM)	**-1.0**	**22.**	**17.9**	**11.7**

Table A1. Environmental Dose Inventory

Because the dose rates on the lunar surface and during transit are fairly well known, SPE's are the one event that can greatly increase the dose the astronaut receives. SPE's are sporadic events whose occurrence follows the 11 year solar cycle. These events consist of large emissions of charged particles which are accelerated away from the sun during solar flares. Because solar flare activity (the size and time of the event) is difficult to predict, the total dose rate the astronaut receives is challenging to estimate. It is therefore assumed by the As Low As Reasonably Achievable (ALARA) principal that one Anomalously Large Solar Particle Event (ALSPE) occurs once per year while the astronauts are on the lunar surface and, that when the event occurs, they are behind 10 g/cm^2 of aluminum shielding. This event is based on the August 1972 SPE documented in the NCRP-98.

Using these assumptions, Table A1 shows the doses received by any astronaut during transit to, and on the surface of the moon. From this table the remaining dose allowance can be calculated. Because the dose from the solar flare is so large, it is not possible to remain under the NCRP guidelines when stay times on the lunar surface are less than 1 month.

A Stirling isotope power system at a power level of 2.5 kWe is used for the shielding calculations. Because no specific mission is known at this time, a variety of doses and times spent at the source are considered. All of the varied parameters are shown in Table A2.

Electrical Power Level	Separation Distance	Allowed Environmental Dose	Mission Times
2.5 kWe	1,3,5,10 Meters	.22,2.2,11.,22. REM	90 Days
2.5 kWe	5 meters	.22,2.2,11.,22. REM	5,10,25,50 Days

Table A2. Shield Parameter Variations

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Space Administration

Report Documentation Page

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590-13-11

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16. Abstract
A preliminary design for a Stirling isotope power system for use as a mobile lunar power supply is presented. Performance and mass of the components required for the system are estimated. These estimates are based on power requirements and the operating environment. Optimizations routines are used to determine minimum mass operational points. Shielding for the isotope system are given as a function of the allowed dose, distance from the source, and the time spent near the source. The technologies used in the power conversion and radiator systems are taken from ongoing research in the Civil Space Technology Initiative (CSTI) program.

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