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Comparison of Dynamic Isotope Power Systems for Distributed Planet Surface Applications

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Summary

In support of the Space Exploration Inititative (SEI), a study was performed to investigate and characterize dynamic isotope power system (DIPS) alternatives for the surface mission elements associated with a lunar base and subsequent manned Mars expedition. System designs based on two convertor types were studied. These systems were characterized parametrically and compared over the steady-state electrical output power range 0.2 to 20 kWe.

Brayton characterizations were based on the "mini-BRU" (Brayton rotating unit) Brayton isotope power system (BIPS) technology. Stirling characterizations were based on scaled-down Civil Space Technology Initiative space power demonstrator engine designs and on small engine designs developed at Mechanical Technology Inc. and the NASA Lewis Research Center. Three methods of thermally integrating the heat source and the Stirling heater head were considered, depending on unit size. Both the Brayton and Stirling systems used the Department of Energy general-purpose heat source (GPHS).

Figures of merit were derived from the characterizations and compared over the parametric range. They ranged from 5.2 We/kg at 0.2 kWe and 15.6 We/kg at 20 kWe for the 1300 K Brayton to 5.7 and 26.5 We/kg, respectively, for the heat pipe Stirling. The radiator requirement for the mass-optimized 1300 K Brayton ranged from 3.0 m^2/kWe at 0.2 kWe to 6.4 m^2/kWe at 20 kWe; for the mass-optimized Stirling it was 0.86 and 3.5 m^2/ kWe, respectively.

Design impacts of mission environmental factors (lunar and Mars surface thermal backgrounds, meteoroids, and dust) are discussed and quantitatively assessed. For manned missions the effect of shielding to protect astronauts from power-system-attributed radiation is examined.

For both manned and unmanned missions DIPS emerged as a strong potential candidate for the power regimes identified by the SEI mission architectures.

Introduction and Background

Surface power systems to support advanced missions such as those embodied in the national Space Exploration Initiative (SEI) Program must be larger, last longer, use less packaging, and be more reliable than systems used for previous missions (ref. 1). In most cases these requirements cannot be met by existing technologies. Prior to SEI, planetary surface mission power requirements were considerably less than a kilowatt. At this level the power benefit per unit of isotope heat source was not substantial enough to justify development of dynamic isotope power systems (DIPS); however, the establishment of multikilowatt-class surface missions on the national agenda rekindles the incentive.

Two DIPS concepts are considered herein. The Brayton design is based on a 6-kWe system proposed by Rockwell for powering the Strategic Defense Initiative (SDI) boost surveillance and tracking satellite (ref. 2). It is based on a technology inherited from the "mini-BRU" (Brayton rotating unit) Brayton isotope power system (BIPS) developed by Garrett in the late 1970's under NASA and Energy Research and Development Administration (ERDA) contracts (ref. 3), which in turn is drawn from previous closed Brayton cycle (CBC) machinery developed during the Apollo era, including the 15-kWe NASA "B" engine (ref. 4). The Stirling design is based on free-piston Stirling engine (FPSE) linear alternator technology currently being developed under the Civil Space Technology Initiative High Capacity Power (CSTI/HCP) Program for space power applications (ref. 5).

Requirements and Assumptions

The electrical output power range considered is 0.2 to 20 kWe. This power requirement is assumed to be continuous. The requirements for surface powerplants specific to SEI as they are presently defined (ref. 6) are as follows:

(1) Fifteen-year minimum service life. Periodic inspection, maintenance, and replacement of limited-life components is allowed.

(2) 0.9955 probability of no single-point failure

(3) Fail-operational and fail-safe capability

(4) No failures due to meteoroid impact

For purposes of characterization, the powerplant is defined as all components necessary to produce, from isotope decay heat, the specified electrical power at the generator output terminal (heat source, convertor, and heat rejection) but does not include electronics or downstream components associated with user integration, since user interface requirements are not known at this time. System performance is estimated at 10 years after beginning of life.

A schematic of the Brayton configuration assumed is shown in figure 1. The isotope heat source assembly was modeled

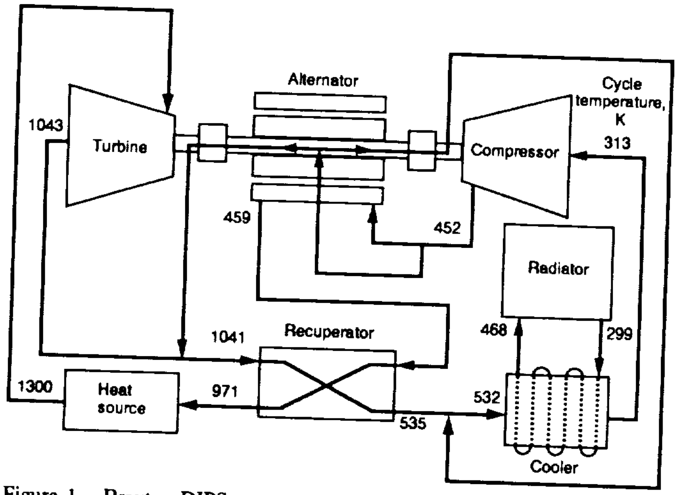


Figure 1.—Brayton DIPS power conversion system. Unit size, 2 kWe; turbine inlet temperature, 1300 K.

TABLE II.—MASS BREAKDOWN FOR 2-kWe BRAYTON DIPS

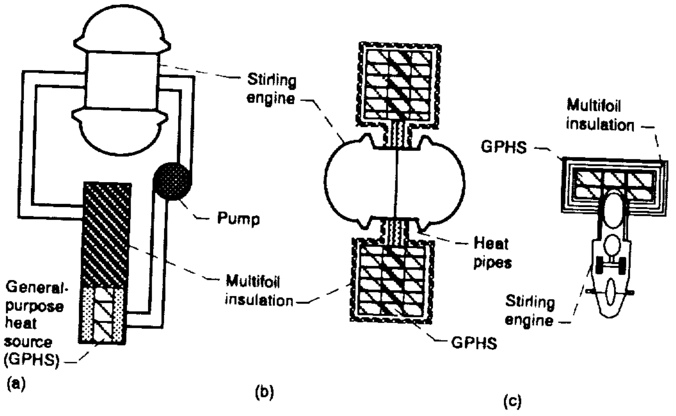
[Turbine inlet temperature, 1300 K; effective sink temperature, 250 K.]

Component	Mass, kg	Volume, m^3
Turboalternator-compressor	12	0.007
Recuperator	16	.009
Ducts	8	.006
Heat source	99	.242
Radiator and pumps	22	.084
Cooler heat exchanger	8	.003
Power conditioning	0	0
Structure	17	0
Total	182	0.35

by using an algorithm developed by Rockwell (ref. 2). The Brayton convertor (turbomachinery, ducting, and heat exchangers) was modeled by using the Closed Cycle Engine Performance (CCEP) Code developed at the NASA Lewis Research Center (ref. 7). CCEP assumes single-stage radial turbomachinery supported on compliant hydrodynamic gas bearings and a counterflow recuperator based on compact-plate fin technology. CCEP was most recently used to estimate performance and physical characteristics, including component dimensions and weights, of the Space Station Freedom solar dynamic power module (ref.8). Two turbine inlet temperatures were modeled: 1144 K, corresponding to near-term superalloy construction; and 1300 K, if refractories were used. Mass optimization was accomplished by varying the Brayton cycle parameters (listed in table I) independently to determine combinations that reduced the mass of the overall system, including the convertor, the HSA, and the radiator, to a minimum. A typical mass breakdown from the simulation, for a 2-kWe Brayton system, is shown in table II. The Stirling powerplant was modeled as a free-piston Stirling engine thermally integrated with an isotope heat source and a radiator. Engine characterizations were based on the CSTI/HCP space power demonstrator engine (SPDE) and small engine designs developed at Mechanical Technology Inc. (MTI) and NASA Lewis. Because Stirling engine development plans for SEI call for demonstration of a superalloy heater head in the near term and then transitioning to 1300 K by using refractory alloys, two heater head temperatures were considered: 1050 K, corresponding to superalloy construction of the heater head used on the development engine; and 1300 K, corresponding to the final stage of development, which substitutes a refractory alloy heater head for the superalloy used on the development engine. Three methods of source and head integration (fig. 2) were considered:

TABLE I.—BRAYTON CYCLE PARAMETERS THAT WERE VARIED

Cycle parameter	Range	Optimum for 2 kWe
Temperature ratio	3.5-5	4.17
Pressure ratio	1.7-2.5	2.056
Recuperator effectiveness	0.5-0.95	0.88
Turbine speed, rpm	30 000-110 000	79 786
Cooler effectiveness	0.5-0.75	0.94
Recuperator pressure loss, $\Delta P/P$	0.01-0.025	0.0161
Cooler heat exchanger pressure loss, $\Delta P/P$	0.005-0.02	0.0142
Compressor inlet pressure, psi	14-50	15.51
Molecular weight, g/mole	10-110	95.4
Cooler heat capacity ratio	0.5-1.2	0.76
Cycle Beta	0.9-0.945	0.9406



(a) Pumped loop.
(b) Heat pipe.
(c) Direct.

Figure 2.—Three methods of heat source integration.

(1) Liquid-metal pumped loop. The loop contains one or more heat source assemblies indentical to that used for the BIPS, except that a liquid-metal heat exchanger is substituted for the gas-heat-source heat exchanger. Heat is transferred to the engine through a pumped loop by using electromagnetic pumps.

(2) Heat pipe. A longitudinal array of heat pipes is embedded in a carbon/graphite block surrounded by general-purpose heat source (GPHS) modules on four sides. The modules radiate to the block; intermediate heat transfer is accomplished by the heat pipes (their condenser sections connect into the heater head). The assembly is enclosed by an insulated container that is similar, but not identical, to the BIPS heat source assembly, since the container encloses four stacks of blocks instead of a single stack. Further development would be required to qualify this configuration for flight.

(3) Direct. The heater head itself is surrounded by GPHS blocks, and heat transfer is accomplished by using the heater head as an exposed sink for radiated energy from the blocks. Temperature limitations restrict the number of blocks surrounding the heater head to one layer only (every GPHS block must have a direct view of the FPSE heater head), but the method appears feasible for unit sizes up to about half a kilowatt. This configuration would also require development for flight qualification.

The engine configuration chosen for heat pipe and pumped-loop integration was a 2.5-kWe space engine design loosely based on the reference space Stirling engine (RSSE) that was recently developed by MTI for kilowatt-class space applications (ref. 9). Scaling of this design over the power range of interest was furnished by M. Dhar of MTI. Depending on the temperature ratio, the specific mass of this engine ranges from about 20 kg/kWe at 200 We to about 4.5 kg/kWe at 20 kWe.

The engine configuration for direct integration was based on a 1.5-kWe, single-piston (with dynamic balancer) engine, also related to the RSSE, designed by NASA Lewis for a proposed solar dynamic flight experiment and scaled down for multihundred-watt applications by using the generalized scaling relationships developed by Gedeon (ref. 10). Within the power range applied (300 to 700 We) the specific mass of this engine was about 20 kg/kWe. Stirling mass optimization was performed by varying the engine temperature ratio, which in turn influenced the engine percent of Carnot and its specific mass according to the parametric scaling relationships. Temperature ratio was varied until a minimum, or near minimum, total mass was achieved for each configuration (including the convertor, the heat source integration, and the radiator). Typical mass breakdowns from the simulation for representative 2-kWe Stirling systems and a 300-We direct case are shown in table III.

The following assumptions were common to both Brayton and Stirling systems:

(1) The Department of Energy (DOE) GPHS enclosed by an insulated container and employing radiative heat transfer to the

TABLE III.—PERFORMANCE AND MASS BREAKDOWN FOR FREE-PISTON STIRLING DIPS

(a) Performance

[1300 K heater head; effective sink temperature, 250 K.]

Characteristic	Pumped-loop integration (2.0-kWe unit size)	Heat pipe integration (2.0-kWe unit size)	Direct integration (300-We unit size)
Number of general-purpose heat source (GPHS) blocks	24	26	4
End-of-life thermal performance, kWt	5.684	5.82	0.855
High-temperature heat loss, kWt	0.2927	0.3154	0.049
Engine temperature ratio	2.9	2.8	3
Convertor efficiency	0.38	0.369	0.403
Convertor specific mass, kg/kWe	6.448	6.577	20
Radiator area, m^2	3.467	3.006	0.701
Radiator temperature, K	403	419.3	388

(b) Mass breakdown

Characteristic	Mass, kg		
GPHS blocks	---------	37.72	5.72
Primary heat transport	---------	10.43	0
Insulation package	---------	4.51	4
Heat source assembly	[a]82.219	19.36	6.61
Electromagnetic pump	13.1	--------	-------
Convertor	12.89	13.15	6.21
Radiator	9.3	8.07	1.71
Power conditioning and control	0	0	0
Structure	12.45	9.32	2.42
Total	136.959	102.56	26.67

[a] Including GPHS blocks.

engine or an intermediate heat transfer device is used. A 5-percent heat loss from this heat source assembly was assumed.

(2) A structural mass of 10 percent is applied to the subtotal of all the individual system components.

(3) Waste heat is removed from the engine by a pumped liquid loop.

(4) A pumped-loop, two-sided, vertically oriented radiator is used with a specific mass of 2.44 kg per square meter of radiating surface, as correlated by hardware now being developed for Space Station Freedom. An emissivity of 0.9, a solar absorptivity of 0.1, and a radiator fin effectiveness of 0.85 were assumed. For this configuration, properly oriented on the lunar surface and using a reflective sheet at its base, the equivalent sink temperature should not exceed 250 K.

(5) The performance, mass, and volume of power conditioning and control (PC&C) electronics is ignored, since it is considered to be application specific. On a per-kilowatt basis, the hardware will be similar for both systems and should not affect the overall comparison. The efficiency of the power conditioning associated with dynamic systems typically exceeds 90 percent. Mass penalties associated with PC&C usually fall in the range 5 to 20 kg/kWe.

(6) Integration hardware is not included.

Results and Discussion

Brayton DIPS

Figure 3 shows the mass breakdown for 2-kWe Brayton systems for various cycle temperature ratios. The data presented were generated for a turbine inlet temperature of 1300 K. Minimum system mass was obtained at a temperature ratio of 4.15. At 1144 K, however, the minimum system mass was obtained at a temperature ratio of 3.72. Heat rejection includes the pump, radiator, and waste heat exchanger masses. Figure 4(a) plots the mass, volume, radiator area, specific power, specific volume, and specific radiator area of the minimum-mass-optimized Brayton DIPS versus the output power level for both 1144 and 1300 K turbine inlet temperatures. The data show that the Brayton characteristics are strongly influenced by unit size. Specific power is highest and specific volume and radiator area are lowest at 20 kWe. As power level was decreased over the two-decade range of interest, however, specific power was reduced approximately threefold, specific volume increased by about the same factor, and specific radiator area roughly doubled. This sensitivity is primarily an effect of turbomachinery size. For a tenfold reduction in output power (from 2 to 0.2 kWe) the specific power of the mass-optimized convertor was reduced by approximately 50 percent. Lower power levels result in smaller wheel diameter and consequently much higher clearance loss, which in turn lowers efficiency. The reduced power levels also required the selection of a higher molecular weight working fluid, which reduced heat transfer and required larger heat transfer equipment.

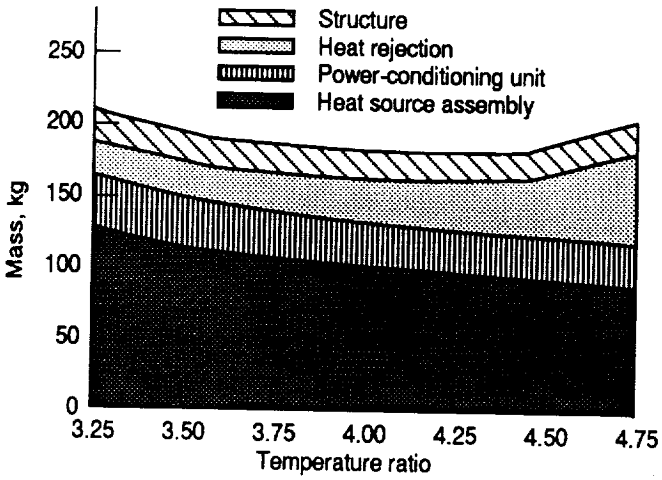


Figure 3.—Mass breakdown with cycle temperature ratio for 2-kWe lunar Brayton DIPS. Turbine inlet temperature, 1300 K; sink temperature, 250 K.

Increasing the peak cycle temperature of the Brayton from 1140 to 1300 K appeared to yield a mass benefit of 3 to 10 percent and a volume benefit of 7 to 15 percent, also a strong function of power level. But it caused an approximately 40 percent reduction in radiator area over the entire power range.

The optimizations presented here do not take into account radiation shielding. The volume data make no assumptions concerning configuration, packaging, or architecture: the system is the sum of its components.

Stirling DIPS

Figure 5 shows the mass breakdown for 2-kWe Stirling systems for various cycle temperature ratios. The data presented were generated for heat-pipe integration at a heater head temperature of 1300 K. Each design was optimized for minimum mass; that is, for each temperature ratio the engine was optimized for percent of Carnot achievable and specific mass according to the design methodology. The mass breakdown exhibited trends similar to that for the Brayton. As the temperature ratio increased, the heat source (GPHS blocks, thermal transport, and insulation) was reduced and heat rejection increased until the saving in heat source was negated by the additional rejection. For the heat-pipe-integrated Stirling, minimum system mass occurred at a temperature ratio of 2.8. Figure 6 plots the mass, volume, radiator area, specific power, specific volume, and specific radiator area of the minimum-mass-optimized Stirling DIPS versus output power level for the three heat source/heater head integration methods considered.

The data show that the Stirling DIPS characteristics were strongly influenced by unit size. As power level decreased over the two-decade range of interest from 20 kWe, the specific power decreased by factors ranging from 2.6 to 4.3 depending on the temperature and integration method used, the specific volume decreased slightly, down to roughly half for the 1300 K heat-pipe heat source assembly, while the specific radiator area

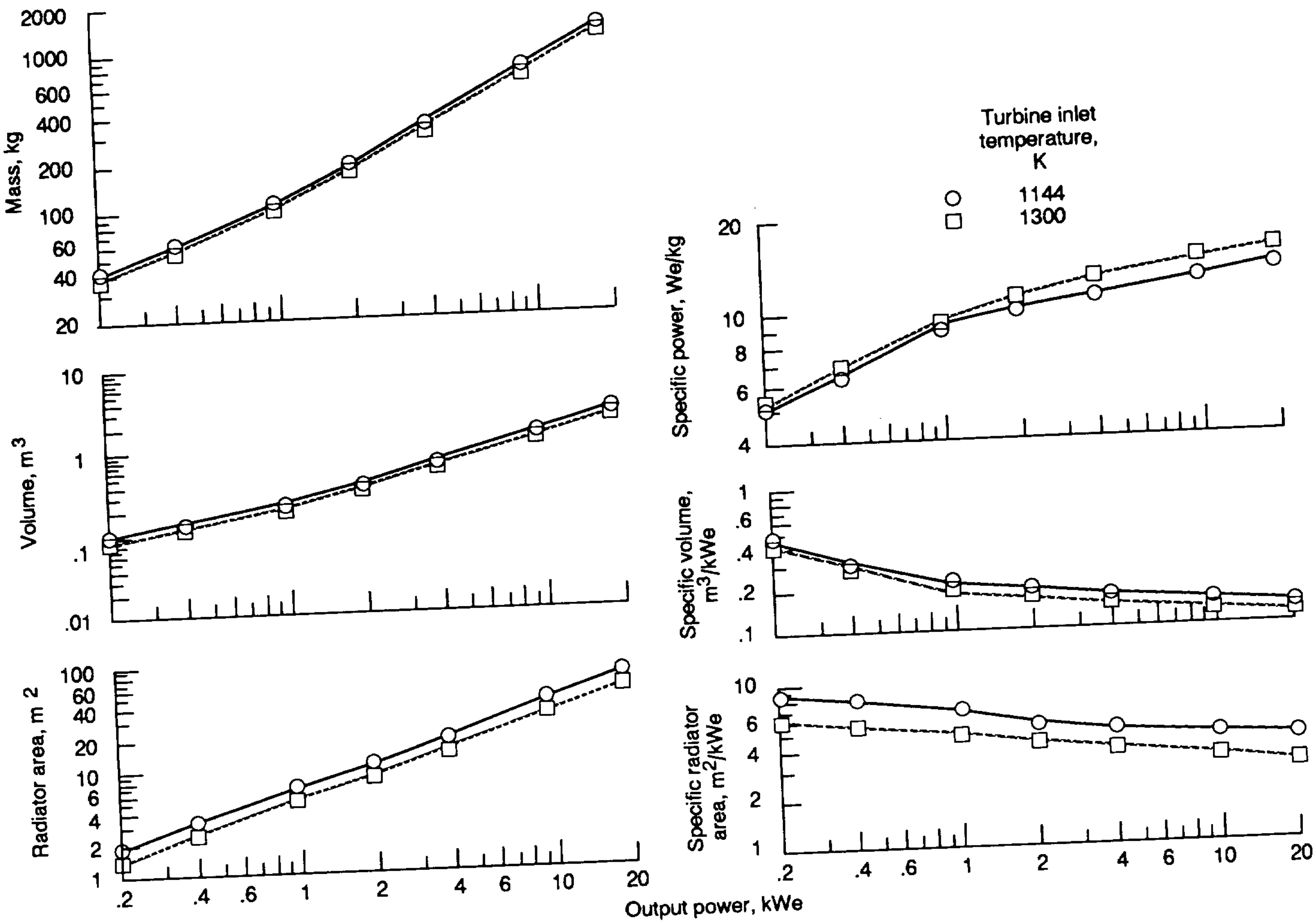


Figure 4.—Characteristics of lunar Brayton DIPS optimized for minimum mass.

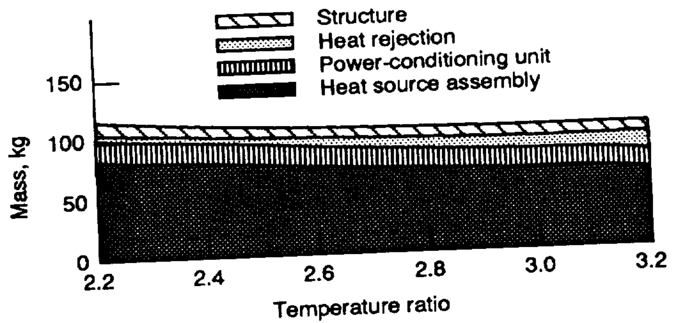


Figure 5.—Mass breakdown with cycle temperature ratio for 2-kWe lunar free-piston Stirling DIPS. Heater head temperature, 1300 K; sink temperature, 250 K.

remained approximately constant. The mass and specific power were strongly influenced by the integration method used. For power levels down to about 2 kWe the heat-pipe integration method appeared to yield the highest specific power, but at power levels of less than a kilowatt it yielded about the same specific power as the pumped loop, which can be considered equivalent to the heat source integration method used for the Brayton. At power levels under 1 kWe direct integration yielded the highest specific power, to approximately double that of the other methods at the smallest unit size. There is an advantage for FPSE in the multihundred-watt power range, where intermediate heat transfer devices are not needed.

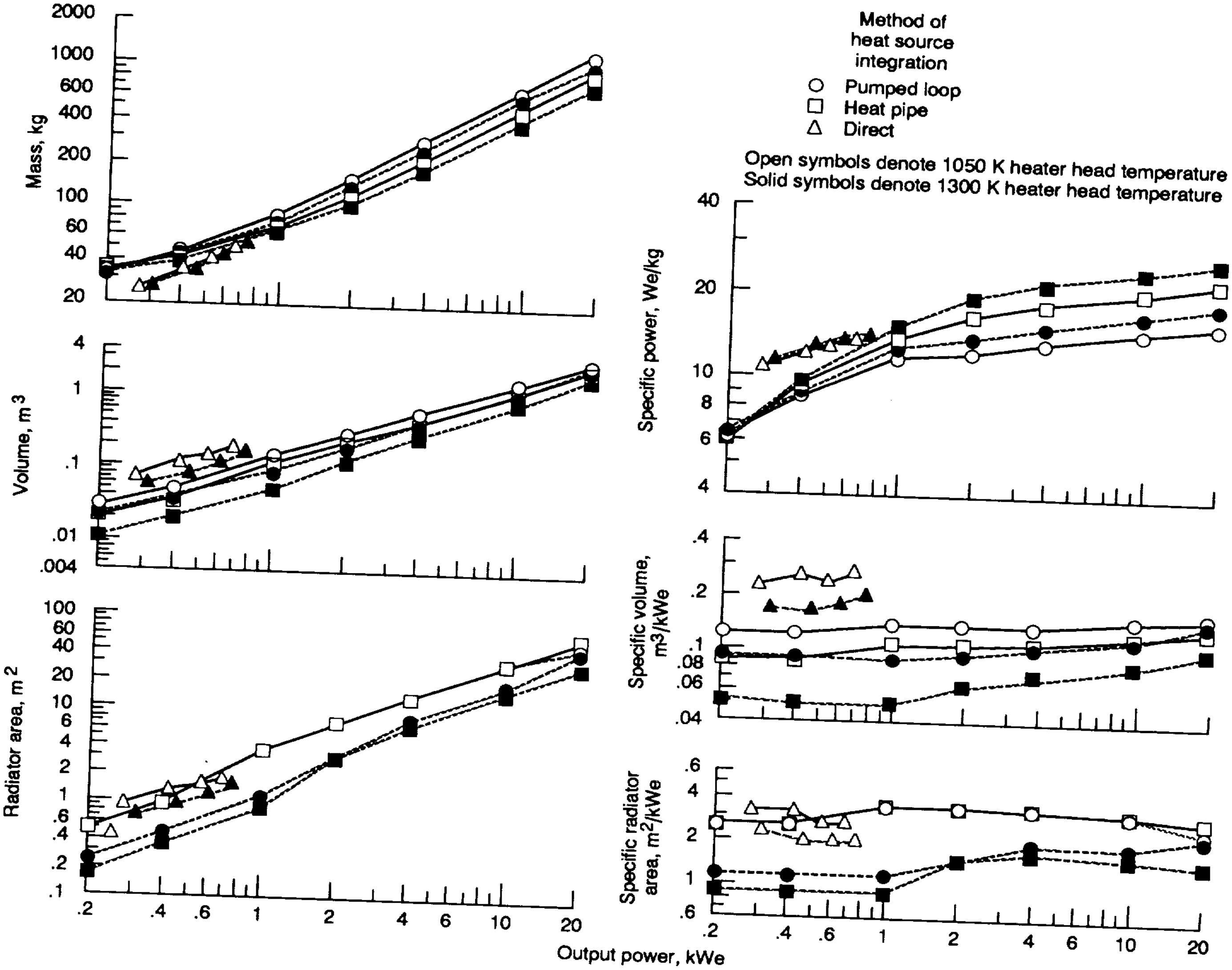


Figure 6.—Characteristics of lunar free-piston Stirling DIPS optimized for minimum mass.

Increasing the peak cycle temperature from 1050 to 1300 K benefited the Stirling, allowing optimization at higher temperature ratios and higher thermal efficiencies for a corresponding reduction in heat source. The mass benefit, as evidenced by specific power, was greatest at higher power levels but less than 10 percent for power levels below 1 kWe.

Over the power range considered, the specific power of the Stirling DIPS was slightly higher than that of the Brayton. The difference was mainly due to convertor mass. The FPSE/linear alternator is a self-contained conversion unit whose working fluid is not circulated through external ducts and heat exchangers to effect the conversion cycle but confined instead to a small locality within the engine. The scaling effect associated with turbomachinery, which gives higher specific power as unit size is increased, penalizes the Brayton, which has relatively low specific power at multihundred-watt unit size.

Comparing figures 4 and 6 also indicates that the Stirling units generally required smaller radiator areas, roughly half those of the Brayton. This is a consequence of the heat rejection characteristic of the Stirling cycle and the subsequent optimization of Stirling systems at lower temperature ratios.

For both Brayton and Stirling DIPS the heat source assembly dominates the mass and drives convertor optimization to higher temperature ratios. As a consequence, higher peak cycle temperature is of most benefit to large unit size and least benefit to multihundred-watt systems.

Environmental Interactions

Because the DIPS must reject waste heat to its immediate surroundings, it will in turn be influenced by the surroundings into which it is placed. Not all the environmental interactions are known at this time, but our present understanding of the mission environment and the fundamental characteristics of the power system allows us to identify some of the major interactions and estimate their effects.

The first effect to consider is equivalent sink temperature. Table IV gives estimated maximum expected equivalent sink temperatures for horizontally and vertically oriented flat-plate radiators on the surfaces of the Moon and Mars. The value that is actually used for system design will depend on the mission. For example, SEI surface elements on the Moon can experience equivalent sink temperatures as low as 220 K for a stationary radiator installation oriented edge-on to the Sun and employing selective emissivity coatings with a reflective sheet at its base (for vertical orientation) to as high as 384 K for a vehicle radiator unable to employ selective coatings or reflective sheets and whose orientation and surface view factor cannot be controlled. Sink temperature will affect the way DIPS is optimized for the mission, as figure 7 shows. Comparing a system that is optimized for 384 K with one that is optimized for 220 K shows that the higher temperature unit must operate at a reduced temperature ratio in order to elevate the radiator temperature. Such operation causes lower cycle efficiency, which in turn requires a larger heat source. Radiator area will change only slightly, but the overall mass penalty is 32 percent.

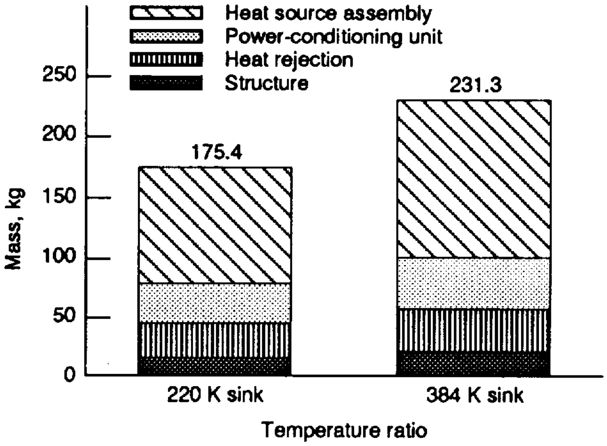


Figure 7.—Mass of 2-kWe Brayton DIPS optimized for two different sink temperatures on Moon.

Effects on the individual DIPS of sink temperature variation over time must also be considered. For a fixed site on the Moon, equivalent sink temperature variation can be easily predicted, since it depends only on the day/night cycle. For Mars the variation is more complex and not as well understood. In addition to seasonal variations, there is also wind-blown dust, which changes the sky optical depth, varying not only the amount and kind of solar radiation received but also the background temperature. Generally, dust reduces the overall thermal background. Sky temperature is increased, but incoming solar radiation is reduced.

The presence of dust will, besides influencing the thermal background, have more direct effects on the radiator. A thin layer of dust can change surface absorptivity and emissivity, and any appreciable layering of dust will greatly increase the thermal impedance to the radiating surface. Figure 8 shows the effects on a 2-kWe Brayton DIPS, considering only the change in radiator surface properties brought on by dusting (thermal emissivity is increased slightly while solar absorptivity rises by a factor of 4, ref. 11). For the original radiator design considered, the net effect was to raise equivalent sink temperature by about 30 percent and to force, with the constant heat input from the isotope source, all of the cycle temperatures (including turbine inlet) to climb upward. In this off-design condition, convertor performance and life were reduced. It is possible to return the turbine inlet temperature to its original value by raising the turbine speed, but only at the expense of further reducing performance. On the other hand, if the Brayton cycle were reoptimized to accommodate the dusted condition, the original performance and turbine inlet temperature can be achieved by a 7-percent increase in heat source and a 14-percent

TABLE IV.—ESTIMATED MAXIMUM EQUIVALENT SINK TEMPERATURES FOR FLAT-PLATE RADIATORS ON SURFACE OF MOON AND MARS

[Thermal emissivity, 0.8; solar absorptivity, 0.08; surface view factors: 50 percent (vertical) and 0 (horizontal).]

Orientation	Moon	Mars (nominal)
	Sink temperature, K	
Vertical	325	250
Horizontal	221	175

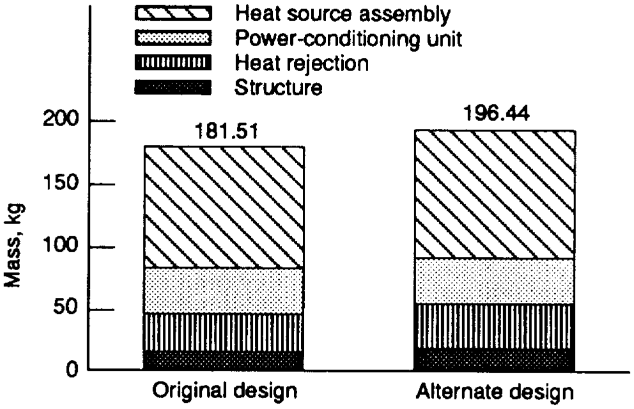


Figure 8.—Effect of dust compensation on mass of lunar Brayton DIPS.

increase in radiator area. The overall mass penalty is about 8 percent compared with the original design.

Another environmental effect on the radiator is meteoroid attack. It may be possible to shield most of the DIPS by partial burial or by careful location, but in any event the radiator must remain exposed in order to do its job. For the 15-year mission life the probability of an unarmored radiator (0.010-in. wall thickness) escaping puncture is less than 95 percent for any exposed area greater than 3 cm^2. Since all of the DIPS radiators considered exceed this area, it will be necessary to armor the radiator, to add redundant capacity in parallel, or to apply both strategies in combination to ensure a high enough probability of radiator survival to meet the failure criteria of table I. Generally, a redundancy factor of approximately 20 percent, in combination with modest levels of armoring, results in the lowest mass for meteoroid survival probability levels exceeding 99 percent (ref. 12). Figure 9 shows the relation between total radiator mass and redundancy for three constant levels of reliability for an armored 2-kWe Brayton DIPS radiator on the lunar surface.

On Mars, exposed surfaces will be subject to corrosive attack by atmospheric constituents that include several oxidizing agents. This is a major concern, since much of DIPS is at elevated temperature and subject to exposure unless hermetically sealed within a container. The choice of materials for outer parts such as the turbine scroll casing or the FPSE heater head will be limited; for example, refractory alloys would be precluded because they cannot be used without external containment and the radiator must remain exposed. Preliminary estimates of the degradation rates for radiator surfaces of carbon, copper, and titanium in the Martian atmosphere at typical operating temperatures have been made from their thermodynamically derived chemical equilibria (ref. 13). Copper and titanium tend to develop protective oxide films when exposed, and their surface emissivities are actually enhanced. On the other hand, carbon/carbon composites will require protective coatings to survive. More detailed investigations covering a wider selection of materials will take place as program resources are made available.

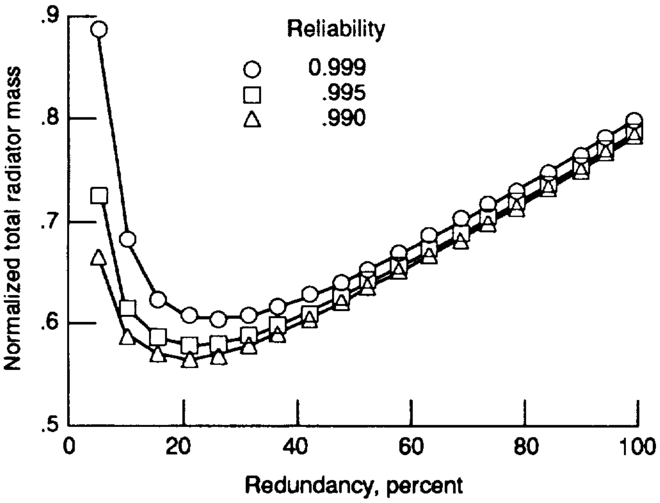


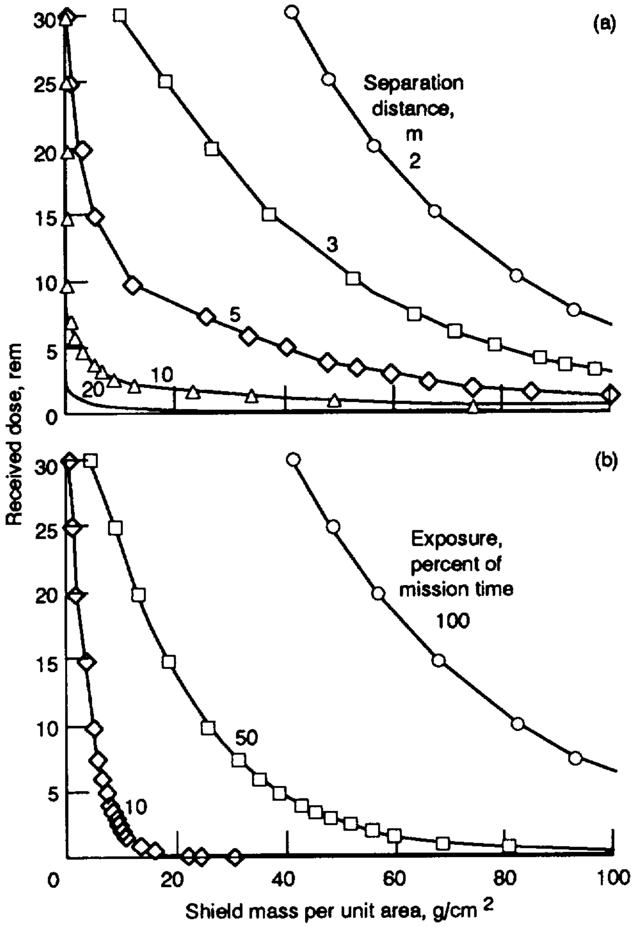
Figure 9.—Effect of redundancy on normalized total radiator mass for three levels of reliability. Reference case, nonredundant radiator; armoring material, aluminum; damage mode, micrometeoroid puncture; expected life, 15 yr.

The combined effects of wind-driven dust and corrosion may limit the usefulness of selective coatings, which are normally desirable, since in their pristine state they exhibit ratios of solar absorptivity to thermal emissivity as low as 0.1. If the coating is eroded and replaced by oxidation, however, that ratio is increased to unity, translating to reduced performance whenever the radiator is illuminated.

The presence of an atmosphere will also affect thermal transport and insulation. With all the present DIPS designs, heat transfer from the GPHS block is radiative. If the heat source assembly is open to the Mars atmosphere, however, convective processes will be present. For example multifoil insulation, which is preferred for space systems because of its low weight, loses effectiveness in the presence of less than 1-millibar ambient atmosphere. A multifoil-insulated heat source assembly cannot be used on Mars without vacuum jacketing. Solid insulation, similar to that used to control heat losses in the Viking lander radioisotope thermoelectric generator, may be preferable in this case. On the other hand, it may be possible to take advantage of convection and use the Mars atmosphere as a heat sink. This is a potentially attractive strategy because the temperature of the Mars atmosphere is lower than the radiator equivalent sink temperature. Because of the low ambient pressure, more than 10 times as much surface area is needed for convective transfer than is needed with radiators; however, this surface area may be packaged compactly as a heat exchanger, which does not need to be directly exposed.

Shielding for Manned Operation

Radiation shielding requirements for a DIPS are application specific. Generally speaking, a user of DIPS must either accept certain operational constraints on manned activity or accept a penalty for shielding mass. Shielding mass can be minimized by restricting proximity to DIPS, restricting the amount of time spent in close proximity, or a combination of both. Figure 10(a) shows the radiation dose received during a 90-day mission from the 2-kWe DIPS versus the amount of shielding required for various separation distances. Figure 10(b) shows the dose received at a 2-m separation distance versus the amount of shielding required when exposure is limited to various percentages of the 90-day mission time. Figure 11 shows the shield mass that would be required to reduce the radiation dose rate seen by a human in the vicinity of the DIPS to 5 rem/yr versus separation distance from the power system according to the geometry of figure 12. The shield is composed of lithium hydride and tungsten. A 2-m-diameter dose plane was assumed. The analysis considered attenuation only; secondary



(a) 100-Percent exposure for various separation distances.
(b) Various exposures at 2-m separation distance.

Figure 10.—Radiation dose from 2-kWe DIPS during 90-day mission.

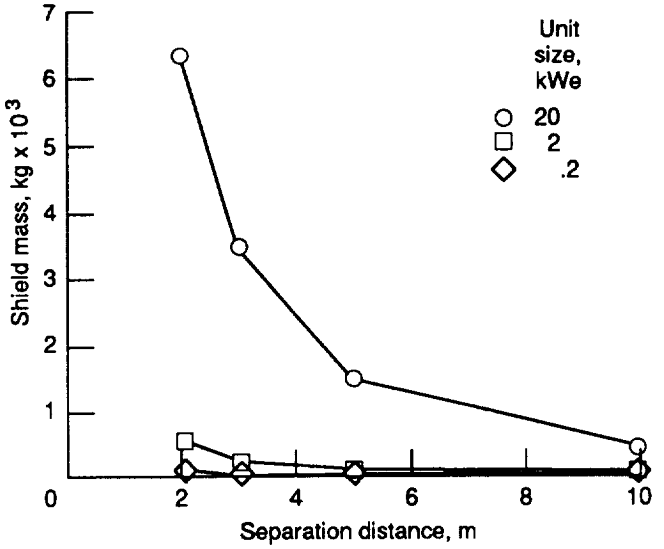


Figure 11.—Shadow shield mass versus distance for 5-rem/yr allowed dose.

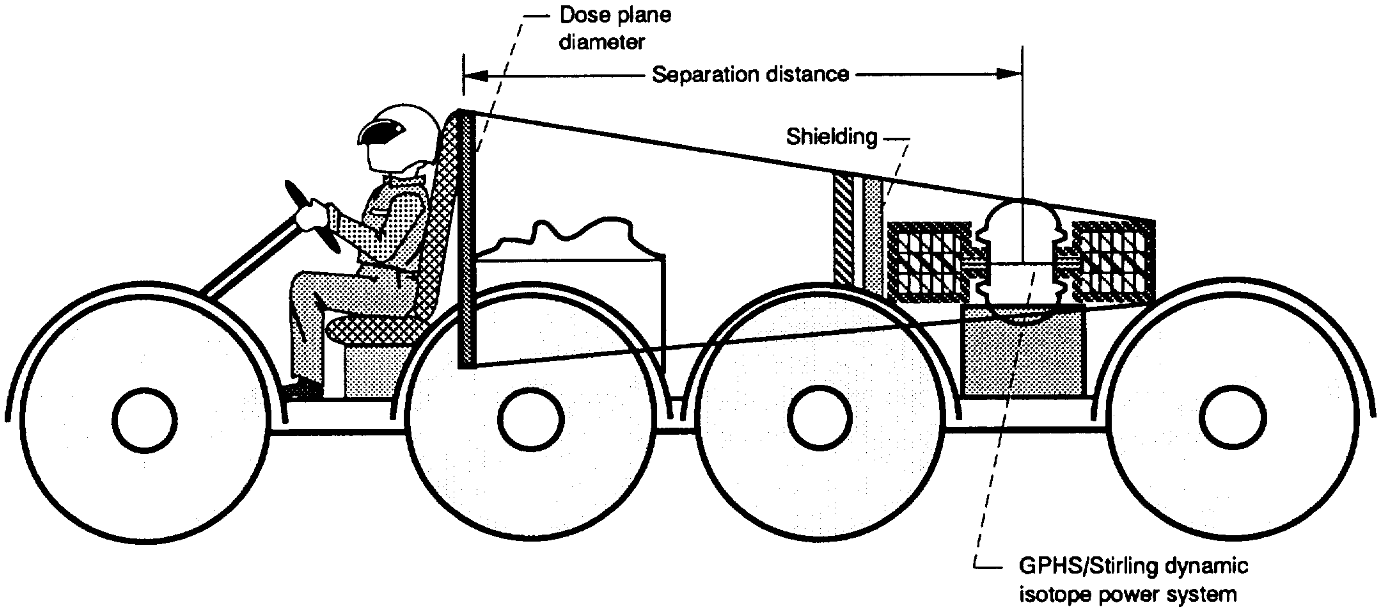


Figure 12.—Geometry of lunar/Mars vehicle.

gamma production, backscattering effects, and self-shielding were ignored. At short separation distances, shielding mass exceeds the balance of the power system mass. Clearly, there is an incentive to configure the installation so that the power system is separated from the human user and access to it is restricted.

Where complete enclosure is required, the use of locally obtained material for shielding is a reasonable approach. Stationary powerplants could be shielded by partial burial of the heat source assembly and the convertor, leaving the radiator exposed. Mobile powerplants could be shielded by surrounding the heat source assembly with soil, perhaps enclosed in bags or a hopper mounted on the vehicle platform. Figure 13 shows the thickness of lunar soil versus the dose plane distance, that is, the separation distance required for an astronaut to limit exposure according to the dosage criteria previously discussed.

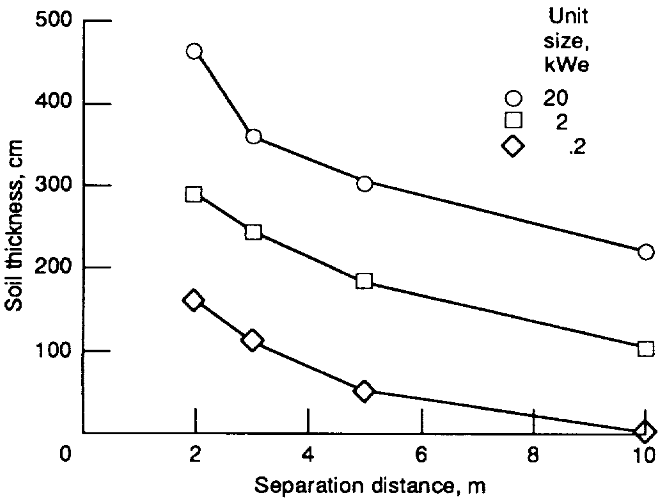


Figure 13.—Lunar soil thickness needed versus dose plane distance for 5-rem/yr allowed dose.

Conclusions

Both the Brayton and Stirling dynamic isotope power systems (DIPS) are viable options to meet Space Exploration Initiative requirements for continuous surface power. Over the power range of interest the Brayton systems exhibited specific power ranging from 5.06 and 5.20 We/kg at 200-We unit size to 14.13 and 15.61 We/kg at 20-kWe unit size for the 1144 and 1300 K turbine inlet cases, respectively. Over the same power range the Stirling systems exhibited from 6.26 and 6.44 We/kg to 16.68 and 19.4 We/kg for pumped-loop integration at 1050 and 1300 K, respectively, and from 5.89 and 6.07 We/kg to 22.4 and 26.5 We/kg for heat-pipe integration. Direct integration, which appeared limited to unit sizes of less than a kilowatt, yielded 11 to 14 We/kg in the range 300 to 700 We. For both Brayton and Stirling systems, specific power improved with increasing unit size. Volumes ranged from 0.1 to 0.4 m^3/kWe depending on unit size and convertor type. The systems exhibited specific radiator areas ranging from 1 to 8.5 m^2/kWe. Generally, the Stirling systems required smaller radiator areas than the Brayton systems, typically about half.

Environmental considerations and shielding requirements exerted greater impact on DIPS mass and volume than peak cycle temperature considerations (superalloy versus refractory construction). The mission environmental factors and their effects include the following:

1. The thermal background, which controls the equivalent sink temperature and subsequently the cycle performance
2. Dust and atmospheric corrosion, which affect the choice of materials used for exterior portions of the heat source assembly and the convertor, the radiator surface properties, and the equivalent sink temperature
3. Meteoroid considerations, which require the radiator to be oversized and contain redundant elements
4. Presence of an atmosphere, which introduces convective heat losses and thus affects the thermal control strategies that can be used. Shielding for manned operation, which is application specific, had the greatest effect. Shielding requirements can be greatly reduced by restricting access, proximity, and exposure time.

The trends discussed herein will emerge more clearly as the mission requirements, and the systems to serve them, become better defined. Bear in mind that neither the Brayton nor the Stirling system that will be needed is developed at present—the technologies of both systems will require further work if the potential indicated herein is to be realized.

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ERRATA

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COMPARISON OF DYNAMIC ISOTOPE POWER SYSTEMS FOR DISTRIBUTED PLANET SURFACE APPLICATIONS

David J. Bents, Barbara I. McKissock, James C. Hanlon, Paul C. Schmitz,
Carlos D. Rodriguez, and Colleen A. Withrow

Page 1: The first sentence under Introduction and Background should read, "Surface power systems to support advanced missions such as those embodied in the national Space Exploration Initiative (SEI) Program must be more powerful but smaller, last longer, and be more reliable than systems used for previous missions (ref. 1)."

Page 2, second column, line 2: "The Stirling . . ." should start a new paragraph.

Page 7, figures 7 and 8: In the keys, "Power-conditioning unit" should be "Power conversion unit."

Page 8, column 2, last paragraph: The sixth sentence should read, "Figure 11 shows the shield mass that would be required to reduce the 90-day-mission dose experienced in the vicinity of the DIPS to 22 rem versus . . . "

Page 9: Figure 11 should be replaced with the following figure.

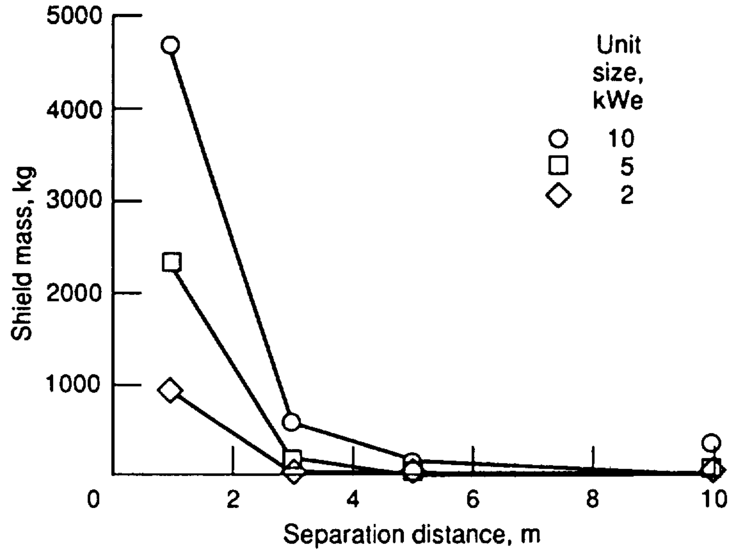

Figure 11.—Shadow shield mass versus dose plane distance for 90-day allowed dose of 22 rem.

Page 10, first paragraph: The fourth sentence should be changed and a sentence added to read, "Figure 13 shows the thickness of lunar soil versus the separation, or "keep-clear," distance that is required to limit exposure. Five rem/yr is a reasonable value for stationary applications, such as a habitat, where prolonged exposure times would be expected."

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16. Abstract
In support of the Space Exploration Initiative (SEI), a study was performed to investigate and characterize dynamic isotope power system (DIPS) alternatives for the surface mission elements associated with a lunar base and subsequent manned Mars expedition. System designs based on two convertor types were studied. These systems were characterized parametrically and compared over the steady-state electrical output power range 0.2 to 20 kWe. Brayton characterizations were based on the "mini-BRU" (Brayton rotating unit) Brayton isotope power system (BIPS) technology. Stirling characterizations were based on scaled-down Civil Space Technology Initiative space ower demonstrator engine designs and on small engine designs developed at Mechanical Technology Inc. and the NASA Lewis Research Center. Three methods of thermally integrating the heat source and the Stirling heater head were considered, depending on unit size. Both the Brayton and Stirling systems used the Department of Energy general-purpose heat source. Figures of merit were derived from the characterizations and compared over the parametric range. They ranged from 5.2 W/kg at 0.2 kWe and 15.6 W/kg at 20 kWe for the 1300 K Brayton to 5.7 and 26.5 W/kg, respectively, for the heat pipe Stirling. The radiator requirement for mass-optimized 1300 K Brayton ranged from 3.0 m^2/kWe at 0.2 kWe to 6.4 m^2/kWe at 20 kWe; for the mass-optimized Stirling it was 0.86 and 3.5 m^2/kWe, respectively. Design impacts of mission environment factors (lunar and Mars surface thermal backgrounds, meteoroids, and dust) are discussed and quantitatively assessed. For manned missions the effect of shielding to protect astronauts from power-system-attributed radiation is examined. For both manned and unmanned missions DIPS emerged as a strong potential candidate for the power regimes identified by the SEI mission architectures.

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