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Preliminary Assessment of Rover Power Systems for the Mars Rover Sample Return Mission

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PRELIMINARY ASSESSMENT OF ROVER POWER SYSTEMS FOR THE MARS ROVER SAMPLE RETURN MISSION

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ABSTRACT

Four isotope power system concepts are presented and compared on a common basis for application to on-board electrical prime power for an autonomous planetary rover vehicle. A representative design point corresponding to the Mars Rover Sample Return (MRSR) preliminary mission requirements (500 W) was selected for comparison purposes. All systems concepts utilize the GPHS isotope heat source developed by DOE. Two of the concepts employ thermoelectric (TE) conversion: one using the GPHS RTG used as a reference case, the other using an advanced RTG with improved thermoelectric materials. The other two concepts employed are dynamic isotope power systems (DIPS): one using a closed Brayton cycle (CBC) turboalternator, and the other using a free piston Stirling cycle engine/linear alternator (FPSE) with integrated heat source/heater head. Near term technology levels have been assumed for concept characterization using component technology figure-of-merit values taken from the published literature. For example, the CBC characterization draws from the historical test database accumulated from space Brayton cycle subsystems and components from the NASA "B" engine through the mini-BRU. TE system performance is estimated from Voyager/MHW-RTG flight experience through Mod-RTG performance estimates considering recent advances in TE materials

under the DOD/DOE/NASA SP-100 and NASA CSTI programs. The Stirling DIPS system is characterized from scaled-down Space Power Demonstrator Engine (SPDE) data using the DOE General Purpose Heat Source GPHS directly incorporated into the heater head.

The characterization/comparison results presented here differ from previous comparison of isotope power (made for LEO applications) because of the elevated background temperature on the Martian surface compared to LEO, and the higher sensitivity of dynamic systems to elevated sink temperature. Although dynamic systems have historically shown advantages of lower specific mass and reduced isotope inventory per delivered electrical watt, the mass advantage of dynamic systems is significantly reduced for this application due to Mars' elevated background temperature.

INTRODUCTION

The Mars Rover Sample Return (MRSR) Mission proposed for the late 1990's [1,2], would place two spacecraft in orbit about Mars and land a surface rover vehicle (Fig. 1). In addition, a separate ascent stage would return about 100 kg of geological samples gathered by the rover to Earth. Building on the legacy from the Viking program, where delivery of payloads to the Martian surface was demonstrated, the MRSR mission takes full advantage of advances in computer, telecommunications, software and robotics technology that have taken place since then; particularly the autonomous land vehicle navigation systems developed under DARPA sponsorship [3]. The reference design Mars rover, at 842 kg, is not much different in size and mass than the Viking lander which weighed 600 kg, but it has greatly improved capability. This vehicle is mobile and capable of traversing the Mars terrain autonomously; that is, performing its local navigation (100 to 1000 m traverse) without human intervention.

Reference 3 gives a fairly complete description of this vehicle as defined to date. Due to its small size and the relatively modest amount of locomotive energy required compared to other mission activities, this vehicle will be powered electrically; that is, one on-board source will be used to provide power for all functions. Table 1 summarizes the requirements as determined to date for this on-board source [4,5].

The electrical load serviced by this source is not constant: modal timelines have been generated for the various surface operations which take into account estimated demands from each on-board system as it is activated. For example, a typical power profile during surface operations for the AREAL rover is shown in Fig. 2 [4]. This profile can be characterized as a base load with intermittent peaks superimposed on it. The peak value is roughly three times the baseload power level, but due to its relatively low repetition rate and duty cycle, the total integrated value is close to the baseload requirement. A steady state generator combined with secondary battery storage system is most appropriate to service this load.

Based on power profile information for all operating modes a conservative estimate of 350 Wh of battery storage has been established to accommodate the peaking requirement. Normally the battery discharge depth will be less than 10 percent of rated capacity, so that a moderate cycle life, high energy density system such as silver/zinc can be used. The battery should weigh less than 20 kg.

The steady-state power system must continuously supply the time-averaged power demand from all users, plus extra energy over time to recharge and maintain the battery. Evèn at idle, power consumption aboard the vehicle is an estimated 240 W [5]. In the aggregate, this translates to a steady state demand of roughly half a kilowatt. Given the requirement for this amount of continuous primary power, the low levels of sunlight experienced on the surface, and the wind and dust environment (see Table 2), solar arrays are very large and cumbersome. Therefore, a nuclear heat source is ideally suited to this mission.

MRSR POWER SYSTEM CONCEPTS

Four different isotope power system concepts have been evaluated in this study; the GPHS-RTG, the Mod-RTG, closed Brayton cycle DIPS and the free-piston Stirling engine DIPS. Each concept is briefly described and performance characteristics for a 500 We system are given.

GPHS-RTG

The GPHS-RTG (Fig. 3) is basically a finned assembly of thermoelectric elements enclosing a stack of GPHS blacks and radiatively coupled to them. Heat flow is outward; the elements take advantage of the temperature difference between the interior to the outer surface, to convert some of the heat flow from the isotope capsule to low voltage dc; the conversion system is well developed for space use [6]. Multiple series-parallel strings of several hundred thermoelectric couples are designed to accommodate failure of any element in the string with only partial degradation. Table 3 summarizes the performance and mass breakdown of a Mars rover power system based on the GPHS-RTG. Power conditioning and controls, structure, and the 350 Wh energy storage elements are included in this estimate.

MOD-RTG

The Mod-RTG [7] is the evolutionary successor to the GPHS-RTG. Based on improvements in the thermoelectric couples the BOL converter efficiency is expected to increase to 7.6 which, combined with packaging refinements over the GPHS-RTG will further improve specific power. Table 4 summarizes the performance and mass breakdown for a Mod-RTG based power system configured for the MRSR mission.

CLOSED BRAYTON CYCLE

The closed Brayton cycle (CBC) dynamic system has been advocated by Rockwell [8] as power source for this vehicle. Known advantages cited for dynamic systems are their higher thermal efficiencies. The conversion efficiencies historically demonstrated by dynamic systems have ranged from 20 to 30 percent. For an isotope system, this translates to less waste heat rejected and to considerably reduced fuel inventory per electrical watt delivered; resulting in a significant heat source mass reduction.

The technology base for this system is the Brayton Isotope Power System (BIPS) developed by the Garrett Corporation for NASA in the late 1970's [9]. The BIPS was a recuperated system consisting of a small single shaft turboalternator (the mini-BRU), one or more heat source assemblies with source heat exchangers, waste heat exchangers and a pumped loop radiator. It was designed to provide 500 to 2100 electrical watts using one mini-BRU by adding the required number of heat source, heat exchanger and radiator modules (Fig. 4). BIPS was intended to be a high performance power source for LEO application: a sink temperature of 216 K was assumed. The mini-BRU was unique for its small size (500 to 2100 W); although turbomachinery generally does not scale well to low power levels a compressor efficiency of 77 percent and a turbine efficiency of 83.6 percent was achieved. In testing BIPS achieved 24.5 percent efficiency (Fig. 5) at a turbine inlet temperature of 1020 K.

Table V presents the performance and mass breakdown of a 500 W Brayton DIPS, based on BIPS technology, and specifically configured for the MRSR mission; for example, dual PCU's for 100 percent redundancy. In order to achieve improved performance, a higher turbine inlet temperature (1150 K) than BIPS was required, nevertheless conventional superalloy materials and construction are retained.

FREE PISTON STIRLING CYCLE

Free piston Stirling cycle engine (FPSE) dynamic conversion was modeled because it provides a thermodynamic advantage over the Brayton cycle. For equivalent performance it operates at a lower cycle temperature ratio which translates to reduced radiator size. It is mechanically simple with few moving parts, which are not in contact during operation. Although on a specific weight basis the Stirling engine does not scale favorably with increased power level, its specific weight is lower than the Brayton cycle in the range 1 to 10 kWe. The FPSE is currently being developed by NASA under the CSTI program. Development goals include a 1300 K engine employing refractory metals at a temperature ratio of 2.0 for SP-100 application with specific weight less than 6 kg/kWe, and a 1050 K superalloy engine at a temperature ratio of

2.0 as an intermediate goal. The first machine representative of a space configuration, the Space Power Demonstrator Engine (SPDE) is the largest FPSE built and demonstrated. It has delivered 17 kWe with a (thermal to mechanical) efficiency of 22 percent, operating at a temperature ratio of 2.0. Although the SPDE was a developmental engine it can, with straightforward material substitutions, and replacing bolts and flanges with welds, provide a specific mass of 7.2 kg/kWe in flight configuration [10].

The Stirling engine scales favorably to lower power levels because surface area to volume increases as unit size is reduced. This reduces the level of heat flux across the heater head boundary into the working fluid. At a few hundred watts it approximates the heat flux from an isotope source. Therefore the separate HSA and intermediate heat transfer loop required for a BIPS design can be eliminated, and at these unit sizes the heater head can be heated directly. Figure 6 shows a concept for direct integration of an FPSE heater head with the GPHS isotope heat source at a unit size of 500 We. The GPHS blocks are arranged around the heater head circumferentially and held in place by a fusible strap assembly (FSA) as shown in Fig. 6(a). The GPHS aeroshell could also be modified in shape from a rectangular block to an annular segment, in order to conform more closely to the heater head cylinder and thus increase isotope packing density as shown in Fig. 6(b). This is desirable to reduce size and heat source/heater head insulation mass. Figure 7 depicts heat source/heater head and engine detail corresponding to a dual engine installation.

When the engine is running, heat continuously evolving from the decaying isotope is transferred to the working fluid in the hot end and removed via the engine low temperature loop which is physically in close proximity to the hot end. Borrowing from earlier practice the heat source/aeroshell heater head is enclosed by multiple layers of metallic foil insulation which will melt and provide a radiative path from the heater head if the engine fails. Further definition, however, will be needed to ensure reentry safety, since current GPHS container designs utilize a fusible link which allows the blocks to be ejected and dispersed. In this concept the FSA releases the GPHS blocks after the multilayer foil has been stripped away.

Figure 8 depicts the dual 500 W, fully redundant FPSE installation attached to the rover vehicle. The radiator basket enclosing the heat source/engine assembly contains two cooling loops. Performance and mass breakdown for this system is summarized in Table 5.

MARS BACKGROUND SINK TEMPERATURE

The specific power of the Mars Brayton and Stirling cycle conceptual designs are lower than those designed for LEO applications because the thermal background seen on Mars surface is considerably higher than the 220 K equivalent sink temperature of LEO. For example, the range of Mars atmosphere temperatures measured by Viking lander was 190 to 240 K. IR measurements of surface temperatures observed during the Viking primary mission ranged from 130 to 290 K. Bearing in mind that radiators would probably have to be mounted on the bottom of the vehicle (the upper surface must remain unobstructed for sensors, communication antennae, etc.) the radiator heats the ground beneath the vehicle which returns an elevated surface temperature. For a stationary vehicle this elevated background could easily exceed the ambient background by 20 to 30 K. Considering the above factors an equivalent sink temperature of 290 K was selected for design purposes.

EFFECT OF ELEVATED BACKGROUND TEMPERATURE

An elevated temperature background has a major impact on the performance of a Brayton cycle. As background temperature is raised, radiator area must be increased to reject the same amount of waste heat or the cycle temperature ratio must be reduced to elevate the radiator temperature. System mass is significantly affected. This can be illustrated by considering the component scaling data for the original BIPS and its cycle performance variation as temperature ratio is reduced (Fig. 5). From this data, mass breakdowns of (mini-BRU) system design points sized to provide the same output power over the range of background temperatures (design points optimized for minimum mass at fixed turbine inlet temperature) can be plotted (Fig. 9). The data illustrates how system mass, mainly due to increased radiator area and heat source which must be added as cycle efficiency falls, would rise as background temperature is elevated from 216 to 290 K.

The mass penalty comes from the increased radiator area which is required to reject heat at reduced delta T. Figure 10 shows area required (emissivity assumed is 0.8) to radiate one thermal kilowatt at two rejection temperatures, 330 and 550 K, as background temperature varies from 210 to 290 K. The radiator area required for a 330 K rejection temperature, which corresponds to the mean effective temperature of the MRSR Brayton radiator, changes by a factor of 2.6, while the area required for a 550 K radiator changes less than 10 percent.

On the other hand a thermoelectric system, which rejects heat at a temperature of 550 K, shows a much smaller change over the same range of sink temperatures. Figure 11 shows the effect of cold-junction temperature on RTG weight and power, system efficiency and specific power for a thermoelectric system [11] similar to the Mod-RTG (a figure of merit of $0.846 \times 10^{-3}/°C$ is assumed for the calculation). For a given fin geometry and radiator area, elevating sink temperature from 20 K (interplanetary space) to 290 K (Mars or lunar surface) raises the cold-junction temperature by only 8 K; resulting in an overall performance reduction of only one percent.

RESULTS AND CONCLUSIONS

System mass breakdowns showing key subsystems for the four system concepts are shown in Fig. 12. Table 7 presents a summary comparison with respect to power system attributes that would be of most concern to a user, including required isotope inventory in kilograms of enriched PuO_2 and number of GPHS blocks, surface area aboard the vehicle which must remain unobstructed for radiator installation, and effective radiator temperature. On the basis of system mass the FPSE power system shows a 21 percent advantage over its nearest competitor, the Mod-RTG power system. On the basis of isotope inventory, both the FPSE and CBC systems require only about a third the fuel of the Mod-RTG system. Comparison of radiator area shows the Mod-RTG with a 39 percent advantage over the FPSE System. Any one of the comparison bases discussed may be an important driver in concept selection. In general, system mass is the most useful comparison at this early stage of concept identification.

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TABLE 1. - MARS ROVER POWER SYSTEM STUDY - THE REQUIREMENTS

Vehicle mass, kg	842
Power, kWe	
Nominal	0.5 continuous
Peak	2.2
Energy storage for peak power, Wh	350
Power system mass	129
Length of mission BOL to EOM, year	5
Reliability	No single point failure
Technology cutoff date	1992

TABLE 2. - MARS ROVER POWER SYSTEM STUDY - THE ENVIRONMENT

Ambient solar flux (surface), Wm^2	
Nominal	590
Dust storm	20
Maximum background temperature, K	
Surface	290
Sky	240
Atmosphere on surface	
Composition	95 percent CO_2
Ambient temperature, K	130 to 290
Ambient pressure, mB	6 to 15
Wind velocity, m/sec	7 to 50
Dust mean particle size, μm	
Suspended	2.5
Storm	100
Saltation height, cm	20

TABLE 3. - MARS ROVER POWER STUDY - GPHS-RTG CHARACTERIZATION

Performance	
Number pf GPHS blocks	39
EOM watts per block	220.6
Heat into converter (5 percent loss assumed), Watts thermal	8 173
At temperature, K	1 273
Cold junction temperature, K	586
Radiator temperature, K	540
Area BOL, m^2	2.0
Converter efficiency, percent	6.13
EOM output power, We	500
Mass breakdown	
GPHS blocks	57
Generator housing (includes radiator)	45
Power conditioning and controls	10
Energy storage, 350 Wh	17
Structure and miscellaneous	26
Total, kg	155

TABLE 4. - MARS ROVER POWER STUDY - MOD RTG CHARACTERIZATION

Performance	
Number pf GPHS blocks	32
EOM watts per block	220.6
Heat into converter (5 percent loss assumed), Watts thermal	6900
At temperature, K	1273
Cold junction temperature, K	600
Radiator temperature, K	598
Area BOL, m^2	0.92
Converter efficiency, percent	7.5
EOM output power, We	500
Mass breakdown	
GPHS blocks	46.4
Generator housing (includes radiator)	23.9
Power conditioning and controls	10.3
Energy storage, 350 Wh	17
Structure and miscellaneous	13
Total, kg	112.2

TABLE 5. - MARS ROVER POWER STUDY - BRAYTON DIPS CHARACTERIZATION

Performance	
Number of GPHS blocks	11
EOM watts per block	220.6
Heat into converter (5 percent loss assumed), Watts thermal	2305
At temperature, K	1105
Cycle temperature ratio	3.5
Fraction of carnot achieved	0.39
Engine efficiency, percent	24
Alternator efficiency, percent	90
Radiator temperature, K	446 to 308
Area BOL, m^2	4.4
EOM output power, We	500
Mass breakdown	
Heat source assembly (HSA)	
GPHS blocks	15.8
Container	5.2
Converter (dual PCU with recuperator)	45
Radiator	27
Power conditioning, 20 kg/kWe	10
Energy storage, 350 Wh	17
Structure and miscellaneous	18
Total, kg	138

TABLE 6. - MARS ROVER POWER STUDY - STIRLING DIPS CHARACTERIZATION

Performance	
Number pf GPHS blocks	11
EOM watts per block	220.6
Heat into converter (5 percent loss assumed), Watts thermal	2305
At temperature, K	1105
Cycle temperature ratio	3.5
Fraction of carnot achieved	0.40
FPSE/linear alternator efficiency, percent	22
Radiator temperature, K	427
Area BOL, m^2	1.5
EOM output power, We	500
Mass breakdown	
GPHS blocks	15.8
Insulation package and heater head MODS	12
Converter (dual FPSE and linear alternator)	10.4
Radiator	10.6
Power conditioning, 20 kg/kWe	10
Energy storage, 350 Wh	17
Structure and miscellaneous	12
Total, kg	87.8

TABLE 7. - COMPARISON OF RADIOISOTOPE POWER SYSTEMS

[Including power conditioning and energy storage at 500 W for 5 years (from BOL) MRSR mission.]

	System mass, 5 years	Thermal to electrical efficiency percent	Number of GPHS blocks required	Isotope fuel required, kg	Radiator area required, m^2	Radiator temperature, K
GPHS - RTG	155	6	39	23.8	2.0	540
MOD RTG	112	7.6	32	19.6	0.92	598
Brayton, dual PCU	138	22	11	6.73	4.4	446 to 308
Stirling, dual PCU	88	22	11	6.73	1.5	427

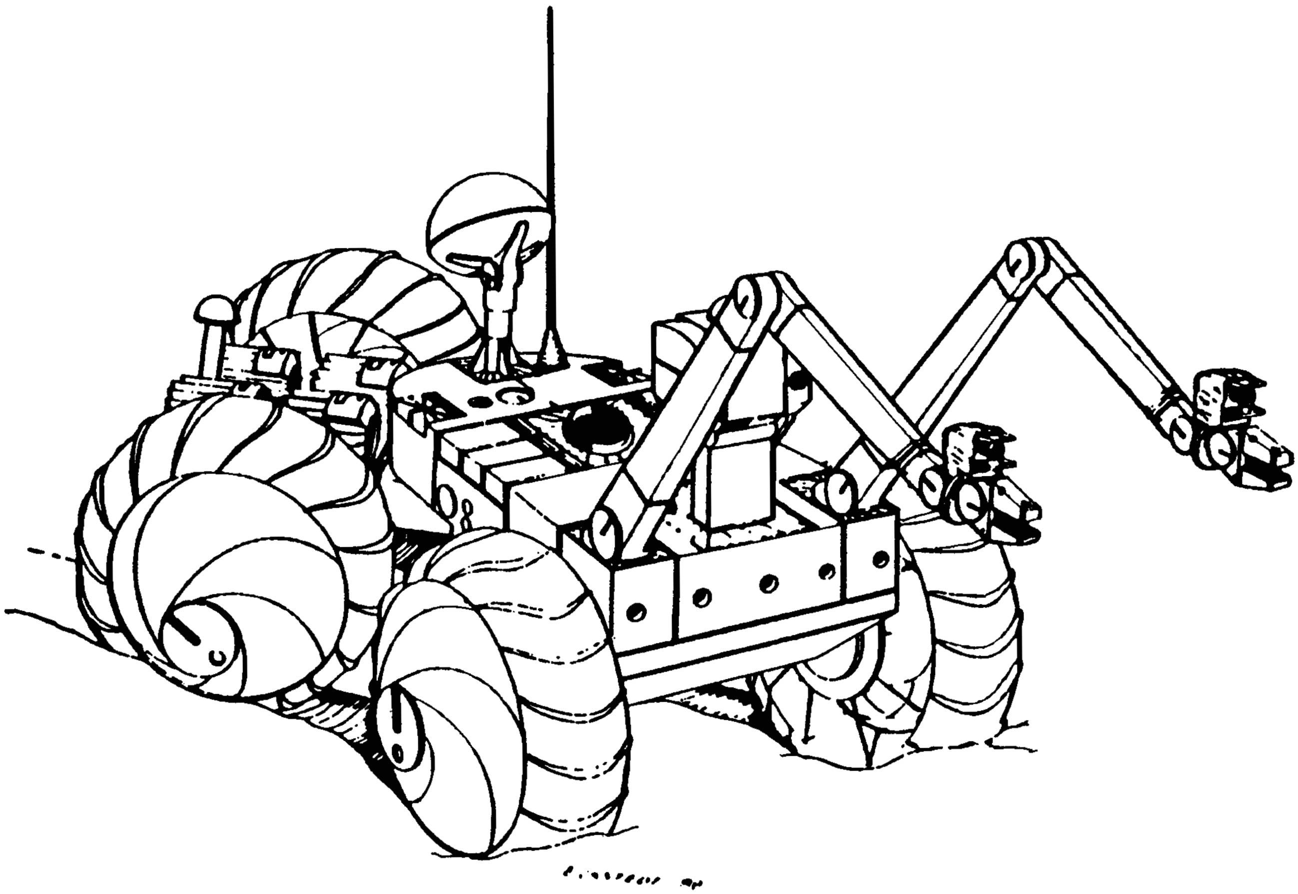


FIGURE 1. - MARS ROVER VEHICLE.

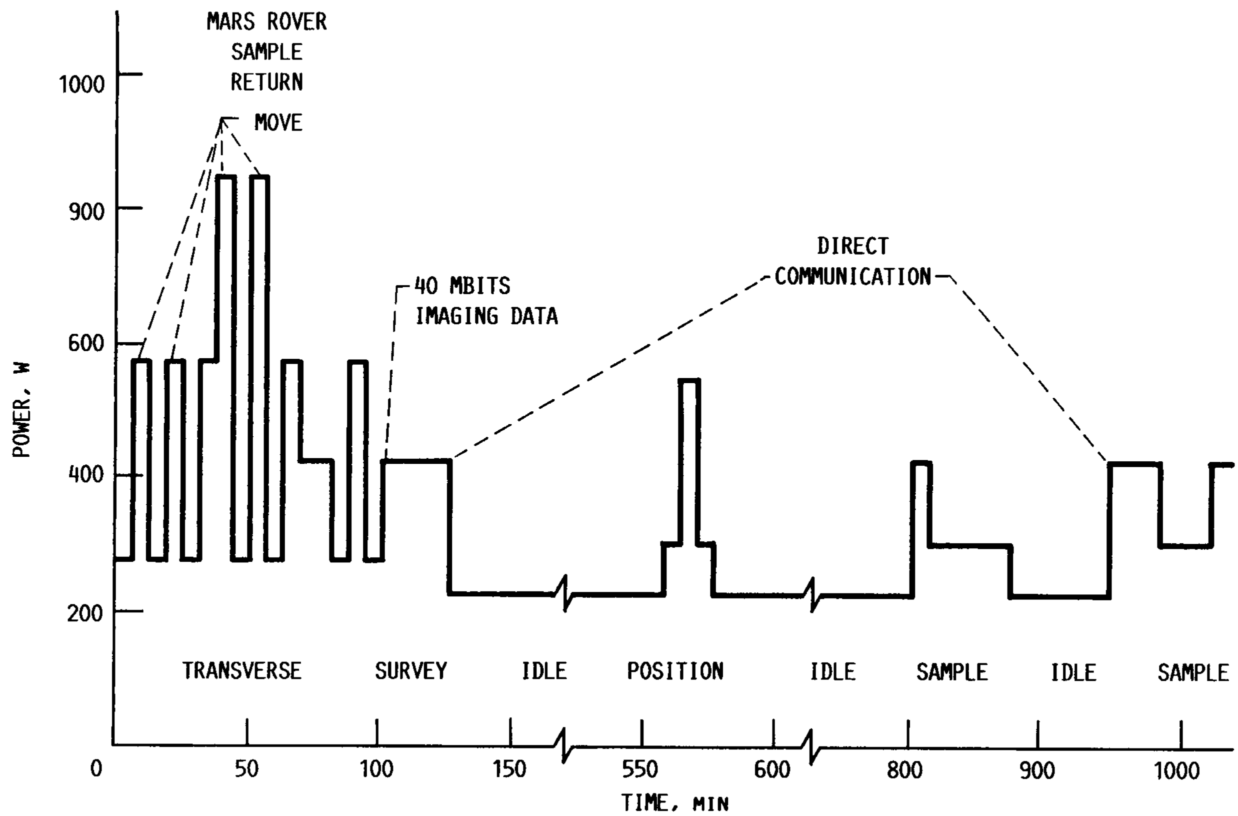


FIGURE 2. - TYPICAL POWER PROFILE FOR SURFACE OPERATIONS. DISTANCE TRAVERSED, 25 m; NUMBER OF SAMPLES COLLECTED, 2.

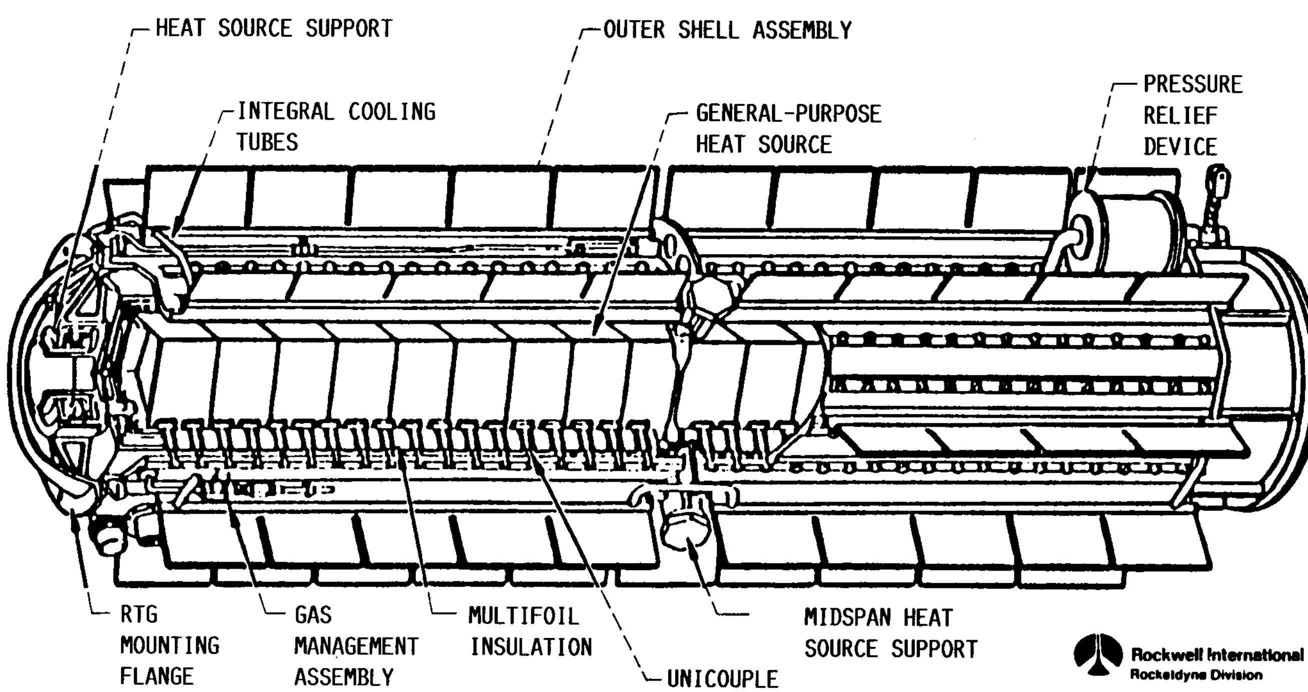


FIGURE 3. - GENERAL-PURPOSE HEAT SOURCE RTG.

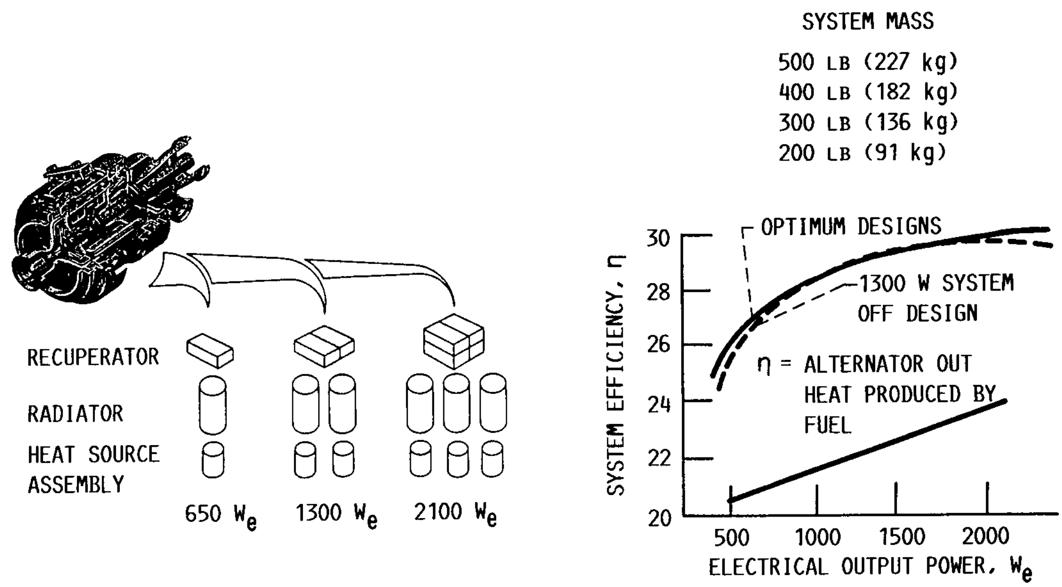


FIGURE 4. - MODULAR MINI-BRU BIPS (FROM REF. 9).

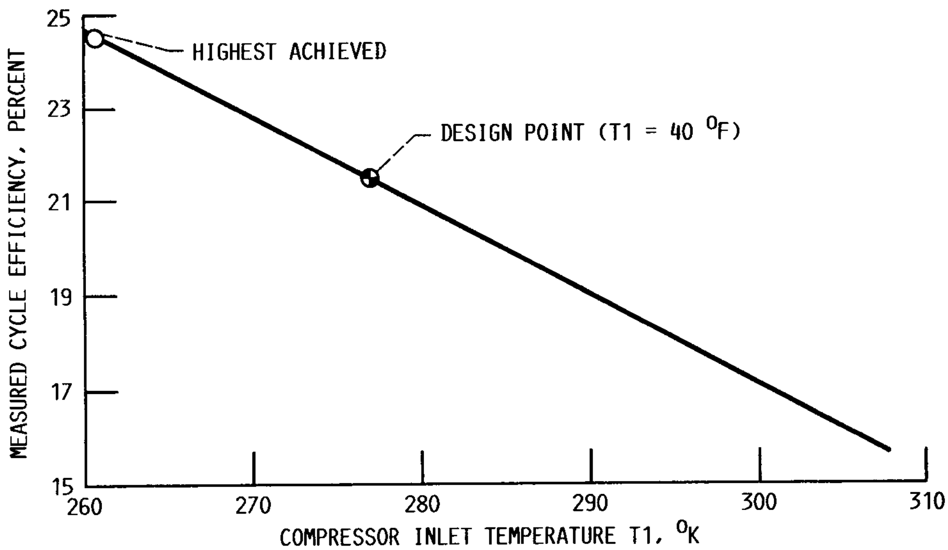
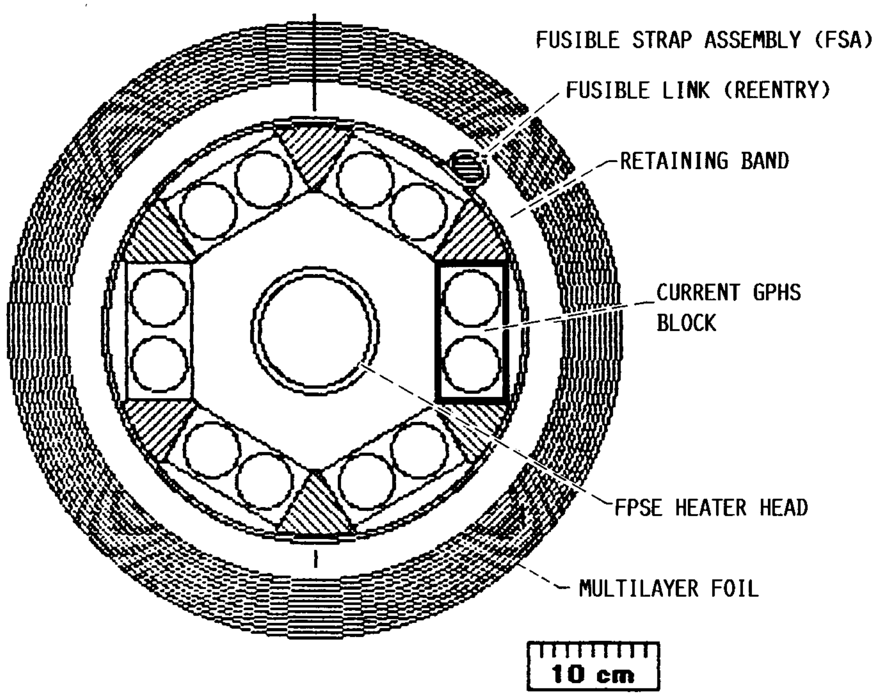
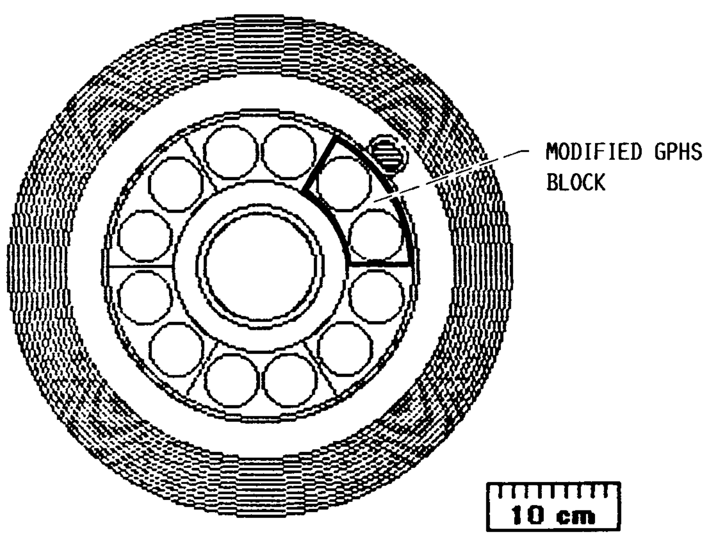


FIGURE 5. - BIPS CYCLE EFFICIENCY (FROM REF. 9).



(A) REFERENCE DESIGN WITH CURRENT GPHS AEROSHELL.



(B) COMPACT DESIGN WITH MODIFIED GPHS AEROSHELL.

FIGURE 6. - CONCEPTS FOR DIRECT INTEGRATION FPSE HEATER HEAD WITH GPHS.

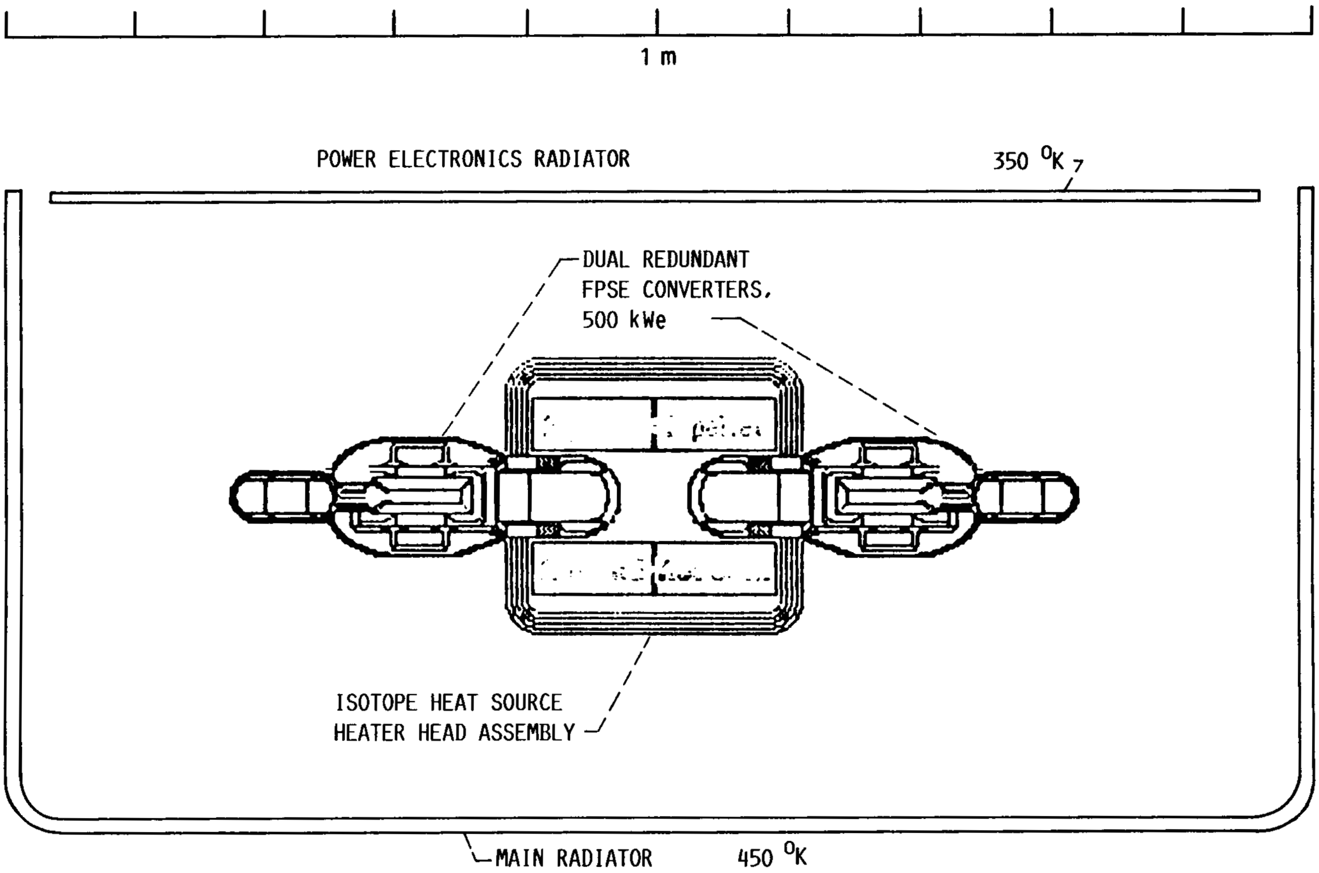


FIGURE 7. - STIRLING DIPS FOR ROVER VEHICLE.

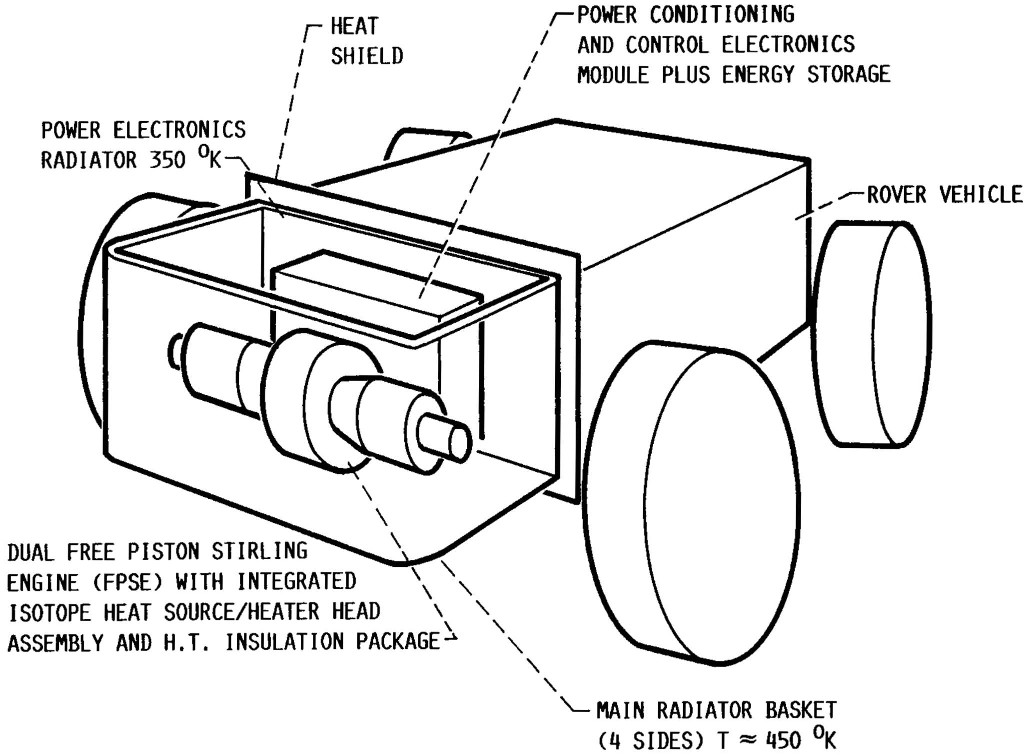


FIGURE 8. - STIRLING DIPS FOR ROVER VEHICLE.

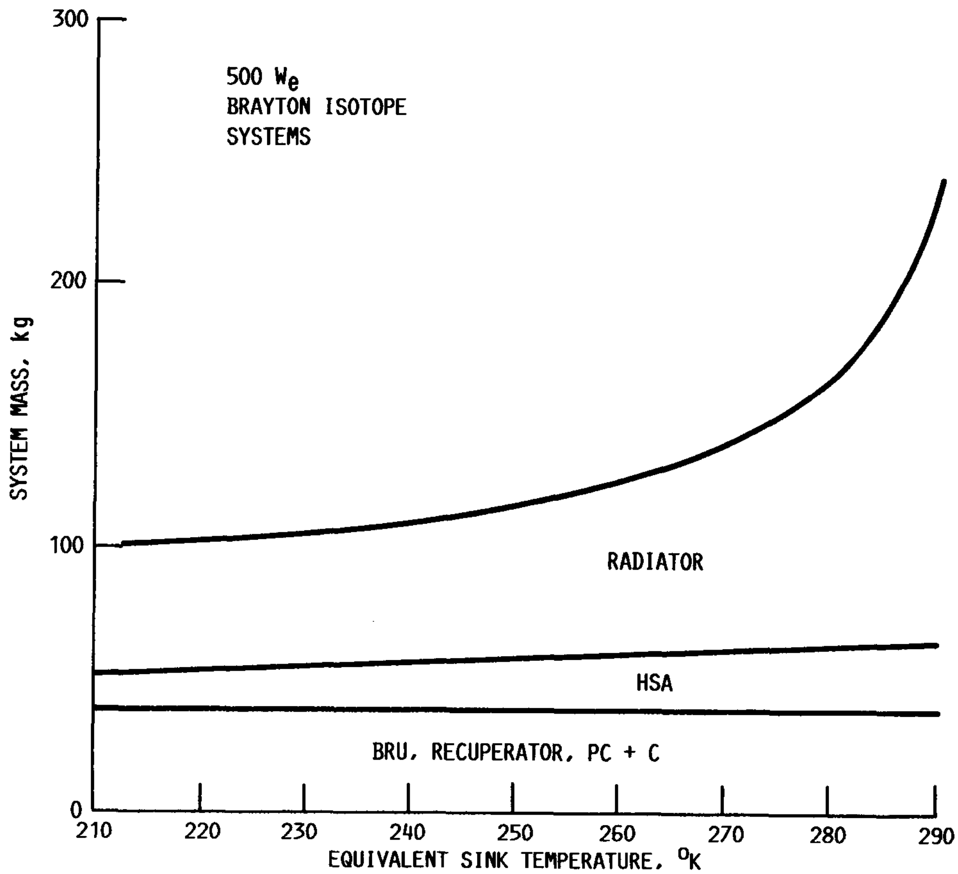


FIGURE 9. - SENSITIVITY OF 500 W_e (MINI BRU) BIPS TO ELEVATED SINK TEMPERATURE (BASED ON DATA FROM REF. 9).

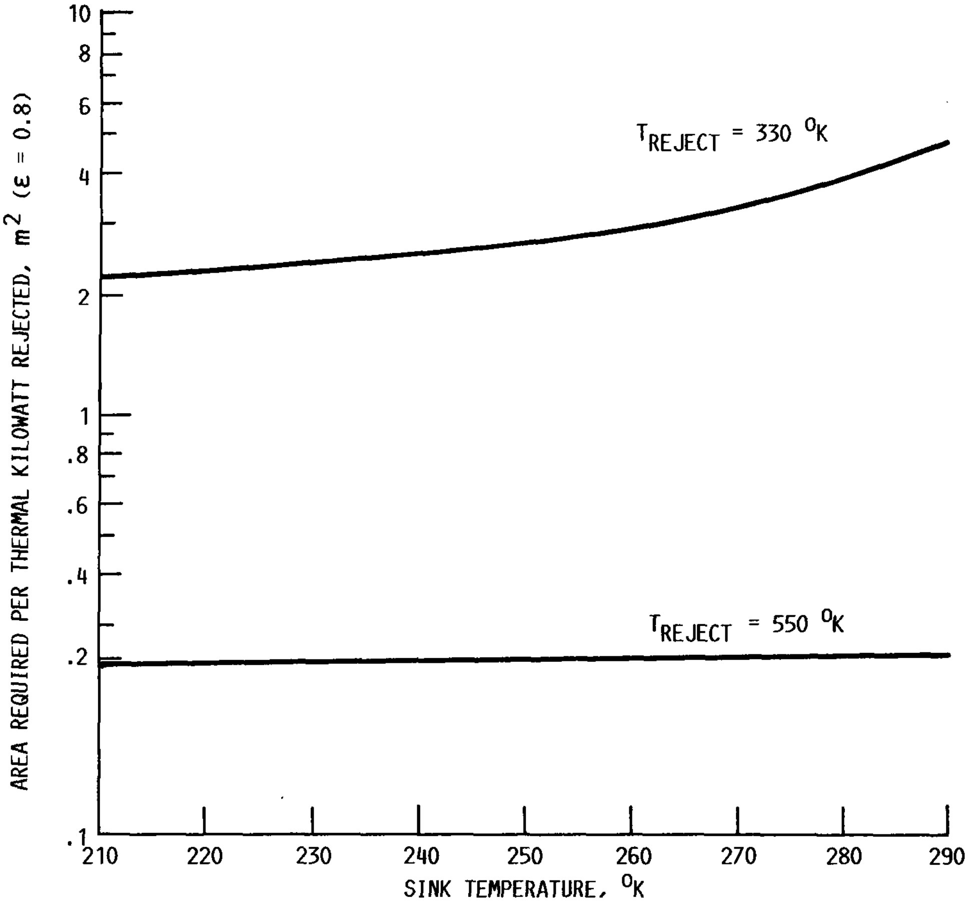


FIGURE 10. - RADIATOR AREA REQUIRED TO REJECT WASTE HEAT.

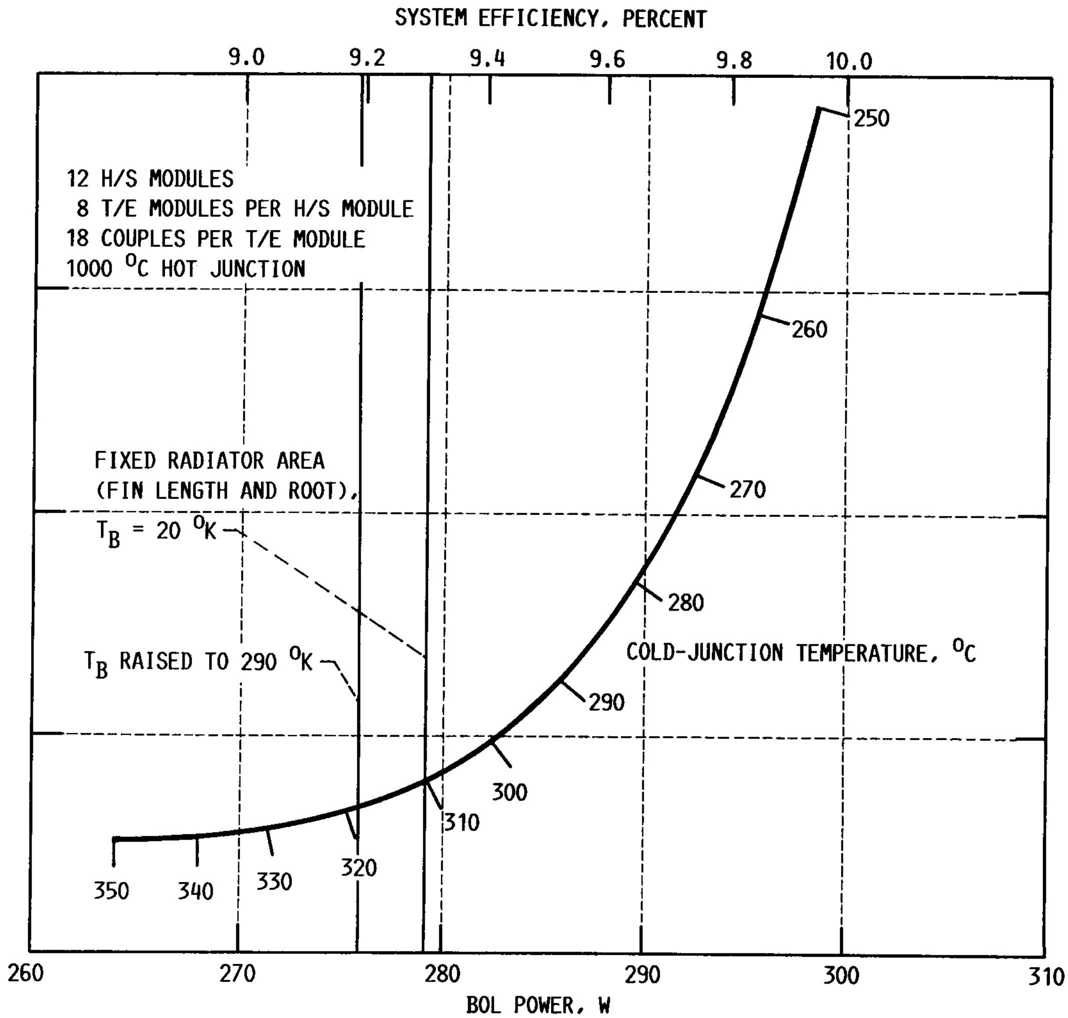


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FIGURE 11.- ELEVATED SINK TEMPERATURE EFFECT ON THERMOELECTRIC ISOTOPE SYSTEMS.

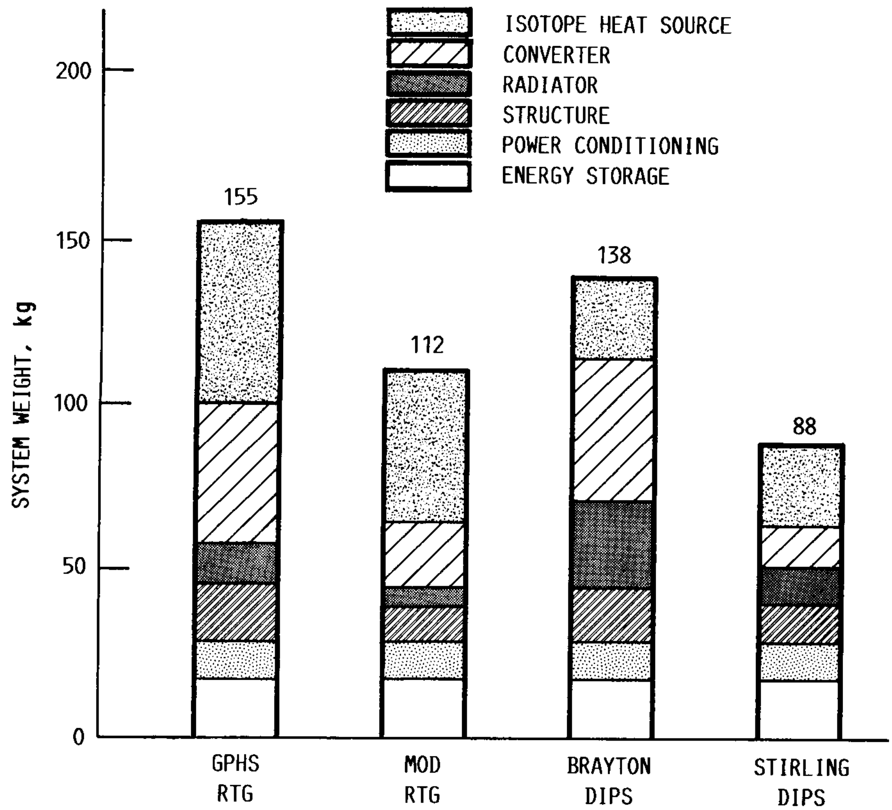

FIGURE 12. - POWER: 0.5 kWe/2.5 kWe PEAK SINK TEMPERATURE, 290 ^{o}K.

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16. Abstract

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