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THERMAL AND ELECTRICAL ANALYSIS OF MARS ROVER RTGs

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ABSTRACT

The RTG designs described in the preceding paper in these proceedings were analyzed for their thermal and electrical performance. Each analysis consisted of coupled thermal, thermoelectric, and electrical analyses, using Fairchild-generated specialized computer codes. These were supplemented with preliminary structural and mass analyses. For each design, various cases representing different operating conditions (water-cooled/radiation-cooled, BOM/EOM, summer/winter, day/night) and different thermoelectric performance assumptions (from conservative to optimistic) were analyzed; and for every case, the heat flow rates, temperatures, and electrical performance of each layer of thermoelectric elements and of the overall RTG were determined. The analyses were performed in great detail, to obtain accurate answers permitting meaningful comparisons between different designs. The results presented show the RTG performance achievable with current technology, and the performance improvements that would be achievable with various technology developments.

INTRODUCTION

The preceding paper [1] in these proceedings described generic designs of RTGs to power the Mars Rover vehicle of the Mars Rover Sample Return (MRSR) mission under study at JPL. Two specific designs were described: one based on standard unicouples, large assemblies of which have demonstrated stable performance in very lengthy space and ground operations (>100,000 hrs); and one based on standard multicouples, which have demonstrated stability in much shorter tests (6000 hrs). The basic design concepts described in that paper are also adaptable to thermoelectric elements containing a variety of geometric and materials improvements.

The present paper presents mass breakdowns and describes detailed thermal, thermoelectric, and electrical analyses of both 250-watt and 125-watt RTG designs employing standard unicouples and demonstrated materials properties. It then proceeds to apply the same analyses to RTG designs employing thermoelectric elements of postulated advanced geometries and/or materials. Its purpose is to define the RTG parameters achievable with current technology, and to determine how much those parameters could be enhanced if various items of new technology could be successfully developed. When this information

is coupled with an assessment of the difficulty, cost, and success probability of developing those items of new technology, it provides a basis for informed decisions about optimum program strategy for given schedule and budget limits.

MASS BREAKDOWN OF BASELINE RTG

The "baseline" Mars Rover RTG design is described in the preceding paper [1], and depicted there in Figures 10 and 11. It contains eighteen General Purpose Heat Source (GPHS) modules and 576 standard unicouples. It is designed for a nominal power output of 250 watts EOM, based on demonstrated thermoelectric performance levels. Its mass breakdown, based on a non-optimized radiator fin design, is presented in the left half of Table 1. The right half of the table shows the corresponding breakdown for the existing Galileo RTG, to ensure that all required RTG components have been properly accounted for in the Rover RTG mass breakdowns.

Table 1. Mass of Baseline RTG Versus Galileo RTG

RTG MASS BREAKDOWN (kg)	ROVER RTG BASELINE DESIGN	GALILEO RTG
HEAT SOURCE (33.9/36.1kg)		
GPHS MODULES (18/18)	26.05	26.05
FUEL (PuO ₂)	10.73	10.73
CAPSULES (V)	4.21	4.21
GRAPHITES	11.11	11.11
H.B. CANISTER (Mo)	0.77	0.00
SIDE WALLS	2.21	----
BELLOWS	0.11	----
END CAPS AND LOAD SPREADERS	1.45	----
H.S. STRUCTURAL SUPPORTS	3.94	4.05
GRAPHITE PRESSURE PLATES	0.42	0.50
LOAD STUCCO-ZIRCONIA	0.27	0.34
BELLEVILLE SPRINGS (Ti)	2.31	0.51
OTHER PRELOAD HARDWARE	0.84	1.09
MID-SPAN SUPPORT ASSEMBLY	----	0.94
CONVERTER (24.9/25.0kg)		
ELECTRICAL CIRCUITS	7.74	7.55
TE ELEMENTS (576/572)	5.43	5.40
TE FASTENERS AND SEALS	1.09	1.05
ALUMINA INSULATORS	0.88	0.84
ELECTR. CONNECTORS + TERMINALS	0.34	0.20
MULTIFOL INSULATION (Mo/Duquartz)	5.94	7.18
SIDES	5.26	5.53
ENDS	0.48	0.55
SUPPORT STRUCTURE	----	1.09
RTG HOUSING (40)	5.43	4.17
SIDE WALL (0.050"/0.040")	7.01	5.47
COVERS & BOLTS	0.68	0.81
RESISTANCE THERMOMETER	0.30	0.30
GAS MGMT. ASSEMBLY	0.16	0.16
PRESSURE RELEASE DEVICE	----	0.43
RADIATOR	2.78	3.00
FINS (Si)	2.38	1.94
AUXILIARY COOLANT MANIFOLDS	0.25	0.26
EMISSIVITY COATING	0.15	0.15
MISCELLANEOUS ELEMENTS	----	0.63
TOTAL RTG MASS (kg)	58.67	56.04

The left column of Table 1 shows that the baseline RTG has a total mass of 58.7 kg. As shown, most (58%) of that mass is in the heat source rather than the converter, and most of that (77%) resides in the heat source modules. It is also noteworthy that the heat source canister, which enables operation of the RTG in the Martian atmosphere, has a mass of 3.8 kg.

The right half of Table 1 shows the corresponding mass breakdown for the existing Galileo RTGs. As seen, the baseline Rover RTG, with its non-optimized radiator fins, is 4.6% heavier than the Galileo RTG. A major part of that difference (3.77 kg) is due to the canister needed for Mars operations. The other subsystems have very similar masses in the two RTGs.

MASS OF HALF-LENGTH RTG

The preceding design assumed that the Rover's 500-watt power requirement would be met by two 250-watt RTGs. For ease of integration, it may prove preferable to employ four 125-watt RTGs, even though these would have a lower efficiency and lower specific power, because of increased end-section heat losses and masses. To assess that option, the reduction in efficiency and specific power must be quantified, to support the Rover design trade-off.

Table 2 presents a mass comparison between the two options. For ease of comparison, the table presents masses not for the single RTGs but for the full set of RTGs required to produce 500 watts. The basic design of the half-length RTG is essentially the same as that of the full-length RTG. The only change, besides the 50% reduction in the number of heat source modules and number of uncouple rings, is a decrease in the wall

thickness of the RTG housing from 0.090" to 0.060", and a reduction from three parallel Belleville springs to one. These changes from the full-length unit are made possible because that the half-length housing is subjected to lower bending moments under traverse loads, and the half-length heat source stack can be held together with only about one fourth the axial preload.

Table 2 shows that the use of four short RTGs instead of two long ones leads to a doubling of the mass of the RTG end sections, including the bellows, graphite pressure plates, load studs, zirconia insulators, other preload hardware, multifoil end insulation, housing ends and covers, and of the mass of the resistance thermometer, gas management assembly, and auxiliary coolant manifolds. In addition, there is also a significant increase in the mass of the canister end caps and load spreaders and of the radiator fin extensions. The total mass addition for the short-RTG option add up to 12.3 kg. But these additions are offset by reductions in the mass of the Belleville springs and of the RTG housing side wall totaling 5.1 kg. Thus, the use of four short RTGs leads to a net mass increase of only 7.2 kg or 6.2%.

MASS OF MULTICOUPLER RTG

Tables 1 and 2 presented the mass summaries of the uncouple RTGs depicted in Figures 10 and 11 of the preceding paper [1]. Table 3 presents the mass summary of the multicoupler RTG depicted in Figures 13 and 14, and compares it to that of the baseline uncouple RTG.

The two RTGs have the same EDM power goal, 250 watts per RTG. The uncouples and

Table 2. Mass of "250-W" RTGs Versus "125-W" RTGs

RTG MASS BREAKDOWN (kg)	TWO 250-W RTGS	FOUR 125-W RTGS	Δ
HEAT SOURCE			
GPMS MODULES (18/9)			
FUEL (PuO ₂)	21.46	21.46	0
CAPSULES (H)	0.42	0.42	0
GRAPHITES	22.22	22.22	0
H.S. CANISTER (Mc)			
SIDE WALLS	4.42	4.42	0
BELLOWS	0.22	0.44	0.22
END CAPS AND LOAD SPREADERS	2.90	4.54	1.74
H.S. STRUCTURAL SUPPORTS			
GRAPHITE PRESSURE PLATES	1.04	2.08	1.04
LOAD STUDS-ZIRCONIA	0.54	1.08	0.54
BELLEVILLE SPRINGS (T)	4.62	2.20	-2.42
OTHER PRELOAD HARDWARE	1.68	3.36	1.68
CONVERTER			
ELECTRICAL CIRCUITS			
TE ELEMENTS (576/280)	10.86	10.86	0
TE FASTENERS AND SEALS	2.18	2.40	0.22
ALUMINA INSULATORS	1.76	1.76	0.00
ELECTR. CONNECTORS + TERMINALS	0.68	0.60	-0.12
MULTIFOIL INSULATION (Mc/Quartz)			
SIDES	10.52	10.52	0
ENDS	1.36	2.72	1.36
RTG HOUSING (Al)			
SIDE WALL (.090"/.060")	13.68	10.44	-2.64
END SECTION	0.34	1.68	0.94
COVERS	1.98	3.92	1.98
RESISTANCE THERMOMETER	0.60	1.20	0.60
GAS MGMT. ASSEMBLY	0.32	0.64	0.32
RADIATOR			
FINS (SiB)	4.76	5.72	1
AUXILIARY COOLANT MANIFOLDS	0.50	1.00	0.50
EMISSIVITY COATING	0.30	0.40	0.10
TOTAL MASS(kg)	117.54	124.58	7.24

Table 3. Mass of Uncouple RTG Versus Multicoupler RTG

RTG MASS BREAKDOWN (kg)	UNCUPLE RTG BASELINE DESIGN	MULTICOUPLER RTG
HEAT SOURCE		
GPMS MODULES (18/18)		
FUEL (PuO ₂)	10.73	9.54
CAPSULES (H)	4.21	3.74
GRAPHITES	11.11	9.68
H.S. CANISTER (Mc)		
SIDE WALLS	2.21	1.97
BELLOWS	0.11	0.10
END CAPS AND LOAD SPREADERS	1.45	1.45
H.S. STRUCTURAL SUPPORTS		
GRAPHITE PRESSURE PLATES	0.52	0.52
LOAD STUDS-ZIRCONIA	0.27	0.27
BELLEVILLE SPRINGS (T)	2.31	1.27
OTHER PRELOAD HARDWARE	0.64	0.33
CONVERTER		
ELECTRICAL CIRCUITS		
TE ELEMENTS (576/120)	5.43	2.09
TE FASTENERS AND SEALS	1.09	0.49
ALUMINA INSULATORS	0.88	0.88
ELECTR. CONNECTORS + TERMINALS	0.34	0.28
MULTIFOIL INSULATION (Mc/Quartz)		
SIDES	5.26	3.44
ENDS	0.69	0.39
RTG HOUSING (Al)		
SIDE WALL (.090"/.060")	6.64	5.20
END SECTION	0.47	0.38
COVERS	0.98	0.74
RESISTANCE THERMOMETER	0.30	0.30
GAS MGMT. ASSEMBLY	0.16	0.16
RADIATOR		
FINS (SiB)	2.38	1.83
AUXILIARY COOLANT MANIFOLDS	0.25	0.25
EMISSIVITY COATING	0.15	0.15
TOTAL MASS(kg)	69.67	45.26

multicouples both use SiGe legs, but the N-legs of the multicouples that were tested contained a GaP additive, which raises the couples' BOM figure of merit (Z) from 0.00058 K^{-1} to 0.00072 K^{-1} . This increases the BOM material efficiency from 7.86% to 8.57%. As a result, the multicouple RTG can achieve its 250-watt output goal with a lower thermal input power. Therefore, the multicouple RTG design is based on 16 rather than 18 heat source modules, as indicated in the table.

Parenthetically, it should be noted that unicouples with GaP-doped N-legs may also be possible. But these have not yet been built and tested, and their development would not be a trivial material substitution because the two types of TE elements employ substantially different hot-junction bonding methods.

As shown in Table 3, the total mass of the multicouple RTG is 23% lower than that of the baseline RTG (45.3 kg versus 58.7 kg). One of the primary causes of that mass reduction is the smaller number of heat source modules and the resultant shorter RTG length. The shorter length not only has a direct effect on the mass of the RTG housing and the heat source canister, but also results in additional mass savings: the housing wall thickness can be reduced, because the bending moments on the cantilevered structure are lower; and the mass of the Belleville springs is reduced because the axial preload to hold the heat source stack together is lowered.

In addition to the above mass savings, which result from the higher thermoelectric material efficiency, there are also significant savings deriving from the thermal insulation used in the multicouple RTG. Elimination of the quartz cloth spacers between the 60 layers of Mo foil results in direct mass savings and in significant indirect savings. The latter occur because the much thinner insulation package and shorter TE legs reduce the RTG housing diameter from 9.1" to 7.5". The table reflects the net result of all these mass changes.

RTG THERMAL ENVIRONMENT

The various RTG designs were analyzed for the following four combinations of thermal power and cooling:

- 1) Beginning-of-Mission (BOM), assumed to be 3 years after fueling, on a hot (300°K) summer day on Mars, to determine the RTG's maximum hot-junction and clad operating temperatures to confirm that they did not exceed established limits.
- 2) End-of-Mission (EOM), assumed to be 7 years after fueling, on a hot summer day on Mars, to compare the EOM power output with the design goal.
- 3) EOM on a cold (140°K) winter night on Mars, to determine the effect of a cold environment on EOM power.
- 4) BOM with the RTG contained within the Rover's aeroshell and with its fins cooled by an

auxiliary coolant loop, to determine the power output and RTG temperatures during transit to Mars. (The auxiliary cooling tubes were tentatively assumed to have a wall temperature of 100°C).

All the design analyses completed to date were based on the unrealistic assumption that each RTG has an unobstructed view of space and of the Martian ground. In addition, we plan to analyze the case of four 125-RTGs mounted in parallel on top of the Rover, at its four corners, to assess the effect of mutual blockage of their radiators. This is a concept currently favored by some Rover designers at JPL.

THERMAL AND ELECTRICAL ANALYSIS

The analysis described in this section consists of three parts (thermal, thermoelectric, and electrical), which must be performed simultaneously and interactively. The analysis uses specialized computer codes generated by Fairchild to compute the heat flows, temperatures, and electrical parameters of each layer of thermoelectric elements. Inputs include the RTG design, the thermal input power (BOM/EOM), the cooling mode (water/radiation, Mars environment), the TE materials and performance, and the desired electrical output voltage.

The thermal analysis employs a 425-node SINDA model of the axisymmetric RTG to compute the axial variation of the temperatures of the various RTG components. That axial variation is appreciable, because of unavoidable end losses through the structural supports at the top and bottom of the heat source stack. Each heat source module and thermoelectric element layer is discretely represented in the SINDA model.

The computed heat flow through the various TE elements includes the effects of Peltier cooling; ohmic heating in legs, electrodes, and leads; heat converted to electricity (i.e., the TE legs effectively act as heat sinks); and heat losses through multifoil, glass, and quartz yarn wrap.

The thermoelectric analysis includes the effects of measured contact resistances and ohmic losses in legs, electrodes, and leads; experimentally determined effects of long-term material degradation of SiGe; and optimized n/p leg area ratios. Other constraints are that all TE elements in series must have the same current, and all in parallel must have the same voltage.

The analysis uses temperature-dependent values of the Seebeck coefficient, electrical resistivity, and thermal conductivity for the SiGe N and P legs, with a temperature-averaged figure of merit (Z) of 0.000583 K^{-1} at BOM and 0.000548 K^{-1} at EOM for the baseline SiGe unicouple. The thermal and electrical results are used to compute the material efficiency, couple efficiency, and converter efficiency of each layer of TE elements, and the overall RTG system efficiency.

The thermal analysis of the initial design assumed an RTG housing wall thickness of $0.090"$

and eight radiator fins of a trapezoidal cross-section, with a fin root thickness of 0.060", a fin tip thickness of 0.015", and a root-to-tip fin height of 3.0". The fins have an axial length of 42.7". Thus, they extend 2.5" beyond each end of the active thermoelectric zone. These dimensions were based on the results of a preliminary structural analyses described in the next paper at this conference [2].

TEMPERATURE DISTRIBUTION OF BASELINE RTG

Figure 1 shows the BOM temperature distribution (in °C) of the radiation-cooled baseline RTG for a 300°K sink temperature. It shows the temperatures of the RTG end regions, and the temperatures at the center of the RTG. The temperatures shown are for an RTG with uncouples of standard dimensions, except that the cross-sectional areas of their SiGe legs have been reduced by 9% from the corresponding values in the Galileo RTG. This was done in order to take full advantage of the uncouples' maximum temperature capability.

Figure 1. BOM Temperature Distribution (°C) in Baseline RTG

The figure shows the maximum temperatures of the iridium (1172°C), the graphite heat source surface (1087°C), the molybdenum canister (1058°C), the SiGe hot junction (996°C) and cold junction (293°C). Of particular interest are the maximum temperatures of the zirconia insulators (1005°C), the Inconel support studs (588°C), the titanium springs (217°C), and the aluminum

housing (272°C), since their mechanical properties and creep characteristics are strong functions of temperature.

To illustrate the approach used in the thermal, thermoelectric, and electrical analyses of the various RTG designs, the BOM results for the baseline RTG radiating to a 300°K sink are presented in detail in Figures 2, 3, and 4. (Similar detailed results were generated for each design option and each environment investigated.)

AXIAL VARIATION OF HEAT FLOW RATES

The BOM temperatures shown in Figure 1 result in the axial variation of heat flow rates to and from each ring of thermoelectric uncouples and their associated converter sections shown in Figure 2.

Figure 2. Axial Variation of Heat Flow Rates

The numbers at the right edge of the figure show the summed heat flows for the whole RTG. As can be seen, this RTG design has a thermal efficiency of $3874/4396 = 88\%$. The 97-watt difference between the 4396 watts generated by the fuel and the 4299 watts flowing to the converter represents the axial heat loss from the ends of the heat source stack; and the 425-watt difference between the heat flow to the converter and the 3874 watts flowing to the TE legs represents the heat losses through the thermal insulation and quartz yarn wrap surrounding the TE elements.

The 292-watt difference between the heat flows to and from the TE legs (curves 4 and 5) represents the gross electrical power output; and the 278-watt difference between the heat flows to and from the converter (curves 2 and 3) represents the net electrical power output, after lead losses.

AXIAL TEMPERATURE PROFILES

Figure 3 depicts the axial temperature variations in the RTG. The heat losses from the end of the heat source stack result in the depicted temperature profiles of the fuel capsule clads, the modules' aeroshell surfaces, the canister, and the uncouple hot junctions. The figure also shows the axial temperature variations of the cold junctions, the fin root, and the fin tip.

The figure shows six temperature drops between the various curves. The first ($\sim 85^{\circ}\text{C}$) represents the drops inside the heat source modules, across the graphitics and helium gaps. The second ($\sim 29^{\circ}\text{C}$) is the drop across the helium gap to the canister, and the third ($\sim 62^{\circ}\text{C}$) is across the vacuum gaps and through the TE heat collectors. The fourth (703 to 728°C) is the temperature drop across the SiGe TE legs. As can be seen, this is the largest of the drops. It is the only one that makes a useful contribution in actually generating electrical power. All the other temperature drops represent thermodynamic losses. The fifth drop ($\sim 29^{\circ}\text{C}$) represents the thermal resistance of the uncouple's cold-end and the loss for circumferential heat transport

through the aluminum housing to the nearest fin; and the sixth drop (44°C) is that due to radial heat flow through the fin itself.

The depicted variation of the hot-junction temperatures would result in a significant performance loss, were it not balanced by a similar convex profile of the cold-junction temperatures. This was achieved by extending the radiator fins beyond the active length of the RTG, as mentioned earlier. In fact, the temperature drop-off of the cold junctions near the RTG ends is greater than that of the hot junctions. This explains why the uncouples' heat flow rates, power outputs, and efficiencies are actually higher at the ends of the RTG than at the center, as shown in Figures 2 and 4.

AXIAL VOLTAGE AND EFFICIENCY PROFILES

The temperature variations shown in Figure 3 result in the uncouple voltage and efficiency profiles displayed in Figure 4. The averaged values for the RTG are shown at the right edge of the figure. The 0.010-volt difference between the gross and net couple voltages represents the electrical losses in the leads.

The difference between the 7.86% material efficiency and the 7.52% couple efficiency is the effect of ohmic losses in the electrodes. The difference between the couple efficiency and the 6.46% converter efficiency shown in the figure reflects the electrical losses in the leads and the thermal losses through the multifoil side

insulation and the quartz yarn wrap. As seen, the axial variation of the efficiencies is quite small. In fact, the couples near the ends have a higher efficiency because of their lower cold-junction temperatures, which result from axially extending the radiator fins beyond the thermoelectric region. The 0.55-percentage-point difference between the overall converter efficiency and the 6.32% system efficiency reflects the heat losses through the RTG ends.

Figure 4 shows that there are substantial differences between the BOM material efficiency, couple efficiency, converter efficiency, and system efficiency. This highlights the importance of specificity in reporting RTG efficiencies.

EFFECT OF COOLING MODE ON RTG PERFORMANCE

Table 4 illustrates the effect of the cooling mode on the BOM temperature distribution, efficiencies, and output of the baseline RTG. The left column shows the results for the water-cooled RTG, representative of the launch and orbital transit conditions; the middle column presents the corresponding results for the radiation-cooled RTG, representative of operations on a Martian summer day (300°K); and the right column shows similar results for a Martian winter night (140°K).

Table 4. Effect of Cooling Mode on BOM Performance of Baseline RTG

Cooling Mode	Convective	Radiative	
Auxiliary Coolant Wall Temp., °C	100	—	—
Radiator Sink Temperature, °K	300	300	140
Maximum Temperature, °C:			
Fuel Clad	1069	1172	1166
H.S. Surface	992	1087	1080
Canister	957	1058	1051
TE Hot Junction	888	996	988
TE Cold Junction	155	293	284
Fin Root	117	264	254
Fin Tip	94	220	210
Efficiency, %:			
Material	7.97	7.86	7.88
Couple	7.51	7.52	7.53
Converter	6.50	6.46	6.48
System	6.37	6.32	6.32
RTG Output:			
Current, amp	9.26	9.26	9.26
Voltage	30.2	30.0	30.1
Power	280	278	278
Specific Power, watt/kg	4.77	4.74	4.74

The left and middle fin root temperatures are used to compute the differential thermal expansion of the aluminum housing, which dictates the required Belleville spring travel of 0.099". This thermal expansion difference results in a relaxation of the axial spring load. Consequently, the lateral G-loads that the heat source stack can tolerate are 40% lower on Mars than during launch.

Comparison of the three sets of efficiencies and RTG outputs show almost identical results for the three cases. This is because, for a fixed design, changes in the cold-junction temperatures

cause similar changes in the hot-junction temperatures; and because the temperature-integrated thermoelectric properties of SiGe are not very sensitive to cold-junction temperature. As a result, the power output of the RTG is quite insensitive to thermal environment, so that the RTG can produce essentially the same power during launch and during transit to Mars as that generated on Mars in either summer or winter. We therefore conclude that the RTG can deliver full operating power during the water-cooled cruise to Mars; and that the power output of the radiatively cooled RTG is essentially independent of the Martian temperature.

EFFECT OF LIFETIME ON RTG PERFORMANCE

Table 5 illustrates the change from BOM (3 years after fuel encapsulation) to EOM (7 years after fuel encapsulation) on the output of the radiation-cooled baseline RTG with a 300°K sink temperature. The left column displays the BOM temperatures and output voltage, current, power, and efficiencies of the RTG, and the right half shows the corresponding EOM values.

Table 5. Effect of Mission Time on Performance of Baseline RTG

Mission Time	BOM	EOM
Years After Fuel Encapsulation	3	7
Years of Full-Temperature TE Operation	1	5
Thermal Power, watts	4396	4261
Maximum Temperature, °C:		
Fuel Clad	1172	1152
H.S. Surface	1087	1065
Canister	1058	1037
TE Hot Junction	996	975
TE Cold Junction	293	289
Fin Root	264	260
Fin Tip	220	218
Efficiency, %:		
Material	7.86	7.41
Couple	7.52	7.12
Converter	6.46	6.13
System	6.32	6.01
RTG Output:		
Current, amp	9.26	8.52
Voltage	30.0	30.0
Power, watt	278	256
Specific Power, watt/kg	4.74	4.37

The biggest cause of power output change during that period is the decay of the radioisotope fuel, which has a half-life of approximately 89 years. As a result, the original 4500-watt thermal power of the 18-module heat source drops to 4396 watts at BOM and to 4261 watts at EOM. As shown in Table 5, this lowers the maximum clad temperature from 1172°C to 1152°C, drops the maximum hot-junction temperature from 996° to 975°C, and reduces the maximum temperature drop in the SiGe legs from 703°C to 686°C.

This temperature drop reduction lowers the conversion efficiency. The reduced thermal power and reduced efficiency combine to cause a greater-than-proportional reduction in power output. This would be true even if there were no concurrent degradation in thermoelectric

properties of the SiGe. But there is a well-characterized material degradation, primarily because of dopant precipitation. As a result, the system efficiency actually drops from 6.32% to 6.01% and the power output drops from 278 watts to 256 watts, as shown in the table. We therefore conclude that the combined effect of fuel decay and thermoelectric degradation is to reduce the power output by ~8%.

Table 5 shows that the power output of the baseline RTG exceeds the goal of 250 watts EOM, without exceeding the 1000°C hot-junction temperature limit or the 1330°C clad limit.

EFFECT OF RTG LENGTH ON PERFORMANCE

The masses of the two "250-watt" RTGs were compared with those of four "125-watt" RTGs in Table 3. The temperatures, efficiencies, and outputs for the two options are compared in Table 6, both for BOM and EOM.

Table 6. Effect of RTG Length on Performance

Number of HS Modules per RTG	18	9
RTG Length, inches	45.9	20.3
Nominal EOM Power per RTG, watts	250	125
Number of RTGs on Rover	2	4
Mission Time	BOM	EOM
Thermal Power per RTG, watt	4396	4261
Maximum Temperature, °C:		
Fuel Clad	1172	1152
H.S. Surface	1087	1065
Canister	1058	1037
TE Hot Junction	996	975
TE Cold Junction	293	289
Fin Root	264	260
Fin Tip	220	216
Efficiency, %:		
Material	7.86	7.41
Couple	7.52	7.12
Converter	6.46	6.13
System	6.32	6.01
Output of Set of RTGs:		
Current, amp	18.5	17.0
Voltage	30.0	30.0
Power, watt	556	512
Mass of Set of RTGs, kg	117.3	117.3
Specific Power, watt/kg	4.74	4.37

The table shows that the short RTGs also meet their design goal (125 watt EOM per RTG) without exceeding the 1000°C hot-junction temperature limit. It shows that the system efficiency of the short RTG is almost as high as that of the long RTG.

This was not expected, because the four short RTGs have twice as many end sections and obviously have greater heat losses from the ends of their heat source stacks. Evidently, these losses are compensated by their higher converter efficiencies, as shown in the table. Their higher converter efficiency is due to their lower cold-junction temperature (271°C versus 289°C) which results from the greater effectiveness of the axial radiator extensions in the short RTGs. It should be noted, however, that the radiator fin design has not yet been optimized for either the long or the short RTGs.

Table 6 shows that the specific power of the short RTGs is 9% lower than that of the long ones. This is primarily due to their higher mass

rather than lower system efficiency. The difference in specific power between the two options is small enough to make the short RTG option a viable alternative to the baseline design, if the shorter units are indeed easier to integrate with the Rover (e.g., because the shorter RTGs are less prone to block the Rover's sensors and/or antennas). But this conclusion will have to be re-examined after the effect of mutual radiator blockage of multiple RTGs is taken into account.

An additional advantage of the short RTGs is that if one of the four should experience catastrophic failure before the end of the mission, the other three would still supply 75% of the Rover's design power, permitting continued Mars operations on a limited scale.

MULTICOUPLER RTG PERFORMANCE

The preceding paper [1] described basic designs for RTGs employing standard uncouples (UC) and standard multicouples (MC). The multicouple RTG design shown in Figures 13 and 14, with demonstrated MC performance parameters, was subjected to detailed thermal, thermoelectric, and electrical analyses, identical to those performed for the baseline (uncouple) RTG.

The results of those analyses for the two RTGs are summarized in Table 7, which compares their temperatures, efficiencies, output powers, and specific powers. Both cases are for

Table 7. Performance of Multicouple RTG Versus Uncouple RTG

Thermoelectric Elements	Uncouples	Multicouples
Number of Elements	576	128
Number of H.S. Modules	18	16
RTG Length, inches	45.9	41.6
RTG Housing Diameter, inches	9.1	7.5
N-Leg Material	SiGe	SiGe/GaP
Couple Figure of Merit, K ⁻¹	0.00058	0.00072
Number of Fins	6	4
Fin Root Thickness, inch	0.060	0.100
Fin Length, inches	3.0	5.5
Mission Time	BOM	EOM
Thermal Power per RTG, watt	4396	4261
Maximum Temperature, °C:		
Fuel Clad	1172	1152
H.S. Surface	1087	1065
Canister	1058	1037
TE Hot Junction	996	975
TE Cold Junction	293	289
Fin Root	264	260
Fin Tip	220	216
Efficiency, %:		
Material	7.86	7.41
Couple	7.52	7.12
Converter	6.46	6.13
System	6.32	6.01
RTG Output:		
Current, amp	9.3	8.5
Voltage	30.0	30.0
Power, watt	278	256
RTG Mass, kg	58.6	58.6
Specific Power, watt/kg	4.74	4.37

radiation cooling with a 300°K heat sink. The uncouples employed SiGe n- and p-legs, with a BOM figure of merit (Z) of 0.00058. In the case of the multicouples, the n-legs contain a GaP additive, which raises the BOM Z to 0.00072. Both cases employed measured values of contact resistances for their respective TE elements. Because of its higher Z and anticipated higher efficiency, the multicouple RTG used 16 instead of 18 heat source modules.

Table 7 shows very similar temperatures for the RTGs, with two exceptions. The first is that the temperature drop from the cold junction to the fin root is much higher (56°C) in the multicouple-RTG than in the uncouple-RTG (29°C). This is due to the fact that each multicouple rejects much more heat than a uncouple, and that this heat has to flow through a greater distance to reach the nearest fins, since the MC-RTG has only four fins instead of eight. In fact, a separate calculation has shown that the specific power of the MC RTG could be substantially improved by going to an eight-fin design.

The second difference between the two RTGs is that the root-to-tip temperature drop in the fins is appreciable greater (75°C) in the MC RTG than in the UC unit (44°C). This is due to the fins' greater length, which is necessitated by the smaller number of fins.

In spite of these increased temperature drops, the MC RTG shows virtually the same system efficiency the UC RTG. This is due to the use of the GaP additive in the n-legs, which raises the figure of merit from 0.00058 to 0.00072, and the BOM material efficiency from 7.86% to 8.57%. As shown in Table 7, the MC RTG with 16 heat source modules produces 5% less power than the UC RTG with 18 heat source modules. In fact, it falls a little below its 250-watt EOM goal.

The last two lines of Table 7 compare the masses (from Table 3) and the specific powers of the two RTGs. As can be seen, the specific power of the MC RTG is 23% higher than that of the UC RTG. This benefit must be weighed against their lower technological maturity and higher programmatic risk.

EFFECT OF THERMOELECTRIC MATERIAL PROPERTIES

The results thus far were all based on demonstrated thermoelectric properties of the SiGe uncouples and the SiGe/GaP multicouples. The present section examines the effect which improvements of those properties would have on the RTG designs and on their mass and performance. RTGs based on five different material models were analyzed:

1. The first is a JPL model for SiGe, with 78% Si in the hotter 85% of the TE legs and 63% Si in the cooler 15% of the leg. This is the same material model used in our baseline design analysis, and is representative of the uncouples used in the Galileo RTGs. At BOM, it yields a figure of merit of 0.000584 K⁻¹ over a 1000°C-to-300°C temperature range.

2. The second material model employed is designated ITM-197. The material's thermoelectric properties have been confirmed by measurements at independent laboratories, but it has not yet been built into a couple. Its BOM figure of merit 0.000768 K⁻¹.

3. The third material model, designated GE Hybrid, represents the materials used in the multicouples built and tested to date. It was used as the basis for our multicouple design. Its BOM figure of merit (Z) 0.000782 K⁻¹. It has not yet been built into uncouples. Doing so would require development of new bonding techniques.

4. The fourth material model, designated SP-100, represents the thermoelectric performance parameters assumed for the SP-100 reactor system reference design. It assumes a GaP-doped n-leg (Z=0.00111) and a SiGe p-leg with an as-yet undefined additive (Z=0.00069), yielding a couple Z of 0.00085 K⁻¹. This performance level has not yet been achieved.

5. The fifth material model is designated "dream". Its composition and development pathway are not known to the authors. It was included at JPL's request, to quantify what effect a figure of merit of 0.00140 K⁻¹ would have on RTG performance, if such a material could be successfully developed.

The five RTG designs were based on the same basic arrangement, i.e., the baseline design employing 16 uncouples (of 0.8" leg length) per horizontal ring, connected four in parallel. However, the number of heat source modules, the number of uncouples, and the cross-sectional areas of the uncouple legs were varied to meet (or come close to) the RTG voltage and power goals. The voltage goal used was 30 volts after lead losses; and the power goal was 250 w EOM or 280 w BOM after lead losses. Each of the five material models employed temperature-dependent resistivities, conductivities, and Seebeck coefficients for the n- and p-legs.

The primary emphasis in the design studies and analyses was to determine the relative RTG performance for the five options, rather than their absolute values. For this reason, and in the interest of expediency, a number of approximating assumptions were made:

The axial variations of the heat flow rates, temperatures, and couple outputs were ignored. All couples were assumed to operate at the same hot-junction temperature (1000°C) and cold-junction temperature (300°C) employed in previous RTG tests. In addition, the fraction of the generated heat that flows to the thermoelectric couples was assumed to be 88%, based on the results of the more detailed and exact analysis of the baseline RTG design.

Based on the same analysis, the effect of the electrode resistances and the electrical contact resistance were accounted for by increasing the materials' resistivities by 10%; and the effect of electrical lead losses was accounted for by subtracting 6% from each couple's output voltage.

Finally, the number of thermoelectric rings per heat source module had been arbitrarily fixed at 2.0 in the baseline design (for consistency with the Galileo RTG), but was varied in each of the five comparison designs so as to maximize the conversion efficiency.

Because of these differences in analytical approach, the results of the material comparison analysis are not an exact match to those of the baseline RTG analysis. But the comparison analysis is internally consistent, and its results are a valid comparison of the relative RTG performance for the five TE materials.

Comparison of the five RTG designs showed, not surprisingly, that Materials 2, 3, and 4 yielded very similar results. Therefore, only the results for Options 1, 3, and 5 are presented below. Table 8 compares their performance, and Table 9 compares their mass breakdown.

Comparison of columns 1 and 2 of Table 8 shows that the addition of GaP in the SiGe n-leg

Table 8. Effect of Thermoelectric Figure of Merit on RTG Design and BOM Performance

Material:				
Material #	1	3	5	
Designation	JPL 78/63	GE HYBRID	DREAM	
BOM Figure Of Merit, K ⁻¹	0.000584	0.000782	0.001387	
RTG Design:				
Number of HS Modules	19	15	10	
Thermal Power, watts	4840	3663	2442	
RTG Height, inches	48.0	39.6	29.1	
Number of Unicouple Rings	37	40	38	
Unicouples per Ring	16	16	16	
Number of Unicouples	592	640	624	
Number in Parallel	4	4	4	
Number in Series	148	160	156	
Area of TE Legs, cm ²	0.359	0.338	0.332	
RTG Performance (BOM):				
Current, amp	9.30	9.13	9.08	
Voltage	30.1	30.3	30.1	
Power, watts	280	276	273	
Couple Efficiency, %	7.26	9.08	13.48	
System Efficiency, %	6.03	7.53	11.18	
Estimated Mass, kg	61.6	50.9	37.7	
Specific Power, w/kg	4.55	5.43	7.24	

produces very significant efficiency increases. For the same output power, these lead to substantial reductions in fuel loading and RTG mass.

Comparison of Columns 2 and 3 shows that the hypothetical and still undefined "dream" material would result in even greater efficiency increase, and correspondingly much larger reductions in fuel loading and RTG mass.

Multicouples employing SiGe/GaP n-legs have already been built and tested for 6000 hours. They exhibited stable performance under positive bias, but anomalous degradation under negative bias with respect to the RTG housing. Thus, they could be considered for use in RTGs in which all multicouples were maintained under positive bias.

Table 9. Effect of Thermoelectric Material on Mass of Unicouple RTG

RTG MASS BREAKDOWN (kg)	JPL 78/63 Z=0.000584	GE HYBRID Z=0.000782	DREAM Z=0.001387
CPHS MODULES (19/15/10)			
FUEL (H ₂ O)	11.32	8.94	5.90
CAPILLARIES (IN)	4.44	3.51	2.34
GRAPHITE	11.72	9.26	6.12
H.S. CARRIER (Mn)			
SIDE WALLS	2.23	1.84	1.23
BELLOWS	0.11	0.11	0.11
END CAPS AND LOAD SPREADERS	1.49	1.45	1.45
H.S. STRUCTURAL SUPPORTS			
GRAPHITE PRESSURE PLATES	0.52	0.52	0.52
LOAD STUDS/SPRINGS	0.27	0.27	0.27
RELIEF SPRINGS (TO)	2.64	1.22	0.35
OTHER PRELOAD HARDWARE	0.64	0.64	0.64
ELECTRICAL CIRCUITS			
TE ELEMENTS (592/60/634)	5.03	5.47	4.92
TE FASTENERS AND SEALS	1.12	1.21	1.18
ALUMINA INSULATORS	0.00	0.08	0.05
ELECTR. CONNECTORS/TERMINALS	0.35	0.38	0.37
MULTIPLY INSULATION (Mn/Quartz)			
SIDES	5.55	4.43	3.92
ENDS	0.88	0.88	0.88
RTG HOUSING (Al)			
SIDE WALL (590°/350°/080°)	0.62	5.28	3.91
END SECTION	0.47	0.47	0.47
COVERS	0.34	0.34	0.34
RESISTANCE THERMISTORS	0.30	0.30	0.30
GAS MOUNT ASSEMBLY	0.18	0.18	0.18
RADIATOR			
FINS (Al)	2.67	2.16	1.55
ALUMINA COOLANT MANIFOLDS	0.25	0.25	0.25
EMISSIVITY COATING	0.15	0.15	0.15
TOTAL MASS (kg)	61.55	50.88	37.73

But if it were deemed too risky to fly an multicouple RTG until the negative-bias anomaly is more fully understood and resolved, Table 8 shows that the use of SiGe/GaP n-legs would still be quite advantageous for use in unicouple RTGs. Such unicouples have not yet been built, and would require significant new bond developments. But the programmatic risk of doing that seems reasonable and well justified by the potential payoff.

As for the dream material, the payoff would obviously be enormous. They would require development of new material fabrication methods, bonding techniques, fabrication procedure, and extensive testing to demonstrate the couples' performance, reproducibility, compatibility with other RTG components at operating temperatures, and long-term performance stability. In the absence of any information about material compositions and development approach, the authors are unable to assess the ultimate success probability of such a development program. But, based on their extensive experience on numerous other RTG development programs, they are convinced that a program to develop a flight RTG employing this material would not come close to meeting the JPL-envisaged MRSR schedule described in Figure 2 of Reference [1].

REFERENCES

- [1] A. Schock, V. Sankarankandath, and M. Shirbacheh, "Requirements and Designs of Mars Rover RTGs," 24th Intersociety Energy Conversion Engineering Conference, 6-11 August, 1989.
- [2] A. Schock and T. Hamrick, "Structural Design and Analysis of Mars Rover RTGs." Ibid.

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