Subsurface Ambient Thermoelectric Power for Moles and Penetrators

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Abstract—A technique for electrical power generation for planetary exploration applications using thermoelectric conversion of subsurface heat flows is described. Sufficiently shallow vehicles can exploit the diurnal temperature cycle as heat flows in and out of the soil - the converter exploits the temperature gradient along the length of the vehicle. Proof-of-concept experiments are described using off-the-shelf thermoelectric CPU cooling plates as generators.

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1. INTRODUCTION

Subsurface investigations are a new focus of planetary exploration, particularly with regard to Mars. Not only is burial useful for some sensing techniques (notably seismic and volume-sensing mineralogic devices such as those based on nuclear techniques such as gamma-ray spectroscopy) but the subsurface environment has been identified as the key to the search for previous or extant life on Mars. Firstly, there is ample evidence of abundant near-surface water on Mars (albeit largely in the form of ice), although the top centimeters of the surface are dessicated. Secondly, the uppermost surface material has been in contact with soil oxidants and strong ultraviolet light – both exposures being highly destructive to life and organic compounds in general.

Thus access to subsurface material is an important enabler for future science goals, either by digging and drilling to extract subsurface material and recovering it to a lander or rover, or by deployment of instrumentation beneath the surface using penetrators or moles.

The question then arises of how to power such vehicles. While primary batteries are an obvious choice for short-duration subsurface applications, longer-term missions may require a power source, rather than simple energy storage. Radioisotope sources are of course a possibility, but have onerous safety and reporting requirements which introduce significant cost.

The aim of this paper is to explore another possibility, that of capturing some of the energy flowing through the subsurface due to diurnal heating by sunlight. While direct sunlight (which obviously is more easily and efficiently converted into electricity by photovoltaic means) does not penetrate more than a few grain diameters into the surface, solar heat penetrates rather further. Note that it is not enough simply to absorb solar energy – there must be an energy flow across a temperature difference in order for the conversion of heat into useful work to take place.

This method of power generation has a limited applicability domain : one or both ends of the generator must experience significant diurnal temperature variation. The method will therefore not work below the diurnal skin depth (which is dependent on the thermal diffusivity of the soil.) Nor will it function at latitudes and seasons where there is little diurnal temperature variation – during polar night and also during polar day.

This type of power source has been considered for terrestrial applications, to support remote sensor packages, e.g. Stevens [1,2] where it has received the rather muddled appelation of ‘ground source’ thermoelectric generation.

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[1] IEEEAC paper #1055, Updated November 15, 2002

We may note that although thermoelectric conversion [3] is discussed in the present paper, other methods of extracting the tidal heat flows in the subsurface have been considered for driving moles, using shape memory metal actuators for example [4]. However, reasons for selecting thermoelectric conversion elsewhere - isimplicity and reliability – also apply here.

2. PROOF-OF-CONCEPT

For these proof-of-concept experiments, two test articles were constructed, using 40mm diameter penetrator forebodies developed 3 years previously for impact tests of the DS-2 Mars penetrators [5,6,7]. All the bodies had been machined from brass. These simply acted as conductive heat sinks with broadly representative size and mass to possible planetary vehicles.

The power generation aspect of the experiment was accomplished using off-the-shelf thermoelectric cooling plates. Thermoelectric modules have now become widely available through their application to enhance cooling of modern high-performance microprocessor chips. The convenience of these modules for power generation applications has been noted previously [8,9].

One article used an ogive penetrator (3 CRH - calibre radius-head) , with a 42x42mm thermoelectric plate (TE Technology TM-TB-127-1.4-1.05(P)) attached to the back of the forebody with a thin layer of cyanoacrylate adhesive ('superglue'). A small finned aluminium heatsink was similarly attached to the other side of the plate. The vehicle length is 11.5cm and its mass 0.88kg (see figures 1 and 2).

An LM335 semiconductor temperature sensor was attached to the heatsink and monitored with a Dickson E-120 pocket data logger. Also recorded on this 2-channel logger was the voltage across the thermoelectric plate shorted by a 100 Ω resistor. For the thermoelectric converters used, the peak power is obtained with a load impedance of only a few Ω. But with this low impedance, the voltage is low and because the resolution of the E-120 datalogger was limited to about 20mV, the higher impedance was chosen to improve the measurement precision at the expense of actually recording the peak power.

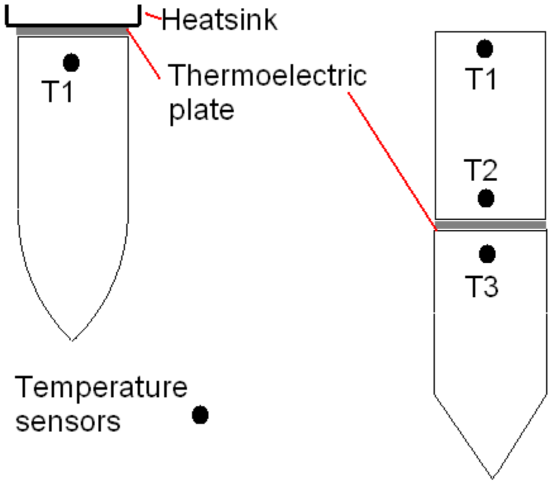

Figure 1. Schematic of the two test articles and the location of the temperature sensors. The each major part is brass, 40mm in diameter and about 100mm long.

Figure 2. The two test articles prior to emplacement in the ground. A set of AA cells provided excitation for the temperature sensors and the offset voltage required to push the thermoelectric output into the range acquired by the datalogger.

The second article is arguably more representative of a flight experiment, and was constructed with two cylindrical parts. The front end is a cone-tipped brass cylinder, linked

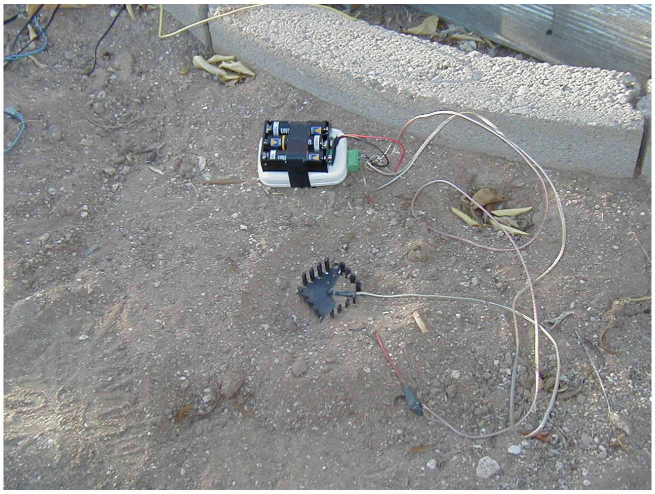

Figure 3. Datalogger (white) and battery supply before installation beneath sunshade. Black heatsink of small penetrator is exposed. Tests with the longer penetrator had it completely buried.

via a rubber adhesive layer in which a thermoelectric plate (TM-TB-35-1.4-1.15(P)) was embedded to a solid brass cylinder. The total length of the assembly is 20.5cm with a mass of 1.64kg.

A Pace XR-440M pocket datalogger was obtained for this later test – this permitted 4 channel sampling and has a higher precision (12 bit vs 8 bit for the E-120.) This allowed the monitoring of three temperatures in addition to the converter voltage. Because of the higher measurement precision, a more 'authentic' 2 Ω load impedance was used.

The devices were emplaced in the author's backyard (a dry clay-sand soil) in early summer 2001. Data were acquired over around a week when air temperatures approached 100F – there was little or no cloud. The excitation batteries and the dataloggers were placed under a wooden block to limit their exposure to direct sunlight. The small penetrator was emplaced with the heatsink exposed to the sun, while the longer penetrator was completely buried, with about 1cm of loose soil above it.

3. RESULTS

Figure 4 shows the first results from the small penetrator – for most of the day there is a significant power output. The thermoelectric voltage is around 100mV, although this was into a large shunt resistor to enable adequate resolution by the datalogger, so the actual power is modest - $V^2/R=.1^2/100=100\mu W$.

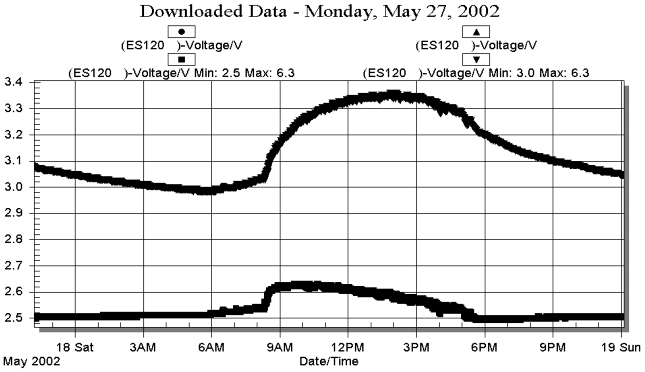

Figure 4. Data from the initial experiment with the ogive/heatsink penetrator and ES-120 datalogger. The ordinate is recorded voltage : upper curve is equal to temperature in K divided by 100, thus the diurnal cycle in late May swings the temperature from 25^{o}C to 50^{o}C. The lower curve is the thermoelectric output in volts+2.5 – i.e. the peak output is about 100mV. Note the rapid increase around 8am when direct sun falls on the heatsink, and the slow fall-off in output in mid-afternoon.

In the evening the body of the small penetrator was quite hot to the touch, suggesting that heat flow and efficiency was being limited by the finite heat capacity of the buried element. A larger ground heat sink would perform better.

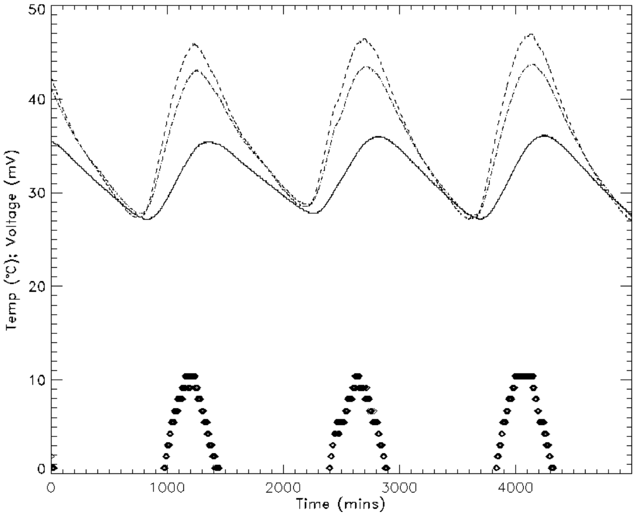

Figure 5. Data from the long penetrator, buried with the aft section beneath about 1cm of dirt. The upper curve (dashed) is T1, the uppermost temperature sensor. This is strongly coupled via the brass body to the second (dash-dot) curve, T2. The lowest curve T3 (solid line) represents the more heavily damped temperature fluctuations of the lower section. Heat flows from T2 to T3 primarily through the thermoelectric converter. The symbols at bottom show the voltage across the thermoelectric generator, running into a 2 ohm load.

Even though the second, larger test article was completely buried and thus received a lower heat flow and temperature gradient, it developed a comparable amount of power, in part due to the better impedance matching of the generator (i.e. operating near its maximum power point, much like a solar cell) and in part due to the better low-temperature heat sinking.

Figure 5 shows the temperatures recorded at the top and bottom of the aft (upper) brass segment – these temperatures are fairly well-coupled since they are of the same piece of metal – even beneath the surface there is a substantial diurnal temperature cycle of >15 ^oC. The temperature of the lower segment is noticeably damped, with an amplitude of about 8 ^oC. The difference between these upper and lower segments drives heat through the converter, as plotted in figure 6.

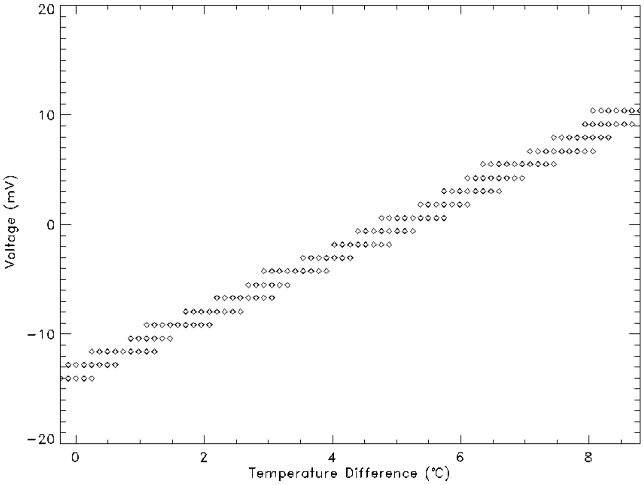

Figure 6. Thermoelectric generator voltage versus temperature difference (T2-T3). There is an arbitrary offset here, possibly due to a voltage offset in the datalogger or one of the temperature sensors, as notionally this curve should pass through zero. Nevertheless, it is clear that voltage is proportional to the temperature difference, with a slope of about 2.8 mV/degree.

Note that the power generated V^2/R is proportional to the square of the temperature difference across the generator. The heat flux through the generator (which to a first order is simply a conductive solid) is proportional to the temperature difference, and the Carnot efficiency, by a fraction of which the heat flux is converted into electrical power, is also proportional to the temperature difference.

The peak power produced by the long penetrator corresponds to 10mV across a 2 ohm load, or 50 microwatts. The power averaged throughout the day is about a factor 5 lower than this, or roughly 1 J per day. Clearly, only modest power requirements will be met with this technique, but these improvised test articles are probably far from optimal configurations.

4. DISCUSSION

By comparison, a 40mm square solar cell with an efficiency of 10% or so receiving full sunlight might generate 200 mW, or 4000 times more useful peak power. There are several reasons for the discrepancy.

First is that some of the sunlight is reflected – the bare ground has a higher reflectivity than a solar cell. Then any sunlight absorbed to heat the ground will be partitioned between radiation back to the atmosphere and space, to convection, and to conduction into the ground. Only the last part – probably at most a third - is exploited by the converter here. The heat available drops rapidly with depth, as more and more of the surface-deposited heat is expended in warming the larger volume of soil; furthermore the heat is degraded by the drop in temperature difference between the diurnally-heated soil and the isothermal soil at depth.

Taking (see later) a heat capacity of about 1000 JK^{-1}, the lower section of the penetrator cycles around 8,000 J during the diurnal cycle. The temperature difference averages only a few K, so the Carnot efficiency – that attainable by an ideal converter - is around 1%. Conductive and electrical losses in the converter itself (see, e.g. [3,8]) mean that only about a fraction – often of the order of one tenth of the ideal efficiency is realized. Thus a few Joules per day is the maximum attainable by such a small vehicle.

Advanced primary battery technology (Lithium Sulphur Dioxide and Lithium Thionyl Chloride) offers performance of around 200 W-hr/kg, or ~700 J/g. The thermoelectric converter mass in these tests was ~10g, and a diurnally-averaged power of 1 milliwatt appears achievable with better design, the 'break-even' mission duration is $700*10/10^{-3} = 7x10^6$ s, or ~2 months.

5. DESIGN CONSIDERATIONS

The accommodation constraints on any payload such as a penetrator are likely to drive its configuration, so no specific design will be optimized here. However, some general principles can be articulated to maximize the possible power output, although it must be recognized that different optima will exist (e.g. maximum power, maximum power per unit mass, maximum power for given contraints on length etc.) depending on the criterion used.

Since it is desired that the bulk of the heat flow along the vehicle go through the converter, the heat conductance of the structure at that point should be minimized, either by selection of nonconductive materials (polymers, titanium or perhaps stainless steel) and/or by configuration.

The length of the aft end of the penetrator should be matched to the penetration depth of the diurnal heat wave, taking into account the likely depth of the vehicle.

As for the forebody, its function here is essentially to dump the heat conducted through the converter. Its own thermal mass is almost certain to be too small for this job, so the heat capacity of the surrounding soil must act as the dominant heat sink. Ideally, the forebody would be shaped (not coincidentally) like the root system of a plant. If the forebody is instead constrained to be a convex and broadly cylindrical shape, as the penetration function is likely to require, then it should be slender so as to maximize the volume of soil heatsink.

Briefly, if the forebody is of radius r and length l, the effective heatsink capacity C_{fb} (in J/K) is the sum of the forebody itself, assumed perfectly conducting, and the soil volume within one skin depth δ of it

$$C_{fb} = \pi r^2 l(\rho_f c_f) + 2\pi l((r+\delta)^2-r^2)\rho_s c_s$$

where $\delta \sim (\kappa\tau)^{0.5}$ with κ the thermal diffusivity of the soil and τ the diurnal timescale, ρ_x and c_x are the density and specific heat capacity respectively, where x=[f,s] denotes the forebody or soil.

For a DS-2 type forebody, with r=0.02m, l=0.1m, $\rho_f \sim 8000$ kgm^{-3} and $c_f \sim 500$ $Jkg^{-1}K^{-1}$, typical for dense metals, $\tau \sim 10^5$s for Earth or Mars, $\rho_s \sim 1000$ kgm-3 ,$c_s \sim 1000$ $Jkg^{-1}K^{-1}$ and $\kappa \sim 10^{-7}$ m^2s^{-1} corresponding to a moderately porous soil we therefore find $C_{fb} = 490 + 8680$ JK^{-1} with $\delta \sim 0.1$m. It is seen that despite the density of the forebody, the metal itself contributes only about 5% of the heat capacity, the rest being due to the soil around it. (Note that for this cylindrical approximation to be accurate, $\delta \ll l$, which is not the case in this example, although the broad result is robust.

One might imagine a larger vehicle, more comparable to the MARS-96 or LUNAR-A penetrators, with r=0.08m, l=0.4m, $\rho_f \sim 4000$ kgm^{-3} and $c_f \sim 500$ $Jkg^{-1}K^{-1}$. This ~30kg vehicle is made of the same materials as before, but with more 'empty space', hence the lower density. The corresponding calculation yields $C_{fb} = 16 + 32$ kJK^{-1}. Again the soil contribution is larger than that of the forebody itself, but in this case only by a factor of two.

The converter itself requires some design attention. In general these are arrays of semiconductor 'legs' mounted in a rectangular array on a ceramic contact plate and potted in a sealing compound. The thermoelectric converter design can be optimized, although note that the materials themselves used in the improvised tests in this paper are, by virtue of finding application as a thermoelectric cooler, among the higher-efficiency class of materials. Both the legs and the plates are brittle, so mounting on a penetrator will require some care in mechanical design – perhaps some sort of spring arrangement should be used to ensure good thermal contact while minimizing loads applied to the converter. Some purely structural elements will likely be required to sustain longitudinal loads and bending moments – clearly the efficiency of the conversion system will be maximized if the heat conductance of the structural path (and any cabling harness that similarly provides a thermal short-circuit around the converter) is minimized.

A narrow cylindrical geometry has been considered heretofore. We may note, however, first that any aftbody is likely to have a larger diameter than the forebody, to ensure the former's deceleration at the surface for communications purposes. Second, the energy collection function of the aftbody more strongly favours large diameters than does the forebody's heat sink function.

6. ENVIRONMENTS

Two fundamental parameters are relevant to consider – the solar flux, and the thermal skin depth, defined by the thermal properties of the surface and the rotation period. On Earth and Mars, with 24-25 hr rotation periods. The moon has a similar solar flux, but a longer period, while asteroids may have almost any period.

Planet	Period	δ	T_{max}	T_{min}	
Mercury	176 days		~2m	90	740
Moon	28 days	~0.5m	100	390	
Earth	24 hrs	0.15m	323	283	
Mars	25 hrs	0.15m	190	260	
Asteroid	8 hrs	0.1m	150	220	
Asteroid	8 days	0.5m	140	230	

Table 1. Approximate thermal parameters for solar system bodies. Thermal skin depth d computed assuming an intermediate thermal diffusivity of surface material of $\sim 3\times10^{-7}$ m^2s^{-1}

Mercury has of course a very high heat flux, but a long period. To optimally extract energy requires the vehicle to have its long dimension comparable with the thermal skin depth. The 2m length scale implied by the calculation above approaches the limit of a practicable penetrator vehicle. The moon appears to be a very promising target.

Note that since the heat sink volume, and thus the amount of heat for a given temperature change that cycles through the system, varies approximately as the square of the skin depth, and the square of the skin depth varies approximately as the period, it follows that daily-averaged power is not a strong function of rotation rate (although obviously the size or depth of the vehicle to optimally extract it is).

7. CONCLUSIONS

Proof-of-concept experiments show that a small but potentially useful amount of electrical energy can be derived just beneath a planet's surface using thermoelectric conversion of diurnal heat flows. The technique may become competitive for long-term (e.g. seismological) monitoring applications where mission duration exceeds a few months and there is no possibility of accessing direct sunlight.

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