FAIRCHILD SPACE

FSC-ESD-217-91-495

DESIGN OF SMALL IMPACT-RESISTANT RTGs FOR GLOBAL NETWORK OF UNMANNED MARS LANDERS

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Abstract

Ongoing studies by the National Aeronautics and Space Administration (NASA) for the robotic exploration of Mars contemplate a network of at least twenty small and relatively inexpensive landers distributed over both low and high latitudes of the Martian globe. They are intended to explore the structural, mineralogical, and chemical characteristics of the Martian soil, search for possible subsurface trapped ice, and collect long-term seismological and meteorological data over a period of ten years. They can also serve as precursors for later unmanned and manned Mars missions.

The collected data will be transmitted periodically, either directly to Earth or indirectly via an orbiting relay. The choice of transmission will determine the required power, which is currently expected to be between 2 and 12 watts(e) per lander. This could be supplied either by solar arrays or by Radioisotope Thermoelectric Generators (RTGs). Solar-powered landers could only be used for low Martian latitudes, but RTG-powered landers can be used for both low and high latitudes. Moreover, RTGs are less affected by Martian sandstorms and can be modified to resist high-G-load impacts. High impact resistance is a critical goal. It is desired by the mission designers, to minimize the mass and complexity of the system needed to decelerate the landers to a survivable impact velocity.

To support the NASA system studies, the U.S. Department of Energy's Office of Special Applications (DOE/OSA) asked Fairchild to perform RTG design studies for this mission. The key problem in designing these RTGs is how to enable the generators to tolerate substantially higher G-loads than those encountered on previous RTG missions.

The Fairchild studies resulted in designs of compact RTGs based on flight-proven and safety-qualified heat source components, with a number of novel features designed to provide the desired high impact tolerance. The present paper describes those designs and their rationale, and a preliminary, quasi-static impact analysis that yielded very encouraging results.

Introduction

NASA has been studying missions to distribute a large number (~20) of small unmanned landers over the surface of the Martian globe, ranging from equatorial to polar regions. These studies have gone under the name of Mars Global Network (MGN) at NASA/JPL [(1)] and of Mars Environmental Survey (MESUR) at NASA/Ames [(2)]. The landers will be deployed by a series of launches over a period of years. They are designed to provide valuable Mars science returns, and can serve as precursors for later Space Exploration Initiative (SEI) missions.

When fully deployed, the robotic landers will form a global network to explore the structural, mineralogical, and chemical characteristics of the Martian soil, search for evidence of subsurface ice, and collect long-term seismological and meterological data over a period of ten years. A principal design goal is to minimize system cost and complexity wherever possible.

The landers at low Martian latitudes could be powered either with Radioisotope Thermoelectric Generators (RTGs) or with solar/photovoltaic systems. But the high-latitude landers would in any case require RTG power supplies, and it would clearly be inefficient to design different landers for low and high latitudes.

Additional considerations favoring the use of RTGs for all landers are the need to be able to operate during and after Martian sandstorms, and the ability to survive Martian ground impacts at relatively high velocities and G-loads. Both of these requirements can more easily be satisfied by RTGs. In addition, the RTG's waste heat can be utilized for thermal control of the lander, particularly for keeping its batteries warm during Martian nights.

To support the NASA studies, the U.S. Department of Energy's Office of Special Applications (DOE/OSA) commissioned Fairchild Space and Defense Corporation to perform conceptual design studies of RTGs for these landers under Contract No. DE-AC01-88NE32137.

Power Requirement

It is anticipated that each lander will collect and store data continuously, and transmit them to Earth periodically. The periodic transmissions will be powered by batteries, and the batteries will be continuously recharged by the lander's RTG. In this manner, the RTG need only operate at a low power level. The required power level will depend on whether the data collected by each lander are relayed via a Mars orbiter or are transmitted directly to Earth. The latter option could be advantageous, because it would avoid the need for an orbiter, whose cost would represent a significant fraction of the total mission cost.

It is currently estimated that each lander's continuous power requirement will be approximately 3 watts for relayed data transmission and roughly 9 watts for direct data transmission to Earth. These power level goals may change as the mission and lander designs are better defined, but they serve as useful targets for designing the RTGs and determining their sizes and masses for the two data transmission options, and for assessing the RTGs' impact resistance.

Both of the above power levels are very modest. RTGs with much higher power outputs have already operated in space with high reliability for even longer mission times. Therefore, the design of a 3-watt or 9-watt RTG for a ten-year mission would be relatively straightforward, except for some special requirements.

Special Design Requirement

The most critical special design requirement for this mission's RTG is high resistance to ground impact on Mars. Hard impacts could be avoided by using retrorockets to decelerate the lander before impact, as was done for the 1976 Viking landings on Mars. But deceleration systems to achieve soft landing require complex attitude control systems and tend to be quite massive and costly. This was acceptable for the large Viking landers, but would not be for the 20-odd small landers for the present mission, which must be designed for minimum complexity and cost.

The landers can be partially decelerated by parachutes. But the Martian atmosphere is quite thin (6 to 10 millibar, 95% CO_2 and 0.15% 0_2 [3]). Therefore, for practical parachute sizes the residual velocity would still be quite high (typically 60 to 100 m/sec [1]). As will be shown, such impact velocities can result in impact loads of thousands of G's. Loads of that magnitude could be tolerated by suitably potted electronic components and batteries, but not by standard RTGs nor by solar panels.

The impact loads can be reduced, either by small retrorockets fired at the end of the parachute descent, or possibly by crushable impact absorbers or gas-filled cushions. But whatever deceleration technique is ultimately used for pre-impact slowdown, it would clearly be highly desirable to maximize the impact tolerance of the RTG. This is because experience has shown that the other components of the lander can be adequately hardened, so that the RTG's impact tolerance is the controlling determinant of allowable impact velocity. The greater the impact velocity that the RTG can survive, the lower the complexity, mass, and cost of the system required to decelerate the spacecraft. Thus, high impact resistance is the dominant goal for the RTG designer.

Proposed RTG Designs

The Fairchild study for the MGN and MESUR missions has resulted in two illustrative but unoptimized RTG designs: a 3-watt design for the case of relayed data transmissions, and a 9-watt design for direct data transmission to Earth. The paper will first describe the 3-watt design and its rationale, followed by a description of the 9-watt design.

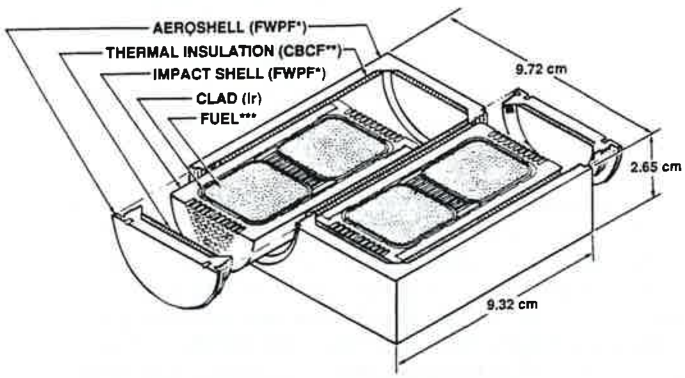
Both designs strive to maximize the use of previously developed technology, including the General Purpose Heat Source (GPHS) used in the Galileo and Ulysses RTGs, the SiGe thermoelectric materials employed in the RTGs for the Voyager, LES-8/9, Galileo and Ulysses missions, and the multicouples developed for DOE's Mod-RTG program. Modifications were introduced only where necessary to improve the RTG's impact resistance and to meet other mission requirements.

Fairchild has completed detailed thermal and electrical analyses of the two designs, and preliminary (quasi-static) analysis of the RTG's impact resistance. Detailed dynamic analyses and confirmatory tests have not yet been performed.

Heat Source

A detailed view of the previously used General Purpose Heat Source module is presented in Figure 1. Its design is driven primarily by safety considerations[4]. Each module contains passive safety provisions to provide fuel containment in case of all credible accidents. Each contains four 62.5-watt PuO_2 pellets, encapsulated in vented clads made of an oxidation-resistant iridium alloy. All other module components are made of graphitic materials, and serve various safety functions. The module's aeroshell protects the internal components against the external heat pulse during atmospheric reentry, the impact shell is an energy absorber provided to prevent breach of the clad during earth impact, and the intervening thermal insulator prevents overheating and excessive grain growth of the iridium clad during the hypersonic reentry heat pulse, and overcooling and embrittlement of the iridium during the subsequent subsonic descent through the Earth's atmosphere.

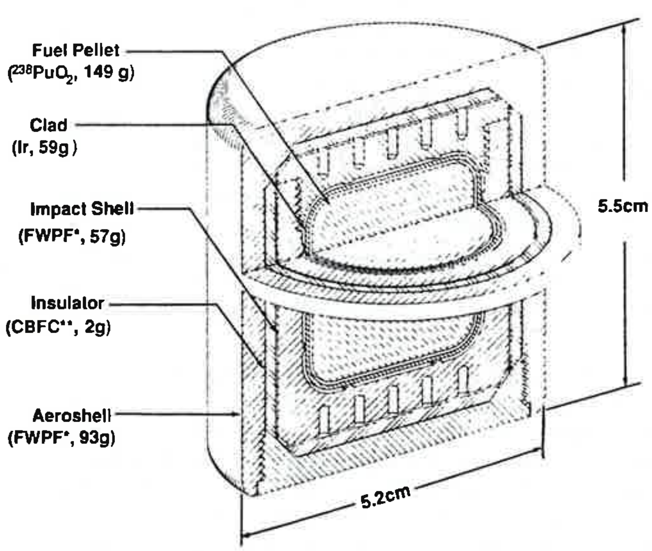
Figure 1. General-Purpose Heat Source Module (250 watts)
Sectioned at Mid-Plane



*Fine-Weave Pierced Fabric, a 90%-dense 3D carbon-carbon composite
**Carbon-Bonded Carbon Fibers, a 10%-dense high-temperature insulator
***62.5-watt $^{238}PuO_2$ pellet

Figure 2 depicts the configuration, size, and mass breakdown of the proposed heat source for the 3-watt RTG. As seen by comparison with Figure 1, the heat source is based as closely as possible on the design of the GPHS module, to minimize the need for costly and time-consuming new safety analyses and tests. It employs the identical fuel pellet, clad, and vent as the GPHS module, as well as the same materials and wall thicknesses for the aeroshell, impact shell, and thermal insulation. The 3-watt RTG only requires a single 62.5-watt fuel capsule, giving a total heat source mass of 360 grams. The use of the same graphite thicknesses as in the 4-capsule GPHS module is probably overconservative, but the reentry and impact analyses to confirm that have not been done yet.

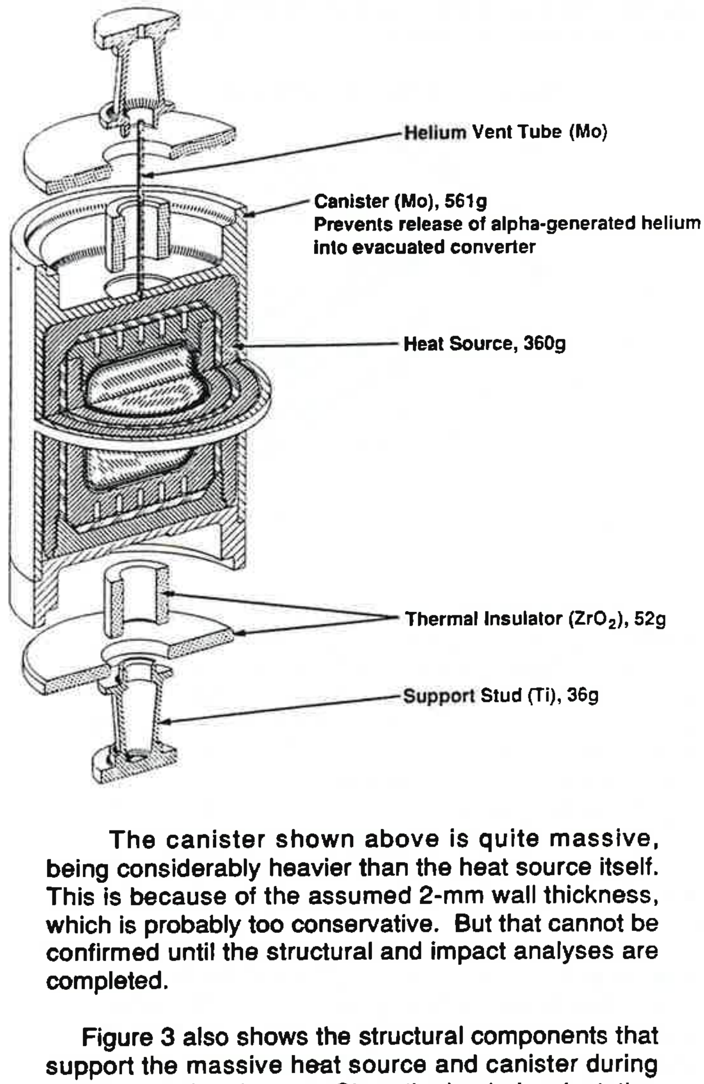
Figure 2. RTG Heat Source with Self-Contained Safety Provisions
(62.5 thermal watts, 360g)



*Fine Weave Pierced Fabric, a 90% dense carbon-carbon composite
**Carbon-Bonded Carbon Fiber, a 10% dense carbon-carbon composite

The heat source's graphite shells are not impervious. They allow the free release of the helium generated by the alpha-decay of the Pu-238 fuel. In conventional RTGs designed for operation in a space vacuum, the helium is discharged into the RTG's converter, which is vented to space. But converters designed for operation on Mars cannot be vented, since that would permit unacceptable access of the Martian atmosphere to their hot components. Therefore, the heat source must be enclosed in a separately vented hermetic canister. Such a canister and vent tube, made of molybdenum, are depicted in Figure 3.

Figure 3. Heat Source, Canister, and Structural Supports



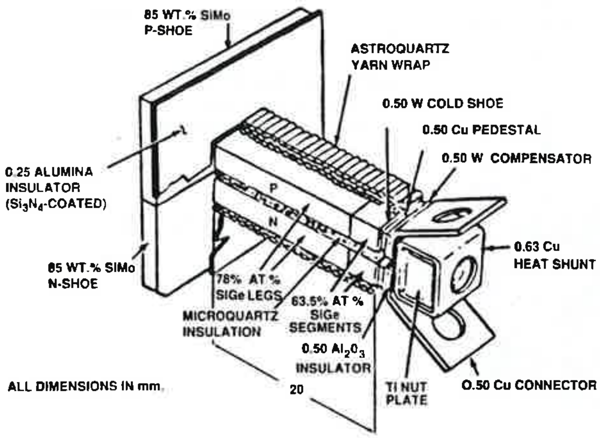
The canister shown above is quite massive, being considerably heavier than the heat source itself. This is because of the assumed 2-mm wall thickness, which is probably too conservative. But that cannot be confirmed until the structural and impact analyses are completed.

Figure 3 also shows the structural components that support the massive heat source and canister during launch and Mars impact. Since the lander's orientation at impact cannot be predicted with certainty, these structural components must provide tri-axial support; but they must do so without excessive heat losses between the hot canister and the cool RTG housing. To reduce those heat losses to acceptable levels, the canister is supported via zirconia insulators, as was done in previous flight RTGs. As shown, the zirconia members are configured to put them under compressive loads but not under tensile or shear loads. They in turn are supported axially and laterally by titanium studs, very similar to those used for supporting the heat source in the Galileo and Ulysses RTGs.

Thermoelectric Converter

The second major subsystem of the RTG is the converter, particularly the thermoelectric element which is its principal component. RTGs flown on previous space missions (Voyager, LES-8/9, Galileo, Ulysses) have used the unicouple depicted in Figure 4 as its thermoelectric element.

Figure 4. Thermoelectric Unicouple



Each unicouple contained an n-doped and a p-doped SiGe leg, which were connected at their hot ends by a SiMo hot-shoe. The hot-shoe also acted as a heat collector, to receive the heat radiated by the heat source and deliver it to the SiGe legs. The cold ends of the two legs contained terminals which were connected to those of neighboring couples, to form the RTG's series/parallel network. The cold ends of the cantilevered unicouples were bolted to the inside of the RTG housing, and a metal C-ring was used to seal each housing penetration.

Although unicouples have demonstrated very high reliability for RTG operating times in excess of ten years, they would not be a good choice for the present application for two principal reasons: inadequate voltage, and insufficient impact resistance.

A typical unicouple produced an output of 0.52 watts at 0.21 volts. Thus, a 3-watt RTG would only require six such unicouples. These could not be connected in a simple series circuit, because in such a circuit open-circuit failure of a single couple would lead to complete loss of power. If instead the six couples were connected in a 3 x 2 series-parallel network, the RTG's output would only be 0.6 volts, which is far below the mission's desired load voltage. A DC-to-DC converter could be used to step up the voltage, but such converters would be very inefficient with an input of only 0.6 volt. This would be a serious disadvantage of the unicouple for the small RTGs.

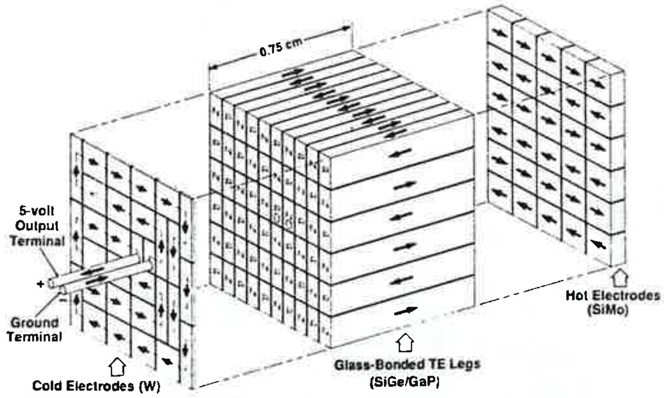
An even more serious drawback of the unicouple for this application is its low impact resistance. The unicouples are cantilevered devices, so that lateral impact loads would produce high bending moments and consequently high tensile stresses in the couple's relatively fragile legs and interface bonds. This is particularly true because the unicouple's legs have such a high length-to-thickness ratio (~8 : 1), which magnifies the bending stresses.

To alleviate both of the above problems, the author selected the use of thermoelectric multicouples instead of unicouples for the small RTGs. Multicouples, shown in the next three figures, differ from unicouples in that they have many legs instead of two, and those legs are glass-bonded to each other along their full length. As a result, the multicouple has a much higher output voltage and its leg assembly has a much smaller length-to-thickness ratio (~1 : 1) than the unicouple.

Multicouples have been under DOE-sponsored development for over ten years, and form the basis of Fairchild's Modular Isotopic Thermoelectric Generator (MITG) design [5,6] and of the Modular RTG which General Electric is developing for DOE [7]. The multicouples built under that program contained 40 series-connected legs, producing an output of 3.5 volts per multicouple. They were tested by Fairchild for DOE [8]. The latest test of an eight-multicouple assembly was terminated after 6000 hours. During that time, the performance of the six multicouples that operated with a positive bias with respect to ground was quite stable (like that of unicouples), but the two negatively biased multicouples showed unstable performance. The cause of the negative-bias problem has since been identified, but not yet proven. A test to do so is in preparation. However, as will be shown, the proposed design of the small RTGs avoids the negative-bias problem by arranging for all couples to operate at a positive bias with respect to ground.

The heart of the multicouple is the thermopile, consisting of the thermoelectric legs, hot and cold electrodes, and terminals. An exploded view of the thermopile design for the proposed RTG is depicted in Figure 5. It is essentially identical to that of the multicouples built for the Mod-RTG program, except that the number of thermoelectric legs has been increased from 40 to 60. This was done to raise the multicouple's output voltage from 3.5 to 5.6 volts.

Figure 5. Multicouple Thermopile
Exploded View Showing Current Path Through 60 Alternating N- and P- Legs



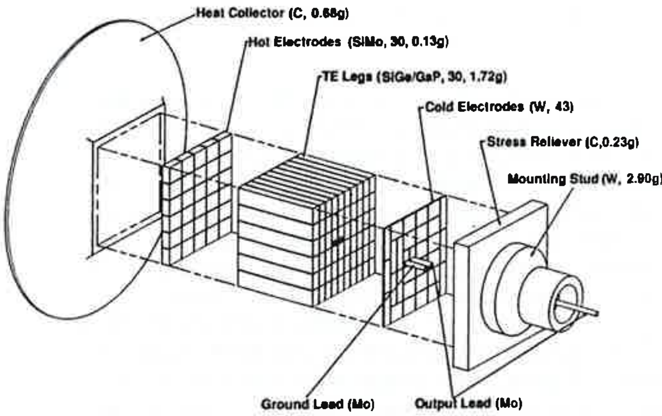
As can be seen, the 60 glass-bonded legs are arranged in a 6 x 10 matrix of alternating n- and p-legs. The glass-bonded leg assembly is roughly cubical, with a length of 0.75 cm and a cross section of 0.66 x 0.66 cm. This aspect ratio of the multicouple leads to much lower bending stresses than those in the long, thin unicouple legs.

The hot ends of the 60 TE legs are bonded to 30 hot-electrodes, to form 30 couples. And the 29 cold-end electrodes connect the 30 couples in series. The direction of the current path is shown by the arrows. Note that the output terminals are located at the center of the thermopile, as in the Mod-RTG.

Figure 6 presents an exploded view and mass breakdown of the thermoelectric multicouple. It shows that the thermopile's hot end is glass-bonded to a graphite heat collector, whose function is to receive heat radiated by the heat source canister and concentrate it at the TE legs; and that the thermopile's cold end is glass-bonded to a graphite pad, which is bonded to a tungsten mounting stud. Graphite is a low-modulus material, and the pad serves to relieve the stresses at the interface bonds. These components are quite similar to those in the already-tested Mod-RTG multicouples.

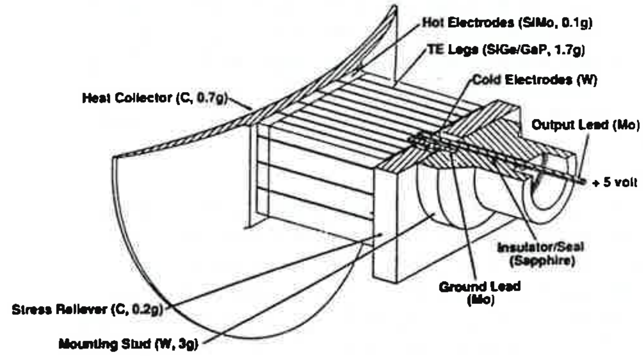
Another noteworthy feature of the multicouple depicted in Figure 6 is the indicated low mass of the TE leg assembly (1.72 g), the hot electrodes (0.13 g), and the heat collector (0.68 g). These low masses are very important, because they determine the impact-induced stresses at the thermopile's cold and hot faces. The lower the mass of the leg assembly and the heat collector, the greater the RTG's allowable impact velocity, since that is primarily dictated by interface stresses in the cantilevered multicouple. This is the primary reason for keeping the heat collector small. On the other hand, increasing its size would lead to a moderate rise in the RTG's efficiency. The 2.5-cm diameter in the figure was selected for the purpose of the thermal analysis. It was based on a qualitative compromise, and may be modified after completion of the impact analysis.

Figure 6. Thermoelectric Multicouple
Exploded View



The multicouple features discussed thus far involve the same materials, fabrication techniques, and bonding materials as those already developed for the Modular RTG program. In addition, the proposed multicouples have two novel features pertaining to the multicouple's terminals and seals. These are seen more clearly in Figure 7, which shows a sectioned view of the assembled multicouple.

Figure 7. Multicouple, Sectioned at Mid-Plane
Showing Built-in Ground Lead and Sealed Output Lead



In previous multicouples, developed for the much larger Modular RTG, each multicouple's two terminal leads passed through the center of the mounting stud to the outside of the RTG housing, and the external leads were then interconnected to form a series-parallel network. In general, eight multicouples were connected in series to produce the desired 28-volt load voltage. The multicouples were not grounded, but operated at a floating potential. This resulted in one end of the eight-multicouple string operating at a positive bias with respect to ground and the other at a negative bias. As previously mentioned, the positively biased units exhibited stable performance (during the 6000-hour test) but the negatively biased ones did not. In the revised design illustrated in Figure 7, the negative-bias problem is avoided by grounding the negative lead of each multicouple, so that all of its 30 couples operate at a positive bias with respect to ground.

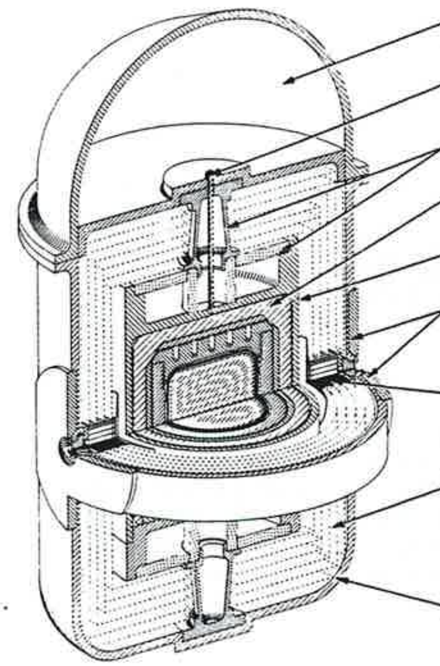
With the negative lead grounded, only one lead needs to pass through the multicouple's mounting stud. This simplifies the feedthrough problem. All RTGs require hermetic feedthroughs to deliver the electrical power generated within the RTG to the external load. Conventional feedthroughs, whether insulated by glass or ceramic, can be a weak point in resisting high G-loads during Martian impact. This problem is alleviated in the proposed design, in which each multicouple incorporates its own feedthrough. As shown in Figure 7, the single output lead is insulated from the grounded stud by a thin layer of cast sapphire. This is expected to exhibit high impact resistance because of the seal's favorable geometry and because of sapphire's good mechanical properties.

Generator

Finally, Figure 8 shows how the heat source, its canister and support structure, and two multicouples are integrated with a multifoil-insulated housing to form the ~3-watt RTG. The insulation, which is shown symbolically by dashed lines, consists of 60 layers of 7.5-micron-thick Mo foils separated by zirconia particles. Besides the novel features discussed in the preceding sections, the RTG design incorporates a number of additional features to enhance its impact resistance. These are discussed below.

As can be seen, the heat source and its canister are by far the heaviest components within the RTG's housing. Their combined mass is two orders of magnitude above that of the multicouples. Therefore, in order to achieve the desired high impact resistance, a cardinal principle employed in the RTG design was to mechanically separate the massive heat source and its canister from the relatively fragile thermoelectric elements. Alternative designs in which the hot ends of spring-loaded multicouples are pressed against the heat-source canister were rejected in our study, because such designs can result in excessive shear stresses in the thermoelectric legs under the influence of lateral g-loads. In the design shown in Figure 8, there is a gap between the canister and the heat collectors, so that the multicouples are only subjected to their own inertial forces. As shown at the end of the paper, these forces are relatively small, even at high g-loads, because of the low mass of the thermoelectric legs and heat collectors.

Figure 8. Integrated RTG Design (~ 3 watts)



However, the small size of the heat collector entails some performance penalty. Reducing the heat collector diameter increases the thermal radiation fraction intercepted by the multifoil insulation. But since multifoil insulation is such a good insulator, the heat lost through it is quite small. Therefore, the heat collector size has only a secondary effect on the RTG's efficiency, but a primary effect on impact stresses.

The heat collector size also has a direct effect on the temperature of the heat source. The only concern is the temperature of the clad, since overheating of the iridium can lead to excessive grain growth and consequent embrittlement. But this is not a problem in the present design, because of the retention of the alpha-generated helium in the canister. In an evacuated heat source, there is a considerable temperature drop between the fuel capsule and the heat source surface. But in a helium-filled heat source that temperature drop is much smaller, which more than compensates for the effect of the small heat collector.

Another important feature of the design shown in Figure 8 relates to the RTG's housing and seals. Each of the RTG's unicouple or multicouple mounting holes must be sealed, to prevent access of the external oxidizing atmosphere into the hot interior. This sealing requirement is not too difficult for conventional RTGs operating in a space vacuum. Such RTGs need only be sealed until launch, after which they are vented to space. For such RTGs, the use of compression seals has been adequate.

But the sealing requirement for RTGs designed to operate on Mars is more stringent, since they must maintain hermeticity throughout their mission life. This rules out the use of compression seals and requires the use of welded or brazed seals between the RTG housing and the multicouples' tungsten mounting studs. That requirement precludes the use of an aluminum housing as in previous RTGs. Since aluminum cannot be welded or brazed to high-melting materials, it would require the use of explosively formed bimetallic joints (e.g., aluminum to a stainless transition). But this option was rejected, because of serious concern about the hermeticity of bimetallic joints after high-G-load impacts. Therefore, the RTG housing shown in Figure 8 is made of titanium, instead of aluminum. Although this is heavier, it can be reliably brazed to tungsten. The choice of titanium also offers the same advantage for the joint between the helium vent tube and the housing.

Another respect in which the proposed RTG design differs from previous RTGs is the disposition of the helium gas generated by alpha decay. In those RTGs, the helium was dumped overboard via the vented converter. But in the present case the converter is not vented. It is separated from the heat source by the canister, which has a capillary vent tube. But if that tube were discharged to the external environment, a semi-permeable vent would be needed to prevent the inflow of the Martian atmosphere while permitting the outflow of the alpha-generated helium. Such a semi-permeable vent, made of Viton elastomer, was used in the Viking RTGs, but they operated at a much lower housing temperature and it is doubtful that such a vent could deliver the impact resistance desired for the present application. To avoid that uncertainty, the RTG design depicted in Figure 8 shows an integral helium accumulator, sized to develop a pressure of 10 atmospheres after 10 years of RTG operations. This avoids the need to dump the helium to the outside and eliminates the need for a semi-permeable vent.

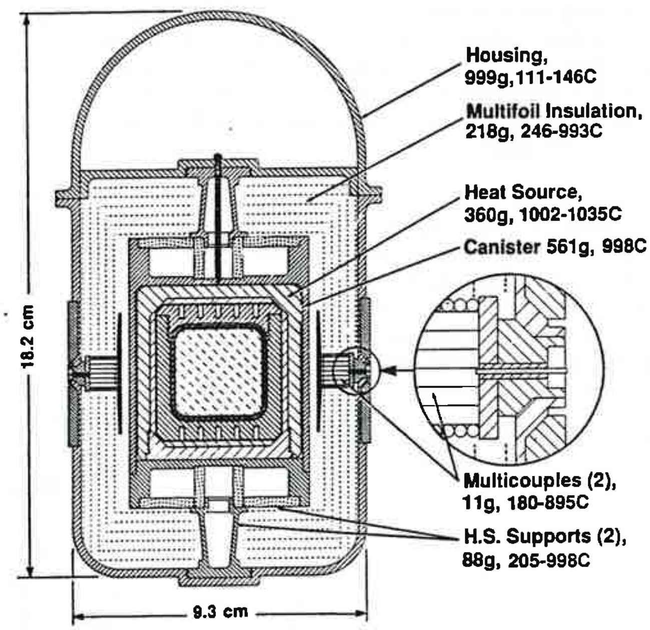
Figure 8 also shows that the proposed design, unlike previous RTGs, does not have any protruding radiator fins. It was found that such fins were unnecessary if each multicouple's mounting stud is surrounded by a circular (copper) heat spreader brazed to the RTG's titanium housing.

Performance Summary

Finally, Figure 9 summarizes the size, mass breakdown, and temperature distribution of the 3-watt RTG. In addition, the tables at the bottom of the figure summarize the heat flows, the efficiencies, and the electrical output of the RTG.

The RTG has an overall diameter of 9.3 cm (3.7 in) and height of 18.2 cm (7.2 in). Its total mass is 2.05 kg (4.52 lb). The analysis yielded a clad temperature of 1035°C, an aeroshell temperature of 1002°C, and hot- and cold-junction temperatures of 895°C and 180°C. These multicouple temperatures are more than 100°C lower than in the previously mentioned Fairchild test, in which positively biased multicouples demonstrated stable performance for 6000 hours. Thus, from the viewpoint of the present RTG design, that test can really be interpreted as an accelerated multicouple test with an effective test time much greater than 6000 hours at design temperatures.

Figure 9. Performance of Illustrative 3-watt RTG
Size, Masses, Temperatures, Heat Flows, Efficiencies, and Output



Heat Flow (w):		Efficiency (%):		Output:	
Fuel	62.5	Thermal	55.8	Current	0.518 Amp
H.S. Supports	17.9	Material	8.8	Voltage	5.68 Volt
Insulation	9.7	Multicouple	8.4	Power	2.94 Watt
TE Legs	34.9	System	4.7	Mass	2.05 kg

As shown in Figure 9, of the 62.5-watt thermal power generated by isotope decay, 17.9 watts (29%) is lost through the heat source supports and 9.7 watts (15%) is lost through the thermal insulation, leaving 34.9 watts (56%) of heat flow through the thermoelectric legs. That is a much lower thermal efficiency then that of large RTGs. This is not surprising, because end losses necessarily constitute a larger thermal power fraction in small RTGs. For the previously cited temperatures, we obtained a thermoelectric material efficiency of 8.8%, a multicouple efficiency of 8.4%, and an RTG system efficiency of 4.7%. The relatively low value of the latter is due to the low thermal efficiency of the small RTG.

Finally, we see that with the RTG's two multicouples connected in parallel, its electrical output at BOM is 0.518 amps at 5.68 volts, for a total power of 2.94 watts(e) and a specific power of 1.43 watt/kg.

Nine-Watt RTG

Having already described the three-watt RTG design details and rationale, the corresponding design of the nine-watt RTG can be covered without much additional discussion.

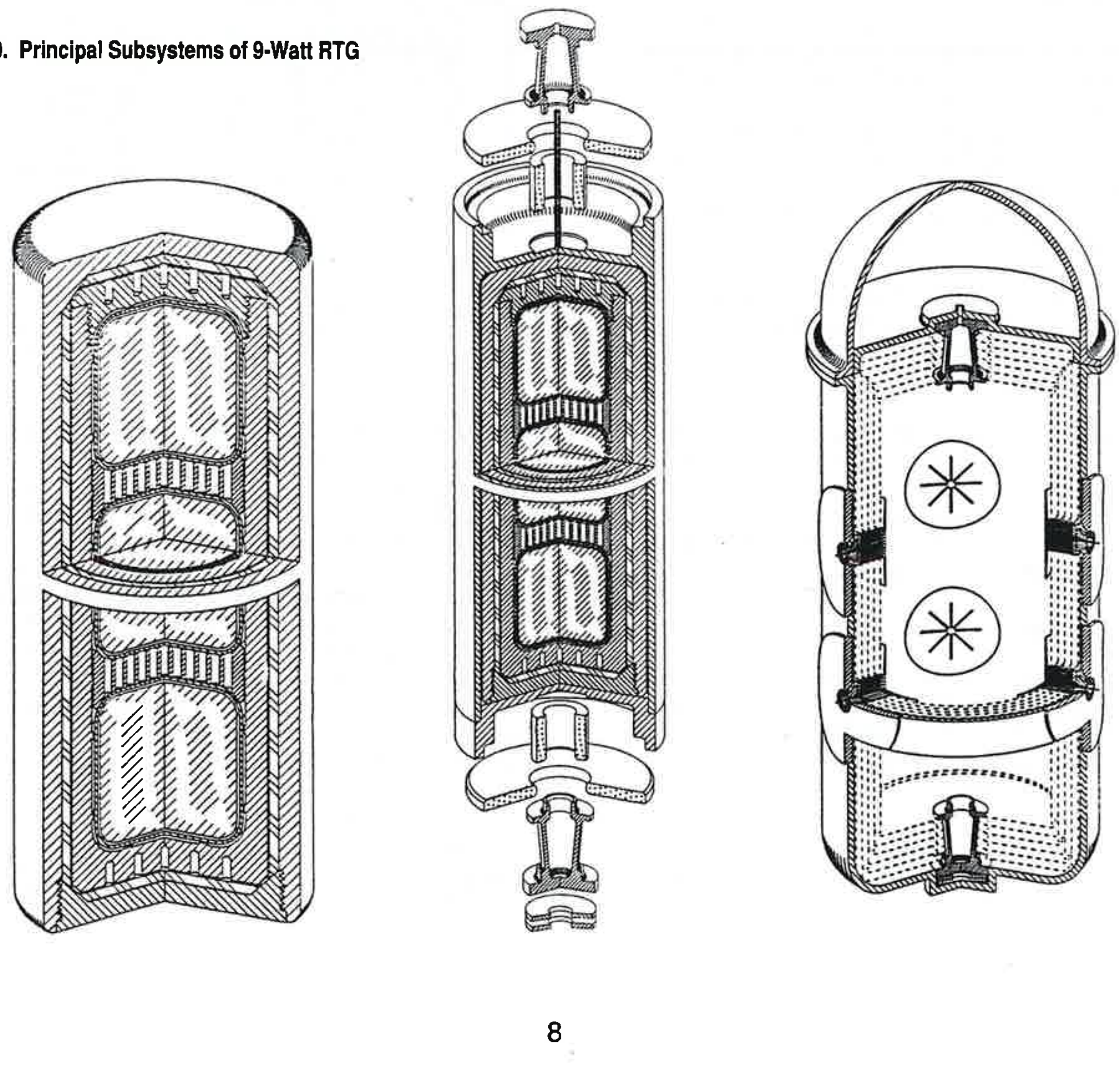
To take advantage of previously developed technology and safety tests, the heat source should be a derivative of the General Purpose Heat Source (GPHS) module, depicted in Figure 1. Therefore, if we wish to use the standard GPHS fuel capsules the heat source's thermal power can only be varied in steps of 62.5 watts. The electrical power required by each lander for direct data transmission to Earth is not yet known, but it is currently expected to be between 9 watts and 12 watts.

For a 12-watt output, it would be possible to use the standard GPHS module shown in Figure 1, containing four fuel capsules and surrounded by eight multicouples, two on each edge. In fact, an electrically heated version of such an assembly has already been built and tested for 6000 hours.

Instead, let us illustrate a design for a 9-watt RTG. For that option, the thermal power requirement can be satisfied with just three standard fuel capsules. The left segment of Figure 10 shows a heat source containing three such capsules, embedded in an impact shell, thermal insulation, and aeroshell of the same graphitic materials and shell thicknesses as the GPHS module. Thus it is analogous to Figure 2 for the 3-watt RTG. Similarly, the figure's middle segment, showing the heat source with its canister and support structure, is analogous to Figure 3.

The right segment of Figure 10 shows a sectioned view of the 9-watt converter, without the heat source. As seen, it contains six multicouples, similar to those used in the 3-watt RTG design. They are arranged in two layers of three multicouples. Other than that, the converter topology is very similar to that of the smaller unit. The figure segment shows that the heat collectors only cover a small fraction of the heat source surface. And yet the multifoil insulation is so effective that only about one third of the generated heat flows through the thermal insulation. Also visible in this segment are the asterisk-shaped stress-relieving slots in the face of each multicouple's heat collector.

Figure 10. Principal Subsystems of 9-Watt RTG



Finally, Figure 11 shows a sectioned view of the assembled 9-watt RTG, and Figure 12 summarizes the RTG's operating temperatures and heat flow rates. The temperatures shown in Figure 12 pertain to the locations of the nearest black dots. As can be seen, there are no radiator fins, the copper heat spreaders being adequate to lower the cold-junction temperatures to 190°C, which is 110°C below the cold-junction temperature of the previously flown GPHS/RTGs. Figure 12 also shows hot-junction temperatures of 894°C and fuel clad temperatures of 1036°C, which respectively are 106°C and 270°C below the corresponding temperatures in previously flown RTGs. The clad temperature is so low because the retention of the alpha-generated helium in the canister greatly reduces the temperature drop between the fuel capsule and the heat source surface. In fact, the low capsule temperature may even permit clads made of a platinum-rhodium alloy, which has an even better oxidation resistance and a much better low-temperature ductility than the iridium alloy used in the standard GPHS modules.

Figure 11. Nine-Watt RTG

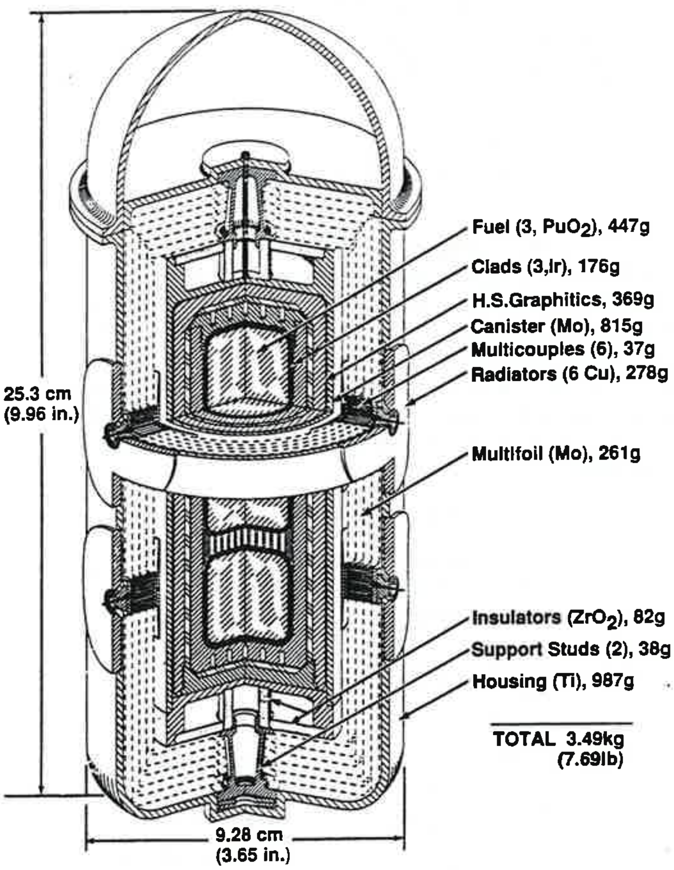
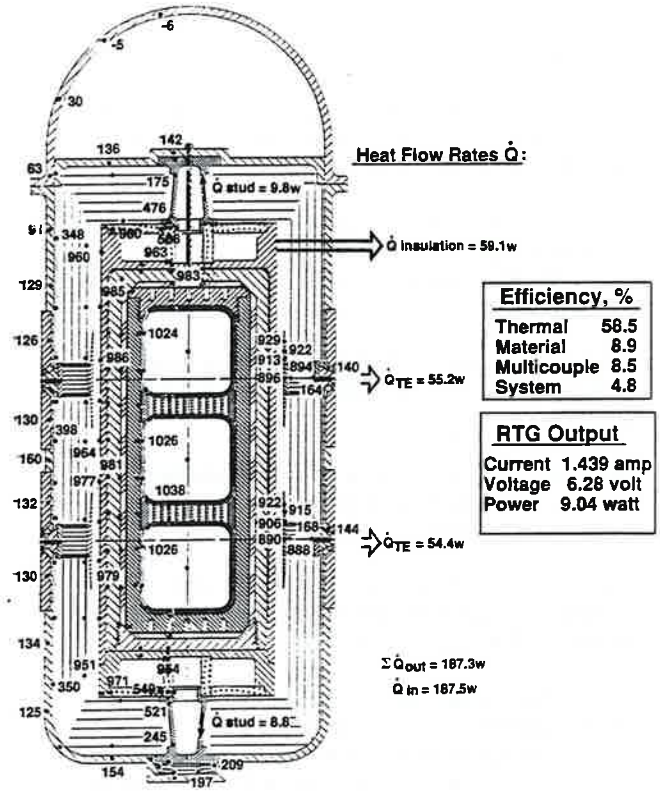


Figure 12. Operating Temperatures and Heat Flow Rates in 9-Watt RTG



Detailed thermal and electrical analyses of this RTG yielded an optimum voltage of 6.28 volts per multicouple. At that voltage, the multicouples have a material efficiency of 8.9% and a couple efficiency of 8.5%, and the RTG has a system efficiency of 4.8%, an output current of 1.439 amps and a BOM output power of 9.04 watts. The RTG's mass is 3.50 kg and its specific power is 2.58 watts/kg, which is 80% above that of the 3-watt RTG.

Design Summary

Two compact RTGs were designed for Martian operation and were subjected to detailed thermal and electrical analyses. One was a 9-watt RTG for direct data transmission to Earth, and the other was a 3-watt RTG for relayed transmission via a Mars orbiter. The principal design objective was high impact resistance to enable these RTGs to survive substantially higher impact loads than those built in the past. Although definitive dynamic analyses to determine the RTGs' allowable impact loads must await availability of the spacecraft design, the RTGs are expected to exhibit high reliability and impact tolerance because of the following factors:

- Their heat sources are based on the impact-tested and flight-proven GPHS design.
- Each heat source is enclosed in a strong refractory-metal canister.
- The massive canned heat source is supported off the RTG housing and does not contact the relatively fragile thermoelectric elements.
- The thermoelectric converter uses short, fat multicouples instead of long, thin unicouples, which greatly reduces the bending stresses due to lateral g-loads.
- The cantilevered multicouples employ small and light heat collectors, to further reduce the bending stresses.
- Each multicouple has an internal ground lead and a single sapphire-sealed terminal, to eliminate the need for fragile feedthroughs.
- The use of multicouples instead of unicouples greatly increases the RTG's output voltage and eliminates the need for DC-to-DC converters.
- The multicouples operate at conservative hot-junction and cold-junction temperatures, far below the temperatures at which thermoelectric devices have demonstrated high reliability in long-term tests and flight operations.
- The RTGs have titanium instead of aluminum housings, to eliminate the need for fragile bimetallic joints.
- The RTGs have integral helium accumulators, to eliminate the need for semi-permeable elastomeric seals for venting the alpha-generated gas to the outside.

Preliminary Impact Analysis

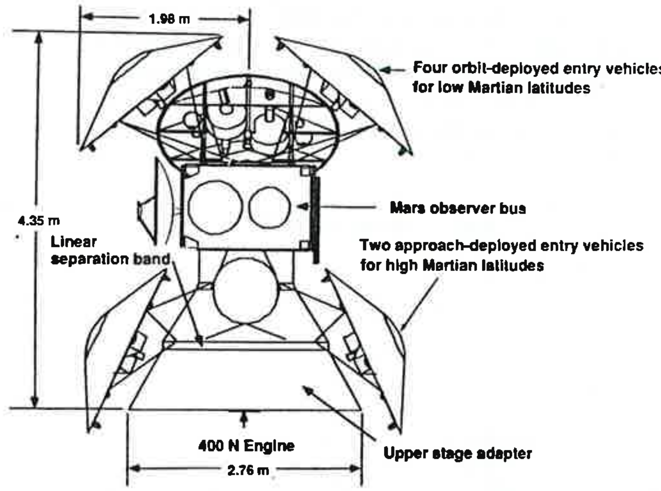
Quantifying the impact tolerance of the RTG designs described above requires detailed dynamic analyses to determine the peak g-loads during impact and continuum-mechanics analyses to compute the RTG's response to those g-loads. These analyses have not yet been carried out because the lander design is not yet sufficiently defined. In the meantime, it was possible to obtain valuable preliminary insights by analyzing the impact of an earlier lander design to determine the maximum g-load it experiences, and by carrying out quasi-static analyses of the dominant RTG stresses for various orientations at that g-load.

G-Load of Illustrative Mars Impact

An earlier JPL design [1] for a Mars Global Network system is depicted in the next three figures. Although that design was subsequently abandoned by JPL, its impact analysis is useful in providing a preliminary indication of the expected G-loads.

The earlier JPL concept envisaged the deployment of two spacecraft in orbit around Mars. As illustrated in Figure 13, each spacecraft was designed to dispense six entry vehicles, four for low Martian latitudes and two for high Martian latitudes.

Figure 13. Spacecraft for Earlier System Concept



As shown in Figure 14, each entry vehicle was shielded by a graphite aeroshell to protect it during its entry into the Martian atmosphere. Each entry vehicle contained two combined penetrators/landers. After extraction from the aeroshell by mortars, each penetrator/lander was slowed by parachute. Depending on the size of the parachute, JPL predicted an impact velocity of 60 to 100 m/sec, without retrorockets.

Figure 14. Entry Vehicle with Landers

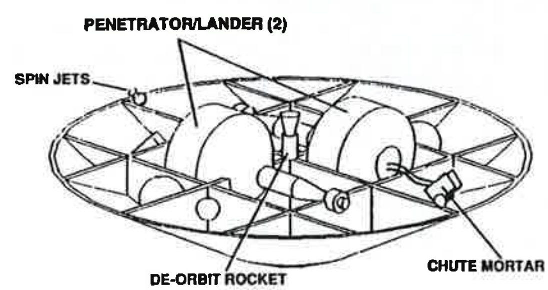
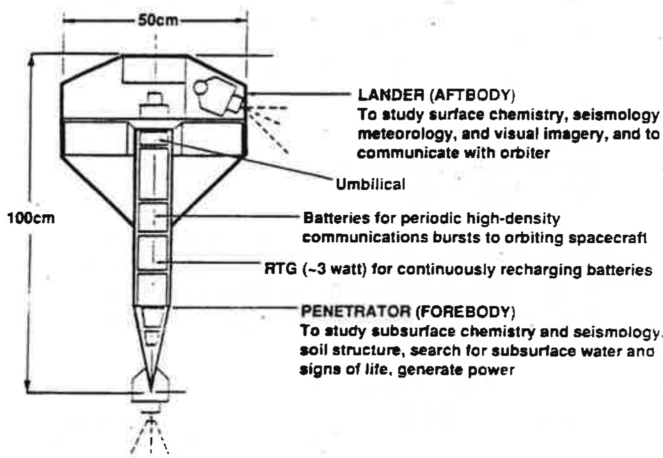


Figure 15 shows a view of JPL's original layout for the combination penetrator/lander and the functions of its principal subsystems. JPL's original concept called for the penetrator and lander to separate during Mars impact, but to remain connected by a flexible umbilical cable.

Figure 15. Earlier Concept for Combined Penetrator/Lander



A detailed hydrocode analysis of the impact of the penetrator/lander on representative soil at a velocity of 100 m/sec was carried out by Fairchild. The soil was modeled using a shock equation of state, based on an experimentally determined relationship between shock and particle velocities[9]. The model was based on a bulk sound speed of 172 m/s, a Grueneisen coefficient of 0.25, and a Mohr Coulomb yield model with a yield stress of 350 bars.

The pictorial and numerical results of the analysis at 4-msec intervals are displayed in Figure 16. At time zero, the tip of the penetrator has just touched the surface of the soil. At 4 msec the tip has penetrated to 0.39 m, and the penetrator and lander are still together, with a velocity of 92 m/sec and a deceleration rate of 432 G. At 8 msec the sharp-nosed penetrator and the blunt-nosed lander have detached, with respective penetration depths of 0.73 and 0.15 m, residual velocities of 76 and 24 m/sec, and g-loads of 540 and 1340. As can be seen, these are the peak g-load during the deceleration process. At 12 msec the two bodies have separated completely, and at 16 msec the blunt-nosed lander has reached its maximum penetration depth (0.2 m) and lost essentially all of its velocity, but the sharp-nosed penetrator still has 52% of its initial velocity and is continuing to penetrate. Extrapolation suggests that the penetrator will come to rest at a depth of about 2 meters.

Impact Response of RTGs

The impact tolerance of the RTGs is dominated by the cantilevered thermoelectric multicouples, specifically by their resistance to axial and lateral g-loads. The critical stress locations in the multicouple are the bonds at the leg assembly's hot and cold ends. Bending and tensile stresses are highest at the assembly's cold ends, but the tensile stresses at the hot end could also be critical because of lower bond strengths at elevated temperatures.

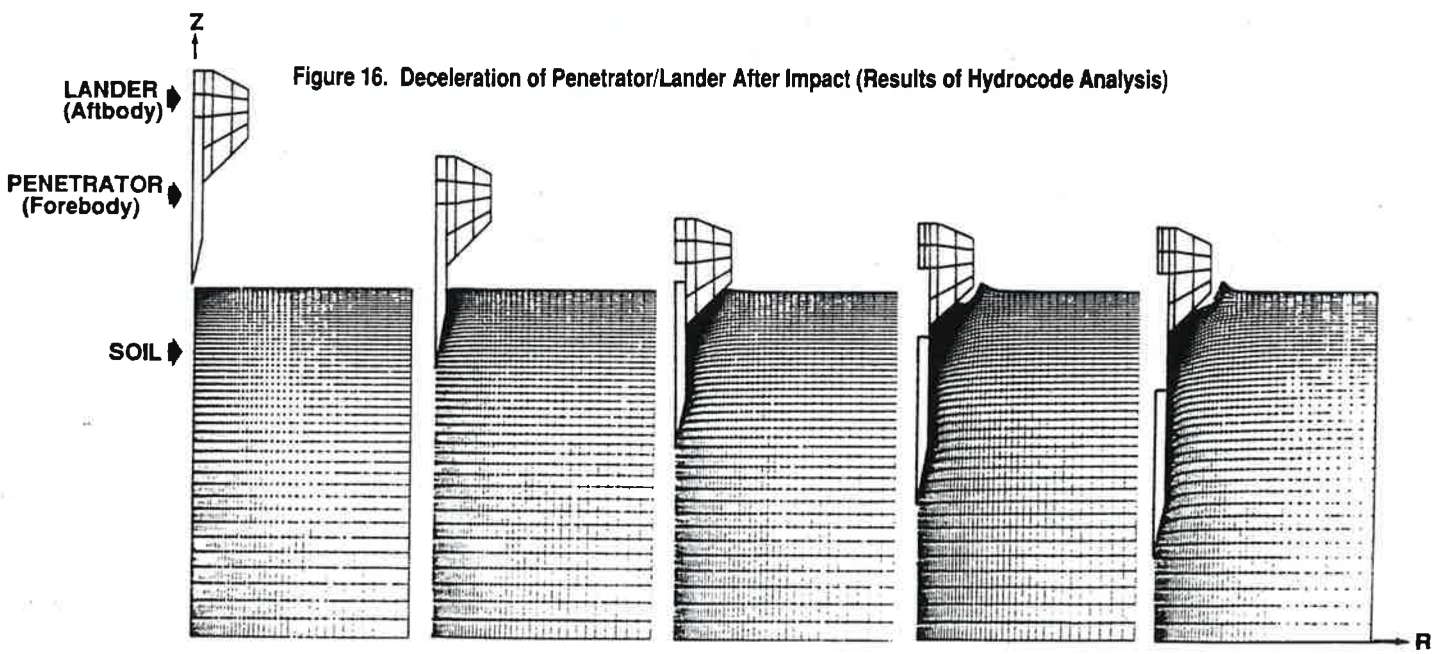


Figure 16. Deceleration of Penetrator/Lander After Impact (Results of Hydrocode Analysis)

TIME, msec	0	4	8	12	16
PENETRATION, m	0/0	0.39/0	0.73/0.15	1.01/0.20	1.23/0.20
VELOCITY, m/sec	100/100	92/92	76/24	62/2	52/1
G-LOAD	0/0	432/432	540/1340	310/400	270/0

To prevent the multifoil insulation from loading the multicouples, they are separated by a circumferential gap filled with low-density quartz fibers. Thus, each leg assembly may be regarded as a cantilevered beam with a uniformly distributed mass m_L of 1.72 gm and a concentrated heat collector mass m_H of 0.68 gm at its hot end. The cantilevered beam has a length of l of 0.75 cm, and a square cross-section of side $a = 0.66$ cm, giving a moment of inertia

$$I = a^4 / 12 = 0.0158\ cm^4 .$$

For a lateral g-load G, the bending moment M at the assembly's cold end is given by

$$M = \left(m_L\, l / 2 + m_H\, l \right) G = 1132\, G\ (dyne\ cm)$$

The corresponding maximum bending stress σ_B is

$$\sigma_B = M\,(a/2)/I = 23600\, G\ (dynes/cm^2) = 0.343\, G\ (psi) .$$

For axial g-loads, the tensile stress at the leg assembly's cold face is given by

$$\sigma_{T,C} = \left(m_L + m_H \right) G / a^2 = 5410\, G\ (dynes/cm^2) = 0.078\, G\ (psi) ,$$

and that at its hot face is given by

$$\sigma_{T,H} = m_H\ G / a^2 = 1530\, G\ (dynes/cm^2) = 0.022\, G\ (psi)$$

Clearly, the dominant stress in the multicouple is the cold-end bending stress due to lateral g-loads.

For a 100 m/sec impact, which reportedly [1] can be obtained by parachutes without retrorockets, the analytical results shown in Figure 16 predict a peak lander load of 1340 G. For that load, the quasi-static analysis presented above predicts a tensile stress of 105 psi at the cold ends and 29 psi at the hot ends of thermoelectric legs parallel to the load direction; and a bending stress of 460 psi at the cold ends of thermoelectric legs perpendicular to that load. Previous measurements on multicouples [10] indicate that a stress of 460 psi would be well within the strength capabilities of the SiGe legs and the glass bonds.

These preliminary results about the proposed RTGs' ability to withstand high-G impacts are very encouraging. But they must be checked by dynamic impact response analyses, followed by confirmatory tests.

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Acknowledgement

The author is pleased to acknowledge the contributions of T. Or and K. Sankarankandath of Fairchild and the support of DOE's Office of Special Applications (R. Lange, Director, E. Mastal, Deputy Director).