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ABSTRACT

The paper describes the design and the structural and mass analysis of a Radioisotope Thermoelectric Generator (RTG) for powering the Mars Rover vehicle, which is a critical element of the unmanned Mars Rover and Sample Return mission (MRSR). The RTG design study was conducted by Fairchild Space Company for the U.S. Department of Energy, in support of the Jet Propulsion Laboratory's MRSR project.

The paper briefly describes a reference mission scenario, an illustrative Rover design and activity pattern on Mars, and its power system requirements and environmental constraints, including the RTG cooling requirements during transit to Mars. It identifies the key RTG design problem, i.e. venting the helium generated by the fuel's alpha decay without intrusion of the Martian atmosphere into the RTG, and proposes a design approach for solving that problem.

Using that approach, it describes a very conservative baseline RTG design. The design is based on the proven and safety-qualified General Purpose Heat Source module, and employs standard thermoelectric uniconouples whose reliability and performance stability has been extensively demonstrated on previous space missions. The heat source of the 250-watt RTG consists of a stack of 18 separate modules that is supported at its ends but not along its length. The paper describes and analyzes the structure that holds the stack together during Earth launch and Mars operations but allows it to come apart in case of an inadvertent reentry.

A companion paper presented at this conference describes the RTG's thermal and electrical analysis, and compares its performance with that of several lighter but less conservative design options.

1.0 SCOPE AND OBJECTIVES OF STUDY

In December 1988 the U.S. Department of Energy's Office of Special Applications (DOE/OSA) asked Fairchild Space Company to investigate RTG (Radioisotope Thermoelectric Generator) design options for powering a Martian Rover vehicle. That vehicle is a critical part of the Mars Rover and Sample Return (MRSR) mission, which is under preliminary study by NASA's Jet Propulsion Laboratory (JPL) with the support of the Johnson Space Center (JSC). JPL is responsible for the overall MRSR study and, among other items, for the design of the Rover vehicle.

The purpose of the DOE-sponsored Fairchild study is to support JPL and JSC by providing the mission planners with information about the RTG masses and sizes for a conservative

baseline design and for various options of differing technology readiness. One of the primary aims of the study is to quantify the performance improvements achievable if new technologies are successfully developed, to estimate the required time, effort, success probability, and programmatic risk in developing those new technologies, and thus to help identify the best strategy for meeting the MRSR system goals.

In addition, the Fairchild study is useful in specifying critical design and operational requirements for integrating the RTG with the Rover and the launch vehicle (particularly cooling during orbit transfer), and in identifying what additional information JPL and JSC will need to furnish before the RTG design can be finalized.

This paper presents an abbreviated description of the MRSR mission, illustrative Rover designs, the Rover's power system requirements, the key RTG design problem and an approach for solving that problem. It then applies that approach to the design of a very conservative baseline RTG, and describes the structural analyses that were required to design the heat source supports and the RTG housing.

The electrical and thermal analysis of the baseline RTG and of a number of alternative designs is described in a separate paper [1] presented at this conference. A much fuller description of the work covered by both papers is contained in a separate Fairchild report [2], available from the author.

2.0 MISSION

2.1 BACKGROUND

The long-term goal of the National Aeronautics and Space Administration is to expand human presence beyond Earth and into the Solar System [3]. Mars, with its potential for eventual habitability, is targeted for human exploration and colonization. A manned mission to Mars must be preceded by robotic exploration of Mars, to bridge the gap between the knowledge gained by the 1976 Viking Mission and the knowledge required for a safe and effective human journey to Mars.

The Jet Propulsion Laboratory and Johnson Space Center are jointly studying such a mission, called Mars Rover Sample Return. That study is focused on understanding the system requirements and generating the first-order system design that meets these requirements [4][5]. The mission requires orbiters, landers and a Rover in Mars orbit and/or on the Mars surface.

RTGs have been selected as the primary power source for the surface elements of the MRSR system. They have a long

and successful history of space flight, and their reliability and performance have been demonstrated in missions such as Pioneer, Viking, and Voyager [6]. The current-generation RTGs, however, are designed for space operation and must be modified for Mars surface operation.

2.2 MRSR OBJECTIVES AND SYSTEM ELEMENTS

The objective of the MRSR mission is to determine the geological, climatological and biological history of the planet Mars, and to characterize its near-surface materials. The mission will also provide information on the Mars environment, and test key technologies for human exploration of the planet. The mission objectives are achieved by making in-situ analyses and returning selected samples to Earth for extensive studies.

A spectrum of possible mission and system designs has been examined against the broad science requirements [7]. These missions, which varied in launch configuration, launch date, and the various elements that constitute the mission, have been narrowed down to a reference mission consisting of five system elements: an Imaging Orbiter (IO), Communications Orbiter (CO), Rover, Sample Return Orbiter (SRO) and Mars Ascent Vehicle (MAV). The reference MRSR mission scenario and possible timeline envisioned by the JPL project team is summarized in Figure 1 and in the following paragraphs. As shown, the five system elements under this scenario are launched in four separate launch segments.

The Imaging Orbiter is launched aboard a Titan IV/IUS in October-November 1996, with Mars arrival in August-October of 1997. It maps the surface of the planet within 39 degrees of the Martian equator for landing site selection and Rover Traverse Planning [8]. A total of ten 10 x 10 km sites are mapped for selection of the landing site, and an area of 20 x 20 km at that site is more finely mapped for Rover Traverse planning.

The Communication Orbiter provides the communication link between the Mars surface elements and Earth [8]. It is launched in November-December 1998 aboard a Titan IV/IUS, and is placed in a stationary orbit such that the region between 65.7° south and north of the equator is covered continuously. The Rover-to-Earth link is available at least 95% of every Mars Sol.

The Rover element is launched aboard a Titan IV/Centaur in December 1998, with arrival at Mars in October 1999-January 2000. The Rover traverses the surface of Mars, performs in-situ analyses, deploys science packages, selects samples and returns them to the ascent vehicle for delivery to Earth. Right after its arrival, the images transmitted by the Rover are used to select a landing site for the MAV. The Rover design and its requirements are described in more detail in the next section.

The Sample Return Orbiter (SRO) and Mars Ascent Vehicle (MAV) are launched together onboard a Titan IV/Centaur in December 1998-February 1999, with arrival on Mars in October 1999-February 2000. The SRO/MAV flight segment is aerocaptured into a circular orbit around Mars [9]. After site certification by the Rover, the MAV descends to the Mars surface, where it deploys a meteorological-geophysical science package and collects contingency samples from its local environment. The SRO remains in orbit awaiting the return of the MAV and the Mars samples. The Rover transfers its collected samples to the MAV from time to time, until MAV's ascent from the Mars surface around December 2000. After liftoff from Mars, the MAV docks with the SRO and transfers the collected samples to it. The Earth return vehicle is then separated from the SRO to bring the samples back for aerocapture into low-Earth orbit, where its Martian samples are picked up by the shuttle.

2.3 MARS ROVER

The Rover element of the Mars Rover Sample Return mission for which the RTG study was performed is required to traverse more than 40 kilometers and collect 100 samples from several geologically distinct sites [10]. The Rover is equipped with semi-autonomous navigation capability, which means it can compare its surroundings with a stored map of the orbital view obtained by the Imaging Orbiter, and plan and execute a local path toward a designated point. This autonomy greatly increases the Rover's range, since it reduces the need for frequent commands from Earth. Theoretically, the Rover can go several kilometers without requiring intervention from Earth.

Figure 1. MRSR Reference Mission Scenario

The Rover returns with samples to the Mars Ascent Vehicle (MAV) several times. Each time the distance traveled expands as the confidence in the Rover is increased. A typical activity pattern is depicted in Figure 2.

The Rover is equipped with an imaging camera, multispectral imaging instruments for science and navigation, optical microscope, spectrometers (alpha, proton, neutron, x-ray), electromagnetic sounders, gas analyzer, and differential scanning calorimeter. The sample acquisition by the Rover is accomplished in several stages: remote sample characterization, location and designation of interesting samples, positioning and manipulation of the Rover to acquire the sample, and preserving the samples for return to the MAV.

Several different Rover designs and mobility systems are under investigation. One possible mobility system is illustrated in Figure 3. It employs a six-wheeled pantograph, with one-meter wheels that can move across rough terrain. This design was developed by a JPL in-house study.

Figure 3. Illustrative Rover Design: Wheeled-Vehicle Option

An alternative Rover design is illustrated in Figure 4. This "walking beam" design was developed by the Martin Company, under contract to JPL. In the illustrated version, it employs two tripods, linked by a tracked beam. During movement, one tripod rests on the ground, and the legs of the other are raised, enabling it to move along the tracked beam. During the next step, the position of the two tripods are reversed. Directional changes are accomplished by using a turntable to pivot the raised tripod about the point where it joins the grounded tripod.

Figure 4. Illustrative Rover Design: Walking-Beam Option

The number and location of RTGs on the Rover are very critical and require trade-off analysis. The Rover designers may prefer several small RTGs distributed around the vehicle, since this arrangement can help in the load distribution and facilitate the use of the RTGs' waste heat for thermal management of the Rover body and electronics bays. Also, shorter RTGs are less likely to block other Rover instruments and/or antennas. On the other hand, longer RTGs offer a higher specific power, because of decreased end losses and weights. They also are less likely to obscure the view of each other's radiators to space. At present, two concepts for integrating the RTGs with the Rover are undergoing evaluation, one employing two 250-watt RTGs, and one employing four 125-watt RTGs mounted on top of the Rover. The four-RTG option is illustrated in Figure 3, and the two-RTG option is shown in Figure 4. Either option could be used with either type of vehicle. Note that the RTGs are mounted vertically, to prevent build-up of sand on their heat rejection surfaces during Martian storms.

3.0 ROVER POWER SYSTEM

3.1 RTG REQUIREMENTS

The MRSR mission calls for the Rover to operate for four years after launch. The launch is assumed to occur three years after fuel encapsulation, and to be preceded by one year of full-temperature operation of the thermoelectric converters. Thus, by the end of the mission the RTG's fuel will have decayed for seven years, and its converters will have degraded as a result of operating at full temperature for five years.

As illustrated in Figure 5, the Rover has an average power requirement of 500 watts, with peak power demands of over one kilowatt when the Rover is climbing a slope or in the process of sample acquisition. The RTGs will be designed to provide continuous power with an output of 500 watts at the end of the mission, and will be supplemented by high-power-density rechargeable batteries for meeting power demand peaks that exceed the output of the RTGs. These batteries will be recharged by the RTGs during periods of low power demand.

Figure 5. Power Demand Profile for Typical Mars Rover Activities

3.2 RTG ENVIRONMENT

Both the Rover and Mars environments present new challenges to the RTG designer. Previous RTGs (MHW, GPHS) were designed primarily for operation in microgravity and in a high vacuum after launch. The Rover and Mars environments are more difficult, mechanically, thermally, and atmospherically.

From the dynamic-environment point of view, the Rover RTG has to withstand launch, entry, landing, and traverse loads that occur at different times in the life of the mission. These loads cannot be accurately determined until the spacecraft and Rover structures are better defined. In the absence of such definition, the RTG design study was conservatively based on 3-axis design loads of 25 G during Earth launch and 15 G during the Mars landing and for the balance of the four-year mission.

During entry into the Martian atmosphere, the Rover-mounted RTGs are enclosed in a protective aeroshell, as illustrated in Figure 6. While they are enclosed in that aeroshell, they are unable to radiate their waste heat to space, and will therefore require an auxiliary cooling loop. For short periods, during Earth launch and Mars entry, a water boiler

dumping steam overboard could be used as the loop's heat sink. But for the much longer orbital transit period, a steady state heat rejection system is required. Therefore, during the cruise to Mars, the RTGs will either require a mechanism for their temporary deployment outside the aeroshell, to permit radiative cooling; or will require continuous operation of the auxiliary cooling loop to transfer their waste heat to radiators located on or outside the Rover's aeroshell. The latter option is probably preferable, because it avoids the mechanical complexity and potential unreliability of a deployment mechanism. The necessary reliability of the auxiliary cooling loop can be achieved by the use of redundant cooling pumps.

Figure 6. Rover with RTGs and Lander Enclosed in Aeroshell

The most difficult problem imposed by the Mars surface environment is the presence of an external atmosphere [11]. The thermoelectric converter elements in the RTG are embedded in multifoil thermal insulation, to minimize heat losses from the hot heat source to the cool generator housing. Thus, the insulation forces most of the heat to flow through the thermoelectric legs. Multifoil insulation performs well in the absence of conducting gases, but degrades rapidly when such gases are present. Moreover, at the projected operating temperatures even small amounts of some of the Martian gases would react with the converter's materials and degrade its performance. Therefore, inleakage of Martian gases and buildup of alpha-generated helium in the converter must be prevented.

4.0 DESIGN APPROACH

The present paper summarizes the design of a "baseline" RTG employing proven components and performance parameters. To minimize the need for new developments, it is conservatively based on: standard General Purpose Heat Source modules, which have been developed and safety-qualified for the Galileo mission; standard SiGe unicouples, developed and extensively lifetested for the Voyager and Galileo missions; and thermoelectric performance parameters and degradation rates that have been demonstrated in extended ground tests and space missions.

A more detailed description of the baseline RTG's design, mass breakdown, and of its structural, thermal, thermoelectric, and electrical analyses for a variety of environmental conditions is presented in a separate Fairchild report [2] available from the author.

through the midplane of a heat source module and through the midplane of a ring of thermoelectric uncouples. Different shading patterns are used to designate the helium volume inside the heat source canister and the Martian atmosphere outside the RTG housing. As shown, the intervening annular converter is evacuated, and is separated from the helium by the heat source canister and from the Martian atmosphere by the RTG housing.

Figure 9. Horizontal Cut Through Baseline RTG

6.0 BASELINE RTG

6.1 DESIGN DESCRIPTION

Figure 10 shows a cutaway view of the top of the thermoelectric converter, before insertion of the radioisotope heat source. The converter contains 576 SiGe uncouples. These are arranged in 36 horizontal rings, each consisting of 16 equispaced uncouples, depicted earlier in Figure 8. Each uncouple has a -1×1 inch heat collector, which concentrates the heat radiated from the heat source and delivers it to the couple's n- and p-legs. Heat transfer from the heat source canister to the uncouples is by radiation across a vacuum gap, without any physical contact. The RTG design is based on a maximum hot-junction temperature of 1000°C , which is the temperature at which uncouple assemblies have demonstrated long-term reliability and performance stability in extended ground tests and space operations.

As indicated in Figure 10, the 576 thermoelectric couples are embedded in 0.8"-thick thermal insulation, to minimize heat loss to the cooler RTG housing. The insulation consists of 60 layers of 0.0003" molybdenum foils separated from each other by alternating layers of quartz cloth. This is a very conservative insulation design, whose reliability has been demonstrated in long-term ground tests and space operations. The alternative of separating the molybdenum foils with zirconia particles instead of quartz cloth, which has been successfully used in more recent thermoelectric converter assemblies, would lead to considerably lighter and more compact insulation packages.

Figure 9b. Unfueled Converter

At the cold-side of the thermal insulation, the 576 uncouples are connected in a series-parallel network. Couples are connected in parallel groups, to eliminate the risk of single-point failures. If any couple were to experience open-circuit failure, its partner(s) would carry the increased current, permitting continued RTG operation. There are 144 parallel couple groups in series, to build up the desired RTG output of 30 volts. To avoid the risk of shorts-to-ground causing single-point failures, the circuit is not grounded to the RTG housing.

The cold ends of the 576 uncouples are bolted to the RTG's 0.090"-thick aluminum housing. In the Galileo RTG, the uncouple bolt holes were sealed by metal c-rings, but these would be inadequate for preventing inflow of the Martian atmosphere during the four-year mission. As shown in the enlarged inset at the lower left corner of Figure 9, the bolt holes in the present design are sealed by 16 aluminum cover strips welded to the aluminum housing ribs.

The uncouples deliver their waste heat to the RTG's aluminum housing. The housing and its eight fins serve to reject the RTG's waste heat, either by radiation to space or (when direct radiative cooling is not possible) by convection to the auxiliary coolant in the fins' integral cooling tubes.

Figure 11 shows a partially exploded cutaway view of the top of the RTG, after fueling. At its center is the heat source, consisting of a stack of 18 GPHS modules. The heat source stack is contained in a cylindrical molybdenum canister which acts as a helium container. The canister's end caps serve to provide the lateral support and axial compressive load to the ends of the heat source stack. The stack does not touch the canister along its length, and does not have any midspan supports.

The conservative baseline RTG, designed to produce 250 watts(e) at the end of the 4-year MRSR mission (i.e., 7 years after fuel encapsulation), has an overall height of 45.9 inches; a housing diameter 9.1 inches, and a tip-to-tip span of 15.2 inches.

Figure 11. Baseline RTG, Upper End

6.2 HEAT SOURCE SUPPORT

One of the most critical issues in designing an RTG with stacked heat source modules is the scheme for supporting that stack.

The GPHS module design is primarily driven by safety considerations. The modules are designed to survive hypersonic reentry and subsequent ground impact without fuel release. To maximize the impact safety margin, one wishes to minimize the impact velocity. Individual modules have a much lower impact velocity (49 m/s) than the stacked heat source (74 m/s). Therefore, it is desirable to support the heat source stack in such a manner that the individual modules separate in case of inadvertent reentry into the Earth's atmosphere. Automatic separation is accomplished by structurally supporting the heat source stack from the RTG's aluminum housing, which melts during reentry, releasing the modules. But the same support structure must hold the stacked modules together during launch and operational vibration and shock loads.

6.2.1 Description of Support Structure: The heat source support arrangement will be described in detail with respect to the baseline RTG design, and the same basic arrangement is used in the alternative RTG designs discussed in the companion paper [1]. Since the heat source stack is only supported at its ends and there are no midspan supports, a large (5500-lb) axial preload is required to hold the stack together during launch under the assumed 25-G transverse load. The axial preload is applied directly to the ends of the stack, via the canister's end caps. The canister's side wall plays no structural role; it is merely a helium container, and is thin enough to burn off during reentry.

Figure 12 presents an exploded closeup of the support structure at the top of the heat source stack. As shown, the top of the heat source stack is followed by a graphite transition section which bears against the top cap of the molybdenum canister via a thin iridium sheet that serves as a reaction barrier between the graphite and the molybdenum.

On the outside of the canister end cap is a set of integral stiffening ribs and load stud seats. These form a square structure, to spread the axial load from the four load studs to the four edges of the heat source end face. The four studs at each end are similar to those used in the Galileo RTG. They are made of low-conductivity Inconel, and are separated from the stud seats by zirconia insulators to reduce axial heat losses and to lower the temperatures of the creep-prone Inconel studs and titanium springs. As indicated in Figure 11, the load studs penetrate through the multifoil thermal insulation.

Figure 12. Support Structure at Top of Heat Source

The tops of the four studs are bolted to a titanium load ring, which is laterally supported and axially loaded by a set of three nested Belleville springs made of 0.2"-thick titanium. Three springs are used in order to generate the required preload without exceeding the allowable stress in the springs. The I.D. of the bottom spring bears against the load ring, and the O.D. of the top spring bears against a titanium preload adjustment ring that is threaded to the I.D. of the aluminum housing. After the load is set, rotation of that ring is prevented by pins protruding from the RTG's aluminum cover. That cover serves only as a pressure dome, and has no other structural function.

Clearly, the heat source stack is ultimately held together by the RTG's low-melting aluminum housing. When that housing and the thin canister burns away during reentry, the heat source modules are free to disperse and impact individually.

Figure 13 shows an exploded view of the heat source's lower support structure (viewed from below), and Figure 14 shows a cutaway view of the lower end of the assembled RTG. As can be seen, the lower support structure uses an identical set of load spreaders, zirconia insulators and Inconel studs as the upper support structure. But there are no springs, and the studs are mounted directly on the RTG's aluminum base plate. The base plate employs 1" x 0.25" radial and circumferential ribs to provide the required stiffness.

The figures also show the helium vent tube at the center of the canister's base. The vent tube passes through the evacuated converter region and is sealed to the RTG base plate. A bimetallic joint is used to seal the vent tube to the aluminum base plate. Similar bimetallic joints are used to connect the aluminum base plate to the metal-ceramic seals which serve for the electrical isolation of the RTG terminals.

Figure 13. Support Structure at Bottom of Heat Source

Figure 14. Lower End of Assembled RTG

The helium generated by the fuel's alpha decay is vented to space, through a semi-permeable Viton seal which prevents inflow of the Martian atmosphere into the heat source canister. In effect, the Viton seal acts as a pressure relief device.

6.2.2 Structural Analysis: The Belleville springs shown in Figures 11 and 12 must supply sufficient force to enable the heat source stack to withstand the lateral G-loads during launch while the RTG fins are water-cooled. Once the Rover aeroshell is discarded after entry into the Martian atmosphere, the RTG is cooled radiatively for the balance of the mission.

When changing from water-cooling to radiation cooling, the RTG housing temperature rises about 100°C (on a summer day). This causes a differential growth of about 0.100" in the length of the high-expansion aluminum housing relative to the low-expansion graphite heat source stack, with a corresponding increase in the Belleville spring length and drop in spring force. In RTGs for other missions, the magnitude of the spring force is only important briefly during launch. In the case of the Rover RTG, the springs must still provide sufficient force after relaxation to hold the heat source together during Mars traverses for the balance of the four-year mission.

The structural analysis and design of the RTG consists of three principal tasks:

1. Determining how large a preload is required to hold the modules together during Earth launch and during Mars operations.
2. Designing the Belleville springs to supply the required spring force and spring travel.

3. Determining the stresses in the heat source modules, and designing the RTG housing to withstand the bending moments on the cantilevered RTG during launch, to be structurally stable against the one-atmosphere external pressure on earth, and to stay below the stresses where long-term creep would occur at the materials' operating temperatures.

The stress analyses to carry out these tasks are described in detail in the full Fairchild report [2], and summarized below.

6.2.3 Required Heat Source Preload Force: The heat source stack may be viewed as a partitioned beam with a distributed side load. If the beam were continuous rather than partitioned, the side load would produce axial compressive stresses on the side to which it is applied, and axial tensile stresses on the opposite side. But a partitioned beam cannot sustain a tensile stress in the axial direction. Therefore, in the absence of an axial preload, the side load would cause the partitioned beam to fall apart. To hold the heat source stack together in the RTG, the axial preload must be high enough to equal or exceed the maximum axial tensile stress produced by the side load.

As shown in the full report [2], for the simplified case of a partitioned hollow box beam having a cross-section bounded by an outer square of side a and inner square of side b , with a length L , mass per unit length m , and subjected to a transverse g -load G , the preload P required to hold the partitioned beam together is given by

$$P = \frac{mGL^2/4a}{1 + (b/a)^2} \quad (1)$$

The actual heat source stack is more complicated. The heat source modules that comprise the stack have curved cavities and non-uniform side walls. Therefore, it was necessary to construct a detailed solids model of the GPHS module's aeroshell, to determine the required axial preload. A stack of 16 such modules was subjected to a side load of 25 G and an axial load of 4000 lbs (18 kilonewton). In the initial NASTRAN analysis, the heat source stack was analyzed without the effect of the simultaneous deformation of the cantilevered RTG housing. This simplification cuts the problem in half, because it results in identical end supports and symmetry about the heat source's midplane. The resultant deformation of the upper half of the 16-module stack is shown in Figure 15.

The corresponding distribution of heat source stresses was analyzed, using orthotropic properties for the carbon-carbon composite (FWPF). All normal-Z stresses were found to be negative (i.e., compressive), except in Module 1 where one small corner section was found to exhibit a tensile stress of 0.53 ksi (3.7 MPa), as shown in Figure 16. It was therefore concluded that the 4000-lb preload is slightly inadequate for the 16-module heat source. Based on these results, it was decided to use a 5500-lb preload for the 18-module heat source in subsequent analyses.

6.2.4 Designing the Belleville Springs: The Mars Rover RTG design differs from other RTGs in that a preload is required not just for a brief period during Earth launch, but also during atmospheric entry and landing on Mars and during Rover activities on Mars for the full four-year duration of the MRSR mission. Although the G -loads during these post-launch operations (15 G) are lower than during launch (25 G), one cannot assume that springs which satisfy the higher requirement will automatically satisfy the lower. This is so because the Rover RTG is water-cooled during Earth launch and radiation-cooled during and after Mars landing, as previously explained.

Figure 15. Deformation of Upper Half of Heat Source Stack Under 4000-lb Axial Load and 25G Side Load (Y)

In switching from water-cooling to radiation-cooling, the RTG's housing temperature rises by about 100°C, causing its length to grow by about 0.1". Since the thermal expansion of the graphite heat source is virtually negligible, the thermal growth of the aluminum housing causes a corresponding expansion of the Belleville preload springs, and consequently a relaxation of the compressive load on the heat source stack.

Figure 16. Normal Z-Stresses in Top GPHS Module (in ksi) (1 ksi = 6.89 MPa)

Therefore, the designer must consider the adequacy of the spring force both during launch and during subsequent Martian operations, at their respective RTG temperatures. At the same time, he must make certain that the maximum stress in the spring material under maximum-load conditions does not exceed the spring material's strength at temperature. Thus, the spring design must satisfy three independent constraints.

Consider a set of N_p parallel (i.e., nested) Belleville springs, and N_s such sets stacked in series. Each spring has an outer diameter D_o , inner diameter D_i , and thickness T . The springs are made of a material with elastic modulus E and Poisson's ratio μ . The overall free height of each spring is $H + T$, and the deflection of each spring from its free height during Earth launch is Y_e . During Martian operations, the deflection of each spring from its free length is given by

$$Y_m = Y_e - \delta/N_s, \quad (2)$$

where δ is the thermal growth of the aluminum housing length due to the change from water cooling to radiation cooling.

The load P_e exerted by the springs during Earth launch is given by [14]

$$P_e = \frac{N_p E Y_e [(H - Y_e/2)(H - Y_e)T + T^3]}{(1 - \mu^2) C_0 (D_o/2)^2}, \quad (3)$$

the corresponding load P_m during Martian operations is given by

$$P_m = \frac{N_p E Y_m [(H - Y_m/2)(H - Y_m)T + T^3]}{(1 - \mu^2) C_0 (D_o/2)^2}, \quad (4)$$

and the maximum stress σ (at the inner diameter of the springs) is given by

$$\sigma = \frac{E Y_e [C_1 (H - Y_e/2) + C_2 T]}{(1 - \mu^2) C_0 (D_o/2)^2}, \quad (5)$$

where C_0 , C_1 and C_2 are dimensionless geometric constants defined by:

$$C_0 = \frac{6(1 - D_i/D_o)^2}{\pi \ln(D_o/D_i)}, \quad (6)$$

$$C_1 = \frac{6}{\pi \ln(D_o/D_i)} \left[\frac{D_o/D_i - 1}{\ln(D_o/D_i)} - 1 \right], \text{ and} \quad (7)$$

$$C_2 = \frac{3(D_o/D_i - 1)}{\pi \ln(D_o/D_i)}. \quad (8)$$

Designing the Belleville springs required the solution of the above three simultaneous cubic equations. The spring design was for an outer diameter of 8.75 inches, to mate with the inside of the RTG housing, and an inner diameter of 3.20 inches, to mate with the load ring. The springs were designed to deliver an axial load of 5500 lbs in the water-cooled RTG and 3300 lbs in the radiation-cooled RTG. The titanium spring alloy was assumed to have an elastic modulus of 11×10^6 psi, a Poisson ratio of 0.31, and an allowable compressive stress of 82 ksi. For these parameters, it was found that the three design goals could be satisfied with a single set of three nested springs, each having a thickness of 0.221 inch, a free height of 0.451 inch, and a compressed height of 0.275 inch in the water-cooled RTG and 0.375 inch in the radiation-cooled RTG.

6.2.5 Von-Mises and Shear Stresses in Heat Source: The same solids model shown in Figure 15 was used to compute the von Mises stresses in the modules. The maximum stresses were found to occur in Module 1, and are shown in Figure 17.

Figure 17. Von Mises Stresses in Module-1 (in ksi)

As can be seen, the maximum von Mises stress, in the upper right corner of Module #1, is 3.15 ksi. This is only 15% of the tensile and compressive strengths of the Fine-Weave Pierced Fabric (FWPF) graphite material, as shown in Table 1, which was supplied by its manufacturer AVCO.

Table 1. Composite Strength (ksi) of AVCO Fine-Weave Pierced Fabric

TEMPERATURE		75	600	1000	2000	3000	4000	5000
	°C	24	-316	537	1093	1649	2204	2760
TENSION	Y	17.74	19.66	20.65	23.86	26.21	27.39	25.20
	X	17.84	19.66	20.66	23.86	26.21	27.38	25.20
	Z	18.17	20.24	21.28	24.57	26.99	28.20	25.95
COMPRESSION	Y	20.61	20.78	20.85	21.59	23.56	26.49	30.61
	X	20.61	20.78	20.85	21.59	23.56	26.49	30.61
	Z	20.8	21.0	21.11	21.89	23.89	26.66	31.00
SHEAR	YZ	1.17	1.11	1.07	1.00	0.99	1.26	1.00
	ZX	1.17	1.11	1.07	1.00	0.99	1.26	1.00
	XY	1.17	1.11	1.07	1.00	0.99	1.26	1.00

Figure 18. Module-1 YZ-Shear Stresses, in ksi

Table 1 shows that FWPF is much weaker in shear than in tension or compression. Therefore, the xy, xz, and yz shear stresses were computed. The maximum shear stress was found to be the yz-stress in Module 1. As shown in Figure 18, the maximum shear stress is 0.138 ksi. This is only 14% of the material's shear strength, as shown in Table 1.

6.2.6 Deformation and Stresses in Full RTG: The preliminary structural analysis described thus far employed a simplified analytical model that did not include the RTG housing, which supports the load springs that compress the heat source stack. In the more complete analysis described in the full report [2], the heat source was supported by the deformable RTG housing. Specifically, the upper springs were connected to the top of the housing side wall, and the lower heat source support studs were mounted on the housing baseplate.

The model of the housing included the fin roots and cooling ducts which act as stiffeners. It also included the radial and circumferential stiffeners of the baseplate. The housing was cantilevered, with only the rim of its baseplate fixed and the rest of the housing free to lean away from the 25-G side load. The resultant angular deflection of the RTG's upper end resulted in highly unsymmetrical heat source supports. Therefore, it was necessary to model the whole 18-module heat source.

The solids model used for the preliminary analysis of the eight-module half-stack had 10,961 grid points and 26,652 degrees of freedom. Using a similar solids model for the full eighteen-module heat source would have exceeded the available computer time and disk space. To avoid that, the solids model was replaced with a plate model having an equivalent stiffness matrix. Even so, a very large (2140-node) NASTRAN model with 10,611 degrees of freedom was required to represent the heat source, its support structure, and the RTG housing.

Figure 19 depicts the model of the RTG in its undeformed and deformed shapes. The deformation shown includes the effects of the 25-G side load and of the 5500-lb spring force, which produces a compressive load on the heat source stack and a tensile load on the housing.

The deformations shown have, of course, been exaggerated for improved visibility. Note the leaning of the housing and the bowing of the heat source in the y-direction, the axial elongation of the housing due to its tensile load, and the outbowing of the RTG's baseplate due to the downward force exerted by the heat source.

Figure 20 shows the von Mises stress distributions in the RTG's 0.062"-thick top cap and in its 0.125"-thick baseplate. Before launch, the top cap is subjected to an external pressure of one atmosphere. Its maximum stress, ~5 ksi, is well below the strength of aluminum.

The heavy white lines in the baseplate stress plot show the location of the eight radial and three circumferential stiffening ribs, which are 0.25" thick and 1" high. The two white dots in the figure denote the locations of the heat source support studs. As can be seen, the maximum launch stress (18 ksi) occurs at the +y side of the inner stiffening ring. A secondary maximum (14 ksi) occurs at the right side of the middle stiffener ring. This location is directly below one of the two support studs at the +y side of the heat source. The maximum baseplate stress is 42% below the 31-ksi yield strength of the aluminum alloy at its 171°C launch temperature.

Figure 19. Deformation of Spring-Loaded Heat Source Supported by Cantilevered RTG Housing

Figure 20. Von Mises Stresses in RTG Top Cover and Base Plate

The right half of the figure shows that the maximum von Mises stress, 2.9 ksi, is again far below the strength limit of the FWPF graphite material. (See Table I.)

Figure 10 displays two 3D wireframe plots of a rectangular prism, showing the distribution of stress components. The left plot is labeled "Normal-Z" and the right plot is labeled "von Mises". Both plots show the stress distribution along the Z-axis, with values ranging from -2.69 to -1.09 for Normal-Z and 0.94 to 2.82 for von Mises. The plots are oriented along the X, Y, and Z axes, with the Z-axis pointing upwards.

Figure 22. Von Mises Stresses in Housing Side Wall (ksi)

The maximum launch stress, which occurs at the -y side near the base of the RTG, is -15 ksi. This is well below the 31-ksi yield strength of the aluminum alloy (2219 T851) at its 171°C launch temperature. Similarly, the maximum stress on Mars, 8.5 ksi, is only 53% of the alloy's 16-ksi yield strength at its 272°C maximum operating temperature.

In addition to yield strength, the long-term creep characteristics of the aluminum housing must be considered. The RTG housing, at its thinnest (0.090") section, has a horizontal cross-section of 2.54 in². Thus, at its maximum operating temperature, the 3300-lb spring load will produce a steady-state tensile stress of 1.3 ksi. Even if the housing were constantly at its maximum Martian operating temperature of 272°C, this tensile stress would produce only negligible creep during the four-year mission.

In summary, the detailed NASTRAN analysis of the spring-loaded heat source supported by the cantilevered RTG housing confirmed the feasibility of supporting an 18-module heat source stack without midspan supports, and demonstrated the adequacy of the spring and housing dimensions on which the mass analyses in the next section are based.

6.3 MASS BREAKDOWN

The mass breakdown of the "baseline" Mars Rover RTG, depicted in Figures 11 and 14, is presented in the left half of Table 2. 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 breakdown.

Table 2. Mass of Baseline RTG Versus Galileo RTG

RTG MASS BREAKDOWN (kg)	ROVER RTG BASELINE DESIGN	GALILEO RTG
HEAT SOURCE (33.8/30.1 kg)		
GPMS MODULES (18/18)	25.05	25.05
FUEL (FUEL)	10.73	10.73
CAPSIDES (P)	4.21	4.21
GRAPHITES	11.11	11.11
H.S. CANISTER (Mo)	3.77	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	0.52	0.52
LOAD STUDS/ZIRCONIA	0.27	0.36
BELLEVEILLE SPRINGS (1)	2.31	0.51
OTHER PRELOAD HARDWARE	0.84	1.69
MID-SPAN SUPPORT ASSEMBLY	-----	0.94
CONVERTER (24.9/25.0 kg)		
ELECTRICAL CIRCUITS	7.74	7.65
TE ELEMENTS (576/572)	5.43	5.40
TE FASTENERS AND SEALS	1.09	1.04
ALUMINA INSULATORS	0.88	0.88
ELECTR. CONNECTORS + TERMINALS	0.34	0.29
MULTIFOIL INSULATION (Mo/Quartz)	5.94	7.16
SIDES	5.26	5.52
ENDS	0.68	0.55
SUPPORT STRUCTURE	-----	1.09
RTG HOUSING (Al)	8.45	8.17
SIDE WALL (0.090" x 0.090")	7.01	6.47
COVERS & BOLTS	0.56	0.81
RESISTANCE THERMOMETER	0.30	0.30
GAS MOUNT ASSEMBLY	0.16	0.16
PRESSURE RELEASE DEVICE	-----	0.43
RADIATOR	2.78	3.00
FINS (Nb)	2.38	1.96
AUXILIARY COOLANT MANIFOLDS	0.25	0.26
EMISSIVITY COATING	0.15	0.15
MISCELLANEOUS ELEMENTS	-----	0.93
TOTAL RTG MASS (kg)	58.67	56.08

The left column of Table 2 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 2 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. Most 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.

Similar mass analyses were performed for the RTG designs discussed in the companion paper [1], and their results are reported there. That paper also presents a detailed description of the thermal, thermoelectric, and electrical analysis of the baseline RTG, and compares its performance with that of several alternative RTG designs.

7.0 RESULTS AND CONCLUSIONS

The work described in the present paper led to the following conclusions:

1. The current multifoil-insulated GPMS-RTG and Mod-RTG designs can be modified to operate in an environment with an external atmosphere (e.g., Mars).
2. The helium generated by the fuel's alpha decay can be vented to the outside without intrusion of the external atmosphere into the RTG.
3. The use of novel selective vents and unproven high-capacity getters is not required.
4. The Rover RTGs can be built from standard and proven General Purpose Heat Source modules and standard SiGe unicouples or SiGe/GaP multicouples, using demonstrated thermoelectric material performance parameters.
5. The modular heat source stack in the Rover RTG is held together by axial load springs, without the use of mid-span supports.
6. The springs will support and hold the heat source together under transverse loads of 25 G in the water-cooled RTG during Earth launch and Mars entry and 15 G in the radiation-cooled RTG during subsequent Mars operations, without exceeding the allowable stresses in the springs, the heat source, or the RTG housing.
7. In case of inadvertent reentry into the Earth's atmosphere, the RTG's aluminum housing will burn off, allowing the heat source modules to separate and impact at a relatively low velocity.
8. An auxiliary cooling loop (e.g., water and antifreeze) will be required to cool the RTG while it is within the Rover's aeroshell during launch and transit to Mars.
9. The RTGs are mounted on the Rover in a vertical orientation, to avoid the buildup of wind-borne Martian sand on its heat rejection surfaces.
10. The ~250-watt baseline RTG containing 18 heat source modules and employing 576 standard unicouples has a mass of 58.7 kg, a length of 45.9 inches, a housing diameter of 9.1 inches, and a tip-to-tip radiator span of 15.2 inches.

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