Structural Design Challenges for Mars Rovers

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Abstract

On July 4, 1997 the Pathfinder Mission successfully began an new era of robotic exploration of Mars. The primary scientific payload for the Pathfinder Lander is the Sojourner Truth Mars Rover, an autonomous robotic vehicle, which is exploring and conducting scientific measurements on the Mars surface. The development of the structure of the Mars Rover required innovative design and testing to overcome the mission constraints from the difficult environments during launch, cruise and surface operational phases of the mission. 'J'here were additional constraints on mass, power and volume and requirements for sterilization for planetary protection. The final design consisted of an integrated structural and thermal design utilizing lightweight thermally insulating composites with aerogel insulation. Over the next several years, a series of Rovers will explore the surface of Mars. These will range from small Nanorovers weighing less than 1 Kg to large science rovers weighing up to 50 Kg, and sample return rovers somewhere in between. Each wil I require special ized composite structures and sampling mechanisms to reduce mass, and provide structural thermal isolation.

Sojourner Rover

The Sojourner Rover is part of the scientific and engineering payload for the Mars Pathfinder mission to explore the Martian surface. The Pathfinder mission is an engineering demonstration of key technologies and concepts for the future exploration of Mars employing surface landers and rovers. The mission successfully landed on Mars on July 4, 1997. A picture of the rover system just after landing is shown in Figure 1. The Sojourner rover was limited to a total mobile mass of 11.0 kg, including the Alpha-Proton X-ray Spectrometer (APXS) scientific instrument, ten engineering experiment packages and an imaging system. The landing site for the Pathfinder mission is a rocky plain in an area known as Ares Val 1 is. The atmosphere is nominal ly 8 torr CO_2 gas, with average surface wind that may range from 0.2 to 1 m/s at night, and up to 4 m/s during the day. The diurnal surface and atmospheric temperatures have ranged from a high of 0°C to a low of -83 °C. The Mars Rover mission operation scenario is driven by the Martian environment and the power limitations on the Rover for heat generation. The primary internal heating is provided by 1{11[1's that produce 2.9 W continuously. Power is provided by the solar array and is used internally for electronic components, and externally for motor and steering drive mechanisms, lasers, cameras for navigation, and for the operation of the APXS. The dissipated heat from the electronics provides the second significant source of internal heating during the day.

The primary structural elements are the Warm Electronics Box (WEB), solar array and the rocker-bogie mobility system. The WEB and the solar array structure are composite structures. The rover is contained within a stowed volume of 340 mm by 275 mm by 150 mm, and the deployed rover size is 650 mm by 470 mm by 320 mm. It's mobility is provided by a six wheel drive, rocker-bogic suspension system with four steerable wheels. Power will be supplied from a single 0.22 m^2 GaAs solar panel that provides a peak power of 16 Watts and has a nonrechargeable battery system that can provide 150 W-hr at 50940 depth of discharge for the night operation of the APXS. The WEB must vent the air pressure during launch, survive launch and landing, and meet strict planetary protection standards. The WEB also has electrical cabling passing through the cable tunnel to connect with the solar array, motors, charge couple device (CCD) cameras, lasers, the drive system and other external experiments. The Sojourner rover design developed from the need to meet conflicting thermal requirements, the need to stay within a system mass allocation without giving up functionality and the requirement to stay within a small volume envelope.

‘l’his requirement for minimal mass and thermal control led to the development of Sojourner's lightweight composite integrated structure and thermal control[1]. This led to a different design solution for rovers than for landers, such as the two Viking Landers[2] and pathfinder[3]. The structural requirements were derived from the vibration and acoustic loads associated with the Delta 11 launch vehicle and from the impact loads that were expected to occur during Pathfinder entry, decent and landing (EDL). ‘l’he highest loads were expected during EDL, where the rover could potentially have seen up to a SO g impact load. For Sojourner, the thermal constraints and mass limitations of the mission were the primary drivers for the mechanical system. The overal 1 thermal system requi rements arc based on the internal temperature requirements of the electronic components during the different phases of operation environments. These were ground operations before launch, launch, cruise to Mars, and Mars surface exploration.

In the last decade, there has been a significant amount of interest in solid aerogel materials, both organic and inorganic[4]. ‘Ibis is a result of their low densities, high surface areas and other unique properties. One unique property of aerogels is there low thermal conductivity. Fricke[5] has studied the thermal properties of aerogels, and has shown that the thermal conductivity of silica aerogel is dependent both on its density and environment. ‘1’here was no data available for the combination of cryogenic temperatures and low densities aerogel that were being considered. A prototype structure was developed and tested at 1 atm, 10 torr and 10“3 torr vacuum. The results of thermal conductivity testing ofthc aerogel with glass-epoxy structure arc shown in ‘l’able 1 and a typical wall structure is shown in Figure 2. Because of the different phases of operation from before and after luanch, there was a significant advantage to have differerent thermal performance in vacuum compared to 1 atmosphere. The composite structure consists of glass/epoxy facesheets with glass/epoxy Z spars and edge close-outs, with solid silica aerogel between the spars. The solid silica aerogel performs as the main thermal insulation, with the thermal design tailored to minimize heat loss through the vertical spars. The number of Z spars and their spacing was determined by the finite clement structural analysis. There is one Z spar is in the middle of the end walls and four spars a spaced between the end c1oscoms on the side and bottom walls. The silica aerogel was manufactured at the let Propulsion Laboratory (JPL) at a density of 15-20 mg/cc (0.94 -1.25 lb/ft^3). To reduce internal radiation, a 5 mil gold coated kapton film was placed between the two layers of solid silica aerogel and to act as a radiation barrier. The solid aerogel used in the Mars Rover is hydrophobic, and has good mechanical shock resistance. The open cavity sheet and spar design was dictated in part by the mechanical properties and handling ability of the aerogel. While the aerogel can mechanically withstand the loading from launch vibration and shock from the Mars surface landing when constrained within the walls, it is essentially a brittle-rubbery material at the low densities used in the Mars Rover. The material has good compressive properties, but low shear strength. This necessitated that the WEB be built around the aerogel in a sequential manner. The fully assembled WEB, shown in Figure 3, has sufficient strength and stiffness to meet a 65 G launch and impact design requirement while supporting delicate internal electronics and external sensors.

One aspect of the small size and volume of the Mars Rover design is that interior components such as the structural axle tube span from side wall to side wal I to provide mechanical stiffening. This is shown in Figure 3. The structural axle provides the mechanical attachment point for the rocker-bogie wheel assembly and transmits most of the WEB's launch and landing structural loads, and houses the RHU's. It is designed out of glass-epoxy to meet structural requirements and minimize conductive losses. Attachments to the walls are through thermally isolating composite fittings made out of G-1 O with steel inserts. The design feature of directly attaching components to the walls was utilized to integrate the interior components with the structural design. All exterior surfaces have cocured gold coated Kapton. This was to provide a low emissivity surface to reduce radiation. All interior surfaces have cocured nickel coated graphite paper. This material serves two purposes, The first is to provide a high emissivity optical property for all internal surface to minimize heat loss and to enhance isothermalization. The second is that the nickel coating on the graphite paper acts as the EMI shielding for all of the interior electronics.

<u>Lightweight Survivable Rover</u>

Future small lightweight rovers for Mars will have serious constraints on mass, volume and power availability. They will be expected to have lifetimes lasting several months to a year, and will be operated in more severe environments than the Sojourner Rover. 'J'here is also the constraint that future rovers may or may not have available RHU's to provide heating of interior electronics. There will also be less and volume allocated to structure and thermal control to provide for more science payload. In order to optimize the integrated structure and thermal design for future rovers, a more focused systems approach was taken than the Sojourner rover. 'Ibis became the objective of the I lightweight Survivable Rover (LSR) development. Its charter was to develop a mass and volume efficient structure and thermal design for future rovers that would not require the use of RHU's. This was accomplished by minimizing thermal losses in the integrated stmcture/thermal design and by using more lightweight composites for structural elements.

Figure 4 shows the finished LSR Rover. Mass has been reduced in the LSR rover by increasing the amount of composite materials being used in the design. 'l'his increases the overall mass efficiency and increases the structural integrity. The LSR chassis uses the same lightweight sheet and spar glass epoxy structure that was used on Sojourner. There arc two significant design improvements, first the structural axis tube has been removed and replaced with shoulder joints that arc bonded to the exterior wall and second is the use of an improved opacified aerogel for thermal insulation. The glass-epoxy tube penetrating the wall accounted for 25% of the heat loss on Sojourner. This changes the mechanical load path for the rover. Before, the axial tube was the load path for two out of the three cable tic downs for launch restraints. It was conceived that all three cable tie downs could be directly tied to the structure as was done for the z-axis restraint on Sojourner. This is plausible because future missions to Mars will usc rocket controlled descent for landing similar to the Viking mission. This reduces the stress requirement from 65G to the range of 20 G. The side wall spars were redesigned to have a series of spars that provided an internal box structure at the attachment location of the rocker-bogie shoulder joints. The other change is the usc of an opacified resorcinol-formaldhyde aerogel. "l'his is a material that recently has become commercially available from Aerojet Corporation. As shown in Figure 5, it has a lower thermal conductivity in an 8 torr simulated Mars environment than conventional foam insulation and the transparent silica aerogel.

To further reduce mass on LSR, graphite-polycyanate composite laminates arc used for the structure of the science trays, the differential, rocker-bcmgic struts, and wheel Segments. The composite wheel segments allowed the design of a collapsible wheel that is lighter than the rigid design used on Sojourner would be at the larger diameter used on LSR. The wheel segments arc [0,+ /-60]s graphite/cyanate-ester laminates formed to the shape of 60 degree arc segment for a 2(I cm wheel. The front and rear science trays are balanced quasi isotropic laminates. The differential struts arc 2-D laminates formed over an tapered interior mandrel. The rocker boogie struts for LSR are [0,0, + /-30]s 1.0 inch diameter tubes that were formed in a closed capture tool with a Teflon mandrel. in this process, both the 1.1). and ().1). are carefully controlled. Similar composite tube struts were usc d in the robotic arm seen on LSR.

Sample Return Rover

Current NASA plans for Mars Exploration include a sample return mission as early as 2005. During the last year there has been an active development of a prototype Sample Return Rover (SRR), which is shown in Figure 6. It is based on an operations scenario where a lander arrives at the surface of Mars, deploys a small rover which collects a sample cache and returns the sample cache to the ascent vehicle for liftoff within a 24 hr period. Other science rovers would stay on the surface for the following year. Using this as the mission operations scenario, SRR was developed. It includes several innovative and novel features in composite structural design. Previous rovers developed for the Pathfinder mission and under the LSR program have utilized a Warm Electronics Box (WEB) approach for the primary structural chassis [1 ,6] For those rovers, the integrated structure has both structural and thermal requirements. This led to the boxy appearance of the WEB. For SRR, the chassis has structural requirements but no thermal insulation requirements and no requirement for a large flat solar array. This allowed more freedom in the mechanical design to minimize the structure and move away from a boxy configuration.

For SRR, the mechanical configuration was driven by the need to provide a stable platform for the robotic arm and the mobility system. SRR changes the paradigm as to how mechanical loads are distributed compared to previous rovers developed at JPL. For the Sojourner rover, the mechanical loads for the mobility system are all carried through the axial composite tube, and tbc WEB provides the mechanical support for the electronics and science instruments. As part of the LSR development the structural axis tube was eliminated to significantly decrease its associated thermal losses, and the WEB was redesigned to take the mechanical loads for the mobility system and science instrumentation For SRR there is a requirement that the robotic arm and the mobility system be rigidly associated. To accomplish this SRR utilizes a "Tee" sandwich panel/shear plate design. This design approach provides high localized stiffness for the load paths required for the mobility system shoulder joints and the robotic arm assembly. This is illustrated in Figure 7. By using M46J/cyanate-ester facesheets and a lightweight aluminum honeycomb sandwich structure selectively only in the load paths, a uniform 16000 inch-lb stiffness is achieved. This compares to the localized 6000 inch-lb stiffness in the Sojourner class WEB chassis design. In SRR the specific stiffness was optimized compared to the specific thermal conductivity optimized in Sojourner. This localized stiffness approach minimizes mass and provides stiffness and load paths as needed for the mechanical system. The robotic arm on SRR is all composite structures. This is natural use of composite structure to provide high stiffness at low mass. All of the tube elements and endfittings arc made from graphite composites. This was to increase stiffness and reduce mass to provide a high stiffness arm.

Transferring all of the mechanical loads into a single plane removes the primary structural requirement from the rest of the SRR chassis. This allows the reduction in mass in the chassis. The rest of the chassis becomes an exoskeleton that is fitted to the volume of the electronics and interior mechanical assemblies. This configuration approach improves the design by removing the boxy appearance of pervious rovers. For SRR, the exterior shell is designed out of lightweight E glass-epoxy with cocured aluminized Kapton. The low emissity aluminized Kapton provides a duel role as a thermal control surface and as the ground plane for the beacon assembly.

The next innovation in the usc of composites in SRR is the hybrid Kevlar/graphite cyanate-ester laminates used in the collapsible wheel segments. This hybrid approach of using Kevlar as the outer surface increases the abrasion resistance of the wheel assembly and adds to the wheels traction, By using proper design and improved material selection, the ncw wheel segments are 300/0 stiffer at the same mass than the wheel segments in LSR graphite composite wheels. For SRR, wc have returned to the use of 17-7 precipitation hardened steel cleats as was used on Sojourner. The return to the steel cleats improves the traction of the composite wheels. The concept of hybrid Kevlar/graphite was also used in wheel hub covers, which are located on the inside of the wheel assemblies. These wheel hub covet-s effectively prevent rocks from hanging up the rover as it drives.

Future Trends

The current trend for the structural development of future Mars rovers is being conducted by the Mars Explorat ion Technology program. This year they plan to develop the Field integration Design &Operations (FIDO) rover. This series of rovers will become the prototype for the 2001 Mars mission rover. One initial concept is to merge the "Tee" sandwich panel/shear plate mechanical load path approach with the thermal insulation improvements developed in the LSR rover. This approach will provide the higher mechanical stiffness required for future rovers with robotic arms and deployable mechanisms. It will also lead to a direct design path for the integrated thermal and structural chassis needed for the 2001 Mars flight system rover. This rover will weigh 30 Kg and carry up to 15 Kg of science payload. Composites will continued to be used for the structural WEB chassis. The wheels are likely to be partially fabricated out of the hybrid Kevlar/graphite-cy anate composite demonstrated in SRR. other primary and secondary components will bc designed and fabricated out of composite materials as appropriate, with reliability, mass and configuration driving the materials selection process. At the other end of the spectrum, there is concurrent development of a 1Kg nanorover which is the engineering prototype for the MUSES C/N mission for an asteroid rendezvous. 'l'his will be a solar powered, 4 wheeled rover that has the capability of flipping itself over and self righting itself. Composites will play a significant role for all of the classes of rovers that are being developed for future Mars missions. It will be used for primary and secondary structure to reduce mass, and to provide thermally insulating structures. The robotic arm on the Mars '98 mission is an composite structure with aluminum end fittings. Future arms on planetary rovers will be composite, as illustrated by MarsArm 1 and on LSR and SRR, respectively

Acknowledgment

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Table 1: Thermal Conductivity measurements of the Aerogel with Glass-epoxy structure at the coupon level.

Condition	Temperature (°C)	Thermal Conductivity (Watts/meter/Kelvin)
1 atm	25	0.0333
10 torr CO_2	-79	0.0089
10 torr CO_2	-27	0.0126
10 torr CO_2	25	0.0163
1.2×10^{-3} torr Nitrogen	-78	0.0049
1.2×10^{-3} torr Nitrogen	-26	0.0074
0.4×10^{-3} torr Nitrogen	25	0.0113

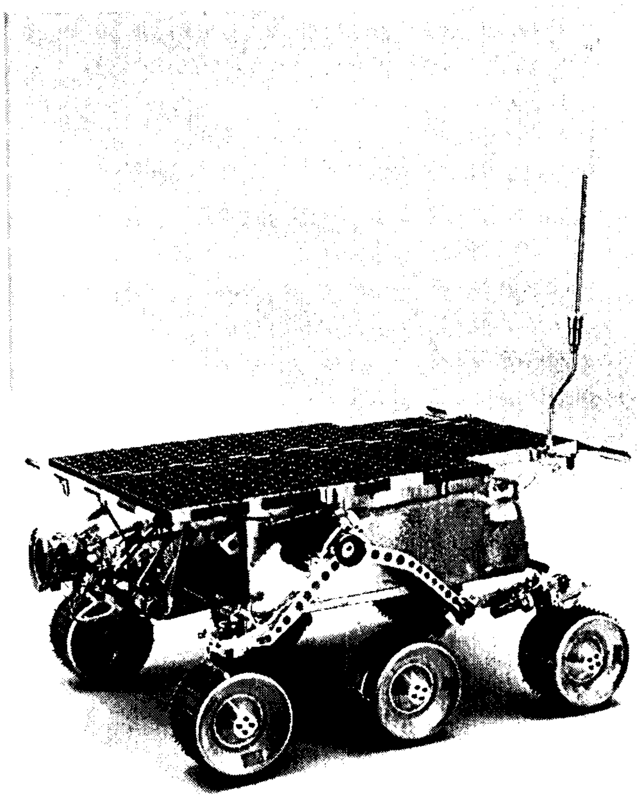

Figure 1: View of the Sojourner Rover in deployed position

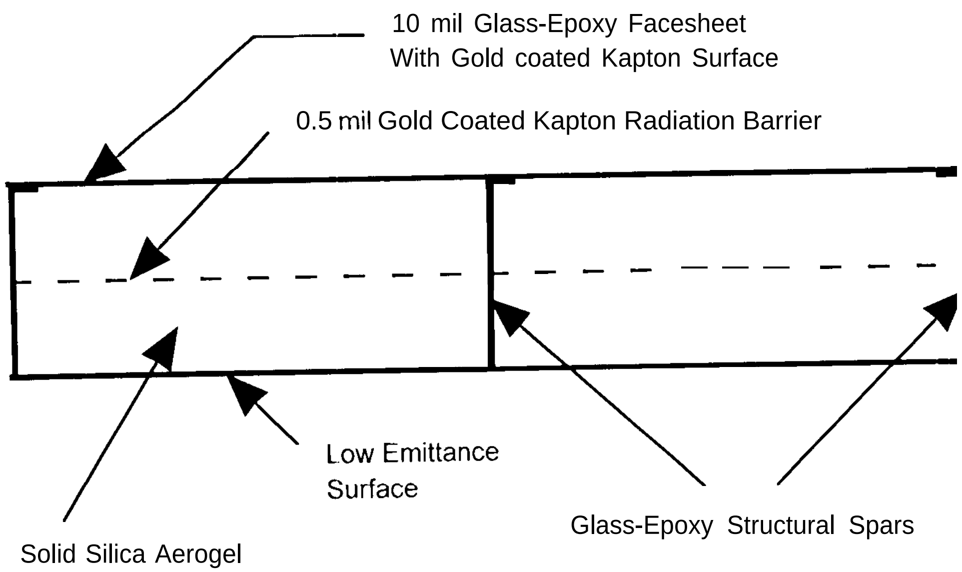

Figure 2: Configuration of aerogel structural insulation assembly for a typical wall.

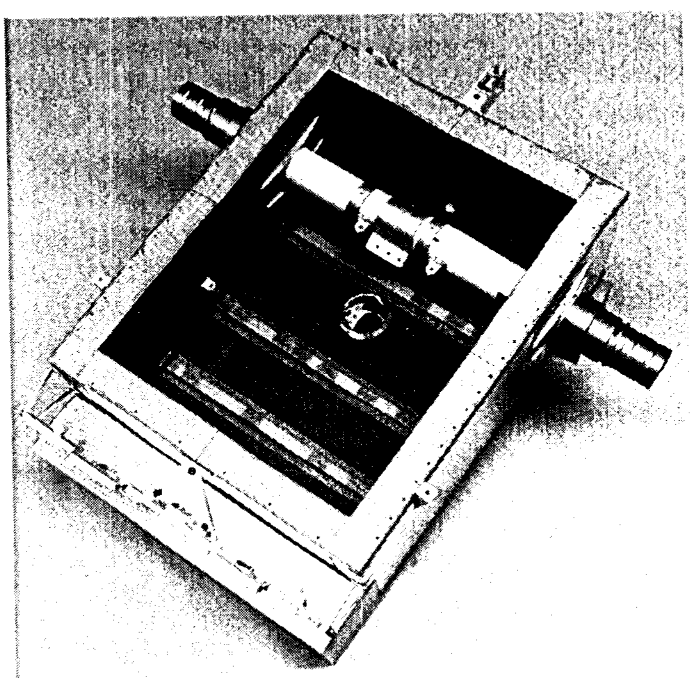

Figure 3: View of the Rover WEB without electronics.

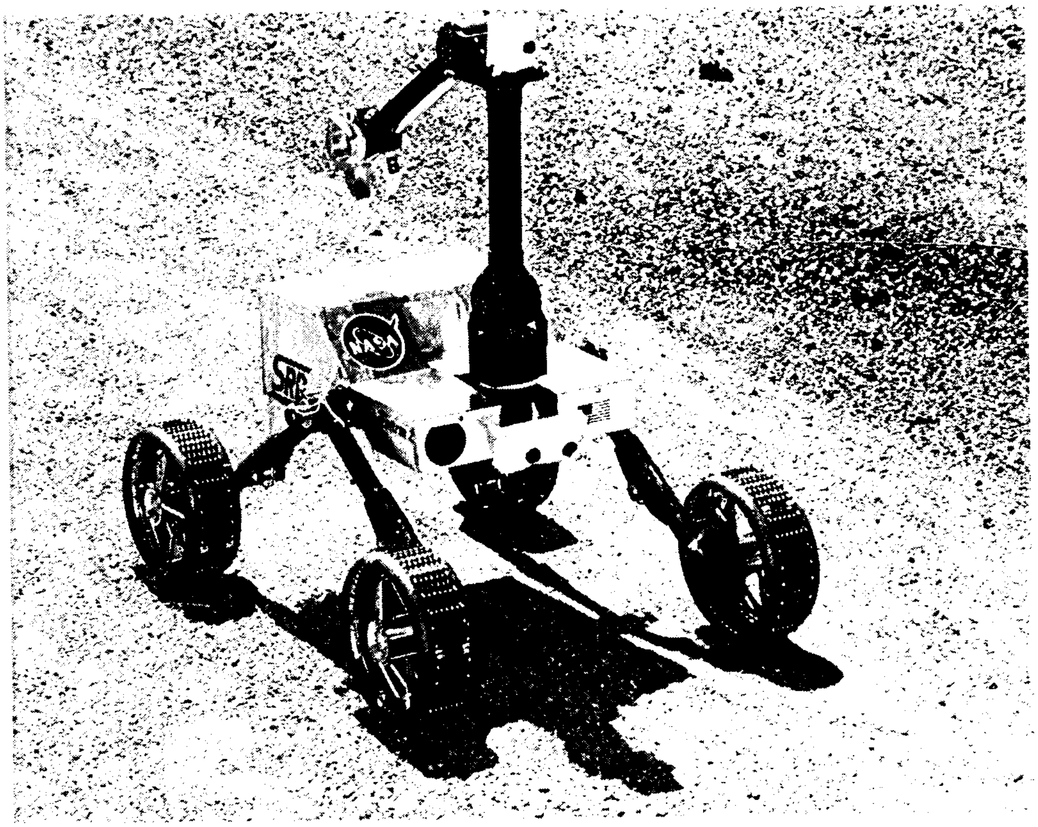

Figure 6: View of the Sample Return Rover

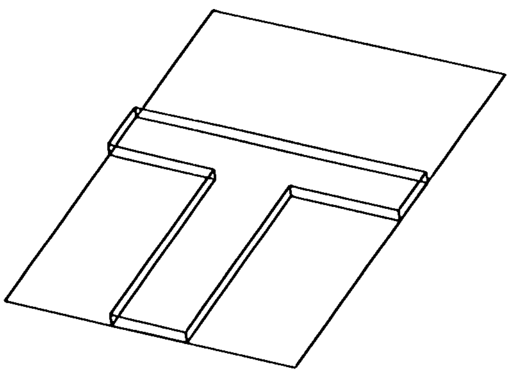

Figure 7: SRR utilizes a "Tee" sandwich panel/sheat plate design for the floor panel.