

# Thermal Insulation For Mars Surface Exploration

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## ABSTRACT

There is currently a significant amount of interest in Mars exploration by NASA to send a series of orbiting spacecraft and landers to Mars over the next decade. For the science and engineering systems that will land on the surface of Mars, there is a great challenge for thermal control. The Pathfinder mission will place a lander with an autonomous rover on Mars in July 1997; and the Mars '98 mission set will have an orbiter and surface lander and surface penetrators. In the planning stages are additional landers and rovers, leading up to a Mars sample return mission for 2005 launch opportunity. The 8 torr CO<sub>2</sub> atmosphere and cryogenic temperatures are a unique thermal environment. The environment constrains the types and duration of missions that can be conducted and the thermal insulation required. All these factors add to a difficult challenge to design thermal control systems for Mars surface exploration. Current thermal insulation control approaches will be described and the needs for future missions.

## BACKGROUND

Thermal control for Mars surface missions is highly dependent on the nature of the mission, the desired lifetime on the surface and the available power. The three types of missions that are either in progress or planned for future opportunities can be described as stationary landers, mobile rovers and surface penetrators. Surface landers would include the Pathfinder lander currently in progress, and the series of Surveyor landers that are planned for the '98 and '01 mission sets. Rovers include the Sojourner microrover that is payload for the Pathfinder mission and the planned microrover for the '01 mission. Each type of mission will have the challenge of a Mars environment that is dynamic. The environmental factors that effect thermal control are temperature variation, the atmospheric density and the atmospheric opacity. Of primary concern to thermal control is temperature variation, which for Mars is characterized by large daily and seasonal and annual temperature variations. The atmospheric density affects the efficiency of insulation materials. The low density Martian atmosphere is primarily CO<sub>2</sub> with small amounts of N<sub>2</sub> and Argon. Table 1 provides the nominal chemical composition. The nominal 8 torr CO<sub>2</sub> will vary on an annual basis by up to +/-150A depending on latitude due to the condensation and sublimation of CO<sub>2</sub>. An example of the pressure variation is

shown in Figure 1 from measured results by the Viking 1 and 2 landers.

Gas	Mole Fraction
CO <sub>2</sub>	0.955 +/- 0.0065
N <sub>2</sub>	0.027 +/- 0.003
Ar	0.016 +/- 0.003
O <sub>2</sub>	0.0015 +/- 0.0005
CO	0.0007
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm

Table 1: Chemical composition of the Mars surface environment.

The evaluation of Martian surface temperatures are based on two types of data. First, there are the direct measurements from the two Viking landers, which provided data for two specific location of the surface. The second type of data are from remote sensing such as from the Viking Orbiter Infrared Thermal Mappers (IRTM), which provided seasonal and latitudinal data. This information can be used to create average temperature surface contours. There have been several papers written on modeling and the interpretation of the Martian surface temperatures [1,2] Kondratiev and Hunt provide a summary of the work completed prior to 1981 [3]; and Haberle and Jakosky take a recent look at atmospheric effects on temperature and thermal inertia [4]. For equatorial and mid latitudes there will be significant temperature variation during the day. For polar regions, the daily temperature variation is less, bounded by the sublimation temperature of CO<sub>2</sub>. Figure 2 shows average daily temperature variation for equatorial and midlatitude regions as a function of time for the four seasons. The four seasonal points being the vernal equinox, summer solstice, autumn equinox, and winter solstice, corresponding to the heliocentric longitudes Ls = 0, 90, 180 and 270. It is of interest to note for thermal design that there is a rapid surface temperature increase at dawn, with the peak temperature nominally two hours after noon, and a slow temperature drop off after sunset for Mars.

The primary hardware that requires protection from the thermal environment are the electronics, batteries, and temperature sensitive components of the telecommunication systems. The temperature range for the electronic components

on Pathfinder was  $\pm 40$  °C. The primary batteries on Pathfinder are the most sensitive of the components. Above 40°C they will autodischarge and below 40 °C will not provide current. Many other electronics can withstand a wider temperature range, but minimizing the temperature swings improves reliability.

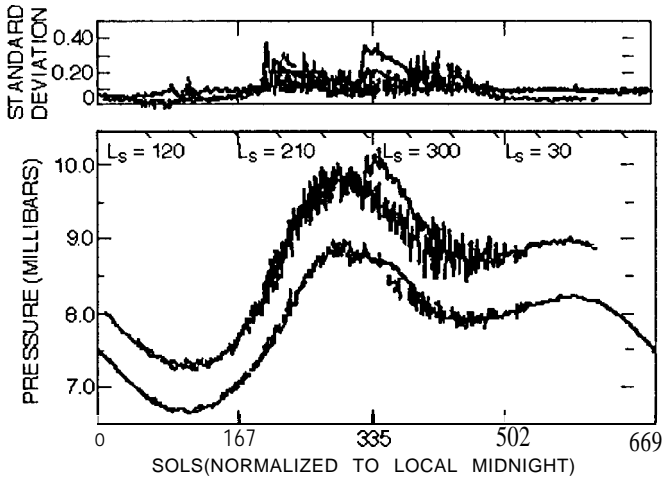
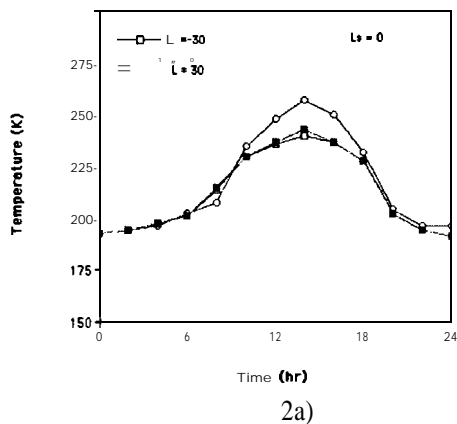
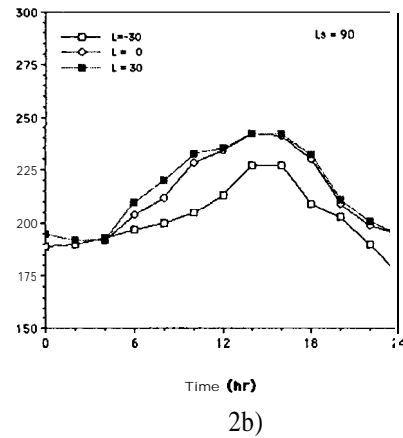


Figure 1: Surface Pressure versus time for the Viking Landers 1 and 2 (From Reference [5]).

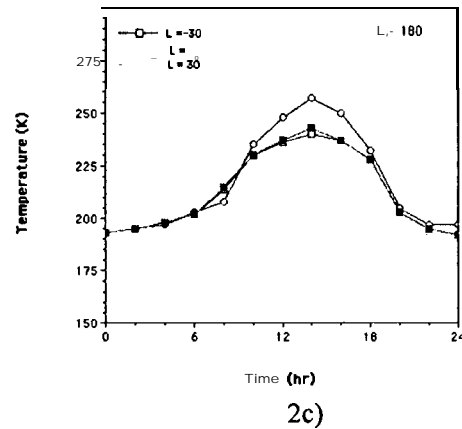
Heat transfer is comprised of conductive, convective and radiative components. Thermal insulation for any environment desires to minimize heat transfer. Conduction will be present in any structure due to the need to accommodate mechanical loads. For the Pathfinder mission, the loads are significant due to the surface landing approach of using airbags. It is expected that the landing loads for Pathfinder will range from 30 to 50 g's. For the '98 Surveyor lander, the landing loads will be significantly less since it will use chemical propulsion for controlled deceleration. For that mission the landing loads are expected to be less than 15 g's, about the same magnitude as the launch loads. For a Mars environment, convection is low but still significant. It is for this reason that multilayer insulation is not the best choice for thermal insulation. The low pressure environment for Mars provides a challenging thermal environments that is in a region of thermal transport that has not been well studied. The nominal 8 torr CO<sub>2</sub>



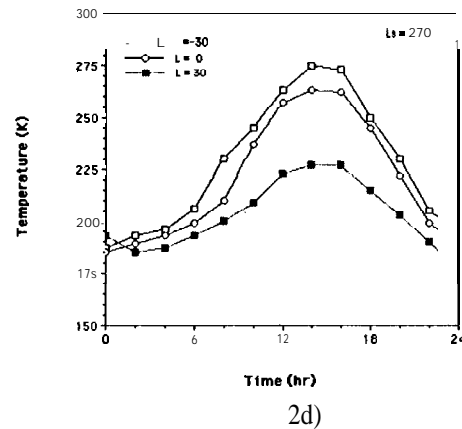
2a)



2b)



2c)



2d)

Figure 2: Typical diurnal surface temperatures for midlatitude Mars a) Ls = 0, b) Ls = 90, c) Ls = 180, d) Ls = 270.

environment falls in a transition regime between the continuum regime (50 torr and above) and the Knudsen free molecular conduction regime (1 torr and below). Due to the low temperatures on the Mars surface, radiative heat transfer is not large but it is still significant.

There has been a limited amount of evaluation of insulation materials for Mars environments. Wilbert, *et.al.* conducted a study for Viking that evaluated foam insulations,

fibrous, powders and multilayer insulation (MLI) for thermal control [6]. They did an initial selection of materials that were expected to meet the terminal sterilization process that was required to meet planetary protection requirements. Planetary protection is a significant restriction on all hardware for Mars missions. The typical process for the Pathfinder mission was to heat subsystems for 5 hours at 125°C. The process for Viking was to sterilize the entire spacecraft. The result of that study was the primary use of several inches of foam insulation and some MLI on the Viking Landers. Other studies of thermal control for Mars in that time period assumed a foam insulation of 3 to 4 inches thick for potential Mars missions [7,8]. A more recent study revisited the issue of Mars thermal control and evaluated additional porous foam insulations [9]. There has not been a significant amount of work for thermal control for Mars surface exploration until the recent Pathfinder mission to Mars. This paper will survey the current work that has been completed for the Pathfinder mission and for part of the planned '98 and '01 launch opportunities.

## INSULATION MATERIALS

Foam insulations are advantageous for many applications. They are inexpensive, easy to handle and machine, and provide moderate insulative properties in environments with atmospheres. They disadvantage is that they tend to be bulky and lose their integrity at very low densities. They can be utilized in structures with minimal difficulty. One restriction on the use of foam insulation for space applications is that they must be able to withstand the depressurization rate to vacuum for the launch vehicle. This limits the selection to mostly open cell foams, though a few closed cell foams with strong cohesive mechanical integrity will pass. For a foam insulation, there is no internal convection or radiation. The primary mode of heat transfer is conduction. Figure 3 shows the thermal conductivity of two different foam insulations. The Eccofoam is an open cell polyurethane foam insulation. The Rohacell is a closed cell

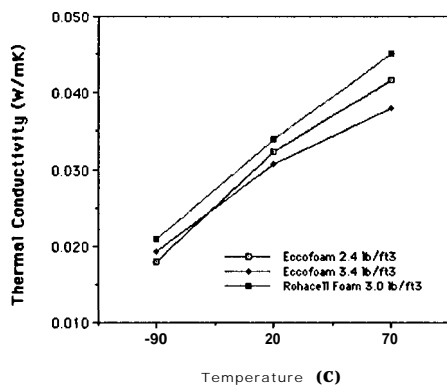


Figure 3: Comparison of foam insulations in a 10 torr CO<sub>2</sub> environment.

polymethacryimide foam The Rohacell has good mechanical properties at the low densities. Both are vacuum rated and have acceptable outgassing characteristics. Data is shown for two densities of the Eccofoam. As expected for a foam insulation, as density decreases the thermal conductivity decreases.

Fibrous insulations have advantages over foam insulation in that they can be obtained in lower densities, but they cannot support mechanical loads, so additional structure must be built around them. The modes of heat transfer of fibrous insulation are conduction, convection and radiation. Conduction is significantly less than for foam insulation, but the inclusion of internal radiation and convection does not result in a significant decrease in thermal conductivity for a Mars low pressure environment. Figure 4 shows data for two types of glass fiber insulation. The TG 1500 is a 2 lb/ft<sup>3</sup> fibrous insulation that has found several applications for thermal insulation on launch vehicles and the Space Shuttle. The other glass fiber insulation is a 1 lb/ft<sup>3</sup> material that is being considered for use for the '98 Surveyor lander. There is a small effect of density of material, but there is also an effect of pressure on the thermal conductivity of the fibrous insulation.

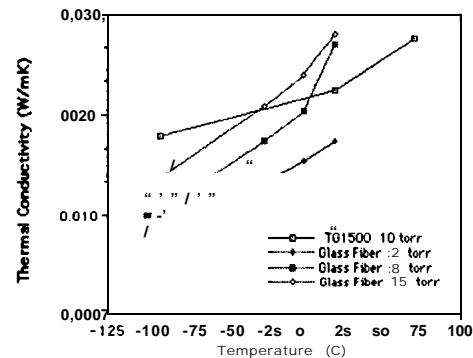


Figure 4: Comparison of fibrous insulations in a low pressure CO<sub>2</sub> environment.

A third type of material that is being used for insulation for Mars missions is aerogel. It has the advantage that it is very lightweight (1 lb/ft<sup>3</sup>) and has low conductivity. The use of aerogel for thermal control on Mars considers the thermal transport limitations for the transition between the continuum and free molecular regime. The effective thermal conductance of an aerogel insulation system consists of two components, the solid conductance-radiative conductance (independent of pressure) and the convective component. Gas conductance depends on the mobility inside the voids of a material, and is governed by the relative dimensions and connectivity of the open volume and the gas mean free path. If the interstitial space between material (whether they be voids, particles or fibers), becomes smaller than the mean free path of the gas within the insulation, the mechanism for gas transport shifts from the continuum regime to free molecular conduction in the Knudsen regime. The mean free path of a gas is inversely proportional to the gas pressure. For CO<sub>2</sub> at 10 torr, the mean free path is approximately 3 to 5 microns in the

temperature range from - 90°C to 25 °C. Solid aerogel has pore dimensions 6 to 11 nanometers. This means that the effective gas conduction within the aerogel is a fraction of value in the continuum regime, and is dominated by the conductive-radiative component of the silica aerogel structure. Since low density aerogels approaches 80 to 90% open cells, direct conductance is minimized. Because of the high void fraction and the resulting low mechanical properties of low density aerogels, a lightweight supporting structure has to be designed and integrated into the thermal control. This basic integrated structure and thermal insulation design became the basis for the Sojourner Rover that is the payload for the Pathfinder mission [10]. Figure 5 shows the thermal conductivity for two types of aerogel. The first is a silica aerogel that is being used for the Sojourner rover. The second is a Resorcinol-Formaldehyde (RF) aerogel that is being considered for future planetary rovers. One basic distinction between the two materials is the silica aerogel is translucent in the infrared and visible spectrum whereas the RF aerogel is opaque.

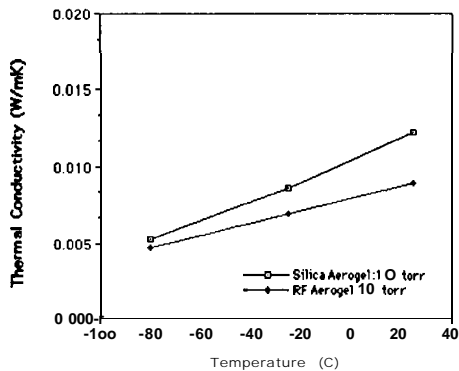


Figure 5: Comparison of aerogel insulations in a 10 torr CO<sub>2</sub> environment.

Other types of material that have been proposed for thermal insulation for Mars missions are opacified powders and vacuum jacketed enclosures [10]. Opacified powders based on aerogels have the potential to have similar properties to the solid aerogels. Low density aerogel powders are not available commercially, and the cost to make them in large quantities is significant. Most of the aerogel powders that are available are silica based and would need to be opacified. A typical opacification process would be the introduction of either carbon black tiller or another material. Work completed for the Pathfinder program found that using 1 micron aluminum powder was more effective than carbon black, but needed a 10% mass fraction to eliminate all internal radiation. This increased the overall mass significantly. There are also problems with working with powders in a clean spacecraft environment. The integration scenario proposed was to place the opacified powder within a honeycomb structure. This raised two problems. The first was the possible degradation of the adhesive bond due to the powder, the second was that the primary heat loss then becomes the direct conduction through the honeycomb cells. Vacuum jacketed enclosures potentially

can have very low effective conductivity. Their problems are several. First, their effective conductivity is related to the overall size. For small areas, the conduction through the external edge and skin material becomes significant. Second, there is a reliability concern for maintaining vacuum integrity over time period that can approach several years. A third concern that is specific to rovers is puncture resistance. There is a finite risk that when a rover traverse's over a rock field, the chassis structure may get punctured by a sharp edge on a rock. This is a concern for Mars V/L- 1 and V/L-2 type terrain. For a vacuum jacketed enclosure, a single puncture would cause the enclosure to lose vacuum, in effect loosing its thermal insulation functionality. To eliminate the concern for puncture resistance, sufficient external structure would have to be added. The added structure would have an increase in direct conduction, and the added mass would not make the vacuum jacketed enclosure mass efficient relative to other approaches.

## THERMAL STRUCTURES

Two types of thermal structures were developed for the Pathfinder mission. The first is the Integrated Structural Assembly (ISA) for the Pathfinder lander. The second is the Warm Electronic Box (WEB) for the Sojourner rover. Although each is expected to operate in equivalent thermal regimes, different engineering requirements lead to very different designs. The ISA is a static structure that supports the camera and antenna assembly, nominally 10 kg of mass. It also acts as a barrier for planetary protection. The electronics inside were not held to the same level of sterilization requirements as hardware external to the ISA. The WEB is the primary structure for the rover, but it is designed for mobility. There was a significant operational penalty for mass on the mobility system and strict limitations on volume.

The ISA is basically a conventional composite honeycomb structure. Its cross-section is illustrated in Figure 6. It is comprised of graphite-cyanate facesheets with 2 inch Nomex core. The core is filled with 2 lb/ft<sup>3</sup> Eccofoam pressed into the honeycomb cells. On the interior surfaces, there is bonded an additional 2 inch thick piece of Eccofoam, with aluminized kapton as the thermal control surface material. The Sojourner rover WEB used a sheet and spar design with silica aerogel to minimize thermal conduction. Its basic design is illustrated in Figure 7, and described in detail in references [10, 11]. Instead of being designed to take loads on any point of the surface, as is typical of a honeycomb design, it was designed to take point loads at the spars by placing them in the direct load paths. This minimized mass and direct thermal conduction through the spars. Figure 8 shows a comparison of the thermal conductivity of the two structures as a function of temperature. The structural design based on aerogel has almost half conduction than the structure design using foam insulation and is approximately one quarter the areal mass for the same effective insulation capability. Also shown in Figure 8 is the effective conductivity of the WEB sheet and spar structural design using the opacified RF aerogel

instead of the silica aerogel. This opacified material is being considered for the '01 Rover WEB.

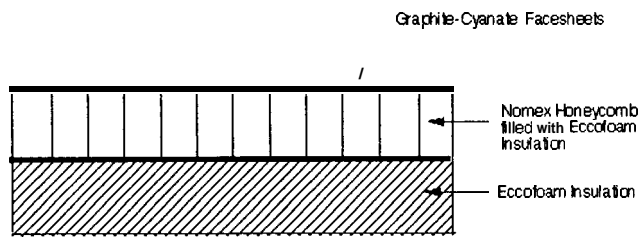


Figure 6: Schematic of the Pathfinder ISA insulation cross section.

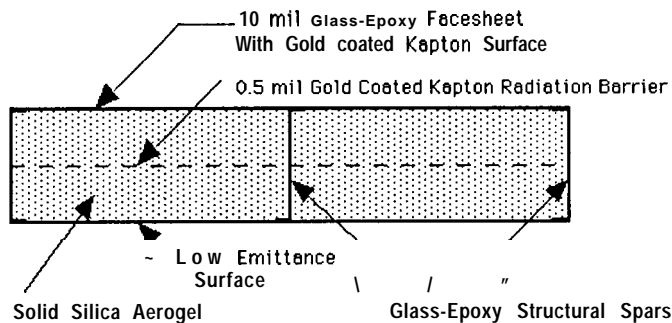


Figure 7: Typical cross section of the sheet and spar design used in the Mars Rover.

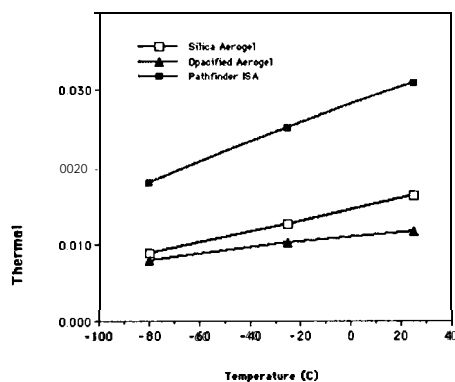


Figure 8: Comparison of thermal insulation structures being used for Mars missions.

## FUTURE TRENDS AND SUMMARY

The need for thermal protection for future Mars landers and rovers will continue. While there are advances in electronics that can withstand cryogenic temperature. Power from batteries at low temperatures will remain a concern. Low temperature primary batteries are becoming available that can operate below  $-40^{\circ}\text{C}$ , but currently the lowest temperature secondary rechargeable batteries can operate is  $-20^{\circ}\text{C}$ . In the next year this may be extended to  $-30^{\circ}\text{C}$  with the goal of  $-40^{\circ}\text{C}$ . The integrated structure with aerogel designs provide a significant improvement over the foam or fibrous insulation.

The opacified RF aerogel is near the limit for optimizing solid insulation materials. There is the potential that vacuum jacketed enclosures can be designed to provide structural integrity. Variations of this theme are vacuum jacketed multilayer insulation, fibrous insulation, or combinations of both. There mass efficiency would have to be evaluated and reliability will remain a concern.

## ACKNOWLEDGMENTS

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