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THERMAL INSULATION PERFORMANCE OF TEXTILE STRUCTURES FOR SPACESUIT APPLICATION AT MARTIAN PRESSURE AND TEMPERATURE

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ABSTRACT:

Protection of astronauts from the extreme temperatures in the space environment has been provided in the past using multi-layer insulation in ultra-high vacuum environments of low earth orbit and the lunar surface. For planetary environments with residual gas atmospheres such as Mars with ambient pressures between 8 to 14 hPa (8 to 14 mbar), new protection techniques are required because of the dominating effect of the ambient gas on heat loss through the insulation. At Mars ambient pressure levels, the heat loss can be excessive at expected suit external temperatures of 172 K with state-of-the-art suit insulation, requiring an active heat source and its accompanying weight and volume penalties. Micro-fibers have been identified as one potential structure to reduce the heat losses, but existing fundamental data on fiber heat transfer at low pressure is lacking for integrated fabric structures.

This baseline study presents insulation performance test data at different pressures and fabric loads for selected polyesters and aramids as a function of fiber density, fiber diameter, fabric density, and fabric construction. A set of trend data of thermal conductivity versus ambient pressure is presented for each fiber and fabric construction design to identify the design effects on thermal conductivity at various ambient pressures, and to select a fiber and fabric design for further development as a suit insulation. The trend data also shows the pressure level at which thermal conductivity approaches a minimum, below which no further improvement is possible for a given fiber and fabric design. The pressure levels and resulting thermal conductivities from the trend data can then be compared to the ambient pressure at a planetary surface, Mars for example, to determine if a particular fiber and fabric design has potential as a suit insulation.

PLANETARY ENVIRONMENTS AND SUIT INSULATION REQUIREMENTS

Moon Environment Overview

The most significant aspects of the lunar environment impacting spacesuit thermal properties are thermal radiation, thermal flux, and the absence of a gaseous atmosphere. The atmosphere of the Moon is a hard vacuum with pressure of about 10^{-8} Pa (10^{-10} torr) or less, with only traces of hydrogen, helium, neon and gases resulting from radioactive decay of lunar material [a]. The absence of a gaseous lunar atmosphere is a very important factor in determining the extent of human activities on the Moon's surface. It exposes humans to the full spectrum of solar radiation, and requires specific spacesuit design for radiation protection. In addition, heating and cooling by radiation occurs swiftly. The resulting thermal flux on objects attains extremes of 111 C (231.8 F) in direct sunlight to –171 C (-275 F) in the lunar night. Extra Vehicular Activity (EVA) operations and spacesuit insulation design were engineered to accommodate a certain range of these harsh environmental conditions. An extended knowledge has been acquired on designing suit components for radiation insulation, and this has led to the development of multi-layer insulations (MLI) with materials having low radiation absorptivity and high emissivity rather than just low thermal conductivity. This knowledge is still valuable for designing and comparing protective garments for vacuum or other reduced pressure applications. However, with the exception of hard vacuum, any reduced pressure application has some gaseous contribution which make the traditional spacesuit MLI inefficient.

Mars Environment for Space Suit EVA

The environment conditions on Mars affecting spacesuit insulation design include the presence of an atmosphere, a gravitational field, and solar and infrared radiation. The Martian atmosphere is 95% CO2 with an average surface pressure of 8 hPa (6 torr). The gas atmosphere allows conduction and convection heat loss through the gas from within and around the suit insulation. Since gravity on Mars is 38% that of earth, this allows for significant amount of free convection heat loss. Both the free convection and gas conduction heat losses are not present in a vacuum such as on the moon and low earth orbit, where ambient pressure is less than 10^{-4} Pa (10^{-6} torr). Mean solar radiation on Mars is roughly half that on earth, so that Mars' average surface temperatures (-143 to 27 C) are colder than on earth [1]. IR radiation is due to ground temperatures and sky temperatures. Both are generally lower than on earth due to a thin atmosphere and lower solar radiation than earth. For spacesuit operations on Mars and for evaluation of suit insulation performance required, the design conditions were selected from the NASA Mars Reference Mission document [2] and are discussed in the next section.

Requirements for Planetary Space Suit Insulation

The design of a space suit insulation for planetary use should be effective in both a hard vacuum environment such as on the earth's moon, and in a gaseous planetary environment such as on Mars. When comparing the two environments, the requirements for insulation are more severe for the Martian environment due to the presence of an atmosphere. Although the hot lunar solar and infrared environments are more severe than that on Mars, lunar EVA activity can be restricted to the less severe environments during the 28 day lunar cycle, as it was during the Apollo lunar missions. On Mars, however, both cold and warm environments can appear within a 24.6 hour period, the duration of a Mars day, with the cold environment being the harsher of the two. Because of the presence of a gas atmosphere on Mars, convection and gas conduction cooling renders conventional multi-layer suit insulation almost useless in cold Martian environments. The multi-layer insulation was designed for use in a vacuum, where only conduction and radiation heat transfer are significant. As described in [2] for typical hot Martian environment in the Mars Candor region, both the suit radiation sink temperature (264 to 269 K) and the atmospheric surface temperature (219 to 300 K) are very nominal and not a concern for suit insulation design. For the cold nominal environment, however, these temperatures are severely cold (211 to 227 K, 189 to 227 K, suit and atmosphere sinks, resp.) and require special insulation in the Mars environment. Therefore, the need arises for a different type of insulation material. For this study, the use of non woven fibers is explored because of their high void spaces and their low conduction paths at the contact point between fibers. Also for this study, values of insulation performance are used to evaluate the relative importance of various fabric parameters in a simulated environment, not necessarily to compare to actual suit conductance requirements.

EARLY THERMAL CONDUCTIVITY STUDIES

Nomex

Early studies were conducted at NASA [3] in 1993 to evaluate the thermal conductivity performance of a particular fibrous structure's dependence on fill-gas pressure. The selected structure was Nomex®, an aramid non woven fabric, and the test apparatus was a guarded hot-plate instrument in a vacuum chamber (see Figure 1, model TCFGM from Holometrix Corp with Hewlett Packard HP3421A data acquisition system). Test gases were air, CO_2, and nitrogen, and test pressures were approximately 1.3 Pa (10^{-2} torr) to atmospheric. The performance of Nomex® followed the traditional "S" curve variation with pressure as observed in cryogenic insulations. The "S" curve is discussed in more detail later in this paper. The test compressive loads on the samples were not controlled to any specified level, with only the weight of the heaters and cold sinks causing compression loading on the samples. Results from these tests showed that Nomex thermal conductivity decreased with decreasing temperature and with decreasing gas-fill pressure, and also decreased in the presence of CO_2 gas versus nitrogen and air due to the lower thermal conductivity of CO_2.

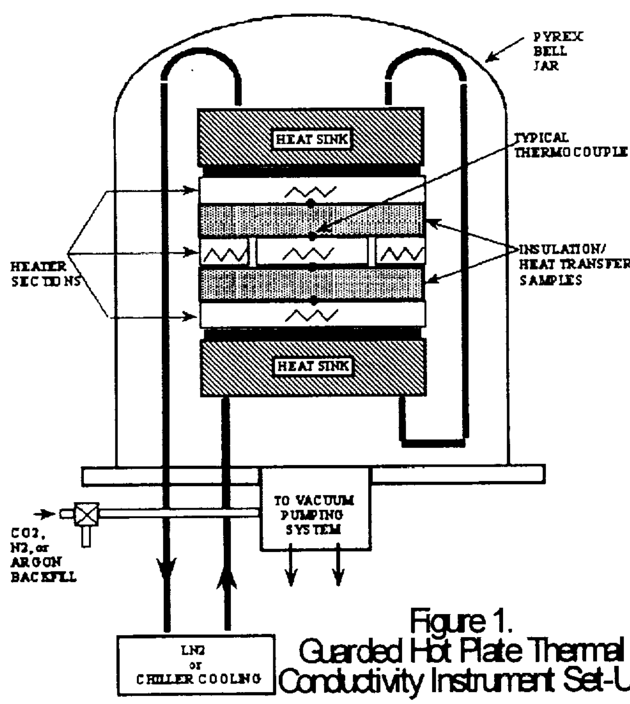

Figure 1.
Guarded Hot Plate Thermal Conductivity Instrument Set-Up

Integrated Suit Layer /TMG Tests

To evaluate various candidate suit insulation structures, a series of tests was conducted at NASA/JSC [4] starting in 1994. The Space Shuttle suit insulation multi-layer lay-up, also known as the TMG for thermal micrometeroid garment, was used as the building lay-up for the tests. Objective of these tests was to screen alternate thermal insulations for thermal performance by substituting them in place of the TMG thermal insulation, which consists of aluminized mylar multi-layer insulation (MLI). The MLI layers were designed for and are only effective at high vacuum pressures encountered in low earth orbit (LEO) and planetary environments without an atmosphere, such as the moon. Initial candidate insulations were tested at Mars pressure of 8 to 13 hPa (6 to 10 torr) and at higher reduced pressures up to 333 hPa (250 torr) to determine trends of thermal conductivity versus pressure. A Shuttle TMG sample was also tested at Mars pressure to demonstrate its low performance at that pressure. Four of the insulations tested were fibrous (Durette®, Velcro® coins, Pilecoins, Primaloft® PL1), while the other (Waffle) consisted of aluminized mylar layers with extended scrim spacers to reduce solid conduction. Results of the initial tests showed that fibrous insulations are better performers at Mars pressures. All samples were compression loaded to 6.9×10^3 N/m^2 (1 psi) to simulate the maximum insulation loading due to suit pressure and motion.

Subsequent tests in March 1998 [4] were conducted only on fibrous insulation layers, again substituted for the MLI layers. The fibrous materials were Airloft® and representative Primaloft® samples from 2.54 cm (one inch) thick mats. For these tests, chamber pressures were hard vacuum of 10^{-3} Pa (10^{-5} torr) and Mars pressure of 13 hPa (10 torr). Test gas was argon instead of CO2 because of chamber pressure control problems due to sublimation of CO2 at cold temperatures and because argon is close to CO2 in thermal conductivity. Sample compressive loads were 0.69×10^3 N/m^2 (0.1 psi) to simulate a more nominal TMG load. Results from these tests show that both Airloft and Pyroloft exhibited similar performance at Mars conditions (0.0241 to 0.0275 W/m-K thermal conductivity).

CURRENT STUDY

Rationale for Selection of Non Woven Fabric Insulations

As described in [2], the atmospheric gas pressure on Mars for space suit operations is between 8 to 11 hPa (6 torr to 8 torr). This is in contrast to 101 kpa (760 torr) atmospheric pressure on earth, and to those at low earth orbit and on the lunar surface, which are between 10^{-4} to 10^{-10} Pa (10^{-6} to 10^{-12} torr). As shown in Figure 2 from reference [5], multi-layer insulation data for cryogenic applications show that a minimum thermal conductance is attained at pressures lower than the Mars environment pressure. That is why the Apollo and Shuttle space suit insulation of choice has been multi-layer shields. However, at Mars pressure, traditional multi-layer insulations cannot offer the same degree of protection required for a space suit (0.62 W/m^2-K) within the volume constraints required for high suit mobility. The failure to provide this protection is largely due to the presence of gas within the insulating layers.

Since the lofty nature of non-woven fabrics makes them the leading insulator on earth for clothing and flexible structures, NASA has selected them as a starting point for develoment of an advanced suit insulation. But development of a fiber insulation first requires understanding of the mechanisms that govern heat transfer in fibers. The first part of the current study addresses

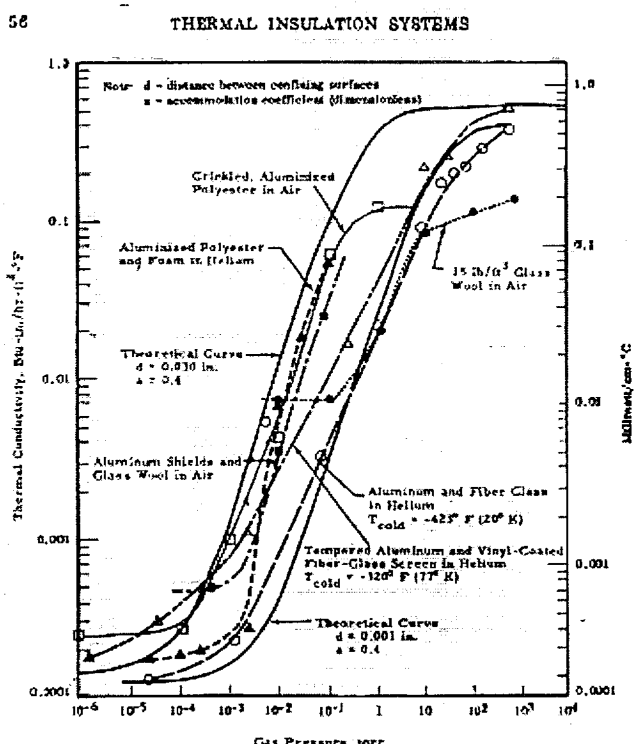

Figure 2. Effect of gas pressure on thermal conductivity

gas pressure dependence on overall thermal conductivity and the contribution of each heat transfer mode within the fibers for a synethic down fabric called Primaloft® Sport, from Albany International. The second part of the study addresses the effect of important fabric parameters on the thermal conductivity of a hollow fiber, non-woven structure, Hollofil® from Dupont, which contains no bonding agent.

Effective Thermal Conductivity of Primaloft® Sport as Function of Gas Pressure

Primaloft® Sport a non-woven polyester fabric, was selected for the current study because it has the highest R value of lofty insulations and the highest recovery from compression. The fabric consists of a 2.54 cm thick blend of 80% or less of 12 micron diameter fibers, 20% or greater of 12 micron diameter fibers, and a low melt polyester binder. Four fabric densities were constructed and tested at NASA/JSC during the summer of 1999 for thermal conductivity. Different fabric densities were obtained by compressing the original fabric. Densities tested were 4.0 , 6.2, 14.8, and 40 kg/cu m, as shown in Table 1, and test pressures and temperatures are shown in Table 2.

Table 1
Primaloft® Sport Configurations Tested at JSC

Sample No.	% Compressed From Original	Fabric Thickness (mm)	Fabric Density (kg/cu m)
1	0	25.5	4.0
2	35	16.5	6.2
3	73	6.89	14.8
4	90	2.55	40.0

Table 2
Test Parameters for JSC guarded Hot Plate Tests on Primaloft® Sport

Test Type and Test Pressure	Hot Side Temp (Deg C) (Note 1)	Cold Side Temp (Deg C) (Note 1)	Average Sample Temperature (Deg C)
A. Standard Tests (All Samples)			
10^{-4} to 10^{-3} Pa (10-6 to 10-5 torr)	20	-50	-15
10^{-1} Pa (10^{-3} torr)	20	-50	-15
11 hPa (8 torr-Mars)(Note 2)	0	-30	-15
66 hPa (50 torr) (Note 3)	0	-30	-15
B. Radiation Extrapolation Tests (Samples 1 and 4 only)			
10^{-4} to 10^{-3} Pa (10-6 to 10-5 torr)	30	10	20

NOTES FOR TABLE 2:
1. Hot side temperatures were selected based on inside suit temperature. Cold side temperatures were selected based on average cold external suit Mars temperatures.
2. At 11 hPa (8 torr) the large delta temperature of 70 degC required long stability periods at this relatively high gas pressure, given the open fabric structure and relatively small insulation thickness. For the purposes of this study (trend data only), an alternate delta temperature of 30 degC was selected to give the same average sample temperature as before while providing good steady state stability.
3. Test data at 66 hPa (50 torr) is not reported in this paper because of instability occuring at or near the critical Rayleigh No's that result in significant free convection in a double-sided, horizontal guarded hot plate apparatus. However, trends were established which showed that the thermal conductivity levels out between 11 hPa (8 torr) and 66 hPa (50 torr), which agrees with the "S" curve trend data (Figure 1).

The test results are shown in Figure 3 for thermal conductivity as a function of pressure from hard vacuum at 10^{-4} Pa (10-6 torr) to 11 hPa (8 torr), the upper Mars pressure for suit operations. For the fibers tested, higher density fibers generally yielded lower thermal conductivity values at a given pressure. This same general trend is reported in references [6] and [7] for glass fiber insulating materials for which the radiation between fibers decreases with increasing density down to some minimum value, and then increases again as density keeps increasing. This trend of density vs conductivity is shown in Figure 4 for all samples at hard vacuum.

As seen in Figure 3, increasing gas pressure resulted in increased thermal conductivity for any given fiber sample. This is the same trend seen from the data of Figure 2 for multi-layer insulations, where thermal conductivity increases with increasing gas conductance resulting from increased gas pressure.

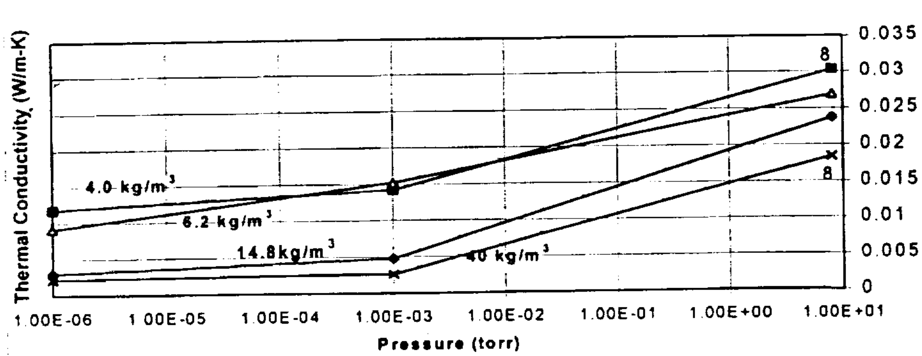

Figure 3. Primaloft Thermal Conductivity Dependence on Gas Pressure

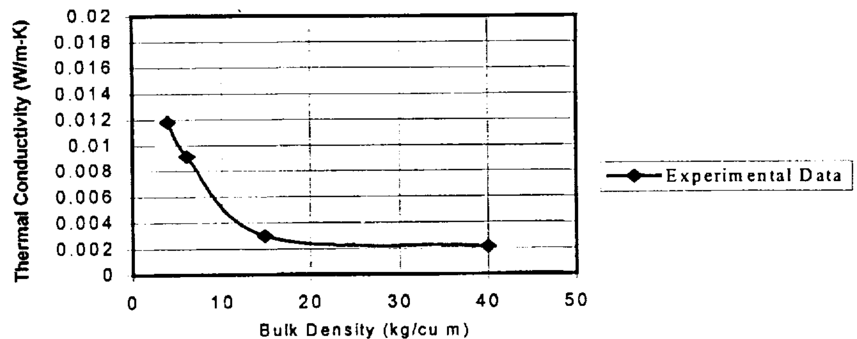

Figure 4. Effect of Density, Primaloft Tests at Hard Vacuum

Heat Transfer Contributions For Primaloft® Sport As A Function of Gas Pressure

It has been shown that in a gas environment, overall thermal conductivity is the sum of the solid, gas and radiation thermal conductivities [8]. For the Primaloft® Sport fabrics tested, the effect of gas conductance was extrapolated by first testing all samples at hard vacuum where gas conduction effects are negligible. As gas was added, the increase in thermal conductivity could then be said to be due to the gas conductance. Figures 5 through 8 show the results for all four samples. The trend for each sample shows gas conductance to increase with increasing pressure. The curves connecting data points are approximations only.

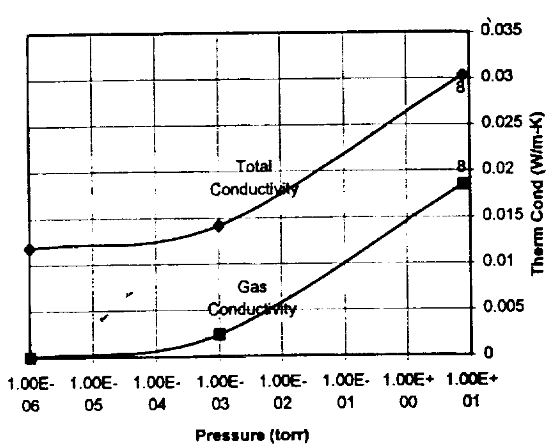

Figure 5

Effect of Gas Thermal Conductivity for Primaloft Sample 1 (4 kg/cu m)

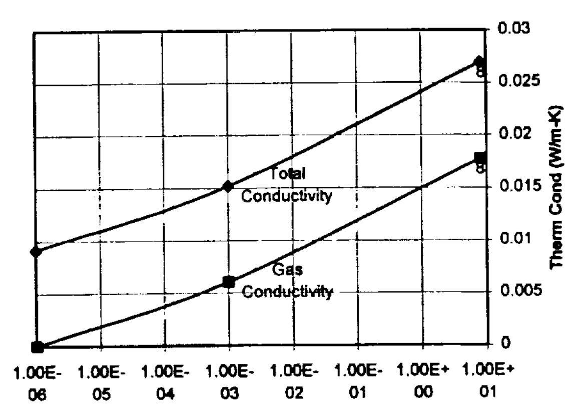

Figure 6

Effect of Gas Thermal Conductivity for Primaloft Sample 2 (6.2 kg/cu m)

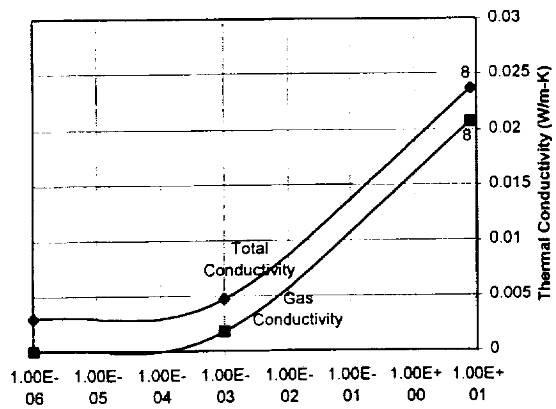

Figure 7
Effect of Gas Themal Conductivity for Primaloft Sample 3 (14.8 kg/cu m)

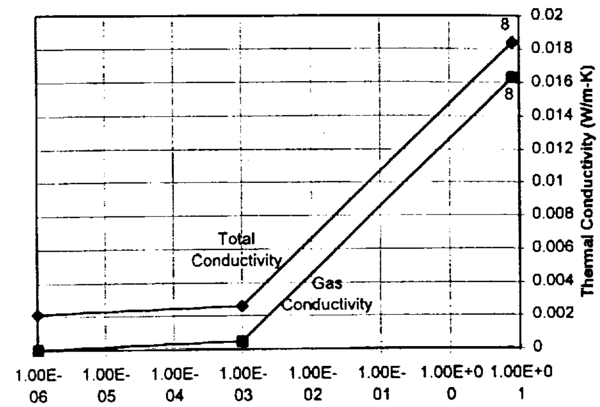

Figure 8
Effect of Gas Thermal Conductivity for Primaloft Sample 4 (40 kg/cu m)

An attempt was made to find the effect of the remaining conductivities, namely the solid and radiation portions, by using the radiation diffusion model technique from ref [9]. In this model, the total conductivity is the sum of the solid conductivity and the product of a constant and temperature to the third power, with the product also equaling the radiation conductivity. By obtaining overall thermal conductivities at two different mean temperatures (see Table 3) in hard vacuum (negligible gas effects), solutions can be obtained for both the solid contribution and the radiation contribution using two simultaneous equations with two unknowns. This technique was attempted for samples 1 and 4 only, since they represent the outer limits for the fabric densities tested. Results for these samples were compared to those reported in [9] and [10] for fibrous materials. It was concluded that the selection of test temperatures requires more refinement to give accurate estimates of the solid and radiation contributions. This refinement is required because the technique of [9] assumes a constant value of solid conduction at two different temperatures, but this assumption is only a good approximation when the two temperatures are close to each other. At any rate, the overall thermal conductivity trend data was established (Figures 3 to 8) as a function of gas pressure, the main parameter affecting the overall thermal conductivity.

The second part of this study addresses the effect of both fabric density and fiber size on the apparent thermal conductivity of non-woven structures.

Evaluation of the Effect of Fabric Density and Needlepunching on Hollofil® Thermal Conductivity

The choice of fibers for studying the effect of fabric and fiber parameters on thermal conductivity has been driven by several considerations. The fibers must be available in a range of deniers, and cross-sectional shapes for studying the effect of density and construction. Other considerations include the effect of fiber diameter, surface area, and optical properties on thermal conductivity. This study focuses on density and construction only. Hollofil®(7 holes polyester) fibers were thus selected because they offer possibilities for comparison to fibers with solid cross-section for future work. The fiber diameter for the selected fibers is 25 microns.

Four nonwoven structures were constructed to study the effect of density and needlepunching on thermal conductivity. Needlepunching was selected as the way to bind the fibers in the structures to give it coherence rather than thermal or chemical bonding. Needlepunching has the advantage of eliminating the contribution of a binder. This was done to minimize the magnitude of fiber contacts. The presence of a binder might reduce heat transfer by radiation if it serves as an opacifying agent [11]. Also it would be difficult with a binder to have two controlled levels of fabric coherence to study. Thermal bonding presents the same problem.

Two 6 denier Hollofil® fiber webs were chosen of 4 and 6 oz/yd^2 respectively. Each web was needlepunched at two levels of needling intensity: 120 NPI (needles per inch) and 240 NPI. Hence, the thermal conductivity of four types of samples made of the same fibers was measured at different pressures. The samples were labeled as follows:

- 120-4 for 120 NPI in the 4 oz/ yd^2 web,
- 240-4 for 240 NPI in the 4oz/ yd^2 web,
- 120-6 for 120 NPI in the 6 oz/ yd^2 web, and
- 240-6 for 240 NPI in the 6 oz/ yd^2 web.

All these samples were tested uncompressed at ΔT=30°C between –30 and 0°C. This temperature range was chosen rather than the 70°C delta temperature range used in the Primaloft® study. It was estimated that the delta temperature range of 30°C was more representative of the Mars suit insulation which would be under some protective layers providing wear and tear resistance as well as dust contamination barrier. Thermal conductivity was measured by the Guarded Hot-Plate method as done in the Primaloft® study. The first results are shown on figure 9. Thermal conductivity decreases with pressure as it is expected from theory. However, the effects of density and needlepunching are not so clearly observed. In vacuum, all four samples have close thermal conductivity values which indicates that neither the variation in density nor needling intensity makes a difference. This could be explained by the fact that the densities and needling intensities were not set at levels enough far apart to measure any significant difference as shown in table 3.

Table 3: Calculated Densities of the Hollofil Samples

	240-6	240-4	120-6	120-4
Density (Kg/m^3)	28.6	19.1	22.1	14.0

As mentioned earlier, little data on the combined effect of density and needling on thermal conductivity. In order to see the effect of density alone, two test samples were made by doubling the thickness of the uncompressed sample and compressing it to the original thickness. The measurements are shown in figure 10. The effect of density is apparent: thermal conductivity is reduced to approximately one half of its original value when the samples' density is doubled. The observed data from the compressed samples of figure 10 clearly demonstrates the expected result of lower thermal conductivity at higher fabric densities when the density is doubled. Since the data in table 3 shows the Hollofil® structure 240-6 to be denser than the 240-4 structure, the same density effect trend would be expected. However, because the density variation of the uncompressed samples is less than that of the compressed samples and because the thermal conductivity values for uncompressed samples are close to each other at the same pressure, experimental error shows the observed data at 10^{-3} torr to be a reverse trend in thermal conductivity for these two samples.

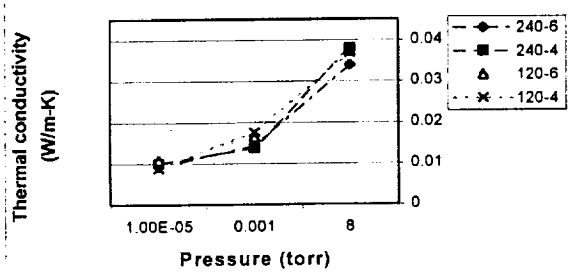

Figure 9
Apparent Thermal Conductivity of Hollofil Nonwoven Structures

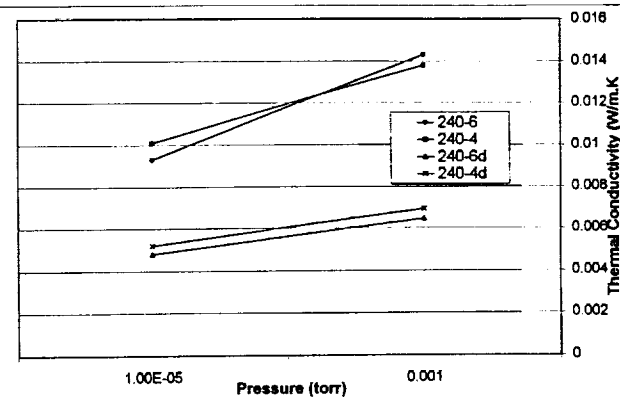

Figure 10
Thermal Conductivity vs. Density for Hollofil Structures

The effect of density on gas conduction was also evaluated as it had been done on the Primaloft® samples. Figures 11 through 14 show that gas conduction seems independent of fabric density and needling intensity for these particular samples. As with Primaloft®, an attempt was made to find solid conduction and radiation contributions, but more test refinements are required as discussed previously.

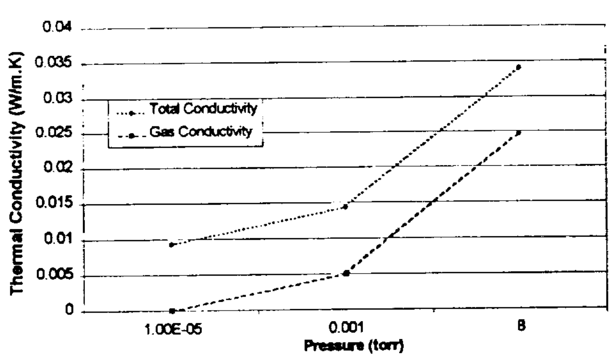

Figure 11.
Effect of Gas Thermal Conductivity on Hollofil Sample 240-6

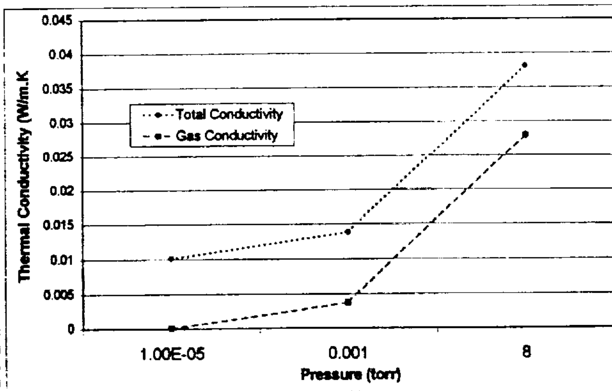

Figure 12
Effect of Gas Thermal Conductivity on Hollofil Sample 240-4

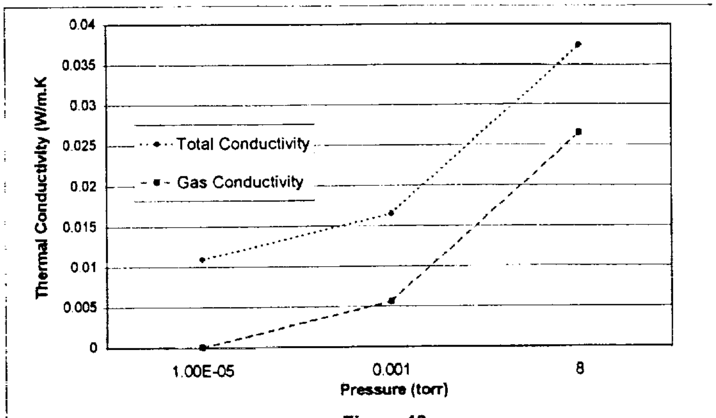

Figure 13
Effect of Gas Thermal Conductivity
on Hollofil Sample 120-6

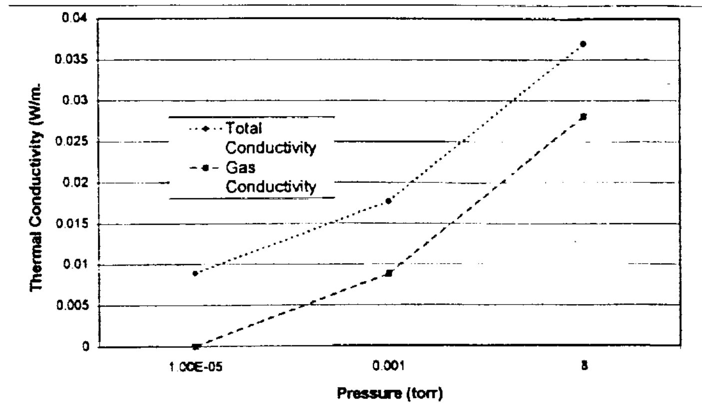

Figure 14
Effect of Gas Thermal Conductivity
on Hollofil Sample 120-4

CONCLUSIONS

In conclusion, this study showed the following concerning fabric density and fiber diameter:

- Different nonwoven structures indicates that at reduced pressures high loft gives no thermal insulation advantage within the range studied. Some comparisons between Primaloft® and Hollofil® were made. It is the combination of density and fiber fineness which gives the lower values of thermal conductivity.
- The apparent thermal conductivity of Primaloft® with a content of 80% fibers less than 12 microns in diameter, was consistently lower than that of any Hollofil® structure tested. A closer examination of the effect of fiber diameter is needed to understand the importance of this parameter in thermal insulation at reduced pressure.
- Since high loft and low fiber to void fraction does not provide lower thermal conductivity as this study demonstrated, it appears that high fiber surface area may be the critical parameter for low thermal conductivity at reduced pressures.

For the effect of needling intensity as a construction parameter, the following is concluded:

- In order to develop a better understanding of the effect of needling intensity on thermal conductivity, if it has any, more data is needed. One can only speculate that more intense needling may create thermal shorts by reducing the randomness of fiber orientation, but it has not been determined in this study.

Finally, the trend data showed that the pressure level at which thermal conductivity approaches a minimum is between 10^{-4} and 10^{-2} Pa (10^{-6} and 10^{-4} torr), consistent with cryogenic test experience. This further indicates that the Mars atmosphere level of 11 hPa (8 torr) is not even close to the optimum pressure level for insulation protection, and that based on current astronaut protection requirements, further work is needed to reduce the suit insulation bulk at this pressure.

FUTURE WORK

The focus of following work will be to continue studying:

- The thermal effects of fiber parameters such as hollow vs solid cross section, and cylindrical vs multilobal shape on thin dense nonwoven structures.
- A more in-depth study of the effect of fiber diameter on thermal conductivity
- The effect of fiber surface area on thermal conductivity at reduced pressures
- Continuation of the effect of needling intensity as a construction parameter and as a thermal parameter

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