

Aerogel Fabrics in Advanced Space Suit Applications

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Abstract

New insulating materials for spacesuits will need to be able to function well in low-pressure and gaseous environments, such as the Martian atmosphere. In order to address this need, Orbital Outfitters, a small spacesuit company, is currently investigating new materials for the insulating layer of the space suit. One such material is an aerogel fabric composite, promising because of its flexibility and low thermal conductivity. The purpose of this study is to characterize the effect stitching an outer layer has on the stiffness, strength, and thermal conductivity of two types of aerogel fabric, ThermalWrap and Pyrogel 2250. Tension tests were used to investigate the mechanical properties, while two different methods were used to evaluate the thermal conductivity of the materials. Results showed a dramatic increase of thermal conductivity when an outer material was stitched directly to the aerogel fabric, while two other geometries showed a decrease in thermal conductivity. Tension tests revealed that stitching increased the strength of the ThermalWrap. Overall, it was determined that stitching the material was not a viable option due to the increase in thermal conductivity and difficult manufacturing. The two other geometries tested proved much more effective, as they were easier to manufacture and showed a decrease in thermal conductivity.

Keywords: aerogel, pyrogel, thermalwrap, thermal conductivity, space suits

1. Introduction

Current spacesuit multi-layer insulation (MLI) is very heavy and has a baggy look while in use. NASA astronauts wear the current suit during extra-vehicular activity (EVA) missions, more commonly known as spacewalks, while stationed in the International Space Station. Figure 1 shows a breakdown of the components in MLI.

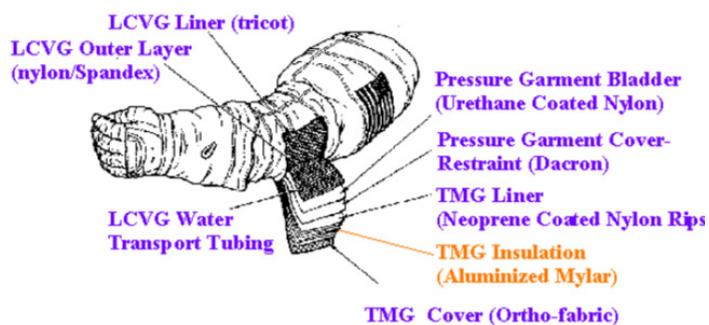


Figure 1: Current NASA standard MLI space suit¹

Although the current design works well for its intended function in Low Earth Orbit, they would not adequately insulate in higher pressure environments such as the Martian atmosphere¹. To address this issue, Orbital Outfitters and NASA are separately investigating and testing new candidate materials for use as insulation in a future space suit design. These materials must be flexible, lightweight, and have low thermal conductivity. Fabric aerogel composites have shown promise as light, thin insulation that can meet the requirements of an insulating layer for a spacesuit without adding excess bulk. Orbital Outfitters has partnered with this senior design group in seeking to describe the properties these aerogel fabric materials used as an insulating layer would give to a spacesuit. Orbital Outfitters is also interested in the effect of stitching on thermal conductivity and mechanical strength of fabric aerogels.

1.1 NASA Standards

NASA has determined that the maximum thermal conductivity value for an insulating layer used in the future space suit be $0.005 \text{ W/m}^2\text{K}$ ($5 \text{ mW/m}^2\text{K}$) at pressures between 10^{-6} and 8 torr. In addition to thermal conductivity standards, NASA also set an operating temperature range of $-157 \text{ }^\circ\text{C}$ to $121 \text{ }^\circ\text{C}$, a maximum thickness of 12.7 mm, and a density of less than 0.68 kg/m^3 .¹

1.2 Overview

This study aims to investigate and determine the effect that stitching has on the thermal insulation and mechanical characteristics of aerogel fabric. Two different materials were studied, Thermal Wrap and Pyrogel 2250. Both contain granules of silica aerogel suspended in a nonwoven polymer fiber matrix and can be seen in Figure 2. To evaluate the materials, several different tests were run to ensure that they would not degrade in the operating temperature range suggested by NASA. Enough material was used to show the representative behavior of the bulk materials. Once baselines were established, stitched samples were manufactured and tested.^{1,7}

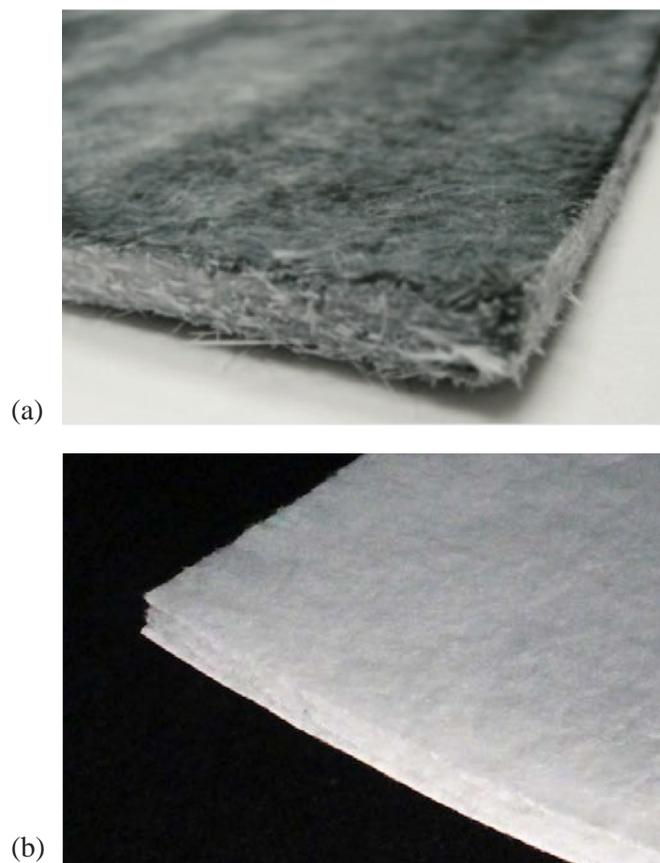


Figure 2: (a) Thermal Wrap (b) Pyrogel 2250. Both fabrics are approximately 3mm thick.

2. Procedure

2.1 DSC

A TA Instruments Q20 Differential scanning calorimeter (DSC) was used to investigate any possible physical transitions (such as glass transition or phase transitions) experienced by the materials when heated. Due to physical limitations of the machine in relation to sample size, only Thermal Wrap 350 and Pyrogel 2250 were able to be tested. Each sample was taken from room temperature to $140 \text{ }^\circ\text{C}$ in the DSC at a rate of $10 \text{ }^\circ\text{C}/\text{min}$. Results were analyzed following the testing.

2.2 TGA

Thermogravimetric analysis (TGA) testing was done with a TA Instruments Q50 to determine if the materials would be usable in the NASA specified temperature range. Both the Thermal Wrap and Pyrogel 2250 materials were prepared and tested using a ramp from room temperature to $750 \text{ }^\circ\text{C}$. A ramp rate of $20 \text{ }^\circ\text{C}/\text{min}$ was used for all tests. Since the maximum operating temperature was set at $121 \text{ }^\circ\text{C}$, results were examined between 20 and $140 \text{ }^\circ\text{C}$ for each sample run.

2.3 DMA

Dynamic mechanical analysis (DMA) was performed on the samples with a TA Instruments Q800 to determine how their flexibility changes with temperature. Both static force bending and static force tension tests were run on rectangular samples, with a temperature range of -140 to $140 \text{ }^\circ\text{C}$.

2.4 Tension Testing

To test the unstitched aerogel material in tension, $150 \times 25 \text{ mm}$ samples were cut out from the larger sheets of material. An ASTM standard dogbone could not be used due to the difficulty in cutting the material. Extra consideration was also taken to investigate whether heat exposure would affect the flexibility of unstitched material. Samples of each type of fabric were heated in a furnace for eight hours at $121 \text{ }^\circ\text{C}$. This time and temperature combination represents the most extreme conditions that would be expected from an EVA mission and the highest range of NASA specified temperature.⁴ After heating, the samples were then tested in tension in an Instron with roller grips to determine whether there was a significant change to the flexibility.

For the quilted samples, the larger 127 mm squares were cut into strips. Each square was able to yield several tensile specimens. To test the outer muslin fabric, $150 \times 25 \text{ mm}$ strips were cut from a larger sheet of material. The samples were loaded onto an Instron load frame with a 5 kN load cell using fabric roller grips. All of the samples were tested at a constant strain rate of $10 \text{ mm}/\text{min}$.

2.5 Hot Disk Testing

Initial thermal conductivity measurements were taken using a Hot Disk thermal measurement system with a 9.73 mm radius Kapton sensor. Prior to testing the aerogel samples, the machine was calibrated using two stainless steel calibration disks. Following calibration, two small samples of material were cut out and used, sandwiching the Kapton sensor in between them. The samples and sensor were held in place using a screw apparatus to ensure that they would not move during testing and disrupt measurements.

2.6 Forward Looking Infrared (FLIR) Imaging

Infrared video of the samples being heated was captured using two FLIR A665sc cameras. Before imaging, each sample was typically coated using Rust-Oleum High Heat black spray paint to get a known emissivity value on the surface of the samples. Once the coatings were properly applied and dried, the samples were hung on a static load frame using 24 gauge stainless steel wire. One FLIR camera was set in front of the samples and focused to capture the front of the sample. The second FLIR camera was placed at an angle behind the sample and focused to capture the back of the sample. Four quartz-panel heaters were placed behind the samples and set at 497°C to produce a heat flux of 10 kW/m². The samples were heated and IR images were recorded for 30 minutes each, ensuring that they reached a steady-state of through-thickness heat diffusion.

3. Results and Discussion

3.1 Proof of Concept

The results obtained from the thermogravimetric analysis indicated that no thermal degradation occurred in the Thermal Wrap and the Pyrogel 2250 samples in the typical EVA temperature range. The DSC measurements revealed that in the Thermal Wrap samples there was melting occurring in the material at 121.76°C, right outside the typical EVA range. This is attributed to the proprietary copolyolefin sheath of the matrix fibers melting.⁸ The DSC findings for the Pyrogel did not indicate any physical transitions upon heating. The flexural modulus of both materials did show a temperature dependency, according to the DMA results. These changes ranged, for ThermalWrap, from 9.06 Pa to 115 Pa and from 92.8 Pa to 360.5 Pa, for Pyrogel.

3.2 Recommendation Testing

3.2.1 Thermal Conductivity Testing

Both the HotDisk and FLIR thermal conductivity measurement systems proved to be fruitful measurement techniques. The thermal conductivity results for the various geometries of both ThermalWrap and Pyrogel are shown in Figure 3a below. No measurements were obtained for the pocketed ThermalWrap and quilted Pyrogel samples due to

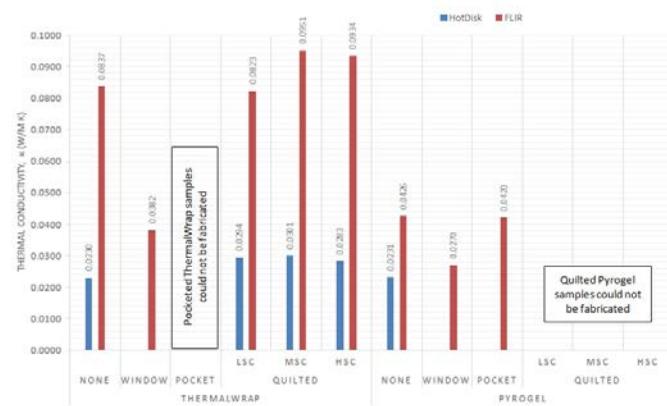


Figure 3a: Thermal Conductivity of Various Samples measured by HotDisk and FLIR. The seemingly large systematic difference between the two methods is apparent because the HotDisk is measuring a single area, and the FLIR is averaging larger areas in the sample. LSC, MSC and HSC stand for low stitch count, medium stitch count and high stitch count, respectively.

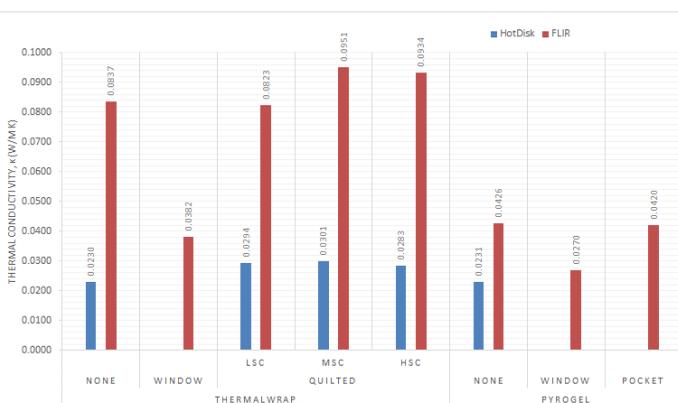


Figure 3b: Thermal Conductivity of various samples measured by HotDisk and FLIR

issues in fabrication: the pocketed ThermalWrap samples were not fabricated in time, and the Pyrogel fabric could not be punctured by the needle and therefore could not be stitched. No HotDisk data were taken for the windowed and pocketed samples, because the contours and changes in topography of these samples proved to be too great and made measuring thermal conductivity accurately with the HotDisk impractical. The simplified findings of the plot in Figure 3a are shown in Figure 3b.

The Hot Disk measurements show that the Thermal Wrap and Pyrogel samples exhibit almost the same thermal conductivity without stitching. It is also shown that for the stitched Thermal Wrap samples there is an apparent increase in thermal conductivity for all stitch counts compared to unstitched. Similarly, for the FLIR data, there appears to be an increase in thermal conductivity for all samples other than the low stitch count. Conversely, the FLIR data in Figure 3b shows that in all instances, both for the Thermal Wrap and Pyrogel, there was a decrease in thermal conductivity in the windowed and pocketed samples.

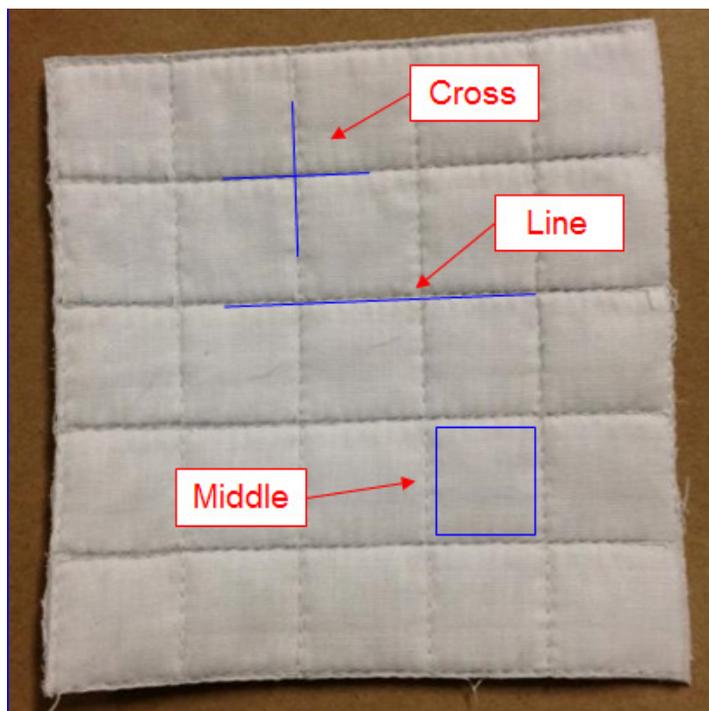


Figure 4: Stitched thermal wrap sample showing zones.

To obtain a better idea of how the stitching affected the thermal conductivity of the aerogel fabrics the thermal conductivity was measured at different zones: lines, which are linear sections of stitching, crosses, where two lines intersect, and middles of the stitched samples, where no stitching is present. Figure 4 shows the different zones of the stitched samples. Crosses were the intersection of two lines of stitching, while lines were single lines of stitching, and middles were unstitched areas.

Figure 5 summarizes the measurements of thermal conductivity for the stitched Thermal Wrap samples in different zones. Measurements by HotDisk are shown first in the blue colors and those measured by FLIR are shown second and in shades of red. The horizontal lines represent the thermal conductivity values of the unstitched samples as measured by HotDisk (bottom, green) and FLIR (top, orange). The data in Figure 5 confirm the observation made from Figure 3b that the addition of stitching increases thermal conductivity, regardless of measurement technique. The FLIR measurements also have a much larger standard deviation than any other measurement shown in Figure 5. Also of note is that there seems to be a large increase in thermal conductivity in the samples measured in FLIR compared to those measured using the HotDisk.

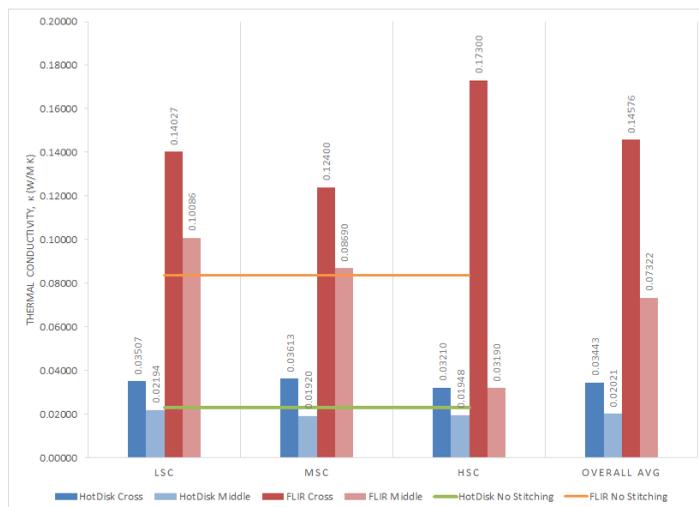


Figure 5: Thermal conductivity of stitched thermal wrap samples in different zones by hot disk and FLIR

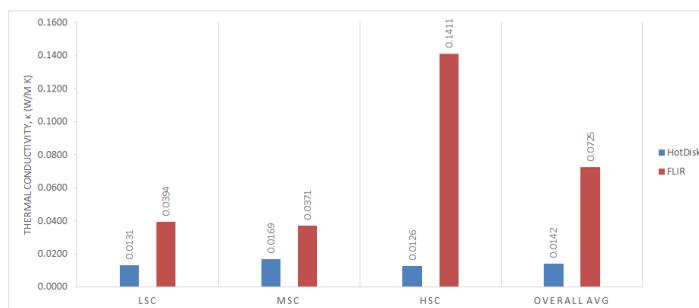


Figure 6: Change in thermal conductivity upon stitching of thermal wrap for various stitching densities

These results can be further summarized by the plot in Figure 6. Here the net change in thermal conductivity from stitching is shown, in all cases the change is an increase. As previously mentioned, the FLIR measurements have both a larger increase in thermal conductivity than the Hot Disk measurements as well as a larger standard deviation when comparing stitched samples to unstitched samples.

To further understanding of what significantly affects the thermal conductivity results, an analysis of covariants (ANCOVA) was done for the Hot Disk data. ANCOVA is a statistical analysis tool that is used to create a linear model to estimate how much change each factor and the interactions between the factors contributes to the results. One level of each factor is arbitrarily chosen as a baseline of comparison for the other levels in that factor. The analysis in this report chose the low stitch count and cross zones as the baseline of comparison, and the model equation is shown below in Equation 1.

$$\kappa = \beta_0 + (\beta_1 \cdot stitch_i) + (\beta_2 \cdot zone_i) + (\beta_3 \cdot stitch:zone_i) + (\beta_4 \cdot probedepth) + \varepsilon_i$$

$$i = 1,2,3..$$

Equation 1: ANCOVA model for hot disk data

In Equation 1, κ is the thermal conductivity measured by the instrument, β_0 is the intercept of the equation, and ε_1 is the error involved. $\beta_1, \beta_2, \beta_3$ and β_4 are either 1 or 0, depending on which area of the sample is being interrogated. The stitch:zonei and probedepth variables are the interactions between the zone and stitch factors and the machine variance, respectively. Probe depth is the size of the area measured by the Hot Disk.

The results of the ANCOVA analysis show that all the variables included in the model significantly affect the thermal conductivity reported by the Hot Disk. This is determined by the p-value, which is a measure of the probability that the estimated value occurs by random chance. For this project, any factor that has a p-value less than 0.05 is considered significant. This p-value corresponds to a 95% confidence that the estimates calculated for the factors and levels chosen are realistic approximations for how the stitching affects the thermal conductivity.

Finally, the analysis results show that both the medium and high stitch counts increase the thermal conductivity over the low stitch count, but, surprisingly, the medium stitch count increases the thermal conductivity more than the high stitch count. This can be attributed to the difficulty in manufacturing of the samples, as the seamstress reported that some rows had to be stitched over and some stitches were skipped because of the nature of sewing a non-woven fabric filled with aerogel. The line zone showed an increase in thermal conductivity, and the middle zone a decrease compared to the cross zone, which was expected. The largest

contribution to the thermal conductivity reading was the machine variance itself, since the probe depth gives the highest estimated contribution. This is also expected, as the HotDisk was being operated near its lower ability to give accurate results, where intrinsic error becomes a larger factor.

This table shows the numerical values resulting from an analysis of covariants done on the HotDisk data. The first column is the estimated value that each level of each factor contributes to the thermal conductivity results, in W/m²K. The second column is the standard error calculated between three data points in each row, and the third column is the t-value which is the estimate divided by the standard error. The last column shows the p-values, which are the probability as to whether or not the estimated values occur by random chance or not. The closer the p-values are to zero, the lower the chance that the t-values are a random occurrence.

Table 2: Young's Modulus in relation to stitch count.

Stitch Count	Young's Modulus (MPa)	Stand. Dev (MPa)
Low	20.13	6.49
Medium	13.10	1.20
High	13.80	1.41
Outer Fabric	161.05	13.45

Table 1: ANCOVA of Hot Disk Results

	Estimate	Std. Error	t value	Pr. t
(Intercept)	0.0122	0.0023	5.407	4.715E-05
Stitch350 HSC	0.0031	0.0010	3.164	5.677E-03
Stitch350 MSC	0.0061	0.0010	6.690	3.802E-06
ZoneLine	0.0090	0.0011	7.845	4.758E-07
ZoneMiddle	-0.0031	0.0012	-2.541	2.108E-2
ProbDepth	0.0141	0.0013	10.477	7.790E-09
Stitch350 HSC:ZoneLine	-0.0077	0.0014	-5.574	3.358E-05
Stitch350 MSC:ZoneLine	-0.0010	0.0014	-7.298	1.244E-06
Stitch350 HSC:ZoneMiddle	-0.0029	0.0011	-2.573	1.975E-02
Stitch350 MSC:ZoneMiddle	-0.0074	0.0011	-6.484	5.612E-06

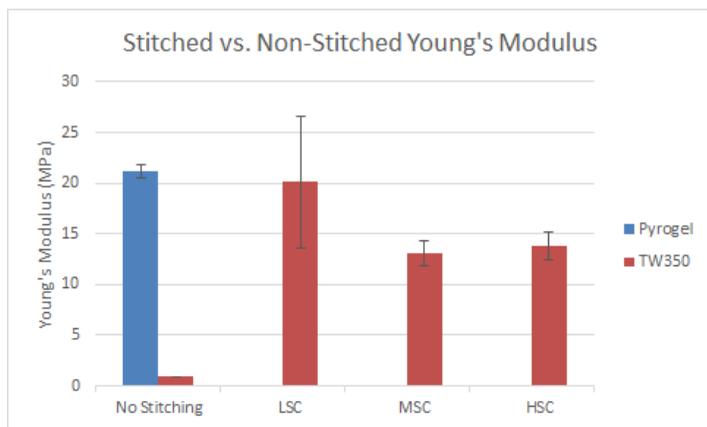


Figure 7: Young's Modulus in relation to stitch count.

3.2.2 Mechanical Testing

The results of the tension tests run on the stitched Thermal Wrap samples are shown in Table 2. The tests were performed with a strain rate of 10mm/min.

From Table 2 and analysis of variance it can be seen that the stitch count does not have an effect on modulus. However, stitching an outer layer directly to the Thermal Wrap samples did increase the resilience of the material system when compared to normal, non-stitched samples. During the tests, the inner aerogel fabric would tear at very low loads, but the overall structure of the system would remain intact for a significantly higher strain. This is encouraging, as it indicates a minimal loss of aerogel insulation even after the insulating layer has failed within the system. Further testing would be needed to quantify the ability of the system to insulate following inner aerogel failure.

The null hypothesis is that the stitch count did not have an effect on modulus and since our p-value is greater than our alpha of 0.05 and our f value was less than our f-crit we fail to reject the null and will proceed with the assumption that stitch count does not have an effect in this stitch density range.

Figure 8 shows that the outer fabric increased breaking strength and that the stitch count did not have an effect on strength in the range of stitch density we looked at.

Table 3: ANOVA comparing stitch counts

ANOVA						
Source of Variation	SS	Df	MS	F	P-value	F crit
Stitch Density	104.97	2.00	52.49	3.34	0.08	4.26
					F < F crit	
Total	246.28	11.00		$\alpha=0.05$	P> α	

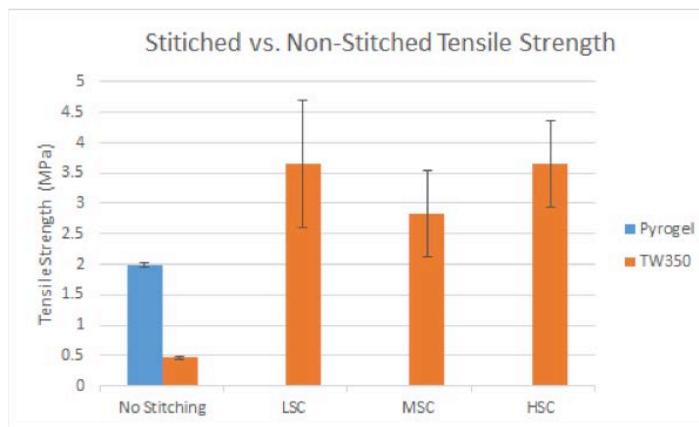


Figure 8: Breaking strength in relation to stitch count.

4. Conclusions

4.1 Materials Conclusions

From the results of this project, two major conclusions have been drawn. First, it is clear that stitching an outer fabric layer directly onto the aerogel fabric is not a viable option. This is due to the fact that the stitching had a significant negative impact on the thermal conductivity of the material system and the difficulty in manufacturing the samples. Without either a way to mitigate the increase in thermal conductivity at the stitches or a much better method of manufacturing the samples, this will not be an optimal geometry.

Second, it has been determined that future work with this materials system should focus on the windowed and pocketed geometries with Pyrogel inside. The Pyrogel demonstrated a lower thermal conductivity and is more mechanically sound than the thermal wrap. Additionally, the windowed and pocketed geometries exhibited a reduction in thermal conductivity, as compared to both the unstitched and stitched samples.

4.2 Future Work

Future work should investigate the effects of lower pressure environments on the thermal conductivity of the material. Literature indicates that a reduction in external pressure will reduce the thermal conductivity for several materials,³ so it should be determined if this holds true for the aerogel fabric systems as well. Also, different geometries that would work well in flexible joints will need to be investigated. Having adequate thermal protection without sacrificing mobility at joints will be a mission critical aspect to future space suits.

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