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# STUDY FOR FABRICATION, EVALUATION, AND TESTING OF MONOLAYER WOVEN TYPE MATERIALS FOR SPACE SUIT INSULATION

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## ABSTRACT

Present multilayer insulation (MLI) material for space suit insulation is costly to fabricate and lacks durability due to its multilayer nature. An alternative concept using a monolayer woven pile material has been suggested to greatly reduce cost and improve the durability of the overgarment, while providing protection similar to that provided by the MLI. Twelve samples of different configurations were fabricated and tested for compressibility and thermal conductivity as a function of compression loading. Two samples which had shown good results in the initial tests were further tested for thermal conductivity with respect to ambient pressure and temperature. Results of these tests were similar to results of the MLI tests, indicating the potential of the monolayer fabric to replace the present MLI. A seaming study illustrated that the fabric can be sewn in a structurally sound seam with minimal heat loss. It is recommended that a prototype thermal meteoroid garment be fabricated.

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## 1. BACKGROUND

It is necessary to insulate the exterior of an EVA pressure suit to provide thermal protection from solar radiation, heat loss to space, and contact with hot or cold objects, as well as protection from micro-meteoroids. A multilayer insulation (MLI) material has been used previously in the fabrication of pressure suit overgarments. This integrated thermal protection garment (ITMG) was very effective-thermally and for meteoroid protection, but was expensive to fabricate and not very durable due to the multilayer nature of the material. An alternative concept using a monolayer woven pile material has been suggested to greatly reduce the cost and improve the durability of the overgarment, while providing protection similar to that of the multilayer material.

The purpose of this program was to evaluate the suitability of the monolayer woven pile concept for use in pressure suit overgarments. Twelve varieties of the monolayer material were fabricated and tested for compressibility and thermal conductivity under various conditions simulating those which may occur in space. Two varieties of MLI and a control sample of known thermal conductivity were also tested to provide comparison data.

## 2. TASK 1 -- FABRICATION OF MONOLAYER TEST SAMPLES

### 2.1 Fabrication Procedure

The monolayer fabric has two components: the orthofabric base and the pile. The orthofabric consists of two layers woven together in a special process that will provide a tight weave and a smooth outer surface with the optical properties of the MLI outerlayer. The outerlayer is Gore-Tex (a teflon); the underlayer is Nomex with Kevlar strengthening threads. The pile is also Nomex and is formed in a "W" weave on the Nomex side of the orthofabric. To avoid a loosening or unevening effect on the Gore-Tex outer layer, the pile is woven through the Nomex only and, therefore, is not locked in place.

### 2.2 Variations of the Material

Three parameters were varied in the construction of the 12 samples as described below. Identification of each sample appears in Table 1.

#### 2.2.1 Pile Density

Two variations included maximum density achievable -- 16 ends/cm (40 ends/inch) and a less dense construction -- 12 ends/cm (30 ends/inch).

#### 2.2.2 Pile Height

Three variations in height were 0.16 cm, 0.32 cm, and 0.48 cm (1/16, 1/8, and 3/16 inch).

#### 2.2.3 Pile Diameter

Two variations in diameter were 3 ply and 2 ply pile.

TABLE 1. FABRIC SPECIMEN CODE IDENTIFICATION

Pile Density, $\frac{\text{ends}}{\text{cm}}$ ( $\frac{\text{ends}}{\text{in}}$ )		Pile Height, cm (in)			Pile Diameter		Sample No.
16 (40)	12 (30)	0.16 (1/16)	0.32 (1/8)	0.48 (3/16)	3 Ply	2 Ply	
X		X			X		1
X		X				X	2
X			X		X		3
X			X			X	4
X				X	X		5
X				X		X	6
	X	X			X		7
	X	X				X	8
	X		X		X		9
	X		X			X	10
	X			X	X		11
	X			X		X	12
Apollo 7 Layer MLI							13
Shuttle 4 Layer MLI							14
Neoprene (control)							15

### 3. TASK 2 -- INITIAL TESTING OF MONOLAYER AND MLI SAMPLES

The 12 samples fabricated under Task 1 were tested initially for compressibility and thermal conductivity. A representative Apollo seven-layer MLI sample (A7LB lay-up with nonaluminized radiation shield) and a Space Shuttle four-layer MLI sample (Gore-Tex, Nomex, Kevlar orthofabric, Style 116, aluminized reinforced mylar, neoprene coated nylon ripstop) were also tested to provide comparison data and verification of the test techniques. Both MLI samples were provided by NASA-JSC.

#### 3.1 Compressibility Testing

The compressibility of the 12 monolayer samples and the Apollo seven-layer MLI was tested at room temperature and compression loads of 3447, 6895, 13,790, 20,684, and 34,474 N/m<sup>2</sup> (0.5, 1, 2, 3, and 5 psi). The test procedure is described in Appendix A. The test consisted of loading a 5 cm (2 inch) square sample with the appropriate weight and measuring the height change of the sample. The data was analyzed in terms of reduced thickness with respect to compression loading, as well as percentage change in thickness from "free" or uncompressed thickness with respect to compression loading. The raw data are shown in Appendix A; results appear in Figures 1 through 4.

Sample 2 had the greatest actual thickness at the highest compression load (Figure 1). Fifth in thickness was the Apollo seven-layer MLI (Figure 2). Examining the characteristics of the five best samples (Table 2) shows that maximum density achievable is important for compressive strength, but there is not a strong correlation between the other characteristics and performance.

In terms of percentage change in thickness, or relative compressive strength, Sample 2 performed the best with the least percentage change in thickness (Figure 3). The Apollo MLI was second best in relative compressive strength (Figure 4). The five best samples (Table 2) again do not reveal a strong correlation between characteristics and performance, but the trend suggests that maximum density and short pile are related to higher compressive strength. The lack of a strong correlation may be due to variation in weave, a problem of prototype fabrication. For example, Samples 1 and 2 are of similar construction, differing only in pile diameter which is maximum in Sample 1. Sample 1 performed considerably below Sample 2, while the characteristics of Sample 1 would seem to give it the qualities for a better performance. However, Sample 1 is a looser, less regular weave than Sample 2, due to its larger pile diameter which makes the weaving process more difficult. This prototype fabrication difficulty would be overcome in large volume manufacturing. As we are mainly concerned with the observance of trends, the validity of the results is unaffected.

A hysteresis check was performed on Sample 2 in which the sample was loaded then unloaded in steps with thickness measured at each step. There was a half-hour pause between loading and unloading, with the highest load on the sample. The test description and data is shown in Appendix A. Test results appear in Figure 5, showing one set of curves

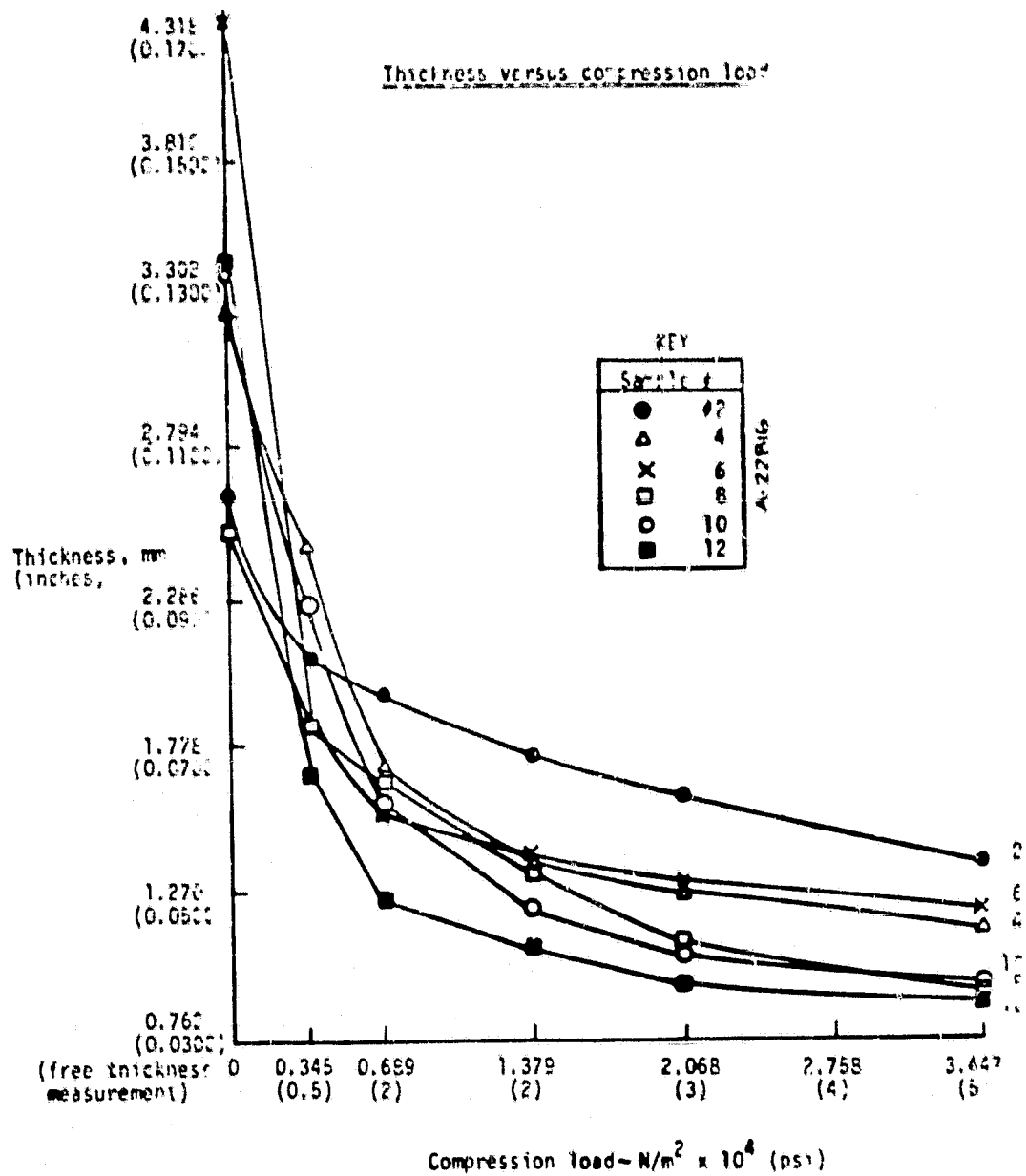


Figure 1. TMG compressibility test, Group 1.

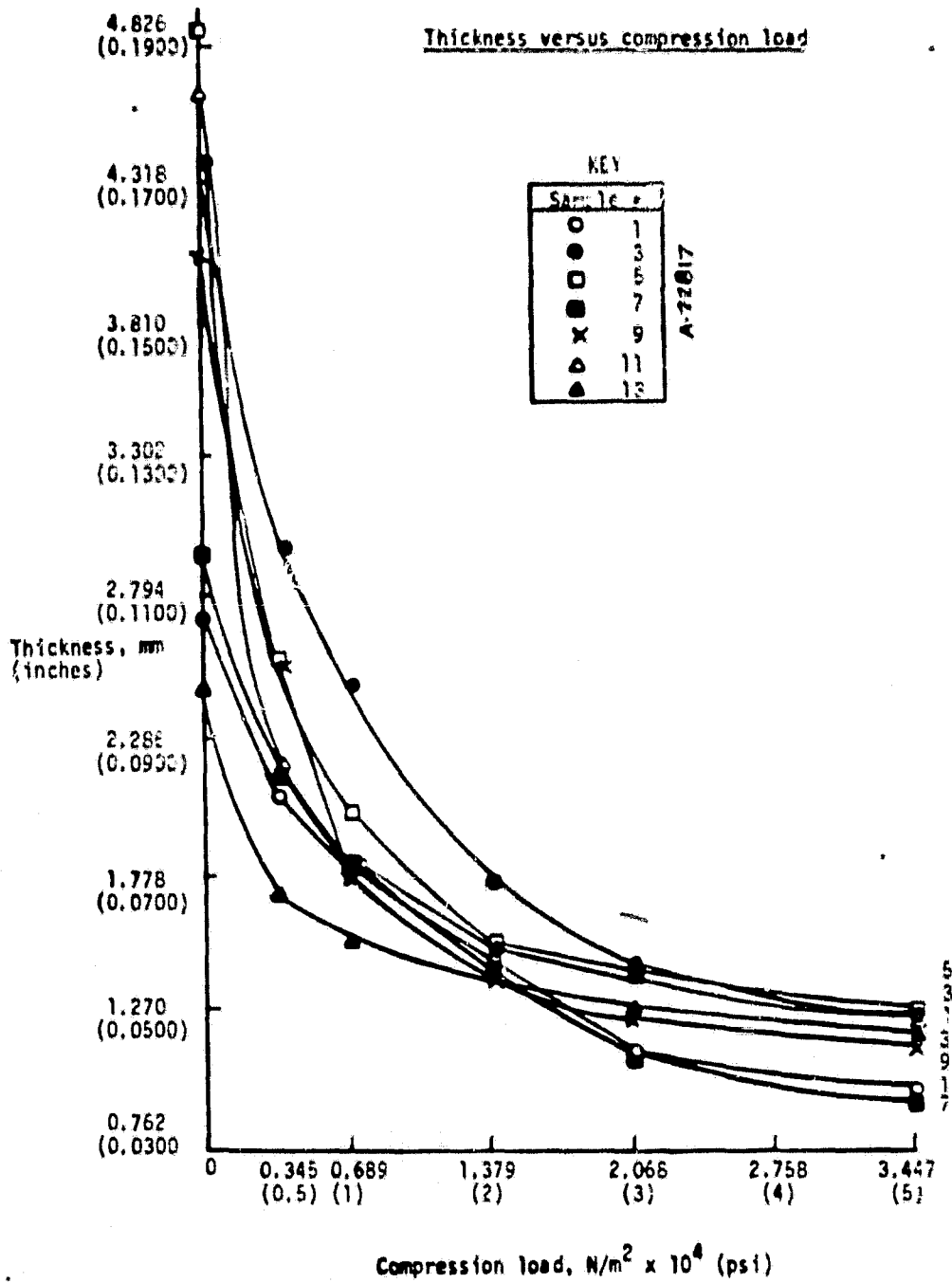


Figure 2. TMG compressibility test, Group 2.

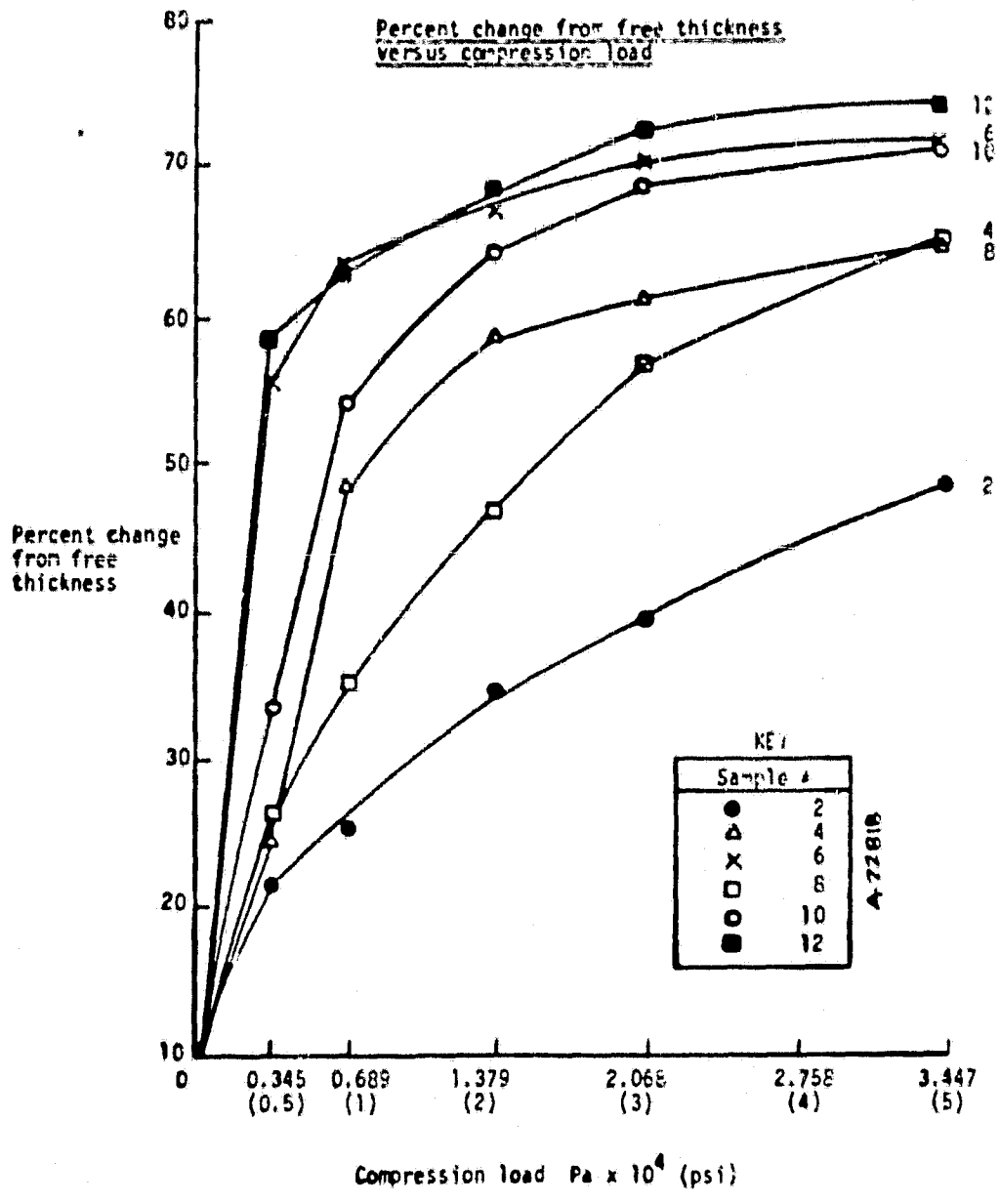


Figure 3. TMG compressibility test, Group 1.

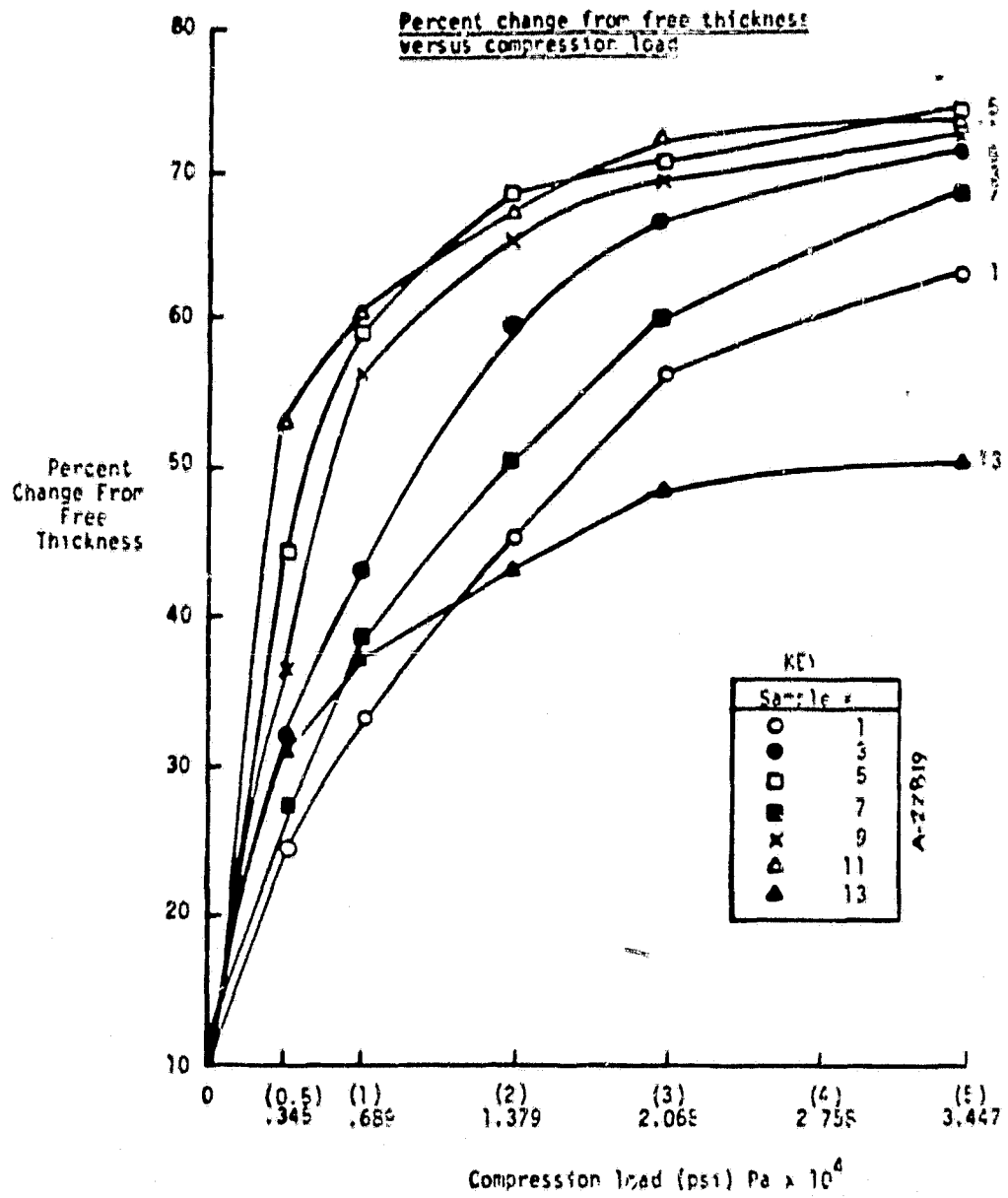


Figure 4. TMG compressibility test, Group 2.

Sample #2

Thickness and percent change from free thickness versus compression load

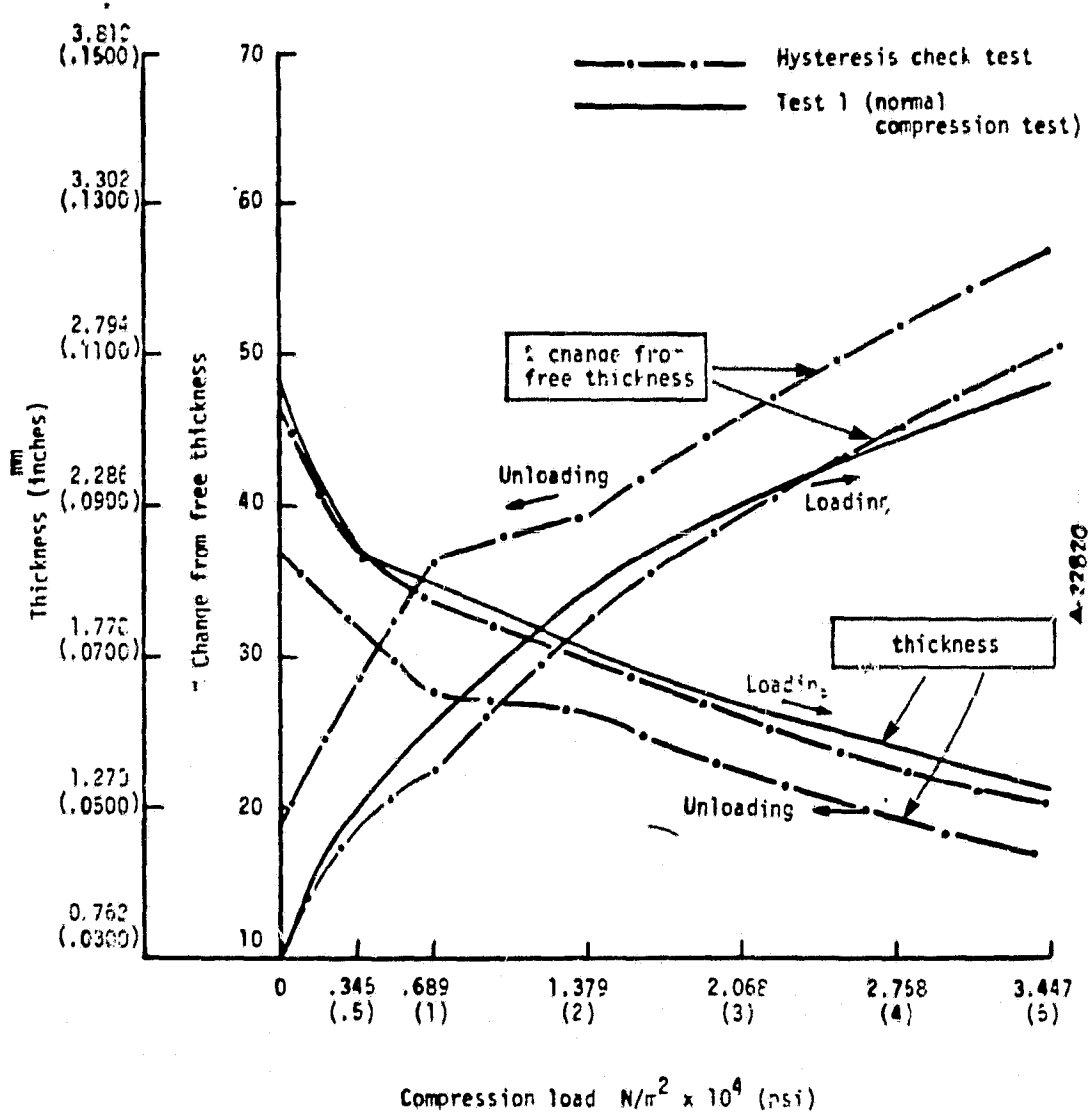


Figure 5. TMG compressibility test hysteresis check.



TABLE 2. CHARACTERISTICS OF THE FIVE TOP PERFORMING SAMPLES IN COMPRESSIBILITY TESTING

Actual Thickness with Respect to Compression Loading				
Performance No.	Sample No.	Pile Description		
		Density	Height	Diameter
1	2	max	low	min
2	5	max	high	max
3	3	max	med	max
4	11	min	high	max
5	13	MLI		

Percentage Change from Free Thickness with Respect to Compression Loading				
Performance No.	Sample No.	Pile Description		
		Density	Height	Diameter
1	2	max	low	min
2	13	MLI		
3	1	max	low	max
4	4	max	med	min
5	8	min	low	max

for actual thickness and one for percentage change in thickness. Also shown in Figure 5 are the results from the first compressibility test on Sample 2 which correspond well with the hysteresis check results, demonstrating the repeatability of these tests. The hysteresis effect is evident but not significant enough to address further.

### 3.2 Thermal Conductivity as a Function of Compression Loading

The 12 samples plus the two MLI specimens underwent steady-state thermal conductivity tests at an average sample temperature of 21°C (70°F) with a temperature difference across the sample of not more than 28°C (50°F) and not less than 16°C (30°F); an ambient pressure of less than  $10^{-4}$  Torr; and compression loads of 0, 3447, and 27,580 N/m<sup>2</sup> (0, .5, and 4 psi). Methods of loading are listed in Appendix B, Table B-2.

The test apparatus consisted of a hot plate sandwiched between two test specimens of the same type and two cold plates, all 10 cm (4 inch) diameter circles. Two thermocouples were placed on each cold plate and on both surfaces of the hot plate. Power was supplied to the hot plate and fluid to the cold plates, both were adjusted to achieve the proper average temperature and temperature difference. With the required power and the temperature difference known, the thermal conductance of the specimen can be calculated. The test procedure, a sample calculation, and test data are included in Appendix B.

The results of this test appear in Figure 6, in which thermal conductance is shown as a function of compression loading. For all test specimens, thermal conductance increased with increasing compression loading. The sample with the lowest conductance was the Apollo MLI, Sample 13. The next lowest, Sample 6, was well above the Apollo MLI, but with lower conductance than the Space Shuttle MLI, Sample 14. Several samples performed in the range of the Shuttle MLI, and three performed better in this test, indicating the potential of the monolayer fabric in certain configurations to provide better thermal protection under compressive loads than the Shuttle MLI.

Also shown in Figure 6 is data provided by NASA on previous thermal conductivity tests of the same type of MLI samples as tested here under conditions similar to those in the tests conducted for this program. The NASA test data fall within 30 percent of the corresponding results of the current tests, indicating the adequacy of the current test apparatus and procedures.

The five monolayer samples with the lowest conductances at the highest load were, in order, Samples 6, 5, 11, 9, and 12. Sample 14 (Shuttle MLI) fell between Samples 11 and 9. Each of these five were constructed with the greatest pile height, except for Sample 9 which was of the middle pile height. Moreover, these five samples had the lowest compressive strength (highest percentage in change from free thickness with respect to compression load), but with the exception of Sample 12, they were among the thickest samples at the highest compression loading.

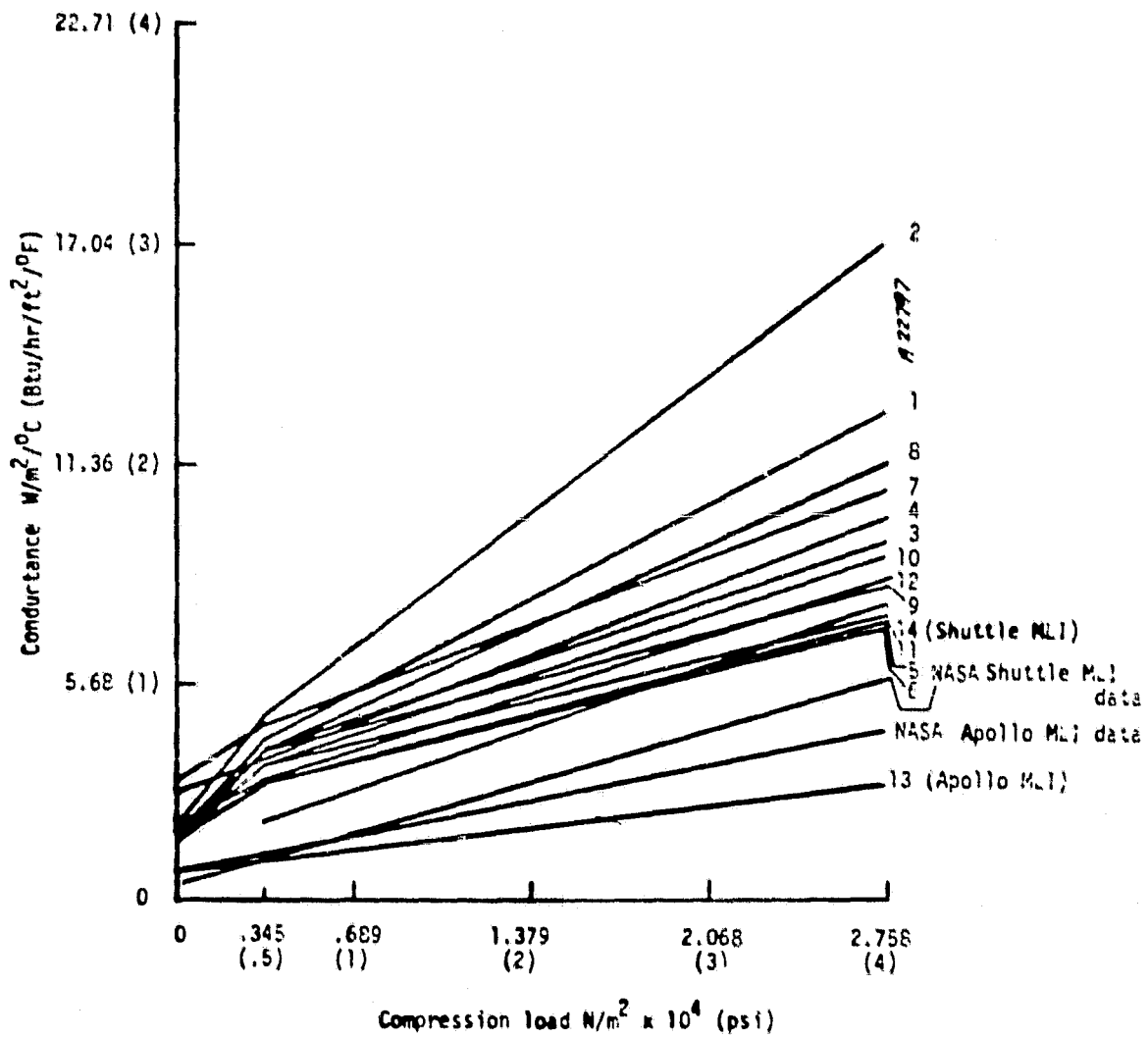


Figure 6. Thermal conductance,  $W/m^2/^\circ C$  ( $Btu/hr/ft^2/^\circ F$ ) vs. compression loading,  $N/m^2$  (psi) at pressures  $\leq 10^{-4}$  torr.

It is interesting to note that the sample which performed best in the compressibility tests had the highest conductance at 27,580 N/m<sup>2</sup> (4 psi). The characteristics of Sample 2 which gave it good compression properties (maximum pile density and tight weave) caused greater conductance at the higher compression loads.

In an effort to understand the effects of each configuration variable, NASA performed a multivariate linear regression, using as input parameters resulting from the thermal conductivity tests at an average temperature of 21°C (70°F), an ambient pressure less than 10<sup>-4</sup> Torr, and a compression load of 0.5 psi. The routine used has the capability to read in as many variables as desired and fit a surface to the data points in multispace, the dimensions of which are determined by the number of input variables. The following equation resulted from this study in the form of conductance as a function of pile density, pile diameter, and pile height:

$$\begin{aligned} \text{Conductance (W/m}^2\text{/}^\circ\text{C)} &= 4.29 + 0.071 \times \text{pile density} \\ &(\text{ends per cm}^2) + 0.130 \times \text{pile diameter (number of strands)} \\ &- 3.610 \times \text{pile height (cm)} \end{aligned}$$

The equation in English units:

$$\begin{aligned} \text{Conductance (Btu/hr/ft}^2\text{/}^\circ\text{F)} &= 0.756 + 0.002 \times \text{pile} \\ &\text{density (ends per in}^2) + 0.023 \times \text{pile diameter (number} \\ &\text{of strands)} - 1.614 \times \text{pile height (in)} \end{aligned}$$

The correlation coefficient is 0.798.

The purpose of this study was not to develop a method of defining the most advantageous sample configuration for low conductance, but to illustrate the effect of each parameter on conductance. Since each term has different units, the coefficients alone cannot be related to conductance. However, the approximate magnitude and direction of each term indicate that conductance decreases as pile density and diameter decrease and as pile height increases, and that pile height is the most influential of the three parameters.

From the group of five samples with the lowest conductance at the highest load, two samples, 5 and 12, were selected for further testing. The selection was based on acceptable performance (in the range of the Shuttle MLI performance) in the initial thermal conductivity tests, as well as on the configuration of the two samples. Sample 5 has the maximum pile density, pile diameter, and pile height, and is close to the same weight per unit area as the Shuttle MLI. Sample 12 has the minimum pile density and diameter, has the maximum pile height, and is about 30 percent lighter in weight per unit area than the Shuttle MLI. The different configurations were chosen to identify trends in the effects of configuration on performance that may occur in the final conductivity tests. The fact that both selected samples had the maximum pile height and varied in the other parameters, but exhibited low conductances at the highest compression loading, corresponds to the trend characterized in the linear regression study by NASA, that pile height has the greatest influence on conductance.

#### 4. TASK 3 -- ADDITIONAL TESTING OF MONOLAYER AND MLI SAMPLES

The two selected samples, 5 and 12, and the Space Shuttle four-layer MLI were further tested for thermal conductivity as a function of ambient pressure and temperature. Also tested was a control sample of known thermal conductivity at room temperature and pressure. The control sample was solid neoprene.

##### 4.1 Thermal Conductivity as a Function of Ambient Pressure

The two selected samples, 5 and 12, and the Shuttle MLI underwent steady state thermal conductivity tests at an average sample temperature of 21°C (70°F) with the temperature difference across the sample between 16°C (30°F) and 28°C (50°F), zero compression load, and ambient pressures of  $1 \times 10^0$ ,  $1 \times 10^{-1}$ ,  $1 \times 10^{-2}$ ,  $1 \times 10^{-3}$ , and  $1 \times 10^{-4}$  Torr. The various ambient pressures were achieved by the use of a controlled air leak into the bell jar apparatus. The remaining test apparatus was the same as described in Section 3.2. The test procedure and sample calculation appear in Appendix B.

The results of this test are illustrated in Figure 7, which shows that for all three samples tested conductance increases as ambient pressure increases. As air is introduced into the system, more heat transfer by convection occurs, thus causing the thermal conductance to increase. Error bars indicate the 15 percent uncertainty determined by analysis.

The monolayer samples and the Shuttle MLI perform in the same range in this test. Although the MLI sample has a lower conductance at lower pressures, Sample 5 performs better with lower conductance than the MLI at the highest pressure. Because the pressures surrounding an EVA pressure suit due to suit leak may be slightly higher than the ambient pressure of space, the monolayer woven pile fabric could provide as much or better thermal protection than the MLI.

Of the two monolayer samples, Sample 5 had lower conductances at each test point than Sample 12, as was the case in the initial thermal conductivity tests. Again, maximum pile height appears to be the strongest influence on conductance since these two samples had the maximum pile height but differed in the other parameters. As stated previously, Sample 5 had the maximum pile density and diameter while Sample 12 had the minimum pile density and diameter.

##### 4.2 Thermal Conductivity as a Function of Temperature

Samples 5 and 12 and the Shuttle MLI underwent thermal conductivity tests as a function of temperature for five different temperatures: 93, 52, 21, -18, and -73°C (200, 125, 70, 0, and -100°F). For the three temperatures above 0°C (32°F), the steady-state method used in the previous tests was similarly used in this test. The temperatures were reached by varying the temperature of the water to the cooling plates. The detailed test procedure and sample calculation are included in Appendix B.

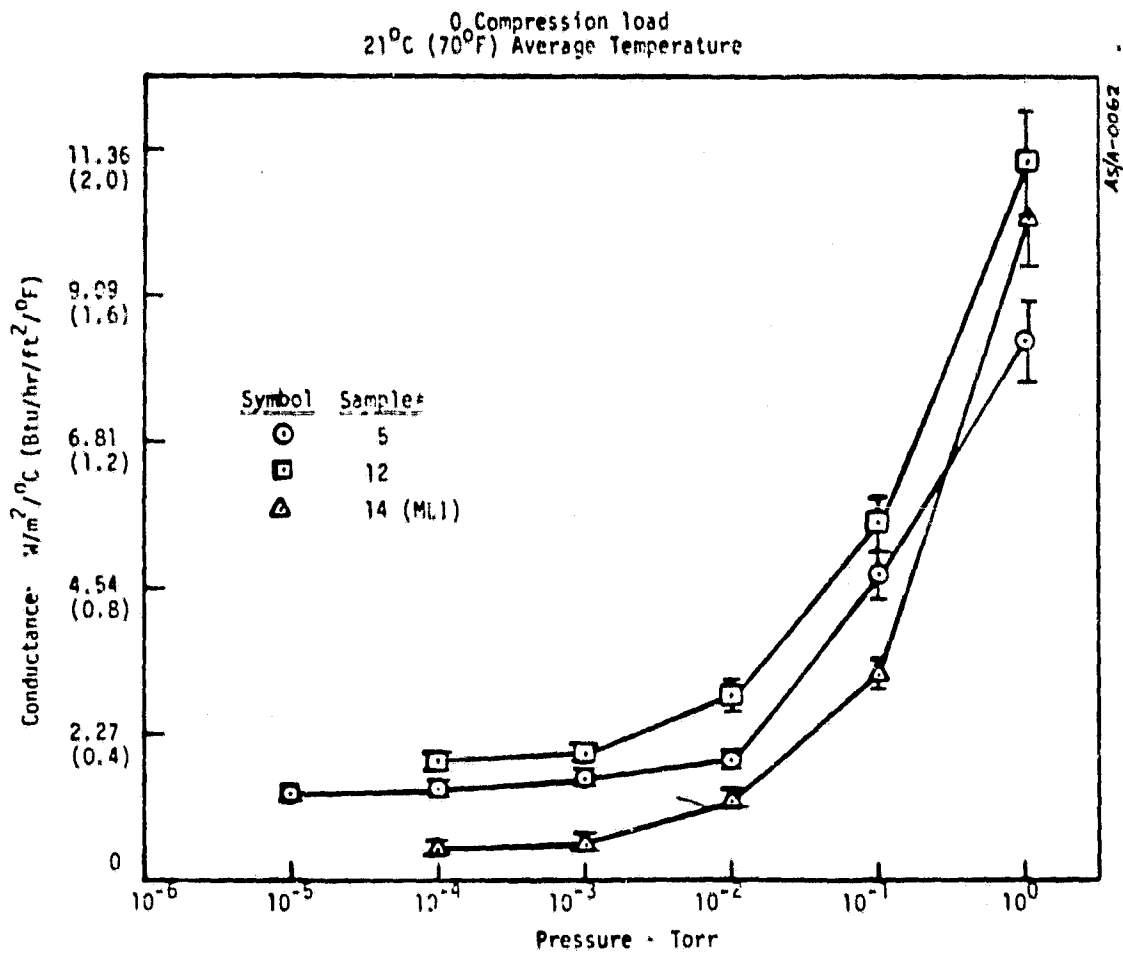


Figure 7. Thermal conductance at zero compression and 21°C (70°F) average temperature.

For the sub-zero temperatures, a transient thermal conductivity test method was employed and is described in Appendix C. The transient method was chosen for the lower temperatures when it was found that a heat leak into the system by way of the heater wire had invalidated the steady-state testing at these conditions.

In the transient tests, the hot plate was replaced by a copper slug with a guard ring to reduce the effects of radial heat loss on the measurements. In considering the dimensions of the slug, it was determined that it should be large enough to store in the sample no more than 5 percent of the energy of the copper. It should also be small enough such that the copper cools down in a reasonable time period. Details of the copper slug size determination are included in Appendix C.

The cold plates were fed with liquid nitrogen regulated by a temperature-sensing controller with the sensing element embedded in one of the cold plates. A time-temperature response test was conducted on the cold plates to ascertain whether the transient method was possible and to determine the change in temperature with respect to time ( $dt/d\theta$ ) of the cold plates. It is desirable that  $dt/d\theta$  of the cold plates be greater than  $dt/d\theta$  of the copper. When this is true, a stable lower temperature is reached, and only the upper temperature varies with time. It was determined that the cold plates response was about  $-4.5^{\circ}\text{C}/\text{min}$  ( $-8.1^{\circ}\text{F}/\text{min}$ ), compared to about  $0.20^{\circ}\text{C}/\text{min}$  ( $0.35^{\circ}\text{F}/\text{min}$ ) for the copper. The test procedure is included in Appendix C.

For the transient tests, conductance was measured by recording the energy change with time in the copper slug and the temperature difference across the sample. The apparatus started at room temperature. The liquid nitrogen was then allowed to flow through the cold plates and controlled such that the plates stabilized at about  $17^{\circ}\text{C}$  ( $30^{\circ}\text{F}$ ) below the average temperature for the test. Thermocouples on the cold plates and the copper slug connected to an Autodata Eight data acquisition system supplied temperature data which was recorded on a paper tape at one minute intervals. The test was terminated when the copper reached a temperature about  $12^{\circ}\text{C}$  ( $22^{\circ}\text{F}$ ) above the desired average temperature. The test procedure and sample calculation are included in Appendix C.

Results from both the steady state and transient tests are illustrated in Figure 8. Note that the sub-zero tests were conducted with a slight compression load due to the weight of the copper slug; therefore, there is a discontinuity between the results of the steady-state tests and the results of the transient test. The dashed line links the two sets of results for identification purposes to preserve as much continuity as possible. The error bars show that the results are accurate to within 15 percent of the measured value.

Again, the Shuttle MLI had lower conductance for each test, but all three samples performed in the same range. The relationship between the MLI and the monolayer samples remained about the same in both parts of the

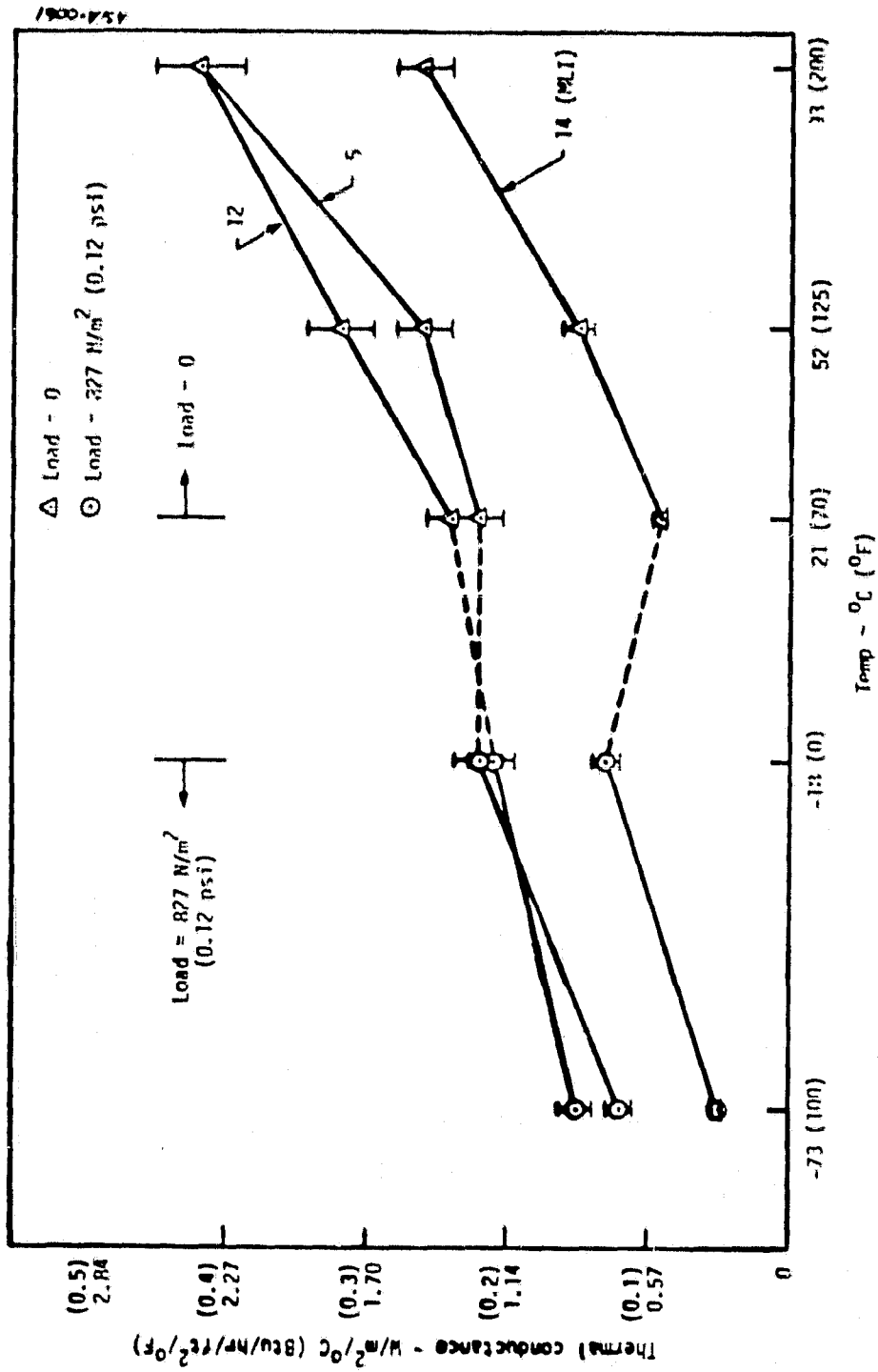


Figure 8. Thermal conductance as a function of temperature at pressure =  $10^{-4}$  torr.



graph. The monolayer samples had measured conductances that were very close for each test. Again, Sample 5 performed slightly better than Sample 12, but no strong correlation between sample configuration and conductance can be drawn.

#### 4.3 Thermal Conductivity of a Control Sample

Solid neoprene was chosen as a control sample with known thermal conductivity and without great surface resistance problems for a test accuracy and repeatability check. The 0.32 cm (1/8 inch) neoprene was tested at room temperature and pressure with the compression load of about  $1.0 \times 10^6$  N/m<sup>2</sup> (150 psi) to minimize the effects of contact resistance. The results for two tests are:

Conductance (Test 1) = 92.0 W/m<sup>2</sup>/°C (16.2 Btu/hr/ft<sup>2</sup>/°F)  
Conductance (Test 2) = 92.6 W/m<sup>2</sup>/°C (16.3 Btu/hr/ft<sup>2</sup>/°F)

There is about a 1 percent difference in the two tests indicating repeatability of the tests.

The thermal conductance of neoprene is known to be 81.20 W/m<sup>2</sup>/°C (Btu/hr/ft<sup>2</sup>/°F), referenced in a technical memorandum, From: J. Frank Wattenbarger, Code 710.1, To: W. W. McCrory, Code 710.1, Naval Coastal Systems Laboratory, Subject: Study on Cold Water Tolerance and Diver Thermal Protection. The measured values of conductance are within 12 percent of the reference value for neoprene, well within the 15 percent accuracy of these tests. This comparison illustrates the validity of the laboratory thermal conductivity tests conducted for this program.

### 5. EVALUATION OF TECHNIQUES FOR EDGE FINISHING AND SEAMING

In addition to providing the required protection from the space environment, the monolayer woven pile fabric must have the capability to be sewn into a garment with structurally strong seams that minimize heat loss. To test this capability, edge finishing and seaming techniques were designed and tested with the samples. Test procedures are shown in Appendix D.

#### 5.1 Edge Finishing Techniques

Due to the pile nature of the fabric and to the weaving process, the samples unravel easily at the edges. To avoid unraveling, the edges must be finished in a way that is neither excessively bulky nor time-consuming. Six methods of finishing were tested (Figure D-1, Appendix D):

1. Pile removed along edge by cutting and pulling pile threads with zig-zag stitch close to edge
2. Pile removed as in 1, with vinyl contact adhesive (PM107) applied to edge of orthofabric and edge of pile
3. Pile removed as in 1, with rubber contact adhesive (N136) applied as in 2

4. Zig-zag stitch only
5. PM107 adhesive applied to edge only
6. N136 adhesive applied as in 5

The zig-zag stitch only (4) had the best results in terms of prevention of unraveling, time required for process, bulk, and attractiveness.

The pile removing process was too time-consuming thus more costly, and proved difficult around corners. The reduced bulk of this process is desirable for seaming but requires precision in the seaming process to avoid the high heat loss areas of no pile.

The adhesives added extra bulk and stiffness, and were very time-consuming. Also, the N136 adhesive was unattractive. However, the adhesive method controls the unraveling and keeps end pile threads from pulling out.

The edge finishing techniques employed in the seaming tests were the zig-zag stitch only (4), PM107 with pile removed (2), PM107 only (3), and PM107 with pile removed from one side only, bias tape sewn to edges, and no finishing. The latter three techniques had not been previously tested.

## 5.2 Seaming Techniques

The seams were chosen considering reduced bulk and minimized heat loss. Three types were sewn: flat fell, regular, and French seams. Figure D-2 in Appendix D illustrates these seam types. Fourteen different seam and edge finishing combinations were fabricated, then assessed initially for bulk, structural strength, heat loss, attractiveness, and simplicity of fabrication. Table D-2, Appendix D, identifies the various specimens fabricated. In assessing the 14 seaming test specimens, only the French seam was determined to be acceptable because of its minimal heat loss characteristics, structural strength, and finished appearance. The regular seam was unacceptable for unfavorable heat loss and structural characteristics, although it was the simplest and least time-consuming method. The flat fell seam was unfavorable due to its unfinished appearance. Of the French seam specimens, 6, 10, and 11 were preferred. Specimen 11, which was prepared with a zig-zag stitch, was most preferable because of its pliability, ease of construction, and clean appearance. Specimen 6 was pliable and less bulky than 11, but the edge finishing technique of removing pile is time-consuming and difficult to accomplish at corners and curves. Specimen 10, finished with PM107 adhesive, had an attractive appearance and was structurally acceptable, but due to the adhesive, it was stiff, bulky, and time-consuming to fabricate.

The three French seam specimens were further tested for heat loss, in which infrared film was used to indicate heat loss through the seam area backed by a radiant heat source. The test procedure is included in Appendix D.

The black-and-white photographs show light tones as hot areas and dark tones as cooler areas. Each photograph shows the seam area as the coolest region of the sample. This indicates that the seam area provides better thermal protection than a single layer of the fabric. MLI has shown the opposite: its seams are high conductance regions. However, minor heat loss occurred through the needle holes of the right-hand seam in specimens 6 and 10 (Figures 9 and 10). Little or no heat loss is evidenced by specimen 11 (Figure 11). Specimen 11 was prepared with a zigzag stitch which allows the fabric to retain its insulating capabilities.

In the final evaluation, Specimen 11 with untrimmed, zig-zagged edges and a French seam with pile on the "right" side of the fabric was the recommended technique for seaming the monolayer woven pile material in terms of minimized heat loss, ease of construction, reduced bulk, pliability, and attractiveness.

## 6. CONCLUSIONS

The results of this program demonstrate the potential of the monolayer woven pile fabric as a viable replacement for the presently used multilayer insulation material. Due to its monolayer nature, the fabric is simpler and less costly to fabricate, as well as appearing more durable than the MLI. Production in large quantities will simplify fabrication and lower costs even more.

In compressibility testing, the pile fabric exhibited good compressive characteristics, in some cases better than the MLI specimen tested also.

The initial thermal conductivity tests showed that several samples had lower conductance than the Shuttle MLI at the highest compression load. The two samples chosen for final thermal conductivity testing, 5 and 12, exhibited conductances in the same range as the comparison Shuttle MLI, and at the highest ambient pressure, Sample 5 had a lower conductance than the Shuttle MLI.

In the observance of trends in the effect of configuration on test performance, no strong correlation could be made, but it appeared that the maximum pile height was most desirable for lower thermal conductivity and for higher actual thickness under compression loading.

In the preparation and seaming study, it was determined that the fabric can satisfactorily be finished on the rough edge with a zig-zag stitch without changing the insulation characteristics of the fabric, and that a structurally sound and durable seam can be fabricated that minimizes heat loss, is pliable, is not bulky, and has a clean appearance.

### 6.1 Recommendations

It is recommended that a quantity large enough to ensure uniform construction (100 meters<sup>2</sup>) of a selected configuration with the greatest pile height (i.e., Sample 5) be produced. Because the pile cannot be

Figure 9. Infrared photograph. Seaming Specimen #10.

Figure 10. Infrared photograph. Seaming Specimen #6.

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**Figure 11. Infrared photograph. Seaming Specimen #11.**

locked in the weaving process, uncoated nylon rip-stop should be used in a single layer on the pile side as protection from snags and pulls. The extra layer of rip-stop should also reduce thermal conductivity selected conditions for thermal conductivity and compared with the conductivity of the Shuttle MLI.

Following the small-scale testing, a prototype thermal meteoroid garment should be fabricated using the preparation and seaming techniques suggested by this study so NASA can further assess the applicability of the monolayer woven pile fabric as space suit insulation.

APPENDIX A  
TEST PLAN AND PROCEDURE  
FOR THE  
COMPRESSIBILITY EVALUATION OF THE  
MONOLAYER WOVEN PILE FABRIC

Approved: \_\_\_\_\_  
(Tech Monitor) (Date)

PURPOSE

To determine the compressive deflection of the monolayer insulating fabric. This effort is part of the evaluation of the space suit thermal overgarment monolayer pile fabric.

LIST OF MATERIALS AND EQUIPMENT

- ① Dial height gauge with dual directional counter (see Figure A-1)
- ② Compression test apparatus (see Figures A-1 and A-2)
- ③ Calibrated surface plate, 0.00635 mm (0.00025 inch) flat (see Figure A-1)
- ④ Weight scale, accurate to  $\pm 1$  gm
- ⑤ Fabric specimens, 50.8 x 50.8 mm (2.0 x 2.0 inches), two of each sample (total of 28 specimens). Note: See Table A-1 for identification number of each specimen.

PROCEDURE

- ① Zero reference dial height gauge ① to the surface plate ③. (See Figure A-3 for instructions on use.)
- ② Place top plate ② onto bottom plate ② so the identification lettering on the top plate matches the identification lettering on the bottom plate.
- ③ With the surface plate as the zero reference (established in Step 1), measure and record the height of the top surface of the top plate on all four sides near the edge and centered between the alignment angles. Note that each side is identified by a letter to which the measurement must correspond on the data sheet.
- ④ Remove top plate and center fabric specimen ⑤ identified by the number 1 on the bottom plate, with numbered edge on 'A' side of plate.
- ⑤ Place top plate on fabric specimen making sure the lettering on the top plate and bottom plate correctly correspond.

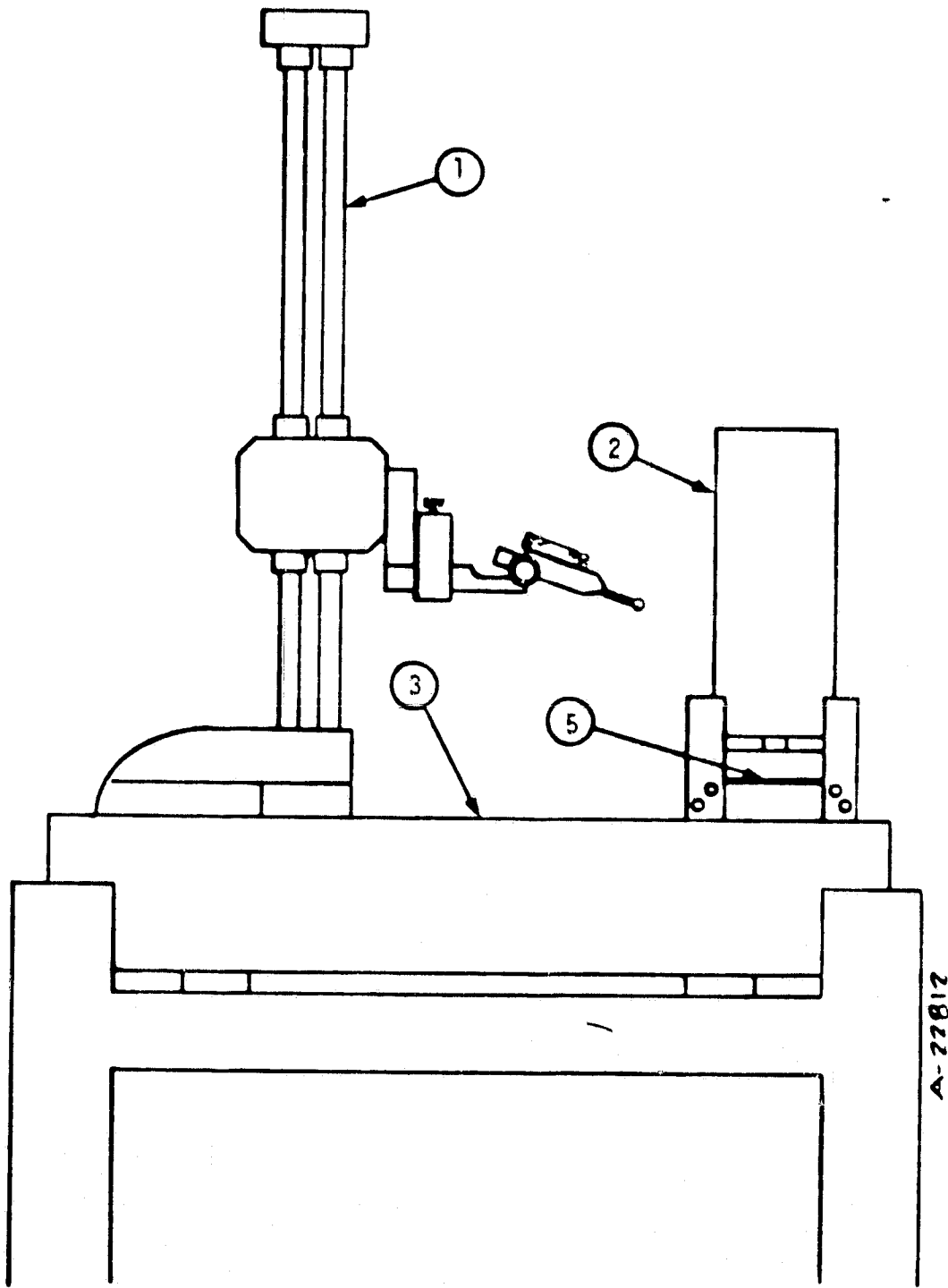


- ⑥ Repeat Step 3. Disassemble test apparatus.
- ⑦ Repeat Steps 4, 5, and 6 using fabric specimens identified by 2 through 14.
- ⑧ Fill short shot container (refer to Figure A-2) with lead shot until the shot container and top plate together weigh  $907 \pm 1$  gm ( $3447 \text{ N/m}^2$  (0.5 psi)).
- ⑨ Center fabric specimen identified by the number 1 on the bottom plate.
- ⑩ Place top plate on fabric specimen making sure the lettering on the top plate and bottom plate correctly correspond.
- ⑪ Slowly and carefully place the shot container on the top plate.
- ⑫ Repeat Step 3. Disassemble test apparatus.
- ⑬ Repeat Steps 9 through 12 with fabric specimens 2 through 14.
- ⑭ Fill short shot container with lead shot until the container and top plate together weigh  $1814 \pm 1$  gm ( $6895 \text{ N/m}^2$  (1 psi)).
- ⑮ Repeat Steps 9 through 13.
- ⑯ Fill tall shot container with lead shot until the container and top plate together weigh  $3629 \pm 1$  gm ( $13,790 \text{ N/m}^2$  (2 psi)).
- ⑰ Repeat Steps 9 through 13.
- ⑱ Fill tall shot container with lead shot until the container and top plate together weigh  $5443 \pm 1$  gm ( $20,684 \text{ N/m}^2$  (3 psi)).
- ⑲ Repeat Steps 9 through 13.
- ⑳ Fill tall shot container with lead shot until the container and top plate together weigh  $9072 \pm 1$  gm ( $34,474 \text{ N/m}^2$  (5 psi)).
- ㉑ Repeat Steps 9 through 13.

#### COMPRESSIBILITY TESTING PROCEDURE FOR HYSTERESIS CHECK

- ㉒ Fill short shot container with lead shot until container and top plate together weigh  $907 \pm 1$  gm ( $3447 \text{ N/m}^2$  (.5 psi)). Fill tall shot container until container plus plate together weigh  $1815 \pm 1$  gm ( $13,790 \text{ N/m}^2$  (2 psi)). Set both aside.
- ㉓ Fill paper container until total weight less weight of paper container is  $907 \pm 1$  gm (for 1 psi). Mark load ( $6895 \text{ N/m}^2$  (1 psi)) on container and level of shot. Set aside.

- ②④ Repeat Step 23 for the following weights:  
1814  $\pm$  1 gm (20,684 N/m<sup>2</sup> (3 psi))  
3629  $\pm$  1 gm (34,474 N/m<sup>2</sup> (5 psi))
- ②⑤ Center specimen on bottom plate with numbered edge on 'A' side.
- ②⑥ Place top plate on fabric specimen making sure lettering on top and bottom plates correspond correctly.
- ②⑦ Slowly and carefully place the short shot container on the top plate.
- ②⑧ Record time.
- ②⑨ Repeat Step 3 (measure height).
- ③⑩ Add shot to shot container from paper container marked "6895 N/m<sup>2</sup>" (1 psi).
- ③⑪ Repeat Steps 28 through 29.
- ③⑫ Repeat Steps 27 through 30 with the tall container and adding shot from containers marked "20,684 N/m<sup>2</sup>" (3 psi) and "34,474 N/m<sup>2</sup>" (5 psi) in order after measuring height with 34,474 N/m<sup>2</sup> (5 psi) load with 1/2 hour. Then repeat Step 3.
- ③⑬ Pour shot back into container(s) marked "34,474 N/m<sup>2</sup>" (5 psi) approximately to mark, until containers hold 3629  $\pm$  1 gm shot.
- ③⑭ Repeat Steps 27 through 29 with tall shot container for 20,684 N/m<sup>2</sup> (3 psi) compression load.
- ③⑮ Pour shot from tall shot container into paper container marked "20,684 N/m<sup>2</sup>" (3 psi) until paper container holds 1814  $\pm$  1 gm shot.
- ③⑯ Repeat Steps 27 through 29 with tall shot container for 13,790 N/m<sup>2</sup> (2 psi) compression load.
- ③⑰ Repeat Steps 27 through 29 with short shot container for 13,790 N/m<sup>2</sup> (2 psi) load.
- ③⑱ Pour shot from short shot container into paper container marked "6895 N/m<sup>2</sup>" (1 psi) until paper container holds 907  $\pm$  1 gm shot.
- ③⑲ Repeat steps 27 though 29 with short shot container for 3447 N/m<sup>2</sup> (0.5 psi) load.



A-77817

Figure A-1. Compression test setup.

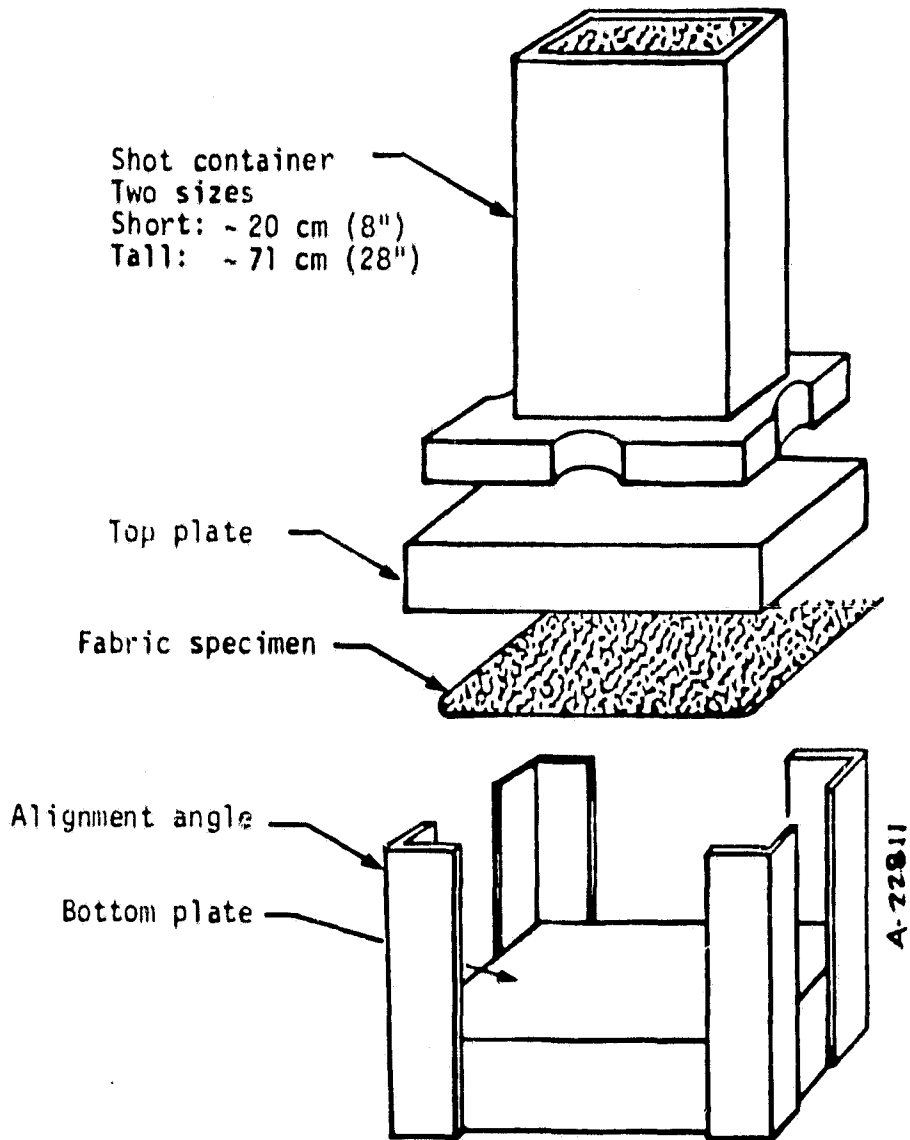
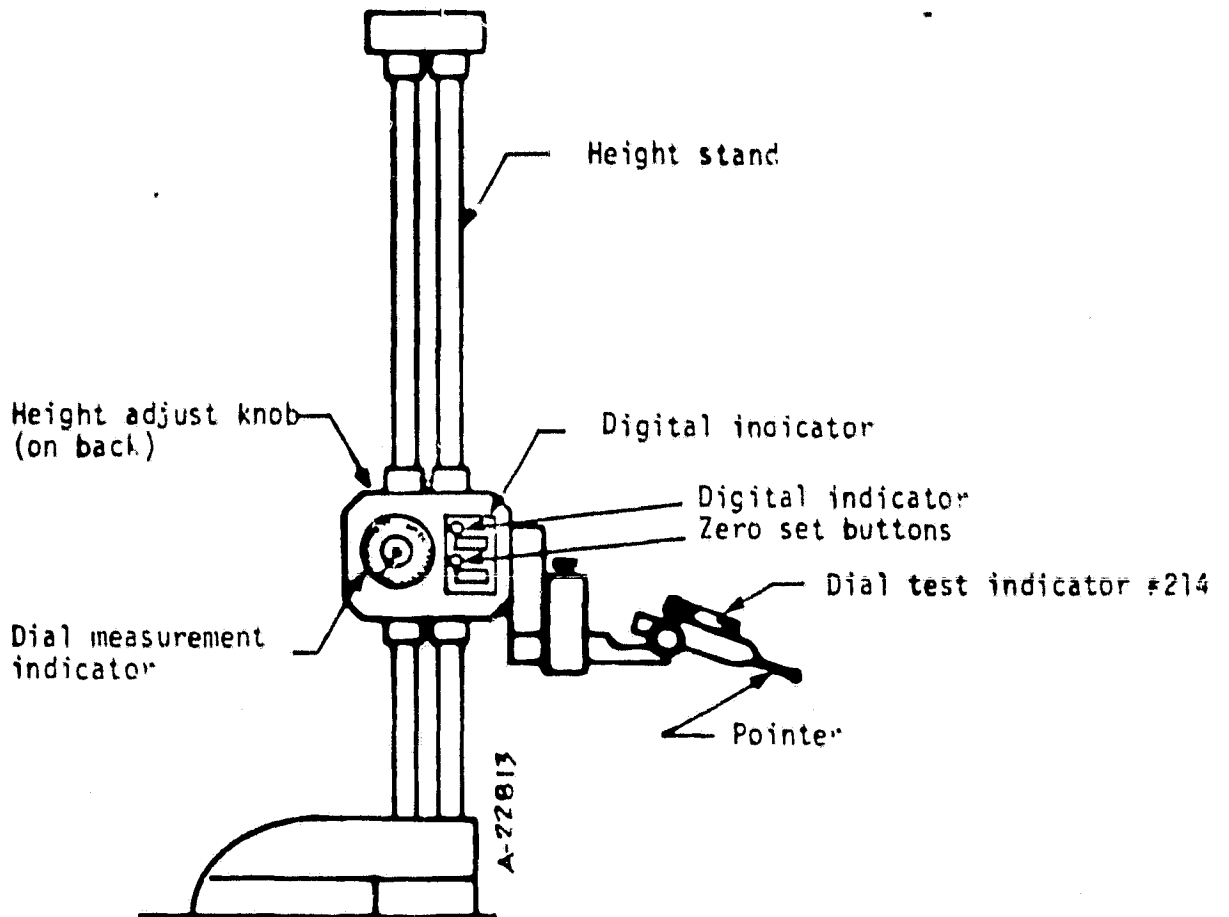


Figure A-2. Detail; compression test apparatus.



1. Rotate dial test indicator to read .0025
2. Orient dial test indicator approximately as shown in sketch
3. Turn the height adjust knob until the pointer tip rests on the reference surface and the dial test indicator reads precisely zero

Figure A-3. Dial height gauge operation.

DATE \_\_\_\_\_

DATA FORM  
COMPRESSIBILITY TESTS

TEST RUN NO. \_\_\_\_\_

TEST CONDUCTOR \_\_\_\_\_

Step 3

Reference Measurement			

Free Thickness Measurement*				
	A	B	C	D
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				

A-22815

\*These measurements will be used to define the free thickness (zero compression load) of the fabric specimens. (Actual compression load = 220.6 N/m<sup>2</sup> (0.032 psi).)

DATA FORM (Continued)

COMPRESSIBILITY TESTS

	Steps 12 & 13				Step 15				Step 17				Step 19				Step 21			
	907 gm (.5 psi)				1814 gm (1 psi)				3629 gm (2 psi)				5443 gm (3 psi)				9072 gm (5 psi)			
1	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
11																				
12																				
13																				
14																				

4-22814

TABLE A-1. TMG COMPRESSIBILITY TEST DATA\*  
Group 1

Reference Height: 25.495 mm (1.00373 in)  
Measurements in mm (inches)

Compression Load	Free Thickness	3487 N/m <sup>2</sup> (0.5 psi)		6895 N/m <sup>2</sup> (1 psi)		13,790 N/m <sup>2</sup> (2 psi)		20,684 N/m <sup>2</sup> (3 psi)		34,474 N/m <sup>2</sup> (5 psi)	
		Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free
<sup>2</sup> (Max. p., 1.558 mm, (1/16") 2 ply)	2.649 (0.1043)	2.078 (0.0818)	21.57	1.948 (0.0767)	26.46	1.730 (0.0681)	34.71	1.605 (0.0632)	39.41	1.369 (0.0539)	48.32
<sup>4</sup> (Min. p., 3.175 mm, (1/8") 2 ply)	3.287 (0.1294)	2.487 (0.0979)	24.34	1.699 (0.0669)	48.30	1.372 (0.0540)	58.27	1.278 (0.0503)	61.13	1.161 (0.0457)	64.68
<sup>6</sup> (Max. p., 4.763 mm, (3/16") 2 ply)	4.285 (0.1687)	1.892 (0.0745)	55.84	1.560 (0.0614)	63.60	1.397 (0.0550)	67.40	1.280 (0.0504)	70.12	1.201 (0.0473)	71.96
<sup>8</sup> (Min. p., 1.588 mm, (1/16") 2 ply)	2.535 (0.0998)	1.859 (0.0732)	26.65	1.643 (0.0647)	35.17	1.339 (0.0527)	47.19	1.100 (0.0433)	56.61	0.892 (0.0351)	64.83
<sup>10</sup> (Min. p., 3.175 mm, (1/8") 2 ply)	3.411 (0.1343)	2.258 (0.0889)	33.80	1.567 (0.0617)	54.06	1.214 (0.0478)	64.41	1.059 (0.0417)	68.93	0.960 (0.0378)	71.85
<sup>12</sup> (Min. p., 4.763 mm, (3/16") 2 ply)	3.432 (0.1351)	1.427 (0.0562)	58.19	1.250 (0.0492)	63.40	1.077 (0.0424)	68.44	0.942 (0.0371)	72.41	0.884 (0.0348)	74.06

\*Each entry is average of four data points

T-1806



TABLE A-2. TMG COMPRESSIBILITY TEST DATA  
Group 2

Measurements in mm (Inches)		3487 N/m <sup>2</sup> (0.5 psi)		6895 N/m <sup>2</sup> (1 psi)		13,790 N/m <sup>2</sup> (2 psi)		20,684 N/m <sup>2</sup> (3 psi)		34,974 N/m <sup>2</sup> (5 psi)	
Sample Number	Free Thickness	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free
		1 (Max. p., 1,588 mm. (1/16") 3 ply)	2.733 (0.1076)	2.062 (0.0817)	24.60	1.826 (0.0719)	33.24	1.481 (0.0583)	45.81	1.191 (0.0469)	56.42
3 (Max. p., 3,175 mm. (1/8") 3 ply)	4.382 (0.1725)	2.977 (0.1172)	32.07	2.474 (0.0974)	43.53	1.763 (0.0694)	59.74	1.450 (0.0571)	66.92	1.257 (0.0493)	71.47
5 (Max. p., 4,763 mm. (3/16") 3 ply)	4.882 (0.1922)	2.708 (0.1066)	44.57	1.996 (0.0786)	59.10	1.542 (0.0607)	68.45	1.433 (0.0564)	70.69	1.265 (0.0498)	74.99
7 (Min. p., 1,588 mm. (1/16") 3 ply)	2.951 (0.1162)	2.119 (0.0842)	27.52	1.806 (0.0711)	38.83	1.461 (0.0575)	50.56	1.179 (0.0464)	60.07	0.932 (0.0367)	68.44
9 (Min. p., 3,175 mm. (1/8") 3 ply)	4.039 (0.1590)	2.573 (0.1013)	36.30	1.773 (0.0698)	56.14	1.389 (0.0547)	65.60	1.245 (0.0490)	69.19	1.128 (0.0444)	72.10
11 (Min. p., 4,763 mm. (3/16") 3 ply)	4.651 (0.1831)	2.187 (0.0859)	53.11	1.871 (0.0717)	60.83	1.521 (0.0599)	67.27	1.384 (0.0545)	70.23	1.250 (0.0492)	73.16
13 (Apollo 7-layer M1)	2.471 (0.0973)	1.702 (0.0670)	31.12	1.544 (0.0608)	37.49	1.397 (0.0548)	43.68	1.273 (0.0507)	48.48	1.212 (0.0477)	50.98

T-1007

TABLE A-3. TMG COMPRESSIBILITY TESTS: HYSTERESIS CHECK

Reference Measurement: 25.509 mm (1.0043 in)  
 Measurements in mm (inches)

Loading	Free Thickness	3447 N/m <sup>2</sup> (0.5 psi)		6895 N/m <sup>2</sup> (1 psi)		13,790 N/m <sup>2</sup> (2 psi)		20,684 N/m <sup>2</sup> (3 psi)		34,474 N/m <sup>2</sup> (5 psi)	
		Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free	Thickness	% Change From Free
Sample Number											
2 (Max. n. 1.589 mm (1/16") 2 ply)	2.629 (0.1035)	2.136 (0.0841)	18.73	1.958 (0.0771)	25.42	1.768 (0.0696)	32.72	1.585 (0.0624)	39.73	1.295 (0.0510)	50.72
Time elapsed since previous measurements (minutes)		3		3		4		4		5	
: : : : : Unloading : : : : :											
	Thickness % Change										
2	2.139 (0.0842)	1.890 (0.0744)	28.13	1.659 (0.0653)	36.85	1.585 (0.0624)	39.68	1.402 (0.0552)	46.67	1.113 (0.0438)	57.68
Time elapsed (min.)	7	4		7		6		14		60	

T-1610

APPENDIX B  
TEST PLAN AND PROCEDURE  
FOR THE  
THERMAL CONDUCTIVITY EVALUATION  
OF THE MONOLAYER WOVEN PILE FABRIC

Approved: \_\_\_\_\_ (Date)  
(Tech Monitor)

PURPOSE

To determine the thermal conductivity of the monolayer insulating fabric as a function of pressure, compression load, and temperature. This effort is part of the evaluation of the monolayer woven pile fabric for space suit insulation.

LIST OF MATERIALS AND EQUIPMENT

- ① Hot plate apparatus
- ② Power supply, Sorensen DCR40-10
- ③ Digital thermometer, Fluke 2100A
- ④ Digital voltmeter, Fluke 8120A
- ⑤ Water chiller, Blue M refrigeration system and plumbing
- ⑥ Pump, Micropump 27 volts, DC
- ⑦ Fiberglass insulation, mylar sheets
- ⑧ Fabric specimens, 10.16 cm (4.0 inch dia.), two of each sample per test. See Table B-1 for identification.
- ⑨ Thermocouple switch
- ⑩ Precision resistance apparatus (for current measurements)
- ⑪ Bell jar apparatus

THERMAL CONDUCTIVITY TEST

Procedure

Task 2.A.2: To determine the thermal conductivity of the samples at a pressure of  $<10^4$  Torr and sample temperature of  $-21^{\circ}\text{C}$  ( $\sim 70^{\circ}\text{F}$ ) at compression loads of 0, 3447.4, and 27,579.0  $\text{N}/\text{cm}^2$  (0, 0.5, and 4.0 psi).

- ① Install specimen set No. 1 into thermal conductivity test apparatus as shown in Figure B-1. Tighten to appropriate spring length for zero compression load as specified in Table B-2.
- ② Place bell jar over apparatus and adjust vacuum to equilibrate between  $10^{-4}$  and  $10^{-5}$  Torr.
- ③ Connect thermocouple leads to thermocouple switch and connect switch to digital thermometer.
- ④ Connect digital voltmeter to heater power output.
- ⑤ Turn on power to chiller, adjust bath temperature control to  $10^{\circ}\text{C}$  ( $50^{\circ}\text{F}$ ). Connect chiller to cold plates.
- ⑥ Turn on power to hot plate.
- ⑦ Adjust chiller bath temperature, and power to hot plate and coolant pump until the following conditions are met:
  - a. Thermocouples 1 through 4 read about  $11^{\circ}\text{C}$  ( $20^{\circ}\text{F}$ ) above reference temperature ( $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ )) and agree to within  $0.5^{\circ}\text{C}$  ( $1^{\circ}\text{F}$ ).
  - b. Thermocouples 5 through 8 read about  $11^{\circ}\text{C}$  ( $20^{\circ}\text{F}$ ) below reference temperature ( $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ )) and agree to within  $0.5^{\circ}\text{C}$  ( $1^{\circ}\text{F}$ ).
  - c. The average of all eight thermocouples is  $21 \pm 5^{\circ}\text{C}$  ( $70 \pm 8^{\circ}\text{F}$ ).
  - d. The  $\Delta T$  between the average of thermocouples 1 through 4 and the average of thermocouples 5 through 8 is between  $17$  and  $28^{\circ}\text{C}$  ( $30$  and  $50^{\circ}\text{F}$ ).
  - e. Thermal conductance measurements taken at three successive one-half hour intervals differ by less than 15 percent.
- ⑧ Record data acquired in Step 7 on Data Sheet (Table B-1).
- ⑨ Release vacuum, remove bell jar, and remove springs from hot plate assembly. Reassemble apparatus so that a compression load of  $3447.4 \text{ N/cm}^2$  ( $0.5 \text{ psi}$ ) on the specimen is established (Table B-2).
- ⑩ Repeat Steps 2, 7, and 8.
- ⑪ Release vacuum, remove bell jar. Reassemble apparatus so that a compression load of  $27,579 \text{ N/cm}^2$  ( $4 \text{ psi}$ ) is established (Table B-2).
- ⑫ Repeat Steps 2, 7, and 8.

- ⑬ Repeat Steps 1 through 12 with remaining twelve specimen sets.

Task 3.1: To determine the thermal conductivity of three selected specimens at a zero compression load, 21°C (70°F) and pressures of 1, 10<sup>-1</sup>, 10<sup>-2</sup>, 10<sup>-3</sup>, and 10<sup>-4</sup> Torr.

Selected specimens: 5, 12, 14

- ⑭ Install selected specimen set into thermal conductivity test apparatus as shown in Figure B-1. Tighten to appropriate spring length for zero compression load as specified in Table B-2.
- ⑮ Place bell jar over apparatus and adjust vacuum to equilibrate at 1 x 10<sup>-4</sup> Torr ± 5 percent.
- ⑯ Turn on power to chiller, adjust bath temperature control to 10°C (50°F). Connect chiller to cold plates.
- ⑰ Connect thermocouple leads to thermocouple switch and connect switch to digital thermometer.
- ⑱ Connect digital voltmeter to heater power output.
- ⑲ Turn on power to hot plate.
- ⑳ Adjust chiller bath temperature, and power to hot plate and coolant pump until the following conditions are met:
- Thermocouples 1 through 4 read about 11°C (20°F) above reference temperature (21°C (70°F)) and agree to within 0.5°C (1°F).
  - Thermocouples 5 through 8 read about 11°C (20°F) below reference temperature (21°C (70°F)) and agree to within 0.5°C (1°F).
  - The average of all eight thermocouples is 21 ± 5°C (70 ± 8°F).
  - The ΔT between the average of thermocouples 1 through 4 and the average of thermocouples 5 through 8 is between 17 and 28°C (30 and 50°F).
  - Thermal conductance measurements taken at three successive one-half hour intervals differ by less than 15 percent.
- ㉑ Record data acquired in Step 20 on Data Sheet.
- ㉒ Readjust vacuum to equilibrate to 0.1333 N/m<sup>2</sup> (1 x 10<sup>-3</sup> Torr).
- ㉓ Repeat Steps 20 and 21.

- ②4 Readjust vacuum to equilibrate to  $1.333 \text{ N/m}^2$  ( $1 \times 10^{-2}$  Torr).
- ②5 Repeat Steps 20 and 21.
- ②6 Readjust vacuum to equilibrate to  $13.33 \text{ N/m}^2$  ( $1 \times 10^{-1}$  Torr).
- ②7 Repeat Steps 20 and 21.
- ②8 Readjust vacuum to equilibrate to  $133.3 \text{ N/m}^2$  ( $1 \times 10^{-3}$  Torr), and repeat Steps 20 and 21.
- ②9 Repeat Steps 1 through 28 with the remaining two sets of specimens.

Task 3.2: To determine the thermal conductivity of three selected specimens at  $10^{-4}$  Torr, zero compression load, and temperatures of 21, 52, and  $93^\circ\text{C}$  ( $70$ ,  $125$ , and  $200^\circ\text{F}$ )

Selected specimens: 5, 12, 14.

- ③0 Install specimen set into thermal conductivity test apparatus as shown in Figure B-1. Tighten to appropriate spring length for zero compression load as specified in Table B-2.
- ③1 Place bell jar over apparatus and adjust vacuum to equilibrate at  $10^{-4}$  Torr  $\pm$  5 percent.
- ③2 Connect thermocouple leads to thermocouple switch and connect switch to digital thermometer.
- ③3 Connect digital voltmeter to heater power output.
- ③4 Turn on power to chiller, adjust bath temperature control to  $10^\circ\text{C}$  ( $50^\circ\text{F}$ ). Connect chiller to water plates.
- ③5 Turn on power to hot plate.
- ③6 Adjust power to hot plate until the following conditions are met:
  - a. Thermocouples 1 through 4 read about  $11^\circ\text{C}$  ( $20^\circ\text{F}$ ) above referenced temperature ( $21^\circ\text{C}$  ( $70^\circ\text{F}$ )) and agree to within  $0.5^\circ\text{C}$  ( $1^\circ\text{F}$ ).
  - b. Thermocouples 5 through 8 read about  $11^\circ\text{C}$  ( $20^\circ\text{F}$ ) below referenced temperature ( $21^\circ\text{C}$  ( $70^\circ\text{F}$ )) and agree to within  $0.5^\circ\text{C}$  ( $1^\circ\text{F}$ ).
  - c. The average of all eight thermocouples is  $-73 \pm 5^\circ\text{C}$  ( $-100 \pm 8^\circ\text{F}$ ).
  - d. The  $\Delta T$  between the average of thermocouples 1 through 4 and the average of thermocouples 5 through 8 is between  $17$  and  $28^\circ\text{C}$  ( $30$  and  $50^\circ\text{F}$ ).

e. Thermal conductance measurements taken at three successive one-half hour intervals differ by less than 15 percent.

- ③⑦ Record data acquired in Step 36 on Data Sheet.
- ③⑧ Turn off power to chiller and disconnect plumbing to cool plates.
- ③⑨ Connect warm water supply ( $40^{\circ}\text{C}$  ( $105^{\circ}\text{F}$ )) to cool plates.
- ④① Repeat Steps 36 and 37, changing to an average reading of  $52 \pm 3^{\circ}\text{C}$  ( $125 \pm 5^{\circ}\text{F}$ ).
- ④② Adjust warm water supply to  $82^{\circ}\text{C}$  ( $180^{\circ}\text{F}$ ).
- ④③ Repeat Steps 36 and 37, changing to an average reading of  $93 \pm 3^{\circ}\text{C}$  ( $200 \pm 5^{\circ}\text{F}$ ).
- ④④ Repeat Steps 30 through 41 with the two remaining sets of specimens.

SAMPLE CONDUCTANCE CALCULATION  
FOR STEADY STATE THERMAL CONDUCTIVITY TESTING

$$H(\text{W/m}^2/^{\circ}\text{C}) = \frac{\text{Total Power}}{2 \times \Delta\text{Temp}} \times \frac{1}{\text{Area}}$$

where Power =  $I \times E_2$

$$I = \frac{E_1}{R}$$

$E_1, E_2$  measured

R known

$$\text{Area} = 81.1 \text{ cm}^2 \quad (12.57 \text{ in}^2)$$

Then

$$\dot{H} = \frac{P}{2 \times \Delta T} \times \frac{1}{81.1 \text{ cm}^2} \times \frac{100^2 \text{ cm}^2}{\text{M}^2}$$

$$H(\text{W/m}^2/^{\circ}\text{C}) = 61.67 \frac{P(\text{W})}{\Delta T(^{\circ}\text{C})}$$

$$H(\text{Btu/hr/ft}^2/^{\circ}\text{F}) = 19.56 \frac{P(\text{W})}{\Delta T(^{\circ}\text{F})}$$



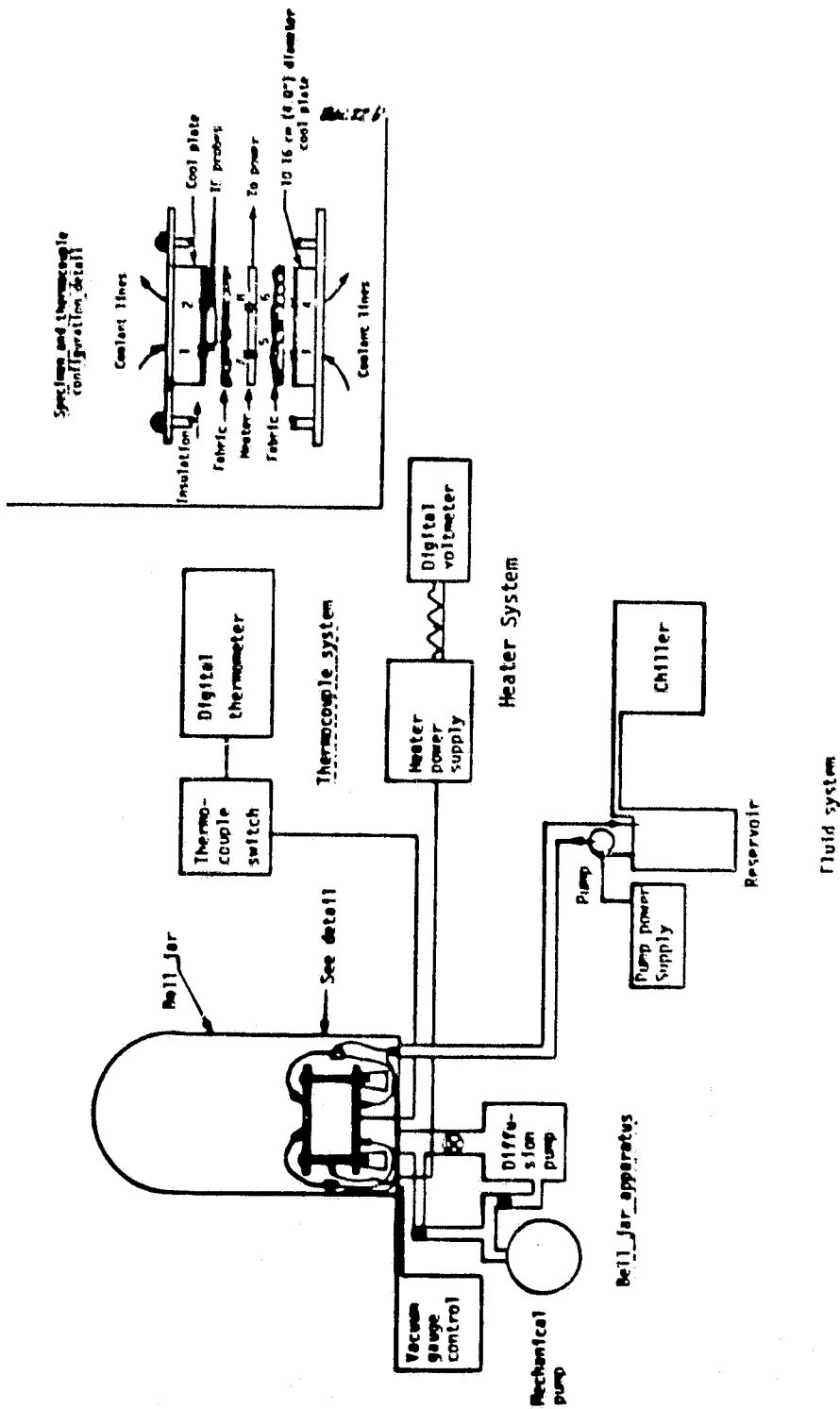


Figure B-1. Thermal conductivity test setup.

TABLE B-1. TMG THERMAL CONDUCTIVITY TEST DATA SHEET

Test Information				Test Data							Calc.		
Test No.	Sample No.	Compression Load	Avg. Temp. Vacuum	Thermocouples							Conduct.		
				T1	T2	T3	T4	T5	T6	T7		T8	
				Tav	T	Heater Circuit			Pump				
				(Av. T1-T8)	(Tav 1-6)	E1	E2	I	P	P			

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TABLE B-2. COMPRESSION LOADING

Compression Load	Method of Achievement
0 N/m <sup>2</sup> (0 psi)	Springs set to allow free thickness of specimens (see table below)
3447.4 N/m <sup>2</sup> (0.5 psi)	Weight of apparatus alone
27,579.0 N/m <sup>2</sup> (4 psi)	Add platform, 11.23 kg (25 lbm) weight plus steel

Specimen No.	Spring Length Needed for Loading	
	Free Thickness mm (in.)	Spring Length Needed mm (in.)
1	2.7330 (0.1076)	41.5341 (1.6352)
2	2.6492 (0.1043)	41.3664 (1.6286)
3	4.3815 (0.1725)	44.8310 (1.7650)
4	3.2868 (0.1294)	42.6415 (1.6788)
5	4.8819 (0.1922)	45.8826 (1.8064)
6	4.2850 (0.1687)	44.6380 (1.7574)
7	2.9515 (0.1162)	41.9710 (1.6524)
8	2.5349 (0.0998)	41.1378 (1.6196)
9	4.0386 (0.1590)	44.1452 (1.7380)
10	3.4112 (0.1343)	42.8904 (1.6886)
11	4.6507 (0.1831)	45.3695 (1.7862)
12	3.4315 (0.1351)	42.9311 (1.6902)
13	2.4714 (0.0973)	41.0108 (1.6146)
14		
15		

TABLE B-3. THERMAL CONDUCTANCE,  $W/m^2/OC(Btu/hr/ft^2/OF)$

Test Conditions:  $T_{av} = 21OC (70OF)$ ,  $P \leq 0.01333 N/m^2 (10^{-4} Torr)$

Sample No.	Compression Load $N/m^2$ (Psi)		
	0 (0)	344.74 (0.5)	27,579 (4.0)
1	1.704 (0.30)	4.202 (0.74)	12.777 (2.25)
2	1.874 (0.33)	4.884 (0.86)	17.376 (3.06)
3	1.817 (0.32)	4.089 (0.72)	9.313 (1.64)
4	2.783 (0.49)	3.691 (0.65)	9.938 (1.75)
5	1.704 (0.30)	3.123 (0.55)	7.269 (1.28)
6	1.476 (0.26)	3.123 (0.55)	7.155 (1.26)
7	3.237 (0.57)	4.543 (0.80)	10.676 (1.88)
8	2.044 (0.36)	3.861 (0.68)	11.584 (2.04)
9	1.704 (0.30)	3.691 (0.65)	8.177 (1.44)
10	1.590 (0.28)	3.634 (0.64)	8.915 (1.57)
11	1.988 (0.35)	3.521 (0.62)	7.439 (1.21)
12	1.931 (0.34)	3.180 (0.56)	8.404 (1.48)
13	0.738 (0.13)	1.079 (0.19)	3.066 (0.54)
14	Not tested	2.044 (0.36)	7.723 (1.36)

TABLE B-4. THERMAL CONDUCTANCE,  $W/m^2/^\circ C$  (Btu/hr/ft<sup>2</sup>)  
 Compression load = 0,  $T_{Av} = 21^\circ C$  (70°F)

Sample Number	Pressure ~ Torr.					
	10 <sup>0</sup>	10 <sup>-1</sup>	10 <sup>-2</sup>	10 <sup>-3</sup>	10 <sup>-4</sup>	10 <sup>-5</sup>
5	8.404 (1.48)	4.770 (0.84)	2.442 (0.43)	1.590 (0.28)	1.420 (0.25)	1.363 (0.24)
12	11.167 (1.97)	5.560 (0.98)	2.890 (0.51)	1.980 (0.35)	1.874 (0.33)	
14	10.278 (1.81)	3.237 (0.57)	0.681 (0.12)	0.568 (0.10)	0.511 (0.09)	

TABLE B-5. THERMAL CONDUCTANCE,  $W/m^2/^\circ C$  (Btu/hr/ft<sup>2</sup>/°F)  
 Pressure = 10<sup>-4</sup> Torr

Sample Number	Compression = 0.0 N/cm <sup>2</sup>			Compression = 827 N/M <sup>2</sup> (0.12 psi)	
	Temp °C (°F)			Temp °C (°F)	
	93 (200)	52 (125)	21 (70)	-18 (0)	-73 (-100)
5	2.385 (0.42)	1.476 (0.26)	1.249 (0.22)	1.249 (0.22)	0.681 (0.12)
12	2.385 (0.42)	1.817 (0.32)	1.363 (0.24)	1.193 (0.21)	0.852 (0.15)
14	1.476 (0.26)	0.852 (0.15)	0.511 (0.09)	0.736 (0.13)	0.284 (0.05)

## APPENDIX C

### TRANSIENT THERMAL CONDUCTIVITY TESTING TIME-TEMPERATURE RESPONSE TESTING OF COLD PLATES ONLY (CHILLED W/LN)

Approved: \_\_\_\_\_  
(Tech Monitor) (Date)

#### TEST PROCEDURE

##### PURPOSE

To determine the time-temperature response of the cold plates of the thermal conductivity test equipment in order to determine slug size.

##### LIST OF MATERIALS AND EQUIPMENT

- ① Bell jar apparatus
- ② Digital thermometer, Fluke 2100A
- ③ Cold plates (no silicon surfaces) with thermocouples
- ④ Fiberglass insulation
- ⑤ Aluminized mylar
- ⑥ Liquid nitrogen and flow controlling equipment

##### PROCEDURE

- ① Attach thermocouples (2 each) to cold plates.
- ② Attach thermocouple for LN controller to lower cold plate near edge.
- ③ Place top cold plate on lower cold plate with nothing between the two plates.
- ④ Insulate outside of cold plate apparatus with fiberglass and mylar.
- ⑤ Place bell jar over apparatus and pump down to less than  $10^{-4}$  Torr.
- ⑥ Record temperatures from thermocouples 1 through 4.
- ⑦ Set LN controller to  $-150^{\circ}\text{F}$  and turn on.
- ⑧ Record thermocouples 1 through 4 with respect to time.

## SIZE DETERMINATION OF COPPER SLUG AND GUARD RING

### Size as a Function of Sample Energy

Energy of monolayer sample should be 5 percent of energy in copper slug:

$$5 \text{ percent } (M C_p)_{\text{copper}} = (2M C_p)_{\text{Sample No. 5}}$$

where  $C_{p_{\text{copper}}} @ -18^{\circ}\text{C } (0^{\circ}\text{F}) = 0.36 \text{ kJ/kg}^{\circ}\text{C} \left( \frac{0.086 \text{ Btu}}{1\text{bm}^{\circ}\text{F}} \right)$

$$C_{p_{\text{Nomex}}} @ -18^{\circ}\text{C } (0^{\circ}\text{F}) = \frac{0.80 \text{ kJ}}{\text{kg}^{\circ}\text{C}} \left( \frac{0.19 \text{ Btu}}{1\text{bm}^{\circ}\text{F}} \right)$$

(sample)

$$M_{\text{Sample No. 5}} @ \text{dia} = 8.89 \text{ cm } (3.5 \text{ in}) = 6.91 \text{ gm } (0.015 \text{ lbm})$$

Solving for  $M_{\text{copper}}$ :

$$M_{\text{copper}} = \frac{(2M C_p)_{\text{No. 5}}}{0.05 C_{p_{\text{copper}}}}$$
$$= \frac{2 \times 6.91 \text{ g} \times 0.80 \frac{\text{kJ}}{\text{kg}^{\circ}\text{C}}}{0.05 \times 0.36 \frac{\text{kJ}}{\text{kg}^{\circ}\text{C}}}$$

$$M_{\text{copper}} = 614 \text{ g } (1.35 \text{ lbm})$$

### Size Determination

Size determined such that:  $\left( \frac{dT}{d\theta} \right)_{\text{copper}} \ll \left( \frac{dT}{d\theta} \right)_{\text{cold plates}}$

Estimate  $\left( \frac{dT}{d\theta} \right)_{\text{copper}}$  and compare to measured  $\left( \frac{dT}{d\theta} \right)_{\text{cold plates}}$

From an energy balance on the copper slug/sample system, estimate  $\left(\frac{dT}{d\theta}\right)_{\text{copper}}$

$$\left(\text{MC}_p \frac{dT}{d\theta}\right)_{\text{Cu}} = 2A H(\Delta T)_{\text{sample}}$$

(energy storage  
in copper)
(heat loss by conduction  
through sample)

where M = 614g from size as function of sample energy

$$A = \left(\frac{8.89}{2} \text{ cm}\right)^2 \pi = 62.07 \text{ cm}^2 \quad (9.62 \text{ in}^2)$$

$$\Delta T = 33^\circ\text{C} \quad (60^\circ\text{F})$$

$$H = 1.42 \text{ W/m}^2/^\circ\text{C} \quad (0.25 \text{ Btu/hr/ft}^2/^\circ\text{F})$$

from previous sample testing

$$C_p = 0.36 \text{ kJ/kg}^\circ\text{C} \quad (0.0855 \text{ Btu/lbm}^\circ\text{F})$$

$$\left(\frac{dT}{d\theta}\right)_{\text{Cu}} = 9.5 \frac{^\circ\text{C}}{\text{hr}} \quad \left(17.4 \frac{^\circ\text{F}}{\text{hr}}\right)$$

Since  $\left(\frac{dT}{d\theta}\right)_{\text{Cu}} = 9.5 \frac{^\circ\text{C}}{\text{hr}} < \left(\frac{dT}{d\theta}\right)_{\text{cold plates}} \approx \frac{55^\circ\text{C}}{\text{hr}}$  from cold plate testing

then M = 614g is acceptable for weight of copper slug.

Slug dimensions: 8.89 cm dia. x 0.94 cm  
(3.50 in dia. x 0.37 in)

Guard Ring dimensions: 8.99 cm I.D. x 10.16 cm O.D. x 0.94 cm  
(3.54 in I.D. x 4.00 in O.D. x 0.37 in)

### TRANSIENT THERMAL CONDUCTIVITY TEST PROCEDURE

#### PURPOSE

To determine the thermal conductivity of the selected monolayer insulating fabric samples and one MLI sample as a function of temperature in a transient test mode.



## LIST OF MATERIALS AND EQUIPMENT

- ① Bell jar apparatus
- ② Copper slug, 8.89 cm dia x 0.94 cm (3.50 in dia x 0.37 in) with two thermocouples each side.
- ③ Copper guard ring, 8.99 cm I.D. x 10.16 cm O.D. x 0.94 cm (3.54 in I.D. x 4.00 in. O.D. x 0.37 in)
- ④ Cold plates without silicon with two thermocouples each side
- ⑤ Autodata Eight data acquisition system
- ⑥ Liquid nitrogen and flow controlling equipment
- ⑦ Fiberglass insulation mylar sheets

## PROCEDURE

Task 3.2: To determine the thermal conductivity of the two selected specimens (No. 5 and No. 12) and of the 4-layer MLI (No. 14) at  $827 \text{ N/m}^2$  (0.1 psi) compression load,  $0.0133 \text{ N/m}^2$  ( $10^{-4}$  Torr) and temperatures of  $-180^\circ\text{C}$  ( $0^\circ\text{F}$ ) and  $-73^\circ\text{C}$  ( $-100^\circ\text{F}$ ).

- ① Install Sample No. 5 into test set-up. Tighten nuts to achieve appropriate springlength for  $827 \text{ N/m}^2$  (0.12 psi) compression load as shown in Table C-1.
- ② Connect thermocouple leads to Autodata Eight.
- ③ Place bell jar over apparatus and pump down to  $0.0133 \text{ N/m}^2$  ( $10^{-4}$  Torr).
- ④ Set Autodata Eight to provide printout of each thermocouple at 5 minute intervals and switch to on.
- ⑤ Set liquid nitrogen controller to  $-100^\circ\text{F}$  ( $-73^\circ\text{C}$ ) and turn power on.
- ⑥ Continue test until copper slug temperature reaches about  $5^\circ\text{C}$  below the point where the copper and cold plate temperatures average to  $-73 \pm 3^\circ\text{C}$  ( $-100 \pm 5^\circ\text{F}$ ).
- ⑦ Terminate test for Sample No. 5.
- ⑧ Repeat Steps ① through ⑦ for Samples No. 12 and No. 14.
- ⑨ Repeat Steps ① through ⑧ for an average temperature of  $-180^\circ\text{C}$  ( $0^\circ\text{F}$ ). Set controller in step ⑤ to  $0^\circ\text{F}$  ( $-180^\circ\text{C}$ ).

TABLE C-1. SPRINGLENGTH FOR 827 N/m<sup>2</sup> (0.12 psi) COMPRESSION LOAD

Specimen No.	Springlength, cm (in)
5	4.22 (1.66)
12	4.06 (1.60)
14	3.87 (1.52)

SAMPLE CONDUCTANCE CALCULATION  
FOR TRANSIENT THERMAL CONDUCTIVITY TESTING

$$\begin{aligned}
 &\text{energy storage in sample} + \text{energy storage in copper slug} = \text{thermal conductance through sample} \\
 &\left( M_{cp} \frac{dT}{d\theta} \right)_{\text{sample}} + \left( M_{cp} \frac{dT}{d\theta} \right)_{\text{copper}} = \frac{2KA}{x} \left( T_{\text{copper}} - T_{\text{cold}} \right)_{\text{sample}} \\
 &\text{(negligible)} \\
 &\frac{K}{x} = H \left( W/m^2/^{\circ}C \right) = \left( M C_p \frac{dT}{d\theta} \right)_{\text{copper}} \times \frac{1}{2A(\Delta T)_{\text{sample}}}
 \end{aligned}$$

where  $m$  = weight of copper

$x$  = sample thickness

$C_p$  = specific heat of copper

$\frac{dT}{d\theta}$  = rate of change in temperature of copper when average temperature of sample reaches desired value

$A$  = area of sample in contact with copper slug

$\Delta T$  = temperature difference across sample

$$@ -18^{\circ}C \text{ (} 0^{\circ}F \text{)} \quad H(W/M^2/^{\circ}C) = \frac{141.4 \frac{dT}{d\theta} \frac{^{\circ}C}{\text{min}}}{\Delta T (^{\circ}C)}$$

$$H \text{ (Btu/hr/ft}^2/^{\circ}F \text{)} = \frac{44.8 \frac{dT}{d\theta} \frac{^{\circ}F}{\text{min}}}{\Delta T (^{\circ}F)}$$

$$@ -73^{\circ}C \text{ (-} 100^{\circ}F \text{)} \quad H(W/M^2/^{\circ}C) = \frac{126.8 \frac{dT}{d\theta} \frac{^{\circ}C}{\text{min}}}{\Delta T (^{\circ}C)}$$

$$H \text{ (Btu/hr/ft}^2/^{\circ}F \text{)} = \frac{40.2 \frac{dT}{d\theta} \frac{^{\circ}F}{\text{min}}}{\Delta T (^{\circ}F)}$$

APPENDIX D  
TEST PLAN AND PROCEDURE  
FOR THE  
SEAMING EVALUATION OF THE MONOLAYER  
WOVEN PILE FABRIC

Approved: \_\_\_\_\_  
(Tech Monitor) (Date)

PURPOSE

To determine means of finishing the raw edges and seaming the monolayer insulating fabric in terms of heat protection and retention. This effort is part of the evaluation of the monolayer woven pile fabric for space suit insulation.

LIST OF MATERIALS AND EQUIPMENT

- ① Monolayer woven pile fabric samples
- ② Adhesive: PM107
- ③ Adhesive: N136
- ④ Sewing machine
- ⑤ Radiant heat source (heat lamp)
- ⑥ Infrared film
- ⑦ 35mm camera and infrared filter

Procedure: Task 4

I Fabric Preparation (Refer to Sketches in Figure D-1)

- ① Cut six 9 cm (3-1/2 inch) squares from fabric No. 11. Mark each square near center with black ink, from A to F.

Seaming Evaluation Test Plan

- ② By cutting and pulling threads, remove pile in a 2.5 cm (1 inch) wide strip on two adjacent edges of Samples A through C, Sketch 1.
- ③ With item ④, run a zigzag stitch 0.64 cm (1/4 inch) from edge along edges with pile removed of Sample A and along one edge of Sample D, Sketch 2.
- ④ Prepare PM107 adhesive in a 2 to 1 ratio with MEK.

- ⑤ Apply PM107 along edges with pile removed of Sample B and along one edge of Sample E to cover raw threads on edge, Sketch 3.
- ⑥ Apply PM107 along edge of pile on edges with pile removed of Sample B, Sketch 3.
- ⑦ Prepare N136 as directed.
- ⑧ Apply N136 along edges with pile removed of Sample C and along one edge of Sample F to cover raw threads on edge, Sketch 3.
- ⑨ Apply N136 along edge of pile on edges with pile removed of Sample C, Sketch 3.

## II Seaming Techniques

- ① Select preparation techniques for further testing. See Table D-1.
- ② Cut 24 7.6 cm (3 inch) square pieces from Sample 6.
- ③ Prepare, seam, and label samples according to Table D-1 following preparation techniques previously described and seaming techniques described below (see sketches in Figure D2):
  - a. Flat fell seam, Sketch 1
    - Step 1 -- With "right" sides together, sew straight seam with 1.25 cm (1/2 inch) allowance minimum.
    - Step 2 -- Lay seam allowances to one side and top-stitch along edge.
  - b. French seam, Sketch 3
    - Step 1 -- With "wrong" sides together, sew straight seam with 2 cm (3/4 inch) allowance minimum. Lay seam allowances to one side.
    - Step 2 -- Trim edge of underneath allowance. Turn top allowance under the underneath allowance.
    - Step 3 -- Lay seam allowances to one side and top-stitch along edge.
  - c. Regular seam -- With "right" sides together, sew straight seam with 1.25 cm (1/2 inch) allowance minimum, Sketch 2.

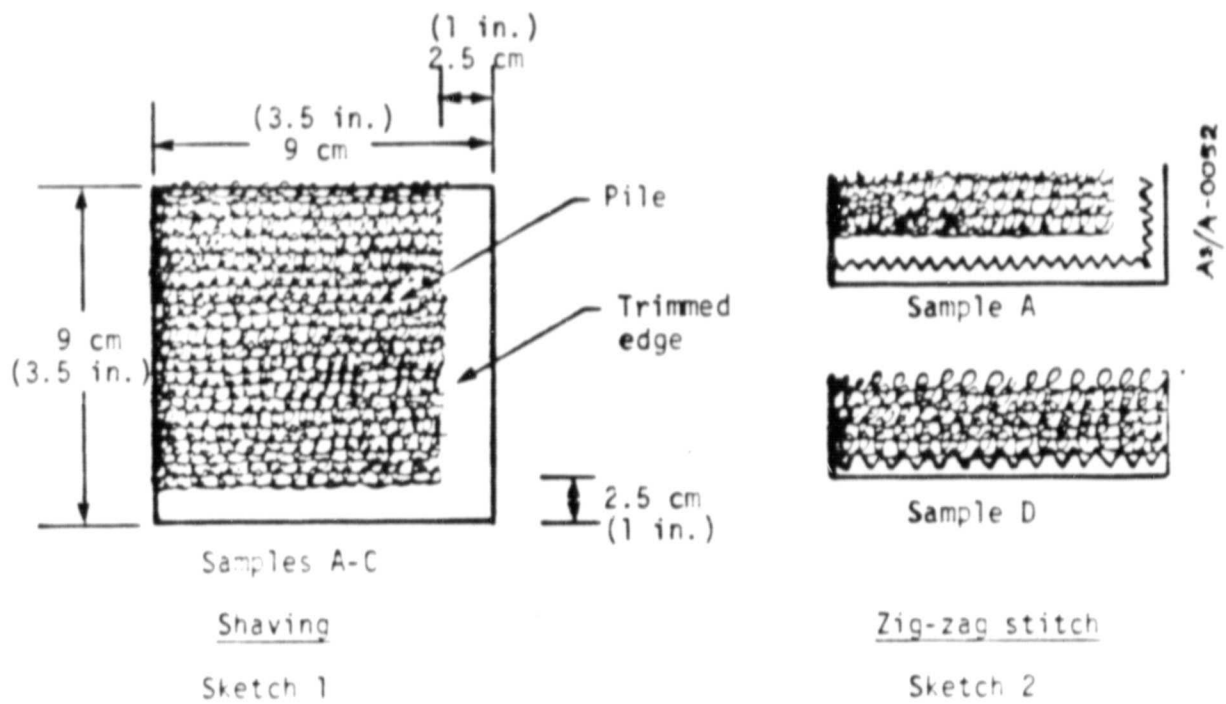
### III Infrared Photography

- ① Set up apparatus as shown in Figure D-3.
- ② Determine filming techniques required by varying exposure time of IR film in a practice session.
- ③ Install selected sample in apparatus.
- ④ Turn heat lamp on.
- ⑤ Take photographs. Exposure time determined to be 0.25 seconds at F16.
- ⑥ Repeat with remaining selected samples.

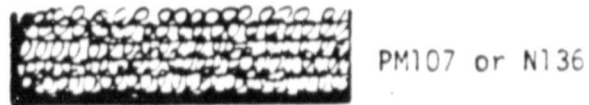
TABLE D-1. TEST SPECIMEN IDENTIFICATION

Preparation Technique	Seaming Technique				
	Flat Fell		Regular	French	
	Pile is "wrong"	Pile is "right"	(Pile is "wrong" side)	Pile is "wrong"	Pile is "right"
Zig-zag stitch, untrimmed	1A	1	2		11
PM107, untrimmed		3	4		10
PM107, both edges trimmed		5		6	
PM107, one edge trimmed	5A			12	9
Unfinished		7			
Bias tape			8		

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Samples B and C



Samples E and F

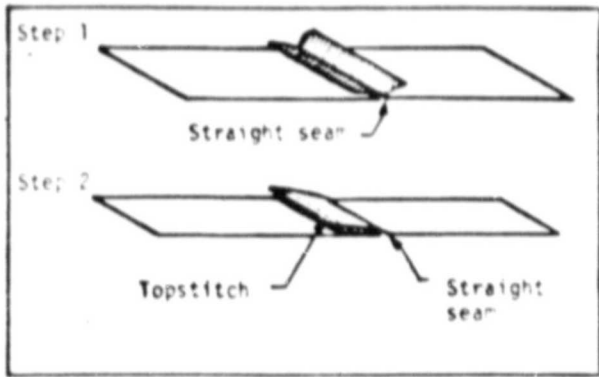
Adhesive finish

Sketch 3

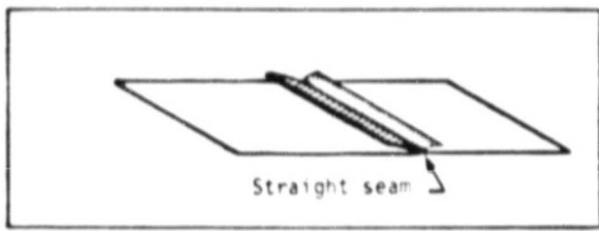
Figure D-1. Fabric preparation.



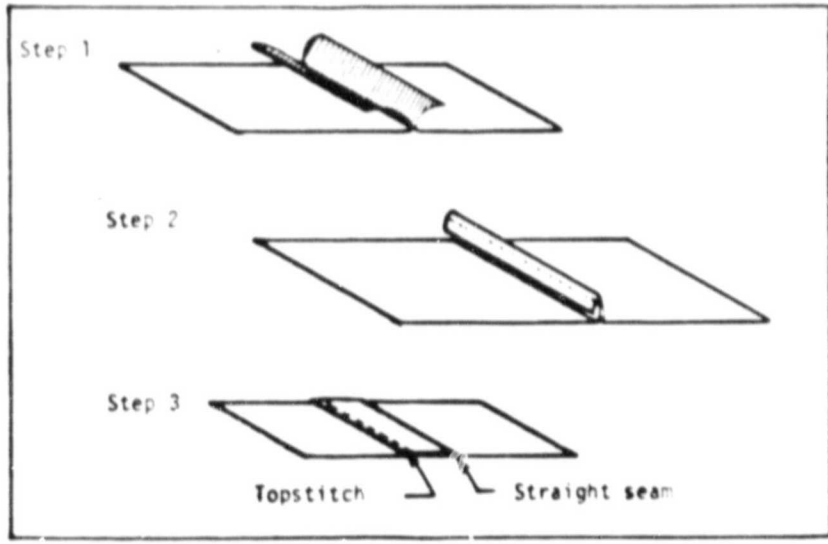
"Right" side shaded



Sketch 1: Flat fell seam



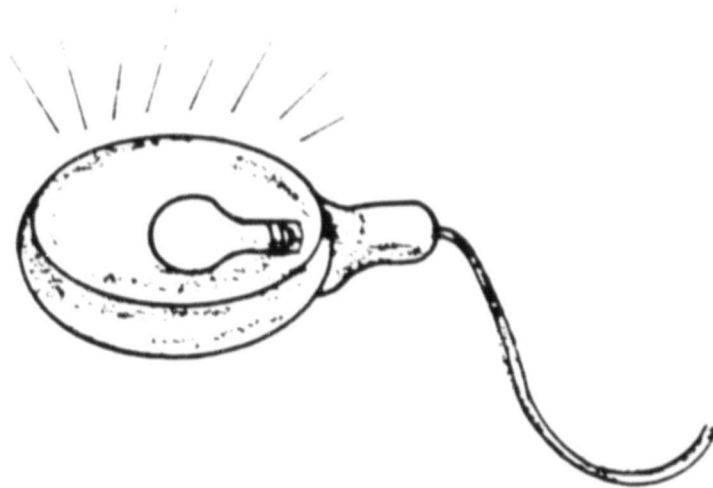
Sketch 2: Regular seam



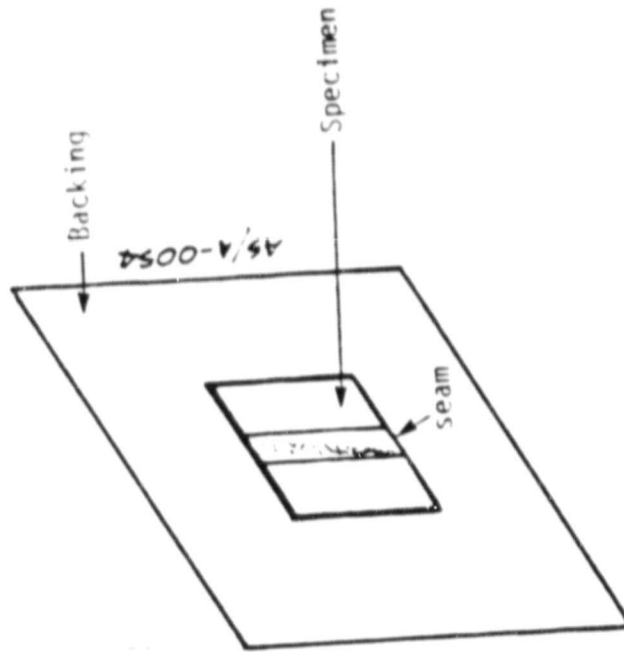
Sketch 3: French seam

Figure D-2. Seaming techniques.

Heat Lamp



D-7



Special filter

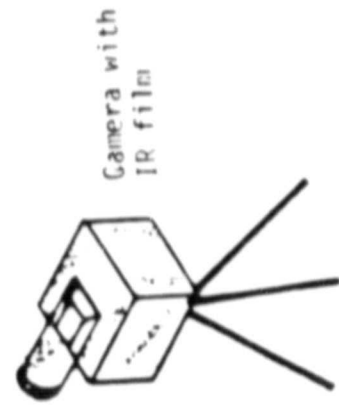
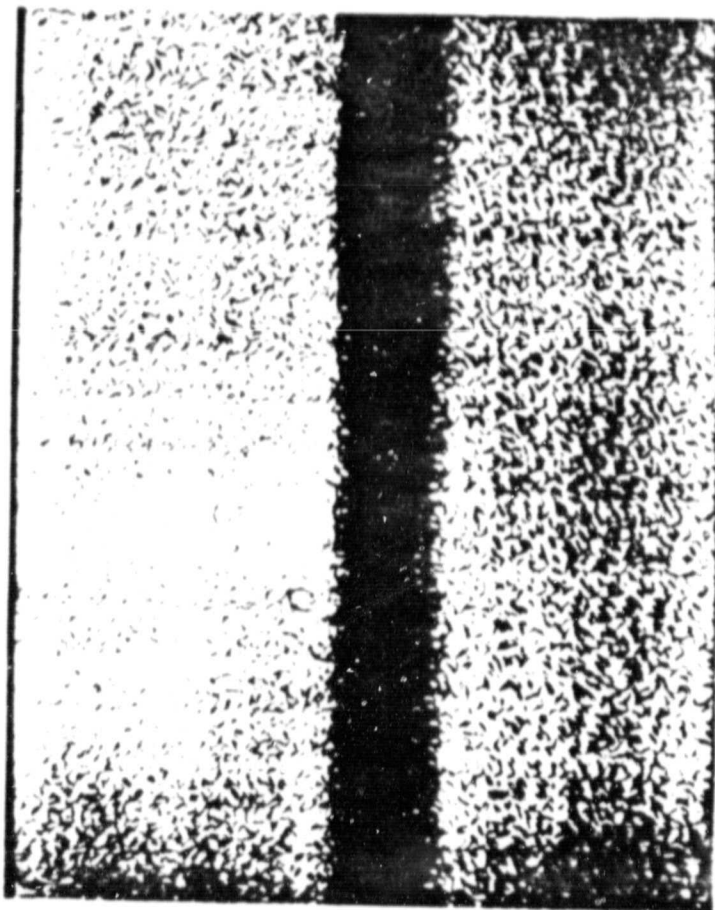
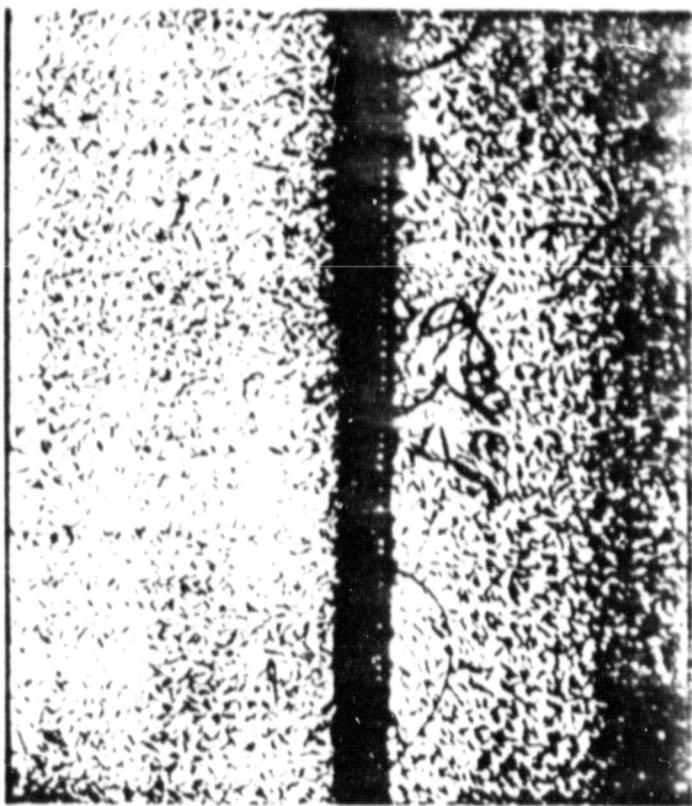


Figure D-3. Seaming test set-up.

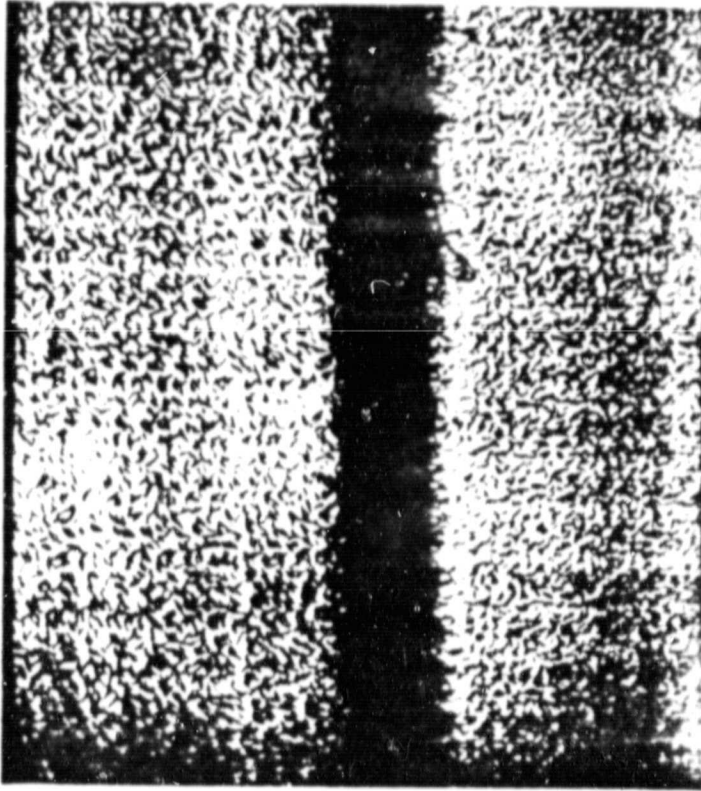


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