CR 151165

THERMAL CONDUCTANCE OF SPACE SUIT INSULATIONS, THERMAL MICROMETEROID GARMENTS, AND OTHER INSULATIONS

final report to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

CONTRACT NAS9-11238

(NASA-CR-151165) THERMAL CONDUCTANCE OF SPACE SUIT INSULATIONS, THERMAL MICROMETEROID GARMENTS, AND OTHER INSULATIONS Final Report (Little (Arthur D.), Inc.) 50 p HC A03/MF A01 CSCL 06C G3/54
N77-16735
Unclas
13265

Arthur D Little, Inc.

FINAL REPORT

THERMAL CONDUCTANCE OF SPACE SUIT INSULATIONS, THERMAL MICROMETEROID GARMENTS, AND OTHER INSULATIONS

by

David L. Richardson

Janet M. Stevens

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

Contract NAS 9-11238

Arthur D. Little, Inc.

Cambridge, Massachusetts 02140

December 1976

72786

TABLE OF CONTENTS

FOREWARD

Arthur D. Little, Inc., Cambridge, Massachusetts, measured thermal conductance of samples from eight operational and developmental thermal micrometeoroid garments (TMG's) by the guarded cold-plate method. Conductance measurements were made by the guarded hot-plate method on samples of the Skylab boot sole, and insulation for a balloon-borne ultraviolet spectrometer, two configurations of the shuttle orbital rescue enclosure, and two shuttle TMG development layups. Elbow sections from the three TMG's were evaluated on a flexible elbow calorimeter both before and after 10,000 cycles of flexure wear.

All of the samples evaluated by the guarded hot-plate method were tested by Dynatech R/D Company, Cambridge, Massachusetts, under the direction of Ronald Tye. That office acknowledges the assistance and cooperation of Mr. Burrell French, the project monitor, and Mr. W. Ellis of the Crew Systems Division, NASA Johnson Space Center. In addition to the authors, the principal ADL personnel contributing to the program included Dr. Alfred E. Wechsler, technical reviewer of the project, and Armand Camus and William Lyle, who were responsible for measurement of insulation conductance and surface properties.

The results of all measurements are reported in the conventional engineering units, rather than in the SI Units. A table for conversion of the former to the latter has been provided.

CONVERSION FACTORS

To Convert From --	Multiply By --	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
Btu/hr	0.2931	watts
Btu/hr ft °F	1.7307	watts/m °K
Btu/hr ft^2 °F	5.6782	watts/m^2 °K
lb	0.4536	kg

$$C = \frac{5}{9}(F-32)$$

$$K = C + 273.18$$

LIST OF SYMBOLS

A	Area	sq ft
C	Conductance	Btu/sq ft hr °F
K	Thermal Conductivity	Btu in/sq ft hr °F
m	number of spaces between radiation shields	
P	gas pressure within voids of the insulation	mm mercury
Q	heat flux	Btu/hr
T	absolute temperature	°R
t	temperature	°F
w	compressive load on insulation	psi
x	thickness	inches
ε	room temperature emittance of radiation shield surface	
σ	Stefan-Boltzman constant 1.714×10^{-9}	Btu/sq ft hr $°F^4$
T	temperature parameter defined by Equation (2)	$°R^3$

Subscripts

1, warm	warm-plate temperature
2, cold	cold-plate temperature
m	mean conditions
o	reference temperature or pressure

I. INTRODUCTION

A. PURPOSE

The purpose of this program was to evaluate the thermal protection capabilities of developmental and operational thermal micrometeroid garments (TMGs) and other insulations, and to define empirically the relationship among sample thermal conductances, surface temperatures, and compressive loads.

B. SCOPE

The program included measurement of the thermal conductance of eight thermal micrometeroid garment insulations in a guarded cold-plate calorimeter in which the cold-plate temperature was maintained at -320°F and a warm-plate temperature was maintained at 200°F or 300°F. The conductance of two samples of insulation, separated by a midplane temperature measurement disc, was measured in all tests. For all samples, the physical compression of the sample was increased incrementally from no-load to 10 psi. From the measured conductance of these eight samples, data correlations were developed presenting conductance as a function of boundary temperatures for gas pressures less than 10^{-5} torr at three compressive loads (no-load, 0.1 psi, and 10.0 psi).

The thermal conductance of six samples was measured in a guarded hot-plate calorimeter by the Dynatech R/D Company in accordance with ASTM Method C177. The temperature boundary conditions for these samples simulated various temperature situations encountered in space orbital missions and high-altitude atmospheric flights.

The program also included three tests of sections of thermal micrometeroid garments on the elbow calorimeter both before and after being subjected to approximately 10,000 cycles of wear flexure. The temperature and pressure boundary conditions on the samples simulated lunar nighttime and daytime conditions.

C. BACKGROUND

For comparison of the effectiveness of various multilayer insulations that make up an astronaut's thermal micrometeroid garment, the important criterion is the amount of heat that will flow through each insulation under any given boundary condition. This flux of heat--either in or out--causes the astronaut discomfort. Thus, the most significant parameter in our study is the thermal conductance--i.e., the heat flux per unit area for a given temperature driving force as given by the following equation.

$$C = \frac{Q}{A(t_{warm} - t_{cold})} \quad (1)$$

Thermal conductivity--the heat flux per unit area per unit of thickness and temperature driving force--is not applicable to space suit insulations because the thickness of each insulation varies unpredictably at various locations on a space suit. Thus, although the measurements taken include a nominal sample thickness, results are not presented in the standard thermal conductivity form, but rather as the thermal conductance as defined by Equation 1.

For identification purposes, all samples tested in the program were numbered consecutively. However, for presentation of results, the samples have been grouped in accordance with the test method used: guarded cold-plate calorimeter, guarded hot-plate calorimeter, and elbow calorimeter test.

II. THERMAL CONDUCTANCE TESTS

A. SAMPLES EVALUATED

Table 1 describes the insulation and garment samples that were tested. The garment layers for each sample are listed in sequence from the outside to the inside of each space suit. Included is a notation of the test technique used for evaluating the sample.

B. TEST TECHNIQUES

Thermal conductance measurements of flat samples were made in a guarded cold-plate calorimeter[1,2,3] that was equipped for applying small compressive loads on the insulation samples[2], and a double-guarded hot-plate calorimeter. Three sections of thermal micrometeroid garments were tested on a flexible elbow calorimeter[3] in a test chamber that is capable of simulating lunar daytime and nighttime conditions.

1. Guarded Cold-Plate Calorimeter

For measurement of the thermal conductance of candidate space suit insulation systems, two identical samples of each space suit layup were prepared and mounted in the sample chamber, as shown in Figure 1. The samples were separated by a midplane temperature measurement disc consisting of 0.002-in thick aluminum foil sandwiched between two 0.002-in thick Mylar films. Three 0.002-in diameter chromel-constantan thermocouples were attached to the aluminum foil and the leads drawn out in such a manner as to minimize conduction to the edge of the foil. The center section of the aluminum foil was 6-in in diameter and separated from the outer section by a 1/16-in gap to reduce edge losses.

The warm-plate temperature of the apparatus was maintained at either 300°F or 200°F, and the cold-boundary temperature at -320°F, the boiling point of liquid nitrogen. Under steady-state conditions, the midplane reaches a temperature that is at an intermediate level between the warm and cold plates of the apparatus. Because the conductance of multilayer

TABLE 1. DESCRIPTION OF INSULATION SAMPLES TESTED

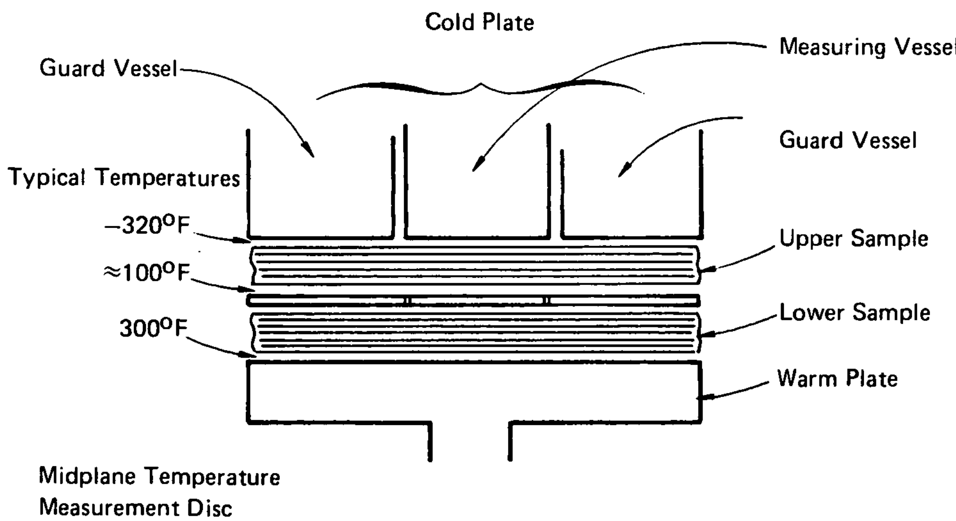
Sample Number	NASA Designation	Layer Sequence	Test Technique
01	A7LB Thermal Micrometeroid Garment	(1) T-162 Teflon fabric (1) 4484 Teflon-coated fiberglass fabric (2) two-sided aluminized Kapton and Kapton tape grid alternating with (3) Beta marquisette spacers (5) one-sided aluminized perforated Mylar shields alternating with (5) Dacron batt spacers (1) neoprene-coated rip-stop bladder	Guarded Cold-Plate
02	A7LB Layup with non-aluminized radiation shields	(1) T-162 Teflon fabric (1) 4484 Teflon-coated fiberglass fabric (2) nonaluminized Kapton with Kapton tape grid alternating with (3) Beta marquisette spacers (5) perforated nonaluminized mylar shields alternating with (5) Dacron batt spacers (1) neoprene-coated rip-stop bladder	Guarded Cold-Plate
03	MSC-15 (ITMG-6) Retest sample	(1) 4484 Beta fiberglass (1) super Beta fiberglass (2) Schjeldahl X-993 radiation shields (8) perforated Mylar, aluminized both sides alternating with (8) Dacron batt spacers (1) neoprene-coated rip-stop bladder	Guarded Cold-Plate
04	Development layup with three layers of nonaluminized radiation shields	(2) 4484 Beta fiberglass (3) perforated Mylar shields non-aluminized alternating with (4) Dacron batt spacers (1) neoprene-coated rip-stop bladder	Guarded Cold-Plate
05	PGA Boot Top layup	(1) Teflon fabric (1) Beta fiberglass fabric (3) two-sided aluminized Kapton and Kapton tape grid alternating with (2) sized Beta marquisette spacers (1) rip-stop bladder fabric	Guarded Cold-Plate

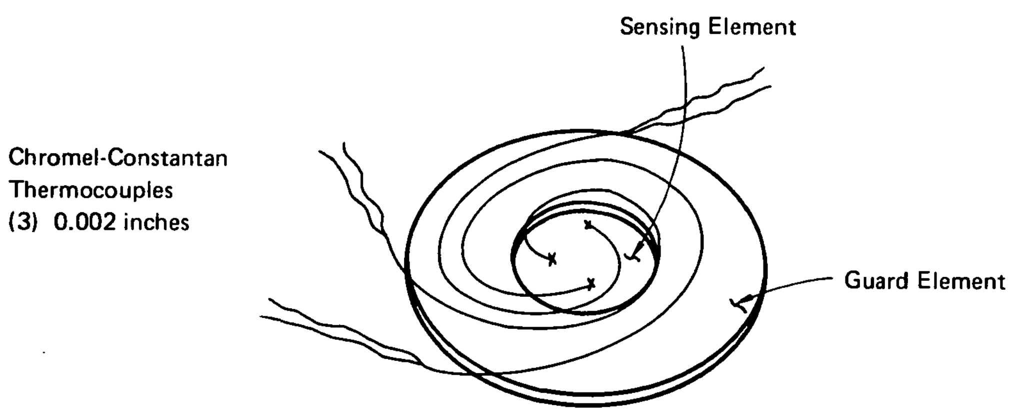
TABLE 1. DESCRIPTION OF INSULATION SAMPLES TESTED (Continued)

Sample Number	NASA Designation	Layer Sequence	Test Technique
05 (cont'd)	PGA Boot Top layup	(1) blue nylon twill (1) neoprene-coated nylon twill bladder (1) blue nylon fabric	Guarded Cold-Plate
06	HITCO 8-PCF Felt on A7LB	(1) T-162 Teflon fabric (1) 4484 Teflon-coated fiberglass fabric (1) 0.125 in HITCO 8-PCF felt (1) neoprene-coated rip-stop bladder	Guarded Cold-Plate
07	A7LB Feedthrough Area	Standard A7LB layup where all layers have been cemented together	Guarded Cold-Plate
08	Skylab Boot Sole	Bootsole center; boot heel and sole; inner soft goods	Guarded Hot-Plate
09	Shuttle Orbital Rescue Enclosure Primary Structure	(1) Nomex (1) yellow micrometeroid shield PRO-49 (1) blue nylon twill 7 oz. (1) neoprene-coated rip-stop bladder (1) white nylon rip-stop 1.2 oz.	Guarded Hot-Plate
10	Balloon-borne Ultraviolet Stellar Spectrometer Insulation	(1) orange nylon rip-stop laminated to a radiation shield with polyurethane adhesive (3) radiation shields 0.25 mil mylar double aluminized alternating with (3) urethane foam spacers 0.125 in. thick (1) green Nomex	Guarded Hot-Plate
11	Shuttle Orbital Rescue Enclosure Primary Structure With Insulation	(1) Nomex (6) double aluminized 0.25 mil Mylar radiation shields alternating with (7) non-woven Dacron batt spacers (1) Gortex, Nomex, Kevlar orthoblend micrometeroid shield (1) blue nylon twill, 7 oz. (1) neoprene-coated rip-stop bladder (1) white nylon rip-stop, 1.2 oz.	Guarded Hot-Plate

TABLE 1. DESCRIPTION OF INSULATION SAMPLES TESTED (Continued)

Sample Number	NASA Description	Layer Sequence	Test Technique
12	Shuttle Orbital Rescue Enclosure Primary Structure with Insulation	(1) Nomex (6) double aluminized 0.25 mil Mylar radiation shields alternating with (7) non-woven Dacron batt spacers (1) Gortex, Nomex, Kevlar orthoblend micrometeroid shield (1) blue nylon twill (1) neoprene-coated rip-stop bladder (1) white nylon rip-stop	Guarded Cold-Plate
13	Shuttle TMG insulation 7-layer developmental layup	(1) Gortex, Nomex, Kevlar orthoblend fabric (1) Nomex scrim (4) net reinforced aluminized Mylar radiation shields, shield facing outward (1) fire resistant neoprene-coated nylon	Guarded Hot-Plate
14	Shuttle TMG insulation 9-layer developmental layup	(1) Gortex, Nomex, Kevlar orthoblend micrometeroid shield (4) net-reinforced aluminized Mylar radiation shields alternating with (3) Nomex scrim spacers (1) neoprene-coated rip-stop bladder	Guarded Hot-Plate





Detail of the Midplane Temperature Measurement Disc

FIGURE 1 MEASUREMENT TECHNIQUE FOR DUAL SAMPLES

insulation is temperature-dependent and increases with increasing temperature, the midplane temperature between the two insulation samples was always above the midpoint temperature of the given range. The heat flux through both insulation samples, of course, was the same. The important measured quantities were heat flux, compressive load on the sample, and the midplane temperature.

Once the sample had been installed and the chamber evacuated to the desired pressure, the guard, measuring, and shield vessels were filled with liquid nitrogen and a warm-plate temperature of 200°F was established. The test procedure then consisted of reducing the gap between the sample and the cold plate (located above the sample) in successive stages. As the sample gap was reduced, the heat flux decreased to a minimum value and then increased when the sample contacted the cold plate. The no-load thermal conductance condition was achieved at the point of minimum heat flux just before the sample contacted the cold plate.

The thermal heat flux through the two samples was determined by measurement of the boil-off rate of the liquid nitrogen from the measuring vessel. After equilibrium conditions had been reached and measurements taken, the temperature of the warm plate was increased to 300°F and another set of equilibrium conditions were established. When both the 200° and 300°F warm-plate conditions had been achieved, the compressive load was increased to 0.1 psi by use of the low-load device. Equilibrium was again achieved for warm-plate temperatures of 300°F and 200°F. After the second set of conditions had been achieved, the load was increased again to approximately 2.0 psi by the use of a hydraulic ram and equilibrium heat flux and midplane temperatures were again achieved at 300° and 200°F. This procedure was repeated for the last compressive load of 10 psi.

The sample thermal conductance was calculated from the heat flux per unit area and the sample boundary temperatures. The test data are contained in Tables A-1 through A-8 in the Appendix, including a description of the sample, the individual sample weights, the midplane weight, the sample chamber pressure, the compressive load, the outside temperature, the inside temperature, the heat flux per unit area, and the sample thickness.

2. Guarded Hot-Plate Calorimeter

The guarded hot-plate calorimeter that was used in the tests by the Dynatech R/D Company is shown schematically in Figure 2. The apparatus consists of a central heater that is located between two identical samples. Water or liquid nitrogen circulating through two heat sinks located outside of the two identical samples allows measurements to be made at the desired cold-side temperature on each sample. Selected pairs of insulation and auxiliary heaters are also used to control the cold-side temperature.

The main central heater is surrounded by a guard heater that is automatically controlled with proportional controllers so as to be at the same temperature as the main heater. This ensures that there are no radial heat losses from the main heater, and that the heat flow through the sample is truly one-dimensional. Under normal operating conditions, one-half of the electrical energy that is dissipated in the central main heater will flow through each of the two identical samples. When the equipment has reached a steady state, the heat input to the main heater is conducted continuously through the top and bottom samples, and through a sample area equal to the area of the main heater. The heat-flow equation for this apparatus is:

$$(q)_{\text{Main Heater}} = A_{\text{Main Heater}} \left[k\left(\frac{\Delta T}{\Delta x}\right)_{\text{Top Sample}} + k\left(\frac{\Delta T}{\Delta x}\right)_{\text{Bottom Sample}} \right] \qquad (2)$$

Ordinarily, if there are no natural convection effects in the sample material and if the auxilliary heaters are controlled to the same temperature, the temperature drops through the bottom and top sample will be close to equal and, hence, the two terms in the bracket on the right-hand

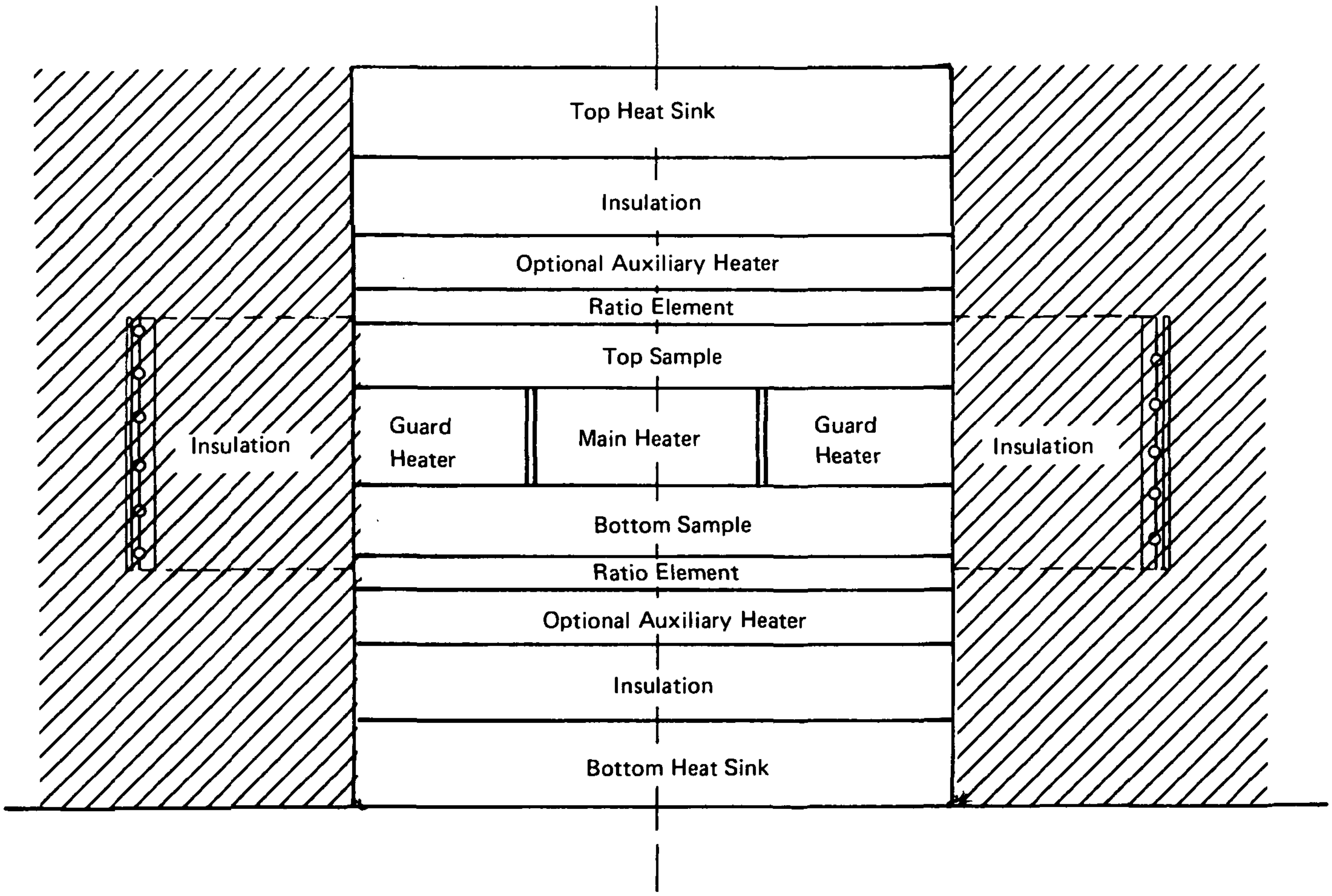


FIGURE 2 ARRANGEMENT OF THE MEASUREMENT SECTION OF THE DYNATECH GUARDED HOT PLATE THERMAL CONDUCTIVITY INSTRUMENT

side of the equation are equal. The conductivity of the samples can then be determined from the equation by measurement of the heat input (q) to the main heater, measurement of the temperature differences (ΔT) across the samples with thermocouples, and use of the measured values for the main heater area (A) and the sample heat conduction length (Δx).

The ratio elements shown in Figure 2 consist of slabs of alumina, which permit the determination of the thermal conductivities of the two samples individually if they are not quite equal, in which case there may be a different heat flux through the top and bottom samples. The ratio of these heat fluxes is determined by measurement and comparison of the temperature differences across the ratio elements. In this way independent heat flow equations can be written for the top and bottom samples, with the heat flux ratio equal to the temperature drop ratio in the ratio elements and the total heat flow adding up to the main heater input.

The gas in the sample chamber can be controlled from atmospheric pressure down to the lowest pressure capability of the pumping system. The nature of atmospheric environment can also be controlled, i.e., air, nitrogen, or other inert atmospheres.

The apparatus, which is capable of measuring thermal conductivities over a wide range, has been used to measure conductivities as low as 0.005 Btu/hr ft °F, using temperature differences of only about 50-100°F. It has also been used to measure conductivities as high as about 2 Btu/hr ft °F. The apparatus should be used, however, within the ASTM-C177-71 specifications of thermoconductivity not in excess of 35 Btu/hr ft °F.

The accuracy of the instrument is well within acceptable laboratory accuracy. All heaters are generally controlled to within ± 1°F of the desired temperatures with relative ease. The guard heaters are often controllable to within about $\pm .25$°F. Temperature measurements can be made within about $\pm$1-6°F if calibrated thermocouples are used. Power dissipation measurements are made to within about $\pm$ 0.25%.

3. Measurement of Heat Flow in a Test Section of an Experimental TMG

In an earlier program,[3] a method was developed whereby test sections of experimental TMGs could be evaluated for thermal protection capability under simulated orbital space nighttime and daytime conditions, both before and after being subjected to 10,000 cycles of flexure.

This method was used to test three samples of space suit TMGs that were manufactured by ILC Industries, Inc. In the test method, a straight cylindrical section of a space suit TMG, approximately 5.7-in in diameter, is slipped over the elbow calorimeter shown schematically in Figure 3. This calorimeter consists of a central measuring section over which is placed a flexible pressurized section of a space suit elbow and the whole volume is pressurized to 4 psia. Guard sections in this calorimeter are attached at each end of the calorimeter and are designed to minimize the heat leak into or out of the calorimeter measuring section.

The calorimeter with the test section of TMG is placed in a small laboratory space-simulation chamber, in which vacuum conditions can be simulated. Lunar daytime conditions are simulated by placement of an electrically heated shroud over the assembly when it is in the extended axial position. Lunar nighttime conditions are simulated by removal of the electrically heated shroud and circulation of liquid nitrogen through the blackened wall shroud within the chamber.

Figure 4 shows the assembled calorimeter with the flexible elbow section mounted in the test chamber. The left end of the calorimeter is anchored by low conductance supports to a structure in the space simulation chamber. The right end of the calorimeter is attached to a flexing mechanism with a yoke which guides the right end as the elbow

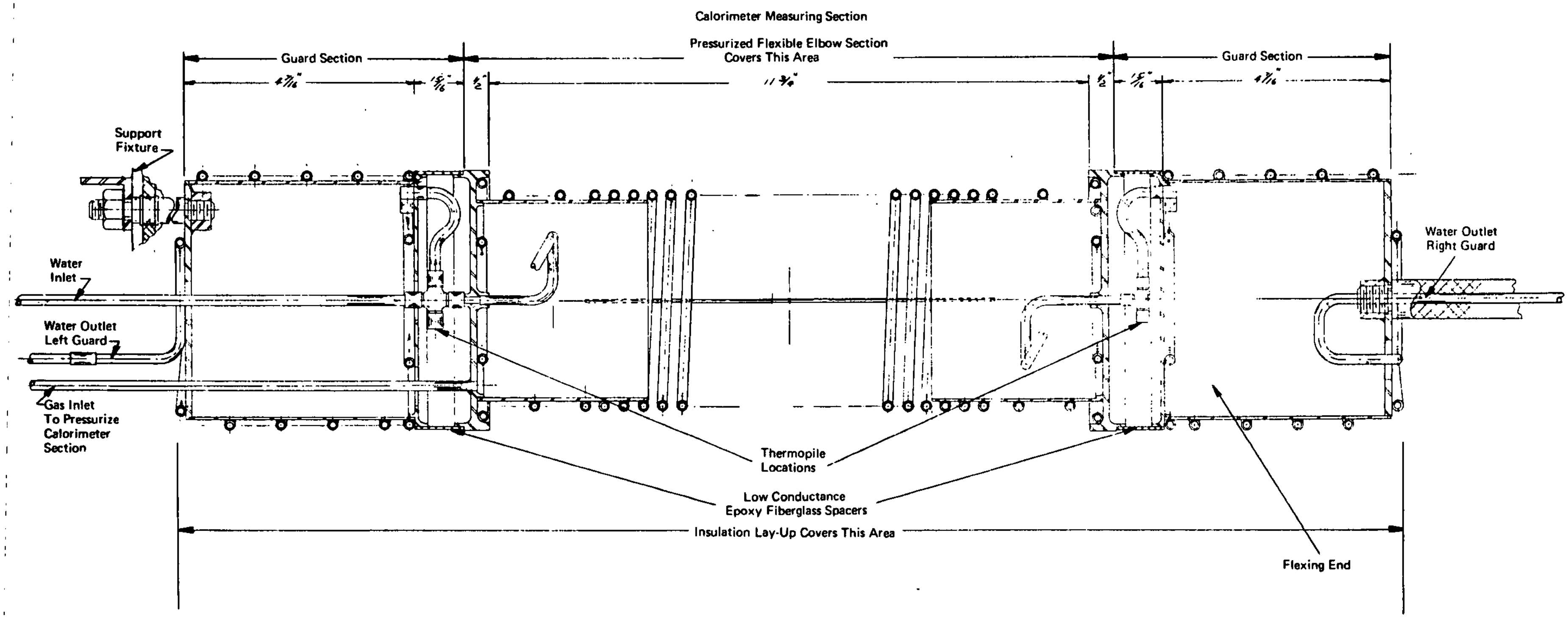


FIGURE 3 ELBOW CALORIMETER ASSEMBLY

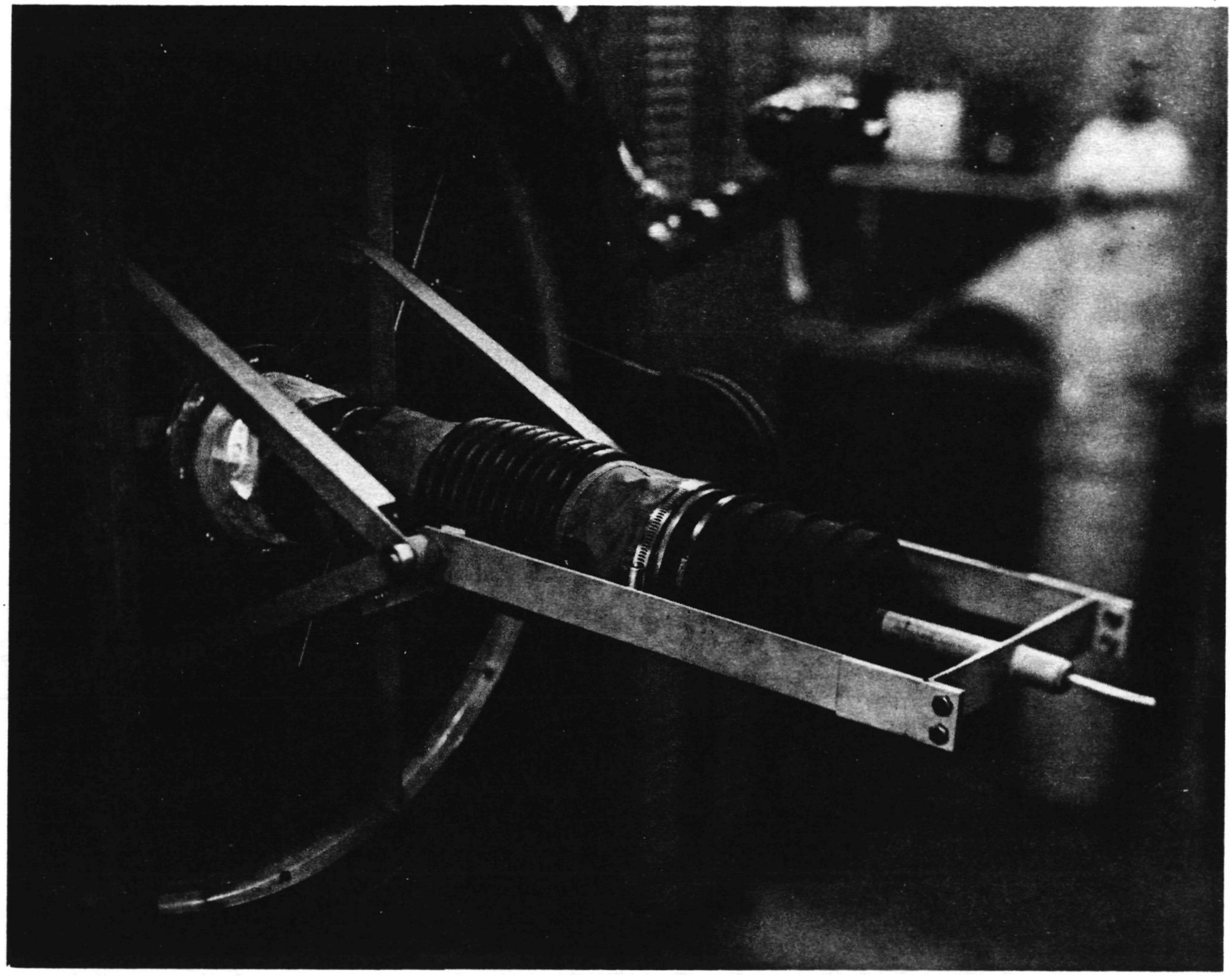


FIGURE 4 GUARDED ELBOW CALORIMETER

is flexed back and forth. The elbow calorimeter was flexed plus or minus 45° from a normal axis. Ideally, the elbow calorimeter should have been flexed 90° in one direction from neutral axis, but space limitation within the test chamber did not allow this range of motion.

The test apparatus and the measurement procedures have been described in detail previously.[3]

4. Emittance Measurements

An important part of the evaluation of high-efficiency insulation such as those used in thermal micrometeroid garments, is an evaluation of the total hemispherical emittance of the surface of the radiation shields. The emissometer that was used in the program was developed in an earlier NASA program[2] to permit the rapid measurement of the total hemispherical emittance of material surfaces at near room temperature.

This instrument operates on the receiver disc principle. A circular, thin-metal, blackened disk, about 2.5-in. in diameter, is placed closely adjacent and parallel to a circular sample piece in an evacuated space. The back side of the blackened receiver disk is surrounded by a black cavity whose temperature is lower than that of the sample temperature. On one side, the receiver disk exchanges heat with the sample and, on the other, with the black cavity, principally by radiative heat transfer. The geometry is such that the heat transfer between the sample and the receiver disk is essentially like that between two infinite parallel planes (see Figure 5). The two surfaces of the receiver disk and the surface of the cavity are assumed to have an emittance of unity. Radiative transfer between the back side of the disk and the black cavity is essentially that between two black bodies. Hence, a heat balance on the disk yields the equation:

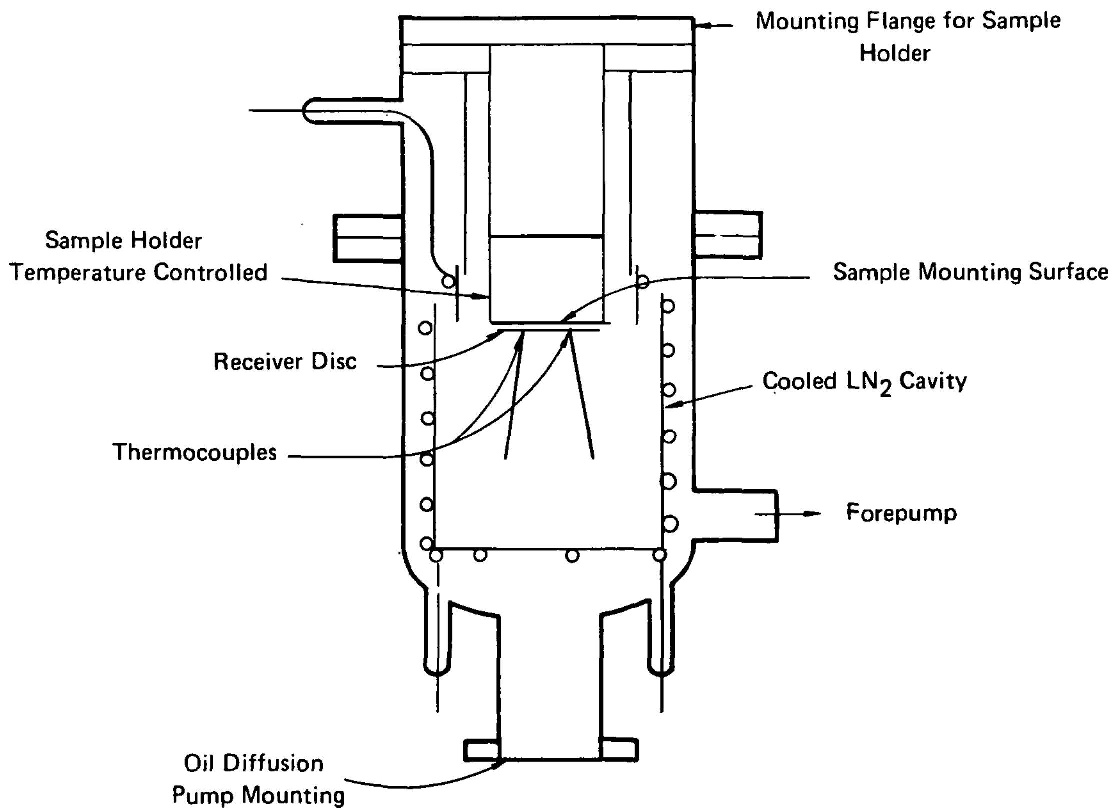


FIGURE 5 EMISSOMETER

$$\varepsilon_s(T_s^4 - T_d^4) = (T_d^4 - T_c^4)$$

or

$$\varepsilon_s = \frac{T_d^4 - T_c^4}{T_s^4 - T_d^4} \quad (3)$$

Thus, if the sample temperature, the cavity temperature, and the disk temperature are measured, the emissivity of the sample can be determined. In this apparatus, the sample temperature is maintained constant at a value slightly above room temperature. The cavity temperature is maintained at the temperature of liquid nitrogen and the receiver disk temperature is measured with a thermocouple.

An error analysis indicates fixed and random errors of approximately 5% at the level of emittances measured in the studies. A calibration of the instrument indicates an instrument error of approximately 7%.

5. Solar Absorptance Measurements

The technique that was used for determining solar absorptance involved measuring the spectral reflectance of the sample in the wavelength range of 0.3 microns to 2.5 microns. Measurements are made in Beckman DK1-A recording spectrophotometer with a reflectance integrating sphere. The spectral refelctance data (r_λ) that are obtained become inputs to a computer program that integrates the spectral reflectance data and solar spectral intensity data in the following formula to calculate the solar absorptance.

$$\alpha_s = \frac{\int_{0.3\mu}^{2.5\mu} (1-r_\lambda) s_\lambda d_\lambda}{\int_{0.3\mu}^{2.5\mu} s_\lambda d\lambda} \quad (4)$$

where

r_λ = spectral reflectance of sample,

s_λ = solar spectral intensity at air mass zero, and

α_s = solar absorptance at air mass zero.

The solar irradiance data for air mass zero are from the standard[4] proposed by Dr. M. P. Thekaekara of NASA-Goddard Space Flight Center.

C. RESULTS OF CONDUCTANCE MEASUREMENTS

1. Guarded Cold-Plate Calorimeter Tests

The heat flux through the sample and boundary temperatures were measured for each sample at no-load conditions and for successively larger compressive loadings up to 10 psi. The sample conductance was calculated from the heat flux and the sample boundary temperatures. The conductance was not measured at the exact boundary conditions required in the program--daytime conditions (the outside temperature of the space suit at 250°F and the inside at 72°F) and nighttime conditions (the outside of the space suit at -310°F and the inside is at 72°F)--instead, all conductance measurements for the cold-plate temperature were made at the boiling point of liquid nitrogen (-320°F) and for the warm-plate temperature at 200°F and 300°F.

The use of a midplane temperature measurement between two identical samples of the space suit insulation allowed simultaneous measurement of the conductance of two samples of space suit insulation for each heat flux measurement. In most instances, the midplane temperature was higher than the 72°F required for the inside boundary condition of the space suit; therefore, interpolations of the basic data were required in order to determine the insulation conductance for the two conditions. The measured conductance of the samples at each pressure loading was plotted as a function of the parameter

$$T = \frac{T_1^{\,4} - T_2^{\,4}}{T_1 - T_2} \tag{5}$$

and values of the conductance at the desired temperature differences (250 to 72°F and 72 to -310°F) were obtained by straight-line interpolation. (A description of this interpolation procedure is given in the Appendix.)

The data for all thermal conductance tests performed during this program (summarized in tabular form in Tables A-1 through A-8 in the Appendix) include the compressive load, the outside temperatures of the insulation, the inside temperature of the insulation, the temperature difference across each insulation, the heat flux, the conductance of the sample, the sample thickness, and T .

The eight samples tested by the guarded cold-plate method are samples 01, 02, 03, 04, 05, 06, 07, and 12. The conductances of the samples as a function of compressive loading for the nighttime conditions (sometimes called the cold conditions), 72° to -310°F, are summarized in Figure 6, and the conductances of the samples as a function of compressive loading for daytime conditions (sometimes called the hot conditions), 72° to 250°F, are summarized in Figure 7.

At the no-load condition, the sample rests under its own weight in the thermal conductance apparatus and the compressive loads within the sample, which result from the sample's own weight, are taken into account. In the case of the samples under nighttime conditions (Figure 6), the range of the self-compression load in the sample is determined from the weight of the sample divided by its area, the maximum, and one-half of the weight of the sample divided by its area, the minimum. For the samples in daytime conditions (Figure 7), the range of self-compression load is determined from the sum of the weights of the two samples and the midplane measuring disc divided by the sample area, the maximum, and the sum of one sample weight and the midplane temperature measuring disc divided by the sample area, the minimum.

Of particular interest in future NASA programs that call for Extra Vehicular Activity (EVA) is the thermal conductances of samples at the no-load condition. In normal operation, the insulation in an astronaut's EVA garment will be under minimum compression, particularly in orbit, where there is no gravity. It is hard to visualize how compressive loads in excess of 1.0 psi can be sustained in a properly

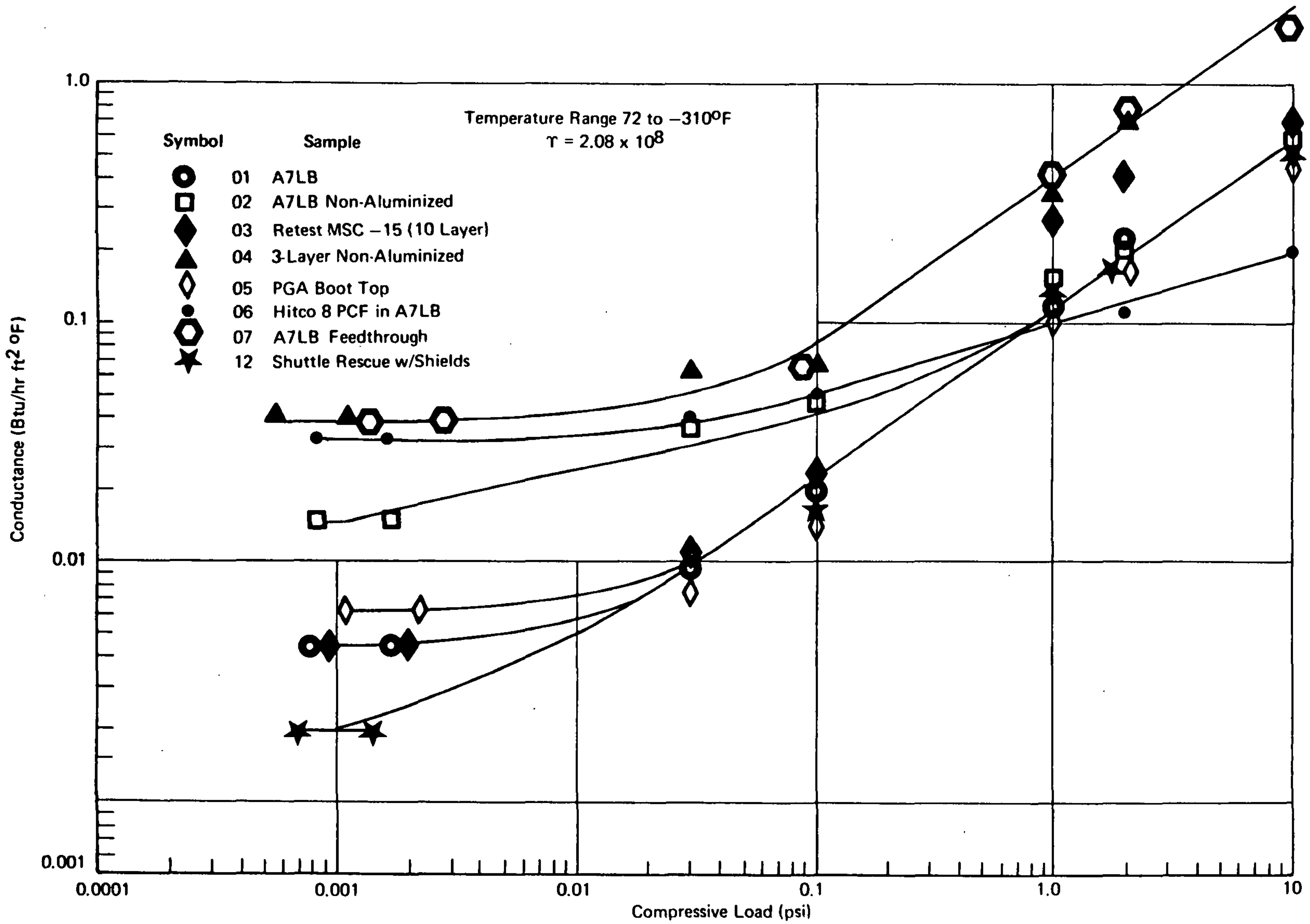


FIGURE 6 SUMMARY OF INSULATION CONDUCTANCE – NIGHTTIME CONDITIONS

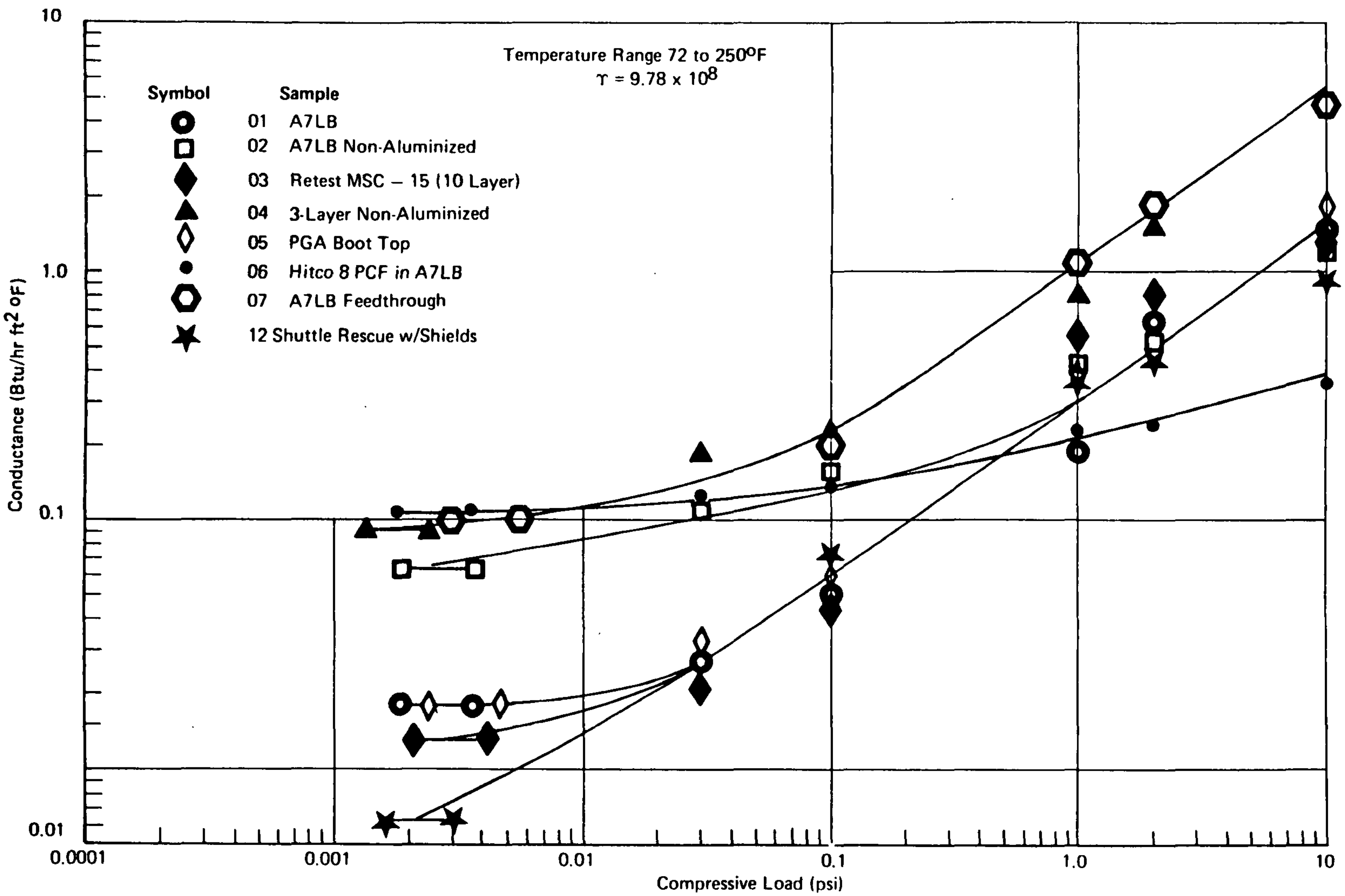


FIGURE 7 SUMMARY OF INSULATION CONDUCTANCE – DAYTIME CONDITIONS

adjusted EVA garment. In isolated circumstances it may be possible to achieve higher compressive loads when the astronaut is leaning on his elbow or is down on his knees, but these are considered transient conditions.

Samples 01, 03, 05, and 11, which have multiple double-aluminized radiation shields, have thermal conductances in the range 0.002 - 0.006 Btu/ft^2 hr °F for the cold condition (see Figure 5) and in the range 0.0064 - 0.0018 for the warm condition (see Figure 6). These values are in the same range as those for similar insulation with multiple double-aluminized or gold-coated radiation shields. Sample 03, which was a retest of a sample (MSC-15) from an earlier program[5] has the same no-load conductance that was measured in the earlier program.

The increase in conductance that comes with removal of the low-emittance surfaces from radiation shields is shown by a comparison between Sample 01 (A7LB aluminized) and Sample 02 (A7LB nonaluminized). As the compressive load increases, the effect of the radiation shield decreases until, at a compressive load of about 1.0 psi, the heat flux is dominated by solid conduction between the insulation layers. This is the reason the conductance of Sample 02 merges with the conductance of Sample 01 at 1.0 psi as the compressive load is increased.

Behaving differently from all other samples tested, Sample 06 is dominated by a 0.125-in thick layer of high-temperature quartz felt that has a density of 8 lb/ft^3. The sample has no radiation shields. At the no-load conditions, it has about the highest thermal conductance that was measured during the program; however, as the load is increased on the sample, the conductance does not rise as fast as does the conductance for the lighter-weight multiple radiation shield insulations. At about 1.0 psi, Sample 06 has approximately the same conductance as the samples with multiple double-aluminized radiation shields. At pressures above 1.0 psi, Sample 06 exhibits significantly lower conductance than the multiple radiation shield insulations.

In the vicinity of a feed-through on a space suit where the layers of insulation have been cemented together and then stitched, there is a marked increase in the conductance. This is shown when one compares the conductance of Sample 07 (A7LB feed-through) with Sample 01 (A7LB without feed-through). For the cold conditions (Figure 6), there is a 9.0-fold increase in the conductance at no-load conditions, and a 3.6-fold increase at a compressive load of 1.0 psi. For the warm conditions, (Figure 7) there is a 5.5-fold increase at no-load conditions and a 3.6-fold increase at 1.0 psi.

The data presented in Figures 6 and 7 can be expressed empirically by linear functions of the temperature parameter, T (see Equation 5). Table 2 summarizes the conductance of all samples tested as a function of the temperature parameter for three compressive loads (no load, 0.1 psi, and 10 psi).

2. Guarded Hot-Plate Tests

The samples tested by the guarded hot-plate method are Samples 08, 09, 10, 11, 13, 14, and 15. These samples are described in Table 1. All samples were tested by the Dynatech R/D Company in accordance with ASTM Test Method C177. In this test, identical samples of material are placed on both sides of a circular guarded hot plate. The external surfaces of the two samples are in contact with cold plates. Boundary temperatures are established by controlling the power input to the hot plate in the center, and controlling the temperature of the two cold plates. For these conditions, half of the power input to the hot plate flows out through one sample and half flows out through the other sample; thus, the heat flux through each sample is established.

For each of the samples tested, the boundary temperatures (hot and cold side of the insulation), the compressive load, and the gas pressure surrounding the insulation were unique to the particular application to the insulation.

TABLE 2. SUMMARY OF CONDUCTANCE AS A FUNCTION OF TEMPERATURE PARAMETER T AND COMPRESSIVE LOAD

Sample Number	Conductance, C (Btu/ft^2 hr °F) No-Load	Compression = 0.1 psi	Compression = 10 psi
01	$C = 1.73 \times 10^{-11}\, T + .0009$	$C = 2.42 \times 10^{-10}\, T + .064$	$C = 1.2 \times 10^{-9}\, T + .325$
02	$C = 6.36 \times 10^{-11}\, T + .0018$	$C = 2.42 \times 10^{-10}\, T + .064$	$C = 1.2 \times 10^{-9}\, T + .325$
03	$C = 1.1 \times 10^{-11}\, T + .0022$	$C = 2.42 \times 10^{-10}\, T + .064$	$C = 1.2 \times 10^{-9}\, T + .325$
04	$C = 6.95 \times 10^{-11}\, T + .024$	$C = 8.9 \times 10^{-10}\, T + .22$	$C = 4.42 \times 10^{-9}\, T + 1.08$
05	$C = 1.48 \times 10^{-11}\, T + .0033$	$C = 2.42 \times 10^{-10}\, T + .064$	$C = 1.2 \times 10^{-9}\, T + .325$
06	$C = 9.35 \times 10^{-11}\, T + .0136$	$C = 1.56 \times 10^{-10}\, T + .068$	$C = 2.53 \times 10^{-10}\, T + .142$
07	$C = 8.18 \times 10^{-11}\, T + .02$	$C - 8.9 \times 10^{-10}\, T + .22$	$C = 4.42 \times 10^{-9}\, T + 1.08$
12	$C = 5.71 \times 10^{-12}\, T + .0008$	$C = 2.42 \times 10^{-10}\, T + .064$	$C = 1.2 \times 10^{-9}\, T + .325$

The results of tests with the Skylab I TMG boot sole (Sample 08) are summarized in Table 3. The purpose of this test was to determine the conductance through the sole portion and the heel portion of the astronaut's boot under extreme conditions of lunar daytime and lunar nighttime conditions. In addition to the heat flux per unit area, temperature measurements were made on the sample hot surface, cold surface, and at the interface between the boot sole material and the insulation liner that is placed between the astronaut's foot and the boot sole. Two compressive loads were simulated: no-load where the sample is under its own weight in the test apparatus and a compressive load of 10 psi which simulates the compressive load that an astronaut might put on the bottom of his feet while walking on the lunar surface. In all tests, the gas pressure surrounding the sample is ± 4 psi of dry nitrogen (the approximate pressure level within the space suit during lunar operation). Two nominal external conditions were simulated, a lunar daytime condition where the external surface was maintained at approximately 250°F and a lunar nighttime condition where the external temperature was maintained at approximately -200°F. The inside temperature was maintained in the range from about 75 - 87°F for the lunar daytime condition and between 52°F and 88°F for the lunar nighttime condition.

The results of the tests are summarized in Table 3. Under lunar daytime conditions, there is very little difference between the performance of the boot sole and the boot heel. In both parts of the boot, the heat flux per unit area is high (about 50 - 60 Btu/ft^2 hr) and the lunar temperature of the boot sole is high (only about 4 - 5°F below the temperature on the outside surface of the boot sole). This means that under steady-state conditions, the inner liner of the boot must provide the thermal protection while at the same time, the garment cooling system must be designed and sized to remove the high heat load.

Under lunar nighttime conditions, the astronaut will lose heat through his boot sole. Under these conditions, both for the no-load and the 10 psi compressive load, the inside temperature of the boot

TABLE 3. THERMAL PERFORMANCE OF SAMPLE 08 -- SKYLAB BOOT SOLE

Description: Boot Sole Center; 0.0410 lbs/sq in
Boot Heel and Sole; 0.132 lbs/sq in
Inner Soft Goods; 0.00787 lbs/sq in
Pressure for all test conditions = 4 ± 1 psia

	Load (psi)	t_w (°F)	t_c (°F)	$t_{interface}$ (°F)	q/A (Btu/sq ft hr)	C (Btu/sq ft hr °F)
Lunar Day						
Boot Sole Center and Soft Goods	no load	252	76.6	249	54.79	.312
	10	251	74.8	248	59.91	.342
Boot Heel and Sole and Soft Goods	no load	245	78.3	242	60.58	.363
	10	245	76.6	241	62.76	.373
Lunar Night						
Boot Sole Center and Soft Goods	no load	73.2	-209.2	-183	15.36	.0544
	10	88.0	-198	-143	38.58	.135
Boot Heel and Sole and Soft Goods	no load	51.8	-188.9	-138	27.60	.114
	10	64.4	-199.7	-114	44.46	.170

is again very low (-114°F to -183°F). The heat loss although lower, is still significant, and, again, the inner liner must provide the needed protection.

The results of the tests on the remaining six samples measured in the guarded hot-plate calorimeter are summarized in Table 4. Included in this table are a description of the samples, the gas pressure, the compressive load, the boundary temperature conditions, the sample thickness, and the conductances. (The layer sequence of each sample is summarized in Table 1.)

Sample 09, the Shuttle Orbital Rescue Enclosure Primary Structure, is a layup that will be used to make a closed pressurized sphere for emergency transport of personnel from one spacecraft to another. Sample 09 has five layers without radiation shields. Sample 11 is the same sample with an insulation consisting of six radiation shields and seven spacers. The conductance of Sample 11 with insulation is about 1/4 that of Sample 09 without insulation.

Sample 11 was also tested by the guarded cold-plate method (see Sample 12). The conductance of Sample 11 compares extremely well with the conductance of Sample 12 at no-load conditions for the two temperature ranges of concern in this program. Comparison was made by calculating the no-load conductance dependency from the two values of the temperature parameter T for Sample 11 as given in Table 3. From this equation the conductance at the values of T corresponding to nighttime and daytime conditions were calculated and compared with the values reported in Figures 6 and 7. This comparison is shown in the following table.

TABLE 4. SUMMARY OF SAMPLES TESTED IN THE HOT PLATE CALORIMETER

Sample Number	Description of Sample	Pressure (torr)	Load (psi)	t_w (°F)	t_c (°F)	x (in)	Conductance (Btu/ft^{2}hr°F)	Remarks
09	Shuttle Orbital Rescue	1×10^{-4}	none	78.8	-194	0.059	9.5×10^{-3}	
	Enclosure Primary Structure	1×10^{-4}	none	147	78.8	0.059	16.7×10^{-3}	
10	Balloon-Borne Ultraviolet	7.9	none	115	53.6	0.245	0.98	
	Stellar Spectrometer Insulation	2.2	none	-12	-36	0.245	0.0074	
11	Shuttle Orbital Rescue	5.9×10^{-5}	none	75.2	-193	0.165	2.5×10^{-3}	See Sample -12 for tests
	Enclosure Primary Structure	1.1×10^{-4}	none	145	77	0.165	4.3×10^{-3}	with Guarded Cold Plate
	With Insulation							$T = 2.87 \times 10^8 (°R^3)$
								$T = 7.47 \times 10^8 (°R^3)$
13	Shuttle TMG 7-layer	8.0×10^{-5}	none	84.2	-191	0.126	0.105	
	Development Layup	9.0×10^{-5}	none	149	80.6	0.126	0.204	
14	Shuttle TMG 9-layer	9.0×10^{-5}	none	86	-195	0.142	0.0313	
	Development Layup	9.0×10^{-5}	none	151	82.4	0.142	0.0504	
15	Shuttle Ejection Suit	760	none	275	122	0.094	2.52	
		760	none	221	106	0.094	2.45	
		33	none	257	117	0.094	2.22	
		33	none	77	-94	0.094	1.48	

COMPARISON OF CONDUCTANCE

FOR SAMPLES -11 and -12

	Sample -11	Sample -12
	Hot-Plate Method (Btu/ft^2 hr °F)	Cold-Plate Method (Btu/ft^2 hr °F)
Nighttime Conditions		
72 → -310°F		
$T = 2.08 \times 10^8$	0.0022	0.0020
Daytime Conditions		
72 → 250°F		
$T = 9.78 \times 10^8$	0.0052	0.0064

Samples 13 and 14 are two development thermal micrometeroid garments each with four net-reinforced aluminized mylar radiation shields for insulation. Each of the radiation shields has only one low emittance surface because the other surface is coated with the net reinforcing. Thus, the conductance of these insulations is considerably greater than comparable insulations with two-sided aluminized radiation shields and separate spacers.

Sample 15 is the complete layup of the flight suit that the astronauts will use in the Space Shuttle vehicle. The purpose of the tests of these samples was to determine the conductance under the extreme conditions that might exist during an aborted launch at altitudes below about 70,000 ft. During the ejection, the astronauts are expected to pass through the plume of the rocket motor that propels the vehicle. These conductance data were used for transient thermal analysis at NASA JSC.

3. TMG Garmet Heat-Flow Tests

The three samples of space suit thermal micrometeroid garments that were tested include the NASA A7LB assembly that had seven aluminized radiation shields, and the Skylab TMG. A description of these samples and the results of the tests are summarized in Table 5.

The test procedure was the same for all three samples. Each was tested in the space chamber for simulated lunar night and lunar day conditions both before and after being subjected to approximately 10,000 cycles of wear flexure. The following is a brief summary of the test procedure.

The first step in the test procedure was to measure the heat flow into the garment section prior to wear during simulated lunar daytime conditions. The TMG garment was fitted over the elbow calorimeter when it is in the extended position. Next, the hot baffle was placed over the insulation assembly. The test chamber was evacuated, checked for leaks and then the hot baffle temperature was adjusted until an equilibrium temperature of approximately 250°F was acheived. The chamber pressure was evacuated to a pressure of 10^{-4} torr. The heat flow into the calorimeter was measured during this simulated lunar daytime condition. At the conclusion of this test, the chamber was again opened, the hot baffle was removed and the chamber was again closed and evacuated. Lunar nighttime conditions were then simulated by cooling the shrouds in the chamber with liquid nitrogen. Heat flow under these conditions is outward from the calorimeter. After equilibrium heat flow is achieved, and measurements are completed, the elbow section was flexed for just over 10,000 cycles while the temperature of the chamber was maintained at that of liquid nitrogen. After flexure cycling, the performance of the garment section was again measured under lunar nighttime conditions. Upon completion of these tests the chamber was opened, the elbow section placed in the extended position, the hot baffle placed over the sample, the chamber closed and evacuated, and the performance was measured again for the lunar daytime condition.

TABLE 5. THERMAL PERFORMANCE OF ELBOW SECTIONS

OF THERMAL MICROMETEROID GARMENTS

	t_w (°F)	t_c (°F)	HEAT FLUX PER UNIT AREA q (Btu/sq ft hr)	CONDUCTANCE C (Btu/sq ft °F)
A7LB with 7 radiation shields				
Lunar Night -- before flexure	70.5	-320	3.98	0.010
-- after 10,000 cycles of flexure	70.2	-320	3.94	0.010
Lunar Day -- before flexure	245	71.1	4.57	0.026
-- after 10,000 cycles of flexure	251	73.3	4.75	0.027
Skylab TMG with 3 radiation shields				
Lunar Night -- before flexure	73.5	-320	7.4	0.019
-- after 10,000 cycles of flexure	72.9	-320	7.7	0.020
Lunar Day -- before flexure	251	73.6	9.8	0.055
-- after 10,000 cycles of flexure	247	71.6	9.1	0.052
A7LB with non-aluminized radiation shields				
Lunar Night -- before flexure	72.8	-320	11.1	0.028
-- after 10,000 cycles of flexure	74.2	-320	11.0	0.028
During flexure	72.8	-320	10.7	0.027
Lunar Day -- before flexure	250	74.3	10.1	0.058
-- after 10,000 cycles of flexure	250	74.2	10.3	0.059

Temperatures were measured every 10 min. after equilibrium had been reached, and the heat fluxes measured every hour. Equilibrium measurements were made for a period of at least 5 hr. at each test condition. For all tests, the equilibrium heat flux either into or out of the elbow calorimeter varied less than $\pm 2\%$ from the average.

As indicated by the results in Table 5, none of the insulation in the garment sections was significantly affected by 10,000 cycles of fluxural wear. The small increases or decreases in heat flux per unit area after wear for a given sample are not believed to be significant. Differences among samples are believed to be significant, however. The A7LB garment with seven aluminized radiation shields had the lowest heat flux per unit area for both lunar nighttime and lunar daytime conditions. The Skylab TMG section had only three radiation shields and the heat flux is higher by a factor of two over that for the A7LB garment.

Comparison of the A7LB garment performance for nonaluminized radiation shields with the same garment and aluminized radiation shields indicates that aluminized radiation shields definitely decrease the amount of heat flow into or out of the insulation during lunar daytime conditions and during lunar nighttime conditions respectively. The heat flux for both lunar night and lunar day are decreased by more than a factor of two by the inclusion of aluminized radiation shields. From these results, we conclude that minimum heat flux insulations must have several low-emittance radiation shields.

4. Results of Surface Property Measurements

As part of a NASA-sponsored round-robin evaluation of silver-backed Teflon materials, the total hemispherical emittance and the zero air mass solar absorbtance were measured in two numbered samples and one non-numbered sample. (The test techniques and the calculation procedure used in this evaluation have been summarized in Section B-5). The results of these tests are summarized in Table 6.

TABLE 6. PROPERTIES OF SILVER FEP TEFLON

Sample Description	Solar Absorptance (α_S), Zero Air Mass	Total Hemispherical Emittance (ε)
Non-numbered sample	.068	0.78
JSC Round-robin 1887-3	.060	0.75
JSC Round-robin 1895-3	.062	0.78

REFERENCES

1. Arthur D. Little, Inc., "Basic Investigation of Multilayer Insulation Systems," Report No. NASA Cr-54191, Contract NAS3-4181, October 1974.

2. Arthur D. Little, Inc., "Advanced Studies on Multilayer Insulation Systems," Report No. NAS Cr-54929, Contract NAS3-6283, June 1966.

3. D. L. Richardson, "Development of an Improved Extravehicular Space Suit Thermal Insulation," NASA Contract NAS9-7519, September 1969.

4. Matthew P. Thekaekara, "Data on Incident Solar Energy", The Energy Crisis and Energy from the Sun, Institute of Environmental Sciences, p. 21-49, November 1974.

5. D. L. Richardson, "Supplement Report, Thermal Conductance of Space Suit Thermal Insulations", NASA Contract NAS 9-7519, January 1970.

APPENDIX

A. CONDUCTANCE OF SPACE SUIT INSULATION

The data for all thermal conductance tests made by the guarded cold-plate method are summarized in Tables A1 - A8. The data include a description of the insulation; the measured quantities were: compressive load (psi), the outside temperature of the insulation (the cold-plate and hot-plate temperatures in the conductance apparatus, °F), the inside temperature of the insulation (the midplane temperature, °F), the heat flux through the insulation (Btu/sq ft hr), the sample thickness (inches), and the sample midplane weights (grams); and the derived quantities were: temperature difference across each of the two samples measured (°F), and the sample conductance (Btu/sq ft hr°F).

B. CONDUCTANCE DATA INTERPOLATIONS

The conductance was not measured at the exact boundary conditions required in the program--lunar daytime conditions (the outside temperature of the space suit at 250°F and the inside at 72°F) and lunar nighttime conditions (the outside of the space suit at -310°F and the inside at 72°F)--instead, all conductance measurements for the cold-plate temperature were made at the boiling point of liquid nitrogen (-320°F) and for the warm-plate temperature at 200°F and 300°F.

The use of a midplane temperature measurement between two identical samples of the space suit insulation allowed simultaneous measurement of the conductance of two samples of space suit insulation for each heat flux measurement. In most instances, the midplane temperature was higher than the 72°F required for the inside boundary condition of the space suit; therefore, interpolations of the basic data were required in order to determine the insulation conductance for the two conditions.

In the interpolation procedure, the heat flux through the insulation was assumed to be comprised of two components, solid conduction and radiation, as given by Equation A-1.

$$Q = \frac{k}{x} A(T_1 - T_2) + \frac{A\sigma}{n(\frac{2}{\varepsilon} - 1)} (T_1^4 - T_2^4) \qquad \text{(A-1)}$$

Introducing the definition of conductance

$$C = \frac{Q}{A(T_1 - T_2)} \qquad \text{(A-2)}$$

and rearranging Equation A-1

$$C = \frac{k}{x} + \frac{\sigma}{n(\frac{2}{\varepsilon} - 1)} \frac{T_1^4 - T_2^4}{T_1 - T_2} \qquad \text{(A-3)}$$

At a given compressive load on the insulation. the solid conductance $(\frac{k}{x})$ and the shield emittance (ε) are assumed to be independent of the temperature difference across the insulation. Thus from Equation A-3 the insulation conductance is linearly dependent on the parameter

$$\text{(A-4)} = \frac{T_2^4 - T_2^4}{T_1 - T_2}$$

The measured conductance at each sample pressure loading was plotted as a function of this parameter and values of the conductance at the desired temperature differences (300 to 70°F and 70 to -250°F) were obtained by straight-line interpolation.

TABLE A-1

Sample No. 01 A7LB Insulation

Description: (1) T-162 Teflon fabric, 4484 Teflon coated fiberglass fabric (1), two-sided aluminized Kapton and Kapton tape grid (2), Beta marquisette alternating (3), one-side aluminized perforated mylar shields (5), Dacron batt spacers (5), ripstop (bladder cloth (1)).

Sample weight: Top 74.7 grams, midplane 9.6 grams
Bottom 74.3 grams

Compressive Load psi	Temperature Outside °F	Temperature Inside °F	ΔT °F	Heat Flux (Btu/hr-ft^2)	Conductance Btu/hr-ft^2°F	Sample Thickness (In)	T (°R3 x 10^8)
1.908-3.59 x 10^{-3}	201	75.5	125.5	2.068	.01647	.186	8.677
.845-1.69 x 10^{-3}	-320	75.5	395.5	2.068	.00522	.186	2.063
1.908-3.59 x 10^{-3}	314	192.0	122	3.144	.02577	.186	14.606
.845-1.69 x 10^{-3}	-320	192.0	512	3.144	.00614	.186	3.521
.03	200	67.0	133	3.684	.02769	.1315	8.466
.03	-320	67.0	387	3.684	.00951	.1315	1.982
.03	307	156.5	150.5	5.297	.0352	.1315	13.422
.03	-320	156.5	476.5	5.297	.0111	.1315	3.014
.1	209	56.3	152.7	6.44	.04217	.1075	8.474
.1	-320	56.3	376.3	6.44	.0171	.1075	1.8725
.1	289	134.1	154.9	10.07	.0650	.108	12.2868
.1	-320	134.1	454.1	10.07	.02217	.108	2.739
1.0	200.4	-8.0	208.4	34.73	.1666	.065	7.106
1.0	-320	-8.0	312	34.73	.1113	.065	1.3237
1.0	299.5	77.3	222.2	48.936	.2202	.0705	11.269
1.0	-320	77.3	397.3	48.936	.12317	.0705	2.084
1.0	199.7	68.3	131.4	54.269	.4130	.046	8.523
2.0	-320	68.3	388.3	54.269	.1397	.046	1.99
2.0	299.4	147	152.4	148.84	.9766	.0678	12.979
2.0	-320	147	467	148,84	.3187	.0678	2.899
10.0	199.7	66.74	133	180.668	1.3584	.05815	8.504
10.0	-320	66.74	386.7	180.668	.4672	.05818	1.970
10.0	306.4	90.7	215.7	355.504	1.648	.05715	11.692
10.0	-320	90.7	410.7	355.504	.86559	.05715	2.3227

TABLE A-2

Sample No. 02 A7LB Layup with nonaluminized radiation shield

Description: (1) T-162 Teflon fabric, 4484 Teflon coated fiberglass fabric (1), nonaluminized Kapton with Kapton tape grid (2), Beta marquisette alternating (3), perforated nonaluminized mylar shields (5), Dacron batt spacers (5), ripstop (bladder cloth) (1).

Sample weight: Top 74.6g, midplane 10.0g, bottom 74.4g

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	ΔT (°F)	Heat Flux (Btu/hr-ft)	Conductance (Btu/hr-ft^2°F)	Sample Thickness (in)	T (°R^3 x 10^8)
1.9 to 3.6×10^{-3}	195.5	76.1	119.4	7.073	0.592	.187	8.55
.845 to 1.69×10^{-3}	-320	76.1	396.1	7.073	0.178	.187	2.07
1.9 to 3.6×10^{-3}	296.4	174.5	121.9	11.25	0.923	.186	13.54
.845 to 1.69×10^{-3}	-320	174.5	394.5	11.25	0.285	.186	4.10
.03	196.6	57.7	138.9	12.61	0.908	.116	8.21
.03	-320	57.7	377.7	12.61	.0334	.116	1.89
.03	300.0	147.4	152.6	22.25	.146	.112	12.95
.03	-320	147.4	467.4	22.25	.0476	.112	2.90
.1	313	166.9	146.1	32.1	.2195	.098	13.85
.1	-320	166.9	486.9	32.1	.0659	.098	3.16
.1	209.7	80.9	128.8	18.95	.1472	.095	8.98
.1	-320	80.9	400.9	18.95	.0473	.095	2.12
1.0	203.9	60.5	143.4	44.78	.312	.078	8.45
1.0	-320	60.5	380.5	44.78	.1177	.078	1.92
1.0	295.5	145.7	149.8	90.05	.600	.076	12.72
1.0	-320	145.7	465.7	90.05	.193	.076	2.88
2.0	210.5	57.2	153.3	70.5	.460	.0705	8.48
2.0	-320	57.2	377.2	70.5	.187	.0705	1.885
2.0	324.3	145.7	178.6	122.3	.685	.071	13.6
2.0	-320	145.7	465.7	122.3	.262	.071	2.88
10.0	209.5	33.9	175.6	178.3	1.016	.0615	8.03
10.0	-320	33.9	353.9	178.3	.504	.0615	2.00
10.0	311.6	122.2	189.4	319.3	1.685	.063	12.6
10.0	-320	122.2	442.2	319.3	0.724	.063	2.59

TABLE A-3

Sample No. 03 [Retest of Sample MSC-15 (10-Layer)]

Description: (1) 4484 Beta fiberglass, (1) super Beta fiberglass, (2) Schjeldahl X-993, (8) perforated Mylar, aluminized both sides, (8) Dacron batt spacers, and (1) neoprene-coated rip-stop nylon

Weight: Top 85.7 g, Midplane 10.0 g, Bottom 86.1 g

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	Temperature ΔT (°F)	Heat Flux (Btu/hr ft^2)	Conductance (Btu/hr-ft^2°F)	Sample Thickness (in)	T (°R^3 x 10^3)
2.159-4.07x10^{-3}	204.4	59.4	145.0	1.88	.0129	.157	8.40
.96-1.92x10^{-3}	-320	59.4	379.4	1.88	.00495	.157	1.903
2.159-4.07x10^{-3}	307.4	149.1	158.3	2.42	.0153	.156	13.18
.96-1.92x10^{-3}	-320	149.1	469.1	2.42	.00515	.156	2.92
.03	204.7	42.0	162.7	3.57	.0219	.105	8.11
.03	-320	42.0	362	3.57	.0099	.105	1.743
.03	301.4	122.9	178.5	4.92	.0275	.105	12.32
.03	-320	122.9	442.9	4.92	.0111	.105	2.60
.1	201.9	33.0	168.9	5.99	.0355	.087	7.86
.1	-320	33.0	353	5.99	.0169	.087	1.66
.1	301.2	120.0	181.2	9.39	.0518	.089	12.26
.1	-320	120.0	440	9.39	.0213	.089	2.56
1.0	203.7	4.1	199.6	65.5	.328	.070	7.41
1.0	-320	4.1	324.1	65.5	.202	.070	1.42
1.0	304.6	107.7	196.9	141	.715	.070	12.1
1.0	-320	107.7	427.7	141	.329	.070	2.42
2.0	211.2	21.0	190.2	104	.545	.064	7.85
2.0	-320	21.0	341	104	.304	.064	1.56
2.0	308.3	99.2	209.1	203	.970	.064	11.97
2.0	-320	99.2	419.2	203	.484	.064	2.32
10.0	202.2	19.0	183.2	227	1.24	.059	7.62
10.0	-320	19.0	439	227	.518	.059	1.189
10.0	306.3	90.9	215.4	309	1.43	.059	11.70
10.0	-320	90.9	410.9	309	.752	.059	2.23

TABLE A-4

Sample -04 -- Three-layer non-aluminized

Description: (2) 4484 Beta fiberglass
(3) perforated Mylar shields non-aluminized
(4) Dacron batt spacers
(1) neoprene-coated rip stop nylon

Sample weight: Top 49.3 g, midplane 9.9g, bottom 48.8 g

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	Temperature ΔT (°F)	Heat Flux (Btu/hr ft^2)	Conductance (Btu/hr-ft^2°F)	Sample Thickness (in)	T (°R^{3}x10^3)
$1.33\text{-}2.45 \times 10^{-3}$	204	38	166	12.13	.073	.128	8.01
$.558\text{-}1.12 \times 10^{-3}$	-320	38	358	12.13	.034	.128	1.71
$1.33\text{-}2.45 \times 10^{-3}$	306.7	128	178.7	22.07	.124	.1235	12.68
$.558\text{-}1.12 \times 10^{-3}$	-320	128	448	22.07	.049	.1235	2.66
.03	199	58	141	21.13	.128	.0635	8.27
.03	-320	58	378	21.13	.056	.0635	1.89
.03	304.7	140	164.7	36.44	.260	.0675	12.92
.03	-320	140	460	36.44	.079	.0675	2.81
.1	199.5	62.3	137.2	24.69	.180	.059	8.33
.1	-320	62.3	382.3	24.69	.065	.059	1.93
.1	299.4	146	153.4	45.21	.295	.061	12.96
.1	-320	146	466	45.21	.097	.061	2.85
1.0	200.4	44	156.4	119.7	.765	.041	8.00
1.0	-320	44	364	119.7	.329	.041	1.76
1.0	303	114	189	155.24	.821	.042	12.49
1.0	-320	114	434	155.24	.358	.042	2.49
2.0	203.2	41.1	162.1	193.5	1.008	.038	7.94
2.0	-320	41.1	361.1	193.5	.536	.038	1.78
2.0	305	119	186	360.6	1.938	.0395	12.37
2.0	-320	119	439	360.6	.821	.0395	2.55

TABLE A-5

Sample No. -05 (PGA Boot Top Layup)

Description: (1) Teflon fabric, (1) Beta fiberglass fabric, (3) two-sided aluminized Kapton and Kapton tape grid alternating with (2) sized Beta marquisette spacers, (1) rip-stop bladder fabric, (1) blue nylon twill, (1) neoprene coated nylon twill, (1) blue nylon fabric.

Weight: Top 104.7 gm; Midplane 10.1 gm; Bottom 105.1 gm

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	ΔT (°F)	Heat Flux (Btu/hr ft^2)	Conductance (Btu/hr ft^2)	Sample Thickness (in)	T (°R^{3}x10^8)
1.12 to 2.23x10^{-3}	-320	71	491	2.19	.00559	.327	1.61x10^{-8}
2.44 to 4.66x10^{-3}	202.6	71	131.6	2.19	.0166	.327	8.61
1.12 to 2.23x10^{-3}	-320	161	581.2	3.33	.00691	.318	2.55
2.44 to 4.66x10^{-3}	308	161	146.8	3.33	.0227	.318	13.57
.03	-320	75.6	395.6	3.56	.009	.216	2.07
.03	202.5	75.6	126.9	3.56	.026	.216	8.69
.03	-320	186	504	5.63	.011	.216	3.44
.03	306.2	186	120.2	5.63	.0471	.216	14.2
.1	-320	86	406	6.86	.0169	.172	2.18
.1	206	86	120	6.86	.0580	.172	8.98
.1	-320	158	478	9.73	.0204	.172	3.04
.1	307.1	158	148.9	9.73	.0653	.172	13.5
1.0	-320	91.2	411.2	37.7	.0917	.109	2.24
1.0	205	91.2	113.8	37.7	.331	.109	9.09
1.0	-320	182	502	81.7	.163	.104	3.38
1.0	312	182	130	81.7	.629	.104	14.2
2.0	-320	94.3	414.3	87.2	.211	.098	2.26
2.0	204	94.3	109.7	87.2	.795	.098	9.13
2.0	-320	172	492.1	109.	.222	.096	3.23
2.0	306.2	172	134.1	109.	.813	.096	15.31
10.0	-320	85	405	190.	.452	.083	2.02
10.0	201	85	116	190.	1.56	.083	9.38
10.0	-320	105	485	307.	.633	.083	3.14
10.0	302	105	137	307	2.24	.083	14.0

TABLE A-6

SAMPLE -06 HITCO 8-PCF Felt in A7LB

Description:
(1) T-162 Teflon fabric
(1) 4484 Teflon-Coated fibreglass fabric
(1) .125 in. HITCO 8-PCF felt
(1) rip-stop bladder cloth

Sample Weight: Top: 77.4 gm Midplane: 9.9 gm Bottom: 77.9 gm

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	ΔT (°F)	Heat Flux (Btu/hr-ft^2)	Conductance (Btu/hrft^2°F)	Sample Thickness (in)	T (°R^{3}x10^8)
1.85×10^{-3} to 3.50×10^{-3}	208	78.3	129.7	13.399	.103	.297	8.89
0.821×10^{-3} to 1.64×10^{-3}	-320	78.3	398.3		.0336	.297	2.09
1.85×10^{-3} to 3.50×10^{-3}	312	167.0	145.0	20.26	.1397	.299	13.83
0.821×10^{-3} to 1.64×10^{-3}	-320	167.0	487.0		.0416	.299	3.17
.03	207	80.5	126.5	15.41	.122	.258	8.92
	-320	80.5	400.5		.038	.258	2.11
.03	313.5	165.5	148	24.85	.168	.258	13.78
	-320	165.5	485.5		.0512	.258	3.15
.10	209.0	83.0	126.0	18.20	.144	.237	9.00
	-320.	83.0	403.0		.045	.237	2.15
.10	313.6	156.5	157.1	28.09	.175	.242	13.65
	-320.	156.15	476.5		.0589	.242	13.02
1.0	208	61.6	146.4	35.18	.240	.218	8.55
	-320	61.6	381.6		.092	.218	1.92
1.0	312.6	125.3	187.3	45.97	.245	.216	12.77
	-320	125.3	445.3		.103	.216	2.62
2.0	208.2	55.8	152.4	32.25	.212	.203	8.41
	-320	55.8	375.8		.085	.203	1.88
2.0	312.2	111.2	201.0	58.84	.293	.201	12.38
	-320	111.2	431.2		.136	.201	2.46
10.0	208.5	38.8	169.7	58.10	.342	.180	8.12
	-320	38.8	358.8		.162	.180	1.71
10.0	316.1	103.5	212.6	80.91	.381	.182	12.31
	-320	103.5	423.5		.226	.182	2.37

TABLE A-7

Sample -07 — A7LB Feedthrough Area

Description: Standard A7LB Lay-up where all layers have been cemented together

Sample Weight: Top: 133.2 gm., Midplane: 7.5 gm., Bottom: 135.4 gm.

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	ΔT (°F)	Heat Flux (Btu/hr ft^2)	Conductance (Btu/hr·ft^2°F)	Sample Thickness (in)	T ($°R^3 x 10^8$)
1.41 to $2.83x10^{-3}$	-320	71	391	13.5	.035	.123	2.02
2.98 to $5.64x10^{-3}$	211	71	140		.096		8.80
1.41 to $2.83x10^{-3}$	-320	144	464	21	.045	.123	2.86
2.98 to $5.64x10^{-3}$	310	144	166		.127		13.16
.1	-320	48	368	20	.053	.081	1.80
	209	48	159		.122		8.41
.1	-320	134	454	48	.090	.081	2.73
	315	134	181		.265		11.07
1.0	-320	54.3	374.3	94	.250	.067	1.86
	205.7	54.3	151.4		.618		8.35
1.0	-320	124	444	274	.614	.067	2.61
	301.3	124	177.3		1.58		12.39
2.0	-320	54	374	154	.411	.061	1.86
	205.7	54	151.7		1.02		8.35
2.0	-320	116.4	436.4	475	1.09	.063	2.52
	298.3	116.4	181.9		2.61		12.11
10.0	-320	55.1	375.1	483	1.27	.061	1.87
	201.9	55.1	146.8		3.29		8.28
10.0	-320	69.1	389.1	791	2.03	.057	2.00
	226	69.1	156.9		5.4		9.12

TABLE A-8

Sample -11 — Shuttle Orbital Rescue Enclosure Primary Structure with Insulation

Description:
Inside
White Nylon rip-stop 1.2 oz.
Rip-stop bladder
Blue Nylon twill 7 oz.
Yellow micrometeroid shield Kevlar-49
Alternative layers of non-woven Dacron batt (7) and double aluminized quarter mil Mylar radiation shields (6)
Nomex
Outside

Weight: Top 66.5 gm; Midplane 11.1 gm; Bottom 66.8 gm

Compressive Load (psi)	Temperature Outside (°F)	Temperature Inside (°F)	ΔT (°F)	Heat Flux (Btu/hr ft^2)	Conductance (Btu/hr ft^2 °F)	Sample Thickness (in)	T (°R^3 x 10^8)
0.71 to 1.42 x 10^{-3}	-320	75.3	395	0.67	0.00169	0.13	2.07
1.65 to 3.06 x 10^{-3}	205	75.3	129.7	0.67	0.00517	0.13	8.75
0.71 to 1.42 x 10^{-3}	-320	168	488	1.49	0.00305	0.13	3.18
1.65 to 3.06 x 10^{-3}	301	168	133	1.49	0.0112	0.13	13.54
0.1	-320	80.8	400.8	8.71	0.0217	0.096	2.13
0.1	203	80.8	122.2	8.71	0.0712	0.096	8.81
0.1	-320	184	504	12.4	0.0246	0.091	3.41
0.1	300	184	116	12.4	0.107	0.091	13.93
1.0	-320	30.2	350.2	37.4	0.107	0.068	1.64
1.0	199	30.2	169.2	37.4	0.221	0.068	7.73
1.0	-320	140	460	78.0	0.169	0.066	2.81
1.0	291	140	151	78.0	0.516	0.066	12.48
2.0	-320	51.9	371.9	59.7	0.160	0.063	1.84
2.0	197	51.9	145.1	59.7	0.412	0.063	8.11
2.0	-320	135	455	86.4	0.190	0.065	2.75
2.0	290	135	155	86.4	0.557	0.065	12.33
10.0	-320	-0.5	320.5	140	0.436	0.055	1.38
10.0	189	-0.5	189.5	140	0.737	0.055	7.01
10.0	-320	72	392	210	0.536	0.054	2.04
10.0	279	72	207	210	1.01	0.054	10.54