INSULATION DEVELOPMENT FOR HIGH-TEMPERATURE
BATTERIES FOR ELECTRIC VEHICLE APPLICATION

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FOREWARD

This report describes the work conducted by Union Carbide Corporation - Linde Division for DOE - Division of Energy Storage Systems on "Insulation Development for High-Temperature Battery for Electric Vehicle Application", Contract No. EM-78-C-01-5160. The DOE Technical Project Monitor is Mr. Rufus Shivers. The report covers the period from October 1, 1978 to November 30, 1979.

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I. INTRODUCTION

1.1 Program Objective and Scope

The overall objective of the program is to develop a high-performance, load-bearing, thermal insulation and a suitable vacuum enclosure to minimize the heat loss, weight, volume and cost of the battery housing for the Li/MS or Na/S high-temperature (600 - 850°F) battery system for use in an electric vehicle application. The need for a high-performance enclosure for the Li/MS and Na/S batteries is well-established, but current insulations could not meet all the goals. A program has been started to develop a load-bearing insulation, design a rectangular enclosure to utilize the insulation, fabricate and test prototype enclosures, and develop manufacturing techniques required to mass-produce large numbers of vacuum-insulated enclosures.

The first phase of the program (1978 - 1979) covered in this report, deals with the development and testing of load-bearing insulation system concepts. The 1980 program will optimize and specify the most-suitable insulation for the EV application; and design, fabricate and test the first module rectangular enclosure, and estimate the manufacturing cost of both the insulation and enclosure.

The program is structured to provide an orderly development of the various components of the system; i.e., insulation, enclosure, vacuum maintenance, manufacturing, enclosure vehicle and battery interface. The results of the development program will be an insulated battery enclosure which can be produced reliably and meet the design goal of weight, life, volume and heat loss at a reasonable cost, (<\$10/KWH).

1.2 Background

The intended automotive application demands a battery system with very high energy density. Li/MS and Na/S type batteries offer the potential of the highest energy density (525 W-Hr/lb) of the various battery systems being currently investigated. Their energy density is 3-4 times better than that of lead-acid type and about twice as good as that of nickel-zinc type. The ultimate design goal of 50 KWH Li/MS battery system is a lightweight system, 1,000 lbs., which is also compact, 10 ft³. These potentially lightweight battery systems, however, operate at elevated temperatures in the range of 600 - 850°F and therefore do not

afford the convenience of ambient temperature operation as in the case of nickel-zinc and lead-acid type batteries. Suitable insulation is required to keep the thermal losses at a reasonably low value. Compact (~1") non-vacuum insulation would result in intolerable thermal loss (~\$500/yr @ 3¢/KWH power), while a thick (10") non-vacuum insulation would result in high-space penalty. The need for high-performance vacuum insulation is therefore apparent.

Vacuum insulation implies "leak-tight" insulation jacket capable of withstanding the atmospheric load of 15 psi or roughly a ton per square foot. One obvious solution is to use thick metal casing with attendant thermal and weight penalty. However, if a suitable insulation was developed which can take the atmospheric load as well as the external "g" load, both inner and outer metal casings will be relieved of the high structural requirements, and their weight will be greatly reduced. Such a structural insulation, henceforth called "load-bearing insulation" will allow construction of more compact rectangular enclosures. Overall strategy of the Linde, UCC program is to reduce the overall weight and volume of the vacuum enclosure system by developing load-bearing high-temperature insulation board. Development of lightweight insulation board with a low thermal conductivity and yet possessing low compression under atmospheric load is the objective for this program. The specific goals set for this load-bearing insulation boards are: conductivity $\sim 140 \times 10^{-5}$ BTU/Hr-Ft⁰F, density ~ 18 pcf and compression under 15 psi load, $\sim 10\%$. It should be noted that the above goal reflects an improvement by a factor of 6 in thermal performance over the state-of-the-art commercial insulation board, JM Min-K 2000, Table I.

1.3 Summary

During the first year's program, three promising insulation concepts were demonstrated. Two of the systems have exceeded the goals of the program in every respect, while the third system may prove practical in some limited applications or in conjunction with either of the other two systems, Table I.

The goals set for the load-bearing insulation are: thermal conductivity, $k = 140 \times 10^{-5}$ BTU/Hr-Ft⁰F*; density = 18 lbs/ft³ and compression between

*The units of all thermal conductivities used in this report will be 10^{-5} BTU/Hr-Ft⁰F. Therefore, a thermal conductivity of $k = 200 \times 10^{-5}$ BTU/Hr-Ft⁰F will be written simply as $k = 200$, and the units and exponent will be assumed.

0 and 15 psi load = 10%. Using an insulation of the above characteristics, a 50 KW-Hr enclosure with outside dimensions of 11" x 13" x 113" would have a weight of 81 lbs. and a heat loss of 140 watts. Compactness, low weight, reliability and reasonable heat loss are the incentives in pursuing the load-bearing insulation concepts.

The three load-bearing insulation concepts utilize aluminum foil as radiation shields and a thin spacer material made of glass fibers. The differences lie in the internal construction concepts dealing with how the load, 15 psi, is transmitted through the insulation to the walls.

The best thermal performance was obtained using a spacer material of varying thicknesses called an "integral discreet load-carrying area spacer" (IDLAS), Figure 1. In this case, the thick areas (~6.6%) of the spacer material were aligned through the insulation thickness to carry the load. The remaining area (~93.4%) of the insulation did not carry any load and remained uncompressed, Figures 1 and 2. The insulation performance parameters are $k = 95$, density = 15 pcf and compression = 21%, Table I. The IDLAS could lead to a low-cost insulation since the spacer could be made in a continuous paper-making process at high speeds.

The second approach is to use the standard uniform thickness spacer and aluminum foil (multifoil insulation) and remove the insulation in a regular array of holes amounting to ~8% of the total area. Load-carrying pegs are then placed in the holes made in the multilayer insulation, Figure 3. In this system, the lower the conductivity of the peg material, the better the performance of the system for a constant peg area. The performance parameters for the pegged multifoil are $k = 101$, density = 11 pcf and compression = 7%, Table I. The pegged multifoil is considered more expensive than the IDLAS system since cutting the holes and the pegs, and placing the pegs into the holes are all additional operations.

The third system consists of multifoil insulation which has been compressed and heated to form a board. The millions of glass fibers per square foot in contact with the enclosure walls form a continuous support for the walls. This

insulation will lend itself to very thin enclosure walls since the walls are continuously supported as opposed to the discreetly supported peg and IDLAS systems. Also, the processed multifoil is easily handled being the strongest board of the three systems. The best performance parameters achieved using this type of board insulation are $k = 147$, density = 25 lbs/ft and compression = 44%. For the design compression goal of 10%, the conductivity was $k = 224$ and density was 22 pcf, Table I.

As a point of comparison, the thermal performance parameters of Johns-Manville⁽¹⁾ Min-K 2000 and Microtherm⁽²⁾ 20 CR are presented in Table I⁽³⁾. These materials represent the best state-of-the-art commercially available microporous-type insulations which are load-bearing. It should be noted that their thermal conductivities are a factor of 9 higher than the newly-developed load-bearing insulations.

The approach taken in developing the load-bearing insulation was based on the analysis of insulation systems and our "hands-on" experience gained from past development of the load-bearing insulation systems.

Two unique test apparatuses were constructed to measure the thermal conductivity, Figure 4, and to study the creep of the insulation systems while at 840°F under load and being subjected to vibration and a simulated battery load, Figure 5. Two insulation calorimeters were built to facilitate insulation sample evaluations. Each sample requires approximately one week to complete the thermal conductivity testing.

The original proposal contained a "rectangular enclosure design task" in which a rectangular enclosure would be designed incorporating the insulation under development. This task was postponed due to budget limitation and will be taken-up in the beginning of the follow-on program.

1.4 Conclusions and Recommendations

A new milestone in high-temperature, load-bearing, preformed insulation has been achieved in this program with demonstration of thermal performance which is nine times better than the best commercially available load-bearing insulation. The conclusions which can be reached at the end of the first 14 months of the

program to develop thermal insulation for use in a rectangular high-temperature battery enclosure are as follows:

1. The program was successful in meeting and exceeding the insulation performance goals.
2. New insulation concepts were demonstrated which look promising:

	$k(x 10^{-5} \text{ Btu/Hr-Ft}^{\circ}\text{F})$	$\rho(\text{lb/ft}^3)$
Peg-Supported Multifoil	100	11
IDLAS Multifoil	95	15
Uniform Glass Mat	225	22

3. The above insulations developed do not require submicron vacuum pressure. They will operate in the range of 1 - 100 μ depending on the type selected.
4. The concept of using load-bearing insulation as a structural support for the flat walls of a rectangular enclosure looks feasible. Although prototype enclosures have not been fabricated to-date, the above three insulations which could be used in the enclosures have been demonstrated.
5. Standard commercial glass fibers, either type 475 or E glass, will withstand the temperature 850 $^{\circ}$ F without excessive creep.

Based on the encouraging results of the first year's program, we recommend a follow-on program to establish the commercial feasibility of the most attractive insulation developed, estimate the insulation and enclosure costs and demonstrate a rectangular enclosure.

2.0 THERMAL CONDUCTIVITY PARAMETERS

This section will give a qualitative overview of the important parameters involved in characterizing a vacuum insulation and how the parameters could be minimized to yield a low thermal conductivity load-bearing insulation. A detailed analytical discussion is not presented since it has been given in numerous other sources and has only limited success in dense fibrous systems.

The heat transfer through an insulation consists of three independent components: gas conduction, solid conduction and radiation.

$$Q_{\text{insulation}} = Q_{\text{gas}} + Q_{\text{solid}} + Q_{\text{radiation}}$$

Each of the components have their own associated parameters which describe the heat transfer through that component.

Gas conduction through the insulation at low pressures is proportional to the pressure and the average insulation pore size. Depending on the insulation system under test, our tests were conducted in the 1 to 10 μ Hg pressure range in which gas conduction contributes very little ($\sim 1\%$) to the overall heat flux. The effect of increasing pressure on heat flux will depend on the insulation pore size and will be different for each of the insulations depending on their fiber diameter, density, etc. A compressed super-insulation (S.I.) or compressed fiber system would be much less sensitive to increasing gas pressures than a non-compressed S.I. or a pegged S.I. system, Figure 6. This is a result of the small interfiber spacing which results from the density difference of the compressed system, 20 pcf, compared to the non-compressed S.I., 11 pcf. The gas pressure sensitivity of the insulation system is important in the design of the vacuum maintenance system so that the enclosure performance is within some heat loss spec over its life. An insulation system which is very sensitive to gas pressure requires low design vacuum pressure and is more expensive to produce due to tighter specifications on the allowable air leak. In our case, the compressed multifoil and all-glass board insulation would operate in the range up to 100 μ Hg vacuum level while the pegged multifoil and IDLAS would require vacuum level in the range of 1 μ .

Solid conduction through a fibrous insulation system is difficult to model due to the random nature of the fiber matrix perpendicular to the heat flow and also accounting for the fibers which are not perpendicular to the heat flow. Various models have been proposed in the past which have led to logarithmic, square or linear dependence of the solid conduction component to the ratio of the interfiber contact radius to the fiber radius. In this study, the solid conduction component was determined empirically from the slope of the thermal conductivity vs. temperature curve which was measured experimentally. The temperature dependence of bulk material thermal conductivity is assumed to follow that of silica (SiO_2) which is $T^{1/2}$.

Radiation contribution is well understood from a theoretical standpoint based on a two-flux model for a fibrous or a multifoil system. The analysis when extended to a high density fibrous system in which the fiber spacings are on the same order

as the wave length of the light starts to breakdown but can still be used as a guide. The radiation heat flux will increase as the absolute temperature raised to the fourth power. The radiation component was determined from the experimental data from the slope of the measured thermal conductivity vs. temperature curve. The radiation heat transfer can be reduced through the use of low emissivity metal foils which reduce radiation through low absorption and reradiation in an insulation system. Radiation transfer can also be reduced through enhancement of radiation scattering by the fibers in the insulation system through selection of an optimum fiber diameter and fiber material.

The insulation model to which the experimental data was curve-fitted is:

$$k_a = A \frac{T_H^{3/2} - T_C^{3/2}}{T_H - T_C} + B \frac{T_H^4 - T_C^4}{T_H - T_C}$$

k_a = apparent thermal conductivity between the hot and cold temperatures, T_H and T_C - Btu/Hr-Ft⁰R.

T_H = hot side temperature - ⁰R.

T_C = cold side temperature - ⁰R.

A = solid conduction parameter - Btu/Hr-Ft⁰R^{3/2}.

B = radiation conduction parameter - Btu/Hr-Ft⁰R⁴.

The parameters A and B determine the relative importance of the solid conduction and radiation component respectively to the total conductivity. By reducing the data in this manner, one can determine relative contributions of solid conduction and radiation components of the conductivity, how various attempts to improve the performance have faired, and project the conductivity of the insulation system at other operating temperatures within the range tested.

3.0 TEST APPARATUS

3.1 Insulation Test Calorimeter

The insulation system thermal conductivity was measured using a guarded hot plate technique. Two specially designed calorimeters were built, Figure 4, which allow testing of the insulation under varying vacuum of less than 1 to 1000 μ Hg, varying loadings from 0 to 30 psi, and varying hot side temperatures from ambient to 1,100⁰F. The test calorimeters performed well and allowed rapid, accurate

and repeatable thermal conductivity measurements to be carried-out.

Measurement of thermal conductivities of high-performance insulations; $k \approx 100$, is difficult because of the low heat flux to be measured and the effect of lateral heat loss from the insulation sample. The lateral heat loss is complicated by the fact that some of the compressed multilayer insulations have a lateral conductivity along the aluminum foil 6000 times the conductivity perpendicular to the foil. In a guarded hot plate calorimeter, the insulation sample area to be measured is surrounded by an independently controlled and identical insulation sample which is maintained at the same temperatures although at a different heat flux as the test section. The guard section is not attached to the test section insulation and minimizes the lateral heat losses in the test section by matching the temperature at the test section edge, and thereby assuring a one-directional uniform heat flux in the test section.

The guarded, flat plate test arrangement for measuring the effective thermal conductivity of the high-temperature insulation under steady-state condition is shown schematically in Figure 7. The characteristic features of the test configuration are:

1. The insulation test sample is 7" in dia. and typically 1" thick.
2. The insulation sample guard, which surrounds the test sample, is the same material as the insulation sample. The guard dimensions are outside dia. 12", inside dia. 7" and thickness is the same as the test sample typically 1".
3. The hot and cold plates provide independent temperature control of the insulation test section and guard section.
4. The heat flux meter measures the heat flux through the center 2" x 2" section of the 7" dia. insulation test sample.

3.1.1 Calorimeter Hardware and Instrumentation

The insulation test calorimeter with the associated hardware and instrumentation is shown schematically in Figure 8 and photographed in Figures 4, 9 and 10.

The principal hardware components are as follows:

Resistance Heaters - The resistance heating elements for the hot face test and guard sections were Chromalox #135870 and #136354, respectively. The heaters are rated at 1,000 watts and were normally used at approximately 20 watts. The

heaters were temperature-controlled by Honeywell Dialatrol Controllers and the power input was limited by a 110-volt variac.

Hot Face Plates - The hot face plates were a composite of machined stainless steel which held the heaters in-place and faced with $\frac{1}{4}$ " copper plates to provide a uniform hot face temperature. The upper portion of the hot face was insulated with Johns-Manville Marinite XLO which is extremely strong, 1000 psi compressive strength, insulation.

Cold Face Plates - The cold face plates consisted of two independently water-cooled stainless steel plates faced with National Electrical Manufacturers Association, Grade G-5 plastic. The G-5 plastic has the same thermal conductivity as the flux meter and thereby maintains the heat flux and the temperature of the cold face uniform in the vicinity of the flux meter. The heat flux through the insulation must not be distorted by the flux meter or its surroundings. If this occurs, the flux meter reading will be higher or lower than the flux through an insulation with ideal isothermal boundaries.

Compression Loading Device - The compression loading of the insulation sample was applied through a movable upper hot plate against the fixed lower cold plate. The force on the upper plate was applied by an air cylinder loading tension rod which entered the vacuum space and was attached to a cross member on the hot face. The air pressure in the air cylinder was kept constant thereby applying a constant 15 psi load on the insulation sample.

Vacuum Enclosure - The insulation test assembly was mounted on a 20" dia. stainless steel base plate and enclosed in an 18" dia. glass bell jar. The electrical power leads, thermocouple leads and water feed throughs; tension rods, air cylinder and evacuation port were all mounted on the base plate.

Evacuation System - The system is evacuated using an 18 CFM mechanical pump and a 3" oil diffusion pump.

The principal calorimeter instrumentation is as follows:

Heat Flow Meter - The heat flow meter is a Hy-Cal Engineering, Model BI-7X. The dimensions are 2" x 2" x .1". The meters are individually calibrated by the factory at two points 25 and 500 Btu/Hr-Ft². The calibrations were 1.833 and 1.55 mV/Btu/Hr-Ft² for the flux meter use in calorimeter #1 and #2, respectively. The linearity of the flux meter is given as $\pm 2\%$, and the repeatability as 0.5%.

Thermocouple Sensors - Nanmac Type T, .0025" thick foil thermocouples were used on the cold face to monitor the temperatures at the center of the flux meter, the edge of the test section, and the left and right inner edge of the guard section. Omega Type J, 1/16" dia. sheathed thermocouples were inbedded in the copper hot face to monitor temperatures at the center and edge of the test section and at the left and right hand inner edge of the guard section.

Heater Controllers - The test section and guard heaters were controlled by Honeywell Dialatrol Controllers whose sensing thermocouples were mounted in the stainless steel plates not on the copper hot face. The heater temperature was set a few degrees above the desired operating temperature and because of the thermal headering arrangement, the copper hot face temperature was constant to within the accuracy of the hot side temperature recorder, $\pm 1^{\circ}\text{F}$.

Cold Face Temperature Control - The cold face test section and guard temperatures were controlled by varying the water flow rate through each section so that the temperature difference was typically within $\pm 2^{\circ}\text{F}$. The entire cold face temperature was allowed to slowly float with the tap water temperature and the sample heat flux. Over the relatively short period of any one test, the cold face temperature remained constant.

Strip Chart Millivolt Recorders - Strip chart recorders continuously monitored all the temperatures and the heat flux meter. The hot side temperature recorder was readable to $\pm 1^{\circ}\text{F}$, and the cold side temperature recorder was readable to $\pm 0.5^{\circ}\text{F}$. The flux meter recorder was used to monitor when the insulation had reached thermal equilibrium. The final flux reading was taken on a Hewlett Packard Digital Multimeter Model 3465A.

Vacuum Level - The bell jar vacuum level was measured using a Granville-Phillips High-Pressure Ionization Gauge Model 224. The ionization gauge is usable over the 10^{-6} to $1,000\mu\text{ Hg}$ range. In the 1 to $10\mu\text{ Hg}$ decade, the gauge is readable to $.5\mu\text{ Hg}$.

Insulation Thickness Indicator - The insulation sample thickness indicator is a direct reading of the hot to cold face spacing (insulation thickness). A $1/8"$ stainless steel rod passes through the base plate and the outer edge of the cold face guard and contacts the movable hot face. Movement of the hot face is transmitted by the rod and is registered on a dial indicator mounted on the base plate. The dial gauge is readable to $\pm .00025"$.

3.1.2 Test Procedure

The insulation system to be tested is made typically in a $12" \times 12" \times 1"$ sample. The sample is cut on a bandsaw with a knife blade into a $7"$ dia. test section and an annular guard section $12" \text{ OD} \times 7" \text{ ID} \times 1"$ thick, Figure 11. A hole is also drilled in the tangential cut area of the guard section to accept the thickness indicator rod. The sample is then placed on the cold plate of the calorimeter and positioned so that the sample test and guard sections align with the respective cold plate areas and the dial indicator rod moves freely through the sample.

The hot face is moved down until the face just touches the insulation sample. The insulation sample compression is measured by loading the air cylinder and measuring the hot face movement in 1.7 psi increments until an insulation loading of 15 psi is reached.

The insulation loading is held constant at 15 psi , the system is evacuated, and the first temperature point is set on the guard and test section hot face controllers. The hot face reaches the set temperature quickly; i.e., 1 hour, when the system is increasing in temperature. The flux reaches thermal equilibrium in

approx. 6 to 8 hours depending on the sample thermal diffusivity. After equilibrium is established, the hot and cold face temperature, insulation thickness, heat flux and vacuum level are recorded in the data book, and the next hot face temperature is set on the controllers. Normally, three to five data points are taken for each insulation sample. A minimum of two data points are required to define the constants A and B from the thermal conductivity vs. temperature curve based on the model, Section 2.0.

3.1.3 Data Reduction

The thermal conductivity is calculated from the measured data by the equation:

$$k_a = \frac{Q \times t}{T_H - T_C}$$

where k_a - apparent thermal conductivity - BTU/Hr-Ft⁰F.

Q - heat flux measured by the heat fluxmeter - BTU/Hr-Ft².

t - measured insulation thickness - ft.

T_H - average hot face test section temperature - ⁰F.

T_C - average cold face test section temperature - ⁰F.

The apparent thermal conductivity is independent of the insulation thickness for multi-foil insulation containing a sufficient number of reflective shields such that the optical properties of the hot and cold boundaries have a small effect. For thermal boundaries which are relatively black, $\epsilon = 1.0$, the product of the insulation thickness in inches, t , and the layer density, n layers/inch, $n \times t \geq 20$ satisfies these conditions. For high-density fibrous insulations without foils, the conductivity is independent of the thickness and boundary when insulation thickness is greater than approx. .15 inches.⁴ All of the insulations tested in this study satisfy one of the above conditions. The apparent conductivity parameter, k_a , therefore enables direct comparison of thermal performance for the various insulation systems even though the systems tested are of somewhat different thicknesses.

3.2 Insulation Creep Test Apparatus

In order to verify that creep of the fiberglass at the hot side would not pose an immediate problem, a test apparatus was fabricated to measure creep in insulation samples, Figure 4. Creep of the insulation can be a problem in a glass-support system especially when the hot side temperature is close to the glass strain point.

The objective of the creep test apparatus was to subject an insulation sample to operating temperatures, one atmosphere loading, battery weight loading and a vibrational loading. The insulation thickness changes are measured during the test, and a steady thickness change indicates insulation creep. In the creep test apparatus, Figure 4 and 12, an insulation sample 10" dia. was loaded at 15 psi by evacuating a 11" dia. x 8" high bellows closed at both ends by standard flanges. The insulation was heated to 850°F by a Chromalox disk resistance heater. The insulation cold side temperature was allowed to float with the ambient temperature since the heat flux in this case was dissipated to the ambient. An additional 1 psi deadweight loading was applied to the insulation sample through the standard flange, 1" thick, and a 3" thick spacer plate. The deadweight simulated a battery load on the insulation which when vibrated, subjected the insulation to a varying dynamic loading.

The entire test fixture was vibrated by mounting it on an Navco air shaker table. The table was dynamically-balanced to have a lateral vibration of approximately .01 "g" peak. The vibration frequency was measured by Endevco Model 2272 accelerameters and displayed on a Tektronics 5103N scope. The RMS acceleration was measured on an Unholtz-Dickie Vibration Monitor 1601M. The acceleration of the air shaker was not sinusoidal but approximated a sine wave, Figure 13. The wave form was constant throughout all the tests.

4.0 LOAD-BEARING INSULATION DEVELOPMENT

The development which led to the three promising load-bearing insulation systems are described in the following sections. The insulation systems are divided into the following four groups:

4.1 Peg-Supported Insulation Development, Fig. 15

4.2 Integral Discrete Load-Bearing Area Spacer, IDLAS Development,
Figure 23

4.3 Compressed Fibrous Multilayer Insulation Development,
Figure 11

4.4 Compressed Multifoil Insulation Development

The goals of the program were to develop an insulation board with a $k_a = 200$ to 140, a density = 18 pcf (lb/ft^3) and a compression or total deflection when loaded from the no-load or free condition to a load of 15 psi of $\alpha = 10\%$, Table I. Each of the goals were chosen to be realistic and result in an enclosure which would be lightweight and have low heat loss. For example, a 50 KWH enclosure with inside dimensions of 9" x 9" x 112" would have an insulation heat loss of 134W using 1" of insulation with a $k_a = 140$ and would weigh 81 lbs. assuming the insulation $\rho = 18$ pcf and the metal walls are .010". The compression goal of 10% was chosen based on past experience with load-bearing insulation used in cryogenic enclosures. The final insulation compression which is allowable has to come out of the enclosure design study. It is possible that with the proper enclosure design that compression higher than 10% would be feasible. The insulation compression is defined as:

$$\alpha = \frac{t_o - t_L}{t_o} \times 100$$

α = insulation compression
in percent.

t_o = insulation thickness under
no load.

t_L = insulation thickness under
15 psi load.

All of the insulation systems except the pegged SI require processing to form the material into a low-compression board system. The processing was performed using either of the following procedures:

1. The sample was compressed to the required thickness either $\frac{1}{2}$ " or 1", and the compressed sample was heated to the strain point of the glass and was held there for several hours. This procedure was carried-out either in air, inert atmospheres or a vacuum.

2. The sample was heated to the strain point of the glass in the uncompressed state. After the strain point was reached, the sample was compressed to the desired thickness. This procedure was carried-out under vacuum in one of the test calorimeters which was modified by installing a lower heating plate. The added lower hot plate was insulated from the cold plate so that the flux meter would not be damaged when the hot plate temperature reached 1100°F.

4.1 Peg-Supported Insulation Development

The concept of a peg-supported insulation system is to utilize the high strength peg material over approximately 10% of the area to carry the atmospheric load and low conductivity multifoil or superinsulation, S.I., over the remaining 90% of the area to provide the majority of the thermal resistance. Ratioing the conductivities to the percent area, a rough estimate of the resulting conductivity can be made:

$$k_a = k_{\text{peg}} \times A_{\text{peg}} + k_{\text{SI}} \times A_{\text{SI}}$$

for Min-K 2000 - $k_{\text{peg}}=1050$; $A_{\text{peg}}=.1$

Linde SI-62 - $k_{\text{SI}}=30$; $A_{\text{SI}}=.9$
 $k_a = 1050 \times .1 + 30 \times .9$
 $k_a = 105 + 27 = 132$

The peg-supported insulation test samples are summarized in Table II. Figure 14 is a cross-section view through the pegged S.I., and Figures 15 and 16 are photographs of a used pegged S.I. sample with some of the pegs removed and a foil exposed in Figure 15 and a spacer in Figure 16.

The first pegged SI sample, #9, used J-M Min-K 2000 as the peg material and SI consisting of .003" thick, glass paper and .0003" aluminum foil. The pegs and holes in the SI were cut by hand using a cork bore. The pegs were .660" dia., in a square array on 2" centers and covered 8.6% of the total area. The k_a of the sample was 380, a factor of 3 higher than expected, Figure 17. Upon examination of the holes in the SI, it was found that the aluminum foils had not been cut cleanly, and the foils were touching around the perimeter of the hole. The thermal shorting

caused by the foils resulted in the high conductivity of the sample. The sample density was very low - 11 pcf - as was the compression 5%, thereby meeting two of the three program goals.

The second pegged SI sample, #15, was of the same materials as the first, #9, but the peg diameter was reduced to .610" which reduced the peg area to 7.3% of the total. The aluminum was cut very clearly, and no shorting was apparent. The conductivity decreased substantially from sample #9 to $k_a = 101$, Figure 18. The density is 11 pcf and the compression was 6%. All of the parameters exceed the goals of the program, and this system is one candidate load-bearing insulation to be evaluated further for use in a rectangular enclosure.

Each peg in sample #15 was carrying 60 lbs. load or a stress of 205 psi. Compression tests on the pegs, Figure 19, indicates failure at 277 psi and 11% compression. The final peg area has to be optimized based on the peg compression strength and the enclosure wall thickness. A very small dia. peg carrying a large load would require a thick wall to transmit the load to the peg without the wall failing. Creep tests were successfully carried out on the pegged SI under vibrational loading, see Section 5.0.

In the peg SI system, the peg contributes 73% of the heat loss, therefore, to improve the system performance further, a lower conductivity peg material had to be developed. This was attempted through use of a glass mat and silica binder, sample #22. The binder was thickened so that it would remain in the glass mat pores when applied to the mat. The glass mat, .050" thick, was saturated with the binder mixture, compressed to 1" thickness, dried, and processed at 950°F. The processing step was required because the binder did not have sufficient strength to restrain the compressed glass and the sample would delaminate. The sample produced was successful with $k_a = 612$, density = 29 pcf, compression = 11%, Figure 20. The conductivity was 40% lower than the Min-K 2000.

A pegged SI sample, #27, was attempted using the new load-bearing board sample #22 as the peg material. Sample #22 had compressive strength of 600 psi and should have resulted in strong low-conductivity peg. Problems were encountered in cutting the pegs using the cork bore. The material delaminated after removal from the tube.

To produce usable pegs, the delaminated peg was saturated with binder. When dried, the peg was inserted into the SI. The binder content of the peg was greatly increased, and the conductivity of the peg also increased due to the added binder. The sample performance measured was $k_a = 254$, density = 13 pcf, and compression = 4%, Figure 21. This k_a is 2.5 times the pegged Min-K sample and back-calculating the peg conductivity is $k_a = 3080$ which is three times Min-K 2000. The concept could produce a low-conductivity peg, but it is apparent that improved cutting methods have to be found along with possibly a better binder.

In summary, an excellent performance of $k_a = 101$ is demonstrated with pegged SI using JM Min-K 2000. Significant further improvement appears possible based on our attempt at lowering the peg conductivity.

4.2 Integral Discrete Load-Carrying Area Spacer (IDLAS) Development

The IDLAS concept is to build-in load-carrying areas as the spacer paper is produced which will align layer to layer through the insulation thickness. The load-carrying areas are thicker than the remainder of the spacer and after the insulation is compressed and processed, a low compression board is produced. A cross-sectional view of the IDLAS spacer is given in Figure 22. The board properties of the system shown are shown in Figure 23. The dark areas are the thick load-carrying areas of the spacer which after processing bind the system together. It is felt that this material should have sufficient strength to be handled during enclosure assembly. After processing, the density of the insulation in the load-carrying area is approx. 40 pcf while the density in the non-load carrying area is approx. 11 pcf. As shown below, the IDLAS system has the possibility of very low conductivity and reasonable density. This is because the conductivity of the high-density area is projected to be on the order of $k_a \approx 500$. Ratioing the conductivities to the areas

$$\begin{aligned}k_a &= A_{SI} \times K_{SI} + A_{peg} \times k_{peg} \\k_a &= .92 \times 30 + .08 \times 500 \\k_a &= 68\end{aligned}$$

Ratioing the density in the same manner:

$$\rho = A_{SI} \times \rho_{SI} + A_{peg} \times \rho_{peg}$$

$$\begin{aligned} &= .92 \times 11 + .08 \times 40 \\ &= 13 \text{ pcf} \end{aligned}$$

Due to the limited test results, some of the trends are not fully explained or understood; i.e., the effect of sample compression and the aluminum foil passing through the load-carrying area. The IDLAS system will be further optimized in the follow-on program. The conductivities of this system are the best measured to-date and the spacer could possibly be manufactured using a high-speed paper-making process which would lead to low costs. The processing of the insulation to form a board could be part of an insulation bake-out prior to enclosure assembly so that the evacuation time would be minimized.

The IDLAS was simulated using disks cut from a glass mat .050" thick, which were placed on the standard glass spacer. The disks were spaced in a square array on 2" centers as in the pegged SI samples to accommodate the 2" x 2" fluxmeter. Alignment from layer to layer was maintained by using an array of needles placed at the corners of the 2" x 2" squares. The disks were then placed on the needles which were kept in place until the sample was completed. The sample was then built up on the needles which located the centers of the disks, Figures 24 and 25. After the sample was completed, the needles were removed, and the stack was placed in the calorimeter for testing or processing. Figure 26 shows processed sample with the spacer exposed. The dark disks are the load-carrying areas and the aluminum foil is showing in a few small areas where the spacer was removed.

The development of the IDLAS samples were first attempted using an open square array of the .050" glass mat as the load-carrying area, Figure 27. In this approach, the entire thick area could be laid over the sample as one piece and alignment could be maintained at the corners of the sample, which were later removed. In the first sample, #14, Table III, the square open mesh aligned well and the sample thickness was .928" which was close to the design thickness of 1". The conductivity of the sample was higher than calculated, $k_a = 265$, Figure 28, and density = 18 pcf. The cause of the high conductivity is thought to be the geometric match of the test sample and the fluxmeter. The high conductivity support area surrounds the flux meter and was 50% overlapping the perimeter. In this configuration, the slightly lower conductivity of the fluxmeter compared to the cold plate G-5 plastic results in more than 50% of the heat flux from load-carrying area around the perimeter being shunted through the fluxmeter giving a high conductivity.

The second IDLAS sample, #25, was made using the same material as sample #14, but the square load-carrying grid was shifted so that it intersected in the center of the fluxmeter rather than boarding the perimeter, Figure 27. This geometry would minimize the shunting of the flux through the load-carrying grid to the fluxmeter. However, in this sample, the grid was misaligned resulting in compression of the SI. The sample thickness was only .698" which was 25% less than sample #14. The conductivity and density are $k_a = 327$, Figure 25, and density = 19 pcf respectively, which are 20% higher than sample #14.

The problem of alignment and lateral conduction of the square grid was overcome by concentrating the support into circular areas one of which was in the center of the fluxmeter, Figure 26. The first samples using the circular support area IDLAS #28 through 32 were not processed, but were compressed in the calorimeter and tested. Sample #28, the support disks were placed on the spacer using a small amount of silica binder and covered 7.3% of the area. The sample conductivity was very high, $k_a = 469$, Figure 30, and the density was = 19 pcf. The binder in the support disks caused a large increase in the support area conductivity which increased the overall conductivity. The aluminum flake in the glass paper spacer increases the radiation resistance of the spacer slightly over the standard paper without the flake.

The next sample, #29, was fabricated of the same materials, but without using a binder on the disks. The conductivity decreased dramatically to $k_a = 196$, Figure 31. The density also decreased to 13 pcf. The low conductivity indicated that the concept was sound and further development was warranted.

Sample #30 was the same material as sample #29, but holes were cut through the foil and spacer and the thick disks were placed in the hole on every other layer. The conductivity was reduced to $k_a = 155$, Figure 32, and density = 14 pcf.

In sample #31, the dia. of the support disks was reduced from .61", 7.3% of the area to .58", 6.6% of the area and the aluminum flake spacer was replaced by the standard glass spacer. The aluminum foil was removed at the support disk, as was every other spacer. The conductivity was reduced to $k_a = 117$, Figure 33, and the density was = 12 pcf.

After testing, sample #31 was placed in the compression fixture and processed in air at 960°F. The processed sample was numbered 33. Processing resulted in an increase in the conductivity to $k_a = 147$, Figure 34 and density = 15 pcf. The compression of the processed sample was = 14%. Only a slight increase in conductivity due to processing in air is very remarkable. Apparently, the oxidation coating on the aluminum remains thin so as to not degrade the foil emissivity to any appreciable degree. Therefore, processing the insulation in air rather than vacuum is possible resulting in lower cost with only a small thermal penalty.

The smaller area support disks and the removal of the aluminum foil from the support area both contributed to the conductivity improvement. In sample #32, the aluminum foil was cut larger than the support disk and the aluminum flake paper was replaced with the standard fiber spacer. The support disks were the same as in sample #31. Sample #32 was unprocessed and had a conductivity of $k_a = 119$, Figure 35 and density = 11 pcf. The conductivity is practically the same as sample #31 which indicates that the aluminum flake paper in this type of insulation system was not extremely effective.

Sample #35 was the same as samples 31 and 33, i.e., the support areas were the same and aluminum flake spacer was used, but the sample was processed in a vacuum. The processing consisted of heating the uncompressed sample to 960°F in a vacuum and then compressing the hot sample to the final thickness. The conductivity was $k_a = 125$, Figure 36, density = 16 pcf and compression = 18%. The conductivity was improved by 15% over the air processed sample #32 and degraded by only 7% over the unprocessed sample #31.

The effect of removal of the foils at the support areas was determined using a sample identical to #35, but with the foils passing through the support area. The measured conductivity of sample #36 was $k_a = 146$, Figure 37, and density = 16 pcf and compression = 8%. The conductivity increased 17% due to shorting of the foils to the support area.

The final IDLAS sample, #37, has the lowest conductivity of all the load-bearing insulations tested in this program, but also points out an area where further development is required. The sample consisted of the standard fiber spacer, with support disks .58" dia., .050" thick. The aluminum foils passed through the support areas, and the sample was processed in vacuum. This sample was the same as

#32, but was processed and had the foils passing through the support areas. The measured parameters were conductivity $k_a = 95$, Figure 38, density = 15 pcf, and compression = 21%. The conductivity would have been expected to be ~150 or ~26% higher than sample #32 which was unprocessed with the foils removed at the support area. Two possible causes of the excellent conductivity are as follows:

1. The assembly technique has improved which resulted in improved disk alignment, more uniform loading of the disks and lower solid conduction through the support areas.
2. There is a strong dependence of the final conductivity on the sample compression. The dependence would result from high solid condition in the support area as a result of the higher density in the low compression samples.

The cause of the excellent conductivity of the last sample will be determined in the follow-on program along with further optimization of IDLAS concept.

4.3 Fiber Board Insulation Development

High-density fiber board insulation and compressed multifoil insulation both provide continuous support for the inner and outer enclosure wall as opposed to the discrete support areas of the pegged SI and IDLAS insulation systems. The continuous support systems will allow thinner walls to be utilized and provide a more reliable design in the critical corner areas of the enclosure. Although the conductivity and density of the glass fiber board insulations are a factor of two higher than pegged SI or IDLAS systems, the glass mat boards could be useful in specialized applications or used in conjunction with either of the other two low conductivity systems. In the fiber board insulation systems, the effect of fiber dia., density and fiber materials on conductivity, was explored to determine the optimum system. The complete test results are summarized in Table IV. The individual sample tests are discussed in the remainder of this section.

The first three samples in Table IV (#1, 10 and 40) all used .6u dia. glass fibers of type 475 glass in the board. The starting mat thickness in samples #1 and #10 were .050" while the mat in sample #40 was only .003" thick. All of the samples were processed in air at 950 to 985⁰F. Sample #1's measured conductivity performance was $K_a = 388$, Figure 39, density = 21 pcf and compression = 10%.

Sample #10 was the same as sample #1 but had undergone 900 hours of 1.8g 20 Hz vibration which because of a lateral loading component, had shifted and delaminated the sample. The measured performance of sample #10 was conductivity $k_a = 280$, Figure 40, density = 24 pcf and compression = 50%. The lateral loading and delaminating caused the compression and density to increase compared to sample #1 and the density increase resulted in the lower conductivity.

Sample #40 was made using a thinner glass mat (.003" thick) of the same material. The thinner mat should have resulted in the same radiation properties but less solid conduction because of the greater number of fibers which would be perpendicular to the heat flow. The density of sample #40 is less than sample #1 (20 pcf compared to 21 pcf) which should have increased the radiation components. The measured performance was conductivity $k_a = 334$, Figure 41, density = 20 pcf and compression = 8%. The conductivity is slightly lower than sample #1 but the solid conduction coefficient has increased and the radiation coefficient has greatly decreased. This trend is opposite to the above predictions and is thought to result from a difference in fiber diameter or mixture of fiber diameters in the .050" thick glass mat used in sample #1 compared to the glass paper used in sample #40. The problem will be resolved in the beginning of the follow-on contract.

Samples #11, 19 and 16 used a larger 3 μ dia. fiber made of E type glass in a .004" thick paper. The E glass has a higher softing point, 1549 $^{\circ}$ F compared to the 475 glass, 1279 $^{\circ}$ F. The higher temperature E glass should relieve any adverse creep effects of the 475 glass at the highest operating temperature of 940 $^{\circ}$ F. The processing temperatures for the E glass are 200 $^{\circ}$ F higher than for the 475 glass. A board could not be formed at 950 $^{\circ}$ F and temperatures of 1135 $^{\circ}$ F to 1170 $^{\circ}$ F had to be reached before a low compression board could be formed. The larger 3 μ fiber dia. is also more optimum for radiation scattering than the smaller .6 μ fiber. The effect of optimum density is shown in samples #11, 19 and 16 which have conductivities of 240, Figure 42, 224, Figure 43, and 260, Figure 44 and densities of 19 pcf, 22 pcf, and 25 pcf respectively. The optimum density is around 22 pcf which results in a minimum conductivity of $k_a = 224$. At approximately the same density, the .6 μ dia. fiber results in a conductivity 25 to 70% higher. Optimum densities cannot be compared because the optimum was not found for the .6 μ fiber. The cost of the 3 μ paper is \$4/lb compared to \$7/lb for the .6 μ paper. The compression of the optimum board, #19, was 7% which is very acceptable.

Samples #17, 7, 18 and 41 were all tested to evaluate different materials in order to determine if any unique advantages exist to warrant further testing. Sample #17 was made from a .004" thick E glass paper with a 6 μ dia. fiber. The advantage of the larger fiber is a lower paper cost of \$2/lb compared to \$4/lb for the 3 μ fiber paper. The unprocessed sample had a conductivity of $k_a = 258$, Figure 45, a density = 19 pcf and a high compression = 67% due to the sample being unprocessed. Comparison of the conductivity with the 3 μ fiber board at the same density, sample #11, indicates an 8% higher conductivity which supports the conclusion that the 3 μ fiber is more efficient in radiation scattering from the 6 μ fiber. This material will be considered further since the factor of 2 lower cost should more than compensate for the 8% higher conductivity.

Sample #7 is a Carborundum Fiberfrax paper, .020" thick, made of 2.5 μ dia. ceramic fibers. The sample was not processed because the processing temperature would be above 2300°F. The measured conductivity was $k_a = 500$, Figure 46 and density = 21 pcf. The conductivity of the sample is double that of the glass samples at the same density, and this material is not suited for this application but could find use in systems with higher operating temperatures.

Sample #18 is an Eagle-Picher mineral fiber board, 7 μ dia. fiber and 1/8" thick. The sample was unprocessed because of the high, 1800°F service temperature. The compressed material had a conductivity $k_a = 510$, Figure #47 and density = 27 pcf. The material is not in board form and the compression is 61%. As in the case of the ceramic fiber, the conductivity of mineral fiber board is twice that of the glass samples at the same density. This material is not suited for this application but could find use in systems with higher operating temperatures.

Sample #41 is a Dexter Grade 3737 glass paper which contains a large percentage (~60% by weight) of glass rovings. The large dia. glass rovings ~.030" are distributed randomly over the surface. The glass rovings when heat set could act as random support system which would decrease the solid conduction component through carrying the load over a smaller percent of the total area. The measured conductivity of the glass board was $k_a = 280$, Figure 48, density = 33 pcf and compression = 18%. The density is the highest, but the solid conduction component is the second lowest measured of all the glass boards. It appears based on the one test that this concept may be useful in reducing the solid conduction and could lead to

an optimized glass board with a conductivity lower than $k_a = 200$.

4.4 Compressed Multifoil Insulation Development

The addition of the aluminum foils to the glass boards, Section 4.3, is to reduce the overall conductivity by reducing the radiation conductivity component while not increasing the solid conduction component. The concept should be feasible because each of the foils lie in an isothermal plane and should not interact with each other or the glass mat spacer except at points of contact. The results of the compressed multifoil insulation development are given in Table V. Prior to this program and during the program, standard non-compressed SI was compressed by a 15 psi load and very low conductivities resulted. Sample #12 is such a test in which .004" thick, 3μ dia. E glass fiber paper with 269 foils/inch was compressed in the calorimeter with a 15 psi load. The thermal conductivity was very low, $k_a = 65$, Figure 58, density = 27 pcf, and compression = 64%.

The problem which characterizes all of the compressed multifoil samples is that when the insulation is processed to form a low compression board, the apparent conductivity is greatly increased. The conductivity increases as compression decreases and all the curves remain very flat indicating low radiation transfer, Samples #12A, 34, 20 and 13. The cause of the increased conductivity is thought to result from an increase in solid conduction caused by the intimate contact between all of the fibers on the surface of the glass on either side of the foil and the foil. The contact achieved between the foil and the glass fibers under compression of the processed SI is much greater than the unprocessed SI due to the deformation and movement of the fibers, Figure 49. The result is that many more fibers are in essence thermally shorted by the high conductivity foil which increases the solid conduction and the overall apparent conductivity.

The problem of increasing solid conductivity with the desired decreasing compression appears to be inherent in the processed multifoil system. Various methods were tried to solve or lessen the problem, but in the 15 samples tested, no success was achieved. The lowest conductivity achieved with a processed SI at 10% compression was $k_a = 250$, Sample #6, Table V, which is slightly higher than the best of all glass board, $k_a = 224$, sample #19, Table IV. The following discussion briefly describes the samples tested and the different attempts which were made to resolve the high conductivity.

Samples #2, 3, 4 and 5 were the first series of processed SI using a .6 μ dia. glass fiber paper of low-temperature 475 glass. All the samples were processed in a compressed state in air. The addition of foils did effectively reduce the radiation coefficient even though the foils were processed in air and were oxidized. In each case, the radiation was reduced but the solid conduction was increased and only a marginal improvement was realized in sample #4 with 12 shields/inch of 17% over sample #40, Table IV, with no radiation shields. There could be an optimum layer density in this system, but it appears the lowest the conductivity that could reach would be $k_g \sim 250$, Figure 50, which is well above the best of all the glass systems $k_a = 224$, sample #19, and above the program goals. The conductivity curves for samples 2, 3, 4 and 5 are presented in Figures 51, 52, 53 and 54 respectively.

Samples #6, Figure 55, and 8, Figure 56, utilized the same glass spacer as samples 2 through 5 but were processed in a nitrogen atmosphere and had 125 layers/inch of aluminum and 60 layers/inch copper foils respectively. The nitrogen processing did reduce the apparent conductivity of the system by 22%, comparing Sample #6 $k_a = 250$ with sample #5 $k_a = 320$, through decreasing solid conduction, but the apparent conductivity is still above the program goal. The copper foil sample performed better to reduce the radiation $k_g = 250$; i.e., the 60 copper layers performed almost as well as the 125 aluminum layers/inch. The solid conduction coefficient is almost the same in both cases, so that from the solid conduction standpoint, the copper did not perform as well as the aluminum.

The aluminum foils when processed in nitrogen, had a brown discoloration where the foil was in contact with the glass suggesting a chemical reaction with the glass. A reaction with nitrogen was ruled-out because the same discoloration was formed in an argon atmosphere. In contrast, when processed in air, the aluminum foil had a white coloring which was attributed to oxidation. A brief analysis conducted by the UCC Central Scientific Laboratory was carried-out using IR, ESCA, Auger, and SEM techniques and suggested that an alumina-silicate was forming at the surfaces of the glass and aluminum. The reaction appears to be related to the temperature, contact between the glass and aluminum and the time and not to the atmosphere under which the processing occurs. Latter samples have shown some discoloration in a vacuum environment when under light pressure at temperatures of 950°F. The reaction which occurs throughout a processed SI sample could also increase the solid conduction by bonding the fibers to the aluminum foil, Figure 57.

Samples #12 and 12A, Figure 58, were the first attempts at using the .004" thick, 3 μ fiber, E glass which is a high-temperature glass compared to the 475 glass. Sample #12 was not processed, but only compressed in the calorimeter at 15 psi. The conductivity was very low, $k_a = 65$, due to the low solid conduction component even though the sample had 269 foils/inch. Again, the problem with this sample is that when the load is removed, the sample springs back to near its original thickness, in this case from .446" to 1.23". An attempt was made to process sample 12 by heating one side to 940°F in the calorimeter then turning the sample over and heating the other side to 940°F. After processing sample 12 in this manner, the conductivity of sample 12A increased to $k_a = 258$, Figure 58. The processed sample still had a high compression = 56% since the strain point of the E glass was not reached.

Samples #34, 23 and 24 are additional samples made with the .004" thick, 3 μ diameter, E glass fiber paper and aluminum foil. Sample #34 was processed in the calorimeter by heating the sample uncompressed to the processing temperature and then compressing the sample while hot to a 1" thickness. In this manner, the contact and time at temperature are minimized and possibly the solid conduction component can also be kept low. The sample was not adequately processed since the compression was still high = 44%, although it was reduced from 64% for the unprocessed sample. The conductivity on the other hand was increased to $k_a = 146$, Figure 59, compared to the unprocessed sample #12, $k_a = 65$. In samples 23 and 29, the aluminum foils were added after the glass was processed by delaminating the glass mat and inserting the foils. Adding the foils in this way avoided exposing the foils to the high-processing temperature. Sample #19 was used as the starting glass board. The conductivity of sample 23 increased to $k_a = 248$, Figure 60, after adding 10 foils and sample 24 increased to $k_a = 302$, Figure 61, after adding 26 foils. The cause of the increased conductivity is attributed to the disruption of the laminar nature of the glass fibers at the interface of the separation. The glass fibers in those areas are no longer perpendicular to the heat flow, but have been stood upright due to the delamination and are now parallel to the heat flow.

Samples #13, 20 and 26 are vacuum-processed .6 μ dia., .003" thick, low temperature 475 glass fiber paper and aluminum foils. The vacuum processed sample in the calorimeter resulted in foils which had the same appearance after processing as

before. Sample #13 was compressed in our standard fixture and processed in a vacuum furnace. The foils after processing had a dull appearance. The conductivity was $k_a = 267$, Figure 62 and solid conduction was predominate. Sample #20 was processed in the calorimeter as described in Sample #34. The foils were shiny and appeared the same as before processing. The conductivity measured the first time was relatively low, $k_a = 223$, Figure 63. The sample was removed, and the edge retrimmed to insure the foils at the edge were not shortened. The handling or trimming must have changed the sample because the measured conductivity increased to $k_a = 303$, Figure 63. Sample #26 has an abnormally high conductivity, $k_a = 514$, Figure 64, and the cause of the high conductivity is not known. Various possibilities exist such as high foil emissivity for contaminated glass spacer, but the sample was not analyzed to determine the cause.

Sample #42 is made from Dexter Grade 3737 glass paper which contains many large dia. glass rovings (multi-strand glass yarn). The rovings are distributed in a random fashion over the surface. The large diameter roving could act as a randomly distributed support system which would carry the load and keep the majority of the aluminum foil from contacting the glass fiber. In this manner, the solid conduction could be kept low, and the overall conductivity reduced below that of a single diameter all glass fiber mat. The processing temperature of this sample was not reached, and the compression was high = 54%. Therefore, no definite conclusion can be drawn from this test. The conductivity was $k_a = 131$, Figure 65, which is not as low as the unprocessed SI, sample #12, but is lower than some of the other processed samples, #20 and 34, with similar compressions.

In summary, the compressed process multifoil is not promising due to high solid conduction which is apparent in the system using single fibers. It may be possible that the solid conduction can be reduced if very large diameter fibers or rovings form a randomly distributed support system reducing the fiber-foil interaction.

5.0 INSULATION CREEP TESTS

An insulation system which is carrying a 15 psi load can creep if the hot side temperature reaches the strain point of the load-carrying material. Glasses have varying viscosity vs. temperatures depending on the type of glass, Figure 66. The

first line on the graph is the strain point which is defined as the temperature at which internal stresses are relieved in four hours. In the load-bearing insulation application in which the temperature and load is continuous for years, the operating point must be above the strain point by some unknown amount. Figure 66 points out that borosilicate glass, types 475 and E, could creep at the upper operating temperature 950°F, and that glasses can be formulated with higher operating temperatures if the standard glass creeps.

Three insulations were tested in the creep apparatus, Section 3.2, one glass mat made of type 475, .6μ dia. glass fiber, one glass mat made of type E, 3μ glass fiber and one JM Min-K 2000 peg-supported SI sample. None of the systems catastrophically failed, and all of the systems would have to be subjectively judged as having passed this preliminary creep test. Long-term tests in an actual enclosure are needed before the creep question and its effect on the enclosure can be fully answered.

Two tests were run on the 475 glass mat, .050" thick, .6μ diameter fibers, 1279°F softening point, which was processed to a 21 pcf board without radiation shields. In the first creep test, Figure 67, a continuous sample thickness change was measured over the 800 hours of the test. On disassembly of the apparatus, it was found that the sample had extruded out of the left side and the movement of the glass had resulted in the continuous thickness change. The glass extrusion resulted from lateral vibration of the shaker table due to unbalanced mass of the apparatus. The mass was balanced by adding weight to one side and the lateral vibration was reduced to less than .01 "g" peak. The second test on the same sample resulted in no glass extrusion and in a much lower total thickness change than the first sample. The thickness change measured is comparable to that for the higher temperature E glass board. The total thickness change of the 1" sample was .035" or 3.5% after 1100 hours (Figure 68) of vibration at 1.78 "g" RMS, 20 Hz frequency and average hot side temperature of 850°F. It is not known whether the thickness change is due to temperature related creep at the hot face or a shifting and redistribution of the fibers throughout the entire sample. This will be resolved by testing the same sample under the same conditions, but without heating the sample.

An all-glass board, compressed thickness 1", was heat set using the high-temperature E glass, 1549°F softening point, 3μ diameter fiber to undergo creep evaluation. The total thickness change was .032" or 3.2% after 740 hours of 1.8 "g" RMS, 20 Hz vibration at an average hot face temperature of 850°F. There was no change in thickness for the last 100 hours of test, Figure 69. The 3.2% thickness change is considered to be acceptable although the actual acceptable thickness change has to be determined through a trade-off between the insulation and enclosure design.

A peg-supported SI sample was subjected to a creep test to evaluate the structural properties of the JM Min-K 2000 pegs under dynamic loading. Our concern was the possibility of the pegs crumbling under dynamic loading due to spalling at the surface of the peg. The sample used had the same dimensions as sample #9, Table II. The pegs were .660" dia., set in a square array on 2" centers, and occupied 8.6% of the total area. The sample was vibrated at 1.75 "g" RMS at 20 Hz for 670 hours with an average hot side temperature of 860°F. The total thickness change of the 1" sample was .017" or 1.7%, Figure 70. The thickness change of this sample was ~1/2 that of the glass board samples, and there was only .00075" thickness change in the last 200 hours of testing. The peg did not show any signs of degradation when examined at the end of the test. Based on this test, the JM Min-K 2000 pegs appear suitable for use in a pegged SI load-bearing insulation system.

J. J. Nowobilski

JJN:ks

Attachment

5.0 REFERENCES

1. Johns-Manville; Denver, CO, 80217 "Min-K Thermal Insulation," #IND-3263, 9/76.
2. Micropore Insulation Ltd., Arrowe Brook Road, Upton, Wirral, Merseyside, UK L49 15X "Microtherm," MIL/102, 104, 105, 106/E.
3. Thermal Performance of High-Temperature Insulation Materials in Aerospace Environments; E. A. Skrabek, R. P. Tye and A. O. Desjarlais; European Thermophysical Properties Conference, Dulsomik Yugoslavia, June, 1978.
4. "Final Report of Research and Development in a Thermal Insulation Study Phase II," AEC Research and Development Report, ALO 2832-43, UC-33, Propulsion Systems and Energy Conversion.

TABLE I

LOAD-BEARING INSULATIONS DEMONSTRATED IN CURRENT PROGRAM

DESCRIPTION	THERMAL CONDUCTIVITY $\times 10^{-5}$ BTU/HR-FT ² F $T_H = 840^{\circ}\text{F}, T_C = 75^{\circ}\text{F}$	DENSITY LBS/FT ³	PERCENT COMPRESSION AT 15 PSI LOAD
LINDE, MULTI-LAYER INSULATION BOARD	224	22	7
LINDE, THICK-THIN SPACER 8% OF TOTAL AREA 40 RADIATION SHIELDS	95	15	21
LINDE, PEGGED SUPER INSULATION (MIN-K PEG SUPPORTS), 7.3% OF AREA, 120 RADIATION SHIELDS	101	11	6
COMMERCIAL STATE-OF-THE-ART COMPARISON			
MIN-K 2000	1050	20	7
PRODUCED BY JOHNS-MANVILLE CO.			
MICROTHERM 20 CR	820	20	2
PRODUCED BY MICROPORE INTERNATIONAL			
PROGRAM GOAL	140	18	10

TABLE II
PEG-SUPPORTED INSULATION TEST SAMPLE SUMMARY

SAMPLE #	DESCRIPTION	THERMAL CONDUCTIVITY - K TEMPERATURES T_1 800°F TO T_2 -75°F $\times 10^{-5}$ BTU/HR-FT ² F	CONDUCTIVITY RADIATION $\times 10^{-14}$	COEFFICIENTS SOLID CONDUCT. $\times 10^{-5}$	DENSITY LB/FT ³	COMPRESSION AT 15 PSI LOAD %	SAMPLE THICKNESS		RADIATION SHIELDS/INCH	PROCESSING
		T_2 FINAL @ 840°F	T_1 INITIAL AFTER PROC.							
9	.003" thk., .6u dia. Fiber glass paper and Al foil, 120 layers. .660" Dia. Min-K 2000 pegs on 2" centers, 8.6% of area.	380	16.4	7.10	11	5	.964	1.010	125	None
16	Same as Above, Sample #9, but pegs .610" dia., 7.3% of area.	101	3.53	1.97	11	6	.951	1.010	126	None
22	.050" thk., .6u dia. fiber glass mat with silica binder.	612	20.2	8.73	29	11	.916	1.028	None	950°F Air
27	Same as Sample #9, but pegs were cut from Sample #22. .610" dia., 7.3% area, and increased binder content.	254	33.3	3.12	13	4	1.004	1.046	120	None

TABLE 111
IDLAS INSULATION TEST SAMPLE SUMMARY

SAMPLE #	DESCRIPTION	PROCESSING TEMPERATURE	THERMAL CONDUCTIVITY - K_a	CONDUCTIVITY COEFFICIENTS		DENSITY LB/FT ³	COMPRESSION P 15 PSI LOAD %	SAMPLE THICKNESS			LAYERS OF FOIL PER INCH
			TEMPERATURES $T_1 = 840^\circ F$ TO $T_2 = 75^\circ F$ $K_a \times 10^{-5}$ BTU/HR-FT- $^\circ F$	RADIATION SOLID CONDUCTION $B \times 10^{-14}$	$A \times 10^{-5}$			T_f FINAL	T_1 AFT. PROC.	T_2 FREE STACK	
14	.003" thk., .6u dia. fiber spacer .050" thk., .6u dia. fiber load-carrying area cut in a 2"x2" open mesh 20% of area which bordered flux meter.	Not Processed	265	48.1	2.19	16	--	.928			96
25	Same as Above (14), but load-carrying area crossing center of flux meter.	Not Processed	327	18.1	5.79	19	--	.698		3.54	126
28	Al flake paper, 50% Al, .060" thk., .6u fiber support disks .61" dia., 7.3% of area attached with inorganic binder.	Not Processed	469	48.8	6.45	19	72	.390		1.413	128
29	Same as Above (28), but without binder and 40% Al.	Not Processed	196	12.3	3.36	13	76	.384		1.570	104
30	Same as Above (29), but with foils and spacer removed at load-carrying areas.	Not Processed	155	28.9	7.19	14	78	.319		1.50	125
31	Same as Above (30), but with Al foils removed and only everyother spacer removed @ support areas and support disk dia. = .58", 6.6%.	Not Processed	117	24.0	.63	12	68	.442		1.37	91
32	.003" thk., .6u fiber paper and Al foil, 40 layers. Al foil cut larger than support disks which are .58" dia.	Not Processed	119	5.49	2.16	11	73	.430		1.62	93
33	Processed Sample #31.	960 Air	147	18.7	1.74	15	14	.320	.373		126
35	Al flake paper spacer 40% of Al cut .62" dia. Supports .060" thk. glass mat .6u fiber disks .58" dia., 6.6% Area.	960 18u Vacuum	125	7.93	2.08	16	18	.324	.396		124
36	Same as Above, but foil and spacer not removed in support area.	960 32u	146	6.01	2.71	16	8	.324	.364		124
37	.003" thk., .6u fiber paper and Al foil 40 layers, Al not removed, supports same as #35.	950 25u	95	8.20	1.43	15	21	.304	.384		132

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TABLE IV
GLASS MAT INSULATION TEST SAMPLE SUMMARY

SAMPLE #	DESCRIPTION	PROCESSING TEMP. °F	THERMAL CONDUCTIVITY - K _a TEMPERATURES T _H =840°F TO T _C =75°F K _a x 10 ⁻⁵ BTU/HR-FT-°F	CONDUCTIVITY COEFFICIENTS RADIATION B x 10 ⁻¹⁴	SOLID COND. A x 10 ⁻⁵	DENSITY LB/FT ³	COMPRESSION @ 15 PSI LOAD %	T _f FINAL @ 840°F	SAMPLE THICKNESSES T _i INITIAL AFT. PROC.	T _f FREE STACK	LAYERS OF GLASS PER INCH
1	.050" thk., .6μ dia. fiber 36 layers - 475 glass low-temp.	950	388	73.8	2.66	21	10	.925	1.056		39
10	Same as Above (1), but vibrated at 1.8g for 900 hours, sample delaminated.	950	280	56.1	1.83	24	50	.864	1.717		42
40	.003" thk., .6μ dia. fiber 475 glass low-temp.	985	334	44.3	3.59	20	8	.991	1.075		477
11	.004" thk., 3μ dia. fiber High-Temp. glass type E.	950	240	44.1	2.25	19	49	1.060	2.080		382 ¹ / ₆₃
19	Same as Above (11), but heat setting temp. reached.	1170	224	34.4	2.36	22	7	1.011	1.090		438
16	Same as Above (19), but heat set to higher density.	1135	260	36.7	2.52	25	8	1.180	1.283		517
17	.004" thk., 6μ dia. Fiber High-Temp. glass type E.	Not Processed	258	63.1	0.85	19	67	1.074		3.250	
7	Ceramic paper, 2.5μ diameter.	Not Processed	500	86.5	4.38	21	40	.968	1.625	1.050	56
18	Mineral Fiber, 7μ diameter.	Not Processed	510	70.9	5.64	27	61	.670		1.630	7
41	Dexter Grade #3737 paper, .013" thk., fiber glass rovings with some 3μ dia. fibers.	950	280	55.4	1.57	33	18	.499	.606		186

TABLE I
COMPRESSED MULTIFOLIA INSULATION TEST SAMPLE SUMMARY

SAMPLE #	DESCRIPTION	PROCESSING TEMPERATURE °F	ATMOSPHERE	THERMAL CONDUCTIVITY - K TEMPERATURES $T_1 = 840^\circ\text{F}$ TO $T_2 = 750^\circ\text{F}$ $K \times 10^{-5} \text{ BTU/HR-FT}^2$	CONDUCTIVITY RADIATION $q \times 10^{-14}$	COEFFICIENTS SOLID COND. $A \times 10^{-5}$	DENSITY LB/FT ³	COMPRESSION AT 15 PSI LOAD	T_1 FINAL @ 840°F	SAMPLE THICKNESS T_1 INITIAL T_2 BEFORE PROCESSING	RADIATION SHIELDS PER INCH
2	.050" thk., .6u dia. fiber, 36 layers. Low temperature 875 glass, 12 Al radiation shields.	1000+	Air	380	45.7	4.17	23	12	.925	1.054	13
3	Same as Above (2), but with 36 Al radiation shields.	1100 Controller Failed	Air	355	23.9	5.95	33	34 After Controller Failed	.707	1.069	51
4	Same as Above (2), but processed at lower temperature.	940	Air	277	32.5	3.56	24	10	.965	1.072	12
5	.003" thk., .6u dia. fiber, 468 layers low-temperature glass, 120 layers Al.	950	Air	320	8.46	6.54	29	13	.973	1.118	123
6	Same as Above (5), but Processed in H_2 .	950	H_2	258	8.82	4.80	24	10	.963	1.071	125
8	Same as Above (5), but with 60 copper shields.	950	H_2	268	13.0	4.73	30	8	.999	1.083	60
12	.004" thk., .3u dia. fiber, high-temperature E glass, 120 radiation shields.	Not Processed		65	---	---	27	64	.446	1.220	269
12A	Same as Above (12), but processed both side in calorimeter.	940	Vacuum	298	9.64	4.78	34	56	.354	.805	339
30	.004" thk., .3u dia. fiber, high-temperature E glass, 120 layers glass and 40 radiation shields.	1160 In Calorimeter	Vacuum	146	12.4	2.25	25	44	.375	.673	107
23	Sample #19, delaminated and 10 radiation shields added.	Not Processed		248	32.3	2.70	24	15	.918	1.082	11
24	Sample #19, delaminated and 25 radiation shields added.	Not Processed		302	48.8	2.68	23	11	.929	1.102	27
13	.002" thk., .6u dia. fiber, low-temperature 875 glass, 120 radiation shields, 468 layers of glass.	930 UCC Metal Furnace	Vacuum	267	14.6	4.92	22	11	.943	1.062	127
20	Same as Above (13), but only 120 layers of glass and 120 radiation shields.	950 In Calorimeter	Vacuum	360	12.2	5.72	26	36	.470	.735	255
26	Same as Above (13), but 360 layers of glass and 72 radiation shields.	950 In Calorimeter	Vacuum	514	72.2	6.20	20	26	1.072	1.445	2.25 67
42	Dexter Grade 3737 paper, .013" thk., fiber-glass with some .3u dia. fibers, 32 rad. shields.	970 In Calorimeter	Vacuum	131	18.9	1.81		54	.489	1.617	68

NOTE: THICK-THIN SPACER IS PRODUCED IN A CONTINUOUS PAPER MAKING PROCESS.

FIGURE 1
DRAWING OF INTEGRAL, DISCREET LOAD-CARRYING AREA INSULATION

FIGURE 2
PHOTOGRAPH OF IDLAS INSULATION

FIGURE 3
PEG-SUPPORTED MULTIFOIL WITH PEGS INSERTED

FIGURE 4
CALORIMETER HARDWARE PHOTOGRAPH

FIGURE 5
CREEP TEST APPARATUS

UCC-LINDE 7/27/79

THERMAL CONDUCTIVITY TEST APPARATUS

FIGURE 7

CALORIMETER TEST SECTION SCHEMATIC

CALORIMETER SCHEMATIC

FIGURE 8

FIGURE 9
INSULATION TEST CALORIMETER

FIGURE 10
CALORIMETER PHOTOGRAPH

FIGURE 11
INSULATION IN CALORIMETER

INSULATION VIBRATION TEST APPARATUS

FIGURE 12

Frequency - 17 Hz
Acceleration - 1.7 "g" Peak
Trace Parameters
Time: 0.2 S/Division
Amplitude: 1 g/Division

FIGURE 13

ACCELERATION WAVE FORM PHOTOGRAPH

FIGURE 14
PEG-SUPPORTED MULTIFOIL INSULATION DRAWING

FIGURE 15

PEG-SUPPORED MULTIFOIL WITH THE FOIL EXPOSED

FIGURE 16
PEG-SUPPORTED MULTIFOIL WITH SPACER EXPOSED

FIGURE 17

INSULATION SYSTEMS THERMAL CONDUCTIVITY

PEG-SUPPORTED INSULATION SAMPLE #9 SEE TABLE II FOR PROPERTIES

FIGURE 18

INSULATION SYSTEMS THERMAL CONDUCTIVITY

PEG-SUPPORTED INSULATION SAMPLE #15 SEE TABLE II FOR PROPERTIES

JH MIN-K 2000 PEG COMPRESSION FIGURE 19

FIGURE 20

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT WITH SILICA BINDER SAMPLE #22 SEE TABLE II FOR PROPERTIES

FIGURE 21

INSULATION SYSTEMS THERMAL CONDUCTIVITY

PEG-SUPPORTED INSULATION SAMPLE # 27 SEE TABLE II FOR PROPERTIES

FIGURE 22
CROSS-SECTIONAL VIEW OF IDLAS INSULATION

FIGURE 23
BOARD PROPERTIES OF THE IDLAS INSULATION

FIGURE 24
IDLAS SAMPLE ASSEMBLY

FIGURE 25.
HULL SAMPLE ASSEMBLY

FIGURE 26
PROCESSED IDLAS SAMPLES

FIGURE 27
OPEN SQUARE MESH IDLAS SAMPLE

FIGURE 28

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #14 SEE TABLE III FOR PROPERTIES

FIGURE 28

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #14 SEE TABLE III FOR PROPERTIES

FIGURE 29

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #25 SEE TABLE III FOR PROPERTIES

FIGURE 30

INSULATION SYSTEMS THERMAL CONDUCTIVITY

FIGURE 31

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #29 SEE TABLE III FOR PROPERTIES

FIGURE 32

INSULATION SYSTEMS THERMAL CONDUCTIVITY

10LAS INSULATION SAMPLE #30 SEE TABLE III FOR PROPERTIES

FIGURE 33

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #31 SEE TABLE III FOR PROPERTIES

FIGURE 34

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #33 SEE TABLE III FOR PROPERTIES

FIGURE 35

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #32 SEE TABLE III FOR PROPERTIES

FIGURE 36

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #35 SEE TABLE III FOR PROPERTIES

FIGURE 37

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #36 SEE TABLE III FOR PROPERTIES

FIGURE 38

INSULATION SYSTEMS THERMAL CONDUCTIVITY

IDLAS INSULATION SAMPLE #37 SEE TABLE III FOR PROPERTIES

FIGURE 39

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #1 SEE TABLE IV FOR PROPERTIES

FIGURE 40

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #10 SEE TABLE IV FOR PROPERTIES

FIGURE 41

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #40 SEE TABLE IV FOR PROPERTIES

FIGURE 42

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #11 SEE TABLE IV FOR PROPERTIES

FIGURE 43

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #19 SEE TABLE IV FOR PROPERTIES

FIGURE 44

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #16 SEE TABLE IV FOR PROPERTIES

FIGURE 45

INSULATION SYSTEMS THERMAL CONDUCTIVITY

GLASS MAT INSULATION SAMPLE #17 SEE TABLE IV FOR PROPERTIES

FIGURE 46

INSULATION SYSTEMS THERMAL CONDUCTIVITY

CERAMIC MAT INSULATION SAMPLE #7 SEE TABLE IV FOR PROPERTIES

FIGURE 47

INSULATION SYSTEMS THERMAL CONDUCTIVITY

MINERAL FIBER INSULATION SAMPLE #18 SEE TABLE IV FOR PROPERTIES

FIGURE 48

INSULATION SYSTEMS THERMAL CONDUCTIVITY

DEXTER 3737 MAT SAMPLE #41 SEE TABLE IV FOR PROPERTIES

THERMAL SHORTING OF THE FIBERS AND FOIL IN COMPRESSED PROCESSED MULTIFOIL

FIGURE 49

ESTIMATED OPTIMUM FOIL LAYER DENSITY
FOR AIR PROCESSED COMPRESSED MULTIFOIL
FIGURE 50

FIGURE 51

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #2 SEE TABLE V FOR PROPERTIES

FIGURE 52

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #3 SEE TABLE V FOR PROPERTIES

FIGURE 53

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #4 SEE TABLE V FOR PROPERTIES

FIGURE 54

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #5 SEE TABLE V FOR PROPERTIES

FIGURE 55

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #6 SEE TABLE V FOR PROPERTIES

FIGURE 56

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #8 SEE TABLE V FOR PROPERTIES

MAGNIFICATION
380X

MAGNIFICATION
1520X

FIGURE 57
SEM OF FIBERS BONDED TO ALUMINUM FOIL

FIGURE 58

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE 12A SEE TABLE V FOR PROPERTIES

FIGURE 59

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #34 SEE TABLE V FOR PROPERTIES

FIGURE 60
INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #23 SEE TABLE V FOR PROPERTIES

FIGURE 61

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #24 SEE TABLE V FOR PROPERTIES

FIGURE 62

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #13 SEE TABLE V FOR PROPERTIES

FIGURE 63

INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #20 SEE TABLE V FOR PROPERTIES

FIGURE 64
INSULATION SYSTEMS THERMAL CONDUCTIVITY

COMPRESSED MULTIFOIL SAMPLE #26 SEE TABLE V FOR PROPERTIES

FIGURE 65

INSULATION SYSTEMS THERMAL CONDUCTIVITY

- STRAIN POINT IS THE TEMPERATURE AT WHICH INTERNAL STRESSES ARE RELIEVED IN APPROXIMATELY FOUR HOURS.

FIGURE 66
GLASS VISCOSITY-TEMPERATURE CURVES

Source: Corning Glass, Properties of Glasses and Glass Ceramics.

CREEP TEST - TYPE 475 GLASS - SECOND TEST FIGURE 68

.6 μ Dia. Fiber
1.78 "g" RMS Vertical
20 Hz
Lateral Vibration ~.01 "g" Peak

CREEP TEST - TYPE E GLASS

FIGURE 69

3 μ Dia. Fiber
1.8 "g" RMS Vertical
20 Hz
Lateral Vibration $\sim .01$ "g" Peak

CREEP TEST - PEG-SUPPORTED MULTIFOIL FIGURE 70

JM Min-K 2000 8.6% of Area
1.75 "g" RMS Vertical
20 Hz
Lateral Vibration ~.01 "g" Peak