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AEC RESEARCH AND
DEVELOPMENT REPORT

UNION CARBIDE CORPORATION

LINDE DIVISION

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FINAL REPORT OF RESEARCH AND DEVELOPMENT
IN A THERMAL INSULATION STUDY
Phase II

September, 1967 - September, 1970

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FINAL REPORT

IN A THERMAL INSULATION STUDY

Phase II

September, 1967 - September, 1970

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A B S T R A C T

This report presents the phase II effort of an AEC thermal insulation research and development program performed by Linde Division of Union Carbide. The report covers the duration from September 1967 to July 1970. The results of the phase I effort (March 1966 to September 1967) are presented in the United States Atomic Energy Commission report ALO 3632-20.

The objective of this development program was to evaluate, develop where necessary and demonstrate thermal insulations for use in radioisotope power systems. The insulation systems investigated were multilayer type designed for operation in vacuum.

The three major areas of effort included;

- (1) Flat Plate thermal conductivity testing
- (2) Long term performance stability
- (3) The effects of interface on insulation thermal performance

Flat Plate testing was utilized to obtain experimental thermal conductivity data for several multi-layer insulations spanning service temperature ranges from 500°F to 2500°F and layer density ranger corresponding to 0-15psi compressive loadings. Effective thermal conductivity in the lateral or longitudinal direction are also presented for several non foil multi-layer insulations.

Empirical expressions were developed which can be utilized to compute thermal conductivity for the multi-layer systems tested at any temperature boundaries within its prescribed service range, and at any layer density corresponding to 0-15 psi compressive loading.

Several multi-layer insulation systems were evaluated to determine thermal performance stability over extended operating periods (2000 - 10,000 hours) at maximum service temperatures. Prior to the stability operating period, effective thermal conductivity data for the installed insulation configuration were determined at several different temperature levels.

The effect of the presence of a penetration through an insulation panel on the insulation thermal performance was determined for the case when the penetration and/or its immediate surroundings give rise to thermal discontinuities. Two types of penetration were investigated: flush penetrations and extended penetrations. For each of the two major types, zero gap, open gap and filled gap configurations are analyzed.

The effect of exposed edges and gaps on thermal performance of various panel geometrics is evaluated with a two dimensional computerized analysis. Verification tests were performed on insulation panels with exposed edges.

SUMMARY

Thermal conductivity and performance stability was determined for several multi-layer insulations in vacuum at temperatures up to 1800°F.

Basic thermal conductivity data was obtained with a flat plate tester for fourteen multi-layer systems over a source temperature range of 500 → 1800°F and for compressive loads from 0 - 15 psi. Molybdenum foil-zirconia cloth insulation was tested at source temperatures up to 2200°F. The recommended utilization temperature range for each of these insulation systems is indicated in table I (page 3). Effective thermal conductivities for each of these insulation systems at source temperatures near their recommended limit are presented in table II (page 4).

Longitudinal thermal conductivity was measured for three opacified fibrous multi-layer insulations and non-opacified 106 glass insulation. The result of these tests are tabulated in table VI (page 73).

Seven insulation systems were tested at source temperatures near their maximum use temperatures for periods ranging from 2000 to 10,000 hours. The objective was to obtain some preliminary indication of long term stability of these insulation systems. A summary of these stability test parameter is presented in the table on page 102 and a summary of the results are shown by Figure 49 (page 111). Of the seven systems tested only nickel opacified refrasil paper indicated significant deterioration in thermal performance for the duration tested (32%).

A mathematical model was set up to analyze the effect of insulation penetrations on insulation thermal performance. A test was conducted to experimentally verify the effects of penetrations on the overall thermal performance for one multifoil insulation configuration with flush penetrations. Agreement was reasonably good between the measured thermal performance data and the analytical predictions for the configuration tested.

A pertinent observation relating to the thermal effect of penetrations is as follows: in the case of flush penetrations the one-dimensional approximation to calculating total heat flow appears adequate provided total heat flow is largely influenced by heat flow through the penetration. For cases where the penetration is considerably longer than the insulation the one-dimensional approximation over estimates system heat loss by a wide margin.

A study relating to insulation gaps indicated that in general the opacified fillers improve overall thermal performance of multifoil insulation panels containing rectangular or angular gaps, in comparison to these same insulation systems with unfilled gaps.

The results of an analysis indicated that the heat loss penalty of an insulation system with exposed edges is significant, panel configuration is critical and losses increase rapidly with temperature due to the radiative loss mechanism at the edges.

There was a reasonably good agreement between the experimental and calculated results for two exposed edge configurations tested. In most cases the analysis is conservative and will overpredict the edge loss to a moderate extent.

The work on this contract was performed under the direction of the United States Atomic Energy Commission, Isotopic Power Branch Division of Space Nuclear Systems. The AEC program director was P.A. O'Riordan. The technical monitor was D.J. Mottern from the Sandia Corporation. The Linde Project Managers were W.D. DeWitt, F. Notaro, W.E. Grunert and D.J. Webster. Other Linde personnel contributing to this program were E.S. Kordyban, H. Morihara, L.D. Potts, R.L. Reid and D.H. Suckow.

1.0 THERMAL CONDUCTIVITY OF MULTILAYER INSULATIONS - FLAT PLATE TEST PROGRAM

The major objectives of the Phase II flat plate thermal conductivity test program were:

(1) Obtain experimental thermal conductivity data under prescribed temperature and compressive load conditions, to a predictable degree of accuracy, utilizing flat plate testing techniques.

(2) From these data, develop empirical expressions for the radiative and solid conduction contributions to thermal conductivity. These empirical relationships are then used to compute K-values for a given multi-layer system at any temperature boundaries within its prescribed service range, and at any layer density corresponding to 0-15 psi compressive loading.

Nine multi-foil insulations were tested under the Phase II program, spanning service temperature ranges from 500°F to 2500°F and layer density ranges corresponding to 0-15 psi compressive loading. Five plain and metal flake opacified multi-layer insulation (i.e., non-foil systems) were also evaluated at 0-15 psi loading and temperatures ranging from 500-1500°F. The extensive effective (or average) thermal conductivity (K_a) data on these insulations have (a) provided some basis for design of multi-layer thermal insulation systems and (b) served as a useful tool in gaining a deeper insight into the characteristic thermal behavior of high temperature multi-layer insulations.

The flat plate configuration employed in this test program combines the desirable features of the total enclosure geometry and the compressible flat plate geometry. The dual-sample, symmetrical configuration is comprised of two square planar multi-layer insulation samples (heated from one side only), with identical multi-layer insulation guarding to minimize edge heat loss. With these lateral losses minimized by the passive edge guards, an accurate, one-dimensional, steady-state heat flow measurement can be made over the center or core section of the multi-layer sample. The test configuration provides for accurate compression of the multi-layer samples (i.e., layer density variation) and, in this way, adds a degree of testing flexibility not previously possible with the cylindrical testers.

All testing was done in a vacuum environment ($p \leq 1 \times 10^{-4}$ torr). Original source temperature capability was to 1800°F and compressive loading variations between 0 and 15 psi. The test equipment has been modified recently to permit testing up to a maximum hot-side temperature of 2500°F.

The multi-foil and fibrous multi-layer insulations tested in the Phase II program are listed in Table I. Maximum rated service temperatures for each system, operating in vacuum, are indicated. All metallic foil shield materials are .0005" thick or less; woven or fibrous paper spacer materials are typically .005" thick or less.

Table II gives the effective thermal conductivity range for each system, operating in vacuum at its maximum rated service temperature. The limiting values, designated by 1 and 2, correspond to a near-zero load layer density and the layer density at 15 psi compression load, respectively. Thermal performance and testing of these insulation systems is discussed in detail in subsequent sections.

A comprehensive error analysis has been made on representative flat plate K_a data. The computerized evaluation considers errors due to two-dimensional effects, mismatch in thermal boundary conditions between sample and guard sections, and measurement deviations. Generally, maximum K_a deviations of ± 10 -30% were estimated for multi-foil systems operating at maximum service temperatures and at compressive loads of .1 psi or above. For low temperatures and low loads (e.g., Al multi-foil systems at low loads) maximum deviations were considerably higher due to the low heat flux quantities involved. Details of this error study and evaluation of the flat plate test method itself are presented in subsequent sections.

Effective thermal conductivity in the lateral or longitudinal direction are also presented for the opacified fibrous multi-layer insulations. These lateral K_a data have been quite useful in thermal performance studies on multi-layer systems where the opacified materials are used as gap fillers (reference Section 3.0).

TABLE I

Utilization Temperature Range for Multilayer Insulations

TABLE II

Effective Thermal Conductivity Range for Multilayer Insulations

1.1 Thermal Performance Parameters for Multi-Layer Insulations

Total heat transport through high temperature multi-layer systems, operating in vacuum ($p < 1 \times 10^{-3}$ torr), is comprised of solid conduction and radiative contributions. These two mechanisms are, strictly speaking, not separable. However, treating the total heat flux as the sum of these two contributions, considered independently, is a reasonable approximation and provides for a somewhat simplified analysis of the multi-layer insulations' thermal characteristics⁽¹⁾.

In predicting or evaluating thermal behavior of multi-layer insulations at other load-temperature conditions, the same generic reasoning cannot be correctly applied to all three insulation configurations; (i.e., multi-foil insulation, plain fibrous multi-layer insulation, metal flake opacified multi-layer insulation) The dominant mechanism by which heat, and particularly radiant heat, is transmitted will vary for each of the systems.

For example, in the alternate layer, multiple foil insulations radiant heat is transmitted primarily by the mechanisms of absorption and re-emission at each foil surface. This, perhaps, is the simplest radiant transfer case to analyze. In the plain fibrous insulations, attenuation of radiant heat is attributed mainly to backward scattering by the fiber array. In the metal flake-opacified systems, both absorption--re-emission and scattering mechanisms exist and are coupled. System behavior depends upon not only the fibrous matrix, but also on the flake structure and density.

Effective thermal conductivity (K_a) is the parameter selected to represent thermal performance of the high temperature multi-layer insulations. In a vacuum environment, the overall K_a value is defined approximately as the sum of the solid conduction (K_s) and radiation (K_r) contributions. These component K_s and (K_r) terms are related to insulation boundary temperatures and layer density (compressive load).

The effective thermal conductivity parameter can be applied in a rather straightforward manner to multiple foil insulations of relatively high shield density. However, the non-foil fibrous paper insulations cannot be treated in such a simplified manner. The fibrous systems are partly transparent to radiation and, as such, cannot be described by a generally applicable effective thermal conductivity, depending only on temperature and load (layer density). With the assumption that radiant heat attenuation in the fibrous materials is mainly by backscattering, the performance depends not only on temperature and compressive load but on amount of material (i.e., thickness) and optical properties of the boundaries as well. In ensuing discussion, a K_a expression involving solid conduction (K_s) and radiation (K_r) components is generated and used in evaluating the fibrous multilayer systems. However, the resulting K_a values reflect the

influence of all the parameters listed above and are not to be interpreted or applied in the usual manner (i.e., as an intrinsic property of the fibrous material).

1.1.1 Multifoil Insulations

For alternate layer multiple foil insulation composites, radiant heat transmission is strongly governed by the foil optical properties and spacing. Radiation transfer [i.e., radiative contribution (K_r) to effective thermal conductivity] is directly proportional to thermal emissivity (ϵ) of the reflective shields and inversely proportional to shield density (n).

Mechanisms contributing to solid conductance (K_s) through the fibrous separator are, on the other hand, far more varied and complex. The surface photomicrograph (at 500X) of Figure 1 shows the fibrous structure of typical multi-layer spacer material. This matrix is typical of quartz or glass fibrous materials in thin "paper" form, which are commonly used in these multilayer insulations.

Conditions contributing to the total solid conduction contribution may include: (a) random fibers disposed parallel to the direction of heat flow; (b) varying number of actual fiber to fiber contacts; (c) interface resistance at each fiber contact; (d) interface resistance between fibers and foil surface; and (e) thermal conductivity of basic fiber materials.

Wang⁽¹⁾, in his analysis of multiple-foil vacuum insulation systems for cryogenic service, suggests an analytical method in which an attempt is made to account for items b, c and e after first "idealizing" the fibrous matrix of Figure 1 into an orderly, stacked fiber array. No attempt has been made to perform a similarly rigorous analysis for the high-temperature multilayer systems under discussion. The increased complexity and uncertainty of predicting fiber-to-fiber contact area and interface resistance at elevated temperatures have precluded this.

In the Phase II program an attempt has been made to fit the high temperature thermal conductivity data to a modified form of Wang's suggested temperature polynomial⁽¹⁾. This polynomial, expressing, $K(T)$, conductivity, of a multifoil system in vacuum as the sum of solid conduction and radiative components, is as follows:

$$K(T) = K_s + K_r = a(n) T^{1/2} + b(n) T^3 \quad (1)$$

The function, $a(n)$, accounts for previously described solid conduction effects in a lump sum fashion. The $T^{1/2}$ relationship is selected to represent the temperature variation of thermal conductivity of the fiber parent material (SiO_2).

* K_s and K_r in Eq. 1 are solid and radiative conductivities at T . These same symbols are also used to mean effective (or average) solid and radiative conductivities between boundary temperatures T_h and T_c , i.e., $K_a = K_s + K_r$ (see Table III). In all cases, it is clear as to which definition is implied.

Figure 1 - Typical Matrix for Multilayer Insulation
Spacer Material

The function, $b(n)$, accounts for the monotonic dependence of radiation heat transfer on the number of discrete shields per unit thickness of multilayer insulation. The T^3 term represents the fourth power dependence of radiant emission from a surface at temperature (T) .

After integration, the expression for $K(T)$ between boundary temperatures T_h and T_c becomes:

$$K_a = \frac{1}{T_h - T_c} \int_{T_c}^{T_h} K(T) dT = \left(\frac{2}{3}\right) a(n) \left(\frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c}\right) + \frac{b}{4}(n) \left(\frac{T_h^4 - T_c^4}{T_h - T_c}\right) \quad (2)$$

The radiative coefficient $\frac{b(n)}{4}$ can be expressed approximately as $\frac{\sigma \epsilon_e}{24n}$ which is the common expression associated with radiative heat transmission through multiple, staged reflective shields of emissivity ϵ_e . For simplicity, the temperature dependency of the emissivity is not expressed in Equation (2). Rather, the shield emissivity (ϵ_e) is taken to be an effective value for the alternate layer system over a temperature gradient T_h to T_c . For aluminum and copper foils (literature ϵ data relatively constant with temperature), the approximation is good. Some error is introduced when evaluating nickel and molybdenum, whose surface emissivities are strong functions of temperature.

1.1.2 Plain and Metal Flake Opacified Fibrous Multilayer Insulations

The thermal performance of plain fibrous insulations has been studied by various investigators⁽²⁻⁴⁾. These fundamental treatments have been based on the simplified two-flux model of Schuster for the treatment of radiation. Larkin and Churchill⁽²⁾ in their studies on heat transmission through fibrous materials comprised of relatively small diameter fibers ($\sim 1.0\mu$ or smaller), determined that radiation attenuation occurs mainly by scattering.

For the special case of a nonabsorbing insulation with constant solid conductivity, Larkin and Churchill⁽²⁾ derived the following solution, based on the standard two-flux model, for total heat flow through a fibrous insulation system operating in vacuum and bounded by opaque surfaces.

$$q = \frac{k_s(T_h - T_c)}{L} + \frac{\sigma (T_h^4 - T_c^4)}{(1/\epsilon_h) + (1/\epsilon_c) - 1 + N_e L} \quad (3)$$

where q is the total heat transferred from a surface at temperature T_h to a surface at temperature T_c , and N_e is the effective backscattering cross-section of the fibrous matrix.

Rewriting the Larkin-Churchill equation in the form of Equation (2), the effective thermal conductivity of the metal flake-opacified fibrous insulation is expressed as:

$$K_a = \frac{1}{T_h - T_c} \int_{T_c}^{T_h} K(T) dT = \frac{2}{3} a'(n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c} + \frac{\sigma L (T_h^4 - T_c^4)}{(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1 + N_e L) (T_h - T_c)} \quad (4)$$

It is important to note that the thermal conductivity for the flake-opacified systems is unlike the more "traditional" K value developed for the multiple foil system. The radiation component of Equation (4) is dependent not only on temperature (T) and effective backscattering cross section (N_e), but also on insulation thickness (L) and optical properties of the boundary surfaces (ϵ_h, ϵ_c).

However, by the proper selection of boundaries and sample thickness, test samples may be described by a simplified, yet sufficiently accurate, version of Equation (4) which lends itself quite well to solution by the graphical techniques. This expression and its attendant boundary conditions are given below:

$$K_a = \frac{1}{T_h - T_c} \int_{T_c}^{T_h} K(T) dT = \frac{2}{3} a'(n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c} + \frac{\sigma}{12 N_e} \cdot \frac{(T_h^4 - T_c^4)}{(T_h - T_c)} \quad (5)$$

where $(1/\epsilon_h + 1/\epsilon_c - 1) \lll NL$ for the case of black boundaries ($\epsilon_h = \epsilon_c = 1.0$) and sample thickness > 0.15 in. Considering that typical effective backscattering cross sections (N_e) for the tested materials are 100 in.⁽¹⁾ or greater⁽²⁻⁴⁾, then $(1/\epsilon_h + 1/\epsilon_c - 1)$ is no less than 15 times lower than the $N_e L$ term and the approximation of Equation (5) is valid.

The implications of the term "effective", as used in describing the predicted N_e -parameters, should be noted. Since the N_e -values are empirically determined from experimental data according to Equation (5), it follows that:

* Factor of 12 required to convert N_e from (inches)⁻¹ to (feet)⁻¹

(1) Values are average for a sample temperature between mean hot-side temperature $(T_h)_{\text{mean}}$ and T_c .

(2) Heat reaching the cold side, T_c , and thus registered by the flux meter, includes radiation from the fibrous structure itself since it is at all points higher in temperature than T_c .

(3) Sample temperature varies from T_h to T_c and will be governed by a balance between the bulk material's solid conductance and net radiation from the fibers, at intermediate temperature, to the cold boundary (T_c).

1.1.3 Empirical - Graphical Data Reduction Techniques

The expressions in Equations (2) and (5) are, at best, an approximate description of the effective thermal conductivity of multi-foil and fibrous multi-layer insulation systems. The approximate nature of these equations derives from: (1) consideration of solid conduction and radiation as uncoupled, additive quantities, (2) the "lump-sum" treatment of solid conduction and the assumption of a $T^{1/2}$ relationship at elevated temperatures, (3) the assumption, in the case of opacified non-foil systems, that radiative attenuation is by scattering only, (4) the use of "effective" emissivity (E_e) and backscattering cross-section (N_e) parameters.

Although approximate in nature, the K_a expressions may be solved empirically (using experimental flat plate test values) to yield useful thermal performance data. Specifically, the K_a relationships have served as a basis for:

- (1) Empirical correlation of K_a as a function of temperature (T) and layer density (n).
- (2) Development of empirical K_a expressions for regenerating K_a values for any boundary temperatures and layer densities (loads) within the tested ranges.
- (3) Comparative studies of effective emissivities and backscattering cross sections for various multilayer insulations and material composites.
- (4) Gaining a deeper insight into thermal behavior of multilayer systems, and how properties of the component materials affect this behavior.

The utility of these empirical expressions is clearly illustrated in the thermal performance discussions of Section 1.3.

In the empirical-graphical data reduction technique, solid conduction and radiation coefficients are determined from experimental thermal conductivity data. In the graphical technique, Equations (2) and (5) are first linearized as shown below:

Multi-Foil Systems

$$K_a \frac{(T_h - T_c)}{(T_h^{3/2} - T_c^{3/2})} = \frac{\sigma \epsilon_e}{24n} \frac{T_h^4 - T_c^4}{T_h^{3/2} - T_c^{3/2}} + \frac{2}{3} a(n) \quad (6)$$

Fibrous Multi-Layer Systems

$$K_a \frac{(T_h - T_c)}{(T_h^{3/2} - T_c^{3/2})} = \frac{\sigma}{12N_e} \frac{T_h^4 - T_c^4}{T_h^{3/2} - T_c^{3/2}} + \frac{2}{3} a'(n) \quad (7)$$

These two equations are of linear form (i.e., $y = C_1 X + C_2$) where the slope C_1 is equivalent to $\frac{\sigma \epsilon_e}{24n}$ or $\frac{\sigma}{12N_e}$ for multi-foil or fibrous multilayer systems, respectively. The y-intercept (C_2), then, represents the solid conduction coefficient for each system.

In applying the methods a plot is generated, corresponding to a particular compressive loading (layer density), by solving Equations (6) or (7) for each set of K_a , T_h and T_c values measured at that particular layer density. From this plot, the effective parameters (ϵ_e or N_e) and the solid conduction component are estimated from the slope and y-intercept respectively. By repeating this procedure at several values of layer density (n), sufficient data are generated to correlate the K_s and K_r coefficients to layer density.

The empirical techniques are illustrated for the aluminum-106 glass paper multifoil insulation system in Figures 2 to 5. Figure 2 presents the measured K_a data for each layer density (loading), plotted as a function of source temperature T_h . Plots of the linearized thermal conductivity expression of Equation (6) are given in Figure 3. The slope and y-intercept for each of these plots yields effective emissivity (ϵ_e) and solid conduction coefficient ($\frac{2}{3} a(n)$) for the Al-106 glass system at specific values of layer density. The relationships of ϵ_e and $\frac{2}{3} a(n)$ to layer density are given in Figures 4 and 5. The approximate expressions were obtained by visual fit of the data.

For multi layer vacuum thermal insulation, the effective emissivity of the foils can increase several fold depending on the properties of the foil and spacer material¹². The lower the emissivity of the foil, in a purely scattering medium, and higher the absorption coefficient of the spacer, the more pronounced is this effect. Spacer material, for example, will have a significant effect on aluminum foil shields, which has a low emissivity of about .05 at 800°F to begin with. (Figure 4).

Effective thermal conductivity values calculated by these empirically-developed expressions [Equations (6) and (7)] generally are in good agreement with measured data. Deviations of 10-20% are common due to the temperature averaging nature of the empirical procedure. The largest discrepancy normally occurs in the low-density region (near zero load) where it is felt that the random effects of disoriented fiber, contact area, and interface resistance variations are more pronounced.

During the Phase II program an effort was made to refine the approximate K_a expression, specifically as pertains to the solid conductance of the fibrous spacer materials. However, the random fibrous structure did not lend itself to thermal modeling and total thermal conductivity data were not sufficient for making substantial empirical refinements to this solid conductance term.

A modified approach in estimating the N_e parameter for fibrous multilayer systems was used in earlier data reduction work. This empirical analysis did not assume a form for the solid conductance term but, rather, found limiting values for N_e by means of maximum and minimum radiative heat transfer assumptions. Significant error was introduced due to the coarseness of the radiative heat transmission assumptions and the resultant large spread between maximum and minimum values. This approach was abandoned in favor of the previously described empirical-graphical technique, which assumes the functional form of the solid conductance term to be $a'(n) T^{1/2}$.

Figure 2 $K_a(T)$ for Al-106 Glass Multifoil Insulation

Figure 3 - Linearized Plots - Al-106 Glass Data Reduction

Figure 4 - Effective Emissivity as a Function of
Layer Density - Al-106 Glass Multifoil

Figure 5 - Solid Conduction Coefficient
Al-106 Glass Multifoil

1.2 Guarded Flat Plate Test Concept and Apparatus

The steady-state, guarded flat plate testing technique has been used successfully in the evaluation of several high temperature multilayer insulation systems, operating in a vacuum environment, at hot-side temperatures from 500°F to above 2000°F. From a testing standpoint, the multiple foil systems are most difficult to treat due to their extremely high ratio of lateral to normal thermal conductivity. By necessity, tester design and development was directed toward reliable and accurate measurement of K_a (normal direction) for these multifoil systems.

The basic multifoil insulation configuration is comprised of highly reflective, discrete metallic foils, oriented normal to the direction of heat flow and separated from each other by low conductance, thin fibrous spacers. Typical thermal conductivities and operating temperatures for several multifoil insulations have been described in Tables I and II.

The primary problem in measuring thermal conductivity of these insulation systems stems from the high thermal impedance of the insulation in the direction normal to the plane of the metallic foils in comparison to the very low impedance in the the plane to the foils. Effective thermal conductivities (K_a) in the plane of the layers are typically 3 to 4 orders of magnitude higher than K_a values normal to the layers. This high impedance in the normal direction combined with the high degree of anisotropy usually results in a substantial temperature difference across the small test sample thickness, which further complicates the edge guarding task.

In addition to the high impedance high anisotropy characteristics of multilayer insulation, an added degree of difficulty is introduced by the compressibility of the composites under mechanical load and the sensitivity of system conductance to the level of compression. It is required, therefore, that the thermal conductivity test device incorporate the ability to accurately control the insulation composite density, as well as provide the required edge thermal guarding. The described flat plate thermal conductivity tester was designed with these two objectives in mind.

1.2.1 Testing Concept

The passively guarded, flat plate test arrangement for measuring effective thermal conductance of high-temperature multilayer insulations under steady-state conditions is shown schematically in Figure 6. Characteristic features of the test sample configuration are:

Figure 6 - Guarded Flat Plate Test Configuration

- ① Multi-Foil Insulation Samples; Typically 15 cm x 15 cm x 1 cm
 - ② Multi-Foil Insulation Guard Sections
 - ③ Resistance Heater Assembly
 - ④ Heat Flow Meter, 5.6 cm x 5.6 cm
 - ⑤ Cold-Side Compression Plates
- Thermocouple Sensors Located as Shown.

Q_H - Flux into hot side;

Q_C - Flux from cold side

1. Flat, planar multilayer insulation samples, typically 6 in. X 6 in. X 0.4 in., fabricated and installed to form a dual-sample, symmetrical tester geometry.

2. The test configuration provides for testing multilayer insulation samples over a wide mechanical compression loading range (typically 0-15 psi), and at several hot-side temperatures up to the service temperature limit for the insulation.

3. Multilayer insulation guards, which are matched to the sample materials and layer density, minimize lateral losses in the highly anisotropic multilayer sample so that one-dimensional heat flow is effectively maintained over the central 2.25 in. X 2.25 in. metering zone.

1.2.1.1 Thermal Performance Parameters

The parameter selected to describe performance of the multilayer insulation systems is thermal conductance. It is defined as the time rate of heat flow per unit area, under steady-state conditions, in a direction normal to the multiple-foil insulation slab and across a temperature gradient, T_h to T_c . The conductance (C) is expressed as follows:

$$C = \frac{Q}{A (T_h - T_c)} \quad (8)$$

where A denotes unit area and T_h and T_c are temperatures of the hot-side and cold-side boundaries, respectively.

For multilayer insulations of relatively high layer density, such as are encountered here, the parameter, effective thermal conductivity (K_a), is defined and used as a performance indicator. The K_a parameter is expressed as:

$$K_a = CL = \frac{QL}{A (T_h - T_c)} \quad (9)$$

where L is the multilayer insulation slab thickness. The effective thermal conductivity is a function of temperature T and layer density (n), where n denotes the number of reflective shields per unit thickness.

The K_a parameter is essentially independent of thickness for multilayer insulations containing a sufficient number of reflective shields such that the optical properties of the hot and cold side boundary surfaces have a negligible

effect on overall performance. For thermal boundaries whose surfaces are relatively black ($\epsilon = 1.0$), the product $n \times L$ greater than 20 effectively satisfies the above condition. The various high temperature multilayer insulations tested are of sufficiently high layer density, and $n \times L$ greater than 20 is satisfied in all test cases. The K_a parameter enables direct comparison of thermal performances for various multilayer insulations, even though the systems are tested at somewhat different thicknesses.

1.2.1.2 Test Configuration

The principal functions of the guarded flat plate test assembly are to:

1. Achieve and maintain steady-state heat flow conditions for hot-side temperatures ranging from 500-1800°F. Corresponding cold side temperatures are 100-400°F.
2. Through the use of matched, multilayer guards, lateral heat flow in the sample is minimized such that one-dimensional heat flow is closely approximated in the metering zone (5.0 in.² central zone out of a total sample area of 36 in.²).
3. Accurately measure (a) heat flux per unit area in the metered zone, (b) hot and cold boundary temperatures, T_h and T_c , and (c) sample thickness (L), to enable computation of corresponding effective thermal conductivity.
4. Achieve and control the mechanical or compressive loading (i.e., layer or shield density) of the multilayer sample. Typically, K_a parameters are measured over a range of layer densities corresponding to 0-15 psi loading range.

The multilayer insulation test sample assembly of Figure 6 has been designed to achieve steady-state heat flow conditions under which K_a values may be obtained. The dual-sample system, when assembled together with the pre-fabricated multilayer insulation guard sections, provides a complete enclosure around the resistance heater. Power input to the heater controls heat flux to the insulation and, ultimately, the temperature gradient through the insulation sample. Hot-side temperature T_h is assumed to be essentially uniform over the hot surface of both sample and guard sections. Temperatures are measured by thermocouple sensors as shown.

Under the conditions of sample symmetry and uniform boundary temperatures, the temperature profiles through the guard and sample sections are

approximately matched in the interior as well as in the vicinity of the perpendicular gap; i.e., butt joint between sample and guard. This gradient correspondence at the gap (.02 in. width or less) implies minimum radiation transfer across the gap and low edge heat loss from the sample sections. In addition, maintaining the gap width at .02 in. or less and using a fibrous gap filler (extended spacer material or powdered filler) further attenuates radiant interchange between sample and guard, as well as the net radiation loss from the gap.

Direct thermal coupling between guard and sample sections (such as by interconnecting foil shields) is avoided. Should the two be strongly coupled, the relatively ill-defined installed guard configuration could significantly alter the correspondence between the measured thermal conductivity and the thermophysical properties of the accurately defined, planar multilayer sample*. However, in its function of an uncoupled, but approximately matched guard section, it acts as an effective deterrent to radiative heat loss from the sample edges. Previous, two-dimensional heat flow analysis on the sample-guard configuration of Figure 6 indicates that gap widths of .02 in. (unfilled) and .05 in. (filled) could exist with deviations in K_a still maintained at less than 15%.

1.2.2 Flat Plate Apparatus and Test Method

The flat plate sample-guard assembly, with pertinent design features and dimensions, is shown in section view in Figure 7 and pictorially in Figure 8. During testing, the sample assembly is contained completely within a bell jar enclosure 18 in. diameter by 30 in. high. The enclosed volume is maintained at a vacuum pressure of $\sim 1 \times 10^{-4}$ torr by means of dynamic pumping, using an oil diffusion pump system.

1.2.2.1 Apparatus - Instrumentation

With reference to the flat plate test schematic of Figure 9, principal hardware components and instrumentation are described.

Hardware Components

Resistance Heater - - The resistance heating element is constructed of woven graphite tape, Type WCB, 1.0 in. wide by .025 in. thick, wound on a flat ceramic plate. Electrical isolation of the heating element is provided by ceramic (quartz or alumina) edge sections and surface plates. Electrical leads are of stranded molybdenum wire. Input power is variac controlled from the 220 volt, 110 amp source.

* A strongly coupled condition would result in a measured K_a corresponding to the sample-guard system rather than the desired K_a -value for the well-defined multi-foil sample alone.

Figure 7 - Flat Plate Test Fixture - Section View

FLAT PLATE TESTER
INSTALLED SAMPLE CONFIGURATION WITH EXTENDED COMPRESSION PLATES

Figure 8 - Flat Plate Test Assembly with Installed Sample

Figure 9 - Flat Plate Test Schematic

Cold Face Sink Plates - - Steel sink plates, 8 in. X 8 in. X 0.6 in., act as the cold-side boundaries for the 6 in. X 6 in. multifoil samples as well as the flat, planar portions of the guard sections. The 2.25 in. X 2.25 in. heat flow meter is mounted on the upper sink plate, as shown. Water coolings coils have recently been added to provide improved control of cold-side temperatures (see Figure 8).

Compression Loading Device - - Compression loading on the sample is regulated through variation of the total gap width between the upper (movable) and lower (stationary) sink plates. Load-deflection data for the tested multifoil insulations relate compressive load to sample thickness (i.e., total gap width).

The upper sink plate is adjusted vertically by means of a threaded coupling, mounted external to the vacuum space, and connected to the upper sink plate by two load transmission rods. The entire sample and planar sections of the guard are compressed simultaneously. The load range specified in testing is 0-15 psi.

Base Plate Assembly - - - The stainless steel, 20 in. diameter base plate, provides a machined bearing surface for the gasket-sealed bell jar enclosure. All vacuum feed-throughs for electrical power leads, instrumentation, and load transmission rods are located in the base plate assembly.

Instrumentation

Pertinent instrumentation for heat flux, temperature, sample thickness, and vacuum pressure measurement are described below. Various readout and control devices used in controlling and monitoring test conditions are also indicated.

Heat Flow Meter - - - Model H 11 (Thermonetics Corporation). Thermopile metering device with dimensions 2.25 in. X 2.25 in. X .07 in. Calibration constant is 10 Btu/hr-ft²-mv and manufacturers rated accuracy is 3%. Maximum use temperature is 450°F.

Thermocouple Sensors - - - Chromel/Alumel*, ISA Type K. Chromel/Alumel thermocouples, .010 in. wire diameter, insulated with quartz sleeving. Thermocouples are calibrated against a certified Pt/Pt-10 Rh thermocouple traceable to NBS standards. Typical deviation is $\pm 1\%$ or less.

Input Power Controller - - - Controller has a range of 0-2200°F with a readability of $\pm 8^\circ\text{F}$. Its function is to attenuate and control input power

* Trademark of Hoskins Company.

to the sample heater to establish steady state test conditions at up to five hot-side temperatures ranging from $\sim 400^{\circ}\text{F}$ to maximum service temperature for the tested insulation. The power attenuation program (i.e., input power level and dwell time) is preselected for each sample.

Strip Chart Millivolt Recorders - - - Millivolt recorders provide a continuous monitoring of thermocouple and flux meter outputs. In general, millivolt recorder sensitivity is $\pm .25\%$. Readability accuracy ranges from .2 - 1.0% of full scale. All recorders are calibrated against an NBS standard potentiometer.

Vacuum Gauge - - - A Philips cold cathode ionization gauge is used to monitor vacuum pressure within the test column. The gauge is calibrated against a McLeod standard vacuum gauge.

Thickness Indicator - - - A dial indicator, readable to .001 in. monitors the total gap width between compression loading (sink) plates.

1.2.2.2 Sample Fabrication and Assembly

In fabricating the 6 in. X 6 in. multifoil insulation samples, the foil and fibrous spacer materials are cut individually to the precise final dimensions. In assemblies where the spacer material also acts as gap filler, the spacers are cut oversize by .040 in. on each dimension. Sample assemblies using a powder filled gap have shield and spacer layers cut to identical 6 in. X 6 in. dimensions. The alternate layer samples are then stacked to form the final sample configurations, using a specially design aligning fixture. Typical multifoil samples are 0.4 in. thick, and contain from 25 to 40 reflective shields.

The guard sections are of the same materials and at the same layer density as the samples. The edge guard envelopes, as shown in Figure 10, are assembled, retained in their desired configuration, and finish cut to the final dimensions.

The sample-guard assembly is constructed as follows:

(a) The two multifoil insulation samples are positioned on either side of the resistance heater.

(b) Edge guard sections or "envelopes" are installed around the perimeter of the 8 in. X 8 in. heater assembly, and are drawn up to meet the insulation samples at a butt joint with gap width $\leq .020$ in.

(c) Cold side sink plates, including the mounted heat flow meter, are positioned at upper and lower sample-guard surfaces.

Figure 10 - Multilayer Insulation Guard Sections

(d) The completed assembly is installed within the bell jar enclosure.

Thermocouple sensors are installed during sample assembly. Two Chromel/Alumel (Pt/Pt 10 Rh for $T_h > 1800^\circ\text{F}$) thermocouples are at the hot-side boundary, to monitor and control temperature T . Cold-side Chromel/Alumel thermocouples are located at: (1) the center of the upper cold surface, in the heat metering zone, (2) the upper cold surface of the edge guard section, and (3) the center of the lower cold surface. All thermocouples are monitored continuously and give a record of hot and cold-side temperatures as well as an indication of the thermal balance between sample and guard.

1.2.2.3 Testing Procedure

Prior to thermal testing, load-deflection characteristics of the multifoil insulation systems are determined using either dead weight or pneumatic apparatus. These P vs. δ data describe the compressibility characteristics of the insulation and give an accurate relationship between layer (shield) density and compressive loading. This relationship is used in subsequently establishing the desired compressive load conditions during thermal testing.

After the sample-guard assembly is installed and instrumented, the test enclosure is evacuated to the desired pressure level ($p \leq 1 \times 10^{-4}$ torr). The initial mechanical loading (i.e., shield density) condition is set, and the hot-side temperature program is begun. The input power controller achieves and maintains temperature (T_h) values which are pre-selected and programmed for the particular multifoil sample. Dwell time to achieve steady-state conditions at any temperature level ranges from 6 to 8 hours. After this elapsed time, power is attenuated automatically to obtain the next hot-side temperature point.

Heat flow data are obtained at a minimum of four or five hot-side temperature points for each loading condition. Subsequent load conditions are set manually; the hot-side temperature program is repeated for each new setting.

From the measured heat flow, temperatures T_h and T_c , and thickness L , the effective thermal conductivity (K_a) values are computed from Equation (9). Thermal conductivity data (as a function of T_h) for each of five shield densities corresponding to the 0 - 15 psi load range are normally generated for each multifoil system, and presented in graphical and tabular form.

1.2.3 Modified Flat Plate Tester Design - 2500°F Service

Late in the Phase II program, the flat plate apparatus was modified to permit higher temperature operation in subsequent testing of the molybdenum-zirconia multifoil insulation. The system modifications were:

- (1) Equipment and instrumentation redesign to permit 2500°F operation.
- (2) Relocation of the cold-side flux meter from the upper to the lower sample, to provide for more uniform surface-to-surface contact between sample and meter.

The modified dual-sample configuration is shown schematically in Figure 11. Samples were 6" X 6" X 0.2" with the 2.25 in. heat flow meter centrally located at the cold boundary. The extended compression fixture, which loads sample and guard sections simultaneously, was used. Equipment modifications for 2500°F service are described briefly below:

Water-Cooled Compression Plates - - - A water cooling system was added to the sink plates to provide positive control of the cold-side temperature. The flux meter is liable to permanent damage if exposed to temperatures above 450°F. The cooling system maintained sink temperature substantially below this level.

Heater Assembly - - - The graphite tape, resistance heater assembly used high purity alumina core and shield plates, extending heater operating capability to ~3000°F.

Instrumentation - - - Pt/Pt-10Rh thermocouples were used in place of Chromel/Alumel for hot-side temperature measurement. Associated changes in read-out and recording equipment were also made.

Problems arose with the Pt/Pt-10Rh thermocouples which prevented accurate measurements at the 2500°F level. Thermocouple degradation was due to platinum reaction with system contaminants in the 2500°F, vacuum environment. The contaminants, mainly attacking the pure platinum leg, affected thermocouple calibration and, in the most severe case, caused thermocouple destruction due to formation of a low melting eutectic (see Appendix B). This problem could likely be avoided in future testing through the use of sheathed thermocouples (either platinum/rhodium or tungsten/rhenium).

Figure 11 - Modified Flat Plate Test Configuration
2500°F Service

1.3 Thermal Conductivity Results - Flat Plate Testing

Key steps in the thermal performance evaluation of multilayer insulations are outlined in Table III. Defining of the performance parameter-- effective thermal conductivity (K_a)-- and description of flat plate testing methods have been discussed previously in Sections 1.1 and 1.2.

Measured flat plate K_a data are presented for multifoil insulations with maximum operating temperature range from 900°F to 2500°F, and fibrous multilayer insulations (non-foil) operating at temperatures from 900°F to 1500°F. The basic K_a values are correlated to layer density (n) and temperature (T), using the empirical-graphical techniques of Section 1.1. The correlations provide for:

- (1) Regeneration of K_a values at any boundary temperatures and layer densities within the stated test ranges.
- (2) Determination of effective thermophysical properties for the multilayer composites (i.e., effective emissivity (ϵ_e) of multifoil systems and effective backscattering cross section (N_e) for fibrous multilayer insulations).
- (3) Some assessment and comparison of thermal behavior of various multilayer insulation systems and the materials which comprise these systems.

1.3.1 Multifoil Insulation Systems

Effective thermal conductivity data are presented for multifoil systems in Figures 12 to 20. The K_a data are plotted as a function of compressive load (layer density) over the 0 - 15 psi test range, at several operating temperature levels. The insulation composites, and their respective operating ranges, are listed on the following page.

<u>Multifoil System</u>	<u>Source Temp. Range</u>	<u>Compressive Load (Layer Density) Range</u>	<u>K_a Data</u>
.00025" Al foil .003" 106 glass	900-300°F	0 - 15 psi (142 - 345 ℓ /inch)	Figure 12
.00025" Al foil .003" Al opacified glass	900-300°F	0 - 15 psi (200 - 450 ℓ /inch)	Figure 13
.0005" Cu foil .005" Refrasil quartz	1400-500°F	0 - 15 psi (80 - 180 ℓ /inch)	Figure 14
.0005" Cu foil .010" Cu opacified quartz	1400-500°F	0 - 15 psi (40 - 110 ℓ /inch)	Figure 15
.0005" Ni foil .005" Refrasil quartz	1800-500°F	0 - 6 psi (85 - 180 ℓ /inch)	Figure 16
.0005" Ni foil .010" Ni opacified quartz	1600-500°F	0 - 15 psi (53 - 110 ℓ /inch)	Figure 17
.0005" Ni foil .005" Astroquartz cloth	1600-500°F	0 - 15 psi (108 - 152 ℓ /inch)	Figure 18
1800°F Composite	1800-500°F	0 - 15 psi (115 - 171 ℓ /inch)	Figure 19
.0005" Mo foil .006" ZrO ₂ cloth	2500-500°F	.3 psi (128 ℓ /inch)	Figure 20

All of the above multifoil systems were tested in a vacuum environment ($P \simeq 1 \times 10^{-4}$ torr).

Empirical coefficients for the solid conductance (K_s) and radiative (K_r) contributions to effective thermal conductivity are presented in Table IV. These coefficients are discussed in conjunction with the basic K_a data.

1.3.1.1 Effects of Compressive Load on Thermal Performance

The K_a curves of Figures 12 to 19 illustrate behavior of the effective thermal conductivity over the full range of compressive load (layer density) from 0 - 15 psi. The K_a versus load plots generally follow a characteristic shape--

TABLE III

Thermal Performance Evaluation - Multilayer Insulations

Multifoil Insulations

Mean Effective Thermal Conductivity

$$K_a = K_s + K_r$$

$$\text{where } K_s = \frac{2}{3} a(n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c}$$

$$K_r = \frac{\sigma \epsilon_e}{24n} \cdot \frac{T_h^4 - T_c^4}{T_h - T_c}$$

Fibrous Multilayer Insulations

Effective Thermal Conductivity

$$K_a = K_s + K_r$$

$$\text{where } K_s = \frac{2}{3} a'(n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c}$$

$$K_r = \frac{\sigma}{12 N_e} \cdot \frac{T_h^4 - T_c^4}{T_h - T_c}$$

Flat Plate Testing

K_a measurement at 5 hot-side temperatures between 300°F and $T_{max.}$ and 5 compressive loads between 0 - 15 psi.

Thermal Performance Characterization

Determine solid (K_s) and radiative (K_r) components of effective thermal conductivity (K_a). Correlate data as a function of layer density (n) and temperature (T). Determine:
(a) Effective emissivity (ϵ_e) for multifoil systems
(b) Effective backscattering cross-section (N_e) for fibrous multilayer systems.

Figure 12 EFFECTIVE Thermal Conductivity -
Al-106 Glass

FIGURE 13 - EFFECTIVE THERMAL CONDUCTIVITY -
ALUMINUM - ALUMINUM OPACIFIED MULTI-LAYER INSULATION

Figure 14 - Effective Thermal Conductivity -
Cu-Refrasil Quartz

Figure 15 - Effective Thermal Conductivity -
Cu-Cu Opacified Refrasil Quartz

Figure 16 - Effective Thermal Conductivity -
Ni-Refrasil Quartz

Figure 17 - Effective Thermal Conductivity -
Ni-Ni Opacified Refrasil Quartz

Figure 18 - Effective Thermal Conductivity -
Ni-Astroquartz Cloth

Figure 19 - Effective Thermal Conductivity -
1800°F Composite

Figure 20 - Effective Thermal Conductivity
Mo-Zirconia Cloth

an initial, sharp rise in K_a at lower compression (0 to 1.0 psi) followed by a wide compressive load span (extending in most cases to 15 psi) where K_a increases relatively slowly.

This pattern is discussed below in terms of the solid conduction and radiative contributions to total conductivity.

Low Load Range - - Effective thermal conductivity increases rapidly over the 0 - 1.0 psi load range, reflecting a significant increase in solid conductance due to a breakdown in interface resistance between adjacent foils and spacers. At "near-zero" load, this interface contact resistance is instrumental in maintaining a low solid conductance (K_s) contribution. In fact, in the theoretical limiting case of $n \leq n_0$ (ideal "zero load" layer density) the K_s term would be zero since foils and spacers would not be in contact at any point. In the practical case, mild loadings (either uniform or localized) reduce this interface resistance with a resultant increase in K_s and, ultimately, K_a . This characteristic is more pronounced at lower source temperatures, where K_s is a substantial portion of the total conductivity.

Load Range 1.0 - 15.0 psi - - In this range, interface effects no longer predominate. Solid conductance (K_s) increase is governed mainly by the increase in inter-fiber contact within the fibrous matrix, the physical characteristics of this matrix (e.g., woven cloth or fibrous paper), and thermal conductivity of the parent fiber material itself. These factors result in inherently slower changes in K_s than were experienced with the interface resistance effects. Within this range, layer density (n) continues to increase with the increasing load, thereby reducing the radiative contribution (K_r). The compensating behavior of the K_s and K_r contributions results in a smaller net increase in total conductivity (K_a). This compensating effect is noted especially at the higher operating temperatures, where the radiative (K_r) term is significant.

At higher compressive loadings (> 15 psi), the K_a values would again increase more rapidly. As the multifoil insulation becomes highly compacted, increases in K_s again become significant and the attendant compensation through reduced K_r is minimal since layer density changes become small. Also, as will be discussed later, the high compaction and high degree of contact between foil and fibrous spacer appear to have a detrimental effect on foil emissivity (note effective emissivity relationships for Ni multifoil systems in Table IV). Illustration of these effects within the 15 psi compression range is seen for the Ni-Astroquartz system in Figure 18.

Comments on thermal behavior of specific multifoil insulation systems, and the relationship of K_a to compressive load, are presented in the ensuing paragraphs.

1.3.1.1.1 Aluminum-Glass Multifoil Systems

In comparing the effective thermal conductivities of the Al-106 glass and Al-Al opacified glass insulation systems at corresponding load and temperature conditions, it is observed that:

(1) K_a values of the Al-Al opacified glass insulation is 30-50% lower than those for the Al-106 glass system at all temperatures in the 0-0.5 psi range.

(2) In the 1-15 psi range the converse is true, with K_a values for the Al-Al opacified glass insulation running 50-100% higher than corresponding values for the Al-106 glass system.

This behavior is explained by examining the solid conduction (K_s) and radiative (K_r) contributions to total conductivity for the two insulations. At near zero load where K_s is very small, the 40% higher layer density of the Al-Al opacified insulation results in a lower K_r contribution for this insulation in comparison with the Al-106 glass. This layer density difference accounts for essentially all of the difference in the K_a value. The use of the aluminum opacified separator in the multi-foil system provides little improvement in radiation attenuation, since the effect of flake opacification is small in comparison to the attenuation achieved by the densely packed, reflective foil shields.

At higher compressive loads where solid conductance is substantial, the higher K_s contribution of the aluminum flake opacified spacer overshadows the better radiation attenuation of the Al-Al opacified glass insulation. The plain glass spacer, on the other hand, has an inherently lower K_s factor resulting in a better overall performance for the Al-106 glass system.

To summarize, in multifoil systems where radiation is already minimized by the foil shields, an opacified spacer does not give significant performance improvement and, furthermore, can be detrimental at high loads due to its higher solid conductance. Other design considerations may, however, dictate the use of the Al opacified spacers in multifoil system design; e.g., cases where the opacified separator will extend beyond the multifoil insulation and serve as a gap filler insulation.

1.3.1.1.2 Copper-Refrasil Quartz Multifoil Systems

Characteristics of K_a over the full 0-15 psi compressive load range are in agreement with the general behavior previously ascribed to multifoil insulations. The system using Cu opacified quartz separators ($\sim .010$ " thick) is performance limited due to the excessive thickness of the separator. The higher layer

densities at relatively low load, which are necessary in efficient radiation attenuation, are not achievable in this system. This same observation holds for the Ni-Ni opacified quartz insulation, where the opacified separator was available only in the .010" thickness.

1.3.1.1.3 Nickel-Refrasil Quartz Multifoil Systems

Again, the characteristic behavior of K_a over the full 0-15 psi load range is typical of what would be expected of the multilayer systems.

The higher basic solid conductance of the woven quartz (Astro-quartz) spacer compared with the Refrasil quartz fibrous paper is noted in comparing the K_a -load relationships of Figures 16 and 18. In the 1.0-15.0 psi loading range, the K_a curves for the Ni-Astroquartz system increase at a significantly faster rate than those for the Ni-Refrasil quartz system, implying a greater solid conduction (K_s) contribution. This is due to the higher density and "parallel-fiber" construction of the woven quartz, which results in substantially more solid conduction heat transfer through the spacer.

Examination of 0-1.0 psi data for these two systems further illustrates the importance of interface resistance. At essentially zero-load, the K_a values for the Ni-Refrasil quartz and Ni-Astroquartz insulations are virtually identical. Only when this interface resistance is overcome by increasing load does the higher solid conductivity of Astroquartz become influential. It can be concluded, then, that under conditions of near-zero load the interface resistance, not the inherent properties of the spacer, govern the solid conductance contribution to total system performance.

1.3.1.1.4 Composite Multifoil System

The 1800°F composite materials system is identical to the composite insulation which were on long-term test (Section 2.0). The shield-spacer component systems are described as follows:

<u>Component</u>	<u>Temperature Range</u>	<u>Number of Layers</u>
Molybdenum foil (.0005") Astroquartz cloth (.005")	1800°F-1600°F	23
Nickel foil (.0005") Refrasil quartz paper (.005")	1600°F-1400°F	11
Copper foil (.0005") Refrasil quartz paper (.005")	1400°F- 900°F	6
Aluminum foil (.00025") Aluminum opacified glass paper (.003")	900°F-Ambient	2

The K_a -compression loading characteristics are similar to those described for the Ni-quartz systems (Figures 16 and 18). Since the 1800°F composite is comprised mainly (~80%) of Mo-Astroquartz and Ni-Refrasil quartz, it is logical that the composite should display similar thermal-mechanical characteristics.

The composite multifoil system represents an efficient utilization of foil-spacer components to achieve an improved overall system thermal performance. The multifoil components are selected for minimum thermal conductivity within their specified operating temperature range, and are physically staged within the composite to span this temperature range. Because of the radiative heat transfer influence on the temperature profile, the composite is dominated by the higher-temperature multifoil components (e.g., Mo-Astroquartz). However, the lower temperature systems also influence overall performance to a noticeable extent, and represent additional savings in system cost and weight.

1.3.1.2 Empirical Correlation and Effective Thermophysical Properties

The empirical K_S and K_T coefficients for the multifoil systems are presented in Table IV. These coefficients, both functions of layer density, were determined by applying the graphical techniques of Section 1.1 to the measured K_a data. Use of these coefficients in the basic K_a equation provides a means of regenerating thermal conductivity values for a given set of boundary temperatures and compressive loads within the test ranges.

In general, thermal conductivity values computed from the empirical correlations of Table IV agree with measured K_a -data to within 10-20%. Deviations in the order of 20-40% occur, in some cases, at lower temperature, "near-zero" load conditions where the rapidly changing K_a (due to interface effects) is difficult to correlate by the empirical techniques. Some improvements can be made by correlating the data in two or more steps corresponding to specific portions of the layer density range. This approach worked well for the 1800°F composite system (see Table IV) but has not been applied generally to all the multifoil correlations.

For thermal performance estimates on installed multifoil insulation systems, where some approximations of geometry and configuration are necessarily made anyway, the 20% level of accuracy on K_a data is felt to be reasonable. Also the correlations generally give regenerated K_a -values which are conservative (i.e., higher than measured). Further refinement of the empirical fitting techniques has not been justified to date for the reasons stated above, along with the fact that the measured K_a -data themselves are subject to experimental error (see Section 1.4). Such refinements in the correlation would necessarily have to be coupled with upgraded experimental measurement techniques.

TABLE IV
Empirical Thermal Conductivity Parameters
For Multifoil Insulations

Multifoil System	Source Temperature Range °F	Layer Density Range (.04-15 psi) ℓ /in.	K_s Coefficient $\frac{2}{3} a (n)$ 10^{-4} Btu/hr-ft-°R ^{3/2}	K_r Coefficient $\frac{1}{4} b (n)$ 10^{-12} Btu/hr-ft-°R ⁴	Effective Emissivity (ϵ_e)
Al - 106 Glass	900-300	142-345	$[.54 \log n - 1.19]$	$72.1 \frac{\epsilon_e}{n}$	$.00033n + .08$
Al-Al Opacified Glass	900-300	200-450	$[1.67 \log n - 3.97]$	$72.1 \frac{\epsilon_e}{n}$	.09
Cu-Refrasil Quartz	1400-500	80-180	$[.408 \log n - .748]$	$72.1 \frac{\epsilon_e}{n}$	.045
Cu-Cu Opacified Refrasil Quartz	1400-500	40-110	$[.464 \log n - .768]$	$72.1 \frac{\epsilon_e}{n}$	.06 - .18
Ni-Refrasil Quartz	1800-500	85-180*	$[.64 \log n - 1.22]$	$72.1 \frac{\epsilon_e}{n}$	$.00008 T_m^{**} + .0013 n - .14$
Ni-Ni Opacified Refrasil Quartz	1600-500	53-110	$[.511 \log n - .842]$	$72.1 \frac{\epsilon_e}{n}$	$.0008 T_m + .002 n - .15$
Ni-Astroquartz	1600-500	108-152	$[5.13 \log n - 10.4]$	$72.1 \frac{\epsilon_e}{n}$	$.000126 T_m - .01$
1800°F Composite	1800-500	115-135 135-171	$[.79 \log n - 1.6]$ $[3.1 \log n - 6.52]$	$72.1 \frac{\epsilon_e}{n}$	$.00004 T_m + .02$
Mo-Zirconia	2500-500	128	.03	$0.56 \epsilon_e$	$.000054 T_m$

Basic Equation:

$$K_a = \frac{2}{3} a (n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c} + \frac{1}{4} b (n) \cdot \frac{T_h^4 - T_c^4}{T_h - T_c}$$

where T_h = hot-side temperature (°R)

T_c = cold-side temperature (°R)

n = layer density (/inch)

*180 ℓ /inch corresponds to 6.0 psi

** $T_m = 0.75 (T_h - T_c) + T_c$
weighted mean average temperature across insulation thickness accounting for typical parabolic shape of the temperature gradient.

1.3.1.2.1 Solid Conductance Coefficient

The K_s coefficient $[\frac{2}{3} a(n)]$ is correlated to layer density (n) by means of a $\log_{10}$ function:

$$\frac{2}{3} a(n) = C_1 \log_{10} n - C_2 \quad (10)$$

This expression closely approximates the observed behavior of the solid conductance contribution to total K_a of multifoil systems. At "near-zero" loads, the K_s coefficient tends toward zero, which reflects the high level of interface resistance developed by these insulations under this loading condition.

In fact, there may be some basis for expressing the K_s coefficient in terms of an empirically-derived, zero load layer density (n_0) where the following condition would hold:

$$\text{For } n \leq n_0 ; \frac{2}{3} a(n) = 0 \quad (11)$$

Applying this approach to three of the multifoil systems yields the following:

Al-106 Glass . . . $n @ .04 \text{ psi} = 142 \text{ } \ell/\text{inch}$

$$[.54 \log n - 1.19] \times 10^{-4} = \frac{1}{.54} [\log n - 2.20] \times 10^{-4} = \frac{10^{-4}}{.54} \left[\log \frac{n}{n_0} \right]$$

where $n_0 = 158 \text{ } \ell/\text{inch}$

Ni-Refrasil Quartz . . . $n @ .04 \text{ psi} = 85 \text{ } \ell/\text{inch}$

$$[.64 \log n - 1.22] \times 10^{-4} = \frac{10^{-4}}{.64} [\log n - 1.91] = \frac{10^{-4}}{.64} \left[\log \frac{n}{n_0} \right]$$

where $n_0 = 83 \text{ } \ell/\text{inch}$

Ni-Astroquartz . . . $n @ .04 \text{ psi} = 108 \text{ } \ell/\text{inch}$

$$[5.13 \log n - 10.4] \times 10^{-4} = \frac{10^{-4}}{5.13} [\log n - 2.02] = \frac{10^{-4}}{5.13} \left[\log \frac{n}{n_0} \right]$$

where $n_0 = 105 \text{ } \ell/\text{inch}$

Except for the highly compression-sensitive Al-glass systems, the empirical n_0 values appear to approach the "zero load" layer densities for the various multifoil systems (see Appendix A). The validity of this relationship is difficult to verify due to the approximate nature of the analysis and the difficulty in obtaining accurate and highly reproducible measurement of ideal zero load layer density. However, the systems K_a -data to date strongly indicate this type of a functional relationship for solid conductance.

Examination of the K_s coefficients also shows the relatively high solid conductance of multifoil systems containing woven spacers (e.g., Ni-Astroquartz and the 1800°F composite). At comparable higher-load layer densities, the K_s coefficients are nearly a factor of 10 higher than coefficients for multifoil systems containing the fibrous paper spacers. However, as mentioned previously, the interface resistance at "near zero" load effectively reduces the K_s contribution for these woven spacer systems.

1.3.1.2.2 Radiative Coefficient

The K_r coefficient ($\frac{1}{4} b(n)$) is of the form $\frac{\sigma \epsilon_e}{24n}$ which derives from the classical radiative heat transfer expression for a system of multiple reflective shields. The coefficient is directly proportional to the effective emissivity of the shield system and inversely proportional to shield density.

The ϵ_e term is defined as the mean effective emissivity of the reflective foil surface in the alternate layer, multiple foil configuration; i.e., foil surfaces in contact (under various degrees of compressive loading) with fibrous paper or cloth separators. The effective emissivity pertains to a multifoil system operating over a relatively large temperature gradient. For this reason, the ϵ_e values are related to a mean operating temperature for the insulation which, considering the typical parabolic temperature profile of multifoil insulations, is approximated as follows:

$$T_m = 0.75 (T_h - T_c) + T_c \quad (12)$$

As can be noted from Table IV, the ϵ_e values for the multifoil systems are generally higher than corresponding literature emissivity values for the particular foil materials. This is attributed to the presence of the spacer material, which is in direct contact with the reflective foil surface. The effect of the fibrous spacer is to increase the apparent emissivity of the reflective surface in comparison to its measured emissivity when radiating to a void⁵. It follows, then, that a high degree of contact (i.e., high compressive load or layer density) would tend to intensify this effect. This is indicated for some multifoil systems, particularly those spaced by the fibrous papers (fiber diameter $< 1.5 \mu$).

In summary, the effective emissivity values estimated from the effective thermal performance (i.e., K_a) data have:

(1) Substantiated the strong temperature dependency of ϵ_e for Mo and Ni foils, and the very mild temperature dependency of ϵ_e for Al and Cu foils. These results agree with published emissivity data for these materials.

(2) Indicated a strong effect on inherent emissivity due to the fibrous spacer materials. In some cases, this effect is intensified by increased compressive load. This behavior has also been noted by other investigators.

The accuracy of the ϵ_e is limited by the approximate nature of the K_a expression and data reduction technique. However, it has proven to be a useful parameter for studying and comparing characteristic thermal behavior of the various multifoil systems.

1.3.1.3 Mo-ZrO₂ Multifoil Insulation

Some limited testing at temperatures to 2200°F has been performed on the Mo-Zirconia cloth multifoil insulation. Because of some high temperature testing difficulties (2500°F range) and contract limitations, experimental K_a -data are somewhat restricted. The K_a (T) data have been obtained over a source temperature range of 900-2200°F and at a single compressive loading. These results, and their implications toward Mo-ZrO₂ multifoil system performance, are discussed.

The Mo-ZrO₂ multifoil insulation system is comprised of alternate layers of molybdenum foil (.0005" thick; 12 gms/ft²) and zirconia cloth (.005" thick; 5-6 gms/ft²). Total normal emissivity of polished molybdenum ranges from .03 - .16 over the temperature span 500-2500°F⁶. The yttria-stabilized zirconia cloth is produced by Union Carbide Research Institute, using a "replica" technique.

Measured values of effective thermal conductivity (K_a) are presented as a function of hot-side temperature in Figure 20. Data were measured on the modified flat plate test apparatus (see Section 1.2) in a vacuum of $\sim 1 \times 10^{-4}$ torr. The sample was tested under low compressive load (.2 - .3 psi) which corresponds to a layer density (n) of 128 lb/inch. Two runs were made at hot-side temperatures ranging from 1000°F-2200°F; the resulting data are in good agreement.

Thermal performance (i.e., K_a) of the Mo-ZrO₂ multifoil insulation was substantially better than the previously tested Ni-Astroquartz system. This lower K_a for the Mo-ZrO₂ insulation can largely be attributed to:

- (a) Lower solid conductance (K_s) due to the lower density, open construction of the zirconia cloth.
- (b) Molybdenum foil emissivities which are lower than nickel foil emissivities at all temperature levels.

Of the two factors, reduced solid conductance appears to be most significant.

Empirical K_a coefficients for the Mo-ZrO₂ insulation are given in Table IV. The computed effective emissivities for the Mo-ZrO₂ system are 10-20% higher than corresponding literature values. Effective emissivities of foil shields can significantly increase with increase in the absorption coefficient of the spacer material.¹² This has been noted for multifoil insulations under high compressive loads. At the low loading (.2-.3 psi) the zirconia cloth has a relatively moderate effect due, most likely, to its relatively low density (5-6 grams/ft²) and open construction in comparison to Astroquartz, for example, which has a density of ~10 gms/ft².

Measured data were obtained at hot-side temperatures up to 2200°F. Instrumentation and temperature control problems were encountered at the 2500°F level, causing these data to be in error. The best assessment of apparent thermal conductivity at 2500°F is obtained by extrapolating the lower temperature data, with the aid of the empirical correlation given in Table IV.

As a result of these test problems, K_a measurement was limited to the one near-zero load condition. Fortunately, this low-load density is typical of installed layer densities commonly achieved in system applications.

The principal error sources in the Mo-ZrO₂ testing were defined as:

- (a) Contamination of the Pt/Pt-10Rh hot-side thermocouples in the ~2500°F environment with a resultant loss of calibration.
- (b) Localized over-heating of the hot-side foils and spacers. Cracks in the alumina heater shield plates permitted direct radiation transfer from the higher-temperature graphite element to the foils.

These error sources, and their possible effects on the multifoil sample and thermocouple instrumentation, are discussed in detail in Appendix B. Possible modifications to the sample configuration designed to minimize these testing errors are also suggested. Incorporation of these design changes and subsequent additional 2500°F testing was not possible within the Phase II program.

From the study described in Appendix B, it was tentatively concluded that the molybdenum foil and zirconia cloth materials are compatible in vacuum at temperatures up to 2500°F. The sample underwent several temperature excursions to 2500°F over a 6 week testing period with no evidence of material interaction in the 2500°F temperature zone. Some local zirconia-molybdenum interaction was observed in the hot-side zones which aligned with the defects in the alumina heater shields. It is thought that these areas were exposed to substantially higher temperatures (2700-2800°F).

The molybdenum foil and zirconia cloth embrittled as a result of the 2500°F temperature exposure. The materials were still handleable, but cracking in foils and spacers was more prevalent. This brittleness was expected in the molybdenum since its recrystallization temperature (1700-1800°F) was exceeded. In examining the samples, the brittle-to-ductile transition, in the molybdenum foil was clearly evident as one progressed from hot-side to cold-side. Brittleness in the zirconia occurred as a result of material sintering (i.e., stiffening) after exposure to temperatures of 2200°F and above. Further details on exposed material characteristics are also given in Appendix B.

1.3.2 Opacified Fibrous Multilayer Insulations

Opacified insulation are basically fibrous structures that have been rendered more opaque to thermal radiation by dispersing within their matrix a high density of finely-divided metallic flakes (typically 325 mesh). Three opacified fibrous multilayer insulations have been evaluated. These opacified systems, along with their plain fibrous counterparts, are listed on the following page.

<u>Fibrous Multilayer Insulation</u>	<u>Source Temperature Range</u>	<u>Compressive Load (Layer Density) Range</u>
106 Glass	800 - 300°F	0 - 15 psi (200 - 450 ℓ /inch)
Al Opacified Glass (30% by wt. Al)	800 - 300°F	0 - 15 psi (275 - 550 ℓ /inch)
Refrasil Quartz	1000 - 500°F	0 - 15 psi (100 - 250 ℓ /inch)
Cu Opacified Refrasil Quartz (40% by wt. Cu)	1400 - 500°F	0 - 15 psi (55 - 110 ℓ /inch)
Ni Opacified Refrasil Quartz (40% by wt. Ni)	1500 - 500°F	0 - 15 psi (55 - 110 ℓ /inch)

Typical effective thermal conductivities (K_a) of the plain fibrous, opacified fibrous and discrete foil multilayer systems are shown in Figures 21 and 22. These data are expressed as a function of system hot boundary temperature and referenced to a constant cold-side boundary at 100°F. All insulations are operating in vacuum, under nominal zero mechanical loading (approximately 0.04 psi), and with essentially black ($\epsilon = 1.0$) hot and cold-side boundaries. The condition of the thermal boundaries is of particular significance when defining thermal performance of the partially transparent, plain and opacified fibrous insulations.

Comparing the various multilayer insulations under corresponding physical and thermal conditions, the relative levels of performance as indicated by the effective thermal conductivity values are as expected. Lowest thermal conductivity is displayed by the discrete foil systems which are, by their configuration, most heavily opacified. The metallic flake-opacified fibrous multilayer systems possess intermediate thermal conductivities, while plain fibrous insulations exhibit the highest K_a values.

The opacified multilayer systems, with their significant improvement in radiation attenuation over plain fibrous systems, can play a key role in special high temperature insulation applications where the highly anisotropic characteristics (i.e., high lateral conduction) of multifoil systems would be detrimental.

Figure 21 - Performance Comparisons for Multilayer Insulations

Figure 22 - Performance Comparisons for Multilayer Insulations

These flake-opacified insulations are substantially more isotropic than corresponding multifoil systems and, as such, could be used as:

(1) Gap filler materials in multifoil systems to interrupt thermal or electrical conductance in the lateral (parallel to layers) direction.

(2) Basic thermal insulation in applications where a high lateral gradient exists such that lateral heat flow in conventional multifoil insulations would be prohibitive.

1.3.2.1 Effective Backscattering Parameter

Studies by Larkin and Churchill² and others^{3,4} have determined that backscattering is the main mechanism by which radiation is attenuated in plain fibrous insulation of small fiber diameters ($\sim 1.0\mu$ or less). Absorption is virtually negligible in comparison. Extending this observation to flake-opacified fibrous insulations as well, the mean effective thermal conductivity (K_a) of these systems is expressed as:

$$K_a = \frac{1}{T_h - T_c} \int_{T_c}^{T_h} K(T) dT = \frac{2}{3} a'(n) \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c} + \frac{1}{4} b'(n) \frac{T_h^4 - T_c^4}{T_h - T_c} \quad (13)$$

where

$$\frac{1}{4} b'(n) = \frac{\sigma}{12} \cdot \frac{\Delta X}{\left(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1 + N_e \Delta X\right)}$$

or

$$\frac{1}{4} b'(n) = \frac{\sigma}{12 N_e} ; \quad \left\{ \begin{array}{l} \left(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1\right) \ll N_e \Delta X \\ \epsilon_h = \epsilon_c \simeq 1.0 \\ X \geq .15 \text{ inch} \end{array} \right.$$

This development of the approximate K_a expression and associated empirical-graphical data reduction techniques are detailed in Section 1.1.

Tests were run under conditons which satisfied the requirements for using the simplified radiative coefficient of Equation (13). The measured K_a -data were used to empirically solve Equation (13) for the effective back-scattering cross-section (N_e) and solid conductance coefficient ($\frac{2}{3} a'(n)$) of the fibrous multilayer systems.

LAYER DENSITY (n) - L/INCH

Figure 24 - Effective Backscattering Cross Section -
Quartz Fibrous Multilayers

FIGURE 25

EFFECTIVE BACKSCATTERING CROSS-SECTION
GLASS AND QUARTZ FIBROUS
MULTILAYER INSULATIONS

Effective backscattering parameters for plain and metal flake-opacified fibrous multilayer insulations are given in Figures 23 and 24. The relationship between the N_e -parameter and insulation bulk density (i.e., layer density or compressive load) is described. The indicated temperature for each N_e curve denotes mean hot-side or source temperature. The implications of the term "effective" have been discussed previously (Section 1.1).

The effective backscattering parameters for the 106 glass and Refrasil quartz fibrous systems (plain and opacified) are plotted together on Figure 25 to enable direct comparison. Based on these N_e plots, several observations on thermal behavior of the fibrous multilayer insulations may be made.

(1) Magnitudes of the N_e values for plain 106 glass (.6 μ nominal fiber diameter) and Refrasil quartz (1.0 - 1.5 μ nominal fiber diameter) multilayer are essentially the same (100 in⁻¹ to 200 in⁻¹ over the density range).

(2) All N_e -density plots show an increase in backscattering cross section corresponding to increasing density.

(3) Both aluminum and nickel flake opacification improve radiation attenuation (i.e., increase effective N_e) of the fibrous materials, with the aluminum flake being much more efficient in this capacity. For example, at low density aluminum flake opacification increases N_e by a factor of 8. Nickel flake opacification, on the other hand, results in a factor of 2 increase in N_e . Copper flake opacification showed the least effect in improving N_e (factor of ~1.3).

Observations 1 and 2 are in accord with findings reported by other investigators (e.g., Larkin and Churchill). Observation 3 is of particular significance and indicates that an important criteria in metal flake opacification is the volumetric quantity of flake which is retained within the fibrous matrix. On a weight basis, nickel opacified quartz contains 40% nickel flake while aluminum opacified glass has 30% aluminum flake. However, on a volumetric basis, the aluminum opacified glass contains a quantity of dispersed flake (per unit volume of bulk fibrous matrix) which is ~2.5 times greater than in the nickel opacified system, due to density difference between aluminum and nickel. This greater volume of dispersed flake (i.e., greater flake surface area) makes the aluminum opacification much more effective.

Although radiation attenuation is attributed entirely to scattering, it is believed that inclusion of the metallic opacifying particles will also improve attenuation by the absorption-re-emission mechanism. This is felt to be most pronounced in the aluminum opacified system, where flake volume (and corresponding surface area) per unit volume of fibrous matrix is approximately 2.5 times greater than for nickel opacified quartz.

The superiority of the nickel opacified system over the copper opacified material is not readily explained. By design, the two materials are virtually identical in all physical properties (e.g., weight, volume of flake, paper thickness, etc.) except the metal used as the opacifier. Under this assumption, and further expecting that some attenuation by the flakes may be by absorption-re-emission mechanism, one might expect the low-emissivity copper flake opacified system to be the better performer. The fact that the converse is true may indicate that:

- (1) The fabricated copper opacified paper may deviate from the initial design specifications and properties, giving a poorer than expected performance.
- (2) Presence of the flake opacifier serves primarily to increase backscattering, with very little absorption-re-emission taking place. This would minimize the effect of different emissivity of the metal flakes.
- (3) Some errors existed in testing of the copper opacified system. A minimum number of K_a data points were obtained and this prevented complete characterization of the system.

The calculational method for predicting effective backscattering parameters [based on Equation (13)] appears to be satisfactory as a method for comparing various fibrous multilayer insulations. The empirical method is subject to some error due to (a) experimental measurement, and (b) possible inaccurate description of the solid conduction component (i.e., $K_s = a'(n) T^{1/2}$). This latter error would be minimized at low densities where the K_s contribution is small. It would become more significant at high density, with the probable effect being a somewhat low prediction for N_e .

1.3.2.2 Thermal Performance Data

Effective thermal conductivity (K_a) data for the four fibrous multilayer systems - 0.6 μ glass fiber, plain and aluminum flake-opacified, and 1.0 - 1.5 μ quartz fiber, plain, nickel flake and copper flake-opacified--are presented in Figures 26 to 30.

Since heat transfer through these fibrous multilayer insulations is primarily by radiation, the effect of increasing backscattering parameters (N_e) with increased load (layer density) is reflected directly in the resultant K_a data. The fibrous multilayer systems generally exhibit mildly decreasing thermal conductivities with increasing load, as would be expected from the behavior of N_e .

Figure 26 - Effective Thermal Conductivity
Glass Fibrous Multilayer

Figure 27 - Effective Thermal Conductivity -
Al Opacified Glass Multilayer

Figure 28 - Effective Thermal Conductivity -
Refrasil Quartz Fibrous Multilayer

Figure 29 - Effective Thermal Conductivity -
Cu Opacified Quartz Multilayer

Figure 30 Effective Thermal Conductivity -
Ni-Opacified Quartz Multilayer

The exception is the aluminum opacified glass system, where a relatively high solid conductance component and a relatively stable N_e -value (as a function of load) result in a net increase in effective thermal conductivity at higher loads. The significance of the aluminum flake opacifier in increasing solid conduction is also illustrated in K_a data for the Al-Al opacified glass multifoil insulation (Figure 13).

Equation (13) indicates that effective thermal conductivity, as presented in Figures 26 to 30, cannot be considered as an intrinsic property of the fibrous multilayer system. Use of this K_a parameter must, in many cases, be restricted to specific boundary conditions and insulation geometry (i.e., thickness, layer density), since these conditions directly affect the radiative contribution.

In the flat plate testing configuration, the use of optically black ($\epsilon = 1.0$) boundaries and sufficiently thick samples rendered the boundary and geometry effects inconsequential. However, these thermal boundaries must be accounted for, particularly when their emissivity is low and insulation thickness is small. Typical effects of these two system parameters on effective thermal conductivity are illustrated in Figure 31 for the nickel opacified quartz insulation. Two extremes of boundary emissivity (ϵ_b of 0.05 and 1.0) and compressive load (0.04 psi and 15 psi) are considered.

For the nickel opacified system, K_a corresponding to boundary temperatures T_h and T_c of 1200°F and 70°F respectively are plotted against insulation thickness. Effective thermal conductivity is constant (i.e., independent of thickness) for thicknesses $\geq .1 - .2$ in. in the black boundary ($\epsilon = 1.0$) case. In this range, the radiant heat attenuation due to the boundary surface is negligible compared with the backscattering coefficient ($N_e \Delta X$). For the highly reflective boundaries ($\epsilon = 0.05$), $N_e \Delta X \gg \left(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1 \right)$ only for insulation thicknesses in excess of 1.0 - 2.0 μ

The plots of Figure 31 are characteristic of all the tested opacified fibrous multilayer insulations. It is evident from these plots that, in thermal design and analysis work, K_a data for these insulations must be applied with consideration of boundary conditions and dimensions.

Empirical thermal conductivity coefficients for the plain and opacified fibrous multilayer insulations are presented in Table V. The form of these K_s and K_r coefficients and the basic equation to which they are applied are similar to that discussed for the multifoil systems. The empirical expression may be used to regenerate K_a data at any boundary temperatures and loads within the test range. Accuracy is generally within 20%.

Figure 31 - Effect of Thickness on K_a -
Nickel Opacified Quartz Multilayer

TABLE V

Empirical Thermal Conductivity Parameters
For Fibrous Multilayer Insulations

Fibrous Multilayer Systems	Source Temperature Range °F	Layer Density Range (.04-15 psi) /in.	K_s Coefficient $\left[\frac{2}{3} a'(n) \right]$ 10^{-4} Btu/hr ft °R ^{3/2}	K_r Coefficient $\left[\frac{1}{4} b(n) \right]$ 10^{-12} Btu/hr ft °R ⁴	Effective Back- scattering Cross Section (N) ₂
106 Glass	800-300	200-450	.15 log n - .33	$144 \frac{\lambda}{n} \frac{1}{E + \frac{\lambda}{n} (N_e)}$	0.32n + 68
Al Opacified Glass	800-300	275-550	1.31 log n - 3.21	$144 \frac{\lambda}{n} \frac{1}{E + \frac{\lambda}{n} (N_e)}$	0.15 n + 1000
Refrasil Quartz	1000-500	100-250	.58 log n - 1.15	$144 \frac{\lambda}{n} \frac{1}{E + \frac{\lambda}{n} (N_e)}$	0.85 n - 10
Cu Opacified Refrasil Quartz	1400-500	55-110	____ @ 55-65 ℓ/inch .16 @ 110 ℓ/inch	$144 \frac{\lambda}{n} \frac{1}{E + \frac{\lambda}{n} (N_e)}$	2.8 n
Ni Opacified Refrasil Quartz	1500-500	55-110	.50 log n - .84	$144 \frac{\lambda}{n} \frac{1}{E + \frac{\lambda}{n} (N_e)}$	5.5 n - 135
Basic Equation:	$K_a = \frac{2}{3} a(n) \cdot \frac{T_h^{3/2} - T_c^{3/2}}{T_h - T_c} + \frac{1}{4} b(n) \cdot \frac{T_h^4 - T_c^4}{T_h - T_c}$				

where: T_h = hot-side temperature (°R)

T_c = cold-side temperature (°R)

n = layer density (ℓ/inch)

λ = number of layers

$\frac{\lambda}{n}$ = ΔX = thickness (inches)

$E = \left(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1 \right)$

The solid conduction coefficient ($\frac{2}{3} a'(n)$) is approximated reasonably well by the $\log_{10}$ function. Although of the same for, the K_s coefficients for the fibrous multilayer systems and the corresponding multifoil systems (i.e., those using the identical fibrous material as a separator) are not interchangeable. In multifoil systems, the presence of the metallic foil between adjacent fibrous separator layers tends to create some additional interface resistance and prevents intimate fiber-to-fiber contact between adjacent spacers*. This results in a somewhat lower overall solid conductance contribution for multifoil insulations in comparison with the non-foil, fibrous multilayer systems.

Mean effective backscattering cross section (N_e) is represented by a linearly increasing function of layer density (n). These expressions are derived from the N_e plots of Figures 23 and 24.

1.3.3 Longitudinal Thermal Conductivity Testing

The test objective was to determine experimentally the longitudinal or lateral effective thermal conductivity (K_A) of opacified fibrous insulations. The longitudinal values are of significance since, in many multilayer insulation configurations (e.g., filled gap penetrations), lateral as well as normal heat flow has a bearing on overall system performance.

Longitudinal "effective" thermal conductivities have been measured for three opacified fibrous multilayer insulations, and non-opacified 106 glass insulation. The three opacified systems evaluated were:

<u>Multilayer Sample</u>	<u>Hot-Side Temperature Range</u> <u>°F</u>
Aluminum opacified glass $n \cong 186$ layers/inch	250 - 900
Copper opacified quartz $n \simeq 68$ layers/inch	500 - 1400
Nickel opacified quartz $n \simeq 72$ layers/inch	500 - 1600

The sample of non-opacified 106 glass paper was tested primarily as an aid in data reduction and approximation of the individual solid conduction and radiative contributions to total longitudinal conductivity.

* This is further indicated by the fact that layer densities corresponding to 0-15 psi compressive loading are lower for the multifoil systems than for corresponding non-foil systems.

1.3.3.1 Test Apparatus - Sample Design

The basic flat plate test configuration and procedures are used in longitudinal thermal conductivity measurement. A flat, planar sample is designed to provide essentially one-dimensional heat flow between hot and cold boundaries over a central portion of the sample. These measured fluxes, along with temperatures and sample dimensions, are sufficient to compute effective thermal conductivity values.

The test configuration, with installed multilayer insulation sample, is shown schematically in Figure 32. In testing, hot-side temperature is maintained by a woven graphite resistance heater. Heat is supplied to the sole plate, which is matched to the 6 inch diameter of the opacified paper sample. The heat flow across the central portion of the sample is measured by a 2.25 inch x 2.25 inch flux meter, centrally located at the cold-face. The sink plate is water cooled to control cold side temperatures in the 100-300°F range throughout testing. Test fixtures are contained within a bell jar enclosure, under vacuum ($P \leq 1 \times 10^{-3}$ torr) during all tests.

The opacified paper samples are of cylindrical geometry with 6 inch diameter and 1.5 inch height. Samples are constructed by spirally-wrapping the fibrous paper (1.5 inch width) from the center outward, to a layer density approximating the specified "zero load" condition. Preliminary analysis indicated that heat flow across the 1.5 inch sample is essentially one-dimensional in the 2.25 inch x 2.25 inch test "core" section. This condition is attainable because of the "self-guarding", in the radial direction, which is achieved in the 6 inch diameter sample design.

1.3.3.2 Evaluation of Results

Measured longitudinal thermal conductivity data for the four fibrous multilayer insulations, along with sample description and test conditions are presented in Table VI.

For the stipulated sample thickness of 1.5 inches, black ($\epsilon_h = \epsilon_c = 1.0$) hot and cold-side boundaries, and expected N_e values in the order of 100 or greater, the simplified Larkin-Churchill radiation expression [Equation (5)] may be used to relate longitudinal K , (K_l).

Now for each multilayer system, for which several K_l data points have been determined, Equation (5) or (7) can be generated and solved graphically to yield the solid conduction coefficient ($\frac{2}{3} a'(n)$) and backscattering cross section (N_e). Corresponding solid conduction and radiative coefficients for all four fibrous multilayer insulations are summarized in Table VII.

Figure 32 - Schematic of Longitudinal Thermal Conductivity Test Configuration

TABLE VI

Longitudinal Thermal Conductivity - Opacified Multilayer Insulations

<u>Insulation System</u>	<u>Vacuum Pressure 10^{-3} torr</u>	<u>T_h °F.</u>	<u>T_c °F</u>	<u>K_l 10^{-3} Btu/hr. ft. °F</u>
Aluminum opacified glass multilayer - $n^* = 186$ ℓ /in.	0.4	250	140	4.72
	0.7	530	245	8.04
	0.3	715	320	10.30
	0.5	900	390	15.00
Copper opacified Refrasil quartz multilayer - $n^* = 68$ ℓ /in.	0.4	460	85	4.76
	0.5	815	135	6.68
	0.3	1080	190	10.44
	0.4	1350	260	15.00
Nickel opacified Refrasil quartz multilayer - $n^* = 72$ ℓ /in.	0.4	465	105	6.70
	0.5	875	160	7.43
	0.6	1190	220	10.28
	0.5	1470	225	13.04
	2.5	1660	260	15.25
106 glass multilayer (non-opacified) - $n^* = 210$ ℓ /in.	0.4	330	65	4.26
	0.2	560	75	4.92
	0.3	710	90	5.56
	0.3	910	110	6.52

*Wrapped layer density, measured in the radial direction.

K_l - longitudinal thermal conductivity; T_h - hot-side temperature; T_c - cold side temperature.

TABLE VII

Empirical Thermal Conductivity Coefficients for Fibrous Multilayer Insulations

Fibrous Multilayer System	Source Temperature Range °F	Layer Density ℓ /in.	K_s Coefficient $\frac{2}{3} a''(n)$ Btu/hr. ft. °F ^{3/2}	K_r Coefficient $\frac{b}{4} (n)$ Btu/hr. ft. °F ⁴	Backscattering Cross-Section $(N'_2)_{in}^{-1}$
106 Glass t = .0028" w = 1.4 gms/ft ²	330-910	210	n 6.1 x 10 ⁻⁶	n 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	n 260
			ℓ 95.0 x 10 ⁻⁶	ℓ 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	ℓ 288
Aluminum Opacified 106 Glass t = .0035" w = 2.7 gms/ft ²	250-900	186	n 6.0 x 10 ^{-6*}	n 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	n 680*
			ℓ 72.0 x 10 ⁻⁶	ℓ 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	ℓ 75
Copper Opacified Refrasil Quartz t = .010" w = 5.5 gms/ft ²	460-1350	68	n 12.5 x 10 ⁻⁶	n 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	n 210
			ℓ 64.0 x 10 ⁻⁶	ℓ 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	ℓ 125
Nickel Opacified Refrasil Quartz t = .010" w = 6.2 gms/ft ²	460-1660	72	n 9.0 x 10 ⁻⁶	n 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	n 300
			ℓ 83.0 x 10 ⁻⁶	ℓ 144 x 10 ⁻¹² $\frac{\Delta X}{EtN_e L}$	ℓ 192

n = normal direction

$$E = \frac{1}{h} + \frac{1}{c} - 1 \quad \text{-- in test case } \epsilon_h = \epsilon_c = 1$$

 ℓ = longitudinal direction

$$L = \text{sample thickness} \quad \text{-- in test case } L = 1-1/2"$$

*Estimated properties for the heavy-weight aluminum opacified paper.

Based on the tabulated coefficients, some comparisons may be drawn between thermal behavior of the fibrous multilayer systems in the normal and longitudinal directions.

1. The solid conduction coefficient (K_s) is substantially higher in the longitudinal direction for all materials tested. For the glass fiber systems, the $(K_s)_\ell / (K_s)_n$ ratios range from 15-50; for the quartz fiber insulations, the ratio is from 5-10. This increase in the longitudinal direction is due to (a) the predominately parallel fiber orientation in the fibrous papers; and (b) the absence of interface resistance. The significance of interface effects is most apparent in K_s comparisons for the glass fibrous multilayer systems.

2. With the exception of the aluminum opacified multilayer, the calculated "effective" backscattering cross sections for the fibrous insulations are of the same order in both the longitudinal and normal directions. The backscattering capability of the metal flake opacified systems appears to be moderately direction-dependent, with performance consistently better in the normal direction. This directional preference is thought to be due to fiber and/or flake orientation which provides more scattering sites in the normal direction.

3. The calculated longitudinal N_e -value for aluminum opacified multilayer insulation is low, and inconsistent with values for the other materials. Considering the physical properties of the two materials--106 glass and aluminum opacified glass-- it is expected that N_e of the opacified glass would be at least equivalent to N_e for the non-opacified glass. The unusually low backscattering cross section is attributed to irregularities in the sample wrap, which promoted lateral gaps or "radiation windows". These high heat flux zones would raise the measured conductivity appreciably. Post-test examination of the aluminum opacified sample showed that the spiral wrap was relatively loose and, although no gaps were observed during sample installation, there was a strong tendency for gaps to develop under slight sample deformation.

4. It would also be expected that the lateral K_s coefficient for the aluminum opacified filler would be at least as high as that for 106 glass, if not higher due to the aluminum flake. As seen in Table VII this is not the case; the computed K_s coefficient for aluminum opacified glass is ~25% lower than the corresponding value for 106 glass. A discrepancy of this order in the solid conduction term would have little effect on the radiation (backscattering) coefficient. The observations on the unusually low N_e -value, as stated in (3), would not be altered by a modest discrepancy in solid conduction.

5. For the two opacified quartz systems, the correspondence between insulation density and resulting thermal properties is as expected. The high-density nickel opacified quartz insulation has a correspondingly higher

indicated K_s coefficient and backscattering cross section (N_e) than that computed for the copper opacified quartz system.

Effective thermal conductivities, in the normal and longitudinal directions, are plotted against hot-side temperature for the four fibrous multilayer insulations (Figures 33 to 36). Effective conductivity (K_a) and the solid conductivity component (K_s) are shown in each case. The curves were generated from the thermal conductivity coefficients of Table VII, for insulations operating in vacuum and at a cold-side temperature of 100°F. Insulation sample thickness was 1.5 inches in all cases.

The significant increase in effective thermal conductivity in the longitudinal compared to the normal direction, and the relative importance of the solid conduction and radiation contributions to total conductivity are illustrated clearly in Figures 33 to 36. The observations drawn in conjunction with Table VII are borne out in examination of these plots.

The utility of the measured longitudinal thermal conductivity (K_ℓ) data in design and analysis is limited in that these data are tied to specific physical conditions (i.e., layer density, thickness) of the insulation. The K_ℓ data are for fibrous multilayer systems at low load (typically 0.1 psi compressive loading or less), and correspond reasonably well to low-load layer densities for multifoil systems using the identical spacer materials. In this regard, the data may be used directly in generic thermal effects studies (e.g., penetration and joint analyses) of multifoil insulation systems where the specified insulation layer density approximates the K_ℓ test conditions.

To be applicable over a wide range of compressive load (e.g., 0-15 psi) and temperature, the lateral thermal conductivity data would have to be at least as comprehensive as the normal thermal conductivity data usually obtained in the flat plate test programs. Although the scope of the K_ℓ testing did not permit this comprehensive testing, some longitudinal thermal conductivity estimates may be made (based on available test data) and used in approximate analyses of systems at other layer densities.

For example, the solid conduction (K_s) contribution to total longitudinal conductivity may be approximated with reasonable accuracy as a proportional function of layer density. For higher or lower density multilayer systems, the K_s contribution for the fibrous filler would increase or decrease accordingly.

The radiation contribution (K_r) would generally decrease for higher density filler systems (i.e., backscattering cross section (N_e) would increase with density). Using the measured K_r contribution in analyzing higher layer density insulations would, at worst, give conservative results. At lower layer

Figure 33 - Effective Longitudinal Thermal Conductivity -
Al-106 Glass

Figure 34 - Effective Longitudinal Thermal Conductivity -
Al Opacified Glass

Figure 35 - Effective Longitudinal Thermal Conductivity -
Cu Opacified Refrasil Quartz

Figure 36 - Effective Longitudinal Thermal Conductivity -
Ni Opacified Refrasil Quartz

densities, approaching zero load, the K_f contribution would be more difficult to analyze. Zero load conditions introduce the possibility of lateral gaps (i.e., radiation windows) within the filler. This "random" condition would be difficult to define.

Longitudinal thermal conductivity data are used in characterizing opacified gap filler materials in the modified program to analyze thermal effects of "filled" joints (reference Section 3.0).

1.4 Effective Thermal Conductivity Data Review and Analysis

A comprehensive review, interpretation and error analysis has been completed on the flat plate testing concept and resultant K_a data for multilayer systems. Principal objectives of the program were:

- (1) Establish and verify accuracy of the measured thermal conductivity by means of an error band analysis.
- (2) Re-evaluate the guarded flat plate testing concept, equipment and procedures to verify its accuracy and utility.

In the absence of experimental proof tests or multilayer insulation standards which could serve as direct verification of data accuracy, the comprehensive data review program was considered the main available method for estimating limits of accuracy for these thermal conductivity data. Extensive K_a data (cylindrical and flat plate testing) were available which related to a variety of operating conditions and multilayer insulation composite materials.

The following tasks, considered instrumental to meeting the above stated objectives, were carried out in the review program:

- (1) Assessment of estimated error bands associated with flat plate test results, using a computerized two-dimensional thermal analysis.
- (2) Review of the flat plate test method, and discussion of potential means of refining or upgrading the equipment and techniques.
- (3) Comparison of cylindrical and flat plate test data in all cases where good correspondence exists in the test conditions (e.g. temperatures, layer density, etc.) Determination of degree of agreement and consistency of agreement between K_a -data obtained by the two methods.

These tasks are discussed at some length in the ensuing paragraphs.

1.4.1 Error Band Analysis

Thermal behavior of the guarded flat plate sample configuration was analyzed using the Fourier conduction law in a finite difference heat balance. The computerized analysis considered the following error sources: (1) inherent two-dimensional effects of the guarded multilayer system (i.e. filled gap analysis), (2) effect of non-ideal boundary conditions, specifically sample-guard temperature mismatch, and (3) instrument and readability deviations in measured data. Integration of these potential error sources into a single analysis resulted in a reasonably

comprehensive error band determination. Details on the development of the analytical approach are given in Appendix C.

Error band analysis was confined to multifoil insulation systems since they represent the more severe testing case; i.e. highest lateral conductivity and resultant two-dimensional effects. The five systems selected for analysis, representing a wide range of materials and operating conditions, are listed below:

<u>Multifoil System</u>	<u>Load (Layer Density) Conditions psi (lb/inch)</u>	<u>Source Temperature Range °R</u>	<u>Measured K_a Range 10^{-3} Btu/hr-ft-°R</u>
Al-106 Glass	0.3-6.0 (185-283)	1280-850	0.2-0.8
Al-Al Opacified Glass	0.3-6.0 (252-365)	1280-780	0.16-1.35
Cu-Refrasil Quartz	0.1-15.0 (90-177)	1900-1000	0.3-1.0
Ni-Refrasil Quartz	0.1-6.0(96-172)	2350-1000	0.3-3.0
Ni-Astroquartz	0.1-6.0(120-142)	2000-1000	1.3-4.7

1.4.1.1 Predicted Error Band on Thermal Conductivity Data

In constructing the analysis the following assumptions were made in defining the potential error sources. These conditions of the analysis were based largely on actual flat plate testing experiences.

Inherent two-dimensional effects An opacified paper filled gap (average width .040 inches) was considered to separate the 6 inch x 6 inch multifoil sample from the guard section. The modified edge effects program was used in analyzing the resultant thermal effects.

Thermal mismatch between sample and guard Hot-side or source boundary temperature was considered uniform across sample and guard. At the cold-side, two limiting cases were considered:

(a) Low error limiting condition Sample and guard temperatures are uniform and equal ($T_s = T_g$)*.

(b) Maximum error limiting condition Sample and guard temperatures are as indicated in actual test monitoring. Because of the method

* T_s = Sample Temperature
 * T_g = Guard Temperature

of measurement*, the $\Delta T = |T_s - T_g|$ values obtained in actual testing are considered to be maximum. It follows, then, that calculated two-dimensional distortion of heat flow will also be a maximum.

Deviation on measured values The total $\pm$ deviations on measured data (i.e., Q , T_h , T_{cs} , T_{cg}) were comprised of instrument calibration accuracy and readability accuracy. The maximum $\pm$ deviation was applied to the data, and resultant deviation in computed values (i.e., K_a) was determined by the root-mean-square method of Kline and McClintock.

Results of the error band analysis on the five multifoil systems are presented in Figures 37 to 41. Effective thermal conductivity (K_a) are plotted as a function of hot-side or source temperature at three compressive loadings 0.1, 1.0, and 6.0 psi. In each figure, the data points joined by the solid curve denote actual measured $K_a(T)$ curves. The broken lines flanking the actual K_a curve, represent the minimum $\pm$ error band assuming $T_{cs} = T_{cg}$ at the cold boundary. The shaded lines denote the maximum error band limits based on the measured $\Delta T = |T_{cs} - T_{cg}|$, and associated $\pm$ measurement deviation.

Corresponding error band data are presented in tabular form in Appendix C.

1.4.1.2 Observations and Recommendations

Some pertinent observations, based on the graphical results of Figures 37 to 41, are as follows:

(1) For the imposed uniform cold-side temperature condition (i.e., $T_{cs} = T_{cg}$), the lower limiting error band on the multifoil K_a -data did not exceed $\pm 6\%$. This condition represents minimized two-dimensional thermal effects and is the optimum condition achievable with this test configuration.

(2) The rather severe cold-side boundary temperature mismatch associated with the maximum error case has, under certain conditions, resulted in a large error band prediction. This wide error band is particularly prevalent on K_a -data corresponding to low temperature, low load** operating conditions: (e.g. the low load (.1 - .3 psi) condition for the Al-glass and Cu-

*Temperatures of sample and guard are measured individually, and $\pm$ deviation applied randomly to each temperature. Also, thermocouple junctions on both sample and guard were located ~ 0.5 inch back from the actual gap edges, which would likely result in a somewhat high measured ΔT .

**Low temperature and low load imply a relatively low heat flux. Measurement deviations and two-dimensional effects can represent large errors when dealing with these for low heat flow values.

Refrasil quartz system of Figures 37, 38, and 39; the .1 psi, 1000°R condition for Ni-Refrasil quartz of Figure 40.)

(3) Again considering the severe mismatch boundary conditions, the predicted error band is considerably lower (generally ± 10 -30%) at compressive loads in excess of 1.0 psi and at higher source temperatures. These operating conditions result in higher measured heat flux values which are less sensitive to measurement error and two-dimensional effects.

(4) Actual error band on these K_a -data should be between the maximum and minimum bands described above. Increase in error band from the ideal minimum ($T_{cs} = T_{cg}$) is directly related to the degree of thermal mismatch (with attendant increase in lateral heat flow) between sample and guard. The actual error band can approach the minimum value ($\sim 6\%$) depending on the ability of the test system to minimize, control, and accurately measure the sample-guard ΔT .

It is evident from the tabular and graphical data that the size of the predicted error band is tied closely to the magnitude of the measured heat flux Q_n^* , as well as the degree of thermal mismatch. For the Al-glass multi-foil systems at .1 psi loading and measured $Q_n > 10$ Btu/hr ft² (Figures 37 and 38), theoretical error bands were in excess of 100%. For Ni-Astroquartz (figure 41) at the same loading and degree of thermal mismatch (i.e. $\Delta T \sim 10^\circ R$), but at measured Q_n of ~ 25 Btu/hr ft² or greater, the predicted error bands were 15% or less. These comparisons illustrate the sensitivity of the estimated error band to thermal mismatch, particularly for multifoil insulations of relatively low conductance.

In summary, it appears that minimizing the error band on K_a -data for typical multifoil systems can only be achieved through minimizing the two-dimensional heat transfer effects (namely, sample-guard temperature mismatch). In the current test configuration and instrumentation set-up, some thermal mismatch exists and is measured approximately. For highly efficient multifoil insulations (e.g. Al-106 glass) where measured Q_n is low, the present degree of mismatch introduces substantial error in the data due to a relatively high Q_ℓ / Q_n ratio. For less efficient systems such as Ni-Astroquartz (measured Q_n substantially higher), this same thermal mismatch results in a small (10-15%) error band due to the low Q_ℓ / Q_n ratio.

* Q_n -- one-dimensional heat flux in the direction normal to the multifoil insulation layers.

Q_ℓ -- heat flux in the lateral direction parallel to the layers.

Figure 37 - Thermal Conductivity Error Bands -
Al-106 Glass Multifoil Insulation

Figure 38 - Thermal Conductivity Error Bands -
Al-Al Opacified Glass Multifoil Insulation

Figure 39 - Thermal Conductivity Error Bands -
Cu-Refrasil Quartz Multifoil Insulation

Figure 40 - Thermal Conductivity Error Bands -
Ni-Refrasil Quartz Multifoil Insulation

Figure 41 - Thermal Conductivity Error Bands -
Ni-Astroquartz Multifoil Insulation

Methods for accurately defining and minimizing sample-guard thermal mismatch and, thereby, increasing the overall accuracy of the flat plate tester are suggested below:

(1) Use differential thermocouples, located close to the gap edges, to accurately measure absolute ΔT between sample and guard.

(2) In tests where the cold-side is force-cooled, sink plates should be redesigned to assure uniform cooling of sample and guard surfaces.

These equipment and instrumentation refinements are discussed at greater length in Section 1.5.

1.4.2 K_a Comparisons for Cylindrical and Flat Plate Tests

Figures 42, 43, and 44 present and compare flat plate K_a data with K_a values obtained with a steady state calorimetric device (i.e., cylindrical tester) operating, under similar test conditions. Figures 42 and 43 show K_a -data for several Ni-Refrasil quartz multilayer insulations; K_a -data for the 1800°F Composite system are presented in Figure 45.

The cylindrical test apparatus⁸, described briefly in Section 2.0, utilizes a spirally-wrapped multifoil sample of cylindrical geometry. This sample configuration completely encloses the heat source, and attempts to eliminate any longitudinal heat flow by maintaining physical continuity of each foil shield around the entire enclosure.

The configuration is, in concept, close to an ideal specimen construction. However, physical discontinuities are introduced in applying the insulation, notably at the end closures and in non-uniform mechanical pressures (affecting layer density) resulting from the spiral wrap technique. Accounting for these discontinuities, as well as measurement and computational errors associated with K_a determination, results in an estimated deviation of up to -25%* for these thermal conductivity data.

Comparison of K_a values obtained by the two test methods reveals that:

(a) The relationships of K_a to hot-side temperature T_h , as defined by the two types of test data, are in agreement.

(b) The K_a values from flat plate tests are approximately 25% lower than cylindrical test data in the lower temperature regions (1000°F or less). In the higher temperature region, this negative deviation may increase to 50%.

* Error estimates indicate that the physical discontinuities in the test system result in a high measured K_a .

The difference in absolute K_a values, is due in part to the uncertainties associated with the average layer density for the cylindrical samples. Because of the sensitivity of thermal conductivity to compressive load and the non-uniform loads (i.e., layer density) inherent in the spirally-wrapped cylindrical sample, it is difficult to establish accurate correspondence in installed layer density conditions between flat plate and cylindrical test samples. Although the overall or average n_a corresponds closely with the n measured for the flat plate samples, the cylindrical wrap may actually be at a higher density near the core (hot surface) due to the pressure amplification effects inherent in the spiral wrapping process. This inner layer compaction and accompanying shield distortion would result in higher K_a values for the cylindrical test samples, particularly at higher temperatures as noted in observation (b) above.

Also, multifoil systems, particularly systems utilizing woven separators such as Astroquartz, are quite sensitive to non-idealities in the cylindrical test geometry (e.g., end closures, non-uniform mechanical pressures). This sensitivity is due mainly to the high sensitivity of solid conductance to the level of compressive load. It is estimated that these factors can combine to cause high-side deviations in the order of 25% in cylindrical testing (i.e. $(K_a)_{cyl} \sim 25\%$ higher than $(K_a)_{actual}$).

Both flat plate and cylindrical testing techniques have utility. The flat plate approach enables measurement of K_a under closely controlled conditions of temperature and layer density. These $K_a(n, T)$ data are useful in assessing thermal behavior of multifoil systems. The wrapped, cylindrical test device, on the other hand, is useful in assessing thermal performance of installed insulation systems over long operating periods.

Comparison of K_a data from both testing approach indicates gross agreement for a particular insulation under similar operating conditions. Precise comparisons are difficult, however, due to the somewhat ill-defined installed physical properties (particularly layer density) of the wrapped cylindrical systems.

Figure 42 - Comparison of Cylindrical and Flat Plate K_a Data -
Ni-Refrasil Quartz Insulation

Figure 43 - Comparison of Cylindrical and Flat Plate K_a Data - Nickel-Quartz Insulations

Figure 44 - Comparison of Cylindrical and Flat Plate K_a Data -
1800°F Composite Insulation

1.5 Conclusions and Recommendations

Based on extensive experimental work and data analysis, it is concluded that:

- (1) The passively guarded, flat plate test configuration represents a valid concept and method for measuring mean apparent thermal conductivity of highly anisotropic multilayer insulations. It has been used extensively throughout the Phase II K_a testing program, with a relatively high degree of success.
- (2) Effective thermal conductivity data have been obtained on fourteen multilayer systems operating in vacuum ($P \leq 10^{-4}$ torr), over a source temperature range of 500-1800°F and for compressive loads from 0-15 psi. Recent tests on a Mo-ZrO₂ multifoil insulation have been run successfully at source temperatures to 2200°F. With minor modifications, testing to 2500°F and above should be tenable.
- (3) The comprehensive $K_a(n, T)$ data have been used widely in; (a) defining empirical correlations for effective thermal conductivity as a function of load (layer density) and temperature, (b) estimating thermal performance of installed multifoil insulation systems (e.g. insulation panels containing penetrations, joints, exposed edges, etc.)
- (4) An extensive error analysis has been conducted to compute total error band for measured K_a -data. The analysis considers combined error effects of: (a) inherent two-dimensional characteristics of the guard-sample configuration (Figure 6), (b) thermal imbalance between multilayer guard and sample, and (c) estimated $\pm$ deviation in measured data such as heat flux (Q_n) and boundary temperatures (T_h and T_c).
- (5) Results of the error analysis (summarized in Figures 37 to 41 of Section 1.4 and Tables C-1 to C-5 of Appendix C) indicate the following:
 - (a) The potential minimum error band for the 6 inch x 6 inch multilayer sample configuration with 0.040 inch wide, filled gap separating sample and guard, is $\pm 6\%$ or less for all systems tested. This error is based on inherent two-dimensional effects and instrument deviation; it assumes that sample and guard temperatures are uniform ($T_s = T_g$)*.
 - (b) For the maximum error case, assuming severe temperature imbalance between sample and guard, an error range of 10 - 30% was computed for K_a -data corresponding to load conditions of 1 psi or greater and

*From a practical standpoint, this condition can be closely realized with some refinement in instrumentation and careful sample installation.

source temperatures of 600°F or higher. For conditions of 0.1 - 0.3 psi loading and/or source temperatures of 600°F or less, the computed error band ranges beyond 50%.

The errors computed for the severe case of (b) still remain reasonably low for load and temperature conditions where measured Q_n (heat flux normal to the layers; i.e., the direction of interest) is relatively large. In these cases, the sensitivity of Q_n to lateral heat flow (Q_ℓ) effects due to thermal mismatch is relatively low. For low load, low temperature conditions where Q_n is a small value, its sensitivity to lateral disturbances is high.

With the results of testing and error band analysis to act as a guide, the flat plate test configuration, equipment design, and methods have been re-evaluated to define potential areas for improvements. Some proposed future K_a testing, specifically directed at higher temperatures systems such as the Mo-ZrO₂ multifoil insulation, is also indicated. This test work would follow implementation of the recommended refinements in equipment and methods. The proposed effort is outlined in block diagram form in Table VIII.

The design/instrumentation modifications are directed specifically at minimizing and accurately defining the temperature mismatch between sample and guard (i.e., $|T_s - T_g|$). This is a key item in improving overall testing accuracy. The heat flow meter accuracy, particularly in measuring the very low heat fluxes associated with certain multifoil systems (e.g. Al-106 glass) needs better definition than currently provided by manufacturer's calibrations. Efforts should be made to establish some reference materials which could serve as standards for periodic flux meter calibration. The needed modifications for improved high temperature operating capability have been discussed previously in Section 1.3.1.3 (Mo-ZrO₂) testing and Appendix B.

Several of the above-proposed modifications are shown in the test configuration schematic of Figure 45. The suggested "total enclosure" water-cooled jacket, incorporating the high conductivity metallic wool in the vicinity of the curved guard sections, would still permit sample compression and would, hopefully, promote more uniform cold-face cooling.

After equipment modification, new test work would concentrate on the Mo-ZrO₂ multifoil system and related composites for service up to 2500°F. Accurate $K_a(n,T)$ data for these insulations would be especially pertinent to insulation system design for silicon-germanium thermoelectric converter applications.

With regard to long range requirements, the following items should be strongly considered in design of second-generation flat plate testing equipment:

TABLE VIII

Proposed Future
Flat Plate Testing
Program

Modifications to
Apparatus - Techniques

Design/Instrumentation

- Use of differential thermocouples to measure $|\Delta T|$ from sample to guard
- Improved flux meter calibration.
- Improve uniformity of cold side sample-guard temperature control (e.g. uniform H_2O cooling of entire surface)

High Temperature Capability

- Use of sheathed thermocouples for added stability (e.g. Pt/Rh or W/Re)
- Heater redesign to achieve better durability and more uniform heating.

K_a Testing

- Additional testing of Mo - ZrO_2 system to get comprehensive $K_a(T, p)$ data over range 500° - 2500°F and 0 - 15 psi loading.
- Similar testing on composite multifoil insulations using Mo- ZrO_2 and other high - temperature materials

Figure 45 - Modified Design for Flat Plate Test Fixture

(1) Configuration employing larger samples -- A guarded multifoil sample of larger dimensions (i. e., surface area) would be used, with the metered area remaining the same. The influence of any Q_ℓ on the metered Q_n would be further reduced; i. e. configuration would be less sensitive to lateral heat flow effects.

(2) Capability of measuring point K values -- This would require both hot-face and cold-face heating with a small ΔT developed across the sample. This capability is contingent upon the availability of an accurate, sensitive heat flow meter or calibrated standard material which can function at the elevated temperatures.

2.0 Long Term Performance Stability of Multilayer Insulations

During the Phase II program, several multilayer insulation systems were evaluated to determine thermal performance stability over extended operating periods (2,000 - 10,000 hours) at maximum service temperature. The objectives of the program were:

(1) To obtain effective thermal conductivity data for the installed insulation configuration at a pre-determined number of different temperature levels within the operating range of each system, and treat the experimental data empirically to enable prediction of thermal conductivity at other temperature levels within these ranges.

(2) To obtain some preliminary indication of long term stability of these insulation systems through extended duration tests with gradients representing maximum recommended use temperatures for each material.

(3) Obtain some preliminary assessment of the effect on thermal conductivity in vacuum due to exposure of the hot insulation system to air.

Phase II testing to meet the above objectives is summarized in Table IX. The first two multifoil systems -- Ni-Refrasil quartz and Al-Al opacified glass -- were tested in Phase I with the 2000 hour testing completed early in Phase II. The bulk of the Phase II effort was then directed toward 10,000 hour testing on copper, nickel, and composite multilayer insulations, designed to operate at source temperatures in the 1400-1800°F range.

Air exposure tests relating to objective (3) have been conducted on Cu-Refrasil quartz and Ni-Refrasil quartz multifoil insulations. These results are reported in the Phase I final report.⁹

Ensuing discussion on long term performance stability is concentrated in the area of the 10,000 hour tests on the high temperature insulations, with special emphasis on the 1800°F composite system. Performance data are presented and potential degradation modes for materials operating in vacuum at the elevated temperatures are discussed (Appendix E). An improved stability testing system, designed to more accurately simulate elevated temperature operation in the vacuum of space, is presented and discussed.

TABLE IX

SUMMARY OF PHASE II LONG TERM PERFORMANCE STABILITY TESTING

SEPTEMBER 1, 1967 - March 1, 1970

Insulation System	Foil	Spacer	Layer Density Nominal Layers/Inch	Total No. of Layers	Test Boundary Temperatures °F	Comments
Nickel-Refrasil quartz	0.0006" thick nickel	Refrasil paper	96	55	1600 338	Test begun in Phase I. 2000-hr test and air exposure test complete
Aluminum-aluminum opacified glass	0.00025" thick aluminum	Al opacified glass paper	150	75	842 113	Test begun in Phase I. 2000-hr test and air exposure test complete
Aluminum opacified glass	--	Al opacified glass paper	75	37	881 293	2000-hr test complete
Copper opacified quartz	--	Cu opacified quartz paper	37	22	1220 415	10,000-hr, long-term test complete
Nickel opacified quartz	--	Ni opacified quartz paper	65	32	1485 577	10000-hr, long-term test is complete
Nickel-nickel opacified quartz	0.0006" thick nickel	Ni opacified quartz paper	56	28	1800 (unstable)	Test interrupted <200 hr due to system instability
Composite #1	0.0006" nickel 0.0005" copper 0.00025" aluminum	Refrasil paper Refrasil paper Al opacified paper	96	48	1800 (unstable)	Test interrupted <200 hr due to system instability
Modified composite	0.0005" moly. 0.0006" nickel 0.0005" copper 0.00025" aluminum	Astroquartz cloth Refrasil paper Refrasil paper Al opacified paper	110	55	1800 500 (est.)	Test interrupted after 7670 hours. Large drift in hot wall Thermocouple Calibration. Figure 55

2.1 Current Performance Stability Test Apparatus and Procedures

2.1.1 Cylindrical Test Method

Apparatus

The basic cylindrical test apparatus and sample configuration is shown in Figure 46. This apparatus, previously described in detail in the Phase I Final Report,⁹ utilizes a spirally-wrapped multilayer sample of cylindrical geometry. The insulation completely encloses the heat source, and attempts to minimize longitudinal heat flow (parallel to layers) by maintaining physical continuity of the insulation layers around the entire enclosure.

The steady-state calorimetric device measures net* heat flow through the wrapped insulation sample, with the hot boundary at source temperature T_h and the cold boundary at T_c . This net heat flow is used in determining effective thermal conductivity (K_a) by means of the Fourier heat conduction equation. During initial $K_a(T)$ and long-term stability testing, the insulation test chamber is pumped continuously with resultant pressure $p \sim 1 \times 10^{-4}$ torr.

The cylindrical configuration is, in concept, close to an ideal specimen construction. However, physical discontinuities are introduced in applying the insulation, notably at the end closures and in non-uniform mechanical pressures (affecting layer density) resulting from the spiral-wrap technique. Accounting for these discontinuities, as well as measurement and computational errors associated with K_a determination, results in an estimated deviation of up to -25%**for these thermal conductivity data. Accuracy of cylindrical test data, and comparisons with flat plate K_a values, are discussed in greater detail in Section 1.4.

The basic cylindrical apparatus was modified to extend its utility to the 1800°F operating range prior to composite testing. These changes, which affected primarily the heater and core designs and tester instrumentation, are described below.

* Net heat flux through the insulation is determined by:

$Q_{net} = Q_{total} - Q_{other\ losses}$
where Q_{total} is input power and $Q_{other\ losses}$ are attributed to heater and thermocouple leads which penetrate the insulation.

** Measured K_a values may be high by as much as 25%.

Figure 46 - Cylindrical Test Apparatus

- Heater design - Platinum - 10% rhodium (0.02 in. dia.) wire has been substituted for the previously used tungsten and nichrome heater wires. Platinum has both a low vapor pressure at high temperature, giving it the required long life as well as good oxidation resistance at high temperature.
- Core design - The stainless steel inner core has been replaced with one of "Mullite" (ceramic). Failures of platinum heaters in previous tests were in part traced to bimetallic compounds containing stainless steel. Elimination of the stainless core was considered necessary to successful use of the platinum heater.
- Instrumentation - Some revisions have been made in the instrumentation of these tests in an effort to improve accuracy. A revised instrumentation circuit is shown in Figure 47.

The cylindrical device does not possess the testing versatility of the flat plate apparatus described in Section 1.2. It is, however, extremely useful for $K_a(T)$ measurements on "installed" multilayer insulations, and subsequent long-term performance stability evaluations.

Procedure

The basic steps in $K_a(T)$ measurement and long-term stability evaluation of multilayer insulations are as follows:

(1) Basic thermal conductivity data (K_a as a function of T) are obtained at a number of hot-side temperatures ranging from 500°F to T_{max} , with the insulation in vacuum ($p - 1 \times 10^{-4}$ torr).

(2) Initiate long-term testing at maximum specified operating temperature, to be continued for the specified operating period (up to 10,000 hours).

(3) Monitor steady-state thermal performance at the T_{max} operating condition as a check on system stability over the extended test period.

*(4) Air exposure study, followed by recheck of system thermal conductivity in vacuum.

Multilayer Insulation Samples

Multilayer insulation samples were spirally-wrapped on the 3 in. diameter x 18 in. long core to an installed thickness of 0.5 in. The wrap was completed by

* Where required as part of the test program.

Figure 47 - SCHEMATIC OF INSTRUMENTATION CIRCUIT

folding the end sections layer-by-layer to form the total insulation enclosure. The specified n_a value was considered to be the average layer density achieved in the spirally-wrapped sample.

Prior to sample fabrication, insulation spacer materials were preprocessed* to remove organic binders present in the as-received condition. All metallic foil shields, with the exception of copper, were used in the as-received condition. The copper was cleaned in an elevated temperature, reducing environment to remove surface oxide.

2.1.2 Data Reduction Technique

For the installed multilayer systems, with the insulation at a specified average layer density (n_a), the $K(T)$ data are correlated by a polynomial of the form:

$$K(T) = aT + bT^3 \quad (14)$$

As originally developed by Wang,¹ the approximate expression for $K(T)$ in vacuum is comprised of a solid conductance contribution ($K_s = aT$) and a radiative contribution ($K_r = bT^3$). The K_s term is approximated as a linear function of T ; the radiation expression bT^3 is based on the classical radiant heat transfer expression for a system of multiple shields.

In integrated form, K_a for an insulation with boundary temperatures T_h and T_c is:

$$K_a = \frac{1}{(T_h - T_c)} \int_{T_c}^{T_h} K(T) dT = \frac{a}{2} \frac{T_h^2 - T_c^2}{T_h - T_c} + \frac{b}{4} \frac{T_h^4 - T_c^4}{T_h - T_c}$$

$$\text{where } \frac{b}{4} \approx \frac{\sigma \epsilon}{24 n_a} \quad (15)$$

In the above expression; T_h and T_c are in °R, ϵ is the effective emissivity for the foil shields, and n_a is the average wrapped layer density (l/inch).

In later flat plate thermal conductivity data analysis (Section 1.1), the K_s term has been modified to reflect a $T^{1/2}$ dependency (i.e., $K_s = aT^{1/2}$). This modified term appears to be somewhat more accurate in representing the spacer material (i.e., SiO_2) conductance at high temperature. The effect of this change on the previously obtained cylindrical data correlations was found to be relatively small.

* Preprocessing is accomplished by controlled oxidation at elevated temperature. This process was discussed in detail in the Phase I Final Report.⁹

Consequently, the modification was not extended to these earlier correlations.

Based on the measured $K_a(T)$ data, Equation (15) was applied to determine solid conductance and radiative coefficients for the multilayer systems of Table IX. Procedures used were as generally outlined in Section 1.1. Effective emissivities for the multifoil systems were also determined and compared to literature data.

2.2 Thermal Performance and Stability Results

2.2.1 Basic Thermal Performance Data

Effective thermal conductivity plots, presented as a function of source temperature, are given in Figure 48. The $K_a(T)$ curves are shown for all multilayer insulations tested in the Phase II cylindrical test program. Basic data and performance comparisons between the various insulation systems are as expected, and discussed previously in Section 1.3.

The solid conductance (K_s) and radiative (K_r) coefficients, along with effective emissivity (ϵ_ℓ) values, are given for each multilayer insulation in Table X. These parameters were determined by applying the empirical-graphical reduction techniques to Equation (15). The effective emissivities were, in all cases, higher than literature data for the particular metals involved. The same observation was true with ϵ_ℓ values determined from flat plate data.

As discussed in Section 1.3, a principal reason for this discrepancy may be the presence of the fibrous spacers in close contact with the reflecting foil surface. Also, some imbalance in the estimated K_s and K_r contributions as dictated by the form of Equation (14), may have contributed to the high ϵ_ℓ values. This possibly is strongly indicated for the Ni-Refrasil quartz and 1800°F composite systems. The negative K_s coefficients of Table X for these two insulations are not realistic, and would result in an overly high K_r coefficient (i.e., high ϵ_ℓ) in order to correlate the measured K_a data.

2.2.2 Thermal Performance Stability

Performance histories of multilayer insulation systems over extended operating periods at elevated temperature and in vacuum are presented in Figure 49. Effective thermal conductivity (K_a) is shown as a function of operating time for each tested insulation. Typical $\pm$ deviation or error bands on instrumentation and measured data are also given.

The multilayer insulations listed below showed no performance deterioration (i.e., K_a increase) for operating periods ranging from 2000 - 10,000 hours.

Figure 48 - Thermal Conductivity Data - Cylindrical Testing

TABLE X

Empirical Thermal Conductivity Parameters

Curve No. (Figure 48)	Foil Type	Spacer Type	No. of Layers Per Inch	$a/2 \times 10^7$ Btu/hr ft °R ²	$b/4 \times 10^{13}$ Btu/hr ft °R ⁴	e
1	Al	Al-opacified Glass Paper	150	0.1	0.66	0.137
2	Al	Refrasil Quartz Paper	120.	0.45	0.52	0.086
3	Cu	Refrasil Quartz Paper	83.3	0.8	0.53	0.062
4	Cu	Cu-opacified Quartz Paper	70.4	3.1	0.61	0.060
5	Ni	Refrasil Quartz Paper	96.1	-0.3	1.8	0.24
6	Ni	Astroquartz Cloth	120	3.1	1.5	0.25
7	Ni	Ni-opacified Quartz Paper	56	0.8	1.41	0.11
8	Ni-Cu-Al (Composite)	Refrasil Quartz Paper + Al-opacified Glass Paper	96	0.8	0.87	0.12
9	None	Al-opacified Glass Paper	74	1.2	5.9	
10	None	Cu-opacified Quartz Paper	30.3	6.1	15.29	
11	None	Ni-opacified Quartz Paper	65	3.2	4.6	
12	Mo-Ni-Cu-Al (Composite)	Quartz Cloth + Quartz Paper + Al-opacified Glass Paper	110	-0.7	1.13	0.17

Figure 49 - Long Term Performance Tests - Multilayer Insulations

<u>Multilayer Insulation</u>	<u>Source Temperature</u> °F	<u>Operating Period</u> hours
Al-Al opacified glass	842	3000
Cu-Cu opacified Refrasil quartz	1265	2000
Ni-Refrasil quartz	1620	2000
Al opacified glass	881	3000
Cu opacified Refrasil quartz	1220	10000

The above results would indicate minimal deterioration for the particular insulations in long term operation at the specified source temperature. The 2000-3000 hour evaluation time is relatively short, but is thought to be sufficient to indicate any significant instabilities which may have existed in the tested insulations.

Performance deteriorations for the Ni opacified Refrasil quartz multilayer and 1800°F composite multifoil insulations will be discussed in more detail below.

2.2.2.1 Nickel Opacified Refrasil Quartz Multilayer

Effective thermal conductivities of the nickel opacified Refrasil quartz multilayer insulation, measured at time zero and after 10,000 hours operation, are tabulated below.

<u>Elapsed Time</u> Hrs.	<u>T_{Hot}</u> °F	<u>T_{Cold}</u> °F	<u>Vacuum</u> 10 ⁻³ mm Hg	<u>Effective Thermal Conductivity</u> 10 ⁻³ Btu/hr-ft-°F
0	1485	577	< 0.5	7.6
10000	1481	644	< 0.5	10.1

The data above indicate a performance deterioration (i.e., K_a increase) of 32% over the 10,000 hour operating period.

Performance history for the nickel opacified quartz multilayer system (no metallic foil shields) is given in Figure 50. Rate of increase in thermal conductivity with time is approximately linear over the operating period. The rate of K_a increase is slower in the 0-6000 hour period than in the 6000-10,000 hour period. This behavior is most likely tied to the hot-side temperature history over corresponding time periods (also shown in Figure 50). In the initial 6000 hours of operation, input power was kept constant with the resultant decrease in hot-side temperature associated with performance deterioration. In the last 4000 hours of operation, average hot-side

Figure 50 - Performance Stability History -
Figure 50 - Performance Stability History - Ni Opacified Refrasil Quartz

temperature was maintained at the desired 1485°F. This higher average temperature may have accelerated the rate of performance deterioration.

As part of the post test evaluation, $K_a(T)$ data have been remeasured at source temperatures ranging from 700°F to 1485°F. The $K_a(T)$ curve after 10,000 hours operation is compared with the time zero curve in Figure 51. The K_a data after 10,000 hours have been corrected to reflect the cold-side temperature of the initial K_a data to provide a basis of comparison. The system deterioration is evident from the increase in the 10,000 hour $K_a(T)$ curve.

A recalibration of the source temperature thermocouple after the test was dismantled indicated virtually no change in calibration during the 10,000 hour exposure. Thus the previously calculated deterioration of 32% is accurate.

The results of the post test analysis for this insulation system are presented in Appendix I. The analysis concluded that both volatilization and oxidation of the nickel flakes were factors causing the performance degradation of the insulation. The source of the oxygen was not determined. It is possible that oxygen may have been one of the gas constituents within the test enclosure which was at a relatively high pressure during testing. ($\sim 5 \times 10^{-4}$ torr)

The results of this test indicated that nickel Opacified Refrasil paper should not be utilized above 1400°F.

2.2.2.2 1800°F Composite Multifoil Insulation

Long term testing of the original 1800°F composite design, using Ni-Refrasil quartz in the 1800-1400°F region, was interrupted early in the program due to instability of the Ni-Refrasil quartz system at 1800°F. This instability was discovered during $K_a(T)$ measurement at source temperatures of $\sim 1800^\circ\text{F}$. It was verified on a second, concurrently-tested, multifoil system comprised entirely of Ni-Ni opacified Refrasil quartz.

The composite system was dismantled and close inspection of the 1800°F materials showed a visible dullness to the nickel shields and an embrittlement of the Refrasil quartz spacer. These apparent changes in the materials pointed to (1) loss of fibrous characteristics in the Refrasil (increased solid conduction) or (2) higher emissivity of the nickel foil (increased radiation) as contributors to the poor performance.

Further analysis of the nickel foil and Refrasil quartz spacer indicated the following:

- (1) Refrasil quartz, exposed to the 1600-1800°F temperature had undergone a change of form from amorphous to crystalline. The change resulted in severe embrittlement and loss of fibrous characteristics.
- (2) The nickel foil surface had undergone severe thermal etching and recrystallization as a result of 1800°F exposure.

Short term, comparative tests were subsequently run to evaluate stability of molybdenum versus nickel foils, and Refrasil quartz paper versus Astro-quartz (higher purity SiO_2) woven cloth. These tests are summarized and discussed in Appendix D.

Figure 51 - Effective Thermal Conductivity Curves
Ni Opacified Quartz

On the basis of the previous experience with Ni-Refrasil quartz at 1800°F and the comparative testing described in Appendix D, a Mo-Astroquartz system was substituted for Ni-Refrasil quartz in the 1800-1600°F range of a modified composite. The Ni-Refrasil quartz component was derated for use up to 1600°F.* The modified composite design and subsequent long term testing is described in the following paragraphs.

2.2.2.2.1 Modified 1800°F Composite Design

Pertinent details of the modified composite design are shown in Figure 52. The predicted steady state temperature profile between 1800°F and 500°F (estimated cold-side temperature) is characteristic of profiles through high temperature multi-layers where heat transmission is radiation controlled. With this type of profile, the bulk of the composite insulation is at relatively high temperature; e.g., 50% of total insulation thickness consists of the molybdenum-Astroquartz component. The composite insulation sample is installed under mild loading (.1 psi). The estimated average layer density is 110 /inch. Wrapped sample thickness is to be 0.5 inches.

Prior to establishing the long-term 1800°F. condition, effective thermal conductivity data were obtained at several hot-side temperatures from 400 - 1800°F. These data are presented in Figure 53. As shown in Figure 54, the effective thermal conductivity of the composite insulation is consistent with performance data for the individual component systems. The K_a of the composite mainly reflects the thermal performance characteristics of the Mo - Astroquartz and Ni-Refrasil quartz systems, which comprise 50% and 30% of the total composite wrap, respectively. The Al-Al opacified glass component, accounting for less than 5% of the composite, has less impact on overall composite thermal performance. However, these lower temperature materials do represent cost and weight savings in the composite system.

* A previous 2000 hour test had shown Ni-Refrasil quartz to be stable at the 1600°F operating temperature.

Figure 52 - Estimated Temperature Profile -
1800' F Composite

Figure 53 - Effective Thermal Conductivity - 1800°F Composite

Figure 54
COMPOSITE MULTILAYER INSULATION PERFORMANCE

2.2.2.2.2 Performance Stability-Modified 1800°F Composite

This test was terminated after 7670 hours because of what appeared to be an acceleration in the deterioration of thermal performance. However a post test check of the hot wall thermocouple indicated that the calibration had drifted to the point where the couple was reading about 200°F low. Therefore the estimated hot wall temperature at the termination of the test was 1950°F. Although the insulation was exposed to a source temperature 150°F above its composite design, actual deterioration in thermal conductivity was less than 5%. Before the test was terminated the erroneous source temperature reading had indicated a deterioration of 65%. The performance history during the 7670 hour excursion is not accurate because of the drift in the source temperature thermocouple calibration. It is postulated that the drift in calibration was caused by a change in wire composition of one or both thermocouple legs.

An initial attempt to evaluate the insulation composite for potential sources of material degradation prior to termination of the test is presented in Appendix E.

2.2.2.2.3 Post Test Analysis of Composite Materials

A summary of the composite materials post test analysis is presented in Table J-1. In general all the materials indicated good compatibility with the test conditions even though the composite had been subjected to an over temperature excursion. The condition of the molybdenum-quartz portion of the composite appeared very good with the exception of some deterioration in mechanical properties. There was some thermal etching of the copper and nickel foils, however, this would be expected since some of these foils were subjected to temperatures above their recommended usage level.

The detailed results of the post test analysis are presented in Appendix J.

2.3 Observations and Recommendations

Long-term testing to date indicates that the following multilayer insulations perform stably over extended operating periods at elevated temperature in vacuum.

<u>Multilayer Insulation</u>	<u>Source Temperature</u>	<u>Operating Period</u>
Al-Al opacified glass	842 °F	3000 hrs.
Al opacified glass	881 °F	3000 hrs.
Cu opacified Refrasil quartz	1220 °F	10,000 hrs.
Cu-Cu opacified Refrasil	1265 °F	2000 hrs.
Ni-Refrasil quartz	1600 °F	2000 hrs.
Composite	>1800 °F	7670 hrs.

Table XI

Multilayer Composite Post Test Analysis

Number of Layers	Maximum* Temperature	Foil	Spacer	Results
30	>1800°F	Molybdenum	Quartz Cloth	(1) Very little evidence of molybdenum surface volatilisation (2) Some reduction in molybdenum ductility due to recrystallization (3) Reduction of quartz strength and flexibility (4) No evidence of quartz devitrification (5) No evidence of incompatibility between molybdenum and quartz
14	>1600°F	Nickel	Silica Paper	(6) Thermal etching and grain growth of foil evident (7) Noted reduction of silica strength (8) No evidence of incompatibility between foil and silica
8	>1400°F	Copper	Silica Paper	The same as 6-8 above.
3	>900°F	Aluminum	Aluminum Opacified Glass Paper	(9) Recrystallization of the aluminum foil was evident (10) No incompatibility between aluminum foil and the aluminum opacified glass spacer was evident

* A post test calibration of the hot wall thermocouple indicated that the couple was reading about 200°F low. Thus, during the test actual hot wall temperature had drifted from 1800°F to near 1950°F at the termination.

FIGURE - 55

ESTIMATED SOURCE TEMPERATURE HISTORY - 1800 °F COMPOSITE

The above insulations indicated less than a 5% performance deterioration over operating times ranging from 2000-10,000 hours. Based on this first-order testing, insulation systems using these designated materials may be designed with some degree of confidence for stable operation to 1800°F in vacuum.

Testing to 1800°F in vacuum has pointed up some potential stability problems. Nickel foil and Refrasil quartz paper, originally designated for use in the temperature range, have not demonstrated the required stability (Section 2.2.2.2). Substitution of molybdenum foil and high purity SiO₂ (woven Astroquartz) have shown marked improvement.

Factors contributing to the 1800°F stability problem are:

(1) Higher operating temperatures accelerate the potential causes of system instability; i.e., foil-spacer material compatibility, metallurgical stability of the metallic foil surface, volatilization of materials, particularly SiO₂ spacers.

(2) Temperatures of 1800°F and above dictate the use of refractory metal foils and ceramic fibrous spacers. These materials, potentially quite attractive based on their thermophysical properties, are somewhat more difficult to handle and fabricate and, in the case of refractory foils, are readily oxidized at elevated temperatures.

Proposed future work directed toward materials and testing upgrading, and subsequent stability tests on composite insulations in the 1800-2000°F operating range is outlined below. The work would develop from current experience gained in the 1800°F composite multifoil tests, and would be concentrated in two basic areas:

(1) Refinement and improvement of test procedures and equipment.

(2) Review and upgrading (if required) of composite insulation materials for stable operation at 1800-2000°F in vacuum.

The key element in test upgrading is an improved vacuum system capable of simulating the space vacuum environment in the composite test chamber. A test pressure of 1×10^{-7} torr is thought to be low enough to simulate the environment and, from a practical standpoint, appears to be achievable in insulation testing. A potential test system design is shown schematically in Figure 56. The desired vacuum pressure is achieved dynamically by an LN₂ baffled, high capacity oil diffusion pumping system. Conductance between the test chamber and pumping equipment is maximized in the test arrangement.

Figure 56 - Modified Performance Stability Test Arrangement

Reliability and accuracy of the temperature sensing instruments would be achieved through the use of sheathed Pt/Rh or W/Re thermocouples. The thermocouples would be protected against contaminants from the test environment. Provisions would be made for periodic recalibration and, if necessary, replacement of thermocouples during testing.

Molybdenum foil and zirconia cloth separator are the principal materials for use in vacuum at temperatures of 2000°F and above. This multifoil system has not, as yet, been evaluated for long term performance stability characteristics under these operating conditions. Stability tests (i.e., 10,000 hour exposure) on these and any other equally attractive materials would be recommended, utilizing the upgraded equipment.

Prior to the long term evaluations, some small scale "bench" tests would be useful to get some preliminary indication of material stability. These tests would be of short duration, and would consist of the following:

- (1) Exposure of materials and specified material (foil-spacer) combinations to the high temperature, vacuum environment (controlled furnace tests).
- (2) Evaluation and comparison of as-received and exposed materials properties, by means of chemical, metallurgical, and mechanical analysis and testing.

These tests would be potentially quite useful in indicating "threshold" or maximum use temperatures for the material combinations. Design and execution of a typical "bench" test program is discussed further in Appendix E.

A test program of this type, including both short duration materials tests and long term (10,000 hour) stability testing, should yield pertinent information on (a) overall performance stability in vacuum and at 1800°F or above, and (b) modes of degradation of materials under these conditions. Such information could then form the basis for some meaningful predictions of multilayer insulation stability for extended periods of service (e.g., 5 year operating life).

3.0 Insulation Interfaces

3.1 Insulation Interfaces - Penetrations

3.1.1 Introduction

The objective of this study has been to determine the effect of the presence of a penetration through an insulation panel on the insulation thermal performance when the penetration and/or its immediate surroundings give rise to thermal discontinuities.

Two types of penetrations have been under investigation; flush penetration as shown in Figure 57(a) and extended penetrations as shown in Figure 57(b). For each of the two major types, zero gap, open gap and filled gap configurations (as described in Figure 57) are analyzed.

Flush penetration studies are aimed directly at the evaluation of disturbances associated with the necessity of passing a multiplicity of regularly spaced thermoelectric elements through a typical energy conversion panel. Specific analyses have been made considering both lead-telluride and silicon germanium element materials.

Extended penetrations studies are aimed primarily at studying similar effects associated with structural members which connect the hot and cold boundaries, where the structural member may or may not be equal in length to the insulation thickness. Investigation of the effects of extended penetrations has been centered around the use of Hastelloy-X as a typical high temperature structural material.

Basis for the calculations and physical and analytical models used in the calculations are discussed in some detail. The discussion is related to the generalized two-dimensional computer analysis for treating either flush or extended penetrations with the three gap configurations. Extensive data on the Hastelloy-X penetrations are presented and discussed. Further details on the analytical development, and additional data for systems containing lead-telluride and silicon-germanium flush penetrations are presented in Appendices F and G.

3.1.2 Basis and Objectives of Calculations

The physical models used to explore the effect of flush and extended penetrations are shown in Figures 58 to 61. Figure 58 shows the idealized configuration for the case where the penetration length is equal in magnitude to the insulation

Figure 57 - Penetration - Insulation Schematic

(a) FLUSH PENETRATIONS

(b) EXTENDED PENETRATIONS

Figure 58 - Flush Penetrations - Idealized Configuration

Figure 59 - Extended Penetrations - Idealized Configuration I

Figure 60 - Extended Penetrations - Idealized Configuration II

Figure 61 - Extended Penetrations - Idealized Configuration III

height. With this configuration as a basis, Figures 59, 60 and 61 are self explanatory.

With regard to the idealized penetration-insulation configurations, the principal objectives of the analysis are outlined and discussed below.

Objective 1 Compare the actual heat flow which may be expected from the various configurations of Figures 58 to 61, to the simplified, one-dimensional calculation associated most realistically with the zero gap, flush penetration configuration of Figure 58(a).

The simplest case to examine is Figure 58(a) flush penetration-zero gap. The simplest calculation which could be made for this case is a one-dimensional calculation where the interface between the insulation and the penetration is considered adiabatic and the hot and cold side temperatures (T_h) and (T_c) are considered both uniform and identical to the insulation hot and cold side temperatures. This calculation can be made simply from knowledge of insulation and penetration thermal conductivities and from boundary temperatures.

It is further believed that given a system of another configuration (e.g., where the penetration extends considerably beyond the insulation), the common tendency would be to treat it thermally in a manner like the system of Figure 58(a). That is, the insulation is considered as spanning the entire temperature difference from T_h to T_c and further that the thermal length of the penetration (i.e., the length effectively spanned by T_h and T_c) is also equal to the insulation thickness.

Objective (1), then, will relate this simplified design calculation to results obtained by two-dimensional thermal analysis. In this manner, some sensitivity can be acquired as to the necessary adjustments required in these one-dimensional values in order to reflect actual system performance.

Objective 2 Compare thermal performance of filled and empty gap configurations versus zero gap cases.

Physical achievement of a zero gap configuration, at least in the thermal sense, (i.e., where the insulation foils are intimately tied to the penetration), is difficult to conceive. Two more practical physical designs are embodied in either the filled gap or empty gap configurations. Thermal performance of these two configurations are related to the reference "one-dimensional, zero gap" case in the analysis.

Objective 3 Explore the various multifoil insulation locations relative to the penetration (i.e., toward hot side, centered, toward cold side) to

determine configurations yielding lowest total heat flow.

Objective 4 In addition to total heat flow studies, examine heat flow through the insulation portion of the system and how it is affected by:

- (a) two-dimensional flow
- (b) physical detachment of the insulation from hot and cold boundaries (i.e., radiative coupling)
- (c) the presence of filled or unfilled gaps

For convenience, all heat flow quantities are reported in dimensionless form, referenced to one dimensional results associated with Figure 58(a). The fraction

$$\frac{Q_{\text{system}}}{Q_{\text{(one dimensional-zero gap)}}$$

is interpreted as a ratio of the heat which flows from T_h to T_c calculated two-dimensionally for each of the cases of Figures 58 to 61, to the heat flow from T_h to T_c which would result from one-dimensional analysis of the configuration of Figure 58(a).

Similarly, the fraction

$$\frac{Q_{\text{penetration}}}{Q_{\text{(penetration-one dimensional)}}$$

is interpreted as a ratio of the heat which enters the penetration at T_h in each of the cases of Figure 58 to 61 to the heat which would flow from T_h to T_c through the penetrations if the penetration were considered equal in length to the insulation thickness and the heat flow through the penetration were calculated one-dimensionally.

The extent to which this ratio is smaller than unity indicates the increase in effective thermal length of the given penetration over the assumption that the effective length is equal to the insulation thickness. The extent to which this observation is valid depends on how large the conductance of the penetration is with respect to the heat exchange between the penetration and insulation.

The fraction

$$\frac{Q_{\text{(into insulation-hot side)}}}{Q_{\text{(insulation-one dimensional-zero gap)}}$$

is interpreted as the ratio of the heat which enters the hot side of the insulation area $\pi(r_3^2 - r_1^2)$ * to the heat which would enter the same area of multilayer insulation (zero gap) when the heat flow is calculated one-dimensionally and the insulation is interposed between uniform temperatures T_h and T_c .

Examination of this quantity in conjunction with the fraction

$$\frac{Q_{\text{from insulation cold side}}}{Q_{\text{(insulation-one dimensional-zero gap)}}$$

will give an indication of the amount of net heat exchange between the penetration and the insulation.

The analytical results of Section 3.1.4 (Tables XII to XLIII) are presented in the form of the previously described dimensionless ratios.

3.1.3 Analytical and Physical Models

The physical or configurational models upon which the analysis is based are described in Figures 58 to 61. The analytical model, along with the governing equations and boundary conditions which describe these configurations, is given in Figures 62 and 63.

3.1.3.1 Analytical Assumptions

The thermal analysis was based upon the geometry shown in Figure 62 and upon the following assumptions:

- (a) If the penetration extends beyond either surface of the insulation panel, its thermal coupling with the panel and gap surface is conductive only, whereas its coupling with the wall is both conductive and radiative (view factor = 1).
- (b) The insulation and gap surfaces are both either prescribed at uniform temperatures or radiantly coupled with the walls facing the respective surfaces (view factor = 1), which are themselves prescribed at uniform temperatures.

* Reference Figure 62.

Figure 62

Penetration System Geometry

Figure 63

Penetration Analysis - Boundary Conditions

Insulation: $\frac{1}{r} \frac{\partial}{\partial r} (r k_{ir} \frac{\partial T_i}{\partial r}) + \frac{\partial}{\partial z} (k_{iz} \frac{\partial T_i}{\partial z}) = 0$

Fourier Equation: Gap (INDEX > 1): $\frac{1}{r} \frac{\partial}{\partial r} (r k_{gr} \frac{\partial T_g}{\partial r}) + \frac{\partial}{\partial z} (k_{gz} \frac{\partial T_g}{\partial z}) = 0$

Penetration: $\frac{\partial}{\partial z} (k_p \frac{\partial T_p}{\partial z}) + \frac{2 Q_p}{r_1} = 0$

Boundary ConditionsAxial (z) Direction:

- (1) Either
 $T_i(r, H) = T_h$ (Indx = 1, 2)
 $T_i(r, 0) = T_c$
Or
 $k_{iz} \frac{\partial T_i}{\partial z} \Big|_{z=H} = \sigma \epsilon_h \epsilon'_h (T_h^4 - T_i(r, H)^4)$
 $k_{iz} \frac{\partial T_i}{\partial z} \Big|_{z=0} = \sigma \epsilon_c \epsilon'_c (T_i(r, 0)^4 - T_c^4)$
 (Indx = 0, 3)
- (2) Same as (1) for T_g, k_{gz}
 ($\epsilon_h = \epsilon_c = 1$)
- (3) Either
 $T_p(H + PLH) = T_h$ (PLH > 0 OR INDEX = 1, 2)
Or
 $k_p \frac{\partial T_p}{\partial z} \Big|_{z=H} = \sigma \epsilon'_h (T_h^4 - T_p(H)^4)$
- (4) Either
 $T_p(-PLC) = T_c$ (PLC > 0 OR INDEX = 1, 2)
Or
 $k_p \frac{\partial T_p}{\partial z} \Big|_{z=0} = \sigma \epsilon'_c (T_p(0)^4 - T_c^4)$

Radial (r) Direction:

- (1) $\frac{\partial T_i}{\partial r} \Big|_{r=r_3} = 0$
- (2) $k_{ir} \frac{\partial T_i}{\partial r} \Big|_{r=r_2} = Q_p$, INDEX = 1
 $= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=r_2}$ INDEX = 2
 $= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=r_2} + (Q_i)_{RAD}$, INDEX = 3
- (3) $Q_p = \sigma \epsilon'_h (T_h^4 - T_p(z)^4)$
 $H < z \leq H + PLH$
- $Q_p = k_{ir} \frac{\partial T_i}{\partial r} \Big|_{r=r_1}$, INDEX = 1
 $Q_p = k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=r_1}$, INDEX = 2
 $Q_p = k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=r_1} + (Q_p)_{RAD}$, INDEX = 3
- $Q_p = \sigma \epsilon'_c (T_c^4 - T_p(z)^4)$
 $0 > z \geq -PLC$

LEGEND:

Subscripts:

p - penetration
 g - gap
 i - insulation
 h - warm side
 c - cold side

r - radial direction
 z - axial direction
 RAD - refers to radiative flux inside gap

$T_p(z)$
 $T_g(r, z)$
 $T_i(r, z)$

Parameters:

Q - Flux
 Temperatures
 σ - Stefan-Boltzmann Constant
 ϵ, ϵ' - Emissivity of foil and walls

- (c) The penetration is conductively isotropic but the insulation and gap filler are not.
- (d) If translucent*, the gap filler is radiatively isotropic.
- (e) Radiant interchange among the surfaces bounding the gap can be either attenuated through backscattering or unattenuated. If the gap filler is translucent, all radiation into the gap is either transmitted directly or scattered at a 180° angle with the line of incidence.
- (f) Radial heat flow vanishes at a given radial position $r = r_3$ within the insulation. Assumption that this "adiabatic circle" exists thus enables the user to approximate the situation in which several penetrations are arranged in an infinite, regular (e.g., square, hexagonal) pattern within the panel.
- (g) Both cylindrical surfaces (penetration and insulation) bounding the gap are black (emissivity = 1). However, the gap ends may have emissivities less than unity.
- (h) Both the walls and the panel surfaces may have emissivities less than unity.
- (i) All emissivities and thermal conductivities are defined as functions of temperature.

These assumptions are reflected in the basic equations and boundary conditions outlined in Figure 63.

3.1.3.2 Characteristics of the Hastelloy-X Penetration System Analyses

Pertinent characteristics are presented for the two penetration-insulation systems analyzed and discussed in Section 3.1.4. The two systems are (a) Hastelloy-X penetrations in an Al-Al opacified glass multifoil insulation (800-200°F), and (b) Hastelloy-X penetrations in a Ni-Refrasil quartz multifoil insulation (1800-800°F). The characteristics described below relate to the basic penetration-insulation configurations of Figures 58 to 61.

* This program properly defines the opacified filler materials as semi-transparent rather than opaque media in which radiative heat is attenuated primarily by backscattering. The semi-transparent nature of the opacified fillers was verified in flat plate thermal performance testing. In the analytical model, the solid conduction and radiation transfer are described separately. In describing the radiation transfer, 180° backscattering in the filler is assumed and the radiant interchange between two surfaces separated by the filler is modified to include the backscattering effects. The radiative backscattering model is described in detail in Appendix F.

(a) Each basic system considers three configurational options:

Zero GapInsulation foils assumed to be in perfect thermal contact with the penetration.

Filled GapAn annular gap between the penetration and the insulation is filled with a buffer insulation with the following thermal properties:

$$\begin{aligned} K_r &= .24 \times 10^{-6} \text{ T} \\ K_n &= .24 \times 10^{-6} \text{ T} \\ N_e^n &= 930 \text{ in}^{-1} \end{aligned}$$

where

$$\begin{aligned} K_r &= \text{thermal conductivity (solid) in the radial or lateral} \\ &\quad \text{direction} \\ K_n &= \text{thermal conductivity (solid) in the normal direction} \\ &\quad \text{(i.e., hot side to cold side)} \\ N_e &= \text{effective backscattering cross-section of the filler} \\ &\quad \text{material in normal and radial directions} \end{aligned}$$

Empty Gap An annular gap between the penetration and the insulation is considered to be empty.

(b) In each of the cases described by the above figures, all radiating surfaces are considered optically black with the exception of the upper and lower boundaries of the multiple layer insulation (r_3-r_2). From the point of view of heat loss from the exposed segments of the penetration, this will be the most severe condition, tending to reduce the penetration's effective thermal length. This effect would be particularly so in these calculations since the thermal balance on a longitudinal increment of the exposed penetration considers only heat leaving its surface by radiation and not heat reaching it by the same mode.

(c) The upper and lower surfaces (T_h and T_c) are both considered to be only radiatively coupled to the upper and lower surfaces of the insulation. It is believed that heat is transferred from the system surface to the insulation surface primarily by radiation and further that the attenuation provided by, say, one spacer between the wall and the insulation surface is small. For example, for the typical conditions assumed,

$$\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 = 10 (N_e \Delta X) \quad (22)$$

- ϵ_1 = hot wall emissivity = 1.0
- ϵ_2 = insulation surface emissivity = 0.05
- N_e = scattering cross-section of a plain spacer
200 in.⁻¹
- ΔX = thickness of one spacer 0.010 in.

One exception to the above condition is the area of the gap filler in the filled gap cases. This small annular area, unlike the remainder of the insulation surface is considered optically black; thus, the attenuating power ($N_e \Delta X$) of even one filler could reduce total heat transfer from the hot surface to this small area by a factor of 2. Effective omission of the filler in this area (unattenuated radiation assumption) will, therefore, result in a slightly elevated temperature at this point. Since the surface areas of interest are small, effect on total heat transfer is believed small.

In those cases where the distance between the wall and the insulation is large, this assumption would, of course, not be accurate unless the space would indeed be void. It is believed that for large spaces, this would be the case; thus, the assumption is believed justified.

It is possible that a configuration could exist where the relatively large space between the insulation and the system surface is filled with a lightweight plain fiber capable of attenuating some radiation. In this case, its effect on decreasing heat transfer between the two surfaces must be considered.

(d) In carrying out the heat balance around the exposed portions of the penetration (i.e., calculating Q_p)

- (1) The geometric view factor is considered unity.
- (2) Only heat interchange between the penetration and the boundary surfaces is considered.

The assumption of unity for a geometric view factor could be in error depending on the actual geometry of the hot and cold surfaces. Under the most unfavorable circumstance, the effect of this assumption would be to increase heat transfer to the penetration. Since the penetration area is a relatively small collector, the effect on the total heat balance is not believed to be significant.

3.1.4 Analytical Results and Observations

Analyses were performed on the Hastelloy-X penetration-insulation system configurations of Figures 58 to 61. Tables XII to XXVII present results

for the Al-Al opacified glass insulation. Results on the Ni-Refrasil quartz system are given in Tables XXVIII to XLIII. Heat fluxes are indicated by the dimensionless ratios described previously in Section 3.1.2.

Pertinent observations on the thermal behavior of the Hastelloy-X/Al-Al opacified glass system, operating between boundary temperatures of 800°F and 200°F in vacuum, are presented in the following paragraphs. Results from the analysis of the Hastelloy-X/Ni-Refrasil quartz system, operating between 1800°F and 800°F, lend themselves to a similar interpretation.

(a) In the case of penetration length equal to insulation height, the one-dimensional approximation to calculating total heat flow appears adequate provided total heat flow is largely influenced by the heat flow through the penetration. In terms of the results shown in Tables XII and XXVIII, for the smaller values of adiabatic radius (r_3) the ratios of $Q_{\text{system}}/Q_{\text{(one dimensional-zero gap)}}$, particularly for the zero gap system, are essentially unity.

Although the filled gap and empty gap cases are also close to unity, the same interpretation cannot be applied since the configurations are not consistent. What the proximity of the results to unity does indicate, however, is that the effects of having a small empty gap or filled gap are not controlling in those cases where a large share of the heat flow goes through the penetration.

The results of these two tables also show that, as the insulation area assignable to any one penetration is larger (i.e., r_3 increases to 6 in.), the one-dimensional approximation overestimates the calculated heat flux. This observation is ascribed to (1) the assumed radiation coupling at the surfaces which, to some extent, limits the heat flux to the insulation, and (2) the larger influence of the increased insulation area assigned to a fixed penetration size. Likewise, increasing penetration size has the effect of increasing its dominance.

(b) For all cases where the penetration is considerably longer than the insulation, (Figures 59, 60, 61) the simple, one-dimensional approximation overestimates system heat loss by a wide margin (in some cases, by as much as one order of magnitude). The primary indication is clearly that even with the assumption of blackbody loss from the surface of the penetration, physically lengthening the penetration results in considerable thermal lengthening and thus lower heat flow. For example, comparing Figures 58 and 59 for the following case:

Panel thickness	- 0.1 "
Penetration diameter	- 0.1 "
Adiabatic radius	- 1.5 "

Empty gap
Gap width - 0.025"

One has $\frac{Q_{\text{system}}}{Q_{\text{(one dimension of zero gap)}}} = 0.989$ (Table XII)

and $\frac{Q_{\text{system}}}{Q_{\text{(one dimensional zero gap)}}} = 0.100$ (Table XIII)

Lengthening the penetration physically by a factor of 20 has lengthened it thermally by approximately a factor of 10.

A secondary observation which can be made is that with the reduced heat flux through the penetration, (Table XIII as compared to XII), increasing the adiabatic radius from 1.5" to 6" improves the accuracy of the one-dimensional calculation in contrast to the observation of Table XII. This observation would suggest that a reversal of this trend would occur in Table XII if the adiabatic radius were increased beyond 6" to the point where the insulation predominated over the disturbance.

(c) If one has a choice, theoretically, calculations indicate that the insulation should be placed toward the center of the penetration. Positioning the insulation toward the hot side is second best, and at the cold side, the least advantageous.

It is believed that this behavior is controlled primarily by the amount and direction of heat exchange between the penetration and the insulation. For any given insulation, therefore, an optimum location would be expected to exist and it may not be exactly at the center of the penetration.

From a practical viewpoint, it is believed that in most designs, the insulation would be placed next to the hot side. Further reduction in heat loss could be achieved by insulating the penetration longitudinally to achieve a greater thermal length.

(d) Results indicate the existence for each configuration (i.e., Figures 59, 60, 61) of a penetration length to area ratio at which the heat loss is a minimum.

For example, for the configuration of Figure 60 (Table XIII), increasing the length of the 0.1 in. diameter penetration from 2 in. to 6 in. seems

to make very little difference to total heat flow. Increasing the length of the 0.5 in. diameter penetration in the same manner still effects a considerable decrease in total heat flow. For the configuration of Figure 59 (Table XIV) on the other hand, increasing the length of the 0.1" diameter penetration from 2 in. to 6 in. causes an increase in the total heat flow. Increasing the length of the 0.5 in. penetration in the same manner causes only a minor increase.

Note that since the configuration of Table XII can be considered to be a special case of any of the configuration of Figures 59, 60 and 61, examination of corresponding cases for each of these configurations will yield, at least for some cases, first a decreasing, then an increasing trend in total heat flow as the exposed length of the penetration is varied from zero to six inches.

(e) Caution must be exercised in examining the results of cases with increased insulation thickness. The height of the insulation as well as the length of the penetration used for the one-dimensional base is increased. This results in lower absolute values of one-dimensional heat quantities and, thus, the larger fractions. The indication, of course, is that although the exposed lengths of penetration are identical to those for the smaller insulation thickness cases, the ratio of unexposed to exposed penetration is increased and, with further increases in insulation thickness, would eventually approach (but not reach) the results of Table XII.

(f) The significance of Tables XVI through XIX and similar figures for the higher temperature range is self-explanatory. Results in these tables give an indication of the amount of heat entering the hot penetration system interface and the change in this quantity as the penetration is lengthened under various system configurations. It is further noted that:

- (1) For the flush case (Table XVI), heat entering the penetration is nearly equal to the one-dimensional prediction.
- (2) A drastic reduction in heat flow occurs as the penetration is lengthened (Tables XVII, XVIII, XIX).
- (3) The reductions in heat entering the penetration are of the order of reductions in heat transfer through the systems, thus indicating the overwhelming dominance of the penetration heat leak.
- (4) Exposing the hot end of the penetration is more detrimental than exposing both ends or the cold end. (Compare Tables XVIII to XVII and XIX.)

(g) The results on Tables XX to XXIII and similar figures for the higher temperature range can be interpreted in a manner similar to the results of Table XVI to XIX.

- (1) For the small penetration diameter, the radiation coupling between the system hot side (T_h) seems to predominate. Thus, the one-dimensional calculation would seem to overestimate heat entering the insulation.
- (2) However for the larger penetration diameter (and/or larger gaps), where heat transfer from the insulation to the penetration (or simply off the insulation edge) is not as limited as it is in the small penetration diameter (or gap) case, the penetration or surroundings seems to be able to cool the hot insulation layers sufficiently to increase heat flow to the insulation substantially. This condition seems to be aggravated by larger insulation thickness which, in turn, represents larger areas from which heat can be lost laterally from the insulation.

(h) Tables XXIV to XXVII show ratios of heat leaving the insulation cold side to heat entering its hot side. Fractions smaller than 1.00 would indicate a net heat transfer from the insulation to the penetration and/or surrounding. Fractions greater than 1.00 would indicate net heat flow in the opposite direction.

- (1) Note that in all cases, with the exception of those cases where the insulation is concentrated at the hot side (Table XXVII), net loss is out of the insulation.
- (2) Note also that concentration of the insulation at either the hot or cold side provides the two extreme cases. From an overall heat loss viewpoint it is believed better to let the insulation cool the penetration rather than the reverse case. It is believed that this accounts in part for the better overall performance of the configuration of Table XXVII in comparison to that of Table XXVI.

The penetration-insulation system computer analysis has been highly useful in evaluating thermal behavior of the penetration-insulation systems and gaining some insight into selection of thermally efficient configurations. The absolute accuracy of the computed heat loss values is, of course, dependent upon:

- (1) The capability of the mathematical model (Figures 62 and 63) to accurately represent the physical cases.

(2) The accuracy of the input data for thermal properties of the multilayer insulations and penetrations.

Refinements and upgrading in both of these areas was made throughout the Phase II analytical program. The previously described analysis incorporates the improved designation of the opacified gap filler materials as being semi-transparent rather than opaque. This refinement was based on flat plate test results for these materials; the development of this analytical refinement is shown in Appendix F. Some further improvement in accuracy of input K_a -data could yet be made, based on flat plate testing completed subsequent to this analysis. The new data would likely improve absolute accuracy of the analytical results. However, the magnitude of these changes in K_a -data are not thought to be sufficient to alter the current observations on thermal behavior of these systems, as discussed in this section.

TABLE XII

$$Q_{\text{system}} \\ Q_{\text{(One-Dimensional Zero Gap)}}$$

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy-X Penetration
Boundary Temperatures - 800°F - 200°F

			PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.989	.839		1.00	.935	0.1
			1.00	.991		1.00	.997	0.5
		0.075	1.01	.851		1.04	.964	0.1
			1.00	.990		1.01	1.00	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.983	.838		.994	.931	0.1
			.996	.990		.999	.995	0.5
		0.075	.983	.839		.994	.931	0.1
			.996	.987		.999	.995	0.5
			ZERO GAP		.993	.853		.999
		1.00	.991		1.00	.997	0.5	
		1.5	6.0		1.5	6.0		
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION
CONFIGURATION

TABLE XIII

 Q_{system} Q (One-Dimensional Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation
 Hastelloy X Penetration
 Boundary Temperatures - 800°F - 200°F

Conservative Q_{p_o}

			PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.100	.242		.291	.461	0.1
			.057	.066		.195	.208	0.5
		0.075	.118	.254		.332	.483	0.1
			.059	.067		.200	.212	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.097	.240		.280	.450	0.1
			.056	.066		.192	.204	0.5
		0.075	.098	.240		.280	.449	0.1
			.056	.066		.192	.204	0.5
			ZERO GAP		.114	.255		.342
		.059	.069		.200	.223	0.5	
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.104	.244		.299	.462	0.1
			.038	.048		.136	.150	0.5
		0.075	.122	.256		.338	.489	0.1
			.041	.050		.141	.155	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.100	.242		.286	.454	0.1
			.038	.048		.133	.146	0.5
		0.075	.100	.242		.286	.454	0.1
			.038	.047		.133	.146	0.5
			ZERO GAP		.114	.255		.338
.039	.050				.141	.166	0.5	
		1.5	6.0		1.5	6.0		
		ADIABATIC RADIUS - INCHES						

PENETRATION DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION

TABLE XIV

 Q_{system} $Q_{\text{(One-Dimensional Zero Gap)}}$ Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.186	.301	.504	.616	0.1
			.084	.093	.276	.293	0.5
		0.075	.205	.313	.548	.638	0.1
			.087	.096	.284	.300	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.179	.295	.476	.582	0.1
			.083	.092	.271	.281	0.5
		0.075	.179	.295	.474	.581	0.1
			.083	.092	.270	.281	0.5
ZERO GAP			.227	.390	.575	.762	0.1
			.088	.105	.286	.333	0.5
		1.5	6.0	1.5	6.0		
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.246	.340	.610	.679	0.1
			.086	.095	.285	.302	0.5
		0.075	.265	.352	.654	.706	0.1
			.088	.097	.293	.308	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.238	.335	.589	.658	0.1
			.084	.093	.280	.290	0.5
		0.075	.238	.335	.588	.657	0.1
			.084	.093	.279	.290	0.5
ZERO GAP			.265	.412	.635	.780	0.1
			.087	.104	.288	.335	0.5
			1.5	6.0	1.5	6.0	
ADIABATIC RADIUS - INCHES							

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PENETRATION-INSULATION CONFIGURATION

TABLE XV

 Q_{system} $Q_{\text{(One-Dimensional Zero Gap)}}$

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.156	.229		.398	.534	0.1	PENETRATION DIAMETER - INCHES
			.074 <td>.083</td> <td></td> <td>.237</td> <td>.250</td> <td>0.5</td>	.083		.237	.250	0.5	
		0.075	.175	.292		.440	.561	0.1	
			.076	.086		.244	.256	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.149	.275		.382	.518	0.1	
			.073 <td>.082</td> <td></td> <td>.232</td> <td>.243</td> <td>0.5</td>	.082		.232	.243	0.5	
		0.075	.149	.275		.381	.518	0.1	
			.073 <td>.082</td> <td></td> <td>.232</td> <td>.243</td> <td>0.5</td>	.082		.232	.243	0.5	
ZERO GAP			.181	.321		.446	.625	0.1	
			.077	.090		.244	.274	0.5	
			1.5	6.0		1.5	6.0		
		ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.205	.312	.466	.578	0.1
			.073	.081	.228	.244	0.5
		0.075	.224	.324	.507	.601	0.1
			.076	.085	.235	.249	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.199	.309	.455	.567	0.1
			.072	.081	.225	.236	0.5
		0.075	.199	.309	.454	.567	0.1
			.072	.081	.224	.235	0.5
ZERO GAP		.213	.338	.484	.636	0.1	
		.073	.086	.229	.261	0.5	
		1.5	6.0	1.5	6.0		
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

TABLE XVI

Q (Into Penetration - Hot Side)

Q (Penetration - One Dimensional)

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	1.00	.997		.997		.986
			1.00	.999		1.00	.998	0.5
		0.075	1.00	.997		.995	.989	0.1
			1.00	.997		1.00	.998	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.998	1.00		.999	.999	0.1
			.997	1.00		1.00	.999	0.5
		0.075	.997	1.00		1.00	1.00	0.1
			.997	.997		1.00	1.00	0.5
ZERO GAP			1.00	.983		.992	.937	0.1
			1.00	.999		.999	.996	0.5
			1.5	6.0		1.5	6.0	
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION
CONFIGURATION

TABLE XVII

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimensional)

Aluminum Foil - Aluminum Opacified Paper Insulation
 Hastelloy X Penetration
 Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.081	.080		.250	.243	0.1
			.055	.055		.188	.187	0.5
		0.075	.081	.080		.247	.243	0.1
			.055	.055		.188	.187	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.082	.082		.260	.260	0.1
			0.56	.056		.191	.190	0.5
		0.075	.082	.082		.261	.262	0.1
			.056	.056		.191	.191	0.5
ZERO GAP			.074	.069		.207	.162	0.1
			.055	.053		.185	.175	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION - INSULATION CONFIGURATION

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.085	.085		.258	.254	0.1
			.037	.037		.131	.129	0.5
		0.075	.085	.085		.257	.254	0.1
			.037	.037		.131	.129	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.086	.086		.267	.268	0.1
			.037	.037		.132	.132	0.5
		0.075	.085	.085		.269	.269	0.1
			.037	.037		.132	.132	0.5
ZERO GAP			.076	.072		.213	.173	0.1
			.036	.035		.127	.122	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION - INSULATION CONFIGURATION

TABLE XVIII
 $Q_{\text{(Into Penetration - Hot Side)}}$

$Q_{\text{(Penetration - One Dimensional)}}$

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

				PANEL THICKNESS						PENETRATION DIAMETER - INCHES
				0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.165	.165		.440	.427	0.1		
			.082	.082		.267	.265	0.5		
		0.075	.165	.165		.435	.427	0.1		
			.082	.082		.267	.265	0.5		
FILLED GAP	GAP WIDTH, IN.	0.025	.166	.166		.459	.459	0.1		
			.082	.082		.269	.269	0.5		
		0.075	.166	.166		.461	.461	0.1		
			.082	.082		.269	.269	0.5		
ZERO GAP			.153	.138		.360	.238	0.1		
			.081	.080		.262	.248	0.5		
			1.5	6.0		1.5	6.0			
ADIABATIC RADIUS - INCHES										

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES
		0.1"	0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.228	.226	.557	.541	0.1
			.083	.083	.277	.274	0.5
		0.075	.226	.226	.552	.541	0.1
			.083	.083	.276	.274	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.229	.228	.577	.578	0.1
			.083	.083	.278	.278	0.5
		0.075	.228	.228	.578	.578	0.1
			.083	.083	.278	.278	0.5
ZERO GAP			.199	.179	.449	.310	0.1
			.080	.080	.264	.252	0.5
			1.5	6.0	1.5	6.0	
		ADIABATIC RADIUS - INCHES					

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PENETRATION-INSULATION CONFIGURATION

TABLE XIX

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimensional)Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.144	.144	.392	.420	0.1
			.073	.074	.235	.245	0.5
		0.075	.145	.145	.402	.420	0.1
			.074	.074	.240	.247	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.137	.137	.369	.370	0.1
			.072	.072	.232	.232	0.5
		0.075	.136	.136	.368	.369	0.1
			.072	.072	.231	.231	0.5
ZERO GAP			.181	.251	.443	.597	0.1
			.077	.083	.243	.273	0.5
			1.5	6.0	1.5	6.0	
		ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.195	.195	.460	.480	0.1
			.073	.074	.228	.237	0.5
	0.075	.195	.195	.468	.481	0.1	
		.073	.073	.232	.239	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.188	.188	.445	.445	0.1
			.071	.071	.224	.224	0.5
	0.075	.188	.188	.443	.443	0.1	
		.071	.071	.224	.223	0.5	
ZERO GAP			.213	.275	.480	.609	0.1
			.073	.080	.229	.259	0.5
			1.5	6.0	1.5	6.0	
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

TABLE XX

 Q (Into Insulation - Hot Side) Q (Insulation - One Dimensional - Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS							
		0.1"			0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.659	.543		1.12	.841	0.1	PENETRATION DIAMETER - INCHES
			1.05	.570		1.65	.939	0.5	
		0.075	1.23	.578		2.43	.916	0.1	
			2.89	.682		6.09	1.20	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.538	.535		.828	.804	0.1	
			.555	.536		.893	.810	0.5	
		0.075	.544	.536		.825	.803	0.1	
			.568	.537		.874	.806	0.5	
ZERO GAP			.800	.609		1.21	.986	0.1	
			.906	.655		1.29	1.06	0.5	
		1.5	6.0		1.5	6.0			
		ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION
CONFIGURATION

TABLE XXI

 Q (Into Insulation - Hot Side) Q (Insulation - One Dimensional - Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

			PANEL THICKNESS					
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.691	.545		1.64	.869	0.1
			1.30	.586		4.37	1.18	0.5
		0.075	1.25	.580		2.95	.942	0.1
			3.09	.695		9.39	1.44	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.542	.536		.843	.803	0.1
			.574	.537		1.16	.827	0.5
		0.075	.545	.536		.843	.803	0.1
			.576	.537		.996	.814	0.5
ZERO GAP			1.32	.606		4.40	1.24	0.1
			3.15	.794		11.9	2.44	0.5
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					
PENETRATION DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.677	.544		1.50	.855	0.1	PENETRATION DIAMETER - INCHES
			1.21	.578		4.02	1.10	0.5	
		0.075	1.23	.579		2.80	.928	0.1	
			2.97	.686		8.70	1.36	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.541	.535		.854	.803	0.1	
			.566	.537		1.08	.819	0.5	
		0.075	.545	.536		.836	.803	0.1	
			.572	.537		.958	.810	0.5	
ZERO GAP			1.26	.599		4.10	1.22	0.1	
			2.84	.741		11.1	2.25	0.5	
			1.5	6.0		1.5	6.0		
		ADIABATIC RADIUS - INCHLS							

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PENETRATION-INSULATION CONFIGURATION

TABLE XXII
 Q (Into Insulation - Hot Side)

Q (Insulation - One Dimensional - Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.831	.555	2.46	.968	0.1	
			1.80	.629	6.78	1.61	0.5	
		0.075	1.40	.590	4.03	1.05	0.1	
			3.77	.739	13.6	1.91	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.553	.536	.974	.812	0.1	
			.621	.540	1.61	.861	0.5	
		0.075	.552	.536	.892	.806	0.1	
			.600	.539	1.21	.827	0.5	
ZERO GAP				2.43	.865	7.13	1.74	0.1
				5.06	1.26	18.6	4.27	0.5
		1.5	6.0	1.5	6.0			
		ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.822	.554		2.24	.945	0.1
			1.80	.629		6.74	1.60	0.5
		0.075	1.39	.589		3.73	1.02	0.1
			3.77	.739		13.6	1.91	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.552	.536		.944	.810	0.1
			.621	.540		1.60	.861	0.5
		0.075	.552	.536		.881	.805	0.1
			.600	.539		1.21	.827	0.5
ZERO GAP			2.37	.852		6.34	1.66	0.1
			5.06	1.26		18.6	4.26	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION

TABLE XXIII
 $Q_{\text{(Into Insulation - Hot Side)}}$

$Q_{\text{(Insulation - One Dimensional - Zero Gap)}}$

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

			PANEL THICKNESS					
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.516	.533		.567	.753	0.1
			.493	.519		.513	.560	0.5
		0.075	1.06	.567		1.60	.828	0.1
			2.07	.625		2.87	.755	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.530	.534		.750	.797	0.1
			.510	.533		.556	.781	0.5
		0.075	.538	.535		.787	.799	0.1
			.542	.535		.701	.795	0.5
ZERO GAP			.190	.451		.560	.679	0.1
			.085	.371		.333	.359	0.5
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					
PENETRATION DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						PENETRATION DIAMETER - INCHES		
		0.1"							0.4"	
EMPTY GAP	GAP WIDTH, IN.	0.025	.526	.533	.649	.763	0.1			
			.492	.519	.502	.556	0.5			
		0.075	1.07	.568	1.68	.837	0.1			
			2.07	.623	2.80	.746	0.5			
FILLED GAP	GAP WIDTH, IN.	0.025	.530	.534	.761	.797	0.1			
			.509	.533	.552	.778	0.5			
		0.075	.538	.535	.791	.799	0.1			
			.541	.535	.701	.793	0.5			
ZERO GAP			.216	.456	.597	.691	0.1			
			.081	.370	.314	.345	0.5			
			1.5	6.0	1.5	6.0				
		ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE XXIV

Q (From Insulation - Cold Side)

Q (Into Insulation - Hot Side)

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

			PANEL THICKNESS					
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.874	.990		.561	.913	0.1
			.714	.953		.440	.732	0.5
		0.075	.932	.990		.694	.918	0.1
			.877	.959		.617	.763	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.990	.998		.914	.990	0.1
			.950	.995		.725	.970	0.5
		0.075	.997	.998		.959	.994	0.1
			.980	1.00		.868	.987	0.5
ZERO GAP			.617	.801		.517	.616	0.1
			.607	.717		.485	.521	0.5
			1.5	6.0		1.5	6.0	PENETRATION DIAMETER - INCHES
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE XXV
 Q (From Insulation - Cold Side)

Q (Into Insulation - Hot Side)

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

				PANEL THICKNESS							
				0.1"		0.4"					
EMPTY GAP	GAP WIDTH, IN.	0.025	.906	.992		.708	.943	0.1	PENETRATION DIAMETER - INCHES		
			.698	.945		.520	.725	0.5			
		0.075	.946	.993		.793	.947	0.1			
			.858	.951		.623	.749	0.5			
FILLED GAP	GAP WIDTH IN.	0.025	.991	.998		.940	.995	0.1			
			.943	.998		.732	.967	0.5			
		0.075	.998	.998		.969	.997	0.1			
			.975	1.00		.850	.985	0.5			
			ZERO GAP			.771	.945	.706		.906	0.1
						.570	.742	.515		.626	0.5
		1.5	6.0		1.5	6.0					
ADIABATIC RADIUS - INCHES											

PENETRATION-INSULATION CONFIGURATION

			PANEL THICKNESS					
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.944	.995		.811	.967	0.1
			.828	.973		.715	.857	0.5
		0.075	.969	.996		.871	.969	0.1
			.942	.976		.789	.868	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.995	1.00		.965	.997	0.1
			.970	.997		.865	.986	0.5
		0.075	.997	.998		.982	.998	0.1
			.987	.999		.932	.994	0.5
ZERO GAP			.859	.967		.807	.949	0.1
			.770	.873		.731	.831	0.5
			1.5	6.0		1.5	6.0	-158-
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

TABLE XXVI

Q (From Insulation - Cold Side)
 Q (Into Insulation - Hot Side)

Aluminum Foil - Aluminum Opacified Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 800°F - 200°F

				PANEL THICKNESS							
				0.1"		0.4"					
EMPTY GAP	GAP WIDTH, IN.	0.025	.595	.957		.149	.744	0.1	PENETRATION DIAMETER - INCHES		
			.248	.818		.035	.299	0.5			
		0.075	.740	.960		.304	.757	0.1			
			.530	.837		.148	.345	0.5			
FILLED GAP	GAP WIDTH, IN.	0.025	.951	.997		.728	.978	0.1			
			.799	.985		.262	.892	0.5			
		0.075	.973	.998		.862	.990	0.1			
			.896	.993		.536	.954	0.5			
			ZERO GAP			.040	.412	.048		.270	0.1
						.008	.171	.009		.038	0.5
		1.5	6.0		1.5	6.0					
		ADIABATIC RADIUS - INCHES									

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.607	.959		.186	.771	0.1	PENETRATION DIAMETER - INCHES
			.249	.818		.036	.302	0.5	
			.748	.961		.348	.783	0.1	
			.530	.837		.149	.348	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.953	.997		.759	.980	0.1	
			.799	.985		.282	.892	0.5	
		0.075	.973	.998		.881	.991	0.1	
			.896	.993		.541	.954	0.5	
ZERO GAP			.048	.426		.059	.292	0.1	
			.008	.171		.009	.038	0.5	
			1.5	6.0		1.5	6.0	-159-	
			ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

TABLE XXVII

Q (From Insulation - Cold Side)

Q (Into Insulation - Hot Side)

Aluminum Foil - Aluminum Opacified Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	1.51	1.03			3.06	1.19
			3.38	1.19		10.2	2.43	0.5
		0.075	1.28	1.03		2.02	1.18	0.1
			1.77	1.16		3.95	2.19	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	1.04	1.00		1.20	1.01	0.1
			1.18	1.01		2.39	1.07	0.5
		0.075	1.02	1.00		1.09	1.01	0.1
			1.09	1.01		1.55	1.03	0.5
ZERO GAP			9.95	1.56		8.31	2.01	0.1
			52.7	2.64		43.5	8.34	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	1.45	1.03			2.50	1.15
			3.39	1.19		10.6	2.47	0.5
		0.075	1.25	1.03		1.78	1.14	0.1
			1.77	1.17		4.05	2.23	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	1.03	1.00		1.16	1.01	0.1
			1.18	1.01		2.42	1.08	0.5
		0.075	1.02	1.00		1.07	1.00	0.1
			1.09	1.01		1.56	1.03	0.5
ZERO GAP			8.31	1.52		6.95	1.90	0.1
			55.4	2.65		47.6	8.86	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

TABLE XXVIII

 Q_{system} Q (One-Dimensional Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.978	.872		1.01		.964
			1.00	.979		1.00	.997	0.5
		0.075	1.04	.887		1.15	.998	0.1
			1.01	.988		1.03	1.02	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.967	.869		.990	.958	0.1
			.998	.977		.999	.993	0.5
		0.075	.968	.869		.990	.958	0.1
			.998	.977		.999	.993	0.5
ZERO GAP			.970	.870		.992	.958	0.1
			.998	.978		.999	.993	0.5
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

TABLE XXIX

 Q_{system} Q (One-Dimensional Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation
 Hastelloy X Penetration
 Boundary Temperatures - 1800°F - 800°F

Conservative Q_p

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.291	.699	.549	.848	0.1
			.085	.181	.263	.353	0.5
		0.075	.350	.713	.675	.881	0.1
			.093	.188	.284	.370	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.280	.694	.506	.834	0.1
			.082	.178	.251	.339	0.5
		0.075	.280	.694	.505	.834	0.1
			.082	.179	.250	.339	0.5
ZERO GAP			.310	.705	.619	.873	0.1
			.088	.186	.282	.384	0.5
			1.5	6.0	1.5	6.0	
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.332	.707	.608		.859	0.1
			.083	.180	.257		.348	0.5
		0.075	.391	.723	.736	.891	0.1	
			.091	.188	.276	.365	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.321	.704	.573	.851	0.1	
			.081	.176	.245	.334	0.5	
		0.075	.321	.704	.572	.851	0.1	
			.081	.176	.245	.334	0.5	
ZERO GAP			.336	.711	.645	.875	0.1	
			.084	.182	.270	.376	0.5	
			1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS - INCHES					-162	

PENETRATION-INSULATION CONFIGURATION

TABLE XXX

 Q_{system} Q (One-Dimensional Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

				PANEL THICKNESS				
				0.1"		0.4"		
EMPTY GAP	GAP WIDTH, IN.	0.025	.444	.736		.791	.906	0.1
			.156	.244		.445	.518	0.5
			.501	.751		.927	.939	0.1
			.166	.251		.469	.538	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.421	.730		.733	.892	0.1
			.151	.238		.422	.489	0.5
			.421	.730		.731	.891	0.1
			.150	.237		.421	.489	0.5
ZERO GAP			.496	.759		.831	.922	0.1
			.168	.264		.473	.571	0.5
			1.5	6.0		1.5	6.0	PENETRATION DIAMETER - INCHES
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.596	.774	.889		.932
			.198	.281	.532	.593	0.5
	0.075	.655	.789	1.02	.964	0.1	
		.207	.288	.556	.612	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.579	.770	.853	.922	0.1
			.193	.275	.514	.569	0.5
	0.075	.579	.770	.852	.922	0.1	
		.193	.275	.513	.568	0.5	
ZERO GAP			.594	.780	.877	.932	0.1
			.195	.287	.528	.616	0.5
			1.5	6.0	1.5	6.0	-163-
		ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

TABLE XXXI

 Q_{system} $Q_{\text{(One-Dimensional Zero Gap)}}$

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.390	.722	.669	.873	0.1
			.133	.223	.364	.442	0.5
		0.075	.449	.737	.794	.906	0.1
			.142	.230	.385	.462	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.374	.719	.632	.866	0.1
			.128	.218	.347	.424	0.5
		0.075	.374	.718	.631	.866	0.1
			.128	.218	.347	.423	0.5
ZERO GAP			.416	.734	.718	.897	0.1
			.139	.234	.383	.482	0.5
		1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.496	.748		.758	.899	0.1
			.170	.257		.421	.494	0.5
		0.075	.554	.762		.882	.932	0.1
			.179	.264		.442	.511	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.483	.745		.735	.892	0.1
			.167	.252		.410	.478	0.5
		0.075	.483	.745		.735	.892	0.1
			.167	.252		.409	.477	0.5
ZERO GAP			.487	.750		.763	.907	0.1
			.164	.255		.421	.511	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

TABLE XXXII

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimensional)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

				PANEL THICKNESS				
				0.1"		0.4"		
EMPTY GAP	GAP WIDTH, IN.	0.025	.998	.997		.975	.962	0.1
			.999	.999		.998	.994	0.5
		0.075	1.00	.999		.981	.970	0.1
			1.00	1.00		.999	.996	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	1.00	1.00		.998	.999	0.1
			1.00	1.00		.999	.999	0.5
		0.075	1.00	1.00		1.00	1.00	0.1
			1.00	1.00		.999	.999	0.5
ZERO GAP			.985	.972		.950	.882	0.1
			.999	.997		.997	.988	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

TABLE XXXIII

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimensional)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.140	.140		.353	.347	0.1
			.074	.074		.237	.233	0.5
		0.075	.140	.140		.353	.348	0.1
			.074	.074		.233	.232	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.143	.143		.393	.393	0.1
			.075	.075		.243	.243	0.5
		0.075	.143	.143		.394	.394	0.1
			.075	.075		.243	.243	0.5
ZERO GAP			.127	.124		.265	.230	0.1
			.072	.071		.223	.213	0.5
			1.5	6.0		1.5	6.0	
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.193	.192		.444	.437	0.1	PENETRATION DIAMETER - INCHES
			.072	.072		.232	.230	0.5	
		0.075	.193	.193		.445	.441	0.1	
			.072	.072		.231	.229	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.195	.195		.478	.478	0.1	
			.073	.073		.237	.237	0.5	
		0.075	.195	.195		.479	.479	0.1	
			.073	.073		.237	.237	0.5	
ZERO GAP			.164	.161		.331	.293	0.1	
			.068	.068		.215	.208	0.5	
			1.5	6.0		1.5	6.0		
ADIABATIC RADIUS - INCHES									

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PENETRATION-INSULATION CONFIGURATION

TABLE XXXIII

TABLE XXXIV

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimensional)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.313	.312		.582	.557	0.1
			.143	.143		.403	.397	0.5
		0.075	.313	.313		.575	.560	0.1
			.143	.143		.400	.395	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.319	.319		.670	.670	0.1
			.144	.144		.414	.414	0.5
		0.075	.319	.319		.674	.674	0.1
			.144	.144		.415	.415	0.5
ZERO GAP			.261	.244		.392	.305	0.1
			.139	.137		.373	.343	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.508	.507		.750	.731	0.1
			.185	.184		.495	.488	0.5
		0.075	.508	.508		.750	.731	0.1
			.185	.184		.492	.486	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.516	.516		.823	.823	0.1
			.187	.187		.507	.507	0.5
		0.075	.516	.516		.826	.826	0.1
			.187	.187		.508	.508	0.5
ZERO GAP			.411	.390		.561	.460	0.1
			.166	.164		.439	.409	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

TABLE XXXVI
 Q (Into Penetration - Hot Side)
 Q (Penetration - One Dimensional)

Nickel Foil - Refrasil Quartz Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.281	.283	.607	.625	0.1
			.127	.128	.358	.373	0.5
		0.075	.283	.283	.615	.628	0.1
			.128	.128	.367	.378	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.262	.262	.559	.559	0.1
			.122	.122	.343	.343	0.5
		0.075	.262	.262	.556	.556	0.1
			.121	.121	.341	.341	0.5
ZERO GAP		.342	.390	.680	.730	0.1	
		.134	.145	.382	.427	0.5	
		1.5	6.0	1.5	6.0		
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						PENETRATION DIAMETER - INCHES
		0.1"			0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.410	.410		.700	.706	0.1
			.163	.164		.418	.429	0.5
		0.075	.411	.411		.706	.713	0.1
			.164	.164		.423	.433	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.399	.398		.684	.685	0.1
			.160	.160		.405	.406	0.5
		0.075	.398	.398		.684	.684	0.1
			.160	.160		.405	.405	0.5
ZERO GAP			.427	.461		.725	.750	0.1
			.160	.169		.419	.458	0.5
			1.5	6.0		1.5	6.0	
ADIABATIC RADIUS - INCHES								

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PENETRATION-INSULATION CONFIGURATION

TABLE XXXVI

 Q (Into Insulation - Hot Side) Q (Insulation - One Dimensional - Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.899	.840		1.17	.965	0.1
			1.11	.854		1.62	1.01	0.5
		0.075	1.20	.859		1.83	1.01	0.1
			2.06	.912		3.88	1.15	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.835	.836		.957	.949	0.1
			.839	.836		.988	.950	0.5
		0.075	.835	.833		.952	.949	0.1
			.837	.836		.960	.948	0.5
ZERO GAP			.906	.844		1.17	.977	0.1
			.977	.854		1.25	1.02	0.5
			1.5	6.0		1.5	6.0	
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION
CONFIGURATION

TABLE XXXVII

 Q (Into Insulation - Hot Side) Q (Insulation - One Dimensional - Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.911	.841		1.34	.974	0.1
			1.22	.861		3.05	1.11	0.5
		0.075	1.20	.859		1.98	1.01	0.1
			2.14	.916		5.33	1.24	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.835	.834		.965	.947	0.1
			.848	.837		1.07	.953	0.5
		0.075	.834	.834		.956	.946	0.1
			.841	.836		1.00	.951	0.5
ZERO GAP		1.06	.853		2.06	1.04	0.1	
		1.80	.913		6.42	1.48	0.5	
		1.5	6.0		1.5	6.0		
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.906	.839		1.28	.968	0.1
			1.19	.858		2.84	1.09	0.5
		0.075	1.20	.859		1.92	1.01	0.1
			2.10	.914		5.04	1.22	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.835	.834		.961	.946	0.1
			.843	.835		1.05	.952	0.5
		0.075	.834	.834		.953	.946	0.1
			.839	.834		.992	.948	0.5
ZERO GAP			1.04	.852		1.92	1.03	0.1
			1.71	.906		6.00	1.44	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION

TABLE XXXVIII
 Q (Into Insulation - Hot Side)
 Q (Insulation - One Dimensional - Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation
Hastelloy X Penetration
Boundary Temperatures - 1800°F - 800°F

			PANEL THICKNESS					
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.979	.844		1.65	.999	0.1
			1.54	.883		4.74	1.29	0.5
		0.075	1.27	.862		2.35	1.04	0.1
			2.52	.939		7.72	1.45	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.839	.834		.989	.948	0.1
			.864	.836		1.24	.965	0.5
		0.075	.837	.834		.966	.947	0.1
			.850	.835		1.08	.954	0.5
ZERO GAP			1.46	.889		2.62	1.08	0.1
			3.20	1.06		10.8	2.02	0.5
			1.5	6.0		1.5	6.0	PENETRATION DIAMETER - INCHES
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.961	.842		1.45	.984	0.1
			1.53	.882		4.35	1.26	0.5
		0.075	1.26	.861		2.14	1.03	0.1
			2.51	.938		7.25	1.41	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.837	.834		.974	.947	0.1
			.864	.836		1.21	.962	0.5
		0.075	.836	.834		.959	.946	0.1
			.850	.835		1.06	.953	0.5
ZERO GAP			1.34	.880		2.18	1.06	0.1
			3.13	1.05		9.86	1.92	0.5
			1.5	6.0		1.5	6.0	-171-
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE XXXIX

 Q (Into Insulation - Hot Side) Q (Insulation - One Dimensional - Zero Gap)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.840	.834		.926	.941	0.1
			.811	.829		.742	.884	0.5
		0.075	1.13	.853		1.52	.980	0.1
			1.65	.883		2.22	.986	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.831	.833		.935	.944	0.1
			.822	.833		.857	.939	0.5
		0.075	.831	.834		.940	.945	0.1
			.827	.834		.906	.943	0.5
ZERO GAP			.722	.821		.879	.940	0.1
			.527	.789		.523	.839	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.851	.834	.992	.947	0.1
			.826	.830	.828	.896	0.5
		0.075	1.14	.853	1.60	.986	0.1
			1.67	.885	2.39	1.00	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.831	.833	.940	.945	0.1
			.823	.833	.869	.940	0.5
		0.075	.831	.833	.942	.945	0.1
			.827	.834	.910	.943	0.5
ZERO GAP			.745	.824	.928	.945	0.1
			.541	.791	.572	.849	0.5
			1.5	6.0	1.5	6.0	
		ADIABATIC RADIUS - INCHES					

PENETRATION DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION

TABLE XL

 Q (From Insulation - Cold Side) Q (Into Insulation - Hot Side)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.957	.994	.751	.972	0.1
			.861	.983	.553	.906	0.5
		0.075	.964	.994	.806	.972	0.1
			.911	.983	.670	.899	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.994	.996	.977	.997	0.1
			.987	.996	.908	.992	0.5
		0.075	.996	.997	.990	.998	0.1
			.992	.996	.962	.996	0.5
ZERO GAP			.828	.974	.578	.924	0.1
			.697	.949	.485	.838	0.5
			1.5	6.0	1.5	6.0	PENETRATION DIAMETER - INCHES
		ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

TABLE XLI

Q (From Insulation - Cold Side)

Q (Into Insulation - Hot Side)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

			PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.978	.995		.886	.987	0.1
			.889	.985		.708	.923	0.5
		0.075	.983	.995		.911	.988	0.1
			.926	.986		.765	.922	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.999	.999		.988	.999	0.1
			.988	.996		.922	.994	0.5
		0.075	.999	.999		.993	.999	0.1
			.993	.996		.963	.996	0.5
ZERO GAP			.958	.993		.930	.991	0.1
			.824	.968		.762	.914	0.5
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS				
				0.1"		0.4"		
EMPTY GAP	GAP WIDTH, IN.	0.025	.986	.998		.916	.991	0.1
			.938	.991		.830	.959	0.5
	0.075	.991	.996		.934	.991	0.1	
		.960	.991		.862	.958	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.999	.999		.992	.999	0.1
			.995	.999		.963	.997	0.5
	0.075	.999	.999		.996	.999	0.1	
		.997	.999		.984	.998	0.5	
ZERO GAP			.981	.995		.971	.996	0.1
			.918	.983		.891	.974	0.5
			1.5	6.0		1.5	6.0	PENETRATION DIAMETER - INCHES
ADIABATIC RADIUS - INCHES								

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PENETRATION-INSULATION CONFIGURATION

TABLE XLII

 Q (From Insulation - Cold Side) Q (Into Insulation - Hot Side)

Nickel Foil - Refrasil Quartz Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 1800°F - 800°F

		PANEL THICKNESS					
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.844	.987	.455	.926	0.1
			.505	.936	.091	.649	0.5
		0.075	.871	.987	.557	.926	0.1
			.638	.937	.210	.644	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.989	.999	.932	.995	0.1
			.949	.996	.657	.970	0.5
		0.075	.993	.999	.969	.997	0.1
			.972	.998	.825	.987	0.5
ZERO GAP		.421	.908	.211	.817	0.1	
		.107	.721	.024	.361	0.5	
		1.5	6.0	1.5	6.0		
ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

			PANEL THICKNESS					PENETRATION DIAMETER - INCHES
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.868	.989		.554	.945	
			.513	.938		.113	.675	0.5
		0.075	.893	.989		.644	.945	0.1
			.646	.938		.241	.671	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.991	.999		.952	.996	0.1
			.949	.996		.682	.973	0.5
		0.075	.994	.999		.978	.998	0.1
			.972	.998		.840	.988	0.5
ZERO GAP			.478	.921		.270	.844	0.1
			.113	.727		.029	.387	0.5
			1.5	6.0		1.5	6.0	-175-
ADIABATIC RADIUS - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE XLIII

 Q (From Insulation - Cold Side) Q (Into Insulation - Hot Side)

Nickel Foil - Refrasil Quartz Paper Insulation
 Hastelloy X Penetration
 Boundary Temperatures - 1800°F - 800°F

			PANEL THICKNESS					PENETRATION DIAMETER - INCHES
			0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN	0.025	1.13	1.01		1.47	1.04	0.1
			1.79	1.06		4.87	1.34	0.5
		0.075	1.11	1.01		1.33	1.04	0.1
			1.47	1.06		2.80	1.35	0.5
FILLED GAP	GAP WIDTH, IN	0.025	1.01	1.00		1.04	1.00	0.1
			1.04	1.00		1.34	1.02	0.5
		0.075	1.00	1.00		1.02	1.00	0.1
			1.02	1.00		1.14	1.01	0.5
ZERO GAP			1.71	1.06		2.48	1.12	0.1
			4.68	1.24		15.1	2.03	0.5
			1.5	6.0		1.5	6.0	
			ADIABATIC RADIUS - INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	1.09	1.01		1.23	1.02	0.1
			1.72	1.05		3.99	1.29	0.5
		0.075	1.08	1.01		1.16	1.02	0.1
			1.44	1.06		2.44	1.29	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	1.01	1.00		1.02	1.00	0.1
			1.04	1.00		1.29	1.02	0.5
		0.075	1.00	1.00		1.01	1.00	0.1
			1.02	1.00		1.13	1.01	0.5
ZERO GAP			1.56	1.05		2.04	1.09	0.1
			4.43	1.23		12.8	1.94	0.5
			1.5	6.0		1.5	6.0	
		ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

3.2 Penetration Effects Test Program

The experimental program was designed to measure the effects on thermal performance of an array of penetrating elements, uniformly spaced over a multifoil insulation section. Principal objectives of the program were to:

1. Verify experimentally, the effects of penetrations on the overall thermal performance of a multifoil insulation system.
2. Assess the effect on overall performance of various methods of insulating around penetrating elements --- e.g., open gap, zero gap, and opacified paper filled gap.

The test sample was comprised of an Al-Al opacified glass multifoil insulation system, containing an array of 0.1 in. diameter lead telluride elements (flush penetrations) located on 1 in. centers. The test system geometry and boundary conditions selected for this study were as follows:

Boundary Temperatures	900°F. (Hot Side) 100-200°F. (Cold Side)
Penetrations	
(1) Material	Lead Telluride (p or n type)
(2) Size	0.1 in. Dia., 0.2 in. length
(3) Spacing	1.0 in.
(Adiabatic Radius)	(0.5 in.)
(4) Gap Encircling Penetration	0.075 in.
Insulation	
(1) Materials	.00025 in. Al foil .003 in. Al opacified glass paper
(2) Thickness	0.165 in.
(3) Layer Density	200 lb/in.

The lead telluride penetration elements were supplied by Gulf General Atomics. The material was readily available only in the ~0.2 in. long elements.

3.2.1 Sample Design and Test Procedures

The guarded flat plate test sample configuration and size was incorporated in the penetration effects testing. A schematic of the installed multilayer insulation samples, containing the flush penetrations, is shown in Figure 64.

Figure 64 - Schematic of Penetration - Insulation Test Configuration

The 6 in. x 6 in. Al-Al opacified glass multilayer insulation sample contains an array of 36 lead telluride elements, mounted flush with the insulation and spaced on 1 in. centers. The edge guard sections are constructed of the same multilayer insulation materials but do not contain penetrations. Heat flux through the penetration-insulation system is measured over a 2.25 in. x 2.25 in. central area by a flux meter located at the cold boundary. The peripheral penetration-insulation sections provide a "self-guarding" feature within the sample. It is thought that this guarding is sufficient to achieve approximately one-dimensional heat flow within the metered section.

Initial testing of penetration-insulation samples (zero and filled gap configurations) uncovered some interface heat transfer problems between the penetrating elements and the thermal boundary surfaces. The unrealistically low heat transfer rates across the penetrations were attributed mainly to high interface resistance at the unbonded penetration-boundary interfaces. The sample design was modified in an effort to minimize this resistance. The new configuration is shown schematically in Figure 65.

With reference to Figure 65, the nature and purpose of the modifications are discussed briefly:

(1) Bearing load at the interface between the penetrating elements and the boundary surfaces was increased substantially. A spring-loaded system was used to compensate for any dimensional changes as the sample was taken up in temperature.

(2) A soft, .010 in. thick indium sheet was used as an intermediate contact layer between the cold boundary (flux meter) and the penetrations. This relatively thick, ductile sheet tended to "absorb" slight deviations in penetration height and promote uniform thermal contact across the entire penetration array.

(3) Ends of penetrations were abraded to mechanically remove the oxide and, then, indium coated to provide a high-conductivity contact surface.

(4) Gold foil tabs ($\sim .002$ in. thick) were bonded to the hot end of the penetrating elements to eliminate reaction between the lead telluride and heater shield plate.

3.2.2 Thermal Test Results -- Penetration-Insulation Systems

Thermal performance was measured on multilayer insulation panels containing lead telluride penetrations at temperatures up to 900°F. Emphasis was

Figure 65 - Modified Sample Design
Penetration Effects Testing

placed on open gap and filled gap configurations, and dimensions were as previously indicated.

Effective thermal conductivity (K_a) was selected as the parameter for rating performance of the penetration-insulation systems. The K_a value has been used extensively as a thermal performance indicator for multilayer^a insulations. The heat flow expression is expanded to include penetration effects as shown below:

$$Q_{a_t} = Q_{a_i} + Q_{a_p} \quad (23)$$

In terms of K_a , the expression becomes:

$$K_{a_t} A \frac{\Delta T}{\Delta X} = K_{a_i} A_i \frac{\Delta T}{\Delta X} + (K_a)_p A_p \frac{\Delta T}{\Delta X} \quad (24)$$

Then, on a unit area basis:

$$K_{a_t} = K_{a_i} \frac{A_i}{A} + K_{a_p} \frac{A_p}{A} \quad (25)$$

The subscripts t, i, and p denote total values and values attributable to the multilayer insulation and lead telluride elements, respectively.

Equations (23) to (25) constitute a one-dimensional approximation of total heat flow (effective K_a) through a "zero gap" penetration-insulation system. Heat flux contributions due to the insulation and penetrations are computed by simple, one-dimensional formulas and are considered as additive quantities. For the zero gap and opacified paper filled gap cases, this approximation is considered adequate in this case.

Thermal test results are summarized on Figure 66. Mean effective thermal conductivities, calculated and experimental, are plotted against hot boundary temperature. All penetration-insulation panels were tested in a vacuum environment ($p \leq 1 \times 10^{-3}$ torr). The results, and conditions of testing, are defined as follows:

1. Reference K_{a_i} data (-- O --)

An Al-Al opacified glass multifoil insulation, at a layer density (n) of 200 #/inch (0.165 in. sample thickness) and without penetrations, was first tested to provide base heat flux data on the multifoil system to be used in all subsequent penetration-insulation system studies, and to provide a simple, compara-

tive calibration on the penetration effects test apparatus. These data agree to $\pm 10\%$ with previous flat plate K_a data on the Al-Al opacified glass system.

2. Computed K_{a1} data - one-dimensional approximation (—)

Effective thermal conductivities of the penetration-insulation system --- Al-Al opacified glass multifoil containing 0.1 in. diameter lead telluride elements (on 1 in. centers) -- were computed for p-type and n-type elements using Equation (25). The 3M Company K_a -data for lead telluride material (Table XLIV) were used. Comparing K_a -data for the insulation alone with corresponding penetration-insulation system values, it is noted that heat transfer through the penetration material comprises greater than 95% of the total flux through the penetration-insulation system.

3. Initial test data on penetration-insulation systems (ZZZZZZZ)

Thermal performance data from the first test series (zero gap and filled gap configurations) clearly illustrate the high degree of interface resistance between the lead telluride elements and the boundary surfaces. Measured K_{at} values were a factor of 15-20 lower than predicted values.

4. Second test series on penetration-insulation systems (XXXXXX)

These results are for open gap and filled gap sample configurations, incorporating the changes designed to reduce interface resistance (Figure 65). On the average, measured K_a values were 40% lower than predicted. It appears that some resistance still exists which may be yet contributing to the disagreement. Also, some inconsistency between filled and open gap results were observed, with the K_{at} values for the latter configuration measuring lower than the former.

5. Second test series -- alternate data reduction method (O, □)

Effective thermal conductivity data for the filled gap system (O) and open gap system (□) were re-evaluated on the basis of net total power input to the penetration-insulation sample panels. The net power input values were estimated by assuming a minimum lateral heat flow effect due to the gap discontinuity and subtracting the heat flow attributable to the guard and gap areas and other fixed losses (e.g., heater leads) from the total heat input. The resulting net heat flow was assessed to the two 6 in. x 6 in. penetration-insulation samples.

Examination of data entries 3, 4, and 5 points up the interface resistance problems which were prevalent in this testing. The sample design modifications illustrated in Figure 65 were effective in reducing this resistance, as can be noted in comparing the first and second test series (entries 3 and 4, res-

MEAN EFFECTIVE THERMAL CONDUCTIVITY (K_a) - 10^{-3} BTU/HR-FT-°F

HOT-SIDE TEMPERATURE - °F

pectively).

Some disagreement and inconsistencies still remained in the second test series. It is felt that resistance was still a factor at the penetration-boundary interface. The heat flux measurement is extremely sensitive to any interface resistance, particularly occurring in the 2.25 in. x 2.25 in. metering zone. Only four penetrations directly affect this meter reading, so that an unrealistically high interface resistance at any one of these critical elements would contribute substantially to the resulting low heat flux measurement. Also, this same phenomenon could be responsible for the inconsistency between the filled gap and open gap thermal performance.*

In an effort to minimize the sensitivity of the heat flux measurement to isolated cases of high resistance between penetration and boundaries, the thermal performance data from the second test series were also assessed on a total heat flux basis over the entire dual-sample system. In so doing, the penetration-insulation sample area was increased from 5 in² to 72 in² (2 - 6 in. x 6 in. samples), which included all 72 penetrating elements rather than just the 4 elements contacting the flux meter. Effective thermal conductivities were computed from a net heat flux value defined as follows:

$$Q_{a \text{ net (panels)}} = Q_{a \text{ total}} - Q_{a \text{ gap, guards, leads}} \quad (26)$$

The $Q_{a \text{ net}}$ value represents an estimate of the total flux through the 2 - 6 in. x 6 in. penetration-insulation samples. The subtractable heat flux quantity ($Q_{a \text{ gap, etc.}}$) was estimated from the initial test data on the Al-Al opacified glass multifoil insulation without penetrations.

Using this method, good agreement and consistency were obtained between measured and predicted K_a values for the n-type penetrations. The filled gap data (O) reflected a $\frac{Q_{\text{system(measured)}}}{Q_{\text{system(1-d, zero gap)}}$ ratio of 1.0, whereas the open gap

data (□) had a corresponding $\frac{Q_{\text{system(measured)}}}{Q_{\text{system(1-d, zero gap)}}$ ratio of 1.1 to 1.2. These results are consistent with previous analytical predictions for a similar penetration-

* Data from the second test series (n-type penetrations) showed the open gap configuration performing better than the filled gap system. This directly contradicts theory and previous analysis, and may be attributable to random, high interface resistance in the metered zone.

insulation system (reference Appendix G).

It is felt that effective thermal conductivity values obtained through total power assessment are somewhat conservative (i.e., K_a values on the high side). The net heat flux values reflect the assumption that there is minimum thermal interaction between the multilayer insulation sample panels and the surrounding gap discontinuity.* This assumption further considers that the subtractable heat loss value, originally estimated from the reference test on the plain multifoil insulation, remains constant in all tests under similar conditions. Actually, the subtractable heat loss in the penetration-insulation sample tests is likely to be higher than this original, reference test value due to more severe two-dimensional effects in the vicinity of the gap.

3.2.3 Conclusions and Observations

Experimental evaluation of total heat flow through an Al-Al opacified glass multifoil insulation containing lead telluride penetrations has provided some first-order indications of penetration-insulation system performance. Agreement was reasonably good between the measured thermal performance data and analytical predictions based on similar configuration and thermal properties of the individual insulation and penetration components.

Two data reduction approaches were used --- one based on heat flow meter readings over a central 2.25 in. x 2.25 in. section of the penetration-insulation panel and the second based on a total heat flow assessment over the entire dual-sample configuration. Deviation between measured and predicted values ranged from < 5% (total heat flow method) to 40% (heat flow meter approach). In the latter case measured values were lower than predicted.

The noted deviation may reflect:

(1) Some residual interface resistance between the lead telluride penetrations and the boundaries. Random resistance effects would likely be magnified

* Assumes heat flow through the entire 6 in. x 6 in. panel is approximately one-dimensional, and that this heat flow can be treated in a manner similar to the flow measurement through the 2.25 in. x 2.25 in. flux meter.

in the heat flow meter evaluation, where the control surface is a small portion of the total sample.

(2) An actual difference which may exist between the thermal conductivity of the sintered lead telluride elements used in testing and the published K-values (Table XLIV) for the base lead telluride material.

Although adequate for total heat flow assessments, the penetration-insulation sample configuration was not sensitive enough to accurately evaluate effects due to subtle changes in the nature or method of the gap insulation around the penetrations. Heat flow through the 0.1 in. diameter lead telluride elements (greater than 95% of the total) far overshadowed the multilayer insulation thermal effects.

Additional sensitivity could be attained in tests at higher temperatures with thicker samples (more interchange area between insulation and penetration). Due to thermal and dimensional limitations on the element material, such tests could not be structured for the lead telluride/Al-Al opacified glass system.

TABLE XLIV

THERMAL CONDUCTIVITY DATA ON LEAD TELLURIDE MATERIAL

Temperature °F	Point Thermal Conductivity Btu/hr-ft-°F	
	<u>Pb-Te - Type TEGS - 2N</u>	<u>(Pb-Sn)Te - Type TEGS - 3P</u>
100	1.50	1.22
200	1.29	1.09
300	1.13	.96
400	1.01	.85
500	.92	.75
600	.87	.67
700	.85	.62
800	.86	.60
900	.92	.63
1000	1.03	.70
1100	1.21	.81

3.3 Insulation Interfaces - Exposed Edge and Gap Effects

A two-dimensional computerized analysis for evaluating the effects on thermal performance of various panel geometries and segment edge conditions was developed and reported⁹ in Phase I of this contract. The analysis treated flat, rectangular insulation panel configurations. The edge conditions evaluated were as follows:

- (a) Radiation and solid conduction across a rectangular gap joint.
- (b) Radiation and solid conduction across an angular gap joint (warm edges in contact).
- (c) Radiation from an exposed edge to an infinite wall at a specified temperature.

Rectangular and angular gap joints, either unfilled or filled with opacified fibrous multilayer insulation, were evaluated. Extensive results in the form of parametric curves (i.e., relating panel dimensions, gap dimensions, etc.) were presented in Phase I⁹. The Phase II effort was directed toward redefinition of the opacified gap fillers as semi-transparent, rather than opaque, materials. This analytical refinement is identical to the incorporated into the penetration analysis, and details may be found in Appendix F.

New analytical results are presented for filled rectangular and angular gap configurations. The Al-106 glass multifoil system and the Ni-Refrasil quartz insulation were evaluated, with Al opacified glass and Ni opacified Refrasil quartz fillers, respectively.

3.3.1 Comments on the Analysis

The mathematical model upon which the computer program is based assumes that the panel consists of filler sheets (glass, quartz, etc.) alternated with highly reflective foils in a layered structure. The panel dimension in the direction parallel to both the interpanel joint and the insulation layers is considered infinite so that a two-dimensional thermal analysis, in the (X - Z) plane normal to this direction, will suffice. The X direction is chosen to be parallel to the layers, the Z direction normal to the layers.

Schematic drawings of insulation panels with various edge configurations and conditions are shown in Figure 67. Thermal analysis was based on these geometries and boundary conditions, along with the following assumptions.

- (1) The panel is part of an infinitely repeating system (i.e., considered infinite in Y direction), so that adiabatic planes bisect the

Figure 67 - Schematic of System Geometry

NOTE: THE Y AXIS IS DIRECTED INTO THIS PAGE

panel and the gap separating it from an adjacent panel.*

- (2) The panel surfaces are prescribed at fixed temperatures. The temperature of either surface is necessarily uniform unless the edge radiates to an infinite wall; the temperature can then vary with distance from the (adiabatic) panel midplane.
- (3) The panel and gap fillers are conductively anisotropic -- they can have different thermal conductivities in the directions parallel to and normal to the insulation layer.
- (4) If translucent, the gap filler is radiatively isotropic.
- (5) Radiant interchange among the surfaces bounding the gap can be either attenuated through backscattering or unattenuated. If the gap filler is translucent, all radiation into the gap is either transmitted directly or scattered at a 180 degree angle with the line of incidence.
- (6) The insulation edges are black (emissivity = 1). However, the gap boundaries may have emissivities less than unity**, as may the infinite wall radiating to an exposed edge.

The governing differential equations and boundary conditions for the edge effects analysis are presented and discussed in Appendix H.

3.3.2. Analytical Results

Computed heat fluxes for rectangular multifoil insulation panels with either angular or rectangular opacified paper filled gaps are presented in Tables XLV and XLVI. Table XLV gives results for Al-106 glass insulation panels of various width, thickness and gap size. Similar results are presented for Ni-Refrasil quartz insulation in Table XLVI.

The meaning of the various heat flux quantities becomes evident when the heat flow conditions of the multifoil panel/gap system are considered. An

* Unless it is a single panel with exposed edges; in this case, there is no gap bisector plane.

** The unfilled gaps are typically bounded by reflective foils of the same material as the foils within the insulation.

TABLE XLV

Filled Joint Analysis -- Al-106 Glass Insulation with Al Opacified Glass Filler

Panel Thickness in.	Gap in.	Panel Width, in.														
		2					10					25				
		Q_i	Q_G	Q_i	Q_l	Q/Q_o	Q_i	Q_c	Q_i	Q_l	Q/Q_o	Q_i	Q_G	Q_i	Q_l	Q/Q_o
.1	.05"	3.47	.19	3.47	-.002	1.65	17.40	.19	17.41	-.012	1.62	43.51	.19	43.54	-.030	1.62
	.10"	3.47	.35	3.45	.017	1.72	17.39	.36	17.39	.007	1.64	43.51	.36	43.52	-.011	1.62
	.50"	3.49	1.72	3.33	.164	2.35	17.41	1.72	17.25	.163	1.76	43.52	1.72	43.38	.145	1.67
.2	.05"	1.73	.10	1.74	-.008	1.66	8.70	.10	8.71	-.013	1.62	21.76	.10	21.78	-.022	1.62
	.10"	1.73	.19	1.73	-.001	1.73	8.69	.19	8.70	-.006	1.64	21.75	.19	21.76	-.016	1.63
	.50"	1.74	.87	1.66	.075	2.35	8.70	.86	8.62	.076	1.76	21.75	.86	21.68	.068	1.67
.5	.05"	.71	.06	1.72	-.010	1.75	3.49	.06	3.50	-.013	1.64	8.71	.06	8.73	-.016	1.62
	.10"	.69	.09	.70	-.008	1.77	3.48	.09	3.49	-.011	1.65	8.70	.09	8.72	-.014	1.63
	.50"	.68	.36	.67	.016	2.36	3.47	.36	3.45	.016	1.77	8.69	.36	8.68	.013	1.67
.1	10°	3.53	.03	3.50	.028	1.62	17.45	.03	17.47	-.015	1.61	43.56	.03	43.60	-.033	1.61
	30°	3.54	.04	3.42	.118	1.63	17.44	.04	17.45	-.009	1.61	43.56	.04	43.58	-.027	1.61
	60°	3.60	.05	3.35	.244	1.65	17.46	.03	17.44	.020	1.61	43.57	.03	43.57	.002	1.61
	90°	3.65	.06	3.31	.345	1.68	17.48	.02	17.42	.054	1.61	43.59	.02	43.55	.036	1.61
.2	10°	1.79	.04	1.76	.024	1.65	8.75	.04	8.76	-.014	1.61	21.80	.04	21.83	-.023	1.61
	30°	1.80	.05	1.68	.115	1.68	8.74	.04	8.74	-.005	1.61	21.79	.04	21.81	-.014	1.61
	60°	1.85	.05	1.62	.238	1.73	8.76	.03	8.73	.025	1.61	21.81	.03	21.79	.016	1.61
	90°	1.90	.06	1.57	.336	1.78	8.78	.02	8.72	.059	1.62	21.83	.02	21.79	.050	1.61
.5	10°	.74	.05	.72	.023	1.61	3.52	.04	3.54	-.015	1.61	8.75	.04	8.76	-.019	1.61
	30°	.75	.05	.64	.108	1.63	3.52	.04	3.52	-.004	1.61	8.74	.04	8.74	-.007	1.61
	60°	.80	.06	.58	.218	1.74	3.54	.03	3.51	.027	1.63	8.75	.03	8.73	.024	1.61
	90°	.84	.07	.54	.303	1.83	3.57	.02	3.51	.061	1.64	8.78	.02	8.72	.059	1.62

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$$T_h = 1500^\circ R$$

$$T_c = 500^\circ R$$

TABLE XLVI

Filled Joint Analysis - Ni-Refrasil Quartz Insulation with Ni Opacified Quartz Filler

Panel Thickness in.	Gap in.	Panel Width, in.														
		2					10					25				
		Q_i	Q_G	Q_i	Q_ℓ	Q/Q_o	Q_i	Q_c	Q_i	Q_ℓ	Q/Q_o	Q_i	Q_G	Q_i	Q_ℓ	Q/Q_o
.1	.05"	24.71	1.80	24.42	.29	2.42	123.7	1.80	123.5	.19	2.34	309.4	1.80	309.3	.009	2.33
	.10"	24.73	3.51	24.14	.59	2.58	123.7	3.52	123.2	.49	2.37	309.4	3.51	309.0	.32	2.34
	.50"	25.03	17.74	23.00	2.03	3.90	123.8	17.76	121.9	1.93	2.63	309.5	17.75	307.7	1.81	2.45
.2	.05"	12.37	1.01	12.23	.14	2.44	61.87	1.01	61.78	.09	2.34	154.7	1.01	154.7	-.004	2.33
	.10"	12.33	1.85	12.04	.29	2.59	61.82	1.86	61.56	.25	2.37	154.6	1.86	154.5	.16	2.34
	.50"	12.55	8.86	11.33	1.22	3.91	61.95	8.85	60.71	1.24	2.63	154.7	8.85	153.6	1.16	2.45
.5	.05"	5.09	.60	5.04	.05	2.60	24.93	.58	25.91	.02	2.38	62.06	.58	62.08	-.02	2.34
	.10"	4.97	.88	4.87	.10	2.67	24.77	.87	24.68	.09	2.40	61.90	.87	61.85	.06	2.34
	.50"	4.96	3.65	4.45	.51	3.93	24.70	3.63	24.12	.59	2.65	61.81	3.64	61.26	.55	2.45
.1	10°	25.23	.22	24.74	.50	2.33	124.2	.21	124.1	.04	2.32	308.8	.21	310.0	-.15	2.32
	30°	25.42	.36	23.94	1.48	2.36	124.1	.28	123.9	.17	2.32	309.7	.28	309.7	-.02	2.32
	60°	25.99	.49	23.18	2.81	2.40	124.1	.24	123.6	.53	2.32	308.8	.24	309.4	.34	2.32
	90°	26.51	.62	22.66	3.85	2.45	124.3	.16	123.3	.92	2.32	309.9	.16	309.2	.73	2.32
.2	10°	12.84	.30	12.34	.50	2.35	62.32	.28	62.27	.05	2.32	155.1	.28	155.2	-.05	2.32
	30°	13.02	.41	11.57	1.45	2.38	62.17	.33	61.98	.19	2.32	155.0	.33	154.9	.09	2.32
	60°	13.61	.53	10.86	2.75	2.49	62.24	.27	61.67	.57	2.32	155.1	.27	154.6	.48	2.32
	90°	14.13	.65	10.38	3.75	2.58	62.36	.17	61.40	.96	2.32	155.2	.17	154.3	.87	2.32
.5	10°	5.40	.40	4.97	.43	2.38	25.16	.36	25.08	.08	2.32	62.33	.36	62.34	-.02	2.32
	30°	5.53	.47	4.22	1.31	2.44	25.02	.37	24.83	.19	2.32	62.15	.37	62.00	.15	2.32
	60°	6.10	.58	3.66	2.44	2.69	25.10	.29	24.51	.59	2.32	62.23	.29	61.68	.55	2.32
	90°	6.59	.69	3.31	3.28	2.90	25.22	.18	24.23	.99	2.32	62.36	.18	61.40	.96	2.32

$$T_h = 2100^\circ R$$

$$T_c = 500^\circ R$$

energy balance written around a typical insulation panel would consist of:

$$Q_w = Q_l + Q_e \quad (27)$$

where:

- Q_w = flux from warm side of panel
- Q_l = flux from panel edge
- Q_e = flux from cold side of panel
- Q_wg = flux from warm side of gap
- Q_cg = flux from cold side of gap

The flux incident to the cold side of the gap, Q_{cg} ,

$$Q_{cg} = Q_l + Q_{wg} \quad (28)$$

Combining equations (27) and (28), the total heat balance around the panel gap is given by:

$$Q_w = Q_{wg} = Q_{cg} + Q_e \quad (29)$$

The effective conductivity of the panels containing rectangular or wedge-shaped gaps or radiating to an infinite wall was determined by the following equations:

For the rectangular gap:

$$K_e = \frac{(Q_{wg}) + (Q_w)h}{(W + d) \Delta T} \quad (30)$$

For the wedge gap and exposed edge:

$$K_e = \frac{(Q_w)h}{W \Delta T} \quad (31)$$

where

h = panel thickness, ft.
 W = panel width, ft.
 d = gap width, ft.
 ΔT = $^{\circ}R$

In the wedge gap cases, W refers to panel width at the warm side.

Parametric curves of the ratio K_e/K_o plotted against panel width are presented for several gap widths and gap angles in Figures 68 to 75. The K_e term refers to effective overall thermal conductivity of a panel containing either an angular or rectangular gap. The K_o term denotes effective thermal conductivity of an undisturbed multifoil insulation panel of identical geometry.

Comparisons of filled to unfilled gaps for the Al-106 glass multifoil insulation with Al opacified glass gap filler are shown in Figures 71 and 75. The correspondence between filled and unfilled gap cases is not exact. Panel thicknesses differ to some extent and multifoil insulation thermal conductivities (K_a), which are part of the input data, also differ.* However, it is felt that conditions correspond closely enough so that some valid comparisons may be made.

Based on the parametric curves (Figures 68 to 75), the following observations are made:

(1) An increasing filled gap width (or gap angle) results in an increase in the K_e/K_o ratio for both the Al-106 glass and Ni-Refrasil quartz multifoil systems. This is expected due to the stronger thermal influence of the larger gaps.

(2) For comparable panel sizes and geometries, the K_e/K_o ratios for Ni-Refrasil quartz systems (ranging from 2.3 to 2.8) are higher than the corresponding ratios for Al-106 glass insulation (ranging from 1.5 to 2.0). This is expected due to (a) higher operating temperatures (higher radiative transfer) for the Ni-Refrasil quartz system and (b) poorer radiation attenuation of Ni opacified quartz filler in comparison to Al opacified glass.

(3) The K_e/K_o ratio is quite sensitive to panel width in the 2 in. - 6 in. range, and relatively insensitive in 6 in. - 25 in. width range. This behavior is

* In the original analysis, $K_a(T)$ for Al-106 glass was obtained from early cylindrical test data. The final filled gap analysis used $K_a(T)$ data from the flat plate testing. The cylindrical $K_a(T)$ data are considered to be conservative (i.e., higher than actual) by up to 25%. The K_e term refers to effective overall thermal conductivity of a panel containing either an angular or rectangular gap. The K_o term denotes effective thermal conductivity of an undisturbed multifoil insulation panel of identical geometry.

Figure 68 - Effect of Panel Width on Thermal Conductivity -
Filled Rectangular Gap

Figure 69 - Effect of Panel Width on Thermal Conductivity -
Filled Rectangular Gap

Figure 70 - Effect of Panel Width on Thermal Conductivity -
Filled Rectangular Gap

Figure 71 - Comparison of Effect on Thermal Conductivity for Filled Versus Unfilled Rectangular Gaps

Figure 72 - Effect of Panel Width on Thermal Conductivity -
Filled Angular Gap

Figure 73 - Effect of Panel Width on Thermal Conductivity -
Filled Angular Gap

Figure 74 - Effect of Panel Width on Thermal Conductivity -
Filled Angular Gap

Figure 75 - Comparison of Effect on Thermal Conductivity for Filled Versus Unfilled Angular Gaps

attributed to the relatively efficient radiation attenuation characteristics of the opacified gap fillers. On the other hand, the K_e/K_o comparisons for Al-106 glass insulations (Figures 71 and 75) show a high sensitivity of K_e/K_o ratio over the entire 2 inch range for the unfilled gap cases.

(4) For all filled gap cases, the sensitivity of the K_e/K_o ratio to insulation panel thickness is evident in the 2-6 in. width range but, again, very low in the 6-25 in. width range. This further demonstrates the high radiation attenuation capability of the opacified fillers in the lateral* as well as normal directions.

In general, the opacified fillers improve overall thermal performance of multifoil insulation panels containing rectangular or angular gaps, in comparison to these same insulation systems with unfilled gaps. This improvement applies to all panel and gap sizes and configurations covered in this evaluation. The beneficial effects of the gap fillers are illustrated in Figures 71 and 75 for Al-106 glass multifoil insulation. These plots indicate that a 0.5 in. filled gap performs essentially the same or better than a 0.05 in. unfilled gap. The same would hold true for the Ni-Refrasil quartz systems. No unfilled gap data are available for comparison of the Ni-Refrasil quartz performance.

The apparent contradiction for the 25 in. panel width case (i.e., unfilled gap performing better than filled gap) is likely due to the differences in the $K_a(T)$ data for the Al-106 glass multifoil insulation which were used in the analysis. The latest filled gap analysis used flat plate $K_a(T)$ data which, as indicated previously, are generally somewhat lower than the cylindrical test data used in the original analysis. This lack of correspondence would have the effect of decreasing the computed K_o values in the new analysis and, ultimately, increasing the K_e/K_o ratios.

The observations based on the improved filled gap analysis are generally in agreement with conclusions reached in the original study and reported in the Phase I Final Report.⁹ The new analysis has served to verify the original observations for filled gap configurations where the thermal behavior of the opacified gap fillers is more accurately characterized.

* Lateral radiant heat transfer (i.e., heat transfer from gap edge) would be strongly affected by panel thickness where no gap filler is present (see Figures 71 and 75).

3.4 Exposed Edge Effects Testing

In multifoil insulation system design, insulation panels may be oriented such that edges are exposed. These edges, which may present a temperature gradient close to the full "hot-side to cold-side" gradient across the insulation proper, radiate freely to the surrounding environment. In evaluating total system performance, it is necessary to determine this exposed edge heat loss. The edge effects study has included analytical prediction and experimental verification of these losses.

Section 3.3 describes a computer analysis performed, in part, in Phase I, in which filled and unfilled gaps and exposed edge configurations were analyzed to determine effects of these edge conditions on overall thermal performance of the insulation system. Verification tests were performed on insulation panels with exposed edges. Results are reported and discussed in this section. Experimental studies were not conducted on the unfilled and filled gap configurations.

3.4.1 Analytical and Experimental Approaches

The exposed edge effects analysis, as described in Appendix H, considers a rectangular multilayer insulation panel as shown schematically in Figure 76. The conditions of the analysis, as interpreted from the boundary conditions and heat flow equation of Figure 76 are given below:

1. Panel is of finite width and thickness and infinite length, implying two-dimensional heat flow (normal across T_h and T_c boundaries and lateral from center to edge).
2. Hot-face and cold-face boundaries are maintained at approximately uniform temperatures.
3. Exposed edges, with an apparent emissivity of 1.0, radiate to an ambient (530°R) environment. Total heat loss from an insulation panel operating at the above conditions is computed and compared with heat flux for an ideal (no edge loss) panel of identical size, to determine the edge effect.

The experimental test set-up is shown schematically in Figure 77. The dual-sample configuration duplicates the size and two-dimensional heat flow characteristics of the analytical model. Hot-face surface temperatures are maintained by a two-stage, ceramic-encased woven graphite resistance heater. Power can be controlled independently to a central element and two narrow edge elements as a means of approximating a uniform, hot surface temperature. This temperature is monitored by thermocouples located at intervals from center to edge of the sample.

HEAT BALANCE:
$$\frac{\partial}{\partial x} \left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial T}{\partial y} \right) = 0$$

K_x = longitudinal thermal conductivity
 K_y = normal thermal conductivity

FIGURE 76 - EXPOSED EDGE HEAT LOSS ANALYTICAL MODEL

Figure 77 - Exposed Edge Test Schematic

$$T_H = 1000^\circ\text{F}$$

$$T_C = 100^\circ\text{F}$$

SECTION A-A

Cold boundaries are maintained at a uniform, near-ambient temperature. The aluminum boundary plates stabilize the multilayer wrap at a specified layer density.

Heat flux is determined by a total power measurement for the system operating at fixed boundary temperatures. Extraneous losses (i.e., heater leads) are subtracted to obtain the net heat loss from the exposed edge sample. Combined radiative and conductive heat loss mechanisms are considered in calculating losses associated with the four stranded molybdenum wire leads. At point of exit from the multilayer sample, the leads are assumed to be at hot-side temperature.

Testing capability, in vacuum, is to 1800°F. Aluminum-106 glass and Ni-Refrasil quartz multilayer insulations were evaluated over a range of hot-side temperatures up to 1000°F and 1800°F, respectively. The experimental configuration, with two-stage resistance heater, provided relatively uniform temperatures over the entire hot face. Center-to-edge temperature decrease was less than 10% in all tests.

3.4.2 Exposed Edge Heat Loss Results

Two multilayer insulation systems have been evaluated --- Al-106 glass to 900°F and Ni-Refrasil quartz to 1700°F. Pertinent physical and thermal properties of the two insulations are listed below:

Exposed Edge Sample Characteristics

	<u>Aluminum-106 Glass</u>	<u>Nickel-Refrasil quartz</u>
1. Materials	aluminum foil (thickness = .00025 in.)	nickel foil (thickness = .0006 in.)
	106 glass paper (thickness = .003 in.)	Refrasil quartz paper (thickness = .005 in.)
2. Temperature Limit	900°F	1800°F
3. Layer Density	111 ℓ /inch	100 ℓ /inch
4. Sample Dimensions		
Length	unit	unit
Width	9.5 in.	9.5 in.
Thickness	0.4 in.	0.4 in.
5. Estimated normal thermal conductivity (Btu/hr-ft-°R)	$K(T) = 10^{-3}(T) \ .106 + .171T^2$	$K(T) = 10^{-3}T \ .4 + .472T^2$
6. Estimated lateral thermal conductivity (Btu/hr-ft-°R)	$K(T) = 3.9 - .76T$	$K(T) = 3.44 - 2.08T; T \leq .7$ $= 2.71 - 1.04T; .7 < T \leq 1.1$ $= .97 + .54T; T > 1.1$
$T = \frac{T_{act}}{1000}$ in the above expressions		

Items 5 and 6 are the normal and lateral conductivity expressions, as derived from cylindrical test data and materials properties for the two insulations. These expressions are used in the analysis.

Exposed edge experimental and analytical results are presented and compared in Table XLVII. In all cases, the exposed edges are radiating to an ambient environment sink (70-100°F), in a vacuum of $< 1 \times 10^{-3}$ torr. The Q_e flux values are net heat losses, obtained by subtracting the estimated lead loss from the total measured flux. The experimental Q_o values were obtained using flat plate thermal conductivity data. The analytical Q_o values were based on the normal K_a temperature polynomials previously listed.

Based on the exposed edge results, it is observed that:

(1) Heat loss penalty for an insulation system with exposed edges is significant. Panel configuration (i.e., exposed edge length to surface area) is critical. The rather severe experimental geometry resulted in Q_e/Q_o ratios of 7.0 and 4.0 for the aluminum and nickel multilayer insulations, respectively.

(2) Exposed edge heat loss increases rapidly with temperature due to the radiative loss mechanism at the edges.

(3) Agreement between analytical and experimental results, as denoted by the $(Q_e/Q_o)_{calc}/(Q_e/Q_o)_{exp.}$ ratio, was good for the aluminum system (estimated within 10%). Agreement for Ni-Refrasil quartz data varied from 0-30% (to 1000°F) to 40-55% (1000-1700°F). In all cases, the analytical results were conservative.

(4) The analytical Q_e and Q_o values were substantially higher, in most cases, than the corresponding experimental values. This is partially the result of using somewhat conservative* thermal conductivities for the multilayer insulations in the analysis.

The reasonably good comparisons between experimental and calculated results indicate that the analytical program can be quite useful in giving approximate performance predictions for multilayer insulation systems with exposed edges. Based on these comparative results, the analysis is conservative and will overpredict the edge loss to a moderate extent.

As indicated in observation (1), the sample size tested (4.75 in. center-to-edge width; 12 in. (unit) length; and 0.4 in. thickness) constituted a severe edge loss geometry. For multilayer insulation panels with a high surface area to exposed edge area ratio (e.g., thinner panels, wider panels), the Q_e/Q_o ratio would be substantially reduced.

* Based on cylindrical test data, which may be high by 25%.

TABLE XLVII

EXPOSED EDGE HEAT LOSS RESULTS

Multi-layer Insulation	T_h (average) °F	T_c °F	Analytical			Experimental			$\frac{(Q_e/Q_o)_{calc.}}{(Q_e/Q_o)_{exp.}}$
			Q_e Btu/hr-ft	Q_o Btu/hr-ft	Q_e/Q_o -	Q_e Btu/hr-ft	Q_o Btu/hr-ft	Q_e/Q_o -	
Aluminum-	685	93	11.5	1.6	7.2	7.5	1.1	7.0	1.03
106 Glass									
n = 11 1/2 in.	935	97	23.7	3.09	7.7	17.0	2.4	7.1	1.08
Nickel -									
Refrasil quartz	665	95	17.4	3.93	4.4	8.0	2.7	3.3	1.33
n = 100 in.									
	950	110	37.3	9.0	4.2	23.0	5.3	4.2	1.00
	1475	155	114.8	25.1	4.6	73.0	21.8	3.3	1.39
	1675	180	161.0	35.6	4.5	100.0	35.0	2.9	1.55

T_h - average hot-side temperature

T_c - cold-side temperature

Q_e - exposed edge heat loss

Q_o - heat loss through corresponding insulation panel with no edge loss.

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Appendix A

Load-Deflection Data Over Loading Range From
0 - 15 psi

Multifoil Insulation Systems

Fibrous Multilayer Insulation Systems

List of Figures Showing Layer Density vs. Compressive Load

- A-1 Aluminum Foil - 106 Glass Paper
- A-2 Copper Foil - Refrasil Quartz Paper
- A-3 Nickel Foil - Refrasil Quartz Paper
- A-4 Nickel Foil - Astroquartz Cloth
- A-5 Molybdenum Foil - Zirconia Cloth
- A-6 Composite (Multifoil): Mo-Astroquartz, Ni-Refrasil, Copper Refrasil, Al-Al Opacified
- A-7 Aluminum Foil - Aluminum Opacified Glass Paper
- A-8 Copper Foil - Copper Opacified Quartz Paper
- A-9 Nickel Foil - Nickel Opacified Quartz Paper
- A-10 Aluminum Opacified Glass Paper
- A-11 Copper Opacified Quartz Paper
- A-12 Nickel Opacified Quartz Paper
- A-13 106 Glass Paper
- A-14 Refrasil Quartz Paper

APPENDIX B

METALLURGICAL EVALUATION OF MOLYBDENUM-ZIRCONIA MULTIFOIL
INSULATION SAMPLE AFTER 2500°F TESTING

R. Zawierucha

B-1 Introduction

Material components of the Mo-ZrO₂ multi-foil insulation test panels; i.e., molybdenum foil and stabilized zirconia cloth, have undergone metallurgical and physical examination. The materials had been subjected to a high temperature (indicated T_{max} = 2500°F), vacuum environment for 4 - 6 weeks in connection with the thermal conductivity measurement program.

Initial post-test visual examination showed that (a) severe degradation of the hot-side Pt/Pt-10Rh thermocouple had occurred and (b) there was some evidence of localized molybdenum-zirconia interaction on the hottest foil layers. These two potential material degradations were evaluated in an effort to determine the nature and causes of the degradations.

B-2 Metallurgical Evaluation

The following tests comprised the metallurgical evaluation:

1. Visual examination of components at low magnifications (10X).
2. Surface examination to 1000X.
3. Limited X-ray diffraction and electron probe scans.
4. Literature survey.

B-3 Results/Observations

1. The disassembled test panel was comprised of the following major components:

- a. Graphite heating elements (interior of panel).
- b. Two alumina shields (next to heating elements).
- c. A fifty layer insulation square or pad composed of alternating molybdenum foil and stabilized zirconia spacers.
- d. A second fifty layer insulation square or pad similar to the above except that two platinum-platinum 10% rhodium thermocouples were included on the hot side for temperature measurement.

Upon disassembly it was observed that the alumina shields were cracked and that one of the thermocouples had been damaged. (Erratic behavior of this thermocouple had been noted during test.) Also, thermal etching patterns corresponding to the cracks on the alumina shields were observed on the hottest layers of the 50 layer insulation squares.

2. Both 50 layer insulation pads were subjected to low power visual examination. In general, the insulation appeared to be in very good condition with the exception of the hottest three or four layers (particularly on the measured pad) where thermal etching and various indications of melting were noted. The detailed high magnification examination was confined to the measured pad which was instrumented with thermocouples. The layers were arbitrarily numbered 1 through 50*. Layer No. 1 is the coldest layer while layer No. 50 was the hottest and located adjacent to the alumina shields covering the graphite heating elements. A more detailed description of the hot layers of the measured panel and the observed damage is given in the following paragraphs.

3. FigureB-1 is a photomicrograph of the area on layers 49 and 50 (Mo and "stabilized" ZrO_2 respectively) where the primary evidence of thermocouple melting and surface degradation is visible. Areas a, b, c, and d are solidified puddles where molten platinum alloy collected. At e in FigureB-1, the remains of a platinum thermocouple are visible. Closeups of two of the puddles (a and d) are visible in FiguresB-2 and B-3. From FigureB-2 and especially FigureB-3 it would appear that there was little reaction between the zirconia fibers and the platinum. Yet, the melted areas had penetrated layer 49 (Mo foil), layer 48 (ZrO_2), and caused isolated holes in layer 47 (Mo foil). Located at i in FigureB-1 is a "frosty" zone which is one of several similar zones (g and h) which lined up exactly with cracks in the alumina shield adjacent to layer 50 (ZrO_2). Considerably less intense "frosty zones" could be seen on layer 47 (Mo).

4. An attempt was made to prepare metallographic mounts of foil samples. This effort was not successful due to the extremely thin thickness of the foils (approximately 0.5 mil), and subsequent metallographic work with foil samples was done by direct observation of foil surfaces with a Leitz metallux microscope.

5. In the examination of "frosty zones" considerable work was done with foil No. 47 because the thermocouple reaction zones were confined to a few isolated holes where the melt produced by the thermocouple reaction had penetrated. Thus, these two effects could be isolated without having to consider complicating side effects. FigureB-4 shows an area adjacent to a frosty zone on layer 47 (Molybdenum).

* The sample was a 25 layer Mo- ZrO_2 multi-foil system where a layer implies one foil and one spacer. In these observations, the foils and spacers are considered individually. Hence, the 1 to 50 numbering system.

An intergranular crack (a in FigureB-4) as well as numerous zirconia rods (b in FigureB-4) which have adhered to the surface are visible. A zirconia rod (c in FigureB-4) which has reacted with the surface is visible in FigureB-4. A closeup of this area is shown in FigureB-5 and dendrites typical of a cast or melted material are evident. FigureB-5 is significant because it indicates that a reaction between the molybdenum foil and zirconia spacer had occurred which was independent of the reaction involving the thermocouples. FigureB-6 shows the center of a frosty zone. There is no doubt that the interface between the molybdenum foil and zirconia spacer had undergone considerable melting in this region. It should be emphasized that this effect was confined to areas on the two or three hottest foils which were in line with the cracks in the alumina shield or adjacent to thermocouple reaction zones. In the latter case it is difficult to determine the effect or relationship between the thermocouple reaction and the Mo-ZrO_2 reaction. On the edges of cooler foils where the foils were in contact with the test frame, scattered zones with similar characteristics were also noted but these were given little attention since they were not considered representative of actual conditions in the center of the affected foils.

6. FigureB-7 is a photomicrograph of the surface of layer No. 27 (molybdenum) on the measured panel. This foil was one of the cooler molybdenum foils which had experienced a ductility loss and, significantly, is the coolest foil on which a recrystallized microstructure could be photographed. Recrystallization temperatures for molybdenum are in the 1700-1800°F range.

7. Visual observations at magnifications between 1 and 1000X suggested that two reactions were occurring:

a. Melting reaction involving platinum thermocouples.

b. Localized melting at the interface between molybdenum foil and stabilized zirconia spacers in the hottest foil layers.

Preliminary surveys⁽¹⁻⁷⁾ of phase diagram information are listed in Table I. Assuming that elemental zirconium was available, a platinum-zirconium alloy (79 Pt, 21 Zr) could be formed that would have a melting point of 2165°F. According to Reference 7, zirconia crucibles are used in melting platinum, thus confirming that zirconia is extremely stable in the presence of platinum even when molten. However, Reference 5 also indicated that so called stabilized zirconia is adversely affected by slags. Similarly assuming that zirconium was available a Mo-Zr alloy (69 Zr, 21 Mo) could be formed that would melt at 2768°F.

8. Platinum thermocouples and zones where platinum "puddles" were observed were initially subjected to X-ray diffraction studies but these were not successful. Electron probe scans of the degraded thermocouple were extremely interesting. Figure B-8 is an electron image of the thermocouple sample and is shown to give the reader some idea of the surface contour. FigureB-9 is a platinum scan

of the same area. Figure B-10 is a rhodium scan of the area shown in Figures B-8 and B-9. The rhodium scan indicated a low level of rhodium contaminant in the wire much below the 10% level noted in Pt - 10 Rh wires. Figure B-11 was surprising in that this scan revealed a substantial amount of phosphorus contamination on the wire surface in degraded areas. Phosphorus was not observed on unaffected portions of the platinum or platinum - 10 rhodium wires.

9. Molybdenum foils were subjected to electron probe scanning in the following areas:

- a. Shiny surface - no apparent surface attack.
- b. "Frosty" areas similar to areas f, g, and h in Figure B-1.
- c. Zones intermediate in appearance to a and b.

Figures B-12 and B-17 are electron probe scans of a frosted area which was directly exposed to cracks in the alumina. An electron image of the surface as shown in Figure B-12 outlines the surface and locates several zirconia fibers. A molybdenum scan, Figure B-13 shows an absence of molybdenum where the fibers were observed. The zirconium scan reveals that zirconium is leaving the fibers and diffusing into the molybdenum. Silicon is shown to be concentrated adjacent to the zirconium in Figure B-15. Figures B-16 and B-17 show the surface to be contaminated with iron and phosphorus respectively. The greater intensity of Figures B-16 and B-17 as compared to Figure B-13 should not be construed to indicate that the concentration of these elements is greater than that of Mo. Certain elements even in small quantities can give very intense indications depending on wave lengths used and the primary element of the sample. Silicon, iron, and phosphorus were virtually absent on the shiny molybdenum sample from the same foil. In areas intermediate between the selected shiny and frosted specimens the silicon was reduced but the iron and phosphorus were still relatively high. The silicon was therefore associated only with foil surfaces directly in line with the cracks in the alumina shields. The wide phosphorus distribution could be the result of phosphorus vapor condensing on a large area. The platinum puddles observed in the molybdenum foil were extremely low in phosphorus.

If phosphorus was present on the wire surface the melting of the wire might allow the phosphorus to boil off and leave a purified platinum melt.

10. In view of the results of the probe scans which revealed the presence of Fe, Si, and P contaminants additional phase diagram data were obtained and tabulated in Table BI. Phosphorus contamination of a platinum thermocouple could result in a drop in the melting point from 3200°F at 100% Pt to 1090°F at 80 Pt, 20 P although a drop to 1090°F is extremely unlikely. Molybdenum alloys could be formed with Fe and P with melting points as low as 2640°F and 3000°F respectively. The phosphorus effect on platinum appears to be the most serious however. Silicon effects that are known seem to be minor. Considerable difficulty was experienced in obtaining phase diagram information involving a metal and a ceramic

such as Mo versus ZrO_2 , Pt versus ZrO_2 , Mo versus Al_2O_3 , etc.

B-4 Discussion

After considering the analytical results it would appear that there are two major factors in the degradation of the test component:

1. Contamination by phosphorus, silicon, and iron.
2. Cracks in the alumina shield which may have resulted in locally increased temperatures in the insulation zones in line with these defects.

Where these factors are totally absent there seems to be no difficulty.

Condition of the individual layers from 1 to 46 on the measured side was considered to be good. Embrittlement of the molybdenum occurred on all foils where recrystallization was observed. However, this was expected. Thermal etching although fairly deep when observed at 1000X on the higher numbered foils was not nearly as deep as expected and this was not thought to be a serious problem in this test.

A reexamination of the test system for possible contaminants is necessary. In view of the extensive amount and variety of contaminants observed it is difficult to fix a temperature at which the degradation occurred. In the frosty zones opposite the cracks the extensive surface melting in the molybdenum where zirconium was present suggests that a temperature of 2700-2800°F is a good possibility in this area. Degradation of the platinum thermocouple could have occurred at 2500°F but an educated guess would put the reaction temperature at least 100°F higher. Diffusion of contaminants on the thermocouples could only have an adverse effect on thermocouple accuracy.

Prior to starting any further panel tests involving zirconia and molybdenum at 2500°F it would be prudent to conduct short duration compatibility tests involving molybdenum, zirconia, and platinum-platinum 10 rhodium thermocouples. In order to pin down the temperatures at which these reactions occur it is suggested that experiments be conducted at various temperatures ranging from 2500°F to about 3250°F. In view of the complicating aspects of the degradation of the 2500°F test panel with respect to various contaminants and, despite the data provided by electron probe scans, it is believed that the degradation that occurred in the 2500°F zirconia-Mo test panel will not be fully understood until the supplementary tests are carried out.

B-5 Conclusions/Recommendations

1. Major factors in the degradation of the platinum thermocouple and the reaction between the molybdenum foil and zirconia spacer are believed to be:

a. Presence of contaminants such as Fe, P, and Si.

b. Cracks in the alumina shield which are thought to have resulted in localized temperatures above 2500°F.

2. Thermocouple accuracy and data are in doubt at the higher temperatures (2200-2500°F) because of the unknown effects of residual elements in the system.

3. Carefully controlled compatibility tests at 2500°F in a vacuum furnace are suggested as the best method to verify the compatibility of Mo, ZrO₂, and Pt, Pt-10 Rh materials at 2500°F.

4. Exclusive of the 3-4 hottest layers (likely subjected to localized temperature greater than 2500°F) of the 50 layer molybdenum-zirconia test panels and the expected embrittlement of recrystallized molybdenum foils there was little evidence of material degradation. It may be concluded that zirconia and molybdenum were compatible on layers 1-45 of this particular test panel.

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TABLE B-I

Melting Behavior of Various Materials
and/or Material Combinations (References 1 through 7)

<u>Material or Material Combination</u>	<u>Melting Point*</u>	<u>Comment</u>
Mo	4,732°F.	
Pt	3,200°F.	
Rh	3,600°F.	
Zr	3,380°F.	
Al ₂ O ₃	3,654°F.	
ZrO ₂	4,802°F.	
Mo - Pt	3,200°F.	Pure platinum is lowest melting component of this system
Mo - Rh	3,524°F.	Composition 60 Mo - 40 Rh
Mo - ZrO ₂	?	No data
Mo - Zr	2,768°F.	Composition 60 Zr ~ 21 Mo
Pt - ZrO ₂	?	No data, but Reference 7 indicates pure ZrO ₂ is used as a crucible for melting Pt indicating a melting point > 3,200°F. However, so called stabilized ZrO ₂ can be troublesome.
ZrO ₂ - Al ₂ O ₃	3,362°F.	Composition approx. 60 Al ₂ O ₃ , 40 ZrO ₂ . This is for pure ZrO ₂ , not for stabilized variety.
Pt - P	1,090°F.	Composition 20 P, 80 Pt
Rh - P	1,380°F.	Composition 25 P, 75 Rh
Mo - Fe	2,640°F.	Composition 20 Mo, 80 Fe
Mo - P	3,000°F.	Composition 12 P, 88 Mo High P content Mo - P Alloys Difficult to prepare
SiO ₂ - ZrO ₂	3,092°F.	Composition approx. 90 ZrO ₂ , 10 SiO ₂ Phase diagram not complete Possibility of a solid state reaction forming ZrSiO ₄ also
P - ZrO ₂	?	No data
P - Al ₂ O ₃	?	No data
Mo - Si	2,430°F.	Pure silicon is lowest melting component of system (unlikely)
	3,300°F.	Composition 24 Si, 76 Mo

* Lowest melting point in the case of a binary system.

Figure B-1- Photomacrograph of Molybdenum and Zirconia layers (layers 49 and 50 respectively) adjacent to alumina shield. These layers experienced highest temperatures. Areas a, b, c, and d are thermocouple melt zones. A visible segment of the thermocouple can be seen at e. Frosty zones at f, g, and h coincide with alumina shield cracks.

Mag. 2X

Met. Job No. 69-44

Figure B-2 This photomacrograph is a closeup of area a in Figure 1 where a thermocouple melted on the Molybdenum foil. A hollow shell in the center of the melt is all that is left of the platinum wire.

Mag. 15X

Met. Job No. 69-44

Figure B-3 This photomacrograph is a close-up of area d in Figure 1. The thermocouple wire is visible lying on the Zirconia spacer. To the left of the wire is a wire melt zone which has almost worked its way through the Mo foil. The Zirconia appears to be playing a minimal role here.

Mag. 15X

Met. Job No. 69-44

Figure B-4- Photomicrograph of surface of Molybdenum foil 47 on the edge of a "Frosted Zone" lining up with a crack in the alumina shield shows following: (a) grain boundary crack in recrystallized Mo foil, (b) Zirconia rods adhering to surface, (c) Zirconia rod reacting with surface. Thermal etching varies considerably.

Mag. 200X

Met. Job No. 69-44

Figure B-5 - This photomicrograph is a closeup of area c in Figure 4. It is obvious that the Zirconia rod was in the process of melting away. A dendritic microstructure typical of a melted or cast alloy is visible.

Mag. 500X

Met. Job No. 69-44

Figure B-6 - This photomicrograph shows the center of a "Frosted Zone" on Foil 47 lining up with a crack in the alumina shield. Massive melting of the Zirconia has occurred on the surface of the Mo foil.

Mag. 200X

Met. Job No. 69-44

Figure B-7 - This photomicrograph shows the surface of foil 27, the coolest Mo foil in the insulation test panel in which Mo recrystallization could be photographed. This foil was not ductile.

Mag. 200X

Met. Job No. 69-44

Figure B-8 - Electron image of degraded end of platinum thermocouple.

Mag. 800X
UCC - Mining and Metals

Figure B-9 - Platinum scan of degraded end of platinum thermocouple. Light areas are platinum rich. Compare with electron image (Figure 8) and scans of Pt and P.

Mag. 800X
UCC - Mining and Metals

Figure B-10 - Rhodium scan of degraded end of platinum thermocouple; light areas are rhodium rich. Compare this photo with identical areas shown in Figures 8 and 9.

Mag. 800X
UCC - Mining and Metals

Figure B-11 - Phosphorus scan of degraded end of platinum thermocouple. All areas rich in rhodium were even richer in phosphorus. Phosphorus is definitely an unsuspected and unwanted contaminant.

Mag. 800X
UCC - Mining and Metals

Figure B-12- Electron image of
"Frosty Zone" in vicinity of area
f in Figure 1. Zirconia fibers
are visible on surface of foil.
Mag. 330X

Figure B-13- Molybdenum scan of
area shown in Figure 12.
Mag. 330X

Figure B-14 - Zirconium scan of area
shown in Figure 12. Extensive
diffusion of Zirconium away from
rods is visible above. Compare
this figure with the shape of the
fibers in Figure 12.
Mag. 330X

Figure B-15- Silicon scan of area shown in Figure 12. Silicon has tendency to concentrate near Zirconia fibers.

Mag. 330X

Figure B-16 - Iron scan of area shown in Figure 12.

Mag. 330X

Figure B-17 - Phosphorus scan of area shown in Figure 12.

Mag. 330X

APPENDIX C

FLAT-PLATE TEST ERROR ANALYSIS PROGRAM

H. Morihara

C-1 Abstract

The computer program described herein, written in FORTRAN IV-G, computes the one-dimensional heat flux, solid conductivity, and their error bands, based on the experimental data which are by nature two-dimensional. This program makes extensive use of the exposed edge program given in Appendix H.

The main objectives of this program are to: (1) establish and verify accuracy of the measured thermal conductivity data, (2) re-evaluate the flat plate test equipment and procedures. These tasks are of utmost importance in the absence of experimental proof tests or multilayer insulation standards.

Accuracy of the measured thermal conductivity data is dependent on two types of errors: (1) errors associated with measuring instruments, and (2) errors due to the two-dimensional nature of the experimental set-up. Measurement errors usually are small and fairly constant, but two-dimensional errors vary from test to test, depending on the degree of temperature mismatch between the guard and the sample at the cold surface.

C-2 Measurement Errors

Measurement-instrumentation errors are based on calibration data for thermocouples and flux meter, and calibration and readability of recording equipment.

1) Flux Metering

Sensitivity: There are 250 divisions, full sweep. The Sargent recorder has a sensitivity of $1/4$ divisions. On the average, if the pointer is assumed to be at the midpoint, sensitivity is about $1/4$ percent.

$$i) \left(\frac{1}{125}\right) \left(\frac{1}{4}\right) \cong 1/4\% \quad \text{or}$$

ii) For a very low heat flux, the full scale at the most sensitive setting is $q = 16.3 \text{ Btu/hr-ft}^2$. If q is much below this value, sensitivity is given by:

$$\left(\frac{1}{250}\right) \left(\frac{1}{4}\right) \left(\frac{16.3}{q}\right)$$

i) or ii), whichever is larger, is chosen.

Readability: Readability is about 1/2 division. If, on the average, we take the reading at the midpoint on the scale, readability is about 1/2 percent.

$$\text{i) } \left(\frac{1}{125}\right) \left(\frac{1}{2}\right) \cong 1/2\%$$

ii) For a very low heat flux, q

$$\left(\frac{1}{250}\right) \left(\frac{1}{2}\right) \left(\frac{16.3}{q}\right)$$

i) or ii), whichever is larger, is chosen.

Calibration: Thermonetics Model H-11 flux meter is calibrated to 3% accuracy. But at very low fluxes its accuracy suffers.

i) .03 (3%) or

ii) .013/ q (note: .001 mv = .013 Btu/hr-ft²)

i) or ii), whichever is larger, is chosen.

2) Temperature Recording

Sensitivity: Brown multipoint circular chart was used to record the hot side temperature. It has the range of 0 to 2600°R and the subdivision is at 20°C interval. Sensitivity is about 1/7 of a subdivision. Brown multipoint strip chart, 0 ~ 2000°R range, was used to record the cold side temperature. Its subdivision is at 10°R interval, and sensitivity is ~ 1/3 of a subdivision.

$$\text{i) Hot side: } \frac{20}{7} \simeq 3^{\circ}\text{C} \simeq 5^{\circ}\text{R}$$

$$\text{ii) Cold side: } \frac{10}{3} \simeq 3^{\circ}\text{R}$$

Readability: On the circular chart 1/5 of a subdivision is the limit, while on the strip chart whose subdivision is narrower 1/4 of a subdivision seems to be the limit.

$$\text{i) Hot side: } \frac{20}{5} = 4^{\circ}\text{C} \simeq 7^{\circ}\text{R}$$

$$\text{ii) Cold side: } \frac{10}{4} = 2.5^{\circ}\text{R}$$

Calibration: Chromel-alumel thermocouples, .010 in. wire diameter, are calibrated against a certified Pt/Pt-10Rh thermocouples traceable to NBS standards. Typical deviation is one percent or less. But at high temperatures deviation is about one-quarter percent. In other words, at around 560°R (=100°F) the possible error is 1°R, and the error increases at the rate of 1°R per every 2.50°R increase in temperature

i) 1°R or

ii) $(T-310)/250^{\circ}\text{R}$

i) or ii), whichever is larger, is chosen.

3) Sample Thickness Measurement

A dial indicator, readable to .001 in., monitors the total gap width between compression loading plates.

Deviation: $\frac{.001}{12}$ ft.

These deviations or uncertainty figures will be used later, when the solid thermal conductivity error band is computed.

C-3 Two-Dimensional Errors

Flat plate test data indicate that the sample and the guard have virtually the same temperature on the hot surfaces but usually have different temperatures on the cold surfaces. This clearly indicates that the heat flow is not one-dimensional. There is a heat exchange between the sample and the guard. Data do not reflect this two-dimensionality, because heat flux is measured at the center 2 inch square on the cold side of the sample and Fourier's 1-D conduction law is used to obtain the thermal conductivity.

If we can compute the net lateral heat flow between the sample and the guard, this two-dimensional error is easily corrected. The exposed edge program given in Appendix H was revised for this purpose. In that program, hot and cold side temperatures of the sample and guard were necessarily identical. Under this assumption, the sample, gap, and guard were divided into small segments. In each segment, the heat transfer system was assumed lumped so that Fourier's 2-D conduction heat balance equation for each segment was linear; and the temperature distribution and the normal and lateral heat fluxes were easily found.

Because of the linear nature of Fourier equations, it is possible to use the principle of superposition in accounting for the difference in temperature between the sample and guard. Some compromises were made in order to conserve computation time, since the resultant accuracy penalty is of second order nature. When the new guard temperature was introduced, the temperature in each segment of the guard was adjusted linearly. The lumped thermal conductivity in each segment in the sample was not altered.

In this way, a new lateral heat flux was obtained. The lateral heat flux obtained by the exposed edge program and this new heat flux are additive, and the sum gives the lateral heat flux when there is a mismatch in the sample and the guard temperatures.

C-4 Error Band

1) Uncertainty Analysis

Suppose a set of measurements is made and the uncertainty in each measurement may be expressed with the same odds. These measurements are then used to calculate some desired result of the experiments. We wish to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements. The result R is a given function of the independent variables $X_1, X_2, X_3, \dots, X_n$. Thus,

$$R = R(X_1, X_2, \dots, X_n)$$

Let W_r be the uncertainty in the result and $W_1, W_2, \dots, W_n$ be the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as

$$W_r = \left[\left(\frac{\partial R}{\partial X_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{1/2}$$

If this relation is applied to Fourier conduction law, we have the following

$$q = R \frac{T_2 - T_1}{h}$$

$$\frac{\partial q}{\partial k} = \frac{T_2 - T_1}{h}$$

$$\frac{\partial q}{\partial T_1} = -\frac{k}{h}$$

$$\frac{\partial q}{\partial T_2} = \frac{k}{h}$$

$$\frac{\partial q}{\partial h} = -k \frac{T_2 - T_1}{h^2}$$

If a subscript "u" denotes the uncertainty in the independent variable, the uncertainty in the heat flux is

$$q_u = \left[\left(\frac{\partial q}{\partial k} k_u \right)^2 + \left(\frac{\partial q}{\partial T_1} T_{1u} \right)^2 + \left(\frac{\partial q}{\partial T_2} T_{2u} \right)^2 + \left(\frac{\partial q}{\partial h} h_u \right)^2 \right]^{1/2}$$

On the other hand, the uncertainty in the heat flux due to the flux meter measurement error is

$$q_u = q \left[(\text{sensitivity})^2 + (\text{readability})^2 + (\text{calibration})^2 \right]^{1/2}$$

Of course, these two q_u are not related.

2) Uncertainty of 1-D Conductivity

Using the revised exposed edge program the lateral heat flux is calculated, and a realistic 1-D conductivity is thus formed. Our task now is to find the probable error band associated with this 1-D conductivity. The thermal conductivity is given by,

$$k = \frac{qh}{T_h - T_c} \quad \text{and}$$

$$\frac{\partial k}{\partial q} = \frac{h}{T_h - T_c} ; \quad \frac{\partial k}{\partial h} = \frac{q}{T_h - T_c}$$

$$\frac{\partial k}{\partial T_h} = -\frac{qh}{(T_h - T_c)^2} ; \quad \frac{\partial k}{\partial T_c} = \frac{qh}{(T_h - T_c)^2}$$

Thus, the uncertainty associated with the conductivity is given by:

$$k_u = \left[\left(\frac{h}{T_h - T_c} q_u \right)^2 + \left(\frac{q}{T_h - T_c} h_u \right)^2 + \left(\frac{qh}{(T_h - T_c)^2} T_{hu} \right)^2 + \left(\frac{qh}{(T_h - T_c)^2} T_{cu} \right)^2 \right]^{1/2}$$

$$\text{where } h_u = \frac{.001}{12}$$

$$\begin{aligned} T_{hu} &= \left[(\text{sensitivity})_h^2 + (\text{readability})_h^2 + (\text{calibration})_h^2 \right]^{1/2} \\ T_{cu} &= \left[(\text{sensitivity})_c^2 + (\text{readability})_c^2 + (\text{calibration})_c^2 \right]^{1/2} \end{aligned}$$

q_u is divided into two parts which are (1) due to measurement error, q_{u1} and (2) due to 2-dimensional nature, q_{u2} . q_{u1} is easily found:

$$q_{u1} = \left[(\text{sensitivity})^2 + (\text{readability})^2 + (\text{calibration})^2 \right]^{1/2}$$

q_{u2} is computed by finding the maximum and the minimum lateral heat fluxes and by subtracting one from the other. The maximum and minimum heat fluxes are computed by employing a suitable combination of extreme temperatures, $T_h \pm T_{hu}$, $T_c \pm T_{cu}$, and $T_g \pm T_{gu}$, where T_g is the guard temperature on the cold surface.

$(T_c - T_g)$ is a very important parameter in obtaining q_{u2} . For all cases, $(T_c - T_g)$ is in the order of T_{cu} and T_{gu} ; which means that the uncertainty associated with $(T_c - T_g)$ is in the order of $(T_c - T_g)$. This is very unfortunate, because q_{u2}

becomes a very large in proportion especially when q is small. This is evidenced by a large error band for a moderate to a small q as seen in the attached tables.

This problem can be eliminated, if we use additional thermocouples which will read the difference of T_c and T_g to a higher degree of accuracy. Then, the uncertainty associated with $(T_c \pm T_g)$ will become much smaller.

3) Tabular Results

Five typical multifoil insulation systems were chosen for error analysis. They are:

- (1) Aluminum foil - 106 glass paper
- (2) Aluminum foil - Aluminum opacified paper
- (3) Copper foil - Refrasil paper
- (4) Nickel foil - Refrasil paper
- (5) Nickel foil - Astroquartz cloth

Results are tabulated and given in the subsequent pages. It is noted that there are two error bands for each case, one smaller and one larger. The smaller error band is applicable if $T_c = T_g$ and $(T_c - T_g)_u = 0$. This case was added to see what will happen if we improve the experimental set-up so that $T_c \approx T_g$ can be assured and also if we add a pair of thermocouples to measure $T_c - T_g$ to make $(T_c - T_g)_u$ small. The bigger error band is for the present case. The error band is large in many cases, but in reality this is unlikely; because usually errors are not random. For example, if a pair of thermocouples reads low at one temperature, it will tend to read low at other temperatures in the same range.

TABLE C-1

Flat Plate Test Error Analysis

Aluminum Foil-106 Glass Paper

LAYER DENSITY	Th (°R)	Tc (°R)	Tg (°R)	Measured		One-Dimensional		
				$Q \frac{\text{Btu}}{\text{hr-ft}^2}$	$K \frac{\text{Btu}}{\text{hr-ft-R}}$	Q	K	ERROR BAND $\pm\%$
* ** 185 1/in (.3 psi)	852	542		2.80	$.195 \times 10^{-3}$	2.77	$.193 \times 10^{-3}$	5.1
	852	542	552	2.80	$.195 \times 10^{-3}$	2.12	$.147 \times 10^{-3}$	132
	1030	548		5.16	$.231 \times 10^{-3}$	5.04	$.226 \times 10^{-3}$	4.0
	1030	548	560	5.16	$.231 \times 10^{-3}$	4.18	$.187 \times 10^{-3}$	79.2
	1276	561		11.3	$.342 \times 10^{-3}$	10.9	$.328 \times 10^{-3}$	3.5
	1276	561	584	11.3	$.342 \times 10^{-3}$	8.73	$.264 \times 10^{-3}$	51.4
214 1/in (1 psi)	852	550		5.85	$.362 \times 10^{-3}$	5.81	$.359 \times 10^{-3}$	4.6
	852	550	558	5.85	$.362 \times 10^{-3}$	5.30	$.328 \times 10^{-3}$	52.7
	1032	560		10.7	$.425 \times 10^{-3}$	10.6	$.421 \times 10^{-3}$	3.8
	1032	560	570	10.7	$.425 \times 10^{-3}$	9.93	$.393 \times 10^{-3}$	33.0
	1287	570		20.0	$.521 \times 10^{-3}$	19.5	$.508 \times 10^{-3}$	3.5
	1287	570	590	20.0	$.521 \times 10^{-3}$	17.8	$.463 \times 10^{-3}$	25.5
283 1/in (6 psi)	852	550		12.4	$.579 \times 10^{-3}$	12.4	$.583 \times 10^{-3}$	4.5
	852	550	557	12.4	$.579 \times 10^{-3}$	12.0	$.562 \times 10^{-3}$	23.5
	1032	564		21.7	$.655 \times 10^{-3}$	21.7	$.658 \times 10^{-3}$	3.8
	1032	564	575	21.7	$.655 \times 10^{-3}$	21.0	$.636 \times 10^{-3}$	15.3
	1284	591		36.0	$.736 \times 10^{-3}$	35.5	$.725 \times 10^{-3}$	3.5
	1284	591	603	36.0	$.736 \times 10^{-3}$	34.6	$.707 \times 10^{-3}$	11.7

* Tc = Tg assumed. Error band includes instrument errors only.

** Measured Tg value used with its associated uncertainty.

TABLE C-2

Flat Plate Test Error Analysis

Aluminum Foil-Aluminum Opacified Glass Paper

LAYER DENSITY	Th (°R)	Tc (°R)	Tg (°R)	Measured		One-Dimensional		
				$Q \frac{\text{Btu}}{\text{hr-ft}^2}$	$K \frac{\text{Btu}}{\text{hr-ft}}\text{-R}$	Q	K	ERROR BAND $\pm\%$
252 1/in (.3 psi)	*	803	537	1.89	$.165 \times 10^{-3}$	1.89	$.164 \times 10^{-3}$	6.1
	**	803	537	1.89	$.165 \times 10^{-3}$	1.49	$.130 \times 10^{-3}$	+207 -73
		1032	542	3.91	$.185 \times 10^{-3}$	3.89	$.184 \times 10^{-3}$	4.1
		1032	542	3.91	$.185 \times 10^{-3}$	3.01	$.142 \times 10^{-3}$	+150 - 56
		1270	552	8.93	$.288 \times 10^{-3}$	8.70	$.281 \times 10^{-3}$	3.5
		1270	552	8.93	$.288 \times 10^{-3}$	6.09	$.196 \times 10^{-3}$	+128 - 45
281 1/in (1 psi)		780	541	5.34	$.464 \times 10^{-3}$	5.37	$.466 \times 10^{-3}$	5.2
		780	541	5.34	$.464 \times 10^{-3}$	5.30	$.460 \times 10^{-3}$	57.4
		1032	540	13.7	$.578 \times 10^{-3}$	13.7	$.579 \times 10^{-3}$	3.7
		1032	540	13.7	$.578 \times 10^{-3}$	12.9	$.542 \times 10^{-3}$	34.4
		1305	556	25.4	$.704 \times 10^{-3}$	25.5	$.707 \times 10^{-3}$	3.4
		1305	556	25.4	$.704 \times 10^{-3}$	23.6	$.654 \times 10^{-3}$	30.3
365 1/in (6 psi)		780	545	16.8	1.15×10^{-3}	16.8	1.15×10^{-3}	5.2
		780	545	16.8	1.15×10^{-3}	16.6	1.14×10^{-3}	17.3
		1032	560	33.7	1.15×10^{-3}	33.6	1.14×10^{-3}	3.8
		1032	560	33.7	1.15×10^{-3}	33.7	1.15×10^{-3}	12.3
		1286	587	58.6	1.35×10^{-3}	58.3	1.34×10^{-3}	3.4
		1286	587	58.6	1.35×10^{-3}	57.1	1.31×10^{-3}	11.7

* Tc = Tg assumed. Error band includes instrument errors only.

** Measured Tg value used with its associated uncertainty.

TABLE C-3

Flat Plate Test Error Analysis

Copper Foil-Refrasil Quartz Paper

LAYER DENSITY	Th (°R)	Tc (°R)	Tg (°R)	Measured		One-Dimensional		
				$Q \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2}$	$K \frac{\text{Btu}}{\text{hr} \cdot \text{ft}} \cdot \text{R}$	Q	K	ERROR BAND $\pm\%$
* ** 90 l/in (.1 psi)	1041	585		5.45	$.299 \times 10^{-3}$	5.07	$.278 \times 10^{-3}$	4.2
	1041	585	578	5.45	$.299 \times 10^{-3}$	5.72	$.313 \times 10^{-3}$	63.2
	1491	628		15.7	$.455 \times 10^{-3}$	10.2	$.295 \times 10^{-3}$	
	1491	628	614	15.7	$.455 \times 10^{-3}$	13.7	$.398 \times 10^{-3}$	
	1905	678		33.2	$.676 \times 10^{-3}$	30.0	$.612 \times 10^{-3}$	3.6
	1905	678	657	33.2	$.676 \times 10^{-3}$	37.2	$.759 \times 10^{-3}$	47.9
113 l/in (1 psi)	1005	576		9.22	$.428 \times 10^{-3}$	9.20	$.427 \times 10^{-3}$	3.9
	1005	576	582	9.22	$.428 \times 10^{-3}$	8.73	$.405 \times 10^{-3}$	39.0
	1451	610		23.6	$.560 \times 10^{-3}$	23.4	$.555 \times 10^{-3}$	3.4
	1451	610	624	23.6	$.560 \times 10^{-3}$	21.8	$.517 \times 10^{-3}$	31.6
	1870	660		42.8	$.705 \times 10^{-3}$	42.6	$.701 \times 10^{-3}$	3.2
	1870	660	678	42.8	$.705 \times 10^{-3}$	39.3	$.647 \times 10^{-3}$	32.1
177 l/in (15 psi)	996	594		22.2	$.705 \times 10^{-3}$	22.2	$.704 \times 10^{-3}$	4.0
	996	594	587	22.2	$.705 \times 10^{-3}$	22.7	$.720 \times 10^{-3}$	14.3
	1446	636		54.3	$.855 \times 10^{-3}$	54.1	$.852 \times 10^{-3}$	3.4
	1446	636	625	54.3	$.855 \times 10^{-3}$	55.2	$.869 \times 10^{-3}$	11.2
	1860	676		91.2	$.982 \times 10^{-3}$	90.6	$.976 \times 10^{-3}$	3.3
	1860	676	673	91.2	$.982 \times 10^{-3}$	91.1	$.981 \times 10^{-3}$	12.2

* Tc = Tg assumed. Error band includes instrument errors only.

** Measured Tg value used with its associated uncertainty.

TABLE C-4

Flat Plate Test Error Analysis

Nickel Foil-Refrasil Quartz Paper

LAYER DENSITY	Th (°R)	Tc (°R)	Tg (°R)	Measured		One-Dimensional		
				$Q \frac{\text{Btu}}{\text{hr-ft}^2}$	$K \frac{\text{Btu}}{\text{hr-ft}} - R$	Q	K	ERROR BAND $\pm\%$
* ** 96 1/in (.1 psi)	996	575		5.17	$.320 \times 10^{-3}$	5.06	$.313 \times 10^{-3}$	4.1
	996	575	587	5.17	$.320 \times 10^{-3}$	3.42	$.211 \times 10^{-3}$	160
	1662	720		30.5	$.844 \times 10^{-3}$	30.5	$.843 \times 10^{-3}$	3.3
	1662	720	728	30.5	$.844 \times 10^{-3}$	27.2	$.751 \times 10^{-3}$	44.1
	2368	882		144	2.53×10^{-3}	141	2.48×10^{-3}	3.3
	2368	882	866	144	2.53×10^{-3}	147	2.58×10^{-3}	16.5
146 1/in (1 psi)	1009	583		15.5	$.625 \times 10^{-3}$	15.6	$.626 \times 10^{-3}$	3.9
	1009	583	586	15.5	$.625 \times 10^{-3}$	15.2	$.612 \times 10^{-3}$	31.5
	1720	700		70.3	1.18×10^{-3}	70.5	1.18×10^{-3}	3.3
	1720	700	711	70.3	1.18×10^{-3}	68.9	1.16×10^{-3}	14.2
	2255	832		207	2.49×10^{-3}	197	2.37×10^{-3}	3.4
	2255	832	846	207	2.49×10^{-3}	193	2.32×10^{-3}	10.0
175 1/in (6 psi)	996	622		27.8	1.06×10^{-3}	27.7	1.06×10^{-3}	4.1
	996	622	621	27.8	1.06×10^{-3}	27.9	1.06×10^{-3}	17.6
	1688	735		114	1.71×10^{-3}	113	1.69×10^{-3}	3.3
	1688	735	731	114	1.71×10^{-3}	114	1.70×10^{-3}	8.8
	2185	823		250	2.62×10^{-3}	274	2.88×10^{-3}	3.0
	2185	823	832	250	2.62×10^{-3}	273	2.86×10^{-3}	6.3

* Tc = Tg assumed. Error band includes instrument errors only.
 ** Measured Tg value used with its associated uncertainty.

TABLE C-5

Flat Plate Test Error Analysis

Nickel Foil-Astroquartz Cloth

LAYER DENSITY	Th (°R)	Tc (°R)	Tg (°R)	Measured		One-Dimensional		
				$Q \frac{\text{Btu}}{\text{hr-ft}^2}$	$K \frac{\text{Btu}}{\text{hr-ft-R}}$	Q	K	ERROR BAND $\pm\%$
120 1/in (.1 psi)	*	1000	564	24.2	1.31×10^{-3}	24.2	1.31×10^{-3}	3.8
	**	1000	564	24.2	1.31×10^{-3}	24.3	1.32×10^{-3}	16.6
		1662	640	67.8	1.57×10^{-3}	67.6	1.56×10^{-3}	3.3
		1662	640	67.8	1.57×10^{-3}	66.2	1.53×10^{-3}	11.3
		1975	690	123	2.27×10^{-3}	120	2.21×10^{-3}	3.3
		1975	690	123	2.27×10^{-3}	116	2.13×10^{-3}	10.4
133 1/in (1 psi)		1000	570	43.3	2.15×10^{-3}	43.3	2.15×10^{-3}	3.8
		1000	570	43.3	2.15×10^{-3}	43.7	2.17×10^{-3}	9.6
		1661	655	113	2.39×10^{-3}	112	2.38×10^{-3}	3.3
		1661	655	113	2.39×10^{-3}	111	2.36×10^{-3}	6.9
		1993	705	161	2.66×10^{-3}	160	2.64×10^{-3}	3.2
		1993	705	161	2.66×10^{-3}	155	2.57×10^{-3}	7.3
142 1/in (6 psi)		1009	571	48.8	2.22×10^{-3}	49.1	2.23×10^{-3}	3.8
		1009	571	48.8	2.22×10^{-3}	49.2	2.34×10^{-3}	8.2
		1661	648	156	3.06×10^{-3}	155	3.05×10^{-3}	3.3
		1661	648	156	3.06×10^{-3}	154	3.02×10^{-3}	5.6
		2004	732	296	4.64×10^{-3}	290	4.54×10^{-3}	3.3
		2004	732	296	4.64×10^{-3}	288	4.51×10^{-3}	5.0

* Tc = Tg assumed. Error band includes instrument errors only.

** Measured Tg value used with its associated uncertainty.

APPENDIX D

INSTABILITY OF NICKEL MULTI-FOIL SYSTEMS AT 1800°F.

D-1 Definition of the Problem

Long-term tests on the nickel-nickel opacified quartz and composite* multi-foil systems, having nickel-refrasil quartz on the hot side, were interrupted due to material instability problems at 1800°F temperature. This instability was discovered during measurement of apparent thermal conductivities (K_a) for the two systems at high-side temperatures of ~1800°F. Erratic behavior of the samples and inability to achieve thermal equilibrium at the 1800°F level indicated a deteriorating K_a . As a check, thermal conductivity at a lower, previously measured level was redetermined and compared to the original K_a -value. Results for the nickel-nickel opacified quartz multi-foil system are illustrated in Figure D-1-1. The 38% increase in this system's performance is attributed to deterioration of the nickel and/or quartz during 1800°F exposure.

The composite system was dismantled and close inspection of the 1800°F materials showed a visible dullness of the nickel shields and an embrittlement of the Refrasil quartz spacer. These apparent changes in the materials pointed to (1) loss of fibrous characteristics in the Refrasil (increased solid conduction) or (2) higher emissivity of the nickel foil (increased radiation) as contributors to the poor performance.

Several samples of nickel foil and Refrasil quartz from the composite insulation system were analyzed. Observations are summarized below:

(a) The nickel foil underwent thermal etching⁺ and recrystallization[□] as a result of the 1800°F exposure. The surface effects are severe at 1800°F, and quite mild at 1600°F.

(b) Photomicrographs (Figure D-1-2) comparing as-received and 1800°F exposed nickel foil show a high degree of surface roughness on the latter samples as a result of (a). The as-received surface is "pinch-rolled" to give high reflectivity.

* Composite was made up of: (1) nickel-refrasil quartz. (2) Copper-refrasil quartz and (3) Aluminum-aluminum opacified glass.

+ Thermal Etching -- Surface grooving at the grain boundaries where boundaries meet the metal foil surface; brought about through re-equilibration of grain boundary and surface free energies. Plastic deformation and surface vaporization are thought to be the mechanisms by which thermal etching occurs. High temperature and a vacuum environment are sufficient conditions for occurrence. Nature of the process suggests a finite time (possibly quite short) to re-stabilize at new equilibrium state.

□ Recrystallization -- Formation and growth of grain nuclei in high temperature environment. Process brings about new grain orientation, proceeding from original cold-worked state (typical condition of as-rolled foils). Grains formed from the nuclei combine and enlarge at the expense of others (grain growth).

Thermal etching and recrystallization are illustrated in Figure D-1-2.

FIGURE D-1-2

NICKEL FOIL SAMPLES

1800° COMPOSITE TEST SYSTEM

AS-RECEIVED NICKEL

NICKEL - HOT-SIDE LAYER (1800°F)
REFRASIL CONTACT

NICKEL - HOT-SIDE LAYER (1800°F)
REFRASIL CONTACT

ALL SAMPLES - 1000X

(c) No evidence of chemical interaction between the Refrasil quartz spacer and nickel foil. Electron probe studies did not indicate silicide, carbide or oxide formations.

(d) At 1800°F, Refrasil quartz underwent a change of form from amorphous to crystalline. The change was accompanied by severe embrittlement and loss of fibrous characteristics. The condition was not observed at lower temperatures.

As previously indicated, the thermal etching and recrystallization bring about an increase in foil surface emissivity and, ultimately, a deterioration in multi-foil system performance. The emissivity increase may be explained as follows:

(1) Thermal etching, in general, creates a more diffusely reflecting surface as illustrated by the highly irregular grain surfaces and grooved boundaries of Figure D-1-2. Optical characteristics are probably more closely described by hemispherical emissivity (ϵ_h) than by the normal emissivity (ϵ_n). The former is usually 20-30% higher than the latter.

(2) Increase in high emissivity boundary area per unit area of surface through thermal etching (widening and deepening of existing boundaries) and recrystallization (formation and growth of new grains). Both phenomena are illustrated in Figure D-1-2

During the photomicrograph work, a gross optical reflectivity comparison was made between "thermally etched" and as-received nickel foil. The reflectivity of the former was estimated to be a factor of 2 lower than the as-received material. Current effort is directed toward getting reflectivity comparisons for incident energy with wave length of 1-2 μ , which is more typical of the wave lengths associated with high-temperature thermal emission.

Recrystallization at 1800°F was evident with both the plain Refrasil quartz and nickel opacified quartz papers. The materials changed from the amorphous phase to the alpha-cristobalite phase. Although the latter has a somewhat higher parent thermal conductivity, the significant increase in spacer conduction is attributed to the destruction of the characteristic fibrous matrix; i.e. a severe increase in fiber-to-fiber contact area. In addition, the material becomes quite brittle with the phase change and may be unstable in a mechanical load environment.

D-2. 1800°F Compatibility Testing - Recommendations

Compatibility tests at 1800°F were carried out in an effort to more thoroughly define the problems and to investigate some alternate materials for potential 1800°F service. Nickel and molybdenum foils, in combination with Refrasil fibrous quartz paper and woven quartz (Astroquartz) cloth were considered.

Sample descriptions and photomicrographs of the nickel and molybdenum foils are given in Figures D-2-1, D-2-2 and D-2-3, D-2-4. Based on these 1800°F compatibility tests, the following conclusions were made:

(1) From a surface stability standpoint, molybdenum is preferred over nickel for 1800°F service. Thermal etching and recrystallization are much less severe with the molybdenum. Grooving at the grain boundaries is light.

(2) Based on its stability in the amorphous state and its apparent minimal effect on the foils at 1800°F, woven, high purity quartz (Astroquartz) is preferred over Refrasil quartz paper.

The superior stability of molybdenum foil at 1800°F is expected because of its high melting point and low vapor pressure in comparison to nickel. The molybdenum appears to be an excellent substitute for nickel from the performance standpoint in high temperature, vacuum multi-foil insulation applications; it also has potential for higher temperature environments (e.g. 2200-2500°F). It is available commercially in .0005" thickness and 12" width.

The compatibility samples indicate that the Refrasil quartz paper, in contact with the metals, promotes the roughness and dull appearance of the foil surface. This is particularly evident in the composite samples (Figure D-1-2), where the Refrasil was in excellent contact, under mild loading, with the nickel during 1800°F exposure.

This effect is not readily explained but may be due, in part to a physical embedding of the fine (1 μ diameter) Refrasil fibers in the foil grain boundaries. On the other hand, the 9 μ diameter Astroquartz fibers in a woven matrix do not permit the intimate contact attained with the Refrasil. A second possibility is that the silica, gradually decomposing at 1800°F, liberates some oxygen which reacts with the nickel. If this decomposition occurs at all*, it would be more pronounced in the fine fiber, Refrasil paper. Accurate definition of any physical interaction between the quartz spacer and metal foil would require considerable further study.

As a result of these tests and the analysis, the recommended maximum long-term service temperature of nickel-Refrasil quartz insulation was reduced from 1800°F to 1600°F. Molybdenum foil-Astroquartz cloth was recommended for the 1600 to 1800°F temperature range.

D-3 Redesigned Composite Test

This 1800°F composite insulation sample has an installed thickness of 0.5" and an average layer density (n) of 110 g/inch. The composite is comprised of molybdenum-Astroquartz operating in the 1800-1600°F temperature range, nickel-Refrasil quartz in the 1600-1400°F range, copper-Refrasil quartz at the 1400-900°F level, and aluminum-aluminum opacified glass at 900-400°F.

** Not substantiated in our analysis to date

FIGURE D-2-1 NICKEL COMPATIBILITY SAMPLES

1. Nickel Properties

Melting Point	2650°F
Vapor Pressure	1×10^{-6} mm Hg @ 1800°F
Emissivity	$\epsilon = .18$ @ 1800°F
2. Sample Description

N-1	Ni (.0006") -- no spacer (control)
N-2	Ni (.0006") -- woven Astroquartz (.005")
N-3	Ni (.0006") -- Refrasil quartz (.005")
3. Test Conditions - - - - Wrapped samples with foil and spacer in light contact; 1 week continuous exposure to 1800°F in vacuum ($P \leq 1 \mu$ Hg).
4. Results - - - - - Micrographs indicate moderate etching on samples N-1 and N-2. Strogm etching and recrystallization sites are indicated on N-3. Visually, N-1 and N-2 had not appeared to loos reflectivity. Sample N-3, on the other hand, was noticeably dulled.
5. Observations - - - - -
 - (a) Refrasil quartz appears to pronote Ni foil surface changes; Astroquartz's role does not appear to be significant.
 - (b) Possible reasons for this are:
 - (1) impurities in Refrasil, (2) greater contact between Refrasil mat and foil, (3) form change in Refrasil, (4) slow decomposition of SiO_2 liberating O_2 .
 - (c) Astroquartz remained in the amorphous state; Refrasil changed from amorphous to crystalline.

FIGURE D-2-2 NICKEL 1800°F COMPATIBILITY SAMPLES

AS-RECEIVED NICKEL

N-1 NICKEL CONTROL (NO SPACER)

N-2 NICKEL - ASTROQUARTZ

N-3 NICKEL - REFRASIL

ALL SAMPLES - 1000X

FIGURE D-2-3 MOLYBDENUM COMPATIBILITY SAMPLES

1. Molybdenum Properties

Melting Point	4750°F
Vapor Pressure	$< 1 \times 10^{-10}$ mm Hg @ 1800°F
Emissivity	$\epsilon = .15$ @ 1800°F
2. Sample Description

M-1	Mo (.0003") -- no spacer (control)
M-2	Mo (.0003") -- woven Astroquartz (.005")
M-3	Mo (.0003") -- Refrasil quartz (.005")
3. Test Conditions - - - - rectangular, alternate-layer samples with foil and spacer in light contact; 1 week continuous exposure to 1800°F in vacuum ($P \leq 1\mu$ Hg).
4. Results:- - - - - Very light thermal etching on samples M-1 and M-2; large grains and shallow boundary grooves. Sample M-3 showed a somewhat higher degree of thermal etching; light boundaries and much smaller grain size than in M-1 and M-2. Visually, all three samples appeared to have retained high reflectivity.
5. Observations- - - - -
 - (a) Surface change of the molybdenum foil was minimal, and appeared to cause less emissivity deterioration than in the Ni foil case.
 - (b) Again, the Refrasil quartz promoted surface changes but the Astroquartz exerted no apparent influence.

FIGURE D-2-4

MOLYBDENUM 1800°F COMPATIBILITY SAMPLES

AS-RECEIVED MOLYBDENUM

M-1 MOLYBDENUM CONTROL (NO SPACER)

M-2 MOLYBDENUM - ASTROQUARTZ

M-3 MOLYBDENUM - REFRASIL

ALL SAMPLES - 1000X

APPENDIX E

THERMAL PERFORMANCE DETERIORATION - 1800°F COMPOSITE INSULATION SYSTEM

R. Zawierucha

E-1 Introduction

This study constitutes an initial attempt to evaluate the 1800°F composite multi-foil insulation system for potential sources of material degradation which may be contributing to the observed thermal performance deterioration. It is based on data and literature currently available.

The areas of high temperature and refractory alloy metallurgy are complicated and problems encountered may be extremely difficult. In this case, the necessity of maintaining a low emissivity surface for insulation purposes is a complicating factor. In most applications that have been discussed in the literature, structural integrity is more important than surface finish.

E-2 Possible Mechanisms

At elevated temperatures and in a vacuum environment the following mechanisms are potential sources of surface degradation:

1. Surface volatilization
2. Reduction of compounds by metals followed by formation of a thermodynamically stable compound
3. Formation of low melting eutectic compounds
4. Substitutional diffusion
5. Interstitial reactions which include massive interstitial diffusion and formation of interstitial compounds
6. Microstructural changes such as recrystallization, grain growth and segregation of impurities/contaminants in grain boundaries

E-3 Consideration of Individual Mechanisms

1. Surface Volatilization (2)

Inasmuch as the components were individually chosen on the basis of low vapor pressures at the desired service temperature, this factor should not be a problem in the 1800°F composite. Within the test setup the pressure is 10^{-3} to 10^{-4} torr. This is not a very high vacuum and it may be argued that substantially higher vacuums should be used to evaluate material volatility, particularly volatility of the woven and fibrous quartz spacer materials where essentially no vapor pressure data now exist.

If surface volatilization were a factor, the effect would be continuous unless some retardation were introduced through pressure build-up within the multi-layer insulation. A more accurate assessment of the volatility problem would require higher vacuum equipment (10^{-6} to 10^{-9} torr level) to more closely simulate a space environment.

2. Reduction of a Thermodynamically Unstable Compound

In this postulated mechanism, various SiO_2 separators would be reduced by Mo, Ni, Cu and Al to form their corresponding oxides. Free energy data from Referenced 4 - 7 indicate that SiO_2 has more thermodynamic stability than any of the possible oxides except Al_2O_3 . At the lower temperatures where aluminum would be used, kinetic factors would be more important than thermodynamic stability.

The most critical relationship would be between molybdenum and the Astroquartz separator. According to data abstracted from Reference 6, even at 2000°K , SiO_2 is more stable than the corresponding oxides of molybdenum. These data are presented in Table E-I. In fact, the stability of SiO_2 with respect to molybdenum and its silicides is one reason why silicide coatings have been successful in preventing elevated temperature oxidation of molybdenum. ⁽⁶⁾ Until further data are available to suggest that SiO_2 is unstable in the presence of molybdenum, it will be assumed that stability problems do not exist with respect to "pure" SiO_2 . Of course, impurities in SiO_2 separators (three basic varieties exist within an insulation) could create problems. Yet, if reduction of a thermodynamically unstable compound were a factor it seems likely that difficulties would be more readily apparent.

The degree of contact between spacer and foil may also be an influencing factor. It is, therefore, on the basis of the uncertainties rather than documented thermodynamic stability on known application that various SiO_2 based separators should be subjected to continued testing in the presence of molybdenum.

3. Eutectic Melting (7, 8, 9)

If it is assumed that SiO_2 can be broken down by some unknown mechanism, low melting (eutectic) phases can be formed in contact with Mo, Ni, Cu and Al at approximately 2570°F , 1724°F and 1071°F , respectively. All of these temperatures are above the service temperatures for the metals involved in the insulation system. This type of reaction would be exceptionally rapid and continue until reacting materials were consumed. It would appear that this mechanism is unlikely.

Conceivably, surface oxides on metals might interact with oxide insulators. CuO and SiO_2 will form a low melting interface at 1940°F . This temperature is above the contemplated service temperature of Cu in the system.

4. Substitutional Diffusion (10)

A serious reaction which could degrade the surface of the molybdenum would be diffusion of silicon into molybdenum - an example of substitutional diffusion. This reaction could reduce molybdenum to a series of silicides and would only take a few hours at 1800 - 2200°F . It would be quickly noted because of its effect on emissivity. There is no reason to suspect that this effect is a problem with respect to Mo and Si. This mechanism has

not been detected in previous tests. If this mechanism were operative it would imply that the SiO_2 separators were broken down₂

5. Interstitial Reactions (10, 11, 12, 13, 14)

Reactions between refractory metals and interstitial elements (C, O, H, N) are the limiting factor preventing greater utilization of refractory alloys.

Oxygen is the most critical interstitial element where molybdenum is concerned. Above 795°C (1463°F) ⁽¹⁰⁾ molybdenum forms a volatile oxide (MoO_3) which allows O_2 to continuously contact and react with the surface. At 800°C ⁽¹⁰⁾ (1472°F), the linear oxidation of molybdenum is proportional to $(\text{PO}_2)^{3/2}$. Figure E-1 ⁽¹⁰⁾ demonstrates the effect of oxygen flow in the oxidation of molybdenum while Figure E-2 ⁽¹¹⁾ compares molybdenum against other refractory metals. In a vacuum of 10^{-3} torr a volatile oxide of molybdenum could be formed although at a much slower rate as compared to air.

A reaction between molybdenum and oxygen would be proportional to the number of collisions between oxygen molecules and the molybdenum surface. The mathematical expression ⁽¹²⁾ for the number of gas molecules striking a surface per unit time as a function pressure is:

$$V = 3.5 \times 10^{22} \left[\frac{P}{(MT)^{1/2}} \right]$$

where $V = \text{collisions cm}^{-2} \text{ sec}^{-1}$
 $P = \text{Torr}$
 $M = \text{Molecular weight}$
 $T = ^\circ\text{K}$

Providing that assumptions were made as to initial gas composition and a proportionality constant (sticking factor 1.0), order of magnitude answers as to metal loss due to generation of volatile molybdenum oxides could be obtained. Analysis of gaseous species in a test chamber could verify that MoO_3 oxidation is occurring.

Metal loss due to rapid oxidation is not the only interstitial effect on refractory metals. Figure E-3 ⁽¹³⁾ and Table E-II ⁽¹³⁾ indicate that refractory metals can absorb appreciable amounts of interstitial elements at temperature; particularly in the case of columbium and tantalum. Massive amounts of interstitials in columbium and tantalum can markedly decrease ductility and reduce the load carrying ability of the metal. In Table E-III ⁽¹³⁾ it can be seen that molybdenum does not maintain high interstitial contents in solution after moderate cooling rates. Instead, interstitials are likely to be segregated in grain boundaries, which account for somewhat better ductility in wrought molybdenum material. Effects ⁽¹³⁾ of various interstitial levels and thermal treatments are shown in Figure E-4 and Table E-III. Numbers in Figure E-4 refer to column numbers listed in Table E-III. Unfortunately, environmental factors in heat treatment are not specified in Table E-III. Embrittlement might be a factor in a thermal insulation subjected to cycling, shut down and startups.

H. Inouye⁽¹⁴⁾ of Oak Ridge studied the reactivities of refractory materials in high vacuum (2.7×10^{-7} torr). His results are shown in Figure E-5. Pure molybdenum was purified by the vacuum heat treatment as compared to other refractory alloys. Residual gases in his system included H_2 , CO, N_2 , CO_2 and unidentified hydrocarbons. It appears that in a reasonably good vacuum molybdenum would resist interstitial absorption and embrittlement. Oxidation, since it generates volatile products such as MoO_3 , might be difficult to detect in a molybdenum alloy.

Oxidation of molybdenum in a test chamber maintained at a low vacuum is a likely possibility for performance degradation. This effect would be long-term within the test chamber. Contaminants such as H_2O , CO, H_2 , and CO_2 are probable contaminants in the Linde test set up. In reference u, it was noted that volatilization may "for many oxides be greatly enhanced in the presence of water vapor through the formation of gaseous hydroxides or hydrated oxides". Dissociation⁽⁵⁾ of H_2O at elevated temperatures to form H_2 and O_2 is another effect which cannot be neglected. An attempt should be made to detect the presence of volatile oxides of molybdenum.

6. Microstructural Changes

Recrystallization and grain growth are two primary microstructural changes that can occur in the insulation system. The recrystallization temperature of course varies with the amount of cold work the material has received. In a severely worked condition pure molybdenum recrystallizes in the temperature range of $2000^\circ F$ ⁽¹⁵⁾. If received in the strain hardened condition, nickel and copper foil would also recrystallize. After recrystallization, grain growth will continue to occur until an equilibrium grain size is reached. Recrystallization and grain growth will most likely change surface emissivity although data to substantiate this could not be found. To minimize emissivity changes it might be possible to stabilize grain size by thermal treatments above contemplated service temperatures.

In the case of molybdenum, recrystallization will tend to cause segregation of interstitial impurities in grain boundaries if interstitial concentrations are above solubility limits. This effect can embrittle, however, unless the insulation unit is cycled back to ambient temperature, this should not be a factor. Volatilization of interstitial compounds in grain boundaries could cause grooving and etching of grain boundaries such that the emissivity might be affected. Although grain growth would be self limiting, slow grooving of grain boundary areas could occur for some time. It was noted previously that pure molybdenum was purified by a vacuum anneal at 10^{-7} torr and this effect would tend to "clean" grain boundaries and eliminate reactivity in these areas.

E-4 Discussion and Test Outline

It would appear that the greatest cause for concern as far as performance deterioration of the insulation is concerned is the general level of interstitial contaminants in the system. Sources of the contaminants are as follows:

1. Vacuum Test Cell -- For stability testing in a simulated space environment, the current operating pressure level of 10^{-3} torr is not adequate. It would be impossible to evaluate materials such as columbium and tantalum in this system. This system also prevents any evaluation of material volatility in a hard vacuum.

2. Outgassing from the Astroquartz, Refrasil, and glass paper separators.

3. Outgassing from the nickel and copper foils, particularly if they are electroplated.

4. Contaminants left on foil and separator surfaces during assembly.

To minimize outgassing and contamination, the following procedures are suggested:

1. A vacuum bakeout of foils and separators at vacuum levels of 10^{-6} - 10^{-7} torr at temperatures above the service temperature to drive off residual gasses, followed by storage in a humidity controlled area after the thermal treatment.

2. Careful attention to assembly of insulation systems. Use white glove technique. Solvent clean and degrease. Assemble insulation in a laminar flow room.

3. Use improved furnace procedures. If furnace elements have not been used for some time bake the elements with a vacuum anneal prior to making a run. Keep the test chamber clean and free of hydrocarbons. When starting a run, flush out all air with the best available grade of pure helium and pump down. Repressurize with helium and pump down again. Repeat previous step several times prior to turning on the heating elements. Helium flushing and depressurizing is a time-proven and effective method of eliminating furnace contaminants.

4. Obtain a better vacuum system for elevated temperature tests. To further verify the compatibility of molybdenum foil and the effect of heat treatment atmospheres, a short test program is suggested. The specimen configuration is shown in Figure E6 and it is designed to differentiate between the effects of intimate contact between molybdenum and the Astroquartz foil and the heat treatment atmospheres. Since 0.5 mil molybdenum foil is not suited to metallographic studies, molybdenum sheet stock 0.100" thick was selected. With this thickness it should be possible to identify diffusion or microstructural effects due to diffusion from the interfaces between the molybdenum, Astroquartz separators and atmosphere. Test temperatures of 800°F, 1800°F, and 2500°F would be used. Tests would allow differentiation between the effects of a poor 10^{-3} torr versus a 10^{-6} torr vacuum. Initially, the molybdenum foil would be tested in the stress-relieved condition only. If desired, later tests could evaluate recrystallized molybdenum, tantalum foil, and zirconia spacer material. An attempt would be made to determine the presence of volatile oxidation products. The test outline is listed in Table EIV.

E-5 Conclusions

1. Interstitial reaction effects are believed to be the primary cause of system performance deterioration in the 1800°F composite insulation system.

2. A number of suggestions for reducing contamination in various stages of manufacture and testing have been made.

3. An improved vacuum system is required carrying out meaningful material stability tests at elevated temperature.

4. In a high vacuum it is highly probable that pure molybdenum sheet will be purified by vacuum exposure.

5. Recommended tests should readily determine the effects of intimate contact between astroquartz and molybdenum as well as thermal treatment atmosphere.

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TABLE E-IFREE ENERGY DATA FOR VARIOUS OXIDES (6)

<u>Oxide</u>	<u>$-\Delta F(2000^\circ\text{K}, \text{K Cal per gm atm. O}_2)$</u>
SiO ₂	62
MoO ₃	28
MoO ₂	26

TABLE E-II INTERSTITIAL CONTENTS LIKELY(a) TO BE MAINTAINED IN
SOLID SOLUTION IN GROUP V-A AND VI-A METALS AFTER
MODERATE COOLING RATES (Contents measured in ppm)

	Hydrogen	Carbon	Nitrogen	Oxygen
Vanadium	10,000	~1,000	5,000	3,000
Columbium	9,000	100	300	1,000
Tantalum	4,000	70	1,000	200
Chromium	0.1-1	0.1-1	0.1	0.1
Molybdenum	0.1	0.1-1	1	1
Tungsten	N.d.(b)	<<0.1	<<0.1	1

(a) Based on estimates of the equilibrium solubility at the temperature where $D = 10^{-11}$ cm² per sec.(25,26)

(b) Not detectable.

TABLE E-III

Composition and Properties of Chromium, Molybdenum and Tungsten after varying Treatments

Curve No. (a)	Reference	Material	Composition, ppm				Heat Treatment	Grain Size, No./mm ²	Strain Rate/Sec	Transition Temp, (b), C
			H	C	N	O				
Chromium										
16	Gilbert, et al. (41)	Iodide chromium	<1	35	12	48	Recrystallized, 1000-1200 C, 1 hr	~200	2 x 10 ⁻⁴	80
	Gilbert, et al. (41)	Iodide chromium	<1	35	12	48	Recrystallized, 1200-1400 C, 1 hr	<10	2 x 10 ⁻⁴	20
17	Weaver (42)	Electrolytic arc melted	--	3	5	140	Recrystallized, 1200 C, 1 hr	375	1 x 10 ⁻⁴	150
18	Allen, et al. (43)	Iodide chromium	<1	44	10	24	Recrystallized, 1100 C, 1 hr	1000	2 x 10 ⁻⁴	300
19	Weaver (42)	Electrolytic arc melted	--	3	12	120	Recrystallized, 1200 C, 1 hr	375	1 x 10 ⁻⁴	350
20	Johansen et al. (44)	Electrolytic arc melted	50	--	20	30	Recrystallized, 1200 C, 30 min	100	3 x 10 ⁻⁴	370
Molybdenum										
21	Lawley, et al. (45)	Electron-beam zone melted	<1	12	<1	<1	Recrystallized	10	3 x 10 ⁻⁴	<-269
22	Spacil and Wulff (46)	Electron-beam zone melted	--	<5	<5	<5	Recrystallized, 1250 C, 30 min	20	8 x 10 ⁻⁴	-80
23	Lement, et al. (47)	Electron beam melted	--	12	3	5	Recrystallized	4000	3 x 10 ⁻⁴	-50

TABLE E-III (CONTINUED)

Curve No. (a)	Reference	Material	Composition, ppm				Heat Treatment	Grain Size, No./mm ²	Strain Rate/Sec	Transition Temp. (b), C
			H	C	N	O				
24	Bechtold and Scott ⁽⁴⁸⁾	Powder metallurgy	--	40	41	60	Recrystallized, 1150 C, 30 min	1650	3×10^{-4}	-40
25	Bechtold ⁽⁴⁹⁾	Arc melted	--	140	56	17	Recrystallized, 1150 C, 1 hr	900	3×10^{-4}	-25
26	Bechtold and Scott ⁽⁴⁸⁾	Arc melted	--	310	56	2	Recrystallized, 1150 C, 30 min	1200	3×10^{-4}	0
27	Pugh ⁽⁵⁰⁾	Arc melted	3	500	10	30	Recrystallized, 1400 C, 4 hr	500	3×10^{-3}	~ 0
28	Bechtold ⁽⁴⁹⁾	Arc melted	--	140	56	17	Recrystallized, 1150 C, 1 hr	900	2×10^{-1}	40
29	Sykes ⁽⁵¹⁾	Powder metallurgy 99.9 per cent purity	--	--	--	--	Recrystallized	10	--	250
<u>Tungsten</u>										
30	Atkinson ⁽⁵²⁾	Powder metallurgy	1	50	24	3	Recrystallized, 1500 C, 30 min	190	--	210
31	Bechtold ⁽⁵³⁾	Powder metallurgy	--	--	--	--	Recrystallized, 2000 C, 1 hr	1500	3×10^{-4}	250
32	Bechtold and Shewmon ⁽⁵⁴⁾	Powder metallurgy	--	200	80	--	Recrystallized, 1950 C, 1 hr	1500	3×10^{-4}	295
33	Pugh ⁽⁵⁵⁾	Powder metallurgy	--	100	30	130	Recrystallized, 1600 C, 1 hr	500	3×10^{-4}	320 ^(e)
34	E. L. Harmon ⁽⁵⁶⁾	Powder metallurgy	2	10	10	30	Recrystallized	--	1×10^{-4}	360

TABLE E-IV

TEST PLAN FOR MO/ASTROQUARTZ EXPOSURE

1. Obtain materials for specimen.
 - A. Obtain high purity molybdenum sheet (0.125" thick) in stress relieved condition.
 - B. Obtain highest quality astroquartz.
2. Process materials in identical manner as for actual insulator.
3. Metallurgical documentation of as-received and processed molybdenum sheet.
 - A. Metallographic exam
 - B. Hardness and microhardness
 - C. Bend ductility
 - D. Surface condition (at 1000X)
 - E. Chemical analysis
4. Assemble test specimens and conduct tests as follows:
 - A. 800°F for 2-8 hours
 - B. 1800°F for 2-8 hours
 - C. 2500°F for 2-8 hours
5. Repeat step 4 except test at BAC
6. Repeat step #3 for tested materials
7. Assemble data, conclusions and report.

OPTIONAL

Repeat steps 1-7, substitute recrystallized molybdenum, columbium or zirconia as required.

FIGURE E-1

SUMMARY OF PUBLISHED RESULTS ON OXIDATION OF
MOLYBDENUM UNDER ATMOSPHERIC CONDITIONS.
SURFACE RECESSION RATES AS A FUNCTION OF $1/T$.

FIGURE E-2 OXIDATION OF REFRACTORY METALS

(Data for Mo, Re, Os, Ru, Ir, and Rh are weight-loss rates)

FIGURE E-3

SOLUBILITIES OF INTERSTITIALS IN
GROUP VA AND VI-A METALS

FIGURE E-4 DUCTILE-BRITTLE TRANSITION CHARACTERISTICS OF UNALLOYED GROUP VI-A METALS TESTED IN TENSION. COMPOSITIONS, TEST CONDITIONS, AND REFERENCES ARE SUMMARIZED IN TABLE 2

FIGURE E-5 Comparative Reactivities of Refractory Metals in High Vacua.

FIGURE E-6 INSULATOR TEST SPECIMEN

Surfaces A and B are in contact with Astroquartz and vacuum, respectively. Metallographic examination and comparison of these specimens tested in vacuum at 10^{-3} mm Hg and 10^{-6} mm Hg should determine the relative effects of the Astroquartz and vacuum environment on the molybdenum surface.

APPENDIX F-1

PENETRATION COMPUTER PROGRAM

APPENDIX F-2

DEVELOPMENT OF EFFECTIVE VIEW FACTORS
FOR RADIANT ENERGY INTERCHANGE BETWEEN
TWO SURFACES SEPARATED BY A
BACKSCATTERING MEDIUM

D.H. SUCKOW

F-1-1 Abstract

The computer program described herein, written in G-Level FORTRAN IV, computes temperatures and heat fluxes within an insulation panel in the vicinity of a cylindrical penetration. The penetration, whose ends may be flush with, or penetrating through, one or both of the insulation surfaces is separated from the panel by an annular gap that is either empty or filled with a conductive and/or translucent substance. The program is similar to the exposed edge program given in Appendix H.

The thermal analysis was based upon the geometry shown in Figure F-1-1 and upon the following assumptions:

1. If the penetration extends beyond either surface of the insulation panel, its thermal coupling with the panel and gap surface is conductive only, whereas its coupling with the wall is both conductive and radiative (view factor = 1).
2. The insulation and gap surfaces are both either prescribed at uniform temperatures or radiantly coupled with the walls facing the respective surfaces (view factor = 1), which are themselves prescribed at uniform temperatures.
3. The penetration is conductively isotropic but the insulation and gap filler are not.
4. If translucent, the gap filler is radiatively isotropic.
5. Radiant interchange among the surfaces bounding the gap can be either attenuated through backscattering or unattenuated. If the gap filler is translucent, all radiation into the gap is either transmitted directly or scattered at a 180 degree angle with the line of incidence.
6. Radial heat flow vanishes at a given radial position $r = R_3$ within the insulation. Assumption that this "adiabatic circle" exists thus enables the user to approximate the situation in which several penetrations are arranged in an infinite, regular (eg. square, hexagonal) pattern within the panel.
7. Both cylindrical surfaces (penetration and insulation) bounding the gap are black (emissivity = 1). However, the gap ends may have emissivities less than unity.
8. Both the walls and the panel surfaces may have emissivities less than unity.

All emissivities and thermal conductivities can vary with temperature. Three basic temperature variations are assumed:

- (a) Three straight lines joined end-to-end
- (b) Two parabolas joined end-to-end
- (c) A cubic polynomial

The thermal conductivities of the penetration and, in the radial direction, of the insulation and gap filler, can assume variations (a) or (b). Thermal conductivities of the insulation and gap filler in the axial direction can assume all three variations. (Ordinarily, variation (c) is assumed. However, if all four cubic coefficients are set equal to zero, the program assumes the insulation or gap filler to be conductively isotropic, with the thermal

Figure F-1-1

Schematic Drawing of System Geometry

conductivity assuming the input variation in the radial direction.) Emissivities of the wall and insulation surfaces can assume variation (a).

Input to the program consists of punched data cards. These cards fall under three categories:

1. Header cards-Total of seven. These cards contain the temperature coefficients for the system emissivities and thermal conductivities, plus the radiation-backscatter cross section (fraction of incident radiation backscattered per unit length of traverse) for the gap filler.
2. Problem Cards-One or more per set of header cards. These cards contain data that define the linear dimensions, mesh spacings, and boundary conditions of the system. Each problem card defines a case to be run.
3. Blank spacer cards

During execution, the program:

- (a) Reads in the first header card. If it is blank, execution is terminated. Otherwise, the six remaining header cards are read in.
- (b) Reads in first problem card.
- (c) Checks problem card data for errors. If an error is found the current problem is terminated and the next problem card is read in. If the problem card is blank, control is transferred back to step (a).
- (d) Integration mesh parameters (spacings and cross section areas), radiation configuration factors, and starting temperature profiles and heat fluxes are computed.
- (e) Corresponding to each integration mesh point, a linear equation is set up that expresses the temperature at that mesh point as a weighted sum of temperatures at the "nearest-neighbor" mesh points plus an optional "constant" term. The weighting factors and constant terms are derived through finite difference approximations to the Fourier heat conduction equation and the appropriate boundary conditions. Thermal conductivities in the region between two adjacent mesh points are evaluated at the arithmetic mean of the temperatures at the two points.
- (f) The resulting set of equations is then solved for the unknown temperatures, which are printed out.
- (g) The linear coefficients used in the equation solution are then recomputed using the arithmetic mean of the two most recent temperature profiles (to accelerate convergence) and used to compute system heat fluxes, which are then printed out.
- (h) If the sum of the fractional changes in the calculated heat fluxes between the two previous iteration cycles is greater than a specified tolerance (0.01), and if the number of iteration cycles does not yet equal 10, steps (e), (f), and (g) are repeated.

Otherwise, flux ratios (ratios of heat fluxes with included effect of the penetration and gap to the corresponding fluxes in an undisturbed insulation panel) are computed and control passes back to step (b).

Printed output for a typical problem is given at the end of the appendix.

F-1-2 Calculations

The major calculations performed during program execution divide into three categories:

1. Evaluation of configuration factors for radiative exchange within the gap.
2. Evaluation of the weighting factors used in the linear difference equations defined at each mesh point.
3. Solution of the difference equations for the temperatures at all mesh points.

A radiative configuration factor can be defined in either one of two ways:

- (a) The fraction of radiation leaving an area that falls upon a second area (view factor).
- (b) The fraction (a), multiplied by the first area (effective exchange area or area factor).

The method used for computing configuration factors between two surfaces separated by empty space is well documented^{1,2}. The technique used when a backscattering medium separates the surfaces is documented in a recent report⁷. The basic equations, along with a schematic drawing of the two radiation-coupled surfaces, are given in Figure F-1-2.

Since closed-form expressions for the configuration factors could not be derived, they were integrated numerically, either once (8 or 32 point Gauss quadrature) or twice.

Figure F-1-3 shows the differential equations and boundary conditions governing the temperature distribution within the system.

When the appropriate differential equations and boundary conditions are discretized at each mesh point, there results a quasi-linear finite difference equation of the form

$$R' (T_{i,j} - T_{j+1,j}) + R'' (T_{i,j} - T_{i-1,j}) + Z' (T_{i,j} - T_{i,j+1}) + Z'' (T_{i,j} - T_{i,j-1}) = C$$

where the weighting factors R' , R'' , Z' , Z'' , and C are themselves temperature dependent because of the variation with temperature of the thermal conductivities and/or emissivities used to compute them. The subscripts i and j refer, respectively, to the radial and axial positions of the central mesh point and its nearest neighbors.

Figure F-1-2

Definition of Radiation Configuration Factors Configuration Factors

(β = Backscatter Cross Section)
 (ρ_i = Reflectivity of Surface A_i)

For a) $i = 1, j = 2$
 b) $i = 2, j = 1$

F_{ij} = Fraction of Radiation Leaving A_i That Falls on A_j (view factor)

A_{ij} = Area factor = $A_i F_{ij}$

$$= \frac{(A')_{ij}}{A_i - \rho_i ((A')_{ij} - (A'_0)_{ij})}$$

$$\text{where } (A')_{ij} = \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j dA_i dA_j}{\pi R^2 (1 + \beta R)}$$

$$(A'_0)_{ij} = (A')_{ij} \Big|_{\beta=0} = \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j dA_i dA_j}{\pi R^2}$$

If the heat transfer mechanisms about point (i,j) are strictly conductive, or radiative to an infinite, uniform-temperature wall (i.e. all mesh points not bounding a translucent gap), the temperature at this point will depend directly only upon nearest-neighbor temperatures, and thus the factor C will be zero. However, if the point bounds the annular gap between the panel and penetration, and if that gap is translucent to radiation, then the temperature at that point will depend directly upon temperatures at other axial levels besides (j-1), j, and (j+1). The finite difference equations for these gap-boundary points can be made consistent with the above form, however, by including heat transfer terms corresponding to non-nearest-neighbor axial positions in the right-hand-side factor C.

In most cases, the derivation of the weighting factors from the finite difference equations is quite straightforward. However, the equations governing the radiative interchange among the surfaces of a translucent gap (e.g. fluxes (Q_i) RAD and (Q_p) RAD in Figure F-1-3) are complicated functions of the gap geometry (as expressed through the geometric configuration factors), backscatter cross section, and temperature profile along the gap boundaries. These equations were derived using the techniques outlined in Chapter 3 of Hottel and Sarofim².

Let N_r equal the number of radial mesh positions from $r=R1$ to $r=R3$. Also, assume that the number of axial positions along the penetration, external to the panel and gap on either side, equals N_z . Then the total number of mesh points (and unknown temperatures) is equal to N, where

$$N = (N_r) (N_z)$$

A is an Nth order coefficient matrix, T is an N-element vector of unknown temperatures, and B is an N-element "constant" vector (containing the C factors as given in the general form of the finite difference equation). Since in many instances a fine mesh must be chosen in order to compute an accurate temperature profile, N can become very large. Solution of the difference equations by direct inversion of matrix A can thus be very time consuming (since computation effort required to invert A is approximately proportional to the cube of N) and exceedingly wasteful of computer core storage (since most of the elements of A are zeroes). However, the "nearest-neighbor" structure of the finite difference equations makes possible a much more efficient solution technique.

If the equations are written so that all N_r equations corresponding to a particular axial level are grouped together, with these groups of equations in order of ascending (or descending) axial position, the coefficient matrix A will subdivide into $(N_z)^2$ submatrices, each one of which is a square matrix of order N_r . (hereafter, N_z will be called the block order of A). However, because of the "nearest-neighbor" effect, only those submatrices lying along, and immediately to the left and right of, the main diagonal of A will contain non-zero elements. Matrix A is therefore block-tridiagonal. The finite difference equations can thus be solved using a matrix analogue of the familiar Gauss Elimination technique for solution of tridiagonal systems of linear equations. The task of inverting one N-th order matrix is then reduced to the inversion of N_z matrices of order N_r , with a subsequent reduction in the number of calculations by a factor of, approximately,

$$\frac{(N)^3}{(N_z) (N_r)^3} = (N_z)^2$$

This solution technique has been used successfully in earlier studies by several investigators, including L.D. Potts³ and D.H. Suckow^{5,6}.

Because of the temperature dependence of the weighting factors included in the equations, the solution must be repeated iteratively until the temperatures converge to final values. Although an iteration cutoff of 10 cycles is included in the program, convergence generally requires only three or four cycles.

Bibliography

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Figure F-1-3

Differential Equations and Boundary ConditionsFourier Equation:

Insulation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r k_{ir} \frac{\partial T_i}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_{iz} \frac{\partial T_i}{\partial z} \right) = 0$$

Gap (INDEX > 1):

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r k_{gr} \frac{\partial T_g}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_{gz} \frac{\partial T_g}{\partial z} \right) = 0$$

Penetration:

$$\frac{\partial}{\partial z} \left(k_p \frac{\partial T_p}{\partial z} \right) + \frac{2 Q_p}{R_1} = 0$$

Boundary ConditionsAxial (z) Direction:(1) EITHER

$$T_i(r, H) = T_H \quad (\text{INDEX} = 1, 2)$$

$$T_i(r, 0) = T_C$$

$$\text{OR} \quad k_{iz} \frac{\partial T_i}{\partial z} \Big|_{z=H} = \sigma \epsilon_H \epsilon'_H (T_H^4 - T_i(r, H)^4)$$

$$k_{iz} \frac{\partial T_i}{\partial z} \Big|_{z=0} = \sigma \epsilon_c \epsilon'_c (T_i(r, 0)^4 - T_C^4) \quad (\text{INDEX} = 0, 3)$$

(2) SAME AS (1) FOR T_g, k_{gz}
($\epsilon_H = \epsilon_c = 1$)(3) EITHER

$$T_p(H + PLH) = T_H \quad (PLH > 0 \text{ OR } \text{INDEX} = 1, 2)$$

$$\text{OR} \quad k_p \frac{\partial T_p}{\partial z} \Big|_{z=H} = \sigma \epsilon'_H (T_H^4 - T_p(H)^4)$$

(4) EITHER

$$T_p(-PLC) = T_C \quad (PLC > 0 \text{ OR } \text{INDEX} = 1, 2)$$

$$\text{OR} \quad k_p \frac{\partial T_p}{\partial z} \Big|_{z=0} = \sigma \epsilon'_c (T_p(0)^4 - T_C^4)$$

LEGEND:SUBSCRIPTS:

P - PENETRATION
g - GAP
i - INSULATION
H - WARM SIDE
C - COLD SIDE

r - RADIAL DIRECTION
z - AXIAL DIRECTION
RAD - REFERS TO
RADIATIVE FLUX
INSIDE GAP

Radial (r) Direction:

$$(1) \frac{\partial T_i}{\partial r} \Big|_{r=R_3} = 0$$

$$(2) k_{ir} \frac{\partial T_i}{\partial r} \Big|_{r=R_2} = Q_p, \text{ INDEX} = 1$$

$$= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=R_2}, \text{ INDEX} = 2$$

$$= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=R_2}$$

$$+ (Q_i)_{\text{RAD}}, \text{ INDEX} = 3$$

$$(3) Q_p = \sigma \epsilon'_H (T_H^4 - T_p(z)^4) \quad H < z \leq H + PLH$$

$$\left. \begin{aligned} Q_p &= k_{ir} \frac{\partial T_i}{\partial r} \Big|_{r=R_1}, \text{ INDEX} = 1 \\ &= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=R_1}, \text{ INDEX} = 2 \\ &= k_{gr} \frac{\partial T_g}{\partial r} \Big|_{r=R_1} \\ &\quad + (Q_i)_{\text{RAD}}, \text{ INDEX} = 3 \end{aligned} \right\} H < z \leq H + PLH$$

$$Q_p = \sigma \epsilon'_c (T_C^4 - T_p(z)^4) \quad 0 > z \geq -PLC$$

PARAMETERS:

$T_p(z)$
 $T_g(r, z)$
 $T_i(r, z)$ } - TEMPERATURES
Q - FLUX

σ - STEFAN-BOLTZMANN CONSTANT
 ϵ, ϵ' - EMISSIVITY OF FOIL & "H"

F-1-4 Output For A Typical Problem

NEW THERMAL CONDUCTIVITY DATA:

PENETRATION:	2000.0000	0.0	5000.00	0.0	0.0	0.0	0.0	0.0
SLAB(AXIAL):	0.0	0.500000	0.0	0.0	1.000000	0.0	0.0	0.0
SLAB(RADIAL):	13.0000	49.0000	1200.00	0.0	0.0	0.0	25.0000	0.0
GAP(AXIAL):	13.000000	0.0	0.0	3.000000	0.0	0.0	0.0	0.0
GAP(RADIAL):	46.0000	0.0	1000.00	-54.0000	100.0000	5000.00	0.0	0.0

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TEMPERATURE COEFFICIENTS OF FOIL EMISSIVITY:

0.2000000	0.0	5000.000	0.0	0.0	0.0	0.0	0.0
-----------	-----	----------	-----	-----	-----	-----	-----

TEMPERATURE COEFFICIENTS OF WALL EMISSIVITY:

0.5000000	0.0	5000.000	0.0	0.0	0.0	0.0	0.0
-----------	-----	----------	-----	-----	-----	-----	-----

BACKSCATTER CROSS SECTION (IN-1) : 0.0

```

PROBLEM NUMBER:      1
SLAB THICKNESS (IN):  4.000
PENETRATION L.R. (IN): 0.0
PENETRATION O.R. (IN): 0.2000
SLAB L.W. (IN):      7.5000
SLAB O.R. (IN):      3.0000
ENVIRONMENT TEMPERATURES (R): 1500.00 , 500.00
HOT SIDE PENETRATION (IN): 5.0000
COLD SIDE PENETRATION (IN): 2.0000
RADIAL INSULATION MESHES: 6
RADIAL GAP MESHES:      2
AXIAL MESHES:           6
INDEX:                  2
END:                     2

```

INITIAL TEMPERATURE PROFILE (INSULATION UNDISTURBED) AFTER 1 ITERATION CYCLES:

1500.00 1483.11 1409.23 1311.23 1178.01 991.77 722.82 500.00

ITERATION CYCLE NUMBER 1

TEMPERATURES:

1500.00
 1499.93
 1499.78
 1499.33
 1498.09
 1494.72
 1485.93
 1463.77
 1409.71
 1281.92 1445.01 1466.84 1472.46 1479.26 1480.53 1480.87 1480.97 1480.99
 1247.38 1328.18 1354.18 1367.16 1395.11 1401.09 1402.73 1403.24 1403.35
 1211.02 1246.76 1261.30 1271.24 1301.48 1309.15 1311.48 1312.24 1312.42
 1173.94 1169.16 1167.84 1171.12 1190.18 1195.68 1197.66 1198.41 1198.60
 1136.95 1083.11 1056.14 1046.67 1038.85 1038.12 1038.72 1039.16 1039.29
 1100.93 964.34 909.86 868.12 774.47 766.17 765.60 765.72 765.77
 1012.52
 933.14
 860.80
 793.87
 730.97
 671.70
 613.02
 556.24
 500.00

INCREMENTAL NORMAL FLUXES (BTU/HR.):

INTO HOT SIDE: FROM COLD SIDE:
 0.11855880 02 0.61713810 01

0.16277920 01 0.29880730 00
 0.42571220 00 0.50264630 00
 0.49747480 00 0.57612160 00
 0.26291140 00 0.30289240 00

0.34593610 00 0.39854270 00
 0.94075880 00 0.94971980 00
 0.13645660 01 0.13854630 01
 0.18078000 01 0.18433760 01
 0.22472020 01 0.23055970 01
 0.12917220 01 0.13259710 01

TOTAL FLUXES (BTU/HR.):

INTO PENETRATION HOT SIDE: 0.11855880 02
 INTO GAP HOT SIDE: 0.29133410 01
 INTO INSULATION HOT SIDE: 0.79925840 01
 FROM PENETRATION COLD SIDE: 0.61713810 01
 FROM GAP COLD SIDE: 0.16804680 01
 FROM INSULATION COLD SIDE: 0.82090560 01
 FROM INSULATION TO GAP: -0.21647230 00
 FROM GAP TO PENETRATION: 0.10164010 01
 TOTAL FLUX IN: 0.22765800 02
 TOTAL FLUX OUT: 0.16060910 02

ITERATION CYCLE NUMBER 2

TEMPERATURES:

1500.00
 1499.94
 1499.88
 1499.62
 1498.86
 1496.60
 1490.12
 1471.92
 1421.99
 1289.51 1441.71 1465.34 1471.55 1478.44 1477.71 1480.77 1480.12 1480.22
 1251.06 1321.49 1346.64 1362.07 1390.41 1396.65 1398.47 1399.07 1399.21
 1210.75 1237.76 1251.46 1261.01 1251.95 1300.46 1303.27 1304.25 1304.49
 1169.87 1156.60 1152.07 1154.41 1175.87 1183.24 1186.12 1187.24 1187.53
 1130.10 1083.11 1056.14 1046.67 1038.85 1038.12 1038.72 1039.16 1039.29
 1100.93 964.34 909.86 868.12 774.47 766.17 765.60 765.72 765.77
 1012.52
 933.14
 860.80
 793.87
 730.97
 671.70
 613.02
 556.24
 500.00

1089.82 925.72 870.65 832.88 763.58 759.29 759.74 760.17 761.17
 996.77
 916.11
 844.50
 779.46
 719.11
 662.00
 607.00
 553.23
 500.00

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INCREMENTAL NORMAL FLUXES (BTU/HR.):

INTO HOT SIDE: FROM COLD SIDE:
 0.97912190 01 0.97061060 01

0.98928620 00 0.58473950 00
 0.81255650 00 0.83235090 00
 0.66786000 00 0.85395910 00
 0.32942080 00 0.41330060 00

0.43344850 00 0.54342180 00
 0.10549210 01 0.10841690 01
 0.14894740 01 0.15621880 01
 0.19517270 01 0.20821620 01
 0.24761950 01 0.26072760 01
 0.13932690 01 0.15000860 01

TOTAL FLUXES (BTU/HR.):

INTO PENETRATION HOT SIDE: 0.97912190 01
 INTO CAP HOT SIDE: 0.27991320 01
 INTO INSULATION HOT SIDE: 0.87490340 01

FROM PENETRATION COLD SIDE: 0.97061060 01
 FROM GAP COLD SIDE: 0.26840500 01
 FROM INSULATION COLD SIDE: 0.93793030 01

FROM INSULATION TO GAP: -0.63026960 00
 FROM GAP TO PENETRATION: -0.51518810 00

TOTAL FLUX IN: 0.21339380 02
 TOTAL FLUX OUT: 0.21769460 02

ITERATION CYCLE NUMBER 3

TEMPERATURES:

1500.00
 1499.98
 1499.94
 1499.79
 1499.35
 1497.92
 1493.37
 1478.99
 1434.04
 1298.08 1439.02 1464.36 1471.06 1477.94 1479.14 1479.48 1479.99 1479.62
 1255.28 1316.97 1345.12 1358.91 1387.08 1393.23 1395.04 1395.65 1395.79
 1210.67 1231.73 1244.56 1253.91 1284.58 1293.31 1296.26 1297.31 1297.56
 1165.48 1148.45 1141.09 1142.31 1164.27 1172.49 1175.80 1177.09 1177.41
 1120.71 1049.21 1014.39 1003.52 1008.60 1013.46 1016.15 1017.33 1017.65
 1077.51 897.11 842.11 807.73 754.41 752.75 753.85 754.48 754.66
 979.62
 897.90
 827.33
 764.45
 706.84
 652.73
 600.82
 550.15
 500.00

INCREMENTAL NORMAL FLUXES (BTU/HR.):

INTO HOT SIDE: FROM COLD SIDE:
 0.97998750 01 0.10102480 02

0.95983600 00 0.55902360 00
 0.85726860 00 0.71053820 00
 0.69141970 00 0.71764600 00
 0.33743330 00 0.34985700 00

0.44399120 00 0.46033820 00
 0.10872780 01 0.10166220 01
 0.15405310 01 0.14956450 01
 0.20196120 01 0.20043650 01
 0.25104110 01 0.25141350 01
 0.14415620 01 0.14470740 01

TOTAL FLUXES (BTU/HR.):

INTO PENETRATION HOT SIDE: 0.97998750 01
 INTO CAP HOT SIDE: 0.28455580 01
 INTO INSULATION HOT SIDE: 0.90433870 01

FROM PENETRATION COLD SIDE: 0.10102480 02
 FROM GAP COLD SIDE: 0.23370650 01
 FROM INSULATION COLD SIDE: 0.89981790 01

FROM INSULATION TO GAP: 0.10520790 00
 FROM GAP TO PENETRATION: 0.61410070 00

TOTAL FLUX IN: 0.21689220 02
 TOTAL FLUX OUT: 0.21377720 02

TEMPERATURES

```

1500.00
1499.98
1499.94
1499.80
1499.37
1498.00
1479.73
1436.02
1302.33 1440.04 1465.11 1471.76 1478.57 1479.70 1480.00 1480.09 1480.11
1260.25 1320.56 1348.47 1362.18 1389.96 1395.76 1397.34 1397.83 1397.94
1215.98 1237.01 1249.94 1259.36 1289.25 1297.24 1299.76 1300.59 1300.78
1171.34 1155.40 1148.41 1149.69 1169.81 1176.73 1179.36 1180.35 1180.59
1127.09 1058.44 1024.40 1013.71 1013.50 1016.34 1018.21 1019.08 1019.32
1094.32 910.79 857.51 821.51 756.91 753.30 753.89 754.35 754.48
986.44
906.97
813.80
770.05
711.40
656.17
603.11
551.29
500.00

```

INCREMENTAL NORMAL FLUXES (BTU/HR.):

```

INTO HOT SIDE: FROM COLD SIDE:
0.97285720 C1 0.10301090 C2

```

```

C.93837830 C0 0.55119950 C0
C.87160760 C0 0.67926260 C0
C.69555880 C0 0.68650080 C0
C.33717100 C0 0.33575060 C0

```

```

0.44364470 C0 0.44177710 C0
C.10881560 C1 0.49233850 C0
C.15466940 C1 0.14649460 C1
C.20307190 C1 0.19649540 C1
C.25258280 C1 0.24653250 C1
0.14506650 C1 0.14190560 C1

```

TOTAL FLUXES (BTU/HR.):

```

INTO PENETRATION HOT SIDE: 0.97285720 C1
INTL GAP HOT SIDE: C.28427150 C1
INTO INSULATION HOT SIDE: 0.50857070 C1

FROM PENETRATION COLD SIDE: 0.10301090 C2
FROM GAP COLD SIDE: 0.22527130 C1
FROM INSULATION COLD SIDE: 0.87483970 C1

FROM INSULATION TO GAP: 0.33730920 C0
FROM GAP TO PENETRATION: 0.92731050 C0

TOTAL FLUX IN: 0.21656550 C2
TOTAL FLUX OUT: 0.21902200 C2

```

ITERATION CYCLE NUMBER 5

TEMPERATURES:

```

1500.00
1499.98
1499.94
1499.80
1499.37
1498.00
1479.73
1436.02
1302.33 1440.04 1465.11 1471.76 1478.57 1479.70 1480.00 1480.09 1480.11
1260.25 1320.56 1348.47 1362.18 1389.96 1395.76 1397.34 1397.83 1397.94
1215.98 1237.01 1249.94 1259.36 1289.25 1297.24 1299.76 1300.59 1300.78
1171.34 1155.40 1148.41 1149.69 1169.81 1176.73 1179.36 1180.35 1180.59
1127.09 1058.44 1024.40 1013.71 1013.50 1016.34 1018.21 1019.08 1019.32
1094.32 910.79 857.51 821.51 756.91 753.30 753.89 754.35 754.48
986.44
906.97
813.80
770.05
711.40
656.17
603.11
551.29
500.00

```

INCREMENTAL NORMAL FLUXES (BTU/HR.):

```

INTO HOT SIDE: FROM COLD SIDE:
0.97285720 C1 0.10301090 C2

```

```

C.93837830 C0 0.55119950 C0
C.87160760 C0 0.67926260 C0
C.69555880 C0 0.68650080 C0
C.33717100 C0 0.33575060 C0

```

```

0.44364470 C0 0.44177710 C0
C.10881560 C1 0.49233850 C0
C.15466940 C1 0.14649460 C1
C.20307190 C1 0.19649540 C1
C.25258280 C1 0.24653250 C1
0.14506650 C1 0.14190560 C1

```

TOTAL FLUXES (BTU/HR.):

INTO PENETRATION HOT SIDE: 0.9646552D 01
INTO GAP HOT SIDE: 0.2816816D 01
INTO INSULATION HOT SIDE: 0.8971618D 01

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FROM PENETRATION COLD SIDE: 0.1029584D 02
FROM GAP COLD SIDE: 0.2325225D 01
FROM INSULATION COLD SIDE: 0.8775234D 01

FROM INSULATION TO GAP 0.1963836D 00
FROM GAP TO PENETRATION: 0.6879747D 00

TOTAL FLUX IN: 0.2143495D 02
TOTAL FLUX OUT: 0.2139630D 02

MINIMUM TOTAL FLUX: 0.7602565D 01
TOTAL-TC-MINIMUM RATIO: 0.2816897D 01
MINIMUM GAP-INSULATION FLUX: 0.7568776D 01
HOT SIDE RATIO: 0.1557509D 01
COLD SIDE RATIO: 0.1466612D 01
MINIMUM FLUX THROUGH SQUARE: 0.9646098D 01
HOT SIDE RATIO: 0.1476318D 01
COLD SIDE RATIO: 0.1402293D 01

F-2-1 INTRODUCTION

Extensive analysis has been done on the effect of discontinuities, typically joints and solid penetrations, on thermal performance of multi-foil insulation systems. One pertinent joint and penetration configuration employs a gap* filler material as a means of reducing the total heat flux in the vicinity of the discontinuity.

These filler materials, typically opacified glass or quartz fiber papers, were assumed to be totally opaque in the original analytical studies (e.g., reference Quarterly Progress Report ALO 3632-33, June-August, 1968). As such, thermal performance of the opacified fillers was characterized by a temperature-dependent "apparent" thermal conductivity of the form:

$$K(T) = a.T + b.T^3 \quad (F-1)$$

where a and b are solid conduction and radiative coefficients, respectively.

Subsequent experimental studies in the flat plate test program showed, in fact, that the opacified filler materials are semi-transparent rather than opaque. As such, an appreciable amount of the total heat flux through these materials is transmitted by radiation. And the attenuating capabilities of these fillers, then, are governed primarily by backscattering rather than by the absorption-emission mechanism.

This appendix describes the derivation of equations for the radiant interchange through a radiation-attenuating medium between two surfaces at different temperatures. To derive the equations, the following assumptions are made:

- a. Absorption and radiant emission within the medium are negligible.
- b. All radiation passing through the medium is either transmitted directly or backscattered 180° along the line of incidence.

First, the radiant exchange between infinitesimal surface elements is derived. The results are then extended to surfaces of finite size.

*For example, gap resulting at a butt joint between two multi-foil insulation panels or the annular gap between the penetrating element and the multi-foil insulation.

F-2-2 CONCLUSION

Assuming that 180° backscattering is the only attenuation mechanism present in the attenuating medium, the equation of radiant interchange between two surfaces separated by the medium is of the same form as the non-attenuated interchange equation. However, the view (or configuration) factors included in the latter equation are replaced by "effective" factors which include the effect of backscattering.

F-2-3- DISCUSSION

One-dimensional heat transfer by conduction and radiation in an absorbing, emitting, and scattering medium can be treated most simply using an approximate two-flux model.² This model, originally suggested by Schuster, has been used by Hamaker,² Larkin and Churchill,⁴ and Lynch.⁵ A detailed description of this model is given by Hottel and Sarofim.³

The indicated references, apply the model to the simple case in which both surfaces are infinite parallel planes. Although this surface geometry adequately describes the structure of a layered insulation, it by no means describes the structure of an insulation discontinuity of finite size and arbitrary shape. This latter structure is defined in the following derivation.

F-2-3-1 Interchange Between Infinitesimal Surfaces

Assuming that all radiation entering the scattering medium between surface elements dA_1 and dA_2 (See Figure F-2-1) is either transmitted directly or backscattered along the line of incidence, the differential equations governing the forward and backward fluxes are:

$$\frac{d}{dx} (dQ_{12}(x)) = \beta (dQ_{21}(x)) \quad (F-2)$$

$$\frac{d}{dx} (dQ_{21}(x)) = \beta (dQ_{12}(x) - dQ_{21}(x))$$

where:

$dQ_{12}(x)$ = Radiant flux from dA_1 and dA_2

$dQ_{21}(x)$ = Radiant flux from dA_2 to dA_1

β = Backscattering cross section (fraction of incident radiation backscattered per unit length of travel)

The solution of equations(F-2) is:

$$\begin{aligned} dQ_{12}(x) &= (C_2 - C_1) e^{-\beta x} + C_1 \\ dQ_{21}(x) &= (C_2 - C_1) e^{-\beta x} + C_2 \end{aligned} \quad (F-3)$$

where C_1 and C_2 are constants, which can be determined by applying the boundary conditions:

$$dQ_{12}(0) = [\epsilon_1 E_1 + r_1 \cdot dQ_{21}(0)] f_{12}$$

$$dQ_{21}(R) = [\epsilon_2 E_2 + r_2 \cdot dQ_{12}(R)] f_{21} \quad (F-4)$$

where:

$$\begin{aligned} \epsilon_1, \epsilon_2 &= \text{Emissivities of } dA_1 \text{ and } dA_2 \\ r_1, r_2 &= \text{Reflectivities of } dA_1 \text{ and } dA_2 \\ (r_1 &= 1 - \epsilon_1, r_2 = 1 - \epsilon_2) \\ E_1 &= \sigma \epsilon_1 T_1^4 \text{ } dA_1 = \text{emissive power of } dA_1 \\ E_2 &= \sigma \epsilon_2 T_2^4 \text{ } dA_2 = \text{emissive power of } dA_2 \\ \sigma &= \text{Stefan-Boltzmann constant} \\ T_1, T_2 &= \text{Temperatures of } dA_1 \text{ and } dA_2 \\ f_{12} &= f \cdot dA_2 = \text{view factor from } dA_1 \text{ to } dA_2 \text{ (The fraction of} \\ &\quad \text{energy leaving } dA_1 \text{ that would fall on } dA_2 \\ &\quad \text{if there were no attenuating medium present)} \\ f_{21} &= f \cdot dA_1 = \text{view factor from } dA_2 \text{ to } dA_1 \\ f &= \frac{\cos \theta_1 \cdot \cos \theta_2}{\pi R^2} \end{aligned}$$

Substitution of equations (F-3) into equations (F-4) results in two equations linear in C_1 and C_2 . Solving for these constants, gives:

$$\begin{aligned} C_1 &= [f_{12} E_1 (1 + \beta R (1 - r_2 f_{21})) + f_{21} E_2 r_1 f_{12}] / D \\ C_2 &= [f_{12} E_1 (r_2 f_{21} + \beta R (1 - r_2 f_{21})) + f_{21} E_2] / D \end{aligned} \quad (F-5)$$

$$D = 1 - f_{12} f_{21} r_1 r_2 + \beta R (1 - f_{12} r_1) (1 - f_{21} r_2)$$

The net rightward flux, dQ_R , is thus given by

$$dQ = C_1 - C_2 = \frac{f_{12} (1 - r_2 f_{21}) E_1 - f_{21} (1 - r_1 f_{12}) E_2}{1 - f_{12} f_{21} r_1 r_2 + \beta R (1 - f_{12} r_1) (1 - f_{21} r_2)} \quad (F-6)$$

When $\beta = 0$, equation (F-6) reduces to the general equation of unattenuated radiant exchange given in Brown and Marco.¹ For infinite parallel planes, $f_{12} = f_{21} = 1$.

Note that, when $r_2 = E_2 = 0$,

$$dQ_R = \frac{f_{12} E_1}{1 + \beta R (1 - f_{12} r_1)} = F_{12} E_1 \quad (F-7)$$

FIGURE F-2-1 SURFACE GEOMETRY

Also, when $r_1 = E_1 = 0$, the net leftward flux becomes

$$-dQ_R = \frac{f_{21}E_2}{1 + \rho_R (1 - f_{21}r_2)} = F_{21}E_2 \quad (F-8)$$

Solving (F-7) for f_{12} , solving (F-8) for f_{21} , and substituting the results into (F-6), the expression for dQ_R is obtained:

$$dQ_R = \frac{F_{12}(1 - r_2F_{21})E_1 - F_{21}(1 - r_1F_{12})E_2}{1 - F_{12}F_{21}r_1r_2} \quad (F-9)$$

Equation (F-9) is of exactly the same form as the Brown and Marco equation. However, the view factors now have been redefined to incorporate the effect of backscattering. F_{12} and F_{21} represent the effective view factors.

F-2-3-2 Interchange Between Finite Surfaces

Equation (F-7) - (F-9), which describe the radiant-scattering interchange between infinitesimal surface elements dA_1 and dA_2 , can be extended to surfaces of finite area.

First, the amount of radiant energy originating at dA_1 that strikes dA_2 (dQ_{12}) is computed by solving equations (F-2) subject to a new set of boundary conditions:

$$\begin{aligned} dQ_{12}(0) &= E_1 f_{12} \\ dQ_{21}(R) &= 0 \end{aligned} \quad (F-10)$$

Combining equations (F-3) and (F-10), we obtain

$$\begin{aligned} C_1 &= E_1 f_{12} \\ C_2 &= \frac{E_1 f_{12} R}{1 + R} \end{aligned}$$

which gives for the net flux at $x = R$:

$$dQ_{12}(R) = C_1 - C_2 = \frac{E_1 f_{12}}{1 + R} \quad (F-11)$$

To compute the total radiant interchange between surfaces A_1 and A_2 equations (F-10) and (F-11) are integrated over both surfaces. The total flux originating at A_1 directed toward A_2 thus becomes:

$$(Q_1)_0 = \int_{A_1} \int_{A_2} dQ_{12}(0) = \bar{E}_1 \bar{f}_{12}$$

where

$$\bar{E}_1 = \sigma \epsilon_1 T_1^4 A_1$$

$$\bar{f}_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi R^2} dA_1 dA_2$$

The portion that reached A_2 now becomes:

$$(Q_2)_0 = \int_{A_1} \int_{A_2} dQ_{12}(R) = E_1 \bar{f}_{12}, \text{ where}$$

$$\bar{f}_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{\pi R^2 (1 + \beta R)}$$

Note that the scattering view factor $\bar{f}_{12}$ is the fraction of radiant energy leaving A_1 that reaches A_2 without being backscattered.

The portion $(Q_b)_0$ that is scattered back to A_1 is:

$$(Q_b)_0 = (Q_1)_0 - (Q_2)_0 = E_1 (\bar{f}_{12} - f_{12})$$

However, part of this energy is reflected from A_1 back toward A_2 , this portion being:

$$(Q_1)_1 = r_1 \bar{f}_{12} (Q_b)_0 = E_1 \bar{f}_{12} r_1 (\bar{f}_{12} - f_{12}) = r_1 (\bar{f}_{12} - f_{12}) (Q_1)_0$$

The portions of $(Q_1)_1$ that are transmitted to A_2 and scattered back to A_1 are, respectively,

$$(Q_2)_1 = r_1 \bar{f}_{12} (Q_b)_0 = r_1 (\bar{f}_{12} - f_{12}) (Q_2)_0$$

$$(Q_b)_1 = (Q_1)_1 - (Q_2)_1$$

This transmit-backscatter-reflect cycle can be repeated indefinitely, resulting in a total flux arriving at A_2 given by

$$(Q_2)_{\text{tot}} = \sum_{i=0}^{\infty} (Q_2)_i = (Q_2)_0 \sum_{i=0}^{\infty} [r_1 (\bar{f}_{12} - f_{12})]^i$$

or, by summing the infinite geometric series,

$$(Q_2)_{\text{tot}} = \sum_{i=0}^{\infty} \frac{(Q_2)_0}{1 - r_1 (\bar{f}_{12} - f_{12})} = \frac{E_1 \bar{f}_{12}}{1 - r_1 (\bar{f}_{12} - f_{12})}$$

(F-12)

Note that when $\beta = 0$, $\bar{f}_{12} = f_{12}$ and equation (F-12) reduces to

$$(Q_2)_{\text{tot}} = E_1 \bar{f}_{12}$$

(F-13)

Therefore, by comparing equations (F-12) and (F-13) and by a similar analysis of radiant energy originating at A_2 , expressions for effective view factors $(F_{12})_{\text{eff}}$ and $(F_{21})_{\text{eff}}$, are given by:

$$(F_{12})_{\text{eff}} = \frac{\bar{f}_{12}'}{1 - r_1 (\bar{f}_{12} - \bar{f}_{12}')} \\ (F_{21})_{\text{eff}} = \frac{\bar{f}_{21}'}{1 - r_2 (\bar{f}_{21} - \bar{f}_{21}')}$$

(F-14)

The overall radiant interchange equation can now be derived simply by replacing the view factors in the Brown and Marco equation by the effective values given by equation (F-14).

IV. REFERENCES

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APPENDIX G

THERMAL EFFECTS OF LEAD TELLURIDE
AND SILICON GERMANIUM ELEMENTS
IN A PENETRATION-INSULATION SYSTEM

G.1. INTRODUCTION:

These flush penetration studies are aimed directly at the evaluation of disturbances associated with the passing of a multiplicity of regularly spaced thermoelectric elements through a typical energy conversion panel. To this end investigations have been centered around Lead Telluride and Silicon Germanium penetrations-both currently potential element materials.

Results of flush penetration calculations, considering lead telluride (to 800°F) and silicon germanium (to 1800°F) as the thermoelectric element materials, are presented in Figures G.2 to G.13 and Tables G.1 to G.6.

The results are based on the initial version of the penetration analysis described in Section 3.0, in which the opacified gap fillers were considered as opaque materials. Also, the hot and cold boundary temperatures were considered fixed.

G.2. CONFIGURATION

The penetration-insulation configuration in which the lead telluride and silicon germanium materials were evaluated is shown schematically in Figure G.1. The typical physical system to which the analysis is directed comprises a number of penetrations of diameter (D) (e.g., thermoelectric elements) and height (t) disposed through an insulation panel of the same height, and uniformly spaced on center distance (c).

Three specific configurations have been considered for the immediate surroundings of each penetration:

- (A) No gap-The penetration is closely fit to the insulation ($D = G$) and there is good thermal contact at the penetration-insulation interface.
- (B) Filled gap-An annular gap ($G-D$) between the insulation and the penetration is completely filled with a "buffer" insulation (e.g., Johns Manville Min-K or Linde opacified papers).
- (C) Empty gap-An annular gap ($G-D$) between the insulation and the penetration is left completely void.

G.3. DISCUSSION

Figures G.2 to G.13 present a comparison of magnitudes of the heat which enters the hot side of the disturbed insulation system to the heat which would enter and leave an undisturbed-zero gap system of multi-layer insulation identical in surface area and configuration, and operating between identical boundary temperatures.

The insulation in this case includes all of the area around one penetration (i.e., the area covered by the multi-layer insulation as well as the area covered by the gap-filled or unfilled).

The significance of the above parameters can best be clarified with reference to Figure G.1.

For each of the three configurations;

q_{zh} = is interpreted as the local heat flux entering the hot side of the system at any location within the area A_i

A_i = the area $(A^2 - \frac{\pi D^2}{4})$

$$\sum q_{zh} = \int_{A_i} q_{zh} dA$$

q_{oh} = the local heat flux entering the hot side of the system at any location within the area A_i under the following conditions

- A_i is all multi-foil insulation (e.g., Case 1)
- heat transfer through A_i between T_h and T_c is one-dimensional (i.e., the i penetration has no disturbing effect).

$$\begin{aligned} \sum q_{oh} &= \int_{A_i} q_{oh} dA = q_{oh} A_i = q_{oc} A_i = q_o A_i \\ \text{then } \left(\frac{\sum q_z}{\sum q_o} \right)_{\text{hot side}} &= \frac{\int_{A_i} q_{zh} dA}{q_o A_i} \\ \left(\frac{\sum q_z}{\sum q_o} \right)_{\text{cold side}} &= \frac{\int_{A_i} q_{zc} dA}{q_o A_i} \end{aligned}$$

When presented in this form, the heat flux data provides the most pessimistic estimate of the performance of a multi-layer insulation system in the presence of typical thermoelectric elements.

Even though this most pessimistic estimate yields tolerable results, e.g., apparent deteriorations lower than a factor of 2 for all filled gap and zero gap cases, as well as for those empty gap cases with gap width smaller than 0.025", it is believed that evaluation of system performance on the basis of total heat transferred, including heat transferred through the penetration, is more meaningful. Comparison of system performance on the basis of total heat transferred is shown in Tables G.2 and G.4 for 800°F and 1800°F systems, respectively. In these Tables, the total heat loss through a filled gap and empty gap system are compared to the total heat flux through a zero gap system.

With the hot and cold side temperatures fixed, the two-dimensional nature of the heat flow is inconsequential to the total heat transferred through the zero gap system. The same is true for a filled gap system under the conditions of this earlier analytical treatment-i.e., the gap filler is treated as an opaque material as opposed to a partially transparent material. Thus, from a heat transfer standpoint, this becomes the most ideal configuration(i.e., minimum heat flow). The improved analytical method, as described in Section 3.0, considers the gap filler as a semi-transparent material.

For each of the three configurations, the parameters varied were: gap width, penetration radius, penetration spacing (i.e., adiabatic radius) and insulation thickness.

FIGURE G-2

Flux Ratio: Hot Side
 Penetration: .5" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F., 200°F.

G-6

FIGURE G-3

Flux Ratio: Hot Side
 Penetration: .2" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F., 200°F.

FIGURE G-4

Flux Ratio: Hot Side
 Penetration: .1" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F, 200°F

G-8

FIGURE G-5

Flux Ratio: Cold Side
 Penetration: .1" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F., 200°F.

FIGURE G-6

Flux Ratio: Cold Side
 Penetration: .2" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F., 200°F.

FIGURE G-7

Flux Ratio: Cold Side
 Penetration: .5" diameter Lead Telluride
 Insulation: Aluminum Foil - Aluminum Opacified Paper
 Boundary Temperatures: 800°F., 200°F.

G-11

FIGURE C-8

Flux Ratio: Hot Side
 Penetration: .1" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperatures: 1800°F., 800°F.

FIGURE G-9

Flux Ratio: Hot Side
 Penetration: .2" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperatures: 1800°F., 800°F.

FIGURE G-10

Flux Ratio: Hot Side
 Penetration: 5" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperature: 1800°F., 800°F.

G-14

FIGURE G-11

Flux Ratio: Cold Side
 Penetration: .1" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperatures: 1800°F., 800°F.

FIGURE G-12

Flux Ratio: Cold Side
 Penetration: .2" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperatures: 1800°F., 800°F.

FIGURE G-13

Flux Ratio: Cold Side
 Penetration: .5" diameter Silicon Germanium
 Insulation: Nickel Foil - Refrasil Quartz Paper
 Boundary Temperatures: 1800°F., 800°F.

G-17

Q system

Q (One-Dimensional Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation

Lead - Telluride Penetration

Boundary Temperatures = 800°F - 200°F

		INSULATION PANEL THICKNESS									PENETRATION DIA. - INCHES	
		0.1"			0.2"			0.4"				
	EMPTY GAP	0.1"			0.2"			0.4"				
FILLED GAP	GAP WIDTH - INCHES	0.025	1.02	1.02	1.02	1.04	1.04	1.04	1.07	1.07	1.07	0.1
		0.05	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04	0.2
		0.075	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	0.5
		0.1	1.04	1.04	1.03	1.04	1.10	1.10	1.18	1.17	1.15	0.1
		0.15	1.01	1.02	1.02	1.03	1.04	1.04	1.07	1.08	1.08	0.2
		0.2	1.00	1.01	1.01	1.01	1.01	1.01	1.02	1.03	1.03	0.5
		0.3	1.06	1.05	1.04	1.15	1.15	1.13	1.31	1.30	1.27	0.1
		0.4	1.02	1.02	1.02	1.06	1.06	1.06	1.13	1.14	1.13	0.2
FILLED GAP	GAP WIDTH - INCHES	0.025	1.00	1.01	1.01	1.00	1.02	1.02	1.04	1.05	1.04	0.5
		0.05	1.01	1.02	1.02	1.01	1.02	1.02	1.00	1.02	1.03	0.1
		0.075	1.00	1.00	1.01	1.00	1.00	1.01	1.00	1.01	1.01	0.2
		0.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
		0.15	1.01	1.02	1.02	1.02	1.03	1.03	1.01	1.02	1.03	0.1
		0.2	1.00	1.01	1.01	1.00	1.01	1.01	1.00	1.01	1.01	0.2
		0.3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
		0.4	1.01	1.02	1.02	1.02	1.02	1.03	1.01	1.03	1.03	0.1
ZERO GAP	GAP WIDTH - INCHES	0.025	1.00	1.01	1.01	1.00	1.01	1.01	1.00	1.01	1.01	0.2
		0.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
		0.075	1.01	1.02	1.02	1.02	1.02	1.03	1.01	1.03	1.03	0.1
		0.1	1.00	1.01	1.01	1.00	1.01	1.01	1.00	1.01	1.01	0.2
ZERO GAP	GAP WIDTH - INCHES	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
		0.2	1.00	1.01	1.01	1.00	1.00	1.01	1.00	1.01	1.01	0.2
		0.3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
		0.4	1.00	1.02	1.02	1.01	1.02	1.03	1.00	1.02	1.03	0.1
		ADJACENT RADIUS - INCHES										

G-18

$$Q_{\text{(Penetration - One Dimensional)}}$$

Aluminum Foil - Aluminum Opacified Paper Insulation
Lead - Telluride Penetration
Boundary Temperatures - 800°F - 200°F

		INSULATION PANEL THICKNESS										
		0.1"			0.2"			0.4'				
EMPTY GAP	GAP WIDTH - INCHES	0.025	0.995	0.992	0.990	0.990	0.974	0.963	0.974	0.941	0.911	0.1
			0.999	0.995	0.995	0.997	0.990		0.995	0.982	0.969	0.2
			1.00	0.999	0.997	1.00	0.998	0.995	0.999	0.996	0.993	0.5
			1.00	0.997	0.997	1.01	0.990	0.974	0.990	0.959	0.932	0.1
			1.00	0.999	0.998	1.00	0.997	0.992	1.00	0.992	0.979	0.2
			1.00	1.00	1.00	1.00	1.00	0.999	1.00	1.00	0.998	0.5
			1.01	1.00	1.00	1.02	1.00	0.995	1.01	0.985	0.959	0.1
			1.00	1.00	0.999	1.01	1.00	0.999	1.02	1.01	0.992	0.2
			1.00	1.00	0.999	1.00	1.00	1.00	1.01	1.01	1.00	0.5
FILLED GAP	GAP WIDTH - INCHES	0.025	0.974	0.937	0.909	0.974	0.921	0.869	0.969	0.913	0.846	0.1
			0.992	0.979	0.967	0.991	0.975	0.954	0.990	0.974	0.943	0.2
			0.997	0.994	0.991	0.997	0.994	0.990	0.997	0.994	0.989	0.5
			0.974	0.943	0.919	0.974	0.927	0.874	0.966	0.910	0.847	0.1
			0.990	0.980	0.970	0.990	0.974	0.956	0.990	0.971	0.907	0.2
			0.996	0.994	0.992	0.996	0.994	0.990	0.996	0.994	0.989	0.5
			0.969	0.943	0.929	0.969	0.921	0.880	0.961	0.908	0.847	0.1
			0.989	0.980	0.972	0.988	0.974	0.959	0.987	0.971	0.948	0.2
			0.996	0.994	0.992	0.996	0.993	0.990	0.996	0.993	0.989	0.5
ZERO GAP			0.974	0.927	0.877	0.979	0.921	0.859	0.972	0.913	0.843	0.1
			0.992	0.977	0.960	0.992	0.975	0.952	0.992	0.974	0.948	0.2
			0.997	0.995	0.991	0.997	0.995	0.995	0.997	0.995	0.990	0.5
			0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5	
ADJACENT RADIUS - INCHES												

G-19

$$Q_{\text{(Into Insulation - Hot Side)}}$$
$$Q_{\text{(Insulation - One Dimensional - Zero Gap)}}$$

Aluminum Foil - Aluminum Opacified Paper Insulation
Lead Telluride Penetration
Boundary Temperatures - 800°F - 200°F

[illegible]

G-20

 $Q_{(\text{System})}$
$$Q_{\text{(One Dimensional - Zero Gap)}}$$

		INSULATION PANEL THICKNESS										
		0.1"			0.2"			0.4"				
EMPTY GAP	GAP WIDTH - INCHES	0.025	1.05	1.03	1.02	1.09	1.07	1.04	1.15	1.11	1.09	0.1
			1.02	1.02	1.02	1.04	1.04	1.03	1.08	1.07	1.07	0.2
			1.01	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.03	0.5
			1.09	1.06	1.04	1.21	1.15	1.09	1.40	1.28	1.19	0.1
			1.04	1.03	1.03	1.10	1.09	1.08	1.19	1.17	1.15	0.2
			1.01	1.01	1.01	1.03	1.04	1.03	1.07	1.07	1.07	0.5
			1.12	1.08	1.05	1.33	1.23	1.16	1.70	1.49	1.33	0.1
			1.05	1.04	1.04	1.14	1.13	1.12	1.31	1.29	1.25	0.2
			1.01	1.01	1.01	1.04	1.05	1.05	1.10	1.11	1.11	0.5
FILLED GAP	GAP WIDTH - INCHES	0.025	1.01	1.01	1.00	1.02	1.02	1.01	1.02	1.03	1.02	0.1
			1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02	0.2
			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.5
			1.02	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	0.1
			1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02	0.2
			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	0.5
			1.03	1.02	1.01	1.03	1.03	1.02	1.03	1.03	1.03	0.1
			1.01	1.01	1.01	1.01	1.02	1.01	1.01	1.02	1.02	0.2
			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	0.5
ZERO GAP		1.01	1.01	1.01	1.01	1.02	1.01	1.01	1.03	1.02	0.1	
		1.00	1.01	1.00	1.00	1.01	1.01	1.00	1.01	1.02	0.2	
		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	0.5	
		0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5		

ADIABATIC RADIUS - INCHES

TABLE G-5

G-21

 Q (Into Penetration - Hot Side) Q (Penetration - One Dimension)

Nickel Foil - Quartz Paper Insulation
 Silicon Germanium Penetration
 Boundary Temperatures - 1800°F - 800°F

		INSULATION PANEL THICKNESS									
		0.1"			0.2"			0.4"			
	EMPTY GAP										PENETRATION DIA. - INCHES
	GAP WIDTH - INCHES										
FILLED GAP	0.025	0.997	0.994	0.993	0.986	0.963	0.956	0.978	0.921	0.892	0.1
		1.00	0.998	0.997	0.999	0.986	0.981	0.999	0.971	0.949	0.2
		1.00	0.999	0.999	1.00	0.998	0.995	1.00	0.997	0.989	0.5
		1.01	1.01	1.01	1.02	1.00	0.994	1.04	0.989	0.961	0.1
		1.01	1.00	1.00	1.02	1.00	1.00	1.03	1.00	0.983	0.2
		1.00	1.00	1.00	1.01	1.01	1.00	1.02	1.01	1.00	0.5
		1.02	1.02	1.02	1.05	1.03	1.03	1.11	1.06	1.03	0.1
		1.01	1.01	1.01	1.03	1.02	1.02	1.07	1.04	1.02	0.2
	0.05	1.00	1.00	1.00	1.01	1.01	1.01	1.03	1.03	1.02	0.5
		0.956	0.932	0.924	0.941	0.878	0.848	0.936	0.845	0.788	0.1
		0.985	0.973	0.969	0.981	0.953	0.935	0.980	0.940	0.901	0.2
		0.996	0.993	0.991	0.996	0.989	0.983	0.996	0.968	0.977	0.5
		0.958	0.941	0.936	0.940	0.886	0.861	0.934	0.847	0.793	0.1
		0.984	0.979	0.973	0.980	0.955	0.940	0.978	0.941	0.904	0.2
		0.996	0.993	0.992	0.996	0.989	0.984	0.996	0.987	0.977	0.5
		0.957	0.945	0.941	0.939	0.889	0.869	0.929	0.847	0.798	0.1
	0.075	0.984	0.977	0.975	0.980	0.956	0.944	0.977	0.940	0.906	0.2
		0.995	0.993	0.992	0.995	0.984	0.984	0.995	0.987	0.977	0.5
		0.950	0.915	0.902	0.940	0.865	0.827	0.936	0.840	0.780	0.1
		0.984	0.968	0.962	0.982	0.950	0.926	0.981	0.940	0.898	0.2
		0.997	0.992	0.990	0.997	0.989	0.982	0.997	0.988	0.977	0.5
		0.9	1.0	1.0	0.9	1.0	1.0	0.9	1.0	1.0	
ZERO GAP											

ADAPTATION RADIUS - INCHES

ADAPTATION RADIUS - INCHES

$$Q_{\text{(Insulation - One Dimensional - Zero Gap)}}$$

Nickel Foil - Quartz Paper Insulation
Silicon Germanium Penetration
Boundary Temperatures

		INSULATION PANEL THICKNESS									PENETRATION DIA. - INCHES	
		0.1"			0.2"			0.4'				
		GAP WIDTH - INCHES			GAP WIDTH - INCHES			GAP WIDTH - INCHES				
EMPTY GAP	GAP WIDTH - INCHES	0.025	1.30	1.08	1.03	1.64	1.20	1.09	2.08	1.36	1.18	0.1
		0.05	1.50	1.13	1.06	2.02	1.34	1.16	2.77	1.62	1.34	0.2
		0.075	2.14	1.30	1.13	3.20	1.67	1.34	5.11	2.18	1.66	0.5
		0.1	1.50	1.13	1.06	2.21	1.34	1.14	3.27	1.66	1.32	0.1
		0.125	1.77	1.20	1.09	2.82	1.54	1.25	4.56	2.06	1.53	0.2
		0.15	2.70	1.41	1.18	4.83	2.04	1.49	9.10	3.05	2.04	0.5
		0.175	1.66	1.17	1.07	2.80	1.50	1.23	4.78	2.06	1.50	0.1
		0.2	1.96	1.24	1.11	3.56	1.73	1.34	6.56	2.59	1.77	0.2
		0.225	3.04	1.48	1.21	5.97	2.36	1.64	13.0	3.94	2.43	0.5
FILLED GAP	GAP WIDTH - INCHES	0.025	1.32	1.11	1.05	1.42	1.21	1.11	1.46	1.27	1.16	0.1
		0.05	1.44	1.18	1.09	1.54	1.32	1.19	1.57	1.41	1.30	0.2
		0.075	1.70	1.31	1.16	1.75	1.45	1.31	1.76	1.53	1.43	0.5
		0.1	1.34	1.11	1.05	1.46	1.20	1.11	1.51	1.27	1.16	0.1
		0.125	1.50	1.17	1.08	1.62	1.32	1.18	1.67	1.42	1.29	0.2
		0.15	1.92	1.33	1.16	2.00	1.49	1.31	2.02	1.57	1.44	0.5
		0.175	1.39	1.11	1.05	1.52	1.21	1.11	1.58	1.28	1.16	0.1
		0.2	1.58	1.18	1.08	1.72	1.33	1.18	1.78	1.44	1.29	0.2
		0.225	2.17	1.36	1.17	2.27	1.52	1.31	2.30	1.62	1.46	0.5
ZERO GAP	GAP WIDTH - INCHES	0.1	1.33	1.14	1.07	1.40	1.22	1.12	1.43	1.27	1.16	0.1
		0.125	1.41	1.20	1.10	1.47	1.33	1.21	1.50	1.40	1.30	0.2
		0.15	1.49	1.30	1.16	1.52	1.43	1.31	1.52	1.49	1.43	0.5
		0.2	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5	
ADIABATIC RADIUS - INCHES												

APPENDIX H
EXPOSED EDGE COMPUTER PROGRAM

D. H. Suckow

H-1. ABSTRACT

The computer program described herein, written in G-Level FORTRAN IV, computes temperatures and heat fluxes within an (assumed infinitely long) insulation panel with both edges exposed. The edge can be either thermally joined to an adjacent panel edge through a rectangular or sector shaped (one surface touching the same surface of the other panel) gap or completely exposed and radiating to an infinite wall. An interpanel gap can be either empty or filled with a conductive and/or translucent substance. The program is similar to the penetration program given in Appendix F.

The thermal analysis was based upon the geometry shown in Figure H-1. and upon the following assumptions:

1. The panel is part of an infinitely repeating system, so that adiabatic planes bisect the panel and the gap separating it from an adjacent panel.*
2. The panel surfaces are prescribed at fixed temperatures. The temperature of either surface is necessarily uniform unless the edge radiates to an infinite wall; the temperature can then vary with distance from the (adiabatic) panel midplane.
3. The panel and gap fillers are conductivity anisotropic - they can have different thermal conductivities in the directions parallel to and normal to the insulation layer.
4. If translucent, the gap filler is radiatively isotropic.
5. Radiant interchange among the surfaces bounding the gap can be either attenuated through backscattering or unattenuated. If the gap filler is translucent, all radiation into the gap is either transmitted directly or scattered at a 180 degree angle with the line of incidence.
6. The insulation edges are black (emissivity = 1). However, the gap ends may have emissivities less than unity, as may the infinite wall radiating to an exposed edge.

All emissivities and thermal conductivities can vary with temperature. Three basic temperature variations are assumed:

- a. Three straight lines joined end-to-end.
- b. Two parabolas joined end-to-end.
- c. A cubic polynomial.

* Unless it is a single panel with exposed edges; in this case, there is no gap-bisector plane.

Schematic Drawing of System Geometry

NOTE: The y axis is directed into this page.

The lateral thermal conductivities of the insulation and gap filler can assume variations (a) or (b). Thermal conductivities in the normal direction can assume all three variations. (Ordinarily, variation (c) is assumed. However, if all four cubic coefficients are set equal to zero, the program assumes the insulating or gap filler to be conductively isotropic, with the thermal conductivity assuming the input variation in the lateral direction). Emissivities of the wall and insulation surfaces can assume variation (a).

Input to the program consists of punched data cards. These cards fall under four categories.

- a. Header cards - total of six. These cards contain the temperature coefficients for the system emissivities and thermal conductivities, plus the radiation - backscatter cross section (fraction of incident radiation backscattered per unit length of traverse) for the gap filler.
- b. Problem cards - one or more per set of header cards. These cards contain data that define the linear dimensions, mesh spacings, and boundary conditions of the system. Each problem card defines a case to be run.
- c. Surface Temperature Cards (options1) - up to four per problem card. These cards, used only for a totally - exposed - edge case, define a non-uniform prescribed temperature profile on one or both panel surfaces.
- d. Blank spacer cards.

During execution the program:

- a. Reads in the first header card. If it is blank, execution is terminated. Otherwise, the five remaining header cards are read in.
- b. Reads in a problem card.
- c. Checks problem card data for errors. If an error is found, the current problem is terminated and the next problem card is read in. If the problem card is blank, control is transferred back to step (a).
- d. Integration mesh parameters (spacings and cross section areas) panel - surface temperature profiles, radiation configuration factors, and the starting temperature profiles and overall heat flux are computed. The individual system heat fluxes are initially set to zero.
- e. Corresponding to each integration mesh point, a linear equation is set up that expresses the temperature at that mesh point as a weighted sum of temperatures at the "nearest-neighbor" mesh points plus an optional "constant" term. The weighting factors and constant terms are derived through finite difference approximations to the Fourier heat conduction equation and the appropriate boundary conditions. Thermal conductivities in the region between two adjacent mesh points are evaluated at the arithmetic mean of the temperatures at the two points.

f. The system heat fluxes are computed and printed out. If the sum of the fractional changes between the last two sets of heat fluxes is greater than a specified tolerance (0.001), and if the number of iteration cycles does not yet exceed 10, steps (g) - (i) are executed. Otherwise control passes to step (j).

g. The linear set of finite difference equations is solved for the unknown temperatures. Based upon this new set of temperatures, step (e) is repeated. Also, the system heat fluxes are recomputed.

h. A "final" temperature profile for this iteration cycle is computed by taking a weighted sum of the two most recently computed temperature profiles. The weighting factors are derived from the over-all heat imbalances corresponding to the sets of heat fluxes computed in steps (f) and (g).

i. This new temperature profile is printed out and control passes to step (e).

j. The "no-edge" flux (flux through a panel of the same width with zero edge losses), and the ratio of the actual computed flux to the "no-edge" flux, are printed out and control passes to step (b).

Printer output for a typical problem is attached at the end of the appendix.

H-2. CALCULATIONS

The major calculations performed during program execution divide into four categories:

1. Evaluation of prescribed temperature profiles on the panel surfaces.
2. Evaluation of configuration factors for radiative exchange within the gap.
3. Evaluation of the weighting factors used in the linear difference equation defined at each mesh point.
4. Solution of the difference equations for the temperatures at all mesh points.

During the course of this analysis, the temperatures of both panel surfaces are assumed fixed at specified values. In most cases, the temperature along either surface is also assumed to be uniform. However, when the panel edges are completely exposed and radiating to an infinite wall (INDEX=0), experimental data indicates that the true temperature profile is not necessarily uniform along both surfaces. To simulate this condition, a temperature profile can be specified along on or both surfaces. This option executes as follows.

Temperatures for the warm side and/or cold side surfaces are input on cards immediately following the problem card for the case to be run. Each card contains up to four temperatures and corresponding distances from the panel midplane to the surface point that is at that temperature. Up to two temperature cards can be input per surface; warm side surface cards are input first

The cards contain only temperatures at points off the panel midplane; the midplane surface temperature is set to TH (or TC) by the program.

If the number of input temperatures punched on the problem card for either surface is greater than zero, and if INDEX is zero, the surface temperature cards for this surface are read in. The discrete input temperatures are then converted to a continuous temperature profile $T_s(X)$, consisting of a series of parabolic segments joined at the input X-positions. The slope of this temperature profile is also continuous and, because of the assumed adiabatic nature of the midplane, vanishes there.

A radiative configuration factor can be defined in either one of two ways:

a. The fraction of radiation leaving an area that falls upon a second area (view factor).

b. The fraction (a), multiplied by the first area (effective exchange area or area factor).

The method used for computing configuration factors between two surfaces separated by empty space is well documented^{1,2}. The technique used when a backscattering medium separates the surfaces is documented in a recent report⁷. The basic equations, along with a schematic drawing of the two radiation-coupled surfaces, are given in Figure H-2.

Closed form expressions for the configuration factors could be derived only for the no-backscatter case. Configuration factors with included effect of backscattering were evaluated numerically by 64-point double Gauss quadrature.

Figure H-3 shows the differential equations and boundary conditions governing the temperature distribution within the system.

When the appropriate differential equations and boundary conditions are discretized at each mesh point, there results a quasi-linear finite difference equation of the form

$$X'(T_{i,j} - T_{i+1,j}) + X''(T_{i,j} - T_{i-1,j}) + Z'(T_{i,j} - T_{i,j+1}) + Z''(T_{i,j} - T_{i,j-1}) = C$$

where the weighting factors X' , X'' , Z' , Z'' , and C are themselves temperature dependent because of the variation with temperature of the thermal conductivities and/or emissivities used to compute them. The subscripts i and j refer, respectively, to the positions of the central mesh point and its nearest neighbors in the lateral (x) and normal (z) directions.

Definition of Radiation Configuration Factors Configuration Factors

(β = Backscatter Cross Section)
 (ρ_i = Reflectivity of Surface A_i)

For a) $i = 1, j = 2$
 b) $i = 2, j = 1$

F_{ij} = Fraction of Radiation Leaving A_i That Falls on A_j (view factor)

A_{ij} = Area factor = $A_i F_{ij}$

$$= \frac{(A')_{ij}}{A_i - \rho_i ((A')_{ij} - (A'_0)_{ij})}$$

where $(A')_{ij} = \int_{A_i} \int_{A_j} \frac{\cos \Theta_i \cos \Theta_j dA_i dA_j}{\pi R^2 (1 + \beta R)}$

$$(A'_0)_{ij} = (A')_{ij} \Big|_{\beta=0} = \int_{A_i} \int_{A_j} \frac{\cos \Theta_i \cos \Theta_j dA_i dA_j}{\pi R^2}$$

If the heat transfer mechanisms about point (i,j) are strictly conductive, or radiative to an infinite, uniform-temperature wall (ie. all mesh points not bounding a translucent gap), the temperature at this point will depend directly only upon nearest-neighbor temperatures.

However, if the point bounds are interpanel gap, and if that gap is translucent to radiation, then the temperature at that point will depend directly upon temperature at other Z-levels besides (j-1), j, and (j+1). The finite difference equations for these gap-boundary points can be made consistent with the above form, however, by including heat transfer terms corresponding to non-nearest-neighbor Z-positions in the right-hand-side factor C.

In most cases, the derivation of the weighting factors from the finite difference equations is quite straightforward. However, the equations governing the radiative interchange among the surfaces of a translucent gap (eg. flux (Q_i) RAD in Figure H-3. are complicated functions of the gap geometry (as expressed through the geometric configuration factors), back-scatter cross section, and temperature profile along the gap boundaries. These equations were derived using the techniques outlined in Chapter 3 of Hottel and Sarofim².

Let N_x equal the number of lateral mesh positions lying between the panel midplane ($x=0$) and either the panel edge ($x=W/2$, INDEX-0 or 1) or the gap midplane ($x=(W+G)/2$; INDEX-2 or 3).

Then the total number of mesh points (and unknown temperatures) is equal to N, where

$$N = (N_x) (N_z)$$

and N_z equals the number of axial mesh positions inside the panel and gap. Once the equations have been set up, the temperatures can be found by solving the matrix equation

$$(A) (T) = (B)$$

where A is an Nth order coefficient matrix, T is an N-element vector of unknown temperatures, and B is an N-element "constant" vector (containing the C factors as given in the general form of the finite difference equation). Since in many instances a fine mesh must be chosen in order to compute an accurate temperature profile, N can become very large. Solution of the difference equations by direct inversion of matrix A can thus be very time consuming (since computation effort required to invert A is approximately proportional to the cube of N) and exceedingly wasteful of computer core storage (since most of the elements of A are zeroes). However, the "nearest-neighbor" structure of the finite difference equations makes possible a much more efficient solution technique.

* Applies to rectangular gap, 0 Theta/2 for sector-shaped gap.

Differential Equations and Boundary ConditionsFourier Equation:

Insulation:

Rectangular Gap:
(INDEX = 2, 3)Sector-Shaped Gap:
(INDEX = 2, 3)Boundary ConditionsLateral (x or θ) Direction

$$(1) \left. \frac{\partial T_i}{\partial x} \right|_{x=0} = 0$$

$$(2) k_{ix} \left. \frac{\partial T_i}{\partial x} \right|_{x=\frac{W}{2}} = \sigma \epsilon' (TW^4 - (T_i(\frac{W}{2}, z))^4), \text{ INDEX} = 0$$

$$= 0, \text{ INDEX} = 1$$

$$= \begin{cases} k_{yx} \left. \frac{\partial T_g}{\partial x} \right|_{x=\frac{W}{2}} \\ \text{OR} \\ \frac{k_{gx}}{2} \left. \frac{\partial T_g}{\partial \theta} \right|_{\theta=0} \end{cases}, \text{ INDEX} = 2$$

$$= \begin{cases} k_{gx} \left. \frac{\partial T_g}{\partial x} \right|_{x=\frac{W}{2}} + (Q_i)_{RAD} \\ \text{OR} \\ \frac{k_{ix}}{2} \left. \frac{\partial T_g}{\partial \theta} \right|_{\theta=0} + (Q_i)_{RAD} \end{cases}, \text{ INDEX} = 3$$

$$(3) \begin{cases} \left. \frac{\partial T_g}{\partial x} \right|_{x=\frac{W}{2}} = 0 \\ \text{OR} \\ \left. \frac{\partial T_g}{\partial \theta} \right|_{\theta=\frac{TH}{2}} = 0 \end{cases}, \text{ INDEX} = 2, 3$$

LEGEND

SUBSCRIPTS:

g - GAP

i - INSULATION

x (OR θ) - LATERAL DIRECTION

(OR r) - NORMAL DIRECTION

RAD - REFERS TO RADIATIVE FLUX INSIDE GAP

* - REFERRED TO FLUX OF INSULATION ADJACENT

$$\frac{\partial}{\partial x} (k_{ix} \frac{\partial T_i}{\partial x}) + \frac{\partial}{\partial z} (k_{iz} \frac{\partial T_i}{\partial z}) = 0$$

$$\frac{\partial}{\partial x} (k_{gx} \frac{\partial T_g}{\partial x}) + \frac{\partial}{\partial z} (k_{gz} \frac{\partial T_g}{\partial z}) = 0$$

$$\frac{1}{r^2} \frac{\partial}{\partial \theta} (k_{g\theta} \frac{\partial T_g}{\partial \theta}) + \frac{1}{r} \frac{\partial}{\partial r} (r k_{gr} \frac{\partial T_g}{\partial r}) = 0$$

Normal (z or r) Direction

$$(1) T_i(x, 0) = TH, \text{ INDEX} = 0$$

$$= f(x), \text{ INDEX} = 1$$

$$(2) T_i(x, H) = TC, \text{ INDEX} = 0$$

$$= g(x), \text{ INDEX} = 1$$

$$(3) \begin{cases} T_g(x, 0) = TH \\ T_g(x, H) = TC \end{cases}, \text{ INDEX} = 2, 3$$

$$\begin{cases} T_g(\theta, 0) = TH \\ T_g(\theta, H) = TC \end{cases}$$

PARAMETERS

$$\begin{cases} T_g(x, z) \\ T_g(\theta, r) \\ T_i(x, z) \end{cases} \text{ TEMPERATURES}$$

T - SURFACE TEMPERATURE

C - WALL EMISSIVITY

Q - FLUX

If the equations are written so that all N_x equations corresponding to a particular Z-level are grouped together, with these groups of equations in order of ascending (or descending) Z-position, the coefficient matrix A will subdivide into $(N_z)^2$ submatrices, each one of which is a square matrix of order N_x . (Hereafter, N_z will be called the block order of A). However, because of the "nearest-neighbor" effect, only those submatrices lying along, and immediately to the left and right of, the main diagonal of A will contain non-zero elements. Matrix A is therefore block-tridiagonal. The finite difference equations can thus be solved using a matrix analogue of the familiar Gauss Elimination technique for solution of tridiagonal systems of linear equations. The task of inverting one Nth order matrix is then reduced to the inversion of N_z matrices of order N_x , with a subsequent reduction in the number of calculations by a factor of, approximately,

$$\frac{(N)^3}{(N_z)(N_x)^3} = (N_z)^2$$

This solution technique has been used successfully in earlier studies by several investigators, including L. D. Potts³ and D. Suckow^{5,6}.

Because of the temperature dependence of the weighting factors included in the equations, the solution must be repeated iteratively until the temperatures converge to final values. Although an iteration cutoff of 10 cycles is included in the program, convergence generally requires only three or four cycles.

Bibliography

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H.4 Output for a typical problem

H-11

NEW THERMAL CONDUCTIVITY DATA:

SLAB(NORMAL):	0.0	0.500000	0.0	1.000000				
SLAB(LATERAL):	13.0000	49.0000	1200.00	0.0	0.0	0.0	25.0000	0.0
GAP(NORMAL):	13.000000	0.0	3.000000	0.0	0.0	0.0		
AP(LATERAL):	46.0000	0.0	1000.00	-54.0000	100.0000	5000.00	0.0	0.0

TEMPERATURE COEFFICIENTS OF FOIL EMISSIVITY=							
0.20000000	0.0	5000.000	0.0	0.0	0.0	0.0	0.0
TEMPERATURE COEFFICIENTS OF WALL EMISSIVITY=							
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

BACKSCATTER CROSS SECTION (IN-1) : 0.0

```

PROBLEM NUMBER:      1

SLAB THICKNESS (IN): 1.4170
SLAB WIDTH (IN):     14.1700
GAP WIDTH (IN):       2.0000
GAP ANGLE (DEG):      0.0
TEMPERATURES (R):
HOT SIDE:             1500.0000
COLD SIDE:             500.0000
WALL:                  0.0
LATERAL INSULATION MESHES: 7
LATERAL GAP MESHES:   4
NORMAL MESHES:        6
INDEX:                2

```

INITIAL TEMPERATURE PROFILE (INSULATION UNDISTURBED) AFTER 1 ITERATION CYCLE(S):

1500.00 1434.32 1337.16 1186.37 938.35 500.00

ITERATION CYCLE NUMBER 1

TEMPERATURES:

```

1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00
1422.53 1422.53 1422.52 1422.45 1421.94 1418.18 1391.78 1384.79 1381.42 1380.01 1379.64
1322.17 1322.17 1322.15 1322.02 1321.03 1313.71 1262.38 1249.01 1242.95 1240.55 1239.92
1180.98 1180.97 1180.95 1180.78 1179.47 1169.63 1097.42 1078.22 1071.01 1068.41 1067.76
956.59 956.58 956.56 956.40 955.19 945.76 866.00 845.89 840.41 838.67 838.25
500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00

```

INCREMENTAL NORMAL FLUXES (BTU/HR.FT.):

```

INTO HOT SIDE:      FROM COLD SIDE:
0.32586340 01      0.82347050 01
0.69275600 01      0.15520330 02
0.71248120 01      0.15262800 02
0.72069660 01      0.15180830 02
0.36144420 01      0.75805620 01

0.27966860 01      0.32122550 01
0.55934430 01      0.64244550 01
0.55940540 01      0.64239720 01
0.55986610 01      0.64203120 01
0.56330660 01      0.63924960 01
0.58844080 01      0.61782150 01
0.38001520 01      0.22650130 01

```

TOTAL FLUXES (BTU/HR.FT.):

```

INTO GAP HOT SIDE:      0.28132420 02
INTO INSULATION HOT SIDE: 0.34900470 02

FROM GAP COLD SIDE:      0.61779220 02
FROM INSULATION COLD SIDE: 0.37316720 02

FROM INSULATION TO GAP:  -0.24162470 01

TOTAL FLUX IN:          0.63032890 02
TOTAL FLUX OUT:         0.99095940 02

```

ITERATION CYCLE NUMBER 2

TEMPERATURES:

```

1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00 1500.00
1408.76 1408.75 1408.74 1408.64 1407.85 1401.69 1353.25 1337.15 1330.10 1327.34 1326.62
1371.51 1371.51 1371.48 1371.27 1299.64 1286.99 1190.04 1160.92 1148.48 1143.75 1142.56
1166.16 1166.16 1166.12 1165.82 1163.52 1145.67 1005.26 966.11 951.74 946.68 945.44
967.05 967.05 967.01 966.71 964.36 945.84 784.50 747.35 736.65 733.21 732.40
500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00 500.00

```

INCREMENTAL NORMAL FLUXES (BTU/HR.FT.):

```

INTO HOT SIDE:      FROM COLD SIDE:
0.43805130 01      0.63290260 01
0.46877820 01      0.10950590 02
0.10091130 02      0.17462170 02
0.10249130 02      0.10305620 02
0.51450420 01      0.51341510 01

0.32535910 01      0.33347610 01
0.65072770 01      0.66680200 01
0.65081290 01      0.66671070 01
0.65147910 01      0.66600130 01
0.65666610 01      0.66050440 01
0.69664970 01      0.61799000 01
0.49760310 01      0.15630990 01

```

TOTAL FLUXES (BTU/HR.FT.):

```

INTO GAP HOT SIDE:      0.29554500 02
INTO INSULATION HOT SIDE: 0.41229200 02

FROM GAP COLD SIDE:      0.43101550 02
FROM INSULATION COLD SIDE: 0.37677450 02

FROM INSULATION TO GAP:  0.26156740 01

```

TOTAL FLUX IN: 0.80847420 02
TOTAL FLUX OUT: 0.80858300 02

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MINIMUM TOTAL FLUX: 0.28273780 02
TOTAL-T(-MINIMUM RATIO: 0.28596490 01

***** END OF THIS GROUP OF PROBLEMS *****

APPENDIX I

METALLURGICAL EVALUATION OF THE NICKEL-OPACIFIED
REFRASIL QUARTZ MULTILAYER SYSTEM

I.1 INTRODUCTION:

A multilayer nickel opacified Refrasil quartz insulation was operated at a maximum hot side temperature of 1485°F for 10,000 hours. Data obtained indicated that a performance deterioration (i.e., K_a increase) of 32% occurred. It was postulated that volatilization of the nickel flake opacifier had occurred as a result of the high temperature sojourn. The insulation system was sent to the Metallurgical Laboratory for evaluation and verification of the mode of deterioration.

I.2 METALLURGICAL EVALUATION:

The following constituted the Metallurgical Evaluation:

1. Micro inspection of insulation layers at magnifications up to 60X.
2. Micro examination of insulation layers at magnifications up to 1000X.
3. X-ray diffraction.

I.3 RESULTS/OBSERVATIONS:

Squares approximately 1" on a side were removed from the multilayer insulation. It was immediately noted that a color change had occurred in various layers of the insulation. Table I.1 shows the change. Also included are other observations regarding the strength and stiffness of the individual layers.

Segments of layers representative of different colors and zones were removed for comparison with a sample of an as-received sample. Figure I.1 shows the surface of an as-received Ni-opacified Refrasil. Numerous flakes of nickel can be seen in Figure I.1.

Figure I.2 shows the surface of layer number 1, the hottest Ni-opacified Refrasil layer. It is obvious that the quantity of bright shiny nickel flakes is considerably less than the sample shown in Figure I.1.

Figures I.3 and I.4 show the surface of layer number 7, a transition layer, in gray and green areas respectively. It can be seen that the number of bright nickel flakes in Figures I.3 and I.4 is considerably less than layer number 1. What is not obvious in Figures I.3 and I.4 is that there are more flakes in the photos than are indicated by the shiny spots. In the green area represented by Figure I.4 some of the dark spots barely visible in the photograph are nickel flakes which are covered with a green tarnish film or deposit.

Figure I.4 shows the surface of layer 14 which was one of the all green layers. Not a single nickel flake is visible in Figure I.5. However, when all filters were removed from the microscope for observation it was observed that numerous flakes still were present in the refrasil layer. However, virtually all of the flakes were covered with a green deposit or tarnish film. Arrows shown in Figure I.5 point to two obvious flakes. However, more flakes are in the field of view of the photo and not resolvable. Figures I.6 and I.7 show layers 19 and 21 in the transition zone where the condition persisted.

Figure I.8 shows the surface of the coldest layer, number 28, and bright nickel flakes are visible. Comparing Figure I.1 with Figure I.8 it is obvious that the sample of as-received material contains more apparent flakes than the coldest layer in the insulation. This may suggest that the two samples in Figures I.1 and I.9 are not representative of the same lot and processing or possibly that some nickel flakes were lost in layer number 28. When the hottest and coldest layers, Figures I.2 and I.8 respectively, are compared there is some difference in particle size. Larger particles are visible in Figure I.28. This would tend to suggest that some volatilization had occurred as a result of the temperatures and vacuum exposure.

Figure I.9 shows the estimated temperature profile of the nickel opacified Refrasil multilayer insulation system. From Figure I.9, the green color which was noted to be located between layers 5 and 21 is seen to be associated with the temperature interval of 1000-1400°F.

I.4 CONCLUSION

The postulated degradation mode had originally been volatilization of the nickel flakes. Comparison of samples of as-received, cold and hot layers indicate that is possible. However, the green deposit or film observed on the nickel flakes in layers 5 through 21 could also affect the thermal performance by altering the surface emissivity.

These deposits were positively identified as nickel oxide by diffraction techniques. The sources of the oxygen may be the refrasil fibers however, water vapor given off during heating is also a possibility.

TABLE I.1

MACRO OBSERVATIONS ON NICKEL OPACIFIED
REFRASIL QUARTZ MULTILAYER

<u>Layers</u>	<u>Observations</u>
1 - 4	Light gray color, somewhat stiff
5 - 7	Transition Zone, gray-green color
8 - 17	Light green color; tends to powder easily
18	Transition Zone, gray-green color
19 - 28	Gray (Original Color). Layer 28 is the strongest layer.

NOTE: Layer No. 1 is the hottest layer
Layer No. 28 is the coldest layer

Figure I.1 Surface of as-received Ni-opacified Refrasil. Color of material was gray.

Mag: 150X

Figure I.2 Surface of layer No. 1 (hottest) of Ni-opacified Refrasil. Material had a gray color.

Mag: 150X

Figure I.3 Surface of layer No. 7 of Ni-opacified Refrasil in a gray area. Arrows point to dark nickel flakes.

Mag: 150X

Figure I.4 Surface of layer No. 7 of Ni-opacified Refrasil in a green area. Arrows point to green nickel flakes.

Mag: 150X

I-5

Figure I.5 Surface of layer
No. 14 of Ni-
opacified Refrasil.
Flake locations
indicated by arrows.

Mag: 150X

Figure I.6 Surface of layer No.
19 of Ni-opacified
Refrasil

Mag: 150X

Figure I.7 Surface of layer
No. 21 of Ni-
opacified Refrasil.

Mag: 150X

Figure I.8 Surface of layer
No. 28 of Ni-
opacified Refrasil.
This was the coldest
layer in the insulation
package.

Mag: 150X

Figure I-9

ESTIMATED TEMPERATURE PROFILE OF THE
NICKEL-OPACIFIED REFRASIL QUARTZ MULTILAYER

APPENDIX J

METALLURGICAL EVALUATION OF 1800 °F
MODIFIED COMPOSITE MULTIFOIL SYSTEM
AFTER A 7, 760 HOUR TEST

J.1 INTRODUCTION:

A composite multifoil insulation system designed to operate at a maximum hot face temperature of 1800°F was submitted to the metallurgical laboratory for evaluation after 7,760 hours of an intended 10,000 hour test. Figure J-18 shows the estimated temperature profile at the beginning of the test and material combinations used in the composite. The metallurgical evaluation showed that the maximum hot face temperature at the end of the test was probably in the vicinity of 1950-2000°F.

J.2 METALLURGICAL EVALUATION:

The following steps constituted the procedure for the evaluation of the composite:

1. Macro examination of the composite at magnifications up to 60X.
2. Micro examination of selected layers at magnifications up to 1000X.
3. Qualitative bend and tear tests of foil and spacer material.
4. X-ray diffraction studies of selected materials.
5. Heat treatment tests of foil and spacer material.
6. Macro examination of the Pt-Rh heater leads at magnifications up to 60X.

J.3 OBSERVATIONS/RESULTS:

1. Macro examination of individual layers during the disassembly of the composite insulation system revealed that in general, the insulation system was in good condition. With the exception of a copper foil which was in contact with an aluminum opacified glass paper, there was no evidence of any high temperature reactions involving melting, or massive volatilization. The copper foil in contact with the aluminum paper developed cracks probably the result of eutectic reaction between aluminum and copper. This foil will be discussed in more detail later in this report.

2. Table J-I tabulates the results of bend and tear tests of foils and spacer materials in the composite. Each separate foil and spacer was assigned a number as a separate and distinct sub-layer. This is in contrast to the normal practice of considering a foil and a spacer together as a distinct layer. The hottest molybdenum foil was arbitrarily designated with the number 1 and the astroquartz layer immediately adjacent was arbitrarily designated with the number 2. Increasing numbers therefore, indicate increasingly cooler foils and spacers.

As expected, the hotter molybdenum foils (1, 3, 5 and 7) were brittle and cracked easily when bent. Embrittlement of molybdenum is the result of recrystallization at elevated temperatures. An improvement in ductility was noted in molybdenum layers 9 through 17 which either cracked in only one direction or creased when bent. Thus it appeared that layers 9 through 17 were in the early stages of recrystallization. Molybdenum foils 19, 21, 23 and 25 were ductile indicating that recrystallization had not occurred. Abruptly molybdenum foil 27 was observed to be brittle. Cooler molybdenum foils 27 through 57 exhibited varying degrees of ductility. The sudden reversion to brittle behavior in bend tests of the molybdenum foils suggested that more than one lot of molybdenum foil was used in the composite. Since recrystallization, the major cause of embrittlement, is affected by chemistry, previous thermal history and cold work, different foil lots with different histories could exhibit different recrystallization temperatures, thus producing the varying bend behavior shown in Table J-I.

Nickel, copper and aluminum foils were similarly examined. All of these foils maintained their ductility. This even included copper foil 101 which developed numerous cracks as a result of a melting reaction between it and an Al-opacified glass.

3. Figures J-1 through J-6 are photomicrographs of molybdenum in the as-received and temperature exposed conditions. Figure J-1 is a photomicrograph of the surface of an as-received foil. The surface does not show any evidence of recrystallization. Also visible in Figure J-1 are mechanical twins which are typical of heavily worked molybdenum foil.

Figure J-2 is a photomicrograph of molybdenum foil, layer 1, which experienced the hottest temperatures in the system. The microstructure shows the presence of discrete grains indicating that the molybdenum has recrystallized. Some of the original surface markings from manufacture are still visible. That these markings are still visible tends to indicate that volatilization was of minimal importance. Figure J-3 shows a crack in another area on the same foil. The crack occurred in a grain boundary and demonstrated the adverse effect of grain boundaries on mech-

anical properties. In molybdenum foils which had been part of the 2500°F. Mo-ZrO₂ test, grain boundaries were more deeply grooved or vacuum etched than was observed in the hottest Mo layer in this test. Actually very little grooving or surface volatilization occurred in the Mo foils in the 1800°F, composite. That the original manufacturing markings are still visible confirm this fact.

The grain boundary network became much fainter as progressively cooler molybdenum foils were encountered. Figure J-4 shows that a grain boundary network is barely visible in a cooler molybdenum foil (layer 19). The faint grain boundary network indicating the start of recrystallization was visible in most of the cooler molybdenum foils. Figure J-5 shows that even the coolest molybdenum foil, layer 57, was in the early stages of recrystallization when the test was terminated. There was little apparent difference between molybdenum foils intermediate to 14 and 57.

4. Figure J-6 shows a typical as-received nickel foil which does not exhibit any recrystallization. The hottest nickel foil, layer 59, experienced severe recrystallization and grooving in the grain boundaries. Figure J-8 shows that the coldest nickel, layer 83, is in an intermediate stage of recrystallization. Severe grain boundary grooving as shown in Figure J-7 could adversely effect the surface emissivity of a nickel foil used in an insulation composite.

5. The as-received surface of copper foil is shown in Figure J-9. Again there was no evidence of recrystallization in the as-received material. Figures J-10 and J-11 show the surfaces of the hottest copper foil, layer #87, and an intermediate copper foil #95. Extensive grain growth and thermal grooving is visible in Figure J-10 and to a lesser extent in Figure J-11.

Figure J-12 is a photomicrograph of the coldest copper foil, layer #101, which developed numerous cracks. This foil was placed between refrasil and Al-opacified paper and the side which contacted the aluminum opacified paper experienced severe deterioration as a result of localized melting. Eutectic melting in the aluminum-copper system can occur in the vicinity of 1000°F $\pm$ 50 °F. The estimated temperature profile for the 1800°F. composite (Attachment 1), indicated an estimated temperature of 900°F. for the boundary between the Cu-refrasil and Al-Al opacified glass components of the system. Thus, on the basis of the eutectic reaction which was observed, the profile can be raised 50-100°F. at the Cu-refrasil and Al-Al opacified glass interface. Figures J-13 and J-14 are photomicrographs of the two sides of the copper foil shown in Figure J-12.

Figures J-15, J-16 and J-17 are photomicrographs of as-received aluminum foil, the hottest aluminum foil (Layer #103), and the coldest aluminum foil (Layer #110). The as-received aluminum foil in Figure J-15 has not been recrystallized. There is some evidence of recrystallization in Figure J-16 and grain boundaries are visible. The surface of the coldest aluminum foil was relatively indistinct and difficult to resolve.

6. To help obtain a fix on the maximum hot face temperature, x-ray diffraction techniques were used to compare the hottest astroquartz layer, layer #2, with the as-received astroquartz and astroquartz specimens heat treated for 20 hours at 900°C, 1010°C, 1100°C and 1200°C. According to vendor data, Crystobalite, an SiO_2 phase, will start to form if held at temperatures as low as 1900°F (1038°C). Crystobalite was not detected in the as-received astroquartz, the hottest astroquartz layer or astroquartz specimens heated to 900°C and 1010°C. A small amount of Crystobalite was detected in astroquartz specimens heated to 1100°C and large amounts were detected in specimens heated to 1200°C. On the basis of these tests the hottest astroquartz layer experienced a maximum temperature of less than 1100°C (2012°F).

7. As-received molybdenum foil was heated and observed in a microscope hot stage. Recrystallization on heating occurred between 1820 and 1920°F. With longer hold times recrystallization might occur as low as 1750°F. Comparison of recrystallized molybdenum foil with the hottest molybdenum foil, layer #1, in the system suggested that the maximum hot face temperature was between 1950°F and 2050°F. However, when the results of the astroquartz experiments previously mentioned are considered, it is apparent that the estimated maximum hot face temperature was probably between 1950°F and 2012°F.

8. Heater wires (Pt-Rh) which were part of the system were examined. Although there was some evidence of thermal etching and grain growth there was no evidence of localized eutectic melting which damaged 1 or 2 layers of a molybdenum-zirconia 2500°F insulation test panel.

J.4 DISCUSSION:

Generally it can be concluded that the condition of the 1800°F composite after completion of the 10,000 hour test is very good. The one instance of incompatibility which was observed occurred between a

copper foil and an Al-opacified paper because of a low melting eutectic reaction between copper and aluminum which occurs at approximately 1000°F. The solution is simply to avoid combinations of copper and Al-opacified glass where there is any possibility of being in the vicinity of 1000°F.

After a comparison of the surfaces of copper and nickel foils with the molybdenum foils it is apparent that the copper and nickel foil surfaces experienced some grain growth, and thermal etching, i.e., grain boundary grooving whereas the molybdenum foils seemed much less affected by the temperature exposure. It is therefore thought that the emissivities of the copper and nickel foil may have experienced some increase whereas it is believed that the emissivity change in molybdenum foils was little if any.

Examination of the surface of the molybdenum foil indicated some evidence of at least the start of recrystallization throughout the molybdenum portion of the composite. The recrystallization of a material is affected by impurities, previous thermal and mechanical history and time at temperature. Different lots of molybdenum foil could be expected to show recrystallization at different temperatures. Generally the lowest temperature range associated for recrystallization of commercial molybdenum is 1750-1800°F. Since the start of recrystallization was detected in the coldest molybdenum foil, it would appear that a temperature of 1750-1800°F could be assigned to the interface between the molybdenum-astroquartz and nickel-refrasil. This would place the nickel portion of the composite above the 1600°F maximum use temperature associated with nickel-refrasil super insulation. Similarly an estimate of 1950-2050°F is assigned to the hottest molybdenum foil because excessive grain growth and thermal etching was not observed. Grain boundaries with the exception of the hottest molybdenum foils were barely outlined. Recrystallization experiments of as-received molybdenum foil in a microscope heating stage did cause recrystallization of as-received molybdenum foil in the 1870-1920°F on heat up.

When the results of the metallographic work, molybdenum recrystallization experiments and X-ray diffraction studies are compared it is apparent that a good estimate of the maximum hot face temperature is 1950°F to 2012°F.

On the basis of the 7,760 hour test it appears that if maximum intended hot face temperatures are exceeded, it would be better in a composite insulation to use molybdenum-astroquartz, for insulation lower than 1600°F to preclude possible volatilization effects if actual temperatures were higher than expected. Using the same concept, nickel-refrasil could be used below 1380-1400°F and the copper-refrasil could replace

the aluminum-aluminum opacified system. Possibly an all molybdenum-astroquartz would offer fewer problems.

J.5 CONCLUSIONS:

1. The following temperatures are estimated on the basis of recrystallization experiments coupled with metallographic and X-ray diffraction evidence:

- a) Maximum hot face temperature, 1950-2012°F
- b) Mo-Astroquartz/Ni-Refrasil Interface, 1750-1800°F
- c) Cu-Refrasil/Al-Al Opacified Glass Interface, 950-1050°F

2. With the exception of a copper foil in contact with an Al-opacified glass, there was no evidence of low melting reactions.

3. The Mo-astroquartz components were in satisfactory condition after the test. This conclusion assumes that molybdenum embrittlement and mechanical deterioration are not problems to be concerned about at this time.

4. Thermal etching of nickel and copper foils suggest a possible increase in emissivity and indicates that the nickel and copper may have been used in excess of their capability.

TABLE J-IMACRO EXAMINATION & QUALITATIVE TESTS

<u>Layer</u>	<u>Material</u>	<u>Comments</u>
1	Mo	Hottest foil, brittle, stick to ceramic tube, no evidence of reaction with Astroquartz
2	Astroquartz	Brittle, did not react with Mo
3	Mo	Brittle, no evidence of reaction with astro-quartz cloth, shiny
4	Astroquartz	Brittle, pulls apart easily
5	Mo	Brittle
6	Astroquartz	Brittle
7	Mo	More ductile than hotter Mo foils, still breaks when bent
8	Astroquartz	Brittle
9	Mo	Creases when bent, did not crack
10	Astroquartz	Brittle when bent
11	Mo	Cracks when bent in one direction but not in other
12	Astroquartz	Creases when bent
13	Mo	Similar to 11
14	Astroquartz	Similar to 12
15	Mo	Similar to 11
16	Astroquartz	Some powder noted
17	Mo	Similar to 11
18	Astroquartz	Similar to 12
19	Mo	Increasing ductility, doesn't crack when bent
20	Astroquartz	Similar to 12

TABLE J-I CONTINUED

<u>Layer</u>	<u>Material</u>	<u>Comments</u>
21	Mo	Similar to 19
22	Astroquartz	Will bend without cracking, brittle when pulled
23	Mo	Bends in both ways without cracking, will crease
24	Astroquartz	Similar to 22
25	Mo	Ductile, no evidence of reaction with Astroquartz
26	Astroquartz	Some improvement in tensile properties
27	Mo	Mo 27 is more brittle than Mo 25. Possible difference in material lot?
28	Astroquartz	Similar to 26
29	Mo	Brittle
30	Astroquartz	Similar to 26
31	Mo	Brittle in 1 direction
32	Astroquartz	Greater resistance to bending
33	Mo	Similar to 31
34	Astroquartz	Similar to 32
35	Mo	Creases when bent
36	Astroquartz	Similar to 34
37	Mo	Somewhat brittle in 1 direction
38	Astroquartz	Similar to 34
39	Mo	Similar to 37
40	Astroquartz	Similar to 34
41	Mo	Similar to 37
42	Astroquartz	Similar to 34

TABLE J-I CONTINUED

<u>Layer</u>	<u>Material</u>	<u>Comments</u>
43	Mo	Brittle, another change in material? No evidence of surface reaction
44	Astroquartz	Bends OK
45	Mo	Ductile in both directions
46	Astroquartz	Somewhat improved tensile & Bends
47	Mo	Similar to 45
48	Astroquartz	Similar to 46
49	Mo	More brittle than 47
50	Astroquartz	Similar to 48
51	Mo	Similar to 45
52	Astroquartz	Similar to 48
53	Mo	Similar to 45
54	Astroquartz	Improved tensile & bends
55	Mo	Creases when bent, won't crack
56	Astroquartz	Similar to 54
57	Mo	Coldest Mo foil, brittle in one direction
58	Astroquartz	Coldest astroquartz cloth, exhibits decreased tensile & bend properties when compared with as-received astroquartz, however, mechanical properties still better than hotter astroquartz layers.
59	Ni	Hottest nickel foil, ductile, no evidence of reaction with astroquartz or reffrasil.
60	Reffrasil	Hottest reffrasil layer, tears easily, no evidence of reaction nickel layers.

TABLE J-I CONTINUED

<u>Layer</u>	<u>Material</u>	<u>Comments</u>
Remaining Ni Layers		
61, 63, 65, 67, 69, 71, 73, 75, 77, 79, 81, 83, 85		All ductile, little difference visually at low magnification, no apparent reaction with refrasil.
Refrasil in Contact with Ni		
62, 64, 66, 68, 70, 72 74, 76, 78, 80, 82, 84		Refrasil tears apart easily, mechanical properties improve with decreasing temperature.
86	Refrasil	Coldest refrasil layer in contact with Ni and hottest refrasil layer in contact with Cu. No evidence of any reaction.
87	Cu	Ductile, some black discoloration noted.
Remaining Refrasil Layers		
88, 90, 92, 94, 96, 98, 100		Mechanical properties continued to improve with decreasing temperature. Coldest refrasil layer (No. 100) has inferior mechanical properties to as-received refrasil.
Other Cu Layers		
89, 91, 93, 95, 97, 99, 101		Ductile, Cracked, Coldest Cu layer in contact with refrasil on hot side and Al opacified paper on other developed numerous cracks. Reacted with Al opacified paper.
102	Al opacified paper	Reacted with Cu foil 101. Possible low melting eutectic (Cu Al_2).
103, 105, 107, 109	Al	All Al layers are ductile. No evidence of surface reaction.
104, 106, 180, 110	Al opacified paper	Hottest Al opacified paper tears more easily than 110. No further evidence of surface reaction.

J-11

Figure J-1. Photomicrograph of surface of as-received Mo foil shows that the microstructure has not been recrystallized

mag: 300X

Figure J-2. This photomicrograph shows the Mo foil (Layer #1) which experienced the hottest temperatures. Recrystallization is evident. Some of the original surface markings (arrow indicative of foil manufacture) are still visible.

Mag: 300X

Figure J-3. Another area on hottest Mo foil (Layer #1) shows that recrystallized Mo is brittle and grain boundaries will develop cracks when Mo foil is bent

mag: 300X

Figure J-4. The above photomicrograph shows typical surface of a Mo foil (Layer #19) in which early stages of recrystallization are barely evident. Faint grain boundaries are indicated by arrows.

Mag: 300X

Figure J-5. This photomicrograph shows the coldest Mo foil (Layer #57) in the package. Even in this cold foil some recrystallization occurred (see arrow). There is little apparent difference between layers 19 and 57.

Mag: 300X

J-13

Figure J-6. Photomicrograph of surface of as-received nickel foil shows no evidence of a grain structure.

Mag: 300X

Figure J-7. This photomicrograph shows the surface of the nickel foil (Layer # 59) which experienced the hottest temperatures. The foil has recrystallized. Some grooving was noted at grain boundaries.

Mag: 300X

Figure J-8. The surface of the nickel foil (Layer # 83) which experienced the lowest temperatures of the nickel in the composite shows the early stages of recrystallization.

Mag: 300X

J-14

Figure J-9. Photomicrograph of as-received surface of copper foil

Mag: 300X

Figure J-10. Surface of copper foil (Layer #87) which experienced hottest temperatures of copper portion of composite; recrystallization and thermal grooving is evident.

Mag: 300X

Figure J-11. Surface of intermediate copper foil (Layer #95) shows evidence of recrystallization.

Mag: 300X

Figure J-12.

J-15

Low magnification photo of coldest copper foil (Layer #101) in composite reveals numerous cracks in foil

Mag: 3X

Figure J-13. Photomicrograph of surface of shiny side of copper foil, shown in Figure 12.

Mag: 300X

Figure J-14. Photomicrograph of surface of tarnished side of foil shown in Figure 12 and opposite surface observed in Figure 13.

Mag: 300X

J-16

Figure J-15. Surface of as-received aluminum foil

Mag: 300X

Figure J-16. Surface of hottest aluminum foil (Layer #103) in composite

Mag: 300X

Figure J-17. Surface of coldest aluminum foil (Layer #110) in composite.

Mag: 300X

Figure J-18 - Estimated Temperature Profile -
1800°F Composite