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UNION CARBIDE CORPORATION

LINDE DIVISION

[Indianapolis, Ind.]

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QUARTERLY PROGRESS REPORT OF RESEARCH AND DEVELOPMENT

IN A THERMAL INSULATION STUDY

December, 1968 - February, 1969

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LINDE DIVISION

QUARTERLY PROGRESS REPORT
IN A THERMAL INSULATION STUDY

December, 1968 - February, 1969

Prepared By:

W. E. Grunert

Contract No. AT(30-1)-3632
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QUARTERLY PROGRESS REPORT OF RESEARCH AND DEVELOPMENT
IN A THERMAL INSULATION STUDY

Prepared By

W. E. Grunert

ABSTRACT

Current results of long-term thermal conductivity tests are presented. The copper opacified multi-layer system completed 10,000 hours continuous operation (at 1220°F. hot-side temperature) with no performance deterioration. The nickel opacified multi-layer system is currently on test. Design and test plans for the modified 1800°F. composite multi-layer insulation system are described..

The flat plate retest program on aluminum multi-foil and glass fibrous multi-layer insulations is outlined. Sample description and tester modification connected with 2500°F. thermal conductivity tests on molybdenum - zirconia cloth multi-layer insulation are discussed.

Detailed results of longitudinal thermal conductivity tests on opacified fibrous multi-layer insulations are presented. Four systems are evaluated --- 106 glass, Al opacified glass, Cu opacified quartz, and Ni opacified quartz. The test program is complete.

New results for "filled gap" penetration - insulation configurations are presented and discussed. A modified analytical program is used, in which the gap filler is characterized as a semi-transparent, backscattering media.

Plans for experimental verification tests on an Al - Al opacified glass multi-layer insulation containing PbTe penetrations are described. Proposed test configurations and penetration - insulation system sample design are presented.

1.0 SUMMARY

1.1 Thermal Conductivity Testing - Cylindrical Tests

The 10,000 hour long term test on the copper opacified multi-layer insulation system has been completed. Thermal performance remained stable for the entire period; i.e., $K_a \approx 11.0 \times 10^{-3}$ Btu/hr.ft. $^{\circ}$ F. (1220 $^{\circ}$ F. to 70 $^{\circ}$ F.) for the system installed at 37 ℓ /in. The nickel opacified multi-layer system remains on test with ~3500 hours accumulated thus far. Performance history is presented in Figure 2.1.1.

The 1800 $^{\circ}$ F. composite multi-layer insulation has been designed to include a molybdenum - Astroquartz shield - spacer combination in the 1800 - 1600 $^{\circ}$ F. zone. The molybdenum and Astroquartz are selected for their greater stability at these temperatures. The cylindrical sample, installed at ~ 110 ℓ /in. and 0.5 in. thick, will use nickel - Refrasil, copper - Refrasil, and aluminum - aluminum opacified glass, in the lower temperature zones below 1600 $^{\circ}$ F. Sample preparation and initial testing will be done in the next quarter.

1.2 Thermal Conductivity Testing - Flat Plate Tests

A flat plate retest program is planned for reevaluation of aluminum and glass fiber multi-layer insulations; i.e., Al - 106 glass, Al - Al opacified glass, 106 glass, Al opacified glass. Previous data* on these insulations are not sufficient to permit correlation and complete thermal performance definition over the useful load and temperature range. The expanded retest program will obtain the needed data, over the complete load range (0 - 15 psi) and temperature range (300-900 $^{\circ}$ F.). Testing will be done during the next quarter.

The flat plate apparatus will be modified for 2500 $^{\circ}$ F. service. Pertinent required changes are: Pt/Pt-10Rh hot-side thermocouples, water-cooled sink plates to control cold-side temperatures at < 300 $^{\circ}$ F., alumina heater assembly with graphite resistance element for the higher temperature service. A multi-layer insulation system comprised of .0005 in. molybdenum foil and .005 in. zirconia cloth will be evaluated at temperatures up to 2500 $^{\circ}$ F. This multi-foil combination is potentially quite useful in this temperature range, due to good thermal properties and high temperature stability and compatibility of the molybdenum and zirconia materials.

1.3 Longitudinal Thermal Conductivity Testing

The longitudinal or lateral thermal conductivities of opacified fibrous multi-layer insulations have been measured and correlated over their full use temperature ranges. Materials evaluated were: aluminum opacified glass (250-900 $^{\circ}$ F.), non-opacified 106 glass (250-900 $^{\circ}$ F.), copper opacified quartz (450-1350 $^{\circ}$ F.), and nickel opacified quartz (450-1650 $^{\circ}$ F.).

* Reference Quarterly Progress Report. ALO 3632-33, June - August, 1968.

A flat plate test configuration is used with a cylindrical sample 6 in. diameter x 1-1/2 in. high. One-dimensional heat flow across the 1-1/2 in. thickness is measured over a 2 in. x 2 in. center "core" section. Tabulated K-data for the four multi-layer fibrous systems are given in Table 2.3.1.

The thermal conductivity data are correlated and solid conduction and radiative contributions to total K_a are estimated (Table 2.3.2). Based on these estimates and comparisons with similar values for normal heat flow, it is observed that:

1. Solid conduction contribution is at least a factor of 10 higher in the lateral direction.
2. The radiation attenuating capability of opacified fibrous multi-layers is somewhat direction dependent. Backscattering cross-section (N) is typically lower in the longitudinal or lateral direction (about 1/2 the normal value for the opacified quartz systems).

These data along with the normal-direction thermal conductivity values for opacified fillers, will be used in subsequent analysis (i.e., Task 3.0) of "filled-gap" joints and penetration configurations.

1.4 Insulation Interfaces - Penetration Effects

Filled-gap, flush and non-flush penetration configurations have been reanalyzed for the following system; Hastelloy-X penetrations in conjunction with Al-Al opacified multi-foil insulation (800-200°F.) or Ni - Refrasil multi-foil insulation (1800-800°F.). The analytical model has been modified in that the opacified filler material is now characterized as a semi-transparent, rather than a opaque media. Radiation attenuation capability is now indicated by the backscattering cross-section for the material. Results of old and new analyses are compared and discussed. Details of the revised analytical model are given in Appendix A-1; original zero gap and open gap results plus revised filled-gap results are given in Appendix A-2.

Experimental studies of a typical flush penetration - insulation configuration will be conducted as a means of verifying the analytical techniques. An Al - Al opacified multi-foil system, containing lead telluride penetrations will be tested at temperatures up to 900°F. Pertinent details of the test apparatus and sample configurations are given in Figures 2.4.2 and 2.4.3.

2.0 TECHNICAL REPORT

2.1 Thermal Conductivity Testing -- Cylindrical Tests

2.1.1 Current Long-Term Performance Tests

During the past quarter, two opacified fibrous multi-layer systems were on test to determine long-term performance stability at maximum operating temperatures. One system, copper opacified quartz multi-layer ($n = 37$ ℓ /inch), has completed 10,000 hours of continuous operation at a maximum temperature of 1220°F. Apparent thermal conductivity (K_a) for the system remained stable over the period at a value of $\sim 11.0 \times 10^{-3}$ Btu/hr-ft-°F. The second sample, nickel opacified quartz multi-layer ($n = 65$ ℓ /inch) has been operating continuously at a maximum temperature of 1485°F for 3500 hours. Apparent thermal conductivity has remained stable at $\sim 7.7 \times 10^{-3}$ Btu/hr-ft-°F. This system is scheduled for 8000 hours continuous testing.

Long-term performance characteristics of these and other, previously tested, multi-layer systems are summarized in Figure 2.1.1.

The long-term, 10,000-hour program on the copper opacified quartz multi-layer was completed during the quarter and testing was terminated. As indicated in Figure 2.1.1, thermal performance remained stable over this period. Previous performance analysis, considering free vaporization of the copper flake opacifier, had predicted a 10 - 20% deterioration (i.e., increased thermal conductivity) of the copper opacified system after 10,000 hours exposure at 1220°F. This was not observed, implying that the free vaporization analysis* was conservative.

The copper opacified multi-layer wrap will be dismantled and the material inspected, with particular emphasis on the layers in the hot (1220°F) zone. Samples will be analyzed for flake content to determine any physical changes from the as-received material which could be attributed to the 1200°F exposure.

2.1.2 Modified 1800°F Composite Multi-Layer Insulation

Recent performance and compatibility studies (reported in Quarterly Progress Report, ALO 3632-36, September-November, 1968) have resulted in reduction of the recommended maximum long-term service temperature of nickel-Refrasil quartz insulation to $\sim 1600^\circ\text{F}$. Consequently, the 1800°F composite design has been modified to include the more stable molybdenum - Astroquartz multi-layer component in the 1800-1600°F range.

The shield-separator components which comprise the new composite insulation are described on the following page.

*Reference Quarterly Progress Report ALO 3632-23, December, 1967 - February, 1968.

<u>Shield-Separator Combination</u>		<u>Temperature Range, °F</u>
0.0005"	molybdenum	1800-1600
0.005"	Astroquartz cloth	
0.0006"	nickel	1600-1400
0.005"	Refrasil quartz paper	
0.0005"	copper	1400- 900
0.005"	Refrasil quartz paper	
0.00025"	aluminum	900- 500
0.003"	106 glass paper	

The physical composite design is based on previously-measured thermal performance data for the individual components. Pertinent details of this design are shown in Figure 2.1.2. The predicted steady state temperature profile between 1800°F and 600°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 ($\sim .1$ psi). The estimated average layer density is 110 lb/inch. Wrapped sample thickness is to be 0.5 inches.

Test Procedure

The procedure for evaluating the modified 1800°F composite system is 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 500-1800°F, with the insulation in vacuum.

(2) Initiate long-term testing at 1800°F, to be continued for a 4000-hour period (limited by currently specified contract period of performance).

(3) Monitor steady-state thermal performance at the 1800°F 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.

Sample preparation and beginning of thermal test program are scheduled for March, 1969.

Figure 2.1.2

1800°F. Composite Multi-Layer Insulation System

Experimental Apparatus

A basic cylindrical, double-walled insulation tester, described previously in Project Plan - Report No. 21, September, 1967, will be used. The resistance heater and test "core" have been modified to extend operating capability to 1800°F. The instrumentation and electrical circuitry have also been revised to improve accuracy and reliability. These changes have been detailed in a previous report.*

*Quarterly Progress Report ALO 3632-33, June-August, 1968.

2.2 Thermal Conductivity Testing - Flat Plate Tests

The major objectives of the flat plate thermal conductivity test program are as follows:

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

(2) From these data, develop empirical expressions for the radiative and solid conduction contributions to thermal conductivity. This empirical relationship is 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.

The originally programmed work on aluminum, copper, and nickel multi-layer insulations has been completed and the data reported.* Additional flat plate testing is being pursued in the following areas:

(1) Re-testing of the aluminum multi-foil and aluminum opacified insulations, to provide sufficient performance data over their operating ranges.

(2) Basic thermal conductivity data measurement (i.e., K_a as a function of temperature and load) on the modified 1800°F composite insulation system defined in Section 2.1.2.

(3) Initial performance testing of a molybdenum - zirconia multi-foil insulation, at hot-side temperatures extending to 2500°F.

2.2.1 Aluminum Multi-Layer Insulations -- Retest Program

Currently available data on the aluminum multi-layer insulations are not sufficient to serve as a good basis for insulation system design over the entire operating range of these materials. In addition, these existing data were the first obtained on the flat plate testing apparatus. Refinements in the equipment operation and testing methods have been incorporated since that time, which improve the accuracy and reliability of the measured data.

The flat plate re-test program, then, is designed to remove this data deficit by applying the up-dated experimental techniques to the re-evaluation and re-correlation of thermal conductivity data for these aluminum systems. Specifically, the multi-layer insulation samples and the revised scope of testing are defined in Table 2:2.1.

*Reference Quarterly Progress Reports ALO 3632-33 and ALO 3632-36, covering the period from June-November, 1968.

TABLE 2.2.1

ALUMINUM MULTI-LAYER SYSTEMS

<u>Multi-layer Sample</u>	<u>Test Program</u>	<u>Objectives</u>
<u>Aluminum - 106 glass</u> .00025" Al foil .003" 106 glass paper	Ka measurement at 5 hot-side tempera- tures between 300- 900°F and 5 com- pressive loads be- tween 0-15 psi.	Determine solid (Ks) and radiative (Kr) components of total thermal conductivity (Ka). Correlate data as a function of layer density (n) and temp- erature (T). Deter- mine effective emissi- vity of foil shields.
<u>Aluminum-Aluminum</u> <u>Opacified Glass</u> .00025" Al foil .003" Al opacified glass	As above.	As above.

<u>106 Glass Paper</u> No foil .003" 106 glass paper	As above.	Determine K_s and K_r components of total Ka. Correlate data as a function of n and T. Determine backscattering cross- section (N) for fiber matrix as a function of n and T.
<u>Aluminum Opacified</u> <u>Glass Paper</u> No foil .003" Al opacified glass	As above.	As above.

The re-test program will be carried out in the next quarter --
March - May, 1969. The standard flat plate apparatus, with combined sample-
guard compressive loading, will be used in these tests. This equipment and
associated test procedures have been described previously.*

*Quarterly Progress Report ALO 3632-33, June - August, 1968, pp. 44-47.

2.2.2 2500°F Test Program

The expanded scope of the flat plate test program includes initial evaluation of a multi-foil insulation operating at hot-side temperatures up to 2500°F.

The flat plate apparatus design is essentially unchanged. The guarded, dual-sample configuration is retained. Samples are 6" x 6" with a 2" x 2" central metered section. The extended compression fixture, with which sample and guard are simultaneously loaded, will again be used.

The 2500°F test sample configuration and associated hardware are shown schematically in Figure 2.2.1. The equipment modifications, primarily material and instrumentation substitutes to permit the 2500°F operation, 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 will maintain sink temperature substantially below this level.

Heater assembly -- The graphite tape, resistance heater assembly will use high purity alumina core and shield plates, extending heater operating capability to ~ 3000°F. The original apparatus used quartz plates which are 1800°F - limited.

Instrumentation -- Pt/Pt-10Rh thermocouples will be used in place of chromel/alumel for hot-side temperature measurement. Associated changes in read-out and recording equipment, to accommodate the Pt/Pt-10Rh thermocouples, will also be made.

The insulation for 2500°F testing is a multi-layer system of molybdenum foil and zirconia cloth. The molybdenum foil is .0005" thick and, in this thickness, weighs 12 gms/ft². Its emissivity ranges from .03 - .18 for temperatures ranging from 500°F to 2500°F. Published emissivities for molybdenum are slightly lower than corresponding values for nickel.

The zirconia cloth is .005" thick with a specific weight of ~ 6 gms/ft². The open weave cloth is produced by Union Carbide Research Institute, by means of a replica* technique. A thin, low-weight zirconia cloth cannot presently be produced using conventional weaving techniques.

Apparent thermal conductivity of the molybdenum-zirconia cloth multi-foil system will be measured at several hot-side temperatures within the 500-2500°F range and at layer densities corresponding to compressive loads in the 0 - 15 psi range. The K_a data will be correlated to layer density and temperature. A suitable expression for apparent thermal conductivity, of the form:

*A woven starter fabric (e.g., rayon) is completely "replaced" by the zirconia material through a chemical reaction in a controlled environment. The woven matrix of the original starter material is retained in the resultant zirconia cloth.

Figure 2.2.1

Schematic of 2500°F. Test Sample Configuration

$$K_a \left| \begin{array}{c} T_1 \\ T_2 \end{array} \right. = \left(\frac{2}{3} a \right) \frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} + \frac{b}{4} \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right), \quad (2.2.1)$$

will be determined for subsequent use in regenerating K_a -values at any temperature and layer density conditions within the 500 - 2500°F and 0 - 15 psi ranges.

It is expected that the level of thermal performance for the molybdenum - zirconia multi-foil system will be comparable to that of nickel-Astroquartz, due to strong similarities in material properties and construction. The molybdenum - zirconia may be a somewhat better performer under load because of the lower density (implying lower solid conduction contribution) of the zirconia cloth in comparison with Astroquartz. Flat plate testing on this system will begin in May, 1969.

The modified 1800°F multi-layer insulation composite, described in Section 2.1.2, will be tested in the modified apparatus to determine apparent thermal conductivity over a 500-1800°F temperature range and layer densities corresponding to 0-15 psi load. Resultant thermal conductivity will also be correlated to temperature and layer density. This work will conclude the currently-programmed flat plate testing task.

2.3 Longitudinal Thermal Conductivity Testing

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

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

<u>Multi-layer Sample</u>	<u>Hot-side Temperature Range °F.</u>
Aluminum opacified glass $n \cong 186$ layers/inch	250-900
Copper opacified quartz $n \cong 68$ layers/inch	500-1400
Nickel opacified quartz $n \cong 72$ 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.

2.3.1 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 apparent thermal conductivity values.

The test configuration, with installed multi-layer insulation sample, is shown schematically in Figure 2.3.1. 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 inch x 2 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 ($P \leq 1 \times 10^{-3}$ mm Hg) during all tests.

The opacified paper samples are of cylindrical geometry with 6 inch diameter and 1-1/2 inch height. Samples are constructed by spirally-wrapping the fibrous paper (1-1/2 inch width) from the center outward, to a layer density approximating the specified "zero load"

FIGURE 2.3.1

Schematic of Longitudinal Thermal Conductivity Test Configuration

condition. Preliminary analysis indicated that lateral heat flow across the 1-1/2 inch sample is essentially one-dimensional in the 2 inch x 2 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.

2.3.2 Evaluation of Results

Measured longitudinal thermal conductivity data for the four fibrous multi-layer insulations, along with sample description and test conditions are presented in Table 2.3.1.

Using these data, the apparent thermal conductivity was fit empirically to the Larkin-Churchill expression which, in integrated form, gives K_a as a function of temperatures T_1 and T_2 :

$$K_a \left| \begin{array}{c} T_1 \\ T_2 \end{array} \right. = K_s + \frac{\sigma (T_1^4 - T_2^4) \Delta X}{12 (E + N \Delta X) (T_1 - T_2)} \quad (2.3.1)$$

where

K_s = Solid conduction contribution - Btu/hr.ft.².°F.

ΔX = Sample thickness - inches

N = Back scattering cross section - inch⁻¹

$E = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1$; ϵ_1, ϵ_2 being hot and cold boundary emissivities, respectively

The integrated form of the K_s term is expressed as:

$$K_s \left| \begin{array}{c} T_1 \\ T_2 \end{array} \right. = (2/3) a \cdot \frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \quad (2.3.2)$$

This expression is based on the published point conductivity values for glass and fused quartz, which may be approximated by $K(T) = a T^{1/2}$.

For the stipulated sample thickness of 1.5 inches, black ($\epsilon_1 = \epsilon_2 = 1.0$) hot and cold-side boundaries, and expected N values in the order of 100 or greater, the Larkin-Churchill radiation term may be simplified without introducing significant error.

TABLE 2.3.1

Longitudinal Thermal Conductivity - Opacified Multi-Layer Insulations

<u>Insulation System</u>	<u>Vacuum Pressure 10⁻³ mm Hg</u>	<u>T_h °F.</u>	<u>T_c °F.</u>	<u>K_l 10⁻³ Btu/hr.ft.°F.</u>
Aluminum opacified glass multi-layer - n* = 186 g/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 multi-layer - n* = 68 g/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 multi-layer - n* = 72 g/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 multi-layer (non-opaci- fied) - n* = 210 g/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.

$$K_r = \frac{\sigma \Delta X (T_1^4 - T_2^4)}{12 (1 + N \Delta X) (T_1 - T_2)} \approx \frac{\sigma}{12 N} \cdot \frac{T_1^4 - T_2^4}{T_1 - T_2} \quad (2.3.3)$$

Then, the final expression for K_a becomes:

$$K_a \left| \begin{array}{c} T_1 \\ T_2 \end{array} \right. = (2/3) a \cdot \frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} + \frac{\sigma}{12 N} \cdot \frac{T_1^4 - T_2^4}{T_1 - T_2} \quad (2.3.4)$$

Regrouping, the following equation in linear form is developed.

$$\underbrace{K_a \cdot \frac{(T_1 - T_2)}{T_1^{3/2} - T_2^{3/2}}}_{(y)} = \underbrace{\frac{\sigma}{12 N}}_{(m)} \cdot \underbrace{\frac{T_1^4 - T_2^4}{T_1^{3/2} - T_2^{3/2}}}_{(x)} + \underbrace{\frac{2}{3} \cdot a}_{(b)} \quad (2.3.5)$$

Now for each multi-layer system, for which several $K_a \left| \begin{array}{c} T_1 \\ T_2 \end{array} \right.$ data

points have been determined, equation 2.3.5 can be generated and solved graphically to yield the solid conduction coefficient $(2/3 \cdot a)$ and backscattering cross section (N) . This graphical technique is illustrated for the copper opacified multi-layer system in Figure 2.3.2. Corresponding solid conduction and radiative coefficients for all four fibrous multi-layer insulations are summarized in Table 2.3.2.

Based on the tabulated coefficients, some comparisons may be drawn between thermal behavior of the fibrous multi-layer 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 $(K_s)_l / (K_s)_n$ 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 multi-layer systems.

2. With the exception of the aluminum opacified multi-layer, the calculated "effective" backscattering cross sections for the fibrous insulations are of the same order in both the longitudinal and normal

* Interface resistance between adjacent layers is an important factor in reducing solid conduction in the normal direction.

Figure 2.3.2

Graphical Evaluation of Multi-layer Insulation Performance -
Copper Opacified Quartz Insulation

3.0

2.0

1.0

0

$$\frac{K_a (T_1 - T_2)}{T_1^{3/2} - T_2^{3/2}} \times 10^4$$

ΔY

$$\frac{\Delta Y}{\Delta X} = \frac{b}{4} = \frac{c}{12 N} = 1.18 \times 10^{-12}$$

ΔX

$$(2/3 a) = .64 \times 10^{-4}$$

$$\frac{T_1^4 - T_2^4}{T_1^{3/2} - T_2^{3/2}} \times 10^{-8}$$

0

1.0

2.0

TABLE 2.3.2

Empirical Thermal Conductivity Coefficients for Fibrous Multi-Layer Insulations

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

n - normal direction

 ℓ - longitudinal direction

$$E = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 \quad \text{-- in test case } \epsilon_1 = \epsilon_2 = 1$$

 ΔX = sample thickness -- in test case $\Delta X = 1-1/2''$

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

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-value for aluminum opacified multi-layer 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 of the opacified glass would be at least equivalent to N 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. Additional testing to investigate these discrepancies is being considered.

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 2.3.2, 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-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 higher-density nickel opacified quartz insulation has a correspondingly higher indicated K_s coefficient and backscattering cross-section (N) than that computed for the copper opacified quartz system.

Apparent thermal conductivities, in the normal and longitudinal directions, are plotted against hot-side temperature for the four fibrous multi-layer insulations (Figures 2.3.3 to 2.3.6). Total 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 2.3.2, for insulations operating in vacuum and at a cold-side temperature of 100°F. Insulation sample thickness was 1-1/2" in all cases.

The significant increase in apparent 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 2.3.3 to 2.3.6. The observations

*

The aluminum opacified sample was the first of the series. Subsequent test samples were more tightly wrapped and were considerably more stable under deformation.

Figure 2.3.3

Apparent Thermal Conductivity - 106 Glass Multi-Layer Insulation

 $n = 210 \text{ } \mu\text{/in.}$
 $T_c = 100^\circ\text{F.}$

KE SEMI-LOGARITHMIC
 46 5493
 3 CYCLES X 70 DIVISIONS
 MADE IN U.S.A.
 KEUFFEL & ESSER CO.

Apparent Thermal Conductivity (K_a) -- 10^{-3} Btu/hr.ft. $^{\circ}$ F.

Figure 2.3.4

Apparent Thermal Conductivity - Aluminum Opacified Glass Multi-Layer Insulation

$n = 186 \text{ } \ell/\text{in.}$
 $T_c = 100^{\circ}\text{F.}$

Figure 2.3.6

Apparent Thermal Conductivity - Nickel Opacified Quartz Multi-Layer Insulation

$n = 72 \text{ g/in.}$
 $T_c = 100^\circ\text{F.}$

drawn in conjunction with Table 2.3.2 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 multi-layer systems at low load (typically 0.1 psi compressive loading or less), and correspond reasonably well to low-load layer densities for multi-foil 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 multi-foil 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 current scope of the K_L testing will 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 linear function of layer density. For higher or lower density multi-layer 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 coefficient (N) 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 densities, approaching zero load, the K_R 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 predict and analyze.

Longitudinal thermal conductivity data will be used in characterizing opacified gap filler materials in the modified program to analyze thermal effects of "filled" joints. Results from this analysis will be reported in the next quarterly progress report.

2.4 Insulation Interfaces - Penetrations

2.4.1 Penetration Effects Reanalysis - Modified Analytical Model

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 are investigated; flush penetrations as shown in Figure 2.4.1 (a) and extended penetrations as shown in Figure 2.4.1 (b).

The penetration studies discussed in this report have been directed primarily at analyzing thermal effects associated with structural members which connect the hot and cold boundaries, and which may or may not be equal in length to the insulation thickness. Hastelloy-X is considered as the structural support material. Both flush and extended penetrations are analyzed for the following configurations ---- zero gap, open gap, and filled gap (Figure 2.4.1).

The original analytical results were presented and discussed in Quarterly Progress Report ALO 3632-33, June - August, 1968, pp. 48-94. The effects of Hastelloy-X penetrations in (a) aluminum - aluminum opacified multi-foil insulation (800-200°F.) and (b) nickel - Refrasil quartz multi-foil insulation (1800-800°F.) were assessed.

The revised analytical results for the identical penetration - insulation systems are presented in this report (Reference - Appendix A-2). The conditions and results for the zero gap and open gap configurations are identical for the original and modified analyses. Changes in the analytical results are confined to the filled gap configuration and reflect a new characterization of the gap filler material.

Modified Analysis

The revised program redefines the filler material (i.e., aluminum opacified glass in this case) as a semi-transparent 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. The filler thermal performance is no longer characterized simply by a thermal conductivity value, as was done in the original analysis where the filler was assumed to be opaque. Rather, in the new analytical model, the solid conductance 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 analytical model modification is described in detail in Appendix A-1.

The differences in the original and refined analytical model for the aluminum opacified gap filler material are illustrated below:

Thermal Conductivity Data - Al Opacified Filler

	<u>Original(1)</u> <u>Analysis</u>	<u>Current(2)</u> <u>Analysis</u>	<u>Future Analysis(2)</u> <u>(Suggested)</u>
Apparent thermal conductivity (10 ⁻³ Btu/hr-ft-°F)			
(a) Normal direction (K _N)	.24τ + 2.36τ ³	.24τ	.08τ
(b) Lateral (radial) direction (K _L)	276.0τ - 54.5	.24τ	2.0τ
Backscattering Cross-section (in ⁻¹)			
(a) Normal direction	-----	930	930
(b) Lateral direction	-----	930	100*

$$\tau = \frac{T}{1000} \text{ } ^\circ\text{R}$$

(1) Defines filler as being opaque

(2) Defines filler as being semi-transparent

*May be in error (i.e. too low a value as discussed in Section 2.3).

In the original analysis, K_N was based on cylindrical test data for a sample at a layer density (n) of 75 per inch. These data are judged somewhat inaccurate due to the non-uniform characteristic of the cylindrical wrap and the unrealistically low wrapped layer density for aluminum opacified filler. In the current analysis, definition of filler thermal performance is modified considerably. The solid conduction contribution is retained and expressed as an "apparent" K_N. The radiation attenuation for the semi-transparent filler is now expressed by a backscattering cross-section (N), derived from analysis of flat plate thermal conductivity data.

In defining the filler properties in the lateral (radial) direction, the following assumptions were made:

(1) The solid conduction contribution (.24 τ x 10⁻³) was considered to be small in comparison to radiation in both normal and lateral directions, and for simplicity, was taken to be the same in both directions.

(2) Backscattering cross-section for the filler was assumed to be independent of direction. A value of 930 in⁻¹ was used in both normal and lateral directions.

These assumptions were made without benefit of subsequent experimental data on lateral thermal conductivity of opacified fillers.

New flat plate thermal conductivity data on aluminum opacified filler (Section 2.3) indicate that the "isotropic" assumption in establishing lateral properties for the current penetration analysis is in error. Revised values of normal and lateral solid conduction and backscattering cross-section are tabulated. These data are felt to more realistically describe the thermal behavior of the opacified filler and are suggested* for use in any future analyses.

In comparing the tabulated sets of aluminum opacified filler properties, it is observed that:

(1) Thermal properties data used in the original analysis are felt to be conservative (high), particularly the lateral thermal conductivity value.

(2) On the other hand, properties used in the currently-reported penetration study are regarded as optimistic, in view of the subsequent K-value data of column 3. This is particularly true for the lateral direction.

The impact of the variation in filler properties on the results of original and current penetration analyses is discussed in the next section. Comparisons are made between current results (Appendix A-2) and the originally reported analysis.**

Discussion of Results

A complete set of results, including the new filled gap data, are presented in Appendix A-2. As was done in the previous analysis, all heat flow quantities are reported in dimensionless form referenced to ideal, one-dimensional heat flow data. Schematics of the configurations analyzed, as well as explanation of the form in which results are tabulated, are also found in Appendix A-2.

Comparing the original and revised analytical results, it is generally concluded that:

1. The pertinent trends and observations on thermal performance of the various penetration configurations, assessed qualitatively in the original analytical study***, remain valid.

* As indicated in Section 2.3, the unusually low lateral N data on aluminum opacified filler require further investigation. However, the essential fact of reduced backscattering in the lateral direction appears to be valid.

** Quarterly Progress Report ALO 3632-33, June-August, 1968, pp. 63-94.

*** Ibid, pp. 57-60.

2. In the filled-gap cases, the effect of the modified insulative properties for the opacified filler has been to:

(a) Further limit lateral (radial) heat exchange between the penetration and multi-foil insulation; i.e., more effective isolation of penetration from insulation is indicated.

(b) Make the thermal behavior of the penetration - gap - insulation system more one-dimensional in nature. (For illustration, compare new results in Tables A-2-13 to A-2-16 and A-2-29 to A-2-32 with corresponding tables of original data in Quarterly Progress Report ALO 3632-33.)

3. In the original analysis, lateral thermal properties of the opacified filler were estimated too conservatively. Excessively high lateral heat exchange was the result. In the new analysis, solid conduction and backscattering capability of the opacified filler, in the lateral or radial direction, were estimated from normal flat plate test data. Recent lateral K-data measurements indicate that these new assumptions were optimistic.

By way of illustrating the above conclusions, the calculated heat flux ratios (Tables A-2-1 to A-2-16) of the current analysis are compared to the original filled-gap calculations (Tables 2.3.1 to 2.3.16 of Quarterly Report ALO 3632-33). The comparisons here are restricted to the aluminum - aluminum opacified multi-layer system (800°F - 200°F), but would apply equally well to the nickel-Refrasil system.

The system heat flux ratios of Tables A.2.1 to A.2.4 (2.3.1 to 2.3.4) and the penetration heat flux ratios of Tables A.2.5 to A.2.8 (2.3.5 to 2.3.8) are not influenced significantly by the gap filler properties. Results obtained using the two analytical methods agreed generally to within 5% for each of the penetration-insulation configurations. Here the calculated heat fluxes are controlled primarily by the relatively high conductivity Hastelloy-X penetration material. Substitution of improved gap filler properties has little effect on the overall calculated heat fluxes.

The insulation heat flux ratios of Tables A.2.9 to A.2.12 (2.3.9 to 2.3.12), for the filled-gap cases, are strongly influenced by the filler performance. In general, heat flux ratios calculated in the current analysis were much closer to unity. This implies a closer correspondence to one-dimensional behavior due to the assumed better performance of the filler (i.e. limits lateral heat exchange between penetration and insulation). In comparing Tables A.2.10 and A.2.11 (2.3.10 and 2.3.11), it is noted that the new ratios are reduced by factors of 5 - 10 in many cases. The new filler properties limit significantly the heat flow from insulation - to-penetration. In Table A.2.12 (2.3.12) the reverse is true. Lateral heat flow from penetration-to-insulation is now restricted by the better-performing filler.

The influence of the improved filler performance on two-dimensional heat exchange is dramatically shown in the heat flux ratios

$$\frac{Q_{\text{(from insulation - cold side)}}}{Q_{\text{(into insulation - hot side)}}$$

of Tables A.2.13 to A.2.16 (2.3.13 to 2.3.16). These ratios give a direct indication of the amount of net heat exchange between the penetration and insulation. Ratios calculated in the current analysis tend toward unity, implying a minimized lateral heat exchange in comparison with system behavior as indicated by the original analysis.

A comparison of data on configurations of Tables A.2.13 to A.2.15 with those of Tables 2.3.13 to 2.3.15 again indicates a restricted lateral heat flow from insulation-to-penetration due to the better performing gap filler. In Table A.2.16 (3.2.16), the reverse case is again true; i.e. penetration-to-insulation heat exchange is restricted in the new analysis.

In summary, the effects of modified gap filler properties are clearly shown in the comparisons for the original and current analytical cases. Although the total system heat fluxes may not be affected significantly,* the accuracy of these filler thermal properties will affect, to a large degree, the assessment of lateral heat exchange within the penetration-insulation system.

The input data still require further refinement. However, the penetration effects program has been established as a useful tool in assessing the relative thermal performance of a variety of penetration-insulation configurations and materials combinations. Improvements in quantitative accuracy of the analytical results are tied closely to the reliability and accuracy of the input data; i.e., the thermal properties of the multi-layer insulation systems. The flat plate test programs, for measuring the normal and lateral thermal properties of multi-layer systems, are providing these needed input data. As improved data are available, they will be incorporated into the program.

The experimental verification tests, described in Section 2.4.2, will provide further insight into the quantitative accuracy of the analysis through comparison of corresponding experimental and analytical results. These comparative analyses will incorporate the most recent properties data for the filler material, as determined through flat plate normal and lateral thermal conductivity testing. Other than these specific cases, no further, extensive penetration effects analyses are now planned.

*For example, in cases where penetration heat flux predominates.

FIGURE 2.4.1 - a
FLUSH PENETRATION SCHEMATIC

CATEGORY I

CATEGORY II

FIGURE 2.4.1 - b
EXTENDED PENETRATIONS SCHEMATIC

2.4.2 Penetration Effects - 900°F. Experimental Program

The experimental program is designed to measure the effects on thermal performance of an array of penetrating elements, uniformly spaced over a multi-foil insulation section. Principal objectives of the program are to:

1. Provide verification of the analytical techniques used to assess thermal effects of penetrations.
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.

Testing will be on an aluminum - aluminum opacified glass multi-layer insulation, operating up to a maximum test temperature of 900°F. Thermal performance data for this insulation containing flush penetration elements will serve as the basis for verification of the analytical predictions.

The experimental program will be carried out during the next quarter, and reported in Quarterly Progress Report ALO 3632-42, March - May, 1969.

Experimental Concept

The overall thermal effect of flush penetrating elements contained within a flat, planar multi-layer insulation segment will be determined. Heat flux measurements are taken over a representative section of the insulation - penetration system. This heat flow, measured by means of a flux meter in series with the test sample, is compared to heat flow through an identical multi-layer insulation without the penetrations.

Verification of analytical techniques for treating penetrations requires that thermal tests on multi-foil samples duplicate, as closely as possible, the physical conditions imposed in the analysis. Preliminary investigation indicates that samples of flat configuration, thermally guarded as in the flat plate tester, satisfy the basic requirements for correspondence. To assure the most accurate comparison between experimental and analytical cases, new analytical predictions will be obtained which correspond to the configuration, materials and boundary conditions defined in the experimental runs.

In studying the effects of various penetration - insulation interface configurations on thermal performance (i.e. objective 2), three specific physical cases are selected. These configurations ---- zero gap, open gap, filled gap ---- are described schematically in Figure 2.4.2. In the open gap case, low-emissivity hot and cold boundary surfaces are achieved by extending the aluminum foil ($\epsilon = .05 - .10$) across the gap. The filled gap is achieved by allowing the aluminum opacified spacer, only, to extend across the gap.

Figure 2.4.2

Penetration Test Configurations

The test system geometry and boundary conditions selected for this study are as follows:

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

Based on previous analytical performance data, the described penetration - insulation size and geometry should be suitable for providing meaningful thermal performance comparisons between the various gap configurations.

Test Apparatus and Procedures

The flat plate test configuration, with installed penetration - insulation system samples, is shown schematically in Figure 2.4.3. This configuration will be employed in all testing. Edge thermal guarding, in which the guard is fabricated from the same insulation material used in the sample, will be provided. The test sample overall dimensions are 6 in. x 6 in. Heat flux across the penetrations and surrounding insulation will be measured over a 2 in. x 2 in. section by a flux meter (Geonetics Corporation) centrally located at the cold surface.

The advantages of the flat plate test configuration are:

1. The edge thermal guard of multi-foil insulation offers the most efficient means of minimizing the lateral (edge) loss problem in a typical flat sample of finite dimension.
2. This physical test configuration gives close approximation to the ideal, continuous insulation slab considered in the analytical study.
3. Provides for easy access and interchangeability of samples.
4. Necessary testing techniques have been established and refined during the flat plate test program.

As shown in Figure 2.4.3, the 6 in. x 6 in. sample contains

Figure 2.4.3

Schematic of Penetration - Insulation Test Samples

flush penetrations in a 6 x 6 grid. Heat flux measurements are made in the central portion of the sample, a 2 in. x 2 in. zone containing four penetrations. The remaining penetrations act as a guard or buffer for the test zone. It is felt that, with an arrangement of penetrating elements as shown, a close approximation of the analytically-defined adiabatic insulation boundary (dashed line) can be achieved at the metered portion of the sample.

All tests are run in vacuum environment. Heat flux comparisons are made for zero gap, empty gap, and filled gap (opacified paper) configurations. A reference heat flux determination will be made on the multi-foil insulation system without penetrations.

3.0 ACTIVITIES DURING THE NEXT REPORTING PERIOD

- Continue long-term testing of the nickel opacified multi-layer insulation system.
- Begin long-term testing of the 1800°F composite multi-layer insulation.
- Complete the flat plate re-test program on aluminum multi-foil and fibrous multi-layer insulation systems.
- Complete hardware modification and tester fabrication needed to achieve 2500°F operating capability with the flat plate tester.
- Complete fixture and sample fabrication for the penetration test program. Begin performance tests on an aluminum - aluminum opacified glass multi-foil system with lead telluride penetrations, at temperatures to 900°F.
- Re-analysis of rectangular and angular opacified paper-filled joints, using the revised computer program which treats the opacified filler as a semi-transparent material.

APPENDIX A-1

DEVELOPMENT OF EFFECTIVE VIEW FACTORS FOR RADIANT ENERGY INTERCHANGE BETWEEN TWO SURFACES SEPARATED BY A BACKSCATTERING MEDIUM

A-1-1 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:

$$K(T) = a.T + b.T^3$$

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.

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.

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. 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, plus a recent AEC Quarterly Progress Report (ALO 3632-33),⁶ 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.

Assuming that all radiation entering the scattering medium between surface elements dA_1 and dA_2 (See Figure A-1-1) is either transmitted directly or backscattered along the line of incidence, the differential equations governing the forward and backward fluxes are:

$$\frac{d}{dx} (D Q_{12}(x)) = \beta (dQ_{21}(x) - dQ_{12}(x)) \quad (2)$$

$$\frac{d}{dx} (d Q_{21}(x)) = \beta (dQ_{12}(x) - dQ_{21}(x))$$

where:

$dQ_{12}(x)$ = Radiant flux from dA_1 to 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 (2) is:

FIGURE A-11 - SURFACE GEOMETRY

$$dQ_{12}(x) = (C_2 - C_1) R x + C_1 \quad (3)$$

$$dQ_{21}(x) = (C_2 - C_1) R x + C_2$$

where C_1 and C_2 are constants, which can be determined by applying the boundary conditions:

$$dQ_{12}(0) = [\epsilon_1 E_1 + r_1 \cdot dQ_{21}(0)] f_{12} \quad (4)$$

$$dQ_{21}(R) = [\epsilon_2 E_2 + r_2 \cdot dQ_{12}(R)] f_{21}$$

where:

ϵ_1, ϵ_2 = Emissivities of dA_1 and dA_2

r_1, r_2 = Reflectivities of dA_1 and dA_2
 $(r_1 = 1 - \epsilon_1, r_2 = 1 - \epsilon_2)$

$E_1 = \sigma \epsilon_1 T_1^4 \cdot dA_1$ = emissive power of dA_1

$E_2 = \sigma \epsilon_2 T_2^4 \cdot dA_2$ = emissive power of dA_2

σ = Stefan-Boltzmann constant

T_1, T_2 = Temperatures of dA_1 and dA_2

$f_{12} = f \cdot dA_2$ = view factor from dA_1 to dA_2 (The fraction of energy leaving dA_1 that would fall on dA_2 if there were no attenuating medium present)

$f_{21} = f \cdot dA_1$ = view factor from dA_2 to dA_1

$$f = \frac{\cos \theta_1 \cdot \cos \theta_2}{\pi R^2}$$

Substitution of equations (3) into equations (4) results in two equations linear in C_1 and C_2 . Solving for these constants, gives:

$$C_1 = [f_{12} E_1 (1 + R (1 - r_2 f_{21})) + f_{21} E_2 r_1 f_{12}] / D \quad (5)$$

$$C_2 = [f_{12} E_1 (r_2 f_{21} + R (1 - r_2 f_{21})) + f_{21} E_2] / D$$

$$D = 1 - f_{12}f_{21}r_1r_2 + \alpha R (1 - f_{12}r_1)(1 - f_{21}r_2)$$

The net rightward flux, dQ_R , is thus given by

$$dQ_R = C_1 - C_2 = \frac{f_{12}(1 - r_2f_{21})E_1 - f_{21}(1 - r_1f_{12})E_2}{1 - f_{12}f_{21}r_1r_2 + \alpha R (1 - f_{12}r_1)(1 - f_{21}r_2)} \quad (6)$$

When $\alpha = 0$, equation (6) reduces to the general equation of unattenuated radiant exchange given in Brown and Marco.¹ For infinite parallel planes, $f_{12} = f_{21} = 1$ and (6) reduces to the equation given in the AEC Quarterly Progress Report.⁶

Note that, when $r_2 = E_2 = 0$,

$$dQ_R = \frac{f_{12}E_1}{1 + \alpha R (1 - f_{12}r_1)} = F_{12}E_1 \quad (7)$$

Also, when $r_1 = E_1 = 0$, the net leftward flux becomes

$$-dQ_R = \frac{f_{21}E_2}{1 + \alpha R (1 - f_{21}r_2)} = F_{21}E_2 \quad (8)$$

Solving (7) for f_{12} , solving (8) for f_{21} , and substituting the results into (6), the expression for dQ_R is obtained:

$$dQ_R = \frac{F_{12}(1 - r_2F_{21})E_1 - F_{21}(1 - r_1F_{12})E_2}{1 - F_{12}F_{21}r_1r_2} \quad (9)$$

Equation (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.

A-1-3-2 Interchange Between Finite Surfaces

Equations (7) - (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 (2) subject to a new set of boundary conditions:

$$dQ_{12}(0) = E_1 f_{12} \quad (10)$$

$$dQ_{21}(R) = 0$$

Combining equations (3) and (10), we obtain

$$C_1 = E_1 f_{12}$$

$$C_2 = \frac{E_1 f_{12} \theta R}{1 + \theta R}$$

which gives for the net flux at $x = R$:

$$dQ_{12}(R) = C_1 - C_2 = \frac{E_1 f_{12}}{1 + \theta R} \quad (11)$$

To compute the total radiant interchange between surfaces A_1 and A_2 equations (10) and (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 reaches A_2 now becomes:

$$(Q_2)_0 = \int_{A_1} \int_{A_2} dQ_{12}(R) = \bar{E}_1 \bar{f}'_{12}, \text{ where}$$

$$\bar{f}'_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2 dA_1 dA_2}{\pi R^2 (1 + \theta R)}$$

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:

$$(Q_b)_0 = (Q_1)_0 - (Q_2)_0 = \bar{E}_1 (\bar{f}_{12} - \bar{f}'_{12})$$

However, part of this energy is reflected from A_1 back toward A_2 , this portion being:

$$(Q_1)_1 = r_1 \bar{f}_{12} (Q_b)_0 = \bar{E}_1 \bar{f}_{12} r_1 (\bar{f}_{12} - \bar{f}'_{12}) = r_1 (\bar{f}_{12} - \bar{f}'_{12}) (Q_1)_0$$

The portions of $(Q_1)_1$ that are transmitted to A_2 and scattered back to A_1 are, respectively,

$$(Q_2)_1 = r_1 \bar{f}'_{12} (Q_b)_0 = r_1 (\bar{f}_{12} - \bar{f}'_{12}) (Q_2)_0$$

$$(Q_b)_0 = (Q_1)_1 - (Q_2)_1$$

This transmit-backscatter-reflect cycle can be repeated indefinitely, resulting in a total flux arriving at A_2 given by

$$(Q_2)_{\text{tot}} = \sum_{i=0}^{\infty} (Q_2)_i = (Q_2)_0 \sum_{i=0}^{\infty} [r_1 (\bar{f}_{12} - \bar{f}'_{12})]^i$$

or, by summing the infinite geometric series,

$$(Q_2)_{\text{tot}} = \frac{(Q_2)_0}{1 - r_1 (\bar{f}_{12} - \bar{f}'_{12})} = \frac{\bar{E}_1 \bar{f}_{12}}{1 - r_1 (\bar{f}_{12} - \bar{f}'_{12})} \quad (12)$$

Note that when $R = 0$, $\bar{f}_{12} = \bar{f}'_{12}$ and equation (12) reduces to

$$(Q_2)_{\text{tot}} = \bar{E}_1 \bar{f}_{12} \quad (13)$$

Therefore, by comparing equations (12) and (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:

$$(F_{12})_{\text{eff}} = \frac{\bar{f}_{12}}{1 - r_1(\bar{f}_{12} - \bar{f}_{12}^{'})}$$

(14)

$$(F_{21})_{\text{eff}} = \frac{\bar{f}_{21}}{1 - r_2(\bar{f}_{21} - \bar{f}_{21}^{'})}$$

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 (14).

APPENDIX A-2

Revised Analytical Results - Flush and Non-Flush Penetrations

A.2.1 Physical Models

Physical models used to explore the effect of extended penetrations are shown in Figures A.2.1 to A.2.4.

Figure A.2.1 shows the idealized configuration for the case where the penetration length is equal in magnitude to the insulation height. In this respect Figures A.2.2, A.2.3, and A.2.4 are self-explanatory.

Some pertinent characteristics common to each of these models are as follows:

1. Each basic configuration considers three options; zero gap between penetration and insulation (i.e. insulation foils considered in perfect thermal contact with penetration).

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

$$K_r = .24 \times 10^{-6} \text{ T}$$

$$K_n = .24 \times 10^{-6} \text{ T}$$

$$N = 930 \text{ in}^{-1}$$

K_r = thermal conductivity (solid) in the radial or lateral direction

K_n = thermal conductivity (solid) in the normal direction (i.e., hot side to cold side)

N = backscattering cross-section of the filler material in normal and radial directions

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

FIG. A.2.1
 PENETRATION ELEMENT - INSULATION
 IDEALIZED CONFIGURATION

FIG. A.2.2

PENETRATION ELEMENT-INSULATION
IDEALIZED CONFIGURATION

FIG. A.2.3

PENETRATION ELEMENT - INSULATION
IDEALIZED CONFIGURATION

FIG. A.2.4

PENETRATION ELEMENT - INSULATION
IDEALIZED CONFIGURATION

2. 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 ($r_a - r_g$). 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.

3. 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,

$$\frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} \approx 10 (N\Delta X)$$

ϵ_1 = hot wall emissivity = 1.0

ϵ_2 = insulation surface emissivity ≈ 0.05

N = scattering cross-section of a plain spacer $\sim 200 \text{ in}^{-1}$

ΔX = thickness of one spacer $\sim 0.010''$

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 ($N\Delta X$) 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, affect 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 indeed 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.

 $*r_a$ - adiabatic radius; r_g - gap outer radius

A.2.2 Basis for Calculated Results

The simplest case to examine is Figure A.2.1 (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 the type shown in Figure A.2.2 where the penetration (e.g., structural support) extends considerably beyond the insulation, the common tendency would be to treat it thermally in a manner like the system of A.2.1 (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.

One of the objectives of this study has been to compare the actual heat flow which may be expected from a configuration as shown by Figure A.2.2 (a) to the result of the simplified calculation associated most realistically with the configuration of Figure A.2.1 (a).

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 of Figures A.2.1 (b) and A.2.1 (c). A second objective of this study was, therefore, to compare the performance of filled and empty gap cases versus zero gap cases.

Finally, it is sometimes possible to control the relative locations of the insulation and penetration with respect to each other. A third objective of the study was, therefore, to explore which location of the insulation relative to the penetration (i.e., towards hot side or cold side) would yield lowest heat flow.

In addition to examining total heat flow, an attempt is made to examine the effect of two-dimensional flow, physical detachment of the insulation from the hot and cold faces (i.e., the use of a radiative coupling) and the presence of a gap - either filled or empty - on heat flow through the insulated portion* of the system.

* The combined insulation fraction is the annular insulation segment, outer bounded by the adiabatic radius (r_a) and inner bounded by the penetration radius (i.e., multi-foil plus gap insulation). Refer to Quarterly Progress Report ALQ 3632-33.

For convenience, all heat flow quantities are reported in dimensionless form, referenced to one dimensional results associated with Figure A.2.1 (a). Thus: in Tables A.2.1 to A.2.4 and A.2.17 to A.2.20 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 A.2.1 to A.2.4 to the heat flow from T_H to T_C which would result from one-dimensional analysis on the configuration of Figure A.2.1 (a).

Similarly, in Tables A.2.5 to A.2.8 and A.2.21 to A.2.24 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 Figures A.2.1 to A.2.4 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 to some extent 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. It is believed that for the calculations of this report the penetration conductance is sufficiently large to render this observation valid.

In Tables A.2.9 to A.2.12 and A.2.25 to A.2.28, 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 multi-foil insulation annular area to the heat which would enter the same area of multi-layer 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 yield an idea of the amount of net heat exchange between the penetration and the insulation. (Tables A.2.13 to A.2.16 and Tables A.2.29 to A.2.32.)

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	.989	.839		1.00	.935	0.1	PENETRATION DIAMETER - INCHES	
			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	.954	0.1	
				1.00	.991		1.00	.997	0.5	
				1.5	6.0		1.5	6.0		
				ADIABATIC RADIUS - INCHES						

PENETRATION-INSULATION CONFIGURATION

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

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

Conservative Q_{p_0}

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.100	.242		.291	.461	0.1	PENETRATION DIAMETER - INCHES
			.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	.538	0.1	
			.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	PENETRATION DIAMETER - INCHES		
			.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		.535	0.1
					.039	.050		.141		.166	0.5
		1.5	6.0		1.5	6.0					
		ADIABATIC RADIUS - INCHES									

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PENETRATION-INSULATION CONFIGURATION

TABLE A-2-2

Q (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	
			.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					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.246	.340		.610	.679	0.1	PENETRATION DIAMETER - INCHES
			.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							

PENETRATION-INSULATION CONFIGURATION

TABLE A-2

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	.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	.082		.232	.243	0.5	
		0.075	.149	.275		.381	.518	0.1	
			.073	.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				
				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 DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-4

$$\frac{Q}{Q} \left(\text{Into Penetration - Hot Side} \right)$$

$$Q \left(\text{Penetration - One Dimensional} \right)$$

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	1.00	.997		.997	.986	0.1
			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 A-2-5

$$\frac{Q_{\text{(Into Penetration - Hot Side)}}}{Q_{\text{(Penetration - One Dimensional)}}$$

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

				PANEL THICKNESS						
				0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.081	.080		.250	.243	0.1	PENETRATION DIAMETER - INCHES	
			.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	PENETRATION DIAMETER - INCHES
			.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									

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PENETRATION - INSULATION CONFIGURATION

(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	.165	.165		.440	.427	0.1	PENETRATION DIAMETER - INCHES
			.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					
		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			.195	.179	.445	.310	0.1
			.080	.080	.264	.252	0.5
		1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS - INCHES					

PENETRATION DIAMETER - INCHES	0.1
	0.5
	0.1
	0.5
	0.1
	0.5
	0.1
	0.5
	0.1
	0.5

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-7

$$\frac{Q(\text{Into Penetration} - \text{Hot Side})}{Q(\text{Penetration} - \text{One Dimensional})}$$

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	.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 DIAMETER - 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 DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION

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 A-2-9

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	PENETRATION DIAMETER - INCHES
			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-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 - INCHES								

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PENETRATION-INSULATION CONFIGURATION

TABLE A-2-10

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						PENETRATION DIAMETER - INCHES		
				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-INSULATION CONFIGURATION

$$Q(\text{Into Insulation - Hot Side})$$

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

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

			PANEL THICKNESS					PENETRATION DIAMETER - INCHES
			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-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.526	.533		.649	.763	0.1	PENETRATION DIAMETER - INCHES
			.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						

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PENETRATION-INSULATION CONFIGURATION

TABLE A-2-12

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	
		ADIABATIC RADIUS - INCHES						
PENETRATION DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-13

(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	
		ADIABATIC RADIUS - INCHES						
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PENETRATION-INSULATION CONFIGURATION

TABLE A-2-14

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	.595	.957		.149	.744	0.1
			.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				PENETRATION DIAMETER - INCHES			
		0.1"		0.4"					
EMPTY GAP	GAP WIDTH, IN.	0.025	.607	.959	.186		.771	0.1	
			.249	.818	.036	.302	0.5		
		0.075	.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				
		ADIABATIC RADIUS - INCHES							

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PENETRATION-INSULATION CONFIGURATION

TABLE A-2-15

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		0.1
			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	0.1
			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 A-2-16

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							
				0.1"		0.4"					
EMPTY GAP	GAP WIDTH, IN.	0.025	.978	.872		1.01	.964	0.1	PENETRATION DIAMETER - INCHES		
			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 A-2-17

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

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

Conservative Q_{p_o}

		PANEL THICKNESS						
		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 DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS						
		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						-70-

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-18

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						
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.444	.736		.791	.906	0.1
			.156	.244		.445	.518	0.5
		0.075	.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
		0.075	.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		
		ADIABATIC RADIUS - INCHES						
PENETRATION DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.596	.774		.889	.932	0.1	PENETRATION DIAMETER - INCHES
			.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		
			ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

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								
				0.1"		0.4"						
EMPTY GAP	GAP WIDTH, IN.	0.025	.390	.722		.669	.873	0.1	PENETRATION DIAMETER - INCHES			
			.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						
		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 A-2-20

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	PENETRATION DIAMETER - INCHES
			.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 A-2-21

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	PENETRATION DIAMETER - INCHES
			.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				PENETRATION DIAMETER - INCHES
				0.1"		0.4"		
EMPTY GAP	GAP WIDTH, IN.	0.025	.193	.192		.444	.437	0.1
			.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 A-2-22

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	.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 DIAMETER - INCHES										

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.508	.507		.750	.731	0.1	PENETRATION DIAMETER - INCHES
			.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

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								-76-

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-24

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	.899	.840		1.17	.965	0.1	PENETRATION DIAMETER - INCHES
			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 A-2-25

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	.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	PENETRATION DIAMETER - INCHES
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	PENETRATION DIAMETER - INCHES		
			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									-78-		

PENETRATION-INSULATION CONFIGURATION

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	PENETRATION DIAMETER - INCHES
			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		
		ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.961	.842		1.45	.984	0.1	PENETRATION DIAMETER - INCHES
			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		
		ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

$$\frac{Q(\text{Into Insulation - Hot Side})}{Q(\text{Insulation - One Dimensional - Zero Gap})}$$

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	.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 DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

			PANEL THICKNESS						
			0.1"			0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.851	.834		.992	.947	0.1	PENETRATION DIAMETER - INCHES
			.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									-80-

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-28

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	PENETRATION DIAMETER - INCHES
			.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			
		ADIABATIC RADIUS - INCHES							

PENETRATION-INSULATION CONFIGURATION

TABLE A-2-29

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	.978	.995		.886	.987	0.1	PENETRATION DIAMETER - INCHES	
			.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						PENETRATION DIAMETER - INCHES	
		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		
			ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

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 DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS					
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.868	.989		.554	.945	0.1	PENETRATION DIAMETER - INCHES
			.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		
			ADIABATIC RADIUS - INCHES						

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PENETRATION-INSULATION CONFIGURATION

$$\frac{Q_{\text{(From Insulation - Cold Side)}}}{Q_{\text{(Into Insulation - Hot Side)}}$$

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	1.13	1.01		1.47	1.04	0.1	PENETRATION DIAMETER - INCHES
			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						
		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								

PENETRATION DIAMETER - INCHES

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PENETRATION-INSULATION CONFIGURATION