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AEC RESEARCH AND
DEVELOPMENT REPORT

UNION CARBIDE CORPORATION

LINDE DIVISION

QUARTERLY PROGRESS REPORT OF RESEARCH AND DEVELOPMENT
IN A THERMAL INSULATION STUDY

June - August, 1968

By *[Signature]* (Brockhaven)

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F. Notaro
W. E. Grunert

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QUARTERLY PROGRESS REPORT OF RESEARCH AND DEVELOPMENT
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Prepared By

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ABSTRACT

Long-term thermal conductivity tests are currently in progress on four multi-layer systems operating at temperatures from 1400-1800°F. Thermal conductivity data and correlation coefficients are summarized for all multi-layer insulation systems studied.

Thermal conductivity data (flat plate testing) are presented for (1) four multi-foil insulations for service to 1400°F. and (2) four opacified or non-opacified fibrous multi-layer insulations. The methods for correlating thermal performance to temperature and mechanical load (layer density) are discussed. The correlation coefficients based on experimental data are presented.

A modified flat plate testing fixture, providing for simultaneous compression of sample and guard in thermal conductivity testing of mechanically loaded samples, is described. A brief flat plate error analysis is presented and an estimated error band on experimental data is given.

The penetration analysis is extended to a study of behavior of multi-foil insulation systems in the vicinity of structural supports. Hastelloy-X is considered as a typical structural support material. Effects of penetration size and spacing, as well as insulation thickness and location with respect to the penetration are studied. Results of several analyses are given.

The 10,000 hour test on the Hastelloy-X vacuum enclosure specimen (1400°F, 5000 psi exposure conditions) is complete. Plans for final sample analysis have been made.

1.0 SUMMARY

1.1 Thermal Conductivity Testing - Cylindrical Tests

Tests have been conducted on four insulation systems. A description of the systems tested is given in Table 2.1-1. Experimental results are shown in Figure 2.1-1. Coefficients for the thermal conductivity equation

$$K = aT + bT^3$$

are given in Table 2.1-2.

1.2 Thermal Conductivity Testing - Flat Plate Tests

Data are presented on eight separate insulation systems; four of the discreet foil-spacer type, two of the opacified fibrous type, and two of the plain fibrous type.

For each system, empirical thermal conductivity equations are presented. These empirical equations, which are found in Tables 2.2-1 and 2.2-6, are useful in calculating apparent thermal conductivity of each system as a function of layer density and boundary temperatures.

The fibrous and opacified fibrous equations (Table 2.2-6) are constructed in a manner which will allow inclusion of the effects of the optical characteristics of system boundaries as well as the effects of total insulation thickness. Inclusion of these parameters is particularly important when dealing with small insulation thicknesses.

A method for deriving polynomial coefficients for the foil-spacer systems which is more correct than the method suggested in ALO 3632-29 (March-May quarterly) has been used and discussed.

Apparent thermal conductivities achieved for the foil type systems range from a low of 5×10^{-5} Btu/hr-ft²-°F/ft. at low temperature (500°F.), low density conditions to 2×10^{-3} Btu/hr-ft²-°F/ft. for the high temperature (1400°F), high density (15 psi mechanical load) conditions.

Representative conductivities achieved for the fibrous and opacified fibrous insulations are shown in Figures 2.2.15 to 2.2.18.

1.3 Insulation Interfaces - Penetrations

Results of analytical studies aimed at determining the behavior of foil-type insulation systems in the vicinity of structural supports are presented. Investigation of these effects has centered around the use of Hastelloy-X as a typical structural material.

Parameters investigated include penetration diameter and length, insulation thickness, penetration spacing and location of insulation relative to the vertical axis of penetration.

Pertinent observations can be summarized as follows:

1. In those cases where the penetration length is equal to the insulation height, the one-dimensional approximation to calculation of total heat flow is adequate, provided total heat flow is largely influenced by the heat flow through the penetration.

2. In cases where the penetration is considerably longer than the insulation, the simple one-dimensional approximation widely overestimates heat loss.

3. Best location for the insulation is toward the vertical center of a penetration - second best, and perhaps most practical, is toward the hot side.

4. For penetrations which are very long in comparison to insulation thickness, insulating the exposed penetration can reduce total heat loss.

2.0 TECHNICAL REPORT

2.1 Thermal Conductivity Testing - Cylindrical Tests

During the period covered by this report, thermal conductivity testing using the spirally wrapped cylindrical test technique (Reference Report No. ALO-3532-20) has been conducted on four multi-layer insulation material systems. The four systems, together with pertinent test conditions, are shown on Table 2.1-1.

The objectives to be achieved through these tests are as follows:

- Obtain thermal conductivity data.
- Obtain long-term stability data through extended duration testing.
- Obtain some preliminary assessment of the effect on thermal conductivity in vacuum due to exposure of the hot insulation system to air.

2.1.1 Results

Experimental results in the form of thermal conductivity as a function of hot side temperature are presented on Figure 2.1-1. The new results are presented along with all other results obtained to date on similar systems.

As for all previous data, these experimental results have been fit to the polynomial of the form

$$K = aT + bT^3 \quad 2.1-1$$

An up to date summary of the (a) and (b) constants of equation 2.1-1 is given in Table 2.1-2.

It will be recalled that although the polynomial 2.1-1 has a limited number of terms, the initial selection of these terms by Wang⁽⁶⁾ was theoretically based.

The intent was for the first term (aT) to represent the solid conductivity fraction and was based on the observation of an essentially linear variation of the conductivity of glass with temperature in the region of interest to Wang (the cryogenic region). The second term was intended to represent the radiation contribution to the apparent conductivity.

Although the premise on which the (T³) term was selected remains valid, those underlying the selection of the (T) term are no longer as valid. At the higher temperatures, not only is the temperature dependence of the spacer material's thermal conductivity different, but also changes in material properties (e.g. Young's modulus) can be expected, thus giving some new dimen-

TABLE 2.1-1

CYLINDRICAL TEST CONDITION

<u>Insulation System</u>	<u>Foil</u>	<u>Spacer</u>	<u>Layer Density Nominal</u>	<u>Total Number of Layers</u>	<u>Test Boundary Temperatures °F</u>	<u>Comments</u>
Copper opacified	--	Copper opacified quartz paper	37/inch	22	1220 415	7500 of 10,000 hour test comple- ted
*Nickel opacified	--	Nickel opacified quartz paper	65/inch	28	1480+ 500⊕	
4 *Nickel foil - Nickel opacified quartz paper	.00062" Thick Nickel	Nickel opacified quartz paper	56/inch	35	1800+ 500⊕	
* Composite	Nickel Copper Aluminum	Quartz paper quartz paper glass paper	96/inch	29 } 12 } 50 9 }	1870+ 500⊕	

* New tests

⊕ Estimated

+ Projected

FIGURE 2.1.1 THERMAL CONDUCTIVITY DATA - CYLINDRICAL TESTING

- 1 ALUMINUM FOIL - ALUMINUM OPACIFIED GLASS FIBER PAPER, 150 LAYERS/INCH
- 2 ALUMINUM FOIL - GLASS FIBER PAPER, 120 LAYERS/INCH
- 3 COPPER FOIL - QUARTZ FIBER PAPER, 83 LAYERS/INCH
- 4 COPPER FOIL - COPPER OPACIFIED QUARTZ FIBER PAPER, 70 LAYERS/INCH
- 5 NICKEL FOIL - QUARTZ FIBER PAPER, 96 LAYERS/INCH
- 6 NICKEL FOIL - ASTROQUARTZ CLOTH, 120 LAYERS/INCH
- 7 NICKEL FOIL - NICKEL OPACIFIED QUARTZ PAPER, 56 LAYERS/INCH
- 8 COMPOSITE SYSTEM, 96 LAYERS/INCH
- 9 ALUMINUM OPACIFIED GLASS FIBER PAPER, 74 LAYERS/INCH
- 10 COPPER OPACIFIED QUARTZ FIBER PAPER, 30 LAYERS/INCH
- 11 NICKEL OPACIFIED QUARTZ FIBER PAPER, 65 LAYERS/INCH

$T_{\text{cold}} = 70^{\circ}$

THERMAL CONDUCTIVITY, k_a , BTU/HR FT $R^{\circ} \times 10^{-3}$ BETWEEN T_h AND AMBIENT

TABLE 2.1.2EMPIRICAL CONDUCTIVITY PARAMETERS

<u>Test</u>	<u>Foil Type</u>	<u>Spacer Type</u>	<u>No. of Layers per Inch</u>	<u>$a/2 \times 10^7$</u>	<u>$b/4 \times 10^{13}$</u>	<u>ϵ</u>
1	Ni	Stevens Quartz Cloth	120	3.1	1.5	0.25
2	Al	Dexter Glass Paper	120	0.45	0.52	0.086
3	Cu	Dexter Quartz Paper	83.3	0.8	0.53	0.062
4	Ta	Stevens Quartz Cloth	140	0.3	1.59	0.306
5	Cu	Cu-opacified Quartz Paper	70.4	3.1	0.61	0.060
6	Ni	Dexter Quartz Paper	96.1	-0.3	1.8	0.24
7	Al	Al-opacified Glass Paper	150	0.1	0.66	0.137
8	None	Al-opacified Glass Paper	74	1.2	5.9	-
9	None	Cu-opacified Quartz Paper	30.3	6.1	15.29	-
10	None	Ni-opacified Quartz Paper	65	3.2	4.6	-
11	Ni	Ni-opacified Quartz Paper	56	0.8	1.41	0.11
12	Ni-Cu-Al (Composite)	Dexter Quartz Paper + Al-opacified Glass Paper	96	0.8	0.87	0.12

sions to the effect of temperature.

These difficulties notwithstanding, the reduced polynomial is still being used as an empirical fit to the thermal conductivity data. Some efforts are being made simultaneously to consider some of the effects predominant at the higher temperatures and possibly develop a modified polynomial which will yield an improved fit.

2.1.2 Thermal Conductivity Test Apparatus

Some changes have been made to the cylindrical test apparatus in order to extend its utility to 1800°F.

These changes, which affected primarily the heater and core designs, are described briefly below. The new configurations are shown in Figure 2.1-2.

- Heater design - Platinum - 10% rhodium (.02" dia.) wire has been substituted for the previously used tungsten and nichrome heater wires. Platinum has both a low vapor pressure at high temperature, giving it the required long life as well as good oxidation resistance at high temperature, thus making it suitable to air exposure.
- Core design - The stainless steel inner core has been replaced with one of "Mullite" (ceramic). Failures of platinum heaters in previous tests were in part traced to bimetallic compounds containing stainless steel. Elimination of the stainless core was considered necessary to successful use of the platinum heater.
- Instrumentation - Some revisions have been made in the instrumentation of these tests in an effort to improve accuracy. A revised instrumentation circuit is shown in Figure 2.1-3. Note that the temperature controller has been eliminated and that temperatures are now read directly on a potentiometer. Note also that voltage readings are now taken directly across the heater in order to avoid a correction for the power consumed by the ammeter. The voltmeter itself is a high impedance vacuum tube type which draws a negligible amount of current.

2.1.3 Test Procedure

Test procedure remains essentially unchanged. (See Report ALO-3632-20.)

FIGURE 2.1.2 HEATER AND CYLINDRICAL CORE CONFIGURATION

FIGURE 2.1.3 SCHEMATIC OF INSTRUMENTATION CIRCUIT

2.2 Thermal Conductivity Testing - Flat Plate Tests

2.2.1 Summary

The major objective of this task has been to develop methods for accurate measurement of thermal performance of multi-layer insulations at temperatures to 1800°F. and layer densities corresponding to a 0-15 psi loading range. Based on the experimental data, thermal performance of each system is correlated to temperature and layer density. The resulting empirical expression may then be used to compute performance (i.e. apparent thermal conductivity) at any temperature and layer density within the ranges indicated.

Eight insulation systems have been evaluated to date. These multi-layers and their operating temperature limits are listed below:

<u>Multi-foil Systems</u>	<u>Temperature</u>
Aluminum - 106 glass paper	900°F
Aluminum - Aluminum opacified glass paper	900°F
Copper - Refrasil quartz paper	1400°F
Copper - Copper opacified quartz paper	1400°F

<u>Fibrous Paper Systems</u>	<u>Temperature</u>
106 glass paper	900°F
Aluminum opacified glass paper	900°F
Refrasil quartz paper	1800°F
Copper opacified quartz paper	1400°F

Apparent thermal conductivity (K_a) is the performance parameter for the multi-foil systems. Operating in vacuum ($p \leq 1 \times 10^{-3}$ mm Hg), heat transmission through the multi-foil insulations is by solid conduction and radiation. The K_a value, then, is defined approximately as the sum of the solid conduction (K_s) and radiation (K_r) components. These component terms (K_s and K_r) are correlated to temperature and layer density by the procedure discussed in Section 2.2.2.

The non-foil fibrous paper insulations cannot be treated in this simplified manner. The fibrous systems are partly transparent to radiation and, as such, cannot be described by a generally applicable apparent thermal conductivity, depending only on temperature and load (layer density). With the assumption that radiant heat attenuation in the fibrous materials is mainly by backscattering, the performance depends not only on temperature and compressive load but on amount of material (i.e. thickness) and optical properties of the boundaries as well. In ensuing discussion, a K_a expression involving solid conduction (K_s) and radiation (K_r) components is generated and used in evaluating the fibrous multi-layer systems. However, the resulting K_a values reflect the influence of all the parameters listed above and are not to be interpreted or applied in the usual manner (i.e. as an intrinsic property of the fibrous

material).

The flat plate experimental data are summarized and an estimated error band on these data is given. The K_a expressions are tabulated for all multi-layer systems and their accuracy is discussed. Refinements in the data correlation, particularly with regard to the solid conduction (K_s) expression, are discussed and will be pursued in subsequent work.

2.2.2 Multi-foil Insulation Systems

Flat plate test data for four multi-foil insulation systems in vacuum ($P \leq 1 \times 10^{-3}$ mm Hg) are summarized in Figures 2.2.1 to 2.2.4. Apparent thermal conductivity values are plotted as a function of compressive load (layer density) at several temperature levels. The curves illustrate the behavior of the apparent conductivity over the full range of compression loads from 0-15 psi.

The K_a vs. load plots generally follow a characteristic shape -- an initial, rapid rise in K_a at the low loads (0 to .1 psi) followed by a wide compressive load span (extending in most cases to 15 psi) where K_a increases relatively slowly. This pattern is discussed in terms of the solid conduction and radiation contributions to total conductivity:

Low load range -- At essentially zero load the interfaces between adjacent foils and spacers are well defined and contribute additional resistance to heat flow (implying a low solid conduction contribution). Even under mild loading this interface resistance is reduced significantly and is reflected in a rapid increase in K_a . This characteristic is more pronounced at lower temperatures where K_s is a substantial portion of the total; e.g. Figures 2.2.3 and 2.2.4.

Load range .1 - 15 psi -- Through this load range, the increase in solid conduction is based mainly on the fiber characteristics and parent material conductivity. At the same time, layer density increases through this range serve to reduce the K_r contribution. These two effects compensate and a reduced rate of rise of K_a is the result. This leveling effect is more pronounced at higher temperatures where the radiation contribution (K_r) is dominant.

At higher compressive loading (15 psi and above), the K_a values would again increase more rapidly. Increases in solid conduction are more significant and the accompanying improvement in radiation attenuation (higher layer density) becomes minimal. This trend within the 15 psi range was indicated in the aluminum - 106 glass system, Figure 2.2.1.

The multi-foil thermal conductivity data are correlated to temperature and layer density by the expression:

$$K_a = K_s + K_r = aT^{1/2} + bT^3 \quad (2.2.1)$$

APPARENT THERMAL CONDUCTIVITY (K_a) - 10^{-3} Btu/hr-ft-°F

After integration, the expression for K_a between boundary temperatures T_1 and T_2 becomes:

$$K_a \left[\begin{matrix} T_1 \\ T_2 \end{matrix} \right] = (2/3) a \left(\frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \right) + \frac{b}{4} \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right) \quad (2.2.2)$$

The radiation (K_r) term is theoretically based and $b/4$ can be replaced by the coefficient $\frac{\sigma \epsilon}{24n}$ where layer density (n) is in ℓ/inch units. The solid conduction (K_s) term is described by a $T^{1/2}$ function of temperature. This function fits approximately literature data* for thermal conductivity of SiO_2 at elevated temperatures. The form of the K_s term is currently being investigated to try and achieve a better representation of the solid conduction effects within the physical multi-layer system.

Based on this empirical expression for total apparent thermal conductivity, the $(2/3)a$ and $b/4$ coefficients were computed as a function of layer density for each of the multi-layer insulations. These coefficients, applicable over the designated range of temperatures and layer densities, are presented in Table 2.2.1.

The solid conduction and radiation coefficients are determined from the experimental thermal performance data. In the graphical technique, Equation 2.2.2 is linearized and expressed in the following form:

$$K_a \frac{(T_1 - T_2)}{T_1^{3/2} - T_2^{3/2}} = \frac{b}{4} \frac{T_1^4 - T_2^4}{T_1^{3/2} - T_2^{3/2}} + (2/3)a \quad (2.2.3)$$

where the coefficient $b/4$ is the slope and $(2/3)a$ the y-intercept. A linear plot is obtained for each compressive loading condition. From these plots, the coefficients are found directly and expressed as functions of layer density (n).

This represents a departure from the data reduction procedure for multi-foil systems previously presented in the Quarterly Report ALO 3632-29. The former approach applied the solid conduction term for the non-foil, fibrous multi-layer insulation to the multi-foil system employing the same fibrous separator; e.g. K_s coefficient for aluminum opacified glass was used in the aluminum-aluminum opacified glass multi-foil correlation. This interchanging of

* Reference 2.

TABLE 2.2.1

EMPIRICAL THERMAL CONDUCTIVITY PARAMETERSFOR MULTI-FOIL INSULATIONS

<u>Multi-foil System</u>	<u>Temperature Range °F</u>	<u>Layer Density Range (0-15 psi) l/in.</u>	<u>K_s Coefficient [2/3 a]</u>	<u>K_r Coefficient(b/4)</u>	<u>Effective Emissivity (ε)</u>
Aluminum - 106 glass	500-900	96	- .9 x 10 ⁻⁶	72.1 x 10 ⁻¹² $\frac{\epsilon}{n}$	.05
Aluminum - Aluminum opacified 106 glass	500-900	120	- 1.4 x 10 ⁻⁶	72.1 x 10 ⁻¹² $\frac{\epsilon}{n}$	.11
Copper - Refrasil quartz	500-1400	80-180	[.408 x 10 ⁻⁴ log n - .748 x 10 ⁻⁴]	72.1 x 10 ⁻¹² $\frac{\epsilon}{n}$	.045
Copper - Copper opacified Refrasil quartz	500-1400	40-110	[.464 x 10 ⁻⁴ log n - .768 x 10 ⁻⁴]	72.1 x 10 ⁻¹² $\frac{\epsilon}{n}$	.06 (40-60 l/in.) .18 (110 l/in.)

the solid conduction term is not suitable since (1) interface conditions are not physically similar in the non-foil and multi-foil cases, and (2) the K_s coefficient for non-foil, fibrous multi-layers is based on a somewhat arbitrary determination of the backscattering cross-section (see Section 2.2.3).

While the resultant inaccuracy in the K_s coefficient is not extremely significant in non-foil system representation where K_s is a small portion of the total K_a , considerable error could be introduced by using this K_s term in multi-foil systems analysis where K_s may be as much as 50% of the total K_a . Consequently, the solid conduction coefficient will not be used interchangeably in non-foil and multi-foil insulation analysis.

The currently-used graphical technique relates the apparent thermal conductivity (K_a) to the temperature and layer density parameters. The correlation is applicable only for the layer density and temperature ranges as specified in Table 2.2.1. The approximate nature of this approach is due mainly to the following assumptions:

1. In describing solid conduction (K_s), interface effects are neglected and possible temperature effects on the structural properties of the fibrous separators are not considered.
2. The emissivity of the metallic foil shields is considered constant throughout the temperature and load range.

Apparent thermal conductivity values are computed, using the empirical coefficients, at temperatures and layer densities corresponding to experimental data points. These calculated values are plotted on Figures 2.2.1 to 2.2.4 for purposes of comparison. Agreement between computed and experimental K_a values is generally to 10% over the major portion of the loading range. Consistent over-prediction of K_a is noted at the low compressive loads, which would be expected since the correlation does not include the interface resistance effects (prominent at low loads).

Although the empirical correlations may be used as a relatively accurate means of regenerating K_a values within specified boundaries, the actual coefficients of Table 2.2.1 are, in some cases, inconsistent with physical behavior or properties of the multi-foil insulations. The two main inconsistencies are:

1. Computed K_s coefficients for the aluminum multi-foils are negative. This implies an artificially large radiation component, which is indicated by the relatively high effective emissivity calculated for the aluminum foil.
2. Unusually large increase in the effective emissivity of copper foil in going from .1 psi loading to 15 psi. The factor-of-three increase is not substantiated by literature data on thermal radiative properties of copper.

These inconsistencies result from an inaccurate split between the solid conduction and radiation components, as indicated by the negative K_s coefficients and unrealistically high calculated emissivities.

The work to date points up the need for further refinement of the correlation techniques. Future study will be directed toward:

- a). Reconsidering the basic method for separating the solid conduction component (K_s) in an effort to improve accuracy and physical correspondence to the multi-foil system.
- b). The accuracy of the $aT^{1/2}$ temperature dependency of solid conduction.
- c). Quantitative assessment of interface effects at low compressive loads.
- d). Assessing the potential for surface interaction between spacer and foil at high temperature and loads which would deteriorate shield emissivity.

2.2.3 Fibrous and Opacified Fibrous Multi-Layer Insulations

Experimental thermal performance data on four non-foil fibrous (opacified and non-opacified) multi-layer insulations are presented in Tables 2.2.2 to 2.2.5*. Emphasis is not placed on presentation of performance data in the form of apparent thermal conductivity since these K_a values are not intrinsic properties of the fibrous material alone. The K_a values are valid only for specified boundary conditions, geometry (thickness) requirements, and fiber material properties. Further discussion of this boundary and geometric dependency, and its significance in fibrous multi-layer applications, is given in Section 2.2.3.3.

2.2.3.1 Thermal Performance Analysis

The fibrous multi-layer systems are characterized as being partially transparent and, as such, are considered to attenuate radiant heat primarily by backscattering. This definition permits description of an "apparent" thermal conductivity for these systems by a modified form of the Larkin-Churchill expression:

$$K_a = (2/3) a \frac{(T_1^{3/2} - T_2^{3/2})}{(T_1 - T_2)} + \frac{\sigma (T_1^4 - T_2^4) \Delta X}{12 \left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 + N\Delta X \right) (T_1 - T_2)} \quad (2.2.4)$$

* A discrepancy in presentation of Al-106 and Al-Al opacified 106 data, which occurred in Report No. ALO 3632-29, has been corrected.

TABLE 2.2.2

FLAT PLATE DATA ON GLASS PAPER INSULATION

Point	T _h °F	T _c °F	T _g °F	n L/In.	Load (PSI)	K (10 ⁻³ $\frac{\text{BTU}}{\text{Hr-Ft-}^\circ\text{F}}$)	Q $\frac{\text{BTU}}{\text{Hr-Ft}^2}$	Remarks
1	500	130	144	128	0	.810	9.6	Points 1-4: Stainless steel foil boundaries
2	700	183	198	128	0	1.47	24.3	
3	900	250	270	128	0	2.54	55.2	
4	700	215	198	138	-	1.59	26.6	
5	500	110	136	138	0	.475	5.94	Points 5-8: Aluminum foil boundaries
6	700	141	122	138	0	.720	12.85	
7	900	190	161	138	0	1.158	26.3	
8	700	204	182	382	15.0	2.25	98.6	

TABLE 2.2.3

FLAT PLATE DATA ON ALUMINUM OPACIFIED GLASS PAPER INSULATION

Point	T _h °F	T _c °F	T _g °F	n L/In.	Load (PSI)	K (10 ⁻³ $\frac{\text{BTU}}{\text{Hr-Ft-}^\circ\text{F}}$)	Q $\frac{\text{BTU}}{\text{Hr-Ft}^2}$	Remarks
1	500	118	120	150	0	.458	5.60	Points 1-12: Stainless Steel foil boundaries
2	700	139	146	150	0	.630	11.32	
3	900	179	185	150	0	.900	20.7	
4	700	178	139	180		.64	12.85	
5	900	227	188	180		.970	25.1	
6	500	136	112	180		.447	6.3	
7	500	148	111	210		.510	8.1	
8	700	142	134	210		.710	16.4	
9	900	251	166	210		.985	29.6	
10	900	286	175	415	15	2.74	149.0	Points 13-15: Aluminum foil boundaries
11	700	233	146	421	15	2.47	104.2	
12	500	182	132	421	15	2.12	61.0	
13	500	115	120	150	0	.309	3.81	
14	900	175	200	150		.525	12.18	
15	700	191	140	440	15.0	1.81	87.0	

TABLE 2.2.4

FLAT PLATE DATA ON REFRASIL QUARTZ PAPER INSULATION

<u>Point</u>	<u>T_h</u> <u>°F</u>	<u>T_c</u> <u>°F</u>	<u>T_G</u> <u>°F</u>	<u>ρ</u> <u>L/In.</u>	<u>Load</u> <u>Psi</u>	<u>K</u> <u>(10⁻³ $\frac{\text{BTU}}{\text{Hr-Ft-°F}}$)</u>	<u>Q</u> <u>Btu/Hr-Ft²</u>
1	548	208	192	100	.04	4.16	45.9
2	798	329	286	100	.04	8.03	122.2
3	968	404	358	100	.04	11.40	217
4	547	228	211	106.6	0.10	4.01	44.1
5	810	339	307	106.6	0.10	7.63	123.8
6	976	417	375	106.6	0.10	11.50	222
7	568	198	209	115	0.30	3.59	42.6
8	810	305	312	115	0.30	6.62	107.5
9	972	385	384	115	0.30	10.21	192.5
10	549	187	210	124	1.0	3.32	41.6
11	800	282	306	124	1.0	5.94	106.8
12	968	352	380	124	1.0	8.84	188.5
13	564	125	193	220	15.0	2.51	37.2
14	782	167	282	220	15.0	3.61	75.2
15	970	220	357	220	15.0	4.66	118.0

TABLE 2.2.5. - FLAT PLATE DATA ON COPPER OPACIFIED QUARTZ PAPER INSULATION

Point	T _h °F	T _c °F	T _g °F	n L/In.	Load (PSI)	K (10 ⁻³ $\frac{\text{BTU}}{\text{HR-FT-°F}}$)	Q $\frac{\text{BTU}}{\text{HR-FT}^2}$	Remarks
1	1000	253	294	53	0	2.76	66	Points 1-14: Stainless steel foil boundaries
2	1200	332	359	53	0	4.8	133	
3	1400	430	435	53	0	8.6	266	
4	1400	535	419	60	.03	11.0	341	
5	1200	433	357	60	.03	6.2	171.5	
6	1000	346	294	60	.03	3.83	90.0	
7	1000	332	291	62.5	.10	4.40	110.3	
8	1183	407	343	62.5	.10	6.58	191.5	
9	800	260	228	62.5	.10	2.93	58.4	
10	510	156	153	62.5	.10	1.46	19.4	
11	500	123	131	107	15	1.575	38.1	
12	800	207	204	111	15	2.52	100	
13	1010	277	267	113	15	3.53	175.3	
14	1200	340	325	113	15	4.8	281	
15	500	125	140	53	0	.261	3.13	Points 15-39: Copper foil boundaries
16	806	162	206	53	0	.477	9.83	
17	1000	201	257	53	0	1.04	26.6	
18	1200	254	299	53	0	1.725	52.2	
19	1400	350	390	53	0	2.81	94.5	
20	500	150	141	60	.03	.915	114.8	
21	800	210	203	60	.03	1.59	33.8	
22	1000	267	257	60	.03	2.23	58.6	
23	1200	333	322	60	.03	3.18	98.8	
24	1400	442	398	60	.03	4.75	163.0	
25	1400	428	401	62.5	.10	4.92	179.0	
26	1200	364	340	62.5	.10	3.71	117	
27	1000	303	278	62.5	.10	2.58	67.6	
28	800	247	224	62.5	.10	1.96	40.6	
29	510	150	150	62.5	.10	1.140	15.4	
30	510	127	126	122.7	15	.845	23.8	Points 32-39: 1/2 Guard Thickness
31	800	189	140	130	15	1.51	71.8	
32	500	133	170	137	15	.957	28.7	
33	800	169	256	137	15	1.475	75.7	
34	1000	233	252	137	15	2.09	131.7	Points 35-39: Black Guard
35	500	139	122	139	15	1.017	30.5	
36	800	189	159	140	15	1.563	80.2	
37	1000	252	215	140	15	2.25	142.0	
38	1200	316	276	141	15	3.27	244.0	
39	1400	382	336	143	15	4.62	397.0	

where the variables constituting the radiation component are as follows:

σ	- Stefan-Boltzmann constant
T_1, T_2	- hot, cold side boundary temperatures, °R
ϵ_1, ϵ_2	- hot, cold side boundary emissivities
ΔX	- multi-layer insulation thickness, in.
N	- backscattering cross-section, in ⁻¹

The boundary and thickness dependencies of the K_r term are evident.

In empirically investigating the radiation attenuating characteristic of the fibrous systems, the parameter N is computed and correlated to layer density (load) and temperature. The current approach uses experimental performance data to compute upper and lower limits of N based on specific limiting assumptions. Once the N boundaries are defined, a relationship for the backscattering cross-section is obtained by a visual fit of the limit points. This N relationship can then be correlated to layer density (n) and temperature and subsequently used in the empirical K_a expression (Equation 2.2.4).

In establishing the bounds on the backscattering coefficient $(N\Delta X)$,* the following assumptions are made:

- a). Minimum $(N\Delta X)$ or (N) - implies maximum radiant heat transfer through the multi-layer. Total measured heat flux at any specified temperature and load is assumed to be due to radiation. In terms of apparent conductivities, $(N\Delta X)_{\min}$ is then expressed as:

$$(N\Delta X)_{\min} = \frac{\sigma(T_1^4 - T_2^4) \Delta X}{12K_a(T_1 - T_2)} - \left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right) \quad (2.2.5)$$

where

$$\begin{aligned} \Delta X &= \frac{\text{no. of layers}}{\text{layer density}} = \frac{\lambda}{n} \\ K_{r_{\max}} &= K_a, \text{ for the lower limit on } N\Delta X \\ \epsilon_1 = \epsilon_2 &= 1.0 \text{ (black boundaries)} \end{aligned}$$

- b). Maximum $(N\Delta X)$ or (N) - implies a minimum radiation heat transfer through the insulation. The minimum Q_r is established as
-

* The $N\Delta X$ term is first computed from the experimental data and the corresponding N is then calculated by dividing by the appropriate thickness.

the difference in heat flux or transfer between the fibrous multi-layer system and a multi-foil insulation operating at the same load and temperature conditions and using the same fibrous material as separator between shields. In this limiting case, it is assumed that the total heat transferred in the multi-foil system is by solid conduction (i.e. Q_r virtually zero due to high efficiency of the multiple shielding). Therefore, if all the heat transfer in the multi-foil system is by conduction (Q_s), a like quantity of Q_s is considered to be present in the non-foil system under identical operating conditions. Then it follows that the residual heat flux for the fibrous multi-layer ($Q_a - Q_{m-f}$) represents the minimum amount attributable to radiation (i.e. maximum $N\Delta X$). In terms of apparent conductivities, the expression is:

$$(N\Delta X)_{\max} = \frac{\sigma(T_1^4 - T_2^4) \Delta X}{12 (K_a - K_{m-f})(T_1 - T_2)} - \left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right) \quad (2.2.6)$$

where

ΔX , ϵ_1 , ϵ_2 are as defined previously

$K_{r_{\min}} = K_a - K_{m-f}$, for the upper limit on $N\Delta X$.

Once the limiting values are established at each temperature and load condition, the backscattering cross-section N is obtained by dividing the $N\Delta X$ coefficient by the multi-layer sample thickness. The N data are finally fit by inspection to a linear function of layer density (n) and hot side temperature (T_1). From this graphical fit, an empirical expression is derived which approximates the behavior of N over the entire operating range of the fibrous multi-layer (Reference Figures 2.2.5 to 2.2.8).

The solid conduction contribution (K_s) to the total apparent conductivity is obtained by subtraction of the computed radiation contribution as follows:

$$K_s = K_a - K_r \quad (2.2.7)$$

The K_r under each set of operating conditions is calculated from the previously generated N expression. The solid conduction coefficient (2/3) a is then fit to a linear function of layer density (Reference Figures 2.2.9 to 2.2.12).

The K_s and K_r coefficients for the four fibrous multi-layer insulations are presented in Table 2.2.6. These coefficients may be used in the empirical expression for total apparent thermal conductivity (Equation 2.2.4) to regenerate K_a values over the designated temperature and load ranges. The coefficients for the Refrasil quartz and copper opacified Refrasil quartz systems are limited to the low layer density region. Additional experimental data are

COULY BOOK COMPANY, INC. NEW YORK, N.Y. 10017
WAS 10 11 26 1960
11 113 201 1 5

FIGURE 2.2.5 - SCATTERING COEFFICIENT VARIATION WITH LAYER DENSITY FOR GLASS PAPER

FIGURE 2.2.6 - SCATTERING COEFFICIENT VARIATION WITH LAYER DENSITY
FOR ALUMINUM SPECIFIED PAPER

- MIN. @ 960° R
- X MIN. @ 1160° R
- ◆ MIN. @ 1360° R
- MAX. @ 1160° R

FIGURE 2.2.7

BACK-SCATTERING CROSS-SECTION
REFRASIL QUARTZ FIBER PAPER

FIGURE 2.2.8

BACKSCATTERING CROSS-SECTION COPPER
OPACIFIED QUARTZ FIBER PAPER

$$\frac{K_{SC}}{T_1 - T_2} = \frac{3/2 - T_2}{3/2}$$

N. 116 20 DIVISIONS PER IN. BOTH WAYS. 1/2 IN. 200 DIVISIONS

FIGURE 2.2.10 - VARIATION OF SOLID CONDUCTION WITH LAYER DENSITY
FOR ALUMINUM OPACIFIED PAPER

DEPT BOOK COMPANY, NORWOOD, MASSACHUSETTS
MADE IN U.S.A.

$$k_{sc} = \frac{T_1 - T_2}{\frac{3}{2} - \frac{3}{2}}$$

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BOON COMPANY INC. NEWBOD MASSACHUSETTS.

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318

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FIGURE 2.2.11 SOLID CONDUCTION COEFFICIENT FOR REFRASIL
QUARTZ PAPER

FIGURE 2.2.12 SOLID CONDUCTION COEFFICIENT FOR
COPPER OPACIFIED QUARTZ PAPER

TABLE 2.2.6

EMPIRICAL THERMAL CONDUCTIVITY PARAMETERS

FOR FIBROUS MULTI-LAYER INSULATIONS

<u>Fibrous Multi-layer System</u>	<u>Temperature Range °F</u>	<u>Layer Density Range (0-15 psi) lb/in.</u>	<u>K_s Coefficient [(2/3)a]</u>	<u>K_r Coefficient (b/4)</u>
106 glass paper	500-900	130-400	$8.9 \times 10^{-8} n - 10.6 \times 10^{-6}$	$\frac{\sigma\lambda}{12n} \cdot \left[\frac{1}{\epsilon + \frac{\lambda}{n} (617 - .18T_1 - .78n)} \right]$
Aluminum opacified 106 glass	500-900	130-380	$[.019 n - 2.17] \times 10^{-6}$	$\frac{\sigma\lambda}{12n} \left[\frac{1}{\epsilon + \frac{\lambda}{n} (836 + .25T_1 - 2.23n)} \right]$
Refrasil quartz paper	500-1000	100-125* (0-1.0 psi)	$[.145 n - 11.0] \times 10^{-6}$	$\frac{\sigma\lambda}{12n} \left[\frac{1}{\epsilon + \frac{\lambda}{n} (4.2 - .02T_1 + 1.0n)} \right]$
Copper opacified Refrasil quartz	500-1400	50-65* (0-.1 psi)	$[.94 n - 43.0] \times 10^{-6}$	$\frac{\sigma\lambda}{12n} \left[\frac{1}{\epsilon + \frac{\lambda}{n} (908 - .19 T_1 - 6.4n)} \right]$

* Coefficients valid only over a limited loading range.

$$\frac{\lambda}{n} = \Delta X$$

$$\epsilon = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1$$

required in the 1 - 15 psi region to complete the correlation.

2.2.3.2 Interpretation of Experimental Results

Functional relationships for the backscattering cross-section (N) are illustrated graphically in Figures 2.2.5 to 2.2.8. The broad band defined by the $N_{\max}$ and $N_{\min}$ data points is clearly evident, particularly at the higher layer densities (loads). The resultant N curves are somewhat arbitrary in that they are obtained by a visual "best-fit" to the maximum and minimum data points. The N values are expressed as linear functions of layer density and temperature. Although this form is not dictated by physical principles, it constitutes a reasonable approximation within the operating range of interest.

For comparison of the various fibrous materials, backscattering cross-section (N) vs. load (psi) plots are generated for each multi-layer insulation. These relationships, at hot side temperatures of 500°F. and 900°F., are given in Figures 2.2.13 and 2.2.14. The following trends are observed:

- a). The 106 glass fiber systems (denoted by (1) and (2)) exhibit a decreasing N with load. For a defined quantity or sample of these materials, this trend indicates that backscattering surface (or sites) are being destroyed* under compressive load. In the thin fiber papers, this site destruction would reflect a high degree of inter-fiber and metal flake contact or "agglomeration" under load. In the glass fiber materials, the thin (<.003") papers, small 106 fiber diameter (~.5 - .6 μ), and the large number of interface surfaces (initially well-defined at zero load) could all contribute to a rather high potential for surface contact or "agglomeration" under load. In the aluminum opacified material, the apparent high flake density at the paper surface would also result in rapid loss of "attenuating" sites (established by these flakes) as interface contact increased at higher loads.
- b). The Refrasil quartz multi-layers (designated (3) and (4)) generally exhibited an increasing N-load relationship. The larger diameter (1.0 - 1.3 μ), stiffer quartz fiber and thicker, .005" - .010" fibrous paper (implying less interface effect) appear to offer more resistance to deformation under load and are felt to be mainly responsible for this increasing trend in N. Some scattering site destruction is occurring at the higher loads (N/psi ratio is 25 up to 1.0 psi and 5 from 1 - 15 psi), but it is considerably lower than in the 106 glass systems.

For both the 106 glass and Refrasil quartz multi-layer systems, the advantage of metal flake opacification in radiant heat attenuation is

* This theory explained in detail in Quarterly Progress Report ALO 3632-29.

FIGURE 2.2.13 SCATTERING CROSS-SECTION FOR FIBROUS PAPERS
AT 500°F TEMPERATURE

FIGURE 2.2.14 SCATTERING CROSS-SECTION FOR FIBROUS PAPERS AT 900°F TEMPERATURE

clearly illustrated. Comparing N values for plain and opacified materials shows the latter to have a 2 - 3 times higher backscattering cross-section.

The maximum-minimum method for approximating the backscattering cross-section (N) yields a first-order indication of the magnitude of the N values and their relationship to the temperature and layer density parameters. However, the current assumptions used in the empirical analysis yield a rather broad $N_{\max} - N_{\min}$ band, making the resultant N estimates somewhat arbitrary. The errors associated with this estimating procedure are further reflected in the computation of the solid conduction (K_s) contribution (based on computed K_r as presented in Table 2.2.6). While accuracy of the K_s term is not as critical in the fibrous multi-layers, where it is relatively small, it may introduce substantial error if used in estimating apparent thermal conductivity of multi-foil systems where K_s and K_r are often of comparable magnitude (Reference Section 2.2.2).

Refined methods for estimating and correlating backscattering and solid conduction mechanisms in fibrous insulations are currently being investigated. One such method involves graphical interpretation of the N (or K_r) and K_s coefficients by evaluating Equation 2.2.4 under special conditions of (1) black boundaries ($\epsilon = 1.0$) and (2) insulation thickness greater than 1/4". For this case, the attenuating capability of the boundaries is very small compared to the backscattering coefficient; i.e. $(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1) \ll N\lambda X$. The simplified K_a becomes:

$$K_a = \frac{2}{3} a \frac{(T_1^{3/2} - T_2^{3/2})}{(T_1 - T_2)} + \frac{\sigma}{12N} \frac{(T_1^4 - T_2^4)}{(T_1 - T_2)} \quad (2.2.8)$$

With sufficient experimental thermal performance data, the coefficients $\frac{\sigma}{12N}$ and $[(2/3) a]$ may be found by graphical methods at specified temperature and layer density conditions. Then the N values, being an intrinsic property of the fibrous material, could be computed directly. This resultant N would be an average value over the temperature range. Previous results show a mild temperature dependency for N, however, so that this simplifying feature would not result in a significant error.

A similar technique has been used with success in evaluating multi-foil systems and has been previously reported (Final Report ALO 3632-20). The accuracy of the method is influenced by the selection of the functional form of the K_s expression. As mentioned in Section 2.2.2, there is some doubt as to this correct form, and several areas are being studied in an effort to improve the accuracy of the K_s term.

2.2.3.3 Apparent Thermal Conductivity as a Design Parameter

A method of characterizing thermal performance of fibrous multi-layer systems (opacified and non-opacified) by means of an apparent thermal conductivity is shown in Figures 2.2.15 to 2.2.18. For each of the four multi-

layer insulations, K_a is plotted against sample thickness (ΔX) for the specific case of 500°F. to 70°F. boundary temperatures and 15 psi compressive load. Two limiting boundary emissivity conditions ($\epsilon = .05$ and $\epsilon = 1.0$) are considered. The curves illustrate one temperature and load condition -- similar plots could be made at any combination of load-temperature conditions within the operating range.

For all the described multi-layers, the apparent thermal conductivity is constant (i.e. independent of thickness) for thicknesses $\geq .2$ " in the black boundary ($\epsilon = 1.0$) case. In this range, the radiant heat attenuation due to the boundary surface is negligible compared with the backscattering coefficient ($N\Delta X$). For the highly reflective boundaries ($\epsilon = 0.05$), $N\Delta X \gg (\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1)$ only for insulation thicknesses in excess of 2.0". The K_a value is strongly thickness-dependent throughout the normal application range.

Apparent thermal conductivity curves can be developed for fibrous multi-layers under any combination of temperature and compressive load within the specified ranges by using the expressions of Table 2.2.6. Higher temperatures would naturally yield higher K_a values. Based on Figures 2.2.5 and 2.2.7 it is felt that reduction in load (layer density) from the illustrated 15 psi case would have the effect of:

1. Slight reduction in the thickness values for which K_a becomes a constant for the 106 glass materials.
2. Slight increase in insulation thickness corresponding to constant K_a for the Refrasil quartz fiber insulations.

These observations are based on the significantly different behavior of the backscattering cross-section (N) for the two fiber types at different layer densities as illustrated in Figures 2.2.5 and 2.2.7.

In a thermal design situation, one must be cautious in computing and applying the correct thermal performance parameter for the fibrous multi-layer insulations. Depending on boundary conditions and system geometry, thermal performance at a given temperature and layer density can vary by as much as a factor of 2. Curves of the type shown in Figures 2.2.15 to 2.2.18 clearly define these performance variables and aid the designer in selecting the correct K_a values.

2.2.4 Flat Plate Tester Modification

The sample testing configuration used in obtaining all flat plate thermal conductivity data to date is shown schematically in Figure 2.2.19. This fixture provides for compression (0 - 15 psi) of the 6" x 6" sample area only, with the guard remaining uncompressed throughout testing. Because of the rather severe load-deflection characteristics of some multi-layer insulations, testing at higher loads (e.g. 1 - 15 psi) results in significant physical and thermal mismatch between sample and guard sections at the gap. To eliminate these problems, it is necessary to physically replace the initial,

FIGURE 2.2.16 APPARENT THERMAL CONDUCTIVITY AS A FUNCTION OF THICKNESS -- ALUMINUM OPACIFIED GLASS MULTI-LAYER

FIGURE 2.2.18 APPARENT THERMAL CONDUCTIVITY AS A FUNCTION OF THICKNESS -- COPPER OPACIFIED QUARTZ MULTI-LAYER

full-thickness guard with a thinner section where making the transition from low load (0 - 1 psi) to high load (1 - 15 psi) tests.

To achieve more uniform matching at the gap and eliminate the inconvenience of guard replacement (requiring test interruption), an extended compression fixture has been introduced. The modified sample configuration is shown schematically in Figure 2.2.20. The loading area of the fixture has been extended to 8" x 8", which effectively bridges the gap between sample and guard and compresses both sections simultaneously. The design modification involved (1) extension of top and bottom compression plates and (2) adding load bearing capability in the guard section. No changes were required in sample dimensions, heater assembly, or instrumentation.

The modified fixture is being used in testing of the nickel-nickel opacified quartz multi-layer specimen. Early data indicate that the system is functioning well, with good thermal matching between sample and guard boundaries. Maintaining gap alignment at the various levels of compression does not appear to be a problem. Contingent upon satisfactory operation, the extended compression fixture will be used on all subsequent flat plate tests.

Check-out testing of the extended compression configuration will determine the following:

1. Assurance that correspondence exists between the load-deflection pattern of the sample + guard assembly and independently measured load-deflection characteristics of the particular multi-layer sample.
2. Remeasure selected data points for a copper-Refrasil quartz sample, originally tested in the Figure 2.2.19 assembly, to assure reproducibility of the thermal performance data.

2.2.5 Flat Plate Testing Accuracy

The estimated error band for flat plate thermal conductivity data is $\pm 15\%$. This estimate was obtained by considering three potential error sources:

1. Measurement-instrumentation error -- based on calibration data for thermocouples and flux meter and calibration and readability of recording equipment. The deviation due to this source alone is $\pm 5\%$.
2. Presence of thermal discontinuity (gap) -- gap effects were analyzed and reported in the Quarterly Progress Report ALO 3632-23, November, 1967. Based on a somewhat conservative case of .020" wide, open gap, the average deviation attributed to data on multi-foil systems was 10%. For non-foil samples, this error would be reduced considerably.

FLAT PLATE TESTER
INSTALLED SAMPLE CONFIGURATION

FIGURE 2.2.19

FLAT PLATE TESTER
 INSTALLED SAMPLE CONFIGURATION WITH EXTENDED COMPRESSION PLATES

FIGURE 2.2.20

3. Random errors in sample installation, testing -- This potential error would consist of sample misalignment, meter or controller failure, or the like. It is not inherent in the test system and is minimized through close monitoring of the tests and frequent calibration checks on the instruments. It is not included in the quantitative error band estimate. When significant error of this type occurs, it is normally identifiable and correctable through test and data monitoring.

The current insulation "gap" design consists of ~.020" wide space filled with the fibrous spacer material. In normal practice the separators in the multi-foil sample are extended to fill the gap. This design gives reasonably low heat loss through the gap;* at the same time temperature profiles in the guard and sample are reasonably well matched to prevent high lateral heat transfer across the gap. It is important that strong thermal coupling (e.g. bridged foils) does not exist between sample and guard. A weak coupling, such as the .020" filled gap, minimizes the sensitivity of the K measurement to mild thermal and physical variations in the guard section. These thermal coupling effects were discussed in the July Progress Report ALO 3632-32.

An experimental proof test has not been run to provide additional verification of flat plate data. Such a test would require a specially designed sample configuration involving, in many cases, rather elaborate sample preparation. The following evidence, however, appears to substantiate the accuracy estimate of $\pm 15\%$.

1. The flat plate K_a data is in agreement (falls within the error band) with cylindrical test data on comparable insulation samples.
2. The flat plate data have been consistent with predicted trends based on heat transfer model for the multi-layer insulations.
3. Instrument calibration and test equipment are checked periodically to assure proper operation.

* This loss is being re-computed using a refined analytical model.

2.3 Insulation Interfaces - Penetrations

2.3.1 Introduction

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

Two types of penetrations have been under investigation; flush penetration as shown in Figure 2.3-1 a and extended penetrations as shown in Figure 2.3-1 b.

Flush penetration studies are aimed directly at the evaluation of disturbances associated with the necessity of passing a multiplicity of regularly spaced thermoelectric elements through a typical energy conversion panel; to this end, investigations have been centered around Lead-Telluride and Silicon Germanium penetrations.

Results of flush penetration studies have been reported in previous reports (Reference ALO 3632-23 and ALO 3632-29).

Extended penetrations studies are aimed primarily at studying similar effects associated with structural members which connect the hot and cold boundaries, where the structural member is not necessarily equal in length to the insulation thickness.

Investigation of the effects of extended penetrations has been centered around the use of Hastelloy-X as a typical structural material. In the period covered by this report, extended penetration calculations have been completed and all results have been reduced. Results are presented in Tables 2.3-1 to 2.3-32.

The configurations investigated are all shown in detail in Figures 2.3-2 to 2.3-5. The analytical procedures used are shown in Figures 2.3-6.

2.3.2 Calculations - Basis

The physical models used to explore the effect of extended penetrations are shown in Figures 2.3-2 to 2.3-5.

The simplest case to examine is Figure 2.3-2 (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 2.3-3 where the penetration (e.g. structural support) extends consider-

ably beyond the insulation, the common tendency would be to treat it thermally in a manner like the system of 2.3-2 (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 2.3-3 (a) to the result of the simplified calculation associated most realistically with the configuration of Figure 2.3-2 (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 and empty gap configurations of Figures 2.3-2 (b) and 2.3-2 (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 fraction of the system (i.e. $\pi (r_3^2 - r_1^2)$ Figure 2.3-6).

For convenience, all heat flow quantities are reported in dimensionless form, referenced to one dimensional results associated with Figure 2.3-2 a. Thus: in Tables 2.3-1 to 2.3-4 and 2.3-17 to 2.3-20, 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 2.3-2 to 2.3-5 to the heat flow from T_H to T_C which would result from one-dimensional analysis on the configuration of Figure 2.3-2 (a).

Similarly, in Tables 2.3-5 to 2.3-8 and 2.3-21 to 2.3-24 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 2.3-2 to 2.3-5 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 2.3-9 to 2.3-12 and 2.3-24 to 2.3-27, 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 area $\pi (r_3^2 - r_1^2)$ 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.

2.3.3 Physical Models

Physical models on which calculations have been based are shown in Figures 2.3-2 to 2.3-5.

Figure 2.3-2 shows the idealized configuration for the case where the penetration length is equal in magnitude to the insulation height. In this respect, Figures 2.3-3, 2.3-4 and 2.3-5 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

FIGURE 2.3.1 - a
FLUSH PENETRATION SCHEMATIC

CATEGORY I

CATEGORY II

FIGURE 2.3.1 - b
EXTENDED PENETRATIONS SCHEMATIC

FIG. 2.3-2
 THERMOELECTRIC ELEMENT - INSULATION
 IDEALIZED CONFIGURATION

FIG. 2.3-3

THERMOELECTRIC ELEMENT INSULATION
IDEALIZED CONFIGURATION

FIG. 2.3-4
THERMOELECTRIC ELEMENT - INSULATION
IDEALIZED CONFIGURATION

FIG. 2.3-5

THERMOELECTRIC ELEMENT - INSULATION
IDEALIZED CONFIGURATION

penetration).

filled gap - an annular gap between the penetration and the insulation is filled with a buffer insulation with the following thermal conductivity

$$K_r = [2.76 \times 10^{-4} (T)] - 0.0545$$

$$K_n = (1.79 \times 10^{-7})T + (6.4 \times 10^{-13})T^3$$

K_r = thermal conductivity in the radial direction

K_n = thermal conductivity in the direction normal to the direction of net heat flow.

empty gap - an annular gap between the penetration and the insulation is considered to be empty.

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 ($r_3 - r_2$). From the point of view of heat loss from the exposed segments of the penetration, this will be the most severe condition tending to reduce the penetration's effective thermal length. This effect would be particularly so in these calculations since the thermal balance on a longitudinal increment of the exposed penetration considers only heat leaving its surface by radiation and not heat reaching it by the same mode.

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.

2.3.4 Pertinent Observations

1. In the case where the penetration length is equal to the insulation height, the one-dimensional approximation to calculating total heat flow appears adequate provided total heat flow is largely influenced by the heat flow through the penetration.

In terms of the results shown in Tables 2.3-1 and 2.3-17, for the smaller values of adiabatic radius (r_3), the ratios of $Q_{\text{system}}/Q(\text{one dimensional-zero gap})$, particularly for the zero gap system, are essentially unity.

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

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

Likewise, increasing penetration size has the effect of increasing its dominance.

2. For all cases where the penetration is considerably longer than the insulation, (Figures 2.3-2, 2.3-3, 2.3-4 etc.) the simple, one-dimensional approximation overestimates system heat loss by a wide margin. In some cases, by as much as one order of magnitude.

The primary indication is clearly that even with the assumption of blackbody loss from the surface of the penetration, physically lengthening the penetration results in considerable thermal lengthening and thus lower heat flow.

For example, comparing Figures 2.3-1 and 2.3-2 for the following case:

Panel thickness	-	0.1"
Penetration diameter	-	0.1"
Adiabatic radius	-	1.5"
Empty gap		
Gap width	-	0.025"

$$\text{One has } \frac{Q_{\text{system}}}{Q_{\text{(one dimension of-zero gap)}}} = 0.989 \text{ (Table 2.3-1)}$$

$$\text{and } \frac{Q_{\text{system}}}{Q_{\text{(one dimensional-zero gap)}}} = 0.100 \text{ (Table 2.3-2)}$$

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

A secondary observation which can be made is that with the reduced heat flux through the penetration, (Table 2.3-2 as compared to 2.3-1), increasing the adiabatic radius from 1.5" to 6" improves the accuracy of the one-dimensional calculation in contrast to the observation of Table 2.3-1. This observation would suggest that a reversal of this trend would occur in Table 2.3-1 if the adiabatic radius were increased beyond 6" to the point where the insulation predominated over the disturbance.

3. If one had a choice, theoretically, calculations indicate that the insulation should be placed towards the center of the penetration -- positioning the insulation towards the hot side is second best, and at the cold side, the least advantageous.

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

From a practical viewpoint, it is believed that in most designs, the insulation would be placed next to the hot side.

Further reduction in heat loss could be achieved by insulating the penetration longitudinally to achieve a greater thermal length.

4. Results indicate the existence for each configuration (i.e. Figures 2.3-2, 2.3-3, 2.3-4) of a penetration length to area ratio at which the

heat loss is a minimum.

For example, for the configuration of Figure 2.3-3, increasing the length of the 0.1" diameter penetration from 2" to 6" seems to make very little difference to total heat flow.

Increasing the length of the 0.5" diameter penetration in the same manner still effects a considerable decrease in total heat flow.

For the configuration of Figure 2.3-3 on the other hand, increasing the length of the 0.1" diameter penetration from 2" to 6" causes an increase in the total heat flow.

Increasing the length of the 0.5" penetration in the same manner causes only a minor increase.

Note that since the configuration of Table 2.3-1 can be considered to be a special case of any of the configurations 2.3-2, 2.3-3 and 2.3-4, examination of corresponding cases for each of these configurations will indeed yield, at least for some cases, first a decreasing, then an increasing trend in total heat flow as the exposed length of the penetration is varied from zero to six inches.

5. Caution must be exercised in examining the results of cases with increased insulation thickness. The height of the insulation as well as the length of the penetration used for the one-dimensional base is increased, therefore, lower absolute values of one-dimensional heat quantities and thus the larger fractions. The indication, of course, is that, although the exposed lengths of penetration are identical to those for the smaller insulation thickness cases, the ratio of unexposed to exposed penetration is increased and with further increases in insulation thickness, would eventually approach - but not reach - the results of Table 2.3-1.

6. The significance of Tables 2.3-5 through 2.3-8 and similar figures for the higher temperature range is self-explanatory. Results in these tables give an indication of the amount of heat entering the hot penetration system interface and the change in this quantity as the penetration is lengthened under various system configurations.

- Note that for the flush case (2.3-5), heat entering the penetration is nearly equal to the one-dimensional prediction.
- Note the drastic reduction as the penetration is lengthened (2.3-6, 2.3-7, 2.3-8).
- Note that the reduction in heat entering the penetration are of the order of reduction of heat transfer through the systems, thus indicating the overwhelming dominance of the penetration heat leak.

- Note that exposing the hot end of the penetration is more detrimental than exposing both ends or the cold end. (Compare Tables 2.3-7 to 2.3-6 and 2.3-8).

7. The results on Tables 2.3-9 to 2.3-12 and similar figures for the higher temperature range can be interpreted in a manner similar to the results of 2.3-5 to 2.3-8.

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

8. Tables 2.3-13 to 2.3-16 show ratios of heat leaving the insulation cold side to heat entering its hot side. Fractions smaller than 1.00 would indicate a net heat transfer from the insulation to the penetration and/or surrounding and vice versa.

- Note that in all cases, with the exception of those cases where the insulation is concentrated at the hot side (Table 2.3-16), net loss is out of the insulation.
- Note also that concentration of the insulation at either the hot or cold side provide the two extreme cases. From an overall heat loss viewpoint it is believed better to let the insulation cool the penetration rather than the reverse case. It is believed that this accounts in part for the better overall performance of the configuration of Table 2.3-16 in comparison to that of Table 2.3-15.
- The results of Tables 2.3-17 to 2.3-32 are similar to 2.3-1 to 2.3-16 except that they relate to higher temperature ranges. They should lend themselves to similar interpretation.

2.3.5 Analytical Model

The analytical model accompanied by the governing equations used for the configurations of Figures 2.3-2 to 2.3-5 is shown in Figure 2.3-6. This model combined with the conditions set forth in Section 2.3.3 - Physical Models, describes fully the conditions for this analysis.

DIFFERENTIAL EQUATIONS

- ① $\frac{\partial}{\partial z} \left(k_p \frac{\partial T_p}{\partial z} \right) + q_p = 0 \quad r \leq r_1, |z| \leq t/2$
- ② $\frac{\partial}{\partial r} \left(k_{gr} \cdot r \frac{\partial T_g}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_{gz} \frac{\partial T_g}{\partial z} \right) = 0 \quad r_1 \leq r \leq r_2, |z| \leq t/2 \quad \text{CASE (1) ONLY}$
- ③ $\frac{\partial}{\partial r} \left(k_{ir} \cdot r \frac{\partial T_i}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_{iz} \frac{\partial T_i}{\partial z} \right) = 0 \quad r_2 \leq r \leq r_3, |z| \leq t/2$

BOUNDARY CONDITIONS

- ① $\frac{\partial T_i}{\partial r} = 0, r = r_3$
- ② $T_p = T_H, z = t/2$
 $T_p = T_C, z = -t/2$
- ③ $q_p = -\frac{2\sigma\epsilon}{r_1} (T_H^4 - T_P^4), \frac{t}{2} \geq z \geq -\frac{t}{2}$

$$\left\{ \begin{array}{l} q_p = k_{gr} \frac{\partial T_g}{\partial r} \text{ (CASE 1)} \\ \text{OR} \\ q_p = (q_p)_{\text{RAD}} \text{ (CASE 2)} \end{array} \right. \quad |z| \leq \frac{t}{2}$$

$$q_p = -\frac{2\sigma\epsilon_c}{r_1} (T_P^4 - T_C^4) - \frac{t}{2} \geq z \geq -\frac{t}{2}$$

$$\text{CASE 1 ONLY} \left\{ \begin{array}{l} k_{gz} \frac{\partial T_g}{\partial z} = -\sigma\epsilon_H (T_H^4 - T_g^4), z = t/2 \\ k_{gz} \frac{\partial T_g}{\partial z} = -\sigma\epsilon_C (T_g^4 - T_C^4), z = -t/2 \end{array} \right\} r_1 \leq r \leq r_2$$

$$\left\{ \begin{array}{l} k_{iz} \frac{\partial T_i}{\partial z} = -\sigma\epsilon_H \epsilon'_H (T_H^4 - T_C^4), z = t/2 \\ k_{iz} \frac{\partial T_i}{\partial z} = -\sigma\epsilon_C \epsilon'_C (T_i^4 - T_C^4), z = -t/2 \end{array} \right\} r_2 \leq r \leq r_3$$

$$\text{CASE 1: } k_{gr} \frac{\partial T_g}{\partial r} = k_{lr} \frac{\partial T_i}{\partial r} \quad r = r_2$$

$$\text{CASE 2: } (q_p)_{\text{RAD}} = k_{ir} \frac{\partial T_i}{\partial r} \quad |z| \leq t/2$$

LEGEND

k = THERMAL CONDUCTIVITY
 T = TEMPERATURE
 σ = STEFAN-BOLTZMAN CONSTANT
 q = HEAT FLUX
 ϵ = EMISSIVITY OF SYSTEM BOUNDARY
 ϵ' = EMISSIVITY OF INSULATION
 p - REFERS TO PENETRATION
 g - REFERS TO GAP
 i - REFERS TO INSULATION

FIG. 2.3-6

The following additional simplifications have been made:

- In carrying out the heat balance around the exposed portions of the penetration (i.e. calculating q_p)
 - The geometric view factor is considered unity.
 - Only heat interchange between the penetration and the boundary surfaces is considered.

The assumption of unity for a geometric view factor could be in error depending on the actual geometry of the hot and cold surfaces.

Under the most unfavorable circumstance, the effect of this assumption would be to increase heat transfer to the penetration. Since the penetration area is a relatively small collector the effect on the total heat balance is not believed to be significant.

Q_{system}

Q (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
			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	.990	.844		.998	.943	0.1
			.999	.991		1.00	.997	0.5
		0.075	.990	.843		.999	.940	0.1
			1.00	.991		1.00	.997	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 DIAMETER - INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-1

Q_{system}

Q (One-Dimensional Zero Gap)

Aluminum Foil - Aluminum Opacified Paper Insulation

Hastelloy X Penetration

Boundary Temperatures - 800°F - 200°F

Conservative Q_{p0}

				PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
				0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.100	.242		.291	.461	0.1	
			.057	.066		.195	.208	0.5	
			0.075	.118	.254		.332	.483	0.1
				.059	.067		.200	.212	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.103	.245		.313	.502	0.1	
			.057	.069		.195	.215	0.5	
		0.075	.106	.246		.320	.488	0.1	
			.058	.067		.198	.213	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
			.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	.102	.244	.311	.497	0.1
			.038	.048	.136	.158	0.5
		0.075	.106	.245	.317	.489	0.1
			.039	.048	.139	.157	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							

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-2

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	.186	.301		.504	.616	0.1	PENETRATION DIAMETER - INCHES
			.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	.204	.340		.535	.716	0.1	
			.085	.099		.279	.313	0.5	
		0.075	.208	.327		.544	.693	0.1	
			.087	.099		.284	.315	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
			.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	.242	.365		.604	.741	0.1
			.084	.099		.279	.320	0.5
		0.075	.247	.353		.611	.726	0.1
			.086	.097		.285	.316	0.5
ZERO GAP			.265	.412		.635	.780	0.1
			.087	.104		.288	.335	0.5
			1.5	6.0		1.5	6.0	PENETRATION DIAMETER - INCHES
			ADIABATIC RADIUS-INCHES				65	

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-3

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

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

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES		
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.156	.229	.398		.534	0.1
		0.075	.074	.083	.237		.250	0.5
		0.025	.175	.292	.440	.561	0.1	
		0.075	.076	.086	.244	.256	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.164	.297	.417	.588	0.1	
		0.075	.074	.086	.237	.265	0.5	
		0.025	.167	.292	.425	.579	0.1	
		0.075	.075	.086	.242	.263	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	.198	.318		.463	.609	0.1
			.071	.082		.223	.251	0.5
		0.075	.201	.314		.468	.598	0.1
			.072	.082		.227	.249	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 2.3-4

Q (Into Penetration - Hot Side)

Q (Penetration - One Dimensional)

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

		PANEL		SS			
		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	.990	.993	.940	0.1
			1.00	.999	.999	.996	0.5
		0.075	.998	.993	.993	.948	0.1
			1.00	.999	.999	.996	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 DIAMETER - INCHES							

PENETRATION-INSULATION
CONFIGURATION

TABLE 2.3-5

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

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

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN	0.025	.081	.080		.250	.243	0.1
			.055	.055		.188	.187	0.5
		0.075	.081	.080		.247	.243	0.1
			.055	.055		.188	.187	0.5
FILLED GAP	GAP WIDTH, IN	0.025	.077	.073		.225	.190	0.1
			.055	.054		.187	.178	0.5
		0.075	.077	.075		.223	.203	0.1
			.055	.054		.185	.180	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					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.085	.085		.258	.254	0.1
			.037	.037		.131	.129	0.5
		0.075	.085	.085		.257	.254	0.1
			.037	.037		.131	.129	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.078	.076		.229	.199	0.1
			.036	.035		.128	.124	0.5
		0.075	.078	.077		.229	.211	0.1
			.036	.036		.128	.125	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

TABLE 2.3-6

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

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

		PANEL THICKNESS					
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.165	.165	.440	.427	0.1
			.082	.082	.267	.265	0.5
		0.075	.165	.165	.435	.427	0.1
			.082	.082	.267	.265	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.158	.151	.393	.292	0.1
			.081	.081	.265	.255	0.5
		0.075	.158	.155	.390	.320	0.1
			.081	.081	.263	.257	0.5
ZERO GAP			.153	.138	.360	.238	0.1
			.081	.080	.262	.248	0.5
		1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS-INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.228	.226	.557	.541	0.1
			.083	.083	.277	.274	0.5
		0.075	.226	.226	.552	.541	0.1
			.083	.083	.276	.274	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.200	.193	.480	.369	0.1
			.080	.080	.267	.257	0.5
		0.075	.200	.197	.476	.399	0.1
			.080	.080	.265	.258	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-INSULATION CONFIGURATION

TABLE 2.3-7

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

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	.160	.198		.415	.553	0.1
			.074	.079		.237	.263	0.5
		0.075	.162	.179		.422	.527	0.1
			.075	.078		.240	.260	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	.197	.230		.459	.572	0.1
			.070	.075		.223	.249	0.5
		0.075	.197	.211		.465	.551	0.1
			.071	.074		.226	.246	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								

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-8

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES			
EMPTY GAP	GAP WIDTH, IN	0.025	.659	.543			1.12	.841	0.1
		0.075	1.05	.570			1.65	.939	0.5
			1.23	.578			2.43	.916	0.1
FILLED GAP	GAP WIDTH, IN <td rowspan="2">0.025</td> <td>2.89</td> <td>.682</td> <td></td> <td>6.09</td> <td>1.20</td> <td>0.5</td>	0.025	2.89	.682		6.09	1.20	0.5	
			.739	.570		1.16	.951	0.1	
		0.075	.885	.617		1.31	1.04	0.5	
			.753	.559		1.16	.926	0.1	
		0.075	.976	.599		1.42	1.02	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

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES
EMPTY GAP	GAP WIDTH, IN	0.025	0.075	0.025	0.075	
FILLED GAP	GAP WIDTH, IN	.691	.545	1.64	.869	0.1
		1.30	.586	4.37	1.18	0.5
		1.25	.580	2.95	.942	0.1
		3.09	.695	9.39	1.44	0.5
	GAP WIDTH, IN	.876	.567	2.99	1.08	0.1
		1.66	.673	6.59	1.92	0.5
		.975	.566	3.17	1.03	0.1
		2.31	.676	9.62	1.80	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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES
GAP WIDTH, IN	GAP WIDTH, IN	0.025	0.075	0.025	0.075	
		.677	.544	1.50	.855	0.1
GAP WIDTH, IN	GAP WIDTH, IN	1.21	.578	4.02	1.10	0.5
		1.23	.579	2.80	.928	0.1
GAP WIDTH, IN	GAP WIDTH, IN	2.97	.686	8.70	1.36	0.5
		.829	.561	2.78	1.06	0.1
GAP WIDTH, IN	GAP WIDTH, IN	1.49	.637	6.13	1.76	0.5
		.929	.562	2.95	1.01	0.1
GAP WIDTH, IN	GAP WIDTH, IN	2.06	.646	8.93	1.66	0.5
		1.26	.599	4.10	1.22	0.1
GAP WIDTH, IN	GAP WIDTH, IN	2.84	.741	11.1	2.25	0.5

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

		I		S			
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN	0.025	.831	.555	2.46	.968	0.1
		0.075	1.80	.629	6.78	1.61	0.5
		0.025	1.40	.590	4.03	1.05	0.1
		0.075	3.77	.739	13.6	1.91	0.5
FILLED GAP	GAP WIDTH, IN	0.025	1.56	.693	4.85	1.51	0.1
		0.075	2.61	.963	10.1	3.31	0.5
		0.025	1.72	.650	5.22	1.40	0.1
		0.075	3.96	.903	16.1	3.05	0.5
ZERO GAP			2.43	.865	7.13	1.74	0.1
			5.06	1.26	18.6	4.27	0.5
			1.5	6.0	1.5	6.0	
		ADIABATIC RADIUS-INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					
		0.1"		0.4"			
C P T	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
		0.125	1.53	.687	4.33	1.44	0.1
			2.61	.964	10.1	3.30	0.5
			1.68	.646	4.66	1.33	
			3.96	.903	16.0	3.04	
			2.37	.852	6.34	1.66	
			5.06	1.26	18.6	4.26	
PENETRATION DIAMETER - INCHES							

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-11

$$\frac{Q}{Q_0} \left(\text{Into Insulation - Hot Side} \right)$$

$$Q_0 \left(\text{Insulation - One Dimensional - Zero Gap} \right)$$

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	.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	.221	.481	.507	.660	0.1
			.094	.401	.330	.368	0.5
		0.075	.304	.504	.530	.677	0.1
			.148	.446	.364	.406	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
		0.075	.492	.519	.502	.556	0.5
		0.025	1.07	.568	1.68	.837	0.1
		0.075	2.07	.623	2.80	.746	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.244	.484	.560	.679	0.1
		0.075	.090	.400	.310	.357	0.5
		0.025	.324	.506	.578	.691	0.1
		0.075	.145	.445	.341	.394	0.5
ZERO GAP		0.025	.216	.456	.597	.691	0.1
		0.075	.081	.370	.314	.345	0.5
			1.5	6.0	1.5	6.0	
		ADIABATIC RADIUS-INCHES					

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-12

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

		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	.565	.887		.506	.652	0.1
			.553	.771		.481	.519	0.5
		0.075	.609	.929		.492	.708	0.1
			.528	.834		.473	.549	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-INSULATION CONFIGURATION

TABLE 2.3-13

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

		ADIABATIC RADIUS - INCHES				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025					
		.906	.992	.708	.943		0.1
FILLED GAP	0.025	.698	.945	.520	.725	0.5	
		.946	.993	.793	.947	0.1	
	0.075	.858	.951	.623	.749	0.5	
		.748	.954	.680	.900	0.1	
	0.025	.552	.788	.494	.626	0.5	
		.795	.967	.722	.906	0.1	
	0.075	.586	.830	.531	.642	0.5	
		ZERO GAP		.771	.945	.706	.906
		.570	.742	.515	.626	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"		
GAP	GAP WIDTH, IN.					
GAP	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
	0.025	.843	.971	.789	.945	0.1
		.746	.895	.707	.829	0.5
	0.075	.878	.980	.833	.947	0.1
		.786	.916	.746	.832	0.5
	0.025	.859	.967	.807	.949	0.1
		.770	.873	.731	.831	0.5
	0.075	.859	.967	.807	.949	0.1
		.770	.873	.731	.831	0.5
	0.025	.843	.971	.789	.945	0.1
		.746	.895	.707	.829	0.5
	0.075	.878	.980	.833	.947	0.1
		.786	.916	.746	.832	0.5

PENETRATION-INSULATION CONFIGURATION

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

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

		.1"		.4"		PENETRATION DIAMETER - INCHES		
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	.063	.629	.060		.313	0.1
			.014	.309	.016		.049	0.5
		0.075	.098	.733	.056		.372	0.1
			.014	.420	.011		.063	0.5
ZERO GAP			.040	.412	.048		.270	0.1
			.008	.171	.009		.038	0.5
			1.5	6.0	1.5		6.0	
ADIABATIC RADIUS-INCHES								

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS					
		0.1"		0.4"			
I, GAP WIDTH, IN.	EMPTY	0.025	.607	.959	.186	.771	0.1
			.249	.818	.036	.302	0.5
	FILLED	0.075	.748	.961	.348	.783	0.1
			.530	.837	.149	.348	0.5
	ZERO	0.025	.073	.640	.076	.340	0.1
			.014	.309	.016	.049	0.5
			.107	.741	.071	.402	0.1
			.014	.420	.011	.064	
			.048	.426	.059	.292	
			.008	.171	.009	.038	

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-15

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

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

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES
EMPTY GAP	GAP WIDTH, IN.	0.025	1.51 1.03	3.06 1.19	0.1	
		0.075	3.38 1.19	10.2 2.43	0.5	
		0.075	1.28 1.03	2.02 1.18	0.1	
		0.075	1.77 1.16	3.95 2.19	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	5.56 1.29	6.32 1.80	0.1	
		0.075	25.1 1.97	24.2 6.40	0.5	
		0.075	4.38 1.20	6.66 1.67	0.1	
		0.075	21.9 1.73	31.7 5.43	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					
		0.1"		0.4"			
GAP WIDTH, IN	EMPTY GAP	0.025	1.45	1.03	2.50	1.15	0.1
		0.075	3.39	1.19	10.6	2.47	0.5
	FILLED GAP	0.025	1.25	1.03	1.78	1.14	0.1
		0.075	1.77	1.17	4.05	2.23	0.5
	ZERO GAP	0.025	4.80	1.27	5.15	1.70	0.1
		0.075	26.3	1.98	26.5	6.73	0.5
	PENETRATION DIAMETER - INCHES	0.1	3.95	1.18	5.52	1.58	1
		0.5	22.4	1.74	34.8	5.69	5
		1	8.31	1.52	6.95	1.90	10
				55.4	2.65	47.6	8.86

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-16

Q_{system}

Q (One-Dimensional Zero Gap)

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

				0.1"		0.4"		PENETRATION DIAMETER - INCHES	
EMPTY GAP	GAP WIDTH, IN.	0.025	.978	.872		1.01	.964		0.1
			1.00	.979		1.00	.997		0.5
			0.075	1.04	.887		1.15		.998
			1.01	.988		1.03	1.02	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	.970	.870		.992	.958	0.1	
			.998	.978		.999	.993	0.5	
		0.075	.972	.870		.994	.960	0.1	
			.999	.978		1.00	.993	0.5	
			ZERO GAP		.970	.870		.992	.958
		.998	.978		.999	.993	0.5		
			1.5	6.0		1.5	6.0		
			ADIABATIC RADIUS-INCHES						

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

Conservative Q_{p0}

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.291	.699	.549		.848
			.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	.295	.700	.579	.864	0.1
			.085	.182	.271	.372	0.5
		0.075	.296	.698	.569	.856	0.1
			.086	.182	.270	.361	0.5
ZERO GAP			.310	.705	.619	.873	0.1
			.088	.186	.282	.384	0.5
		1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS-INCHES					

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.332	.707	.608	.859	0.1
			.083	.180	.257	.348	0.5
		0.075	.391	.723	.736	.891	0.1
			.091	.188	.276	.365	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.321	.706	.613	.867	0.1
			.081	.179	.258	.361	0.5
		0.075	.323	.705	.605	.859	0.1
			.081	.179	.258	.350	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					

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-18

$$Q_{\text{system}}$$

$$Q_{\text{(one-dimensional Zero Gap)}}$$

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	.463	.746		.804	.922	0.1
			.160	.255		.455	.552	0.5
		0.075	.456	.740		.794	.914	0.1
			.160	.248		.453	.532	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
			.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	.573	.772		.867	.932	0.1
			.187	.278		.513	.599	0.5
		0.075	.569	.768		.862	.932	0.1
			.187	.273		.511	.581	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					81	

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-19

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

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

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"0.4"						
		GAP WIDTH, IN.						
EMPTY GAP	GAP WIDTH, IN.	0.025	.390	.722		.669	.873	0.1
			.133	.223		.364	.442	0.5
		0.075	.449	.737		.794	.906	0.1
			.142	.230		.385	.462	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.423	.727		.692	.889	0.1
			.134	.228		.371	.468	0.5
		0.075	.392	.724		.685	.881	0.1
			.134	.225		.369	.454	0.5
ZERO GAP			.416	.734		.718	.897	0.1
			.139	.234		.383	.482	0.5
			1.5	6.0		1.5	6.0	
ADIABATIC RADIUS-INCHES								

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
		GAP WIDTH, IN.					
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	.473	.745	.746	.899	0.1
			.159	.251	.410	.498	0.5
		0.075	.475	.743	.743	.899	0.1
			.160	.248	.409	.486	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							

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES			
EMPTY GAP	GAP WIDTH, IN.	0.025	.998	.997			.975	.962	0.1
			.999	.999			.998	.994	0.5
		0.075	1.00	.999			.981	.970	0.1
			1.00	1.00			.999	.996	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.989	.981			.953	.899	0.1
			.999	.998			.997	.989	0.5
		0.075	.992	.989			.957	.921	0.1
			.999	.998			.997	.991	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

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 <td>.074</td> <td></td> <td>.237</td> <td>.233</td> <td>0.5</td>	.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	.131	.129		.297	.267	0.1	
			.073	.072		.228	.218	0.5	
		0.075	.133	.132		.313	.300	0.1	
			.073	.073		.230	.227	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	.169	.167	.365	.333	0.1	
			.069	.068	.219	.213	0.5	
		0.075	.170	.170	.381	.369	0.1	
			.069	.069	.221	.219	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 2.3-22

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	PENETRATION DIAMETER - INCHES
			.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	.276	.266		.452	.368	0.1	
			.140	.139		.385	.358	0.5	
		0.075	.281	.278		.480	.432	0.1	
			.140	.140		.387	.375	0.5	
ZERO GAP			.261	.244		.392	.305	0.1	
			.139	.137		.373	.343	0.5	
			1.5	6.0		1.5	6.0		
		ADIABATIC RADIUS-INCHES							

PENETRATION-INSULATION CONFIGURATION

				PANEL THICKNESS				
				0.1"		0.4"		
EMPTY GAP	GAP WIDTH, IN.	0.025	.508	.507		.750	.731	0.1
			.185	.184		.495	.488	0.5
		0.075	.508	.508		.750	.731	0.1
			.185	.184		.492	.486	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.431	.418		.618	.529	0.1
			.167	.166		.451	.424	0.5
		0.075	.438	.433		.644	.594	0.1
			.167	.167		.453	.441	0.5
ZERO GAP		.411	.390		.561	.460	0.1	
		.166	.164		.439	.409	0.5	
		1.5	6.0		1.5	6.0	85	
ADIABATIC RADIUS-INCHES								

PENETRATION-INSULATION CONFIGURATION

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

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	.281	.283	:	.607	.625	0.1	PENETRATION DIAMETER - INCHES
			.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	.310	.342		.650	.702	0.1	
			.130	.138		.368	.407	0.5	
		0.075	.300	.308		.642	.677	0.1	
			.129	.131		.367	.388	0.5	
ZERO GAP			.342	.390		.680	.730	0.1	
			.135	.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	.403	.425	.706	.731	0.1
			.155	.163	.408	.441	0.5
		0.075	.395	.402	.700	.719	0.1
			.154	.157	.408	.426	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				8	

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-24

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

		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	.899	.840		1.17	.965	0.1
			1.11	.854		1.62	1.01	0.5
		0.075	1.20	.859		1.83	1.01	0.1
			2.06	.912		3.88	1.15	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.890	.842		1.15	.973	0.1
			.975	.851		1.27	1.02	0.5
		0.075	.890	.840		1.15	.969	0.1
			.996	.849		1.30	1.01	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 DIAMETER - INCHES

PENETRATION-INSULATION
CONFIGURATION

TABLE 2.3-25

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES		
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	.963	.846	1.74		1.01	0.1
			1.41	.887	4.64		1.34	0.5
		0.075	.961	.842	1.62		.995	0.1
			1.43	.875	4.33		1.21	0.5
ZERO GAP			1.06	.853	2.06		1.04	0.1
			1.80	.913	6.42	1.48	0.5	
			1.5	6.0	1.5	6.0		
		ADIABATIC RADIUS-INCHES						

PENETRATION-INSULATION CONFIGURATION

		PANEL THICKNESS				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.906	.839	1.28	.968	0.1
			1.19	.858	2.84	1.09	0.5
		0.075	1.20	.859	1.92	1.01	0.1
			2.10	.914	5.04	1.22	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.947	.843	1.63	1.00	0.1
			1.34	.880	4.33	1.31	0.5
		0.075	.949	.842	1.52	.987	0.1
			1.37	.869	4.03	1.18	0.5
		0.125	1.04	.852	1.92	1.03	0.1
			1.71	.906	6.00	1.44	0.5
			1.0	1.0	1.0	1.0	

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-26

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

		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.979	.844	1.65	.999	0.1
			1.54	.883	4.74	1.29	0.5
		0.075	1.27	.862	2.35	1.04	0.1
			2.52	.939	7.72	1.45	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	1.22	.869	2.25	1.06	0.1
			2.31	.986	7.73	1.78	0.5
		0.075	1.17	.858	2.08	1.04	0.1
			2.23	.936	7.24	1.52	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				PENETRATION DIAMETER - INCHES	
		0.1"		0.4"			
EMPTY GAP	GAP WIDTH, IN.	0.025	.961	.842	1.45		.984
			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	1.15	.863	1.88	1.03	0.1
			2.27	.982	7.11	1.70	0.5
		0.075	1.11	.854	1.76	1.01	0.1
			2.19	.934	6.65	1.47	0.5
		0.125	1.34	.880	2.18	1.06	0.1
			3.13	1.05	9.86	1.92	0.5
				1.5	6.0		

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-27

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

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

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

	GAP WIDTH, IN.	0.1"		0.4"		
		0.025	0.075	0.025	0.075	
ENJOY GAP	0.025	.840	.834	.926	.941	0.1
	0.075	.811	.829	.742	.884	0.5
	0.025	1.13	.853	1.52	.980	0.1
	0.075	1.65	.883	2.22	.986	0.5
FOLLEL GAP	0.025	.745	.824	.853	.936	0.1
	0.075	.565	.796	.521	.844	0.5
	0.025	.782	.830	.864	.936	0.1
	0.075	.647	.815	.552	.858	0.5
ZERO GAP		.722	.821	.879	.940	0.1
		.527	.789	.523	.839	0.5
		1.5	6.0	1.5	6.0	
ADIABATIC RADIUS-INCHES						

PENETRATION-INSULATION CONFIGURATION

	GAP WIDTH, IN.	PANEL THICKNESS		
		0.1"	0.4"	
GAP	0.025	.851	.834	.992 .947
	0.075	.826	.830	.828 .896
	0.025	1.14	.853	1.60 .986
	0.075	1.67	.885	2.39 1.00
FOLLEL	0.025	.765	.827	.909 .941
	0.075	.578	.798	.572 .854
	0.025	.797	.830	.921 .941
	0.075	.658	.816	.603 .866
ZERO GAP		.745	.824	.928 .945
		.541	.791	.572 .849
		1.5	6.0	1.5 6.0
ADIABATIC RADIUS-INCHES				

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

		0.2"		0.4"		PENETRATION DIAMETER - INCHES		
EMPTY GAP	GAP WIDTH, IN	0.025	.957	.994	.751		.972	0.1
			.861	.983	.553		.906	0.5
		0.075	.964	.994	.806		.972	0.1
			.911	.983	.670		.899	0.5
FILLED GAP	GAP WIDTH, IN	0.025	.869	.982	.608		.936	0.1
			.728	.958	.489		.851	0.5
		0.075	.903	.989	.644		.950	0.1
			.772	.972	1.02		.876	0.5
ZERO GAP			.828	.974	.578		.924	0.1
			.697	.949	.485	.838	0.5	
		1.5	6.0	1.5	6.0 <th colspan="2"></th>			
ADIABATIC RADIUS-INCHES								

PENETRATION-INSULATION CONFIGURATION

TABLE 2.3-29

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

		0.1"		0.4"		PENETRATION DIAMETER - INCHES		
EMPTY GAP	GAP WIDTH, IN.	0.025	.978	.995	.886		.987	0.1
			.889	.985	.708		.923	0.5
			.983	.995	.911		.988	0.1
			.926	.986	.765		.922	0.5
FILLED GAP	GAP WIDTH, IN.	0.025	.959	.993	.913		.988	0.1
			.823	.969	.745		.910	0.5
		0.075	.971	.997	.926		.989	0.1
			.855	.979	.779		.930	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	.976	.997	.952		.994	0.1
			.907	.983	.876		.966	0.5
			.985	.998	.965		.994	0.1
			.934	.991	.913		.979	0.5
			.981	.995	.971		.996	0.1
			.918	.983	.891		.974	0.5
			1.5	6.0	1.5		6.0	
		ADIABATIC RADIUS-INCHES						

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

		PENETRATION 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	.547	.939		.249	.842	0.1
			.177	.787		.033	.419	0.5
		0.075	.621	.961		.285	.871	0.1
			.231	.856		.037	.509	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								
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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	.600	.948		.323	.869	0.1	
			.184	.792		.041	.445	0.5	
		0.075	.669	.967		.365	.896	0.1	
			.238	.859		.046	.535	0.5	
ZERO GAP			.478	.921		.270	.844	0.1	
			.113	.727		.029	.387	0.5	
			1.5	6.0		1.5	6.0		
ADJACENT RADIUS-INCHES									93

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	1.13	1.01	1.47	1.04	0.1
			1.79	1.06	4.87	1.34	0.5
	GAP WIDTH, IN	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	1.44	1.04	2.15	1.09	0.1
			3.25	1.17	10.9	1.80	0.5
	GAP WIDTH, IN	0.075	1.35	1.02	2.01	1.07	0.1
			2.88	1.11	9.92	1.57	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 DIAMETER - INCHES

PENETRATION-INSULATION
CONFIGURATION

		PANEL THICKNESS					PENETRATION DIAMETER - INCHES	
		0.1"		0.4"				
EMPTY GAP	GAP WIDTH, IN.	0.025	1.09	1.01	1.23	1.02		0.1
			1.72	1.05	3.99	1.29		0.5
		0.075	1.08	1.01	1.16	1.02	0.1	
			1.44	1.06	2.44	1.29	0.5	
FILLED GAP	GAP WIDTH, IN.	0.025	1.34	1.03	1.76	1.07	0.1	
			3.10	1.16	9.25	1.72	0.5	
		0.075	1.27	1.02	1.65	1.05	0.1	
			2.76	1.11	8.46	1.52	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		
			RADIUS-INCHES					

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PENETRATION-INSULATION
CONFIGURATION

2.4 Insulation Interfaces

2.4.1 Exposed Edge Effects

Certain multi-foil insulation system designs may contain insulation panels with edges exposed to the surrounding environment. In evaluating total system performance, it is necessary to determine the heat loss from these exposed edges.

The magnitude of the exposed edge heat loss is being predicted analytically. The analysis considers a rectangular insulation panel, operating under the conditions listed below:

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

Total heat loss from a multi-layer sample with exposed edges is being measured experimentally to:

1. Verify the edge heat loss as predicted by analysis.
2. Investigate edge guarding techniques to reduce this heat loss.

The experimental test set-up is shown schematically in Figure 2.4.1. The dual sample configuration duplicates the size and two-dimensional heat flow characteristics of the analytical model. Hot face surface temperatures are maintained by a two-stage, ceramic-encased woven graphite resistance heater. Power can be controlled independently to a central element and two narrow edge elements as a means of approximating a uniform, hot surface temperature. This temperature is monitored by thermocouples located at intervals from center to edge of the sample. Cold boundaries are maintained at a uniform ambient (70-100°F) temperature. The aluminum surface plates also stabilize the multi-layer wrap at a specified layer density.

Heat flux is determined by a total power measurement for the system operating at fixed boundary temperatures. Extraneous losses (i.e. heater leads) are subtracted to obtain the net heat loss from the exposed edge sample.

Testing capability, in vacuum, is to 1800°F. Aluminum - 106 glass and nickel-Refrasil quartz multi-layer insulations will be evaluated at hot-side temperatures of 1000°F. and 1800°F., respectively. Results will be compared to the corresponding analytical heat loss predictions.

2.4.2 Longitudinal Conductivity of Opacified Papers

The longitudinal or lateral thermal conductivity of opacified fibrous papers will be measured at hot-side temperatures throughout the service temperature range for the respective materials. The basic flat plate sample configuration will be used, in which essentially one-dimensional heat flow from hot to cold boundaries will be metered over a specified central portion of the sample.

Design of the apparatus and insulation samples for testing to 1800°F. are now in progress. The insulation samples will be of cylindrical geometry with six inch diameter and 1.5 inch height. They will be constructed by spirally wrapping the fibrous paper from the center outward, to a layer density which corresponds to the zero load condition for the particular material. Thermal gradient will be established across the sample by exposing the entire end surfaces to the specified hot and cold temperatures. A two inch x two inch square flux meter, located in the center of the cold sample boundary surface, will meter heat flow.

A numerical analysis of the two-dimensional heat flow condition in the wrapped cylindrical sample indicates that the six inch diameter x 1.5" high geometry will have sufficient "self-guarding" to assure essentially one-dimensional heat flow over the two inch x two inch metered section.

FIGURE 2.4.1 EXPOSED EDGE TEST SCHEMATIC

2.5 Vacuum Enclosure

The 10,000 hour continuous exposure test on the Hastelloy-X vacuum enclosure specimen was completed in August. No apparent loss of vacuum integrity was noted. Exposure testing conditions were: 1400°F. temperature; external vacuum in $\leq 1 \times 10^{-3}$ mm Hg pressure range; internal air pressure of 37.2 psia corresponding to a 5000 psi hoop stress on the cylindrical wall.

Detailed visual inspection (microstructure photographs) and strength testing of the exposed Hastelloy-X specimen will begin in September. The examination and test plans have been previously reported.

3.0

ACTIVITIES DURING THE NEXT REPORTING PERIOD

- Begin long-term, 8000 hour testing on the nickel multi-layer insulation systems described in Section 2.1
- Flat plate thermal conductivity testing to be continued. Ni opacified quartz, Ni-Ni opacified quartz, Ni-Refrasil quartz, and Ni-woven quartz systems will be evaluated.
- Exposed edge experimental study will be performed.
- Test program to determine longitudinal thermal conductivity of opacified fiber filler materials will begin.
- Modified analytical program for computing thermal effects of "filled-gap" penetrations and joints will be operational.
- Metallurgical examination of the Hastelloy-X vacuum enclosure specimen (after 10,000 hour, 1400°F. exposure) will be completed.

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