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Assessment of Reflective Insulations for Residential and Commercial Applications

D. W. Yarbrough

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Metals and Ceramics Division

ASSESSMENT OF REFLECTIVE INSULATIONS FOR RESIDENTIAL AND COMMERCIAL APPLICATIONS

D. W. Yarbrough

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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EXECUTIVE SUMMARY

This technical assessment contains an identification of current issues associated with reflective insulations and a discussion of the existing data base. The reflective assemblies are useful thermal insulation materials having applications in the residential and commerical building sectors. The industry associated with the production and marketing of reflective insulations is small and consequently unable to support the research needed to provide the data base required to promote broader use of this important material. The assessment contains a detailed discussion of the issues with quantification when appropriate.

Issues

- R-value testing and labeling

The question of R-value evaluation overshadows all other issues for this product. There is disagreement on how to measure the R-value of these materials. This can be seen in the wide range of R-value results obtained by different laboratories and discussed in this assessment. The reflective insulation industry does not unanimously accept R-value as rational for their product. The ASTM has not been able to write an accepted standard for the reflectives beyond use of hot boxes.

- R-value installed

Unlike the mass insulations, R-values for the reflectives are dependent on position and thus on installation. The effect of poor spacing on installed R-value is estimated in this assessment using a one-dimensional model developed for such analyses. A mathematical model, however, does not provide insight into poor installation involving uneven gaps, tears, or missing sections. The question of installed versus laboratory R-values is as great an issue with the reflectives as it is with mass insulation.

Installed foil insulation may affect system thermal performance in unexpected ways. Recent measurements at the Florida Solar Energy Research Center suggest interaction between foils and batts in an attic installation. The optimum combination of insulating materials including foils is a major energy conservation issue.

- R-value permanence

The reflective insulations require low emittance surfaces for a major part of their thermal resistance. The literature on long-time behavior of the foil insulations is very limited and contradictory. Increases in surface emittance caused by any process are shown by calculation to significantly decrease the R-value of these products.

The question of long-term performance must be answered for this product as it must for the mass insulations.

- Safety

Competitors of the reflective industry emphasize the fact that aluminum is a good electrical conductor and should be handled with great caution. The reflective industry points to its record to assert that electrical problems are non-existent. This issue must be examined in detail by an unbiased party to determine use constraints, if any.

Overview

The reflective insulations provide a thermal barrier by reflecting radiant energy, by having low emittance surfaces, and by reducing convective transport through subdivision of the insulated region. Unlike mass insulations, the reflective products have a system R-value rather than a material R-value. R-values for reflective assemblies depend on heat flow direction and are sensitive to the temperature difference across the assembly.

Products marketed as reflective insulation for building applications consist of one or more aluminum foils backed by either paper or a polymer and in the case of multifoil products structured to provide air spaces between the layers. The simplest products available consist of single layers of aluminum foil bonded for mechanical strength to one or both sides of a polymer sheet. The second major type of product consists of up to ten foils interleaved with paper and designed to "snap open" upon installation to form a series of small air gaps with reflective surfaces. Aluminum foil is also used as facing material for batt insulation, insulating boards, and as construction foil to reduce air infiltration and water vapor migration.

Reflective foil insulations are used in the same type of building applications as the mass insulations. Reflective insulations can be installed in wall cavities, between ceiling joists, and between floor joists to provide radiant energy barriers and reduced convective transport. In addition, reflectives can be used as a part of a roofing system either below the decking between rafters, within small air gaps between decking and roofing, and in air gaps created, for example, by paneling interior masonry walls. The reflectives are also being used as insulation in metal buildings that cannot readily accommodate loose-fill or batt-type insulations.

The most significant technical advances in the reflective insulation field involve the multilayer systems developed by NASA for the space program. The NASA assemblies may not be directly applicable to building applications but demonstrate the potential of reflective systems.

The industry associated with the production and marketing of reflective insulations is small, commanding less than one percent of the U.S. market. Appendix A of this report contains a listing of the nine producers in business in 1982. The reflective industry in recent months has been depressed, as have other building related industries. The aluminum metal industry produces the foil used by the reflective insulation industry and foil used as insulation facing. The aluminum foil producers are not directly involved in developing reflective assemblies.

The reflective insulation industry has no identifiable research and development activity nor is the industry likely to be in a position to initiate such activity in the near future. The reflective industry relies on testing by commercial laboratories to establish thermal performance data for their products. The industry is essentially a marketing-packaging operation that includes few technical personnel. Innovations developed by the industry are, consequently, limited to identification of new applications, improvement of installation techniques, and improved manufacturing efficiency.

The literature associated with reflective insulations is reviewed in the assessment. Calculations of thermal performance values depends very heavily on heat transfer data obtained by the National Bureau of Standards in the 1950's. Conventional heat transfer measurements other than those from commercial test laboratories have been made for specific products in a few cases. The R-value results from different laboratories do not agree and differ from calculated values. The literature associated with emittance changes is contradictory. Quantitative field data are not in evidence although the industry argues that such data are indicative of true thermal performance.

Non-industry reseach and development on reflective insulations for building applications is also limited. The academic community has not shown interest due in part to lack of support for research in this area. Limited efforts at two university laboratories are noted in the report along with a few publications from the past. The commercial laboratories accept measurement assignments but are not usually in a position to do unsponsored research and development.

In summary, the reflective industry has no internal on-going research and development effort. The external effort is presently limited to a few part-time efforts. The commercial laboratories are not undertaking product development. Competitors of the reflective industry with laboratory facilities study foil properties since they are used as facing materials and do limited testing for business purposes but not to promote use of a competing product.

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NOMENCLATURE

a_{ijk}	constants used in Equation 7.
A	area, m^2
E	Effective Emittance defined by Equation 4.
h	heat transfer coefficient W/m^2K ($Btu/ft^2 \cdot hr \cdot °F$)
	h_c for convection
	h_r for radiation
	$h_{c(50)k}$ for convection with 50°F mean temperature and heat flow direction k.
k_{app}	apparent thermal conductivity $W/m \cdot K$ ($Btu \cdot in/ft^2 \cdot hr \cdot °F$)
k	denotes heat flow direction
ℓ	thickness m (in.)
Q	heat flux, W/m^2 ($Btu/ft^2 \cdot hr$)
	Q_R for radiation
R	thermal resistance $K \cdot m^2/w$ ($°F \cdot ft^2 \cdot hr/BTU$)
	R_i for region i
	R_o for reference configuration
T	Temperature
	T_i for surface i
	T mean value
	ΔT positive temperature difference
x_i	width of gap i inches
ε	emissivity
	ε_i for surface i
σ	Stefan-Boltzmann constant

ASSESSMENT OF REFLECTIVE INSULATIONS FOR RESIDENTIAL AND COMMERCIAL APPLICATIONS

D. W. Yarbrough

ABSTRACT

This report includes a survey of available products, uses, and thermal resistance data for thermal insulations that use combinations of air gaps and reflective surfaces to form thermal barriers. Reflective products like pipe insulation or high thermal resistance evacuated panels that are used exclusively in industrial applications are not included.

A one-dimensional steady-state calculation has been developed to provide a way of discussing the R-values of reflective assemblies and their sensitivity to properties like surface emissivity or positioning of foil surfaces in a cavity. The products considered are used in residential or commercial applications.

INTRODUCTION

Reflective foil insulations currently marketed in this country are fabricated from aluminum foil of minimum thickness 0.009 mm (0.00035 in.) usually with backing materials for support. These products range from single thickness foils to multilayered structures which are designed to expand upon installation to form a series of parallel boundaries separated by air spaces. The relatively thin aluminum foils are combined with backing materials such as kraft paper or a polymer material like polyethylene or nylon for mechanical strength. Reflective insulation manufacturers generally cut, bond, shape, and package products using aluminum foil and backing material purchased from a major supplier. The manufacturers of reflective foil assemblies do not have research and development capability. They rely

on test results from commercial testing laboratories and data in the literature to evaluate their products. Minimal research in this area is presently under way in this country.

The federal specification for reflective thermal insulation identifies five classes of materials divided into two "forms."[1] Classes I-IV identify the number of reflective air spaces provided by a correctly installed reflective assembly while Class V identifies an insulation designed for use in a masonry wall structure. Form one requires reflective air spaces with a minimum thickness of 19 mm (0.75 in.) while Form two requires a minimum reflective air space thickness of 10 mm (0.38 in.). The specification further classifies products according to the number of reflective air spaces formed by the insulation. Each air space is required to have a maximum effective emittance, E, of 0.05 which corresponds to an air space bounded by two surfaces with emissivities, ε, of 0.05 and 0.90. This condition is normally achieved by a bright aluminum foil mounted parallel to kraft paper. A list of companies that are foil insulation fabricators or distributors is given in Appendix A. These companies were contacted in an effort to collect available test results and develop an understanding of the technical issues within the industry. Figure 1 shows typical configurations of installed foil insulations as taken from manufacturer's literature.

Thermal energy is transferred across a region by three mechanisms; conduction, convection, and radiation. Heat transfer by conduction and radiation occur because of temperature differences while natural convective transfer occurs in fluid systems because of bulk movement of

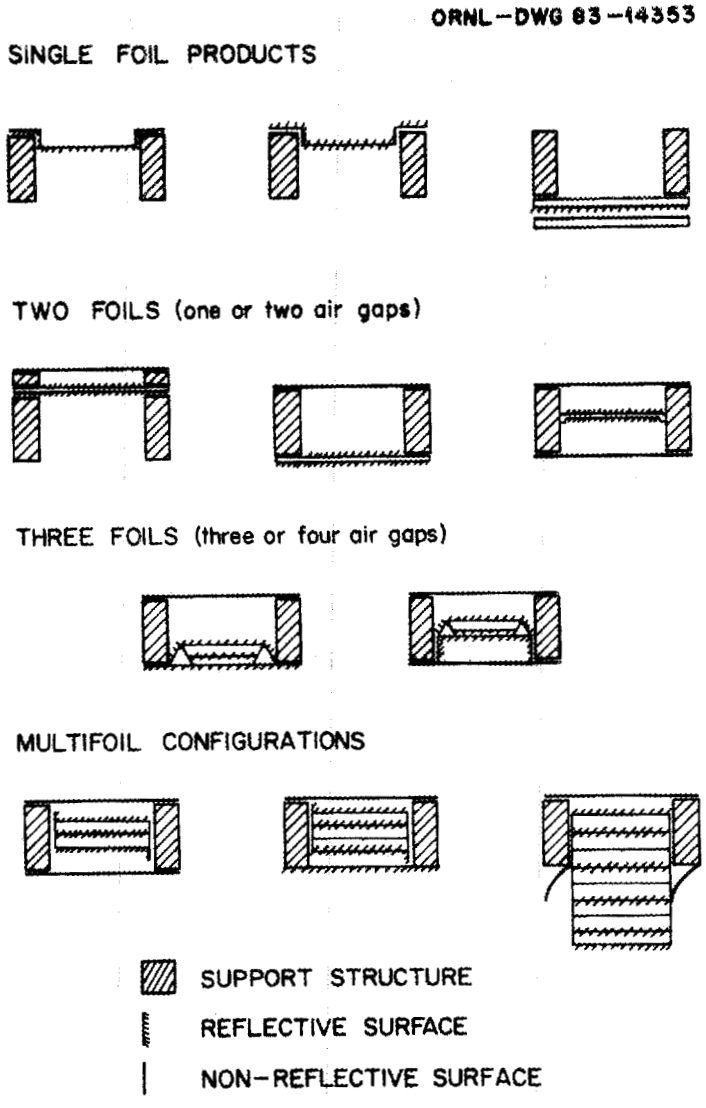

Figure 1. Typical configurations for reflective insulations installed between structural members.

the fluid which is due to fluid density differences resulting from temperature differences.

The mass insulations--loose-fill, batt, and board--greatly reduce radiative and convective transport across an insulated region but increase slightly the conductive component. Reflective foil insulations reduce the radiative component of heat transfer and also change the convective component by dividing the insulated region into smaller regions with reduced temperature differences between the bounding surfaces. Gaseous conductive transport across a region insulated with reflective foil insulation of the type presently used is changed very little by the addition of parallel foil-paper surfaces.

The thermal resistance or R-value of a mass insulation is conventionally regarded as a material property and defined as the ratio of thickness to apparent thermal conductivity. This definition assumes that it is possible to describe a complex steady-state heat transfer process involving all mechanisms by one measured quantity, k_{app}.

$$R = \ell/k_{app} \tag{1}$$

The determination of k_{app} usually requires a steady state measurement of heat flux and temperature difference across a specimen of known dimensions. An alternative expression for the R-value can, consequently, be written in terms of heat flux, Q/A, and temperature difference, ΔT.

$$R = \Delta T/(Q/A) \tag{2}$$

Equation (2) which in fact shows R-values to be the reciprocal of the system conductance[2] can be used for either mass insulations or

reflective foil systems. The use of Equation (2) eliminates in part problems associated with the fact that R-values for reflective insulations are system properties while the R-values for mass insulations are regarded as material properties. Unfortunately, the R-value defined by Equation (2) is not proportional to ΔT in all cases. The heat flux, for example, varies with T^4 when radiative transport occurs and R-values for reflective systems decrease with ΔT.

Reflective foil insulation products provide a barrier to heat transfer by altering the system in which they are installed. These products cannot be tested without a supporting structure which invariably acts as a parallel path for heat transfer. Calculated corrections must be applied to measured heat transfer rates to obtain values for the reflective insulation being tested, thus increasing the uncertainty of the reflective R-value. Thermal resistances derived from measurements on the central region of a very large foil system constructed, for example, by attaching the edges of two or more strips of foil involve air gap dimensions that are not the same as the air gaps in an actual installation. The reflective products do not in general have thermal resistance in the sense of a material property. Since reflective foil products are tested in a supported position the R-value obtained is a system value from which a number to compare with material R-values can be calculated. The accuracy of the calculated R-value requires careful determination of all parallel heat flows so that the flux across the region being evaluated can be obtained from measurements of the total heat flux across the region and supporting structures.

PRODUCT DESCRIPTIONS AND ADVERTISED APPLICATION

Reflective foil insulations range from single foil products with either one side or both sides reflective to complex structures consisting of multiple reflective surfaces with up to ten air gaps. Single foil products are used across entire building sections like walls while multisheet products are generally fixed between wall studs, floor joists, ceiling joists, or rafters. Reflective foil insulations can also be attached to building support elements to provide a thermal barrier, for example, in metal buildings. Reflective insulations have been designed for use in places with limited clearance formed, for example, by furring strips attached to masonry walls or roof decking.

Single sheet products are usually laminates of aluminum foil with paper or a polymer film. The single foil products provide a thermal radiation barrier and often reduce the convective component of heat transfer by enclosing an air space between structural members. Aluminum foil is also commonly used as a facing for mineral fiber batts and rigid insulating boards. Aluminum foils form excellent vapor barriers when sealed around the edges of the region in which they are installed.

Label R-values are obtained either from laboratory test data obtained in accordance with ASTM C-236 (Ref. 2), ASTM C-976 (Ref. 3), or, in some cases, from calculations based on ASHRAE tables.[4,5]

ORNL METHOD FOR CALCULATING R-VALUES FOR AIR SPACES WITH REFLECTIVE BOUNDARIES

Thermal resistance (R-values) can be approximated for various orientations of air spaces and "reflective" boundaries using heat

transfer coefficient data published by Robinson and Powell.[6] In all cases the heat flow is perpendicular to the reflective foil assembly. R-values calculated using Robinson's heat transfer coefficients and the Stefan-Boltzmann Law with a term accounting for repeated reflection of energy between infinite parallel planes will be referred to as "ideal."

The "ideal" model and the resulting calculations are subject to a number of limitations due to the simplifying assumptions but provides a way to compare property measurements and judge the adequacy of existing reflective technology. Heat flow in the calculation is assumed to be one dimensional, the reflective barriers are treated as infinite parallel planes, the air between the gray surfaces does not absorb or emit radiant energy, the bounding surfaces are isothermal and gap widths are uniform. None of these assumptions exactly match the actual installed conditions.

The heat transfer data obtained by Robinson and Powell[6] form the basis for calculations of the thermal resistance of air spaces bounded by surfaces with low emissivity. They made measurements on panels 1.588 to 8.573 cm (0.625—3.375 in.) thick using ASTM 236-53 (Ref. 7). The steady state heat transmission rates were corrected for the transfer occurring along parallel paths between the hot and cold boundaries. Convective heat transfer coefficients were obtained from the data by subtracting a calculated radiative heat transfer rate from the total corrected heat transfer rate. Radiative heat transfer was calculated using an emissivity of 0.028 for the aluminum surfaces.

Thermal resistance numbers tabulated in the *ASHRAE Handbook of Fundamentals*[4] were calculated from the data reported by Robinson and

Powell.[6] The ASHRAE tables recombine the convective and radiative components of heat transfer to obtain a total thermal resistance value. The basic data published by Robinson and Powell are widely used in calculating thermal resistance values for air spaces with reflective boundaries.[8,9]

Thermal resistance values for air spaces with reflective boundaries can be calculated for an idealized model based on infinite parallel surfaces between isothermal boundaries. The calculations reported here are based on the Robinson and Powell[6] data and provide a way of discussing the effect of factors like the number and spacing of low emittance foils, the overall temperature difference across an assembly, or the change of surface emissivity on the thermal performance of the system. Equation (3) is the expression for net radiative flux between infinite gray parallel planes

$$Q_R/A = E\sigma(T_1^4 - T_2^4) \ , \tag{3}$$

where the indicated temperatures are on an absolute scale. The leading term in Equation (3) is identified as the effective emittance E given by

$$E = \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)^{-1} \ , \tag{4}$$

where ε_1 and ε_2 are emissivities for the bounding surfaces. Equation (3) is combined with Newton's "Law" of cooling[10] to give an expression for the effective R-value for the system

$$R = (Eh_r + h_c)^{-1} \ , \tag{5}$$

where h_c is the conduction-convection transfer coefficient and h_r is given by Equation (6) in English units. The formulation of the heat transfer calculation in Equation (5) assumes that radiation and conduction convection are not coupled.

$$h_r = 0.172 \times 10^{-8} (T_1^4 - T_2^4)/(T_1 - T_2) = 0.00686 (T/\overline{100})^3 \qquad (6)$$

Values for h_c were determined experimentally as a function of heat flow direction, mean temperature, and gap width.[6] The results which were published in graphical form have been described analytically with the temperature difference across a gap, ΔT, and gap width, ℓ, as independent variables and $h_{c(50)}$ as the dependent variable using Equation (7). The term $h_{c(50)}$ identifies the heat transfer coefficient for a mean gap temperature of 10°C (50°F).

$$h_{c(50)k} = \sum_{i=1}^{4} \left[\left(\sum_{j=0}^{3} a_{ijk}\ell^j \right) + a_{i4k}/\ell \right] \Delta T^{\,i-1} \qquad (7)$$

Equation (7) was obtained by least square fitting the $h_{c(50)}$ data for a given heat flow direction and ℓ. The subscript k identifies the direction of heat flow with k=1 for heat flow up, k=2 for heat flow up at 45°, k=3 for horizontal heat flow, k=4 for heat flow down at 45°, and k=5 for heat flow down. The $h_{c(50)}$ values for constant k, and ΔT were described using a third degree polynomial in ℓ plus a term containing ℓ^{-1}. The coefficients obtained at constant k and ΔT were then described by a third degree polynomial in ΔT using the "Method of Least Squares." A set of 20 constants were obtained for the description of the convective heat transfer coefficient for a given heat flow direction.

Appendix B contains the numerical values for the constants a_{ijk} obtained by the procedure described above. Heat transfer coefficients calculated using Equation (7) agree with the published data as accurately as the graphs can be read. A table of $h_{c(50)}$ values computed using the a_{ijk} is in Appendix B along with a detailed discussion of Equation (7) and a comparison of calculated $h_{c(50)}$ values with the published values.

The calculation of R-value for a given combination of surfaces and air gaps is accomplished using the Method of Successive Approximations[11] to calculate the temperature of surfaces between bounding isothermal surfaces representing, for example, walls. The governing iterative equation is

$$\Delta T_i^{(j+1)} = \left(\sum_{i=1}^{n} \Delta T_i^{(j)}\right) R_i^{(j)} / \sum_{i=1}^{n} R_i^{(j)} , \qquad (8)$$

where $\Delta T_i^{(j)}$ and $R_i^{(j)}$ are the temperature differences across gap i at steady state and the R-value of the gap after j iterations. Equation (8) follows from the requirement that at steady state the total heat transfer across each region in a reflective assembly must be equal. The ΔT_i are also constrained by the temperature on the isothermal boundaries so that $\sum_{i=1}^{N} \Delta T_i$ equals the total temperature difference across the assembly.

A Fortran program (REFLECT) for the calculation of ΔT_i and the total system R-value, ΣR_i, is given in Appendix C. The program uses Equations (6), (7), and (8) and branches to an h_c value which includes conduction only when a given gap is less than 1.27 cm (0.5 in.) wide.[4]

The $h_{c(50)}$ values are adjusted for gap temperatures other than 10°C (50°F) using the equations given by Robinson and Powell.[6] Successive approximations for $\Delta T_i^{(j)}$ are based on starting values given by Equation (9) for an assembly with n reflective air spaces in series

$$\Delta T_i^{(1)} = x_i \sum_{i=1}^{n} \Delta T_i^{(1)} / \sum_{j=1}^{n} x_i \qquad i=1,2,\ldots n \tag{9}$$

and continues until

$$| \Delta T_i^{(j+1)} - \Delta T_i^{(j)} | < 1 \times 10^{-4} \tag{10}$$

for all i. Values for $R_i^{(j)}$ are calculated using $T_i^{(j)}$ in Equation (5) with substitution into Equation (8) to obtain a new set of gap temperature differences. Once ΔT_i satisfying Equation (10) have been determined, the system R-value can be obtained from Equations (5), (6), and (7). An example of the iterative calculation with intermediate results is given in Appendix C.

Figure 2 shows results obtained with REFLECT for multiple reflective air gaps resulting from foils installed in a 88.9 mm (3.5 in.) cavity for five directions of heat flow ranging from heat flow up to heat flow down. The curves in Figure 2 were obtained with reflective surfaces having $\varepsilon = 0.05$ and bounding surfaces with $\varepsilon = 0.90$ and an overall temperature difference of 27.8°C (50°F). The foils were taken to be in the cavity in such a way that N foils produce N+1 equal thickness gaps. All interior surfaces were assigned low ε values on both sides. The curves come together for 7 aluminum foils or 8 reflective gaps since the heat transfer coefficient data indicate that

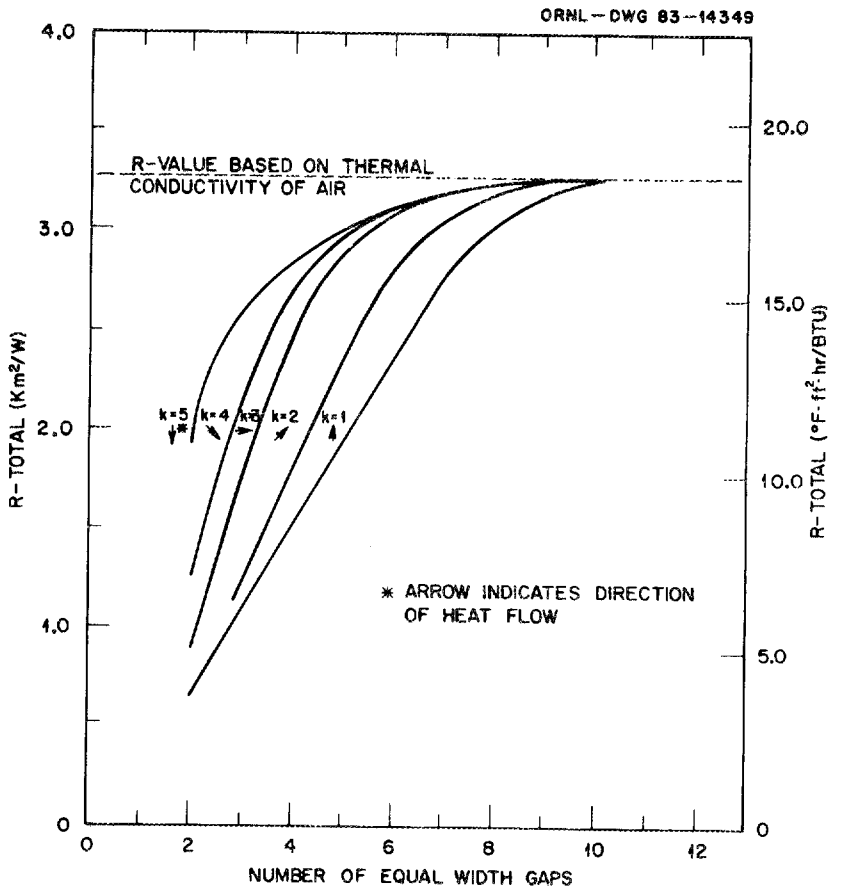

Figure 2. R-Values for a multiple foil system in a 88.9 mm (3.5 in.) cavity calculated with the program REFLECT.

convection-conduction reduces to pure conduction at gaps less than 12.7 mm (0.5 in.) and orientation becomes unimportant. This calculation shows that R-values greater than 3.25 $K \cdot m^2/W$ (18.4 $F \cdot ft^2 \cdot hr/BTU$) can be obtained in a 8.89 cm (3.5 in.) cavity with an "ideal" reflective foil structure.

Poppendiek et al.[12] have developed a one-dimensional steady state model for heat transfer through a system of parallel planes (foils) separated by air gaps. Poppendiek assumes a linear temperature profile between bounding isothermal surfaces and uses an expression for the heat transfer coefficient for a plane surface that varies as the fourth root of the temperature difference between the surface and the adjacent air space. Some trends in Poppendiek's calculated R-values agree with the model discussed earlier in that the system R-values increase linearly with increase in the number of air gaps, and R for heat flow down exceeds R for heat flow horizontal which exceeds R for heat flow up. Detailed comparisons, however, are not possible since Poppendiek's paper does not contain sufficient information to evaluate the experimental results or make supporting calculations.

Hollingsworth[13] has reported the thermal resistance of four reflective foil assemblies consisting of aluminum foil insulations installed in a vertical cavity. The thermal resistances of the assembly were obtained using a calibrated hot box. R-values were also calculated from the tables in the *ASHRAE Handbook of Fundamentals*.[4] For comparison purposes the information given in Hollingsworth's paper was used to make R-value calculations using the numerical procedure described in this report. Results of the calculations are shown in Table 1 along with the

Table 1. A comparison of measured R-values for a 88.9 mm (3.5 in.) thick vertical cavity with reflective insulation installed to provide E = 0.05

	System identification (horizontal heat flow)	Cavity ΔT °C (°F)	Mean cavity temperature °C (°F)	R-values Experimental K•m²/W (°F•ft²•h/BTU)	Calculated[13] (Hollingsworth)	Calculated (REFLECT)
1.	Two Foils (three spaces)	34.1 (61.4)	-0.4 (31.2)	1.04 (5.90)[13]	1.84 (10.47)	1.61 (9.14)
2.	Two Foils (three spaces)	19.5 (35.1)	11.3 (52.3)	1.21 (6.86)[13]	1.85 (10.52)	1.76 (9.99)
3.	Two Foils (three spaces)	20.2 (36.3)	24.9 (76.8)	0.82 (4.63)[13]	1.84 (10.46)	1.66 (9.43)
4.	Three Foils (four spaces)	32.3 (58.2)	-1.3 (29.7)	0.82 (4.66)[13]	2.16 (12.28)	2.42 (13.74)
5.	Three Foils (four spaces)	18.5 (33.3)	22.7 (72.8)	0.82 (4.66)[13]	2.10 (11.90)	2.48 (14.06)
6.	Three Foils (four spaces)	20.4 (36.8)	28.5 (83.3)	0.80 (4.55)[13]	2.35 (13.32)	2.40 (13.61)
7.	Three Foils (four spaces)	31.6 (56.9)	0.2 (32.4)	1.03 (5.86)[13]	2.47 (14.05)	2.43 (13.79)
8.	Three Foils (four spaces)	17.8 (32.0)	11.2 (52.2)	1.13 (6.39)[13]	2.44 (13.84)	2.62 (14.86)
9.	Two Foils (three spaces)	27.9 (50.2)	7.5 (45.5)	1.28 (7.27)[14]		1.71 (9.73)
10.	Two Foils (three spaces)	27.6 (49.7)	17.0 (62.6)	1.10 (6.25)[14]		1.48 (8.40)
11.	Two Foils (three spaces)	27.3 (49.1)	26.7 (80.1)	0.97 (5.51)[14]		1.32 (7.52)
12.	Three Foils (four spaces)	27.8 (50.0)	5.7 (42.3)	1.85 (10.51)[14]		2.75 (15.62)
13.	Three Foils (four spaces)	28.7 (51.7)	16.3 (61.3)	1.32 (7.50)[14]		2.49 (14.12)
14.	Three Foils (four spaces)	28.6 (51.5)	27.2 (81.0)	1.07 (6.08)[14]		2.28 (12.94)

experimental numbers. The average difference between the two sets of calculations is approximately 7%. The differences came about partly because different numerical procedures are being used to interpolate in the heat transfer coefficient data. In both sets of calculations the calculated R-values are substantially above the corresponding measured values. The ratio of experimental R-value to calculated R-value averages 0.46 for the eight data points using either calculation scheme.

Table 1 also contains a comparison of measured R-values[14] with calculated R-values for two types of reflective foil installed in a 88.9 mm (3.5 in.) thick 244 cm (8 ft.) high vertical cavity arranged for horizontal heat flow. The measured R-values in this case are also below the R-values calculated with the one-dimensional model. The ratio of experimental R-value to calculated R-value averages 0.65 for the six representative points shown.

Thermal resistance measurements have been reported by the Midwest Research Institute (MRI)[15] for heat flow down, horizontal, and up through reflective foil assemblies. Results for two types of insulation are shown in Table 2. In this case the measured R-values range from 85 to 126% of the calculated R-value. The average deviation between the calculated and measured R-values is less than 4% of the measured value. The R-values reported by MRI were obtained with square cross-section panels approximately 2.44 m (8.0 ft.) on each side. This was done in order to reduce heat transfer along paths parallel to the test specimen in the metering section. The differences in the test configurations used by MRI and the other laboratories could in part account for the differences in test results.

Table 2. A comparison of measured R-values for 139.7 mm (5.5 in.) thick cavity with reflective insulation installed to provide E = 0.05

System identification	Cavity ΔT °C (°F)	Mean cavity temperature °C (°F)	R-values Experimental[15] K•m²/W(°F•ft²•hr/BTU)	Calculated (REFLECT)
Three Foils, Four Gaps[(a)]				
1. Heat Flow Down	27.4 (49.4)	42.1 (75.7)	3.15 (17.9)	3.28 (18.6)
2. Heat Flow Horizontal	27.6 (49.6)	41.8 (75.2)	1.95 (11.1)	2.29 (13.0)
3. Heat Flow Up	27.6 (49.6)	41.9 (75.5)	1.85 (10.5)	1.51 (8.6)
Two Foils, Three Gaps[(b)]				
4. Heat Flow Down	27.8 (50.0)	41.9 (75.4)	2.41 (13.7)	2.69 (15.3)
5. Heat Flow Horizontal	27.2 (49.0)	41.9 (75.5)	1.69 (9.6)	1.58 (9.0)
6. Heat Flow Up	27.9 (50.2)	41.7 (75.0)	1.36 (7.7)	1.07 (6.1)

Gap Dimensions

(a) 1.91 cm (.75 in.), 2.22 cm (.875 in.), 2.22 cm (.875 in.), 7.62 cm (3.0 in.)

(b) 1.91 cm (.75 in.), 2.54 cm (1.0 in.), 9.53 cm (3.75 in.)

EFFECT OF CHANGING EMITTANCE ON R-VALUE

The program REFLECT has been used to estimate the effect of increasing reflective foil emissivity on system R-value. Calculations were carried out for two reflective assemblies mounted in a 8.89 cm (3.5 in.) cavity bounded by isothermal surfaces at 10°C (50°F) and 37.8°C (100°F) with ε values of 0.9. One set of calculations was for a single reflective foil mounted in the center of a cavity presenting low ε surfaces to both isothermal boundaries. The second set of calculations are for a two foil assembly centered in the cavity. Results of the calculations are shown in Figs. 3 and 4 where the percentage decrease in R-value is shown as a function of the percentage increase in the effective emittance E. A tabulation of calculated R-values for the five heat flow directions in Figs. 3 and 4 is in Appendix D. E values are related to ε by Equation (4) and the subscript "o" signifies values obtained with reflective surface assigned the value $\varepsilon = 0.03$. The results show, for example, that in the case of downward heat flow (k=5) where radiative transfer dominates, an increase of ε from 0.03 to 0.10 results in a 26% decrease in R-value for a two foil assembly.

Robinson et al.[16] observed decreases in R-value of 10-30% for reflective foils that were found to have stains attributed to the presence of a film of water. A film of water on an aluminum surface raises the emittance of the surface significantly and reduces the ability of the assembly to reduce radiative transfer. The greatest effect, 30%, was observed in the case of downward heat flow. Condensation can be avoided by making the assembly permeable to water

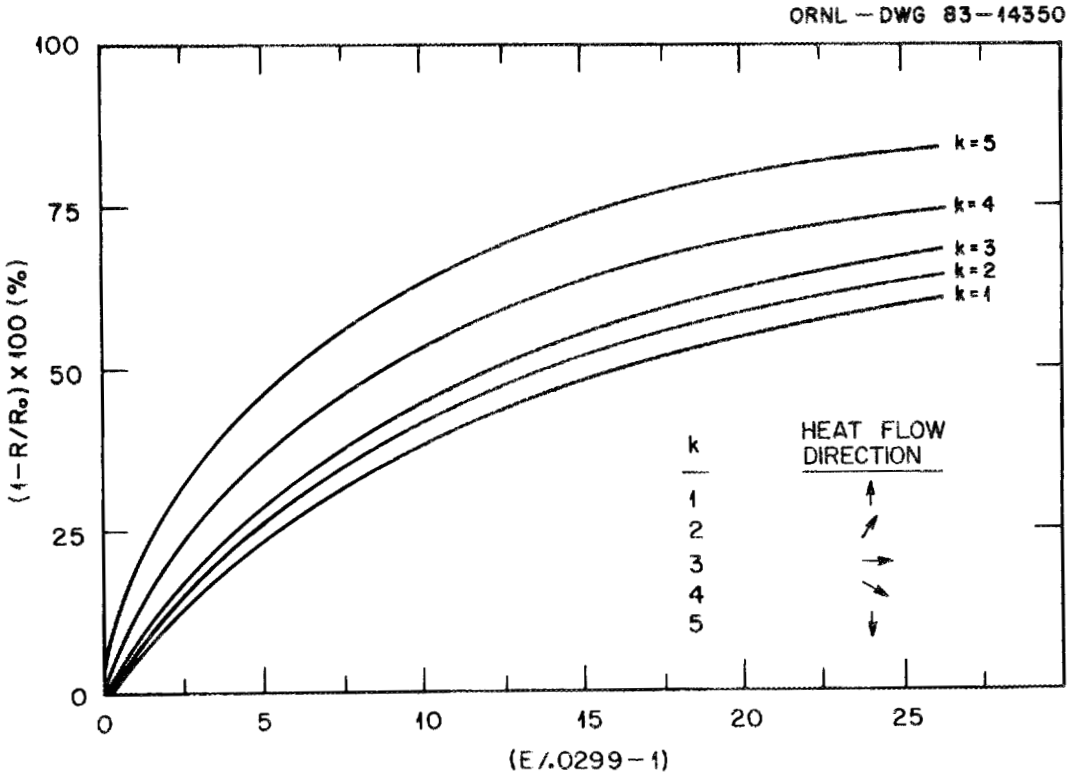

Figure 3. Percentage change in R-value for a single reflective foil in a 8.89 cm (3.5 in.) space due to change in foil emissivity calculated for a 27.8°C (50°F) temperature difference across the space.

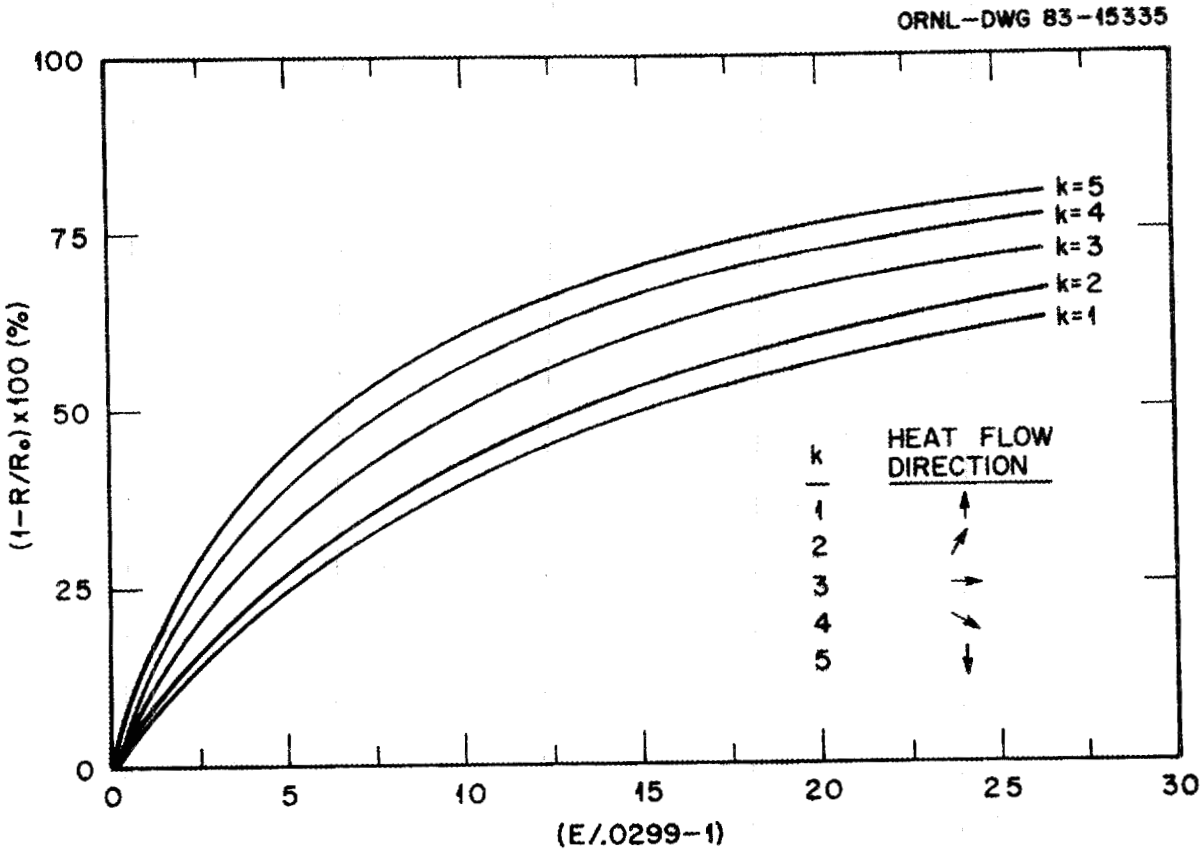

Figure 4. Percentage change in R-value for a two-foil reflective system in a 8.89 cm (3.5 in) space due to change in foil emissivity calculated for a 27.8°C (50°F) temperature difference across the space.

vapor but the R-value will be decreased if air movement between gaps or direct radiation through holes in the foil assembly are allowed. Measurements on stained foils showed no permanent increase in the emittance.[16]

Wilkes et al.[17] cite eight examples of aluminum foil retaining a low ε value after installation. The foils were in place for up to 10 years before being removed and examined. The surroundings in the list include sea air environments and foils suspended in a laboratory. The emissivity of one material exposed to salt spray for two years was found to be 0.1. Emissivity changes in less hostile environments were much less than the preceding two year observation. In three cases of aluminum foil installed in residences for up to 10 years and in a laboratory for 10 years foils showed no changes in appearance but ε measurements were not reported.

In contrast to the above observations, Lund[18] measured emissivity of aluminum foils installed in four residences. Foil emissivity was measured annually for three years starting with a value of 0.022. The results after three years were 0.207, 0.341, and 0.432. A fourth value of 0.545 after two years was discarded because of the addition of insulation in the attic where the foil was installed. Lund attributed the increase in emissivity to dust accumulations on the horizontal film surfaces.

EFFECT OF POSITIONING ON THE PERFORMANCE OF REFLECTIVE FOIL SYSTEMS

The thermal performance of a system of reflective foils is significantly affected by position since part of the thermal resistance

comes from a reduction in the convective component of heat transfer. The batt or loose-fill mass insulations are somewhat less dependent on positioning since the usual requirement is that they fill the cavity or maintain a specified thickness. Robinson et al.[19] determined the effect of nonuniformity by measurements on reflective assemblies with wedge shaped air spaces. The results indicate R-values as low as 52% of the value for an assembly with uniform air spaces. The largest percentage effect of the nonuniform air space on R-value occurs with heat flow down which also is the heat flow direction for which a reflective assembly has the highest R-value.

Figures 5 and 6 show the effect of position on R-values calculated with REFLECT using E = 0.0299. Both figures show the variation of R-value as the center of the reflective assembly is displaced from the center of a 8.89 cm (3.5 in.) cavity. The curves in the figures show results obtained for all five heat flow directions. The optimum R-value for horizontal heat flow does not occur for foil assemblies mounted in the exact center of a cavity but the R-value increase is less than 8%. The results in Fig. 5 indicate R-value variations of about 5% for a single foil product placed within 2.54 cm (1 in.) of the cavity mid-plane. The predicted variations shown in Fig. 6 for a two foil assembly are somewhat larger with 5% R-value decrease occurring at about 1.3 cm (0.5 in.) displacement. Both sets of calculations indicate R-value reductions up to 20% as the foil assembly approaches maximum displacement.

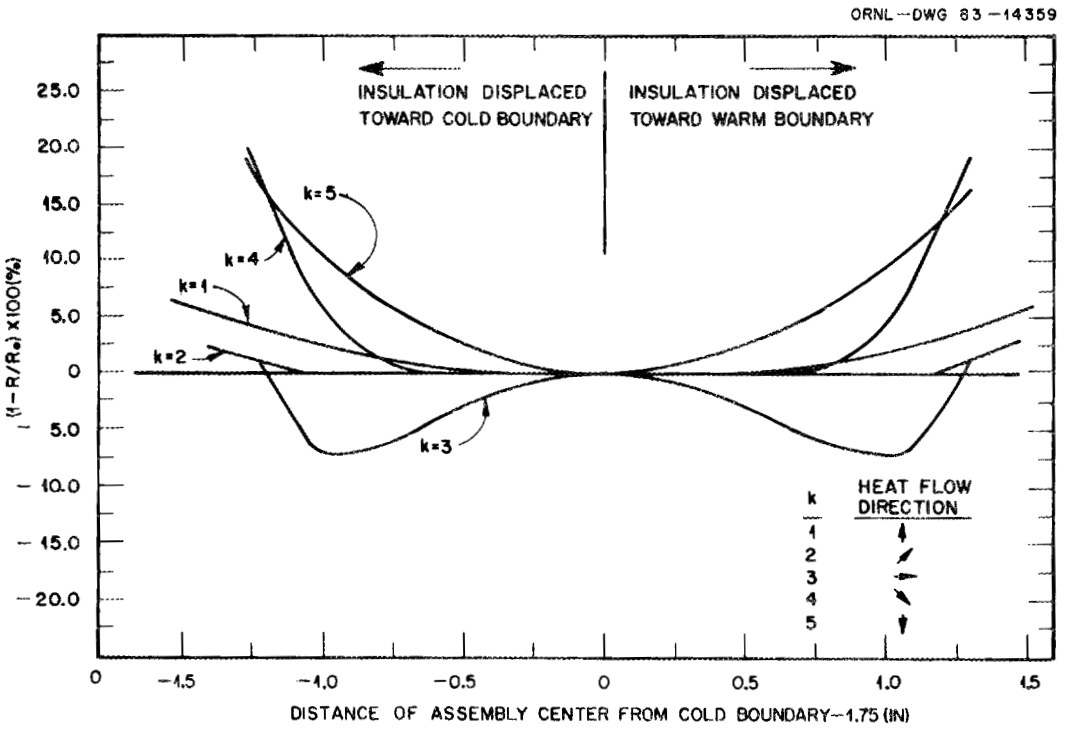

Figure 5. Percentage decrease in the R-value of a single reflective foil assembly as a function of displacement from the center of the insulated region.

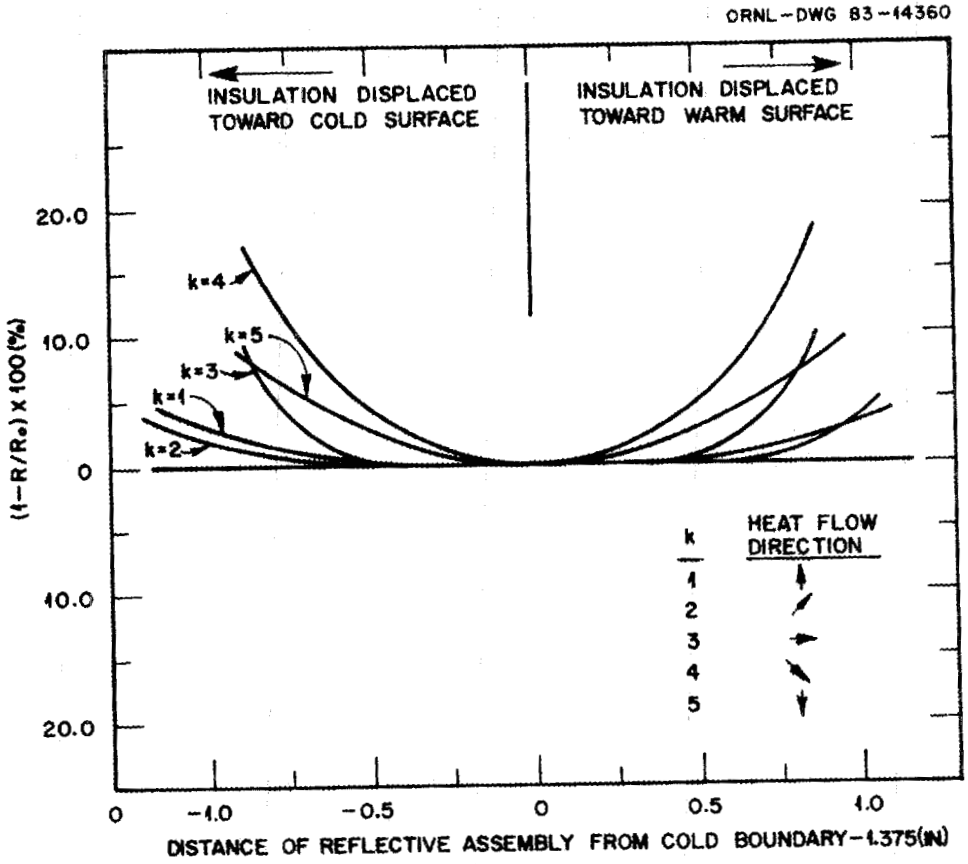

Figure 6. Percentage decrease in the R-value of a two foil assembly as a function of displacement from the center of the insulated region.

EFFECT OF TEMPERATURE DIFFERENCE ON THE PERFORMANCE OF REFLECTIVE FOIL SYSTEMS

The R-value of a reflective system decreases as the temperature difference across the assembly increases.[14] The magnitude of the change in R-value with increased temperature difference was studied using REFLECT. Results are given in Fig. 7 for a single foil mounted in a 8.89 cm (3.5 in.) region. Figure 8 shows results obtained for an insulation consisting of two aluminum foils forming three reflective air spaces. Both sets of calculations were made with E = 0.0299. In both cases the biggest percentage changes occur with the horizontal and 45° heat flow calculations where R-values are reduced by as much as 40% for the single foil and by 30% for the two foil assemblies as the temperature difference increases from 5.56°C (10.0°F) to 27.78°C (50.0°F). In general, the calculated R-value for the two foil assembly was greater than that calculated for the single foil and was less sensitive to the overall temperature difference across the insulated region. These calculations illustrate the importance of correctly specifying and identifying temperature differences used to obtain R-values for reflective systems.

DISCUSSION OF MODELING RESULTS

Published effective thermal resistance calculations for assemblies of reflective foils separated by air gaps have been limited to one-dimensional analysis.[4,12,13,16] Measured thermal resistance values for commercial reflective assemblies[13,14,15] in most cases show R-values less than the R-values calculated with REFLECT. Three entries in

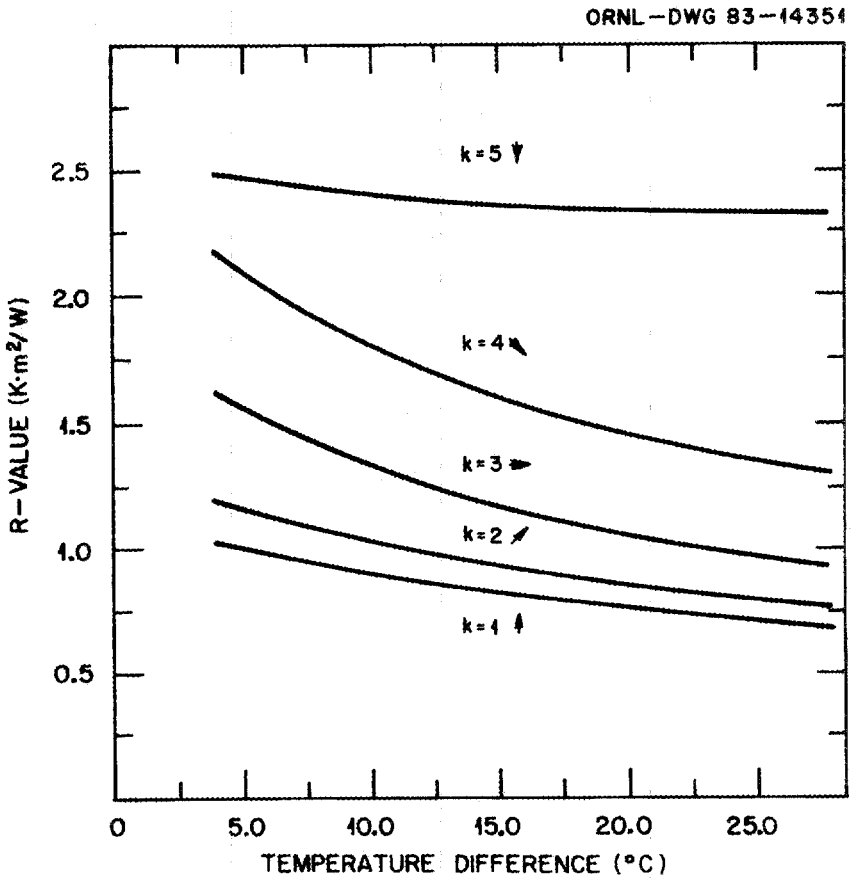

Figure 7. Calculated R-values for a single reflective foil in a 8.89 cm (3.5 in.) region as a function of the temperature difference across the region.

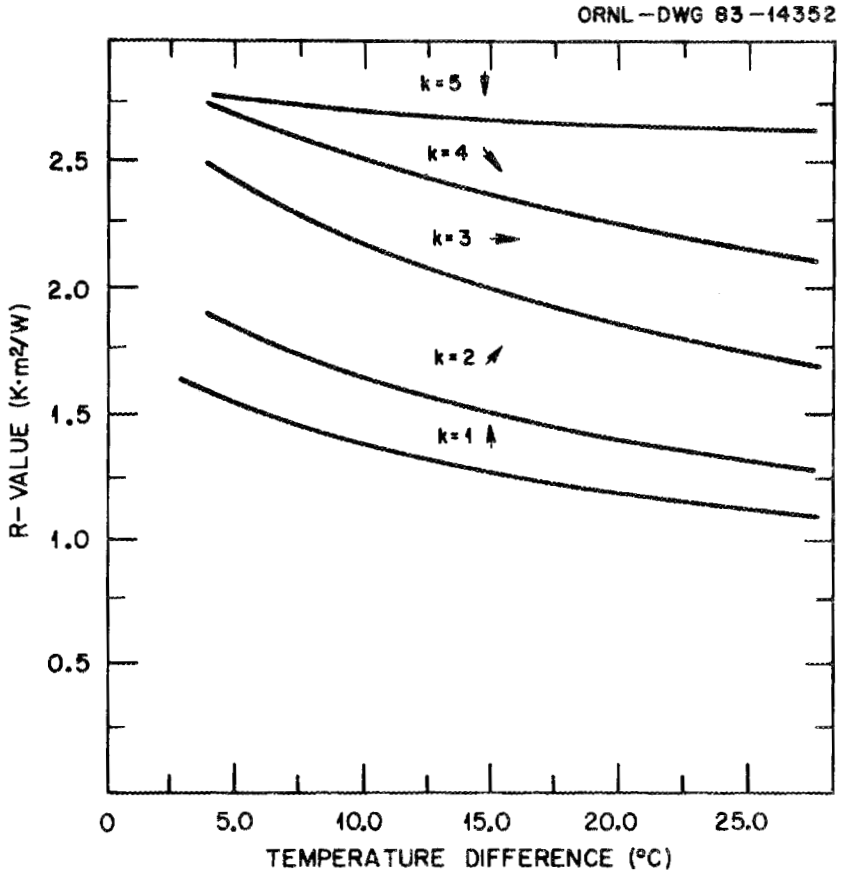

Figure 8. Calculated R-values for a two foil reflective insulation in a 8.89 cm (3.5 in.) region as a function of the temperature difference across the region.

Table 2 show measured R-values greater than the corresponding calculated values. The test configuration for these measurements approaches that implicit in the one-dimensional model. R-value calculations with altered spacings and reduced E move toward the experimental values but the difference remains larger than the declared uncertainty in conductance. The fact is that commercial reflective assemblies do not exactly satisfy the constraints of infinite parallel surfaces that is implicit in one-dimensional models. The disagreement between measured and calculated R-values is no doubt due in part to heat transfer along edges and supporting materials of a reflective insulation assembly that are not accounted for in a one-dimensional model. One-dimensional models are useful for making comparative calculations and studying the sensitivity of R-value to emittance or positioning, but an accurate, realistic three-dimensional model is needed to bring measured and calculated R-values into coincidence.

ISSUES IDENTIFIED BY THE INSULATION COMMUNITY

One facet of the current assessment involved discussion of the properties and use of reflective insulations with the thermal insulation community. Information was obtained from those listed in Appendix A, specialists working on other types of insulation, and researchers having no direct affiliation with a commercial interest. The following discussion reflects the concerns of various segments of the industry.

The most repeated comment about reflective insulation is the uncertainty about the correct R-value to associate with a given product. Reflective insulation manufacturers argue that guarded hot box[2]

measurements are not valid for their product because of parallel path heat flow, bridging effects, and the fact that the tested configuration seldom matches the use configuration. Concerns, for example, are expressed about moisture formation in testing configurations which may not be representative of true performance.

The reflective insulation producers argue that field test data should be used to evaluate their product. The mass-type insulations are tested and sold on the basis of a material property and then are used in a building where the system R-value is invariably less than the property value because of heat transfer parallel to the insulation.

Fairey[20] has recently obtained performance data for an assembly in which a single foil reflective insulation was installed about 24 cm (9.5 in.) below the roof decking in a test building. The attic below the roof contained R-19 mineral fiber batts installed on the floor of the attic. The heat flow was down for the observations published. The effective R-value for a series of resistances from the bottom side of the roof to the top side of the ceiling increased from 3.33 $K \cdot m^2/W$ (18.9°$F \cdot ft^2 \cdot h/Btu$) to 6.89 $K \cdot m^2/W$ (39.1 °$F \cdot ft^2 \cdot h/Btu$) as a result of foil installation. The data indicates that installation of low emittance foil below the roof improves the performance of the batt insulation by reducing the radiative component of heat transfer to the surface and interior of the batt. Insulating systems that combined fibrous thermal insulation and metallized film were developed by NASA for space applications.[21] The NASA objective was to reduce insulation

weight but retain the thermal barrier. The use of combinations of insulating materials in building applications will no doubt receive continued attention.

Aluminum is a good electrical conductor. The consequences of installing quantities of aluminum foil in spaces containing an electrical distribution system must be considered. Concern about the installation of aluminum foil insulation would seem to apply equally to other insulation products that have aluminum foil backing. No documentation of electrical problems was found in the present study. One reflective insulation manufacturer with history dating from the 1940 era and several hundred thousand sites with reflective insulation states that no claims of electrical problems have ever been substantiated.[22] It is also noted that the "ASTM Standard Recommended Practice for Use of Reflective Insulation in Building Constructions"[23] does not identify a potential electrical hazard.

The effect of increasing surface emittance on the thermal performance of reflective assemblies has been shown in Figs. 3 and 4. Surface emittance can change because of moisture or fouling with fouling occurring from dust or chemical reaction. It was suggested by Robinson et al.[16] concerning moisture effects and the observation that the effect was reversible. Data addressing rates of surface deterioration due to fouling and conditions under which fouling can occur are scarce and represent a real need within the industry.

RECOMMENDATIONS

This section is prefaced by the observation that the industry engaged in fabricating and marketing reflective products does not have a significant research and development capability.

The five project areas that follow are intended to quantify the thermal performance of the reflective insulations, provide a basis for optimizing the design of reflective assemblies, and establish bounds for the use of reflective insulations. The final figure in this report contains a suggested project schedule for work on these materials.

STUDY DETAILS OF LABORATORY EVALUATIONS OF REFLECTIVE ASSEMBLIES

Data exist which show that reflective materials are valid insulation materials when used as barriers to radiant energy transfer. The overriding issue, however, is a defensible measure of the effective thermal resistance of reflective assemblies. It is recommended, therefore, that a detailed study be conducted to identify limitations of hot box measurements on reflective insulations and seek alternate laboratory thermal test methods. Laboratory studies should be used to design methods for the evaluation of installed materials. The existing data base for the thermal performance of reflective insulations can be expanded after an accepted test method is defined.

DEVELOP COMPUTATIONAL MODELS OF REFLECTIVE INSULATION ASSEMBLIES

Numerical modeling of reflective foil assemblies should be undertaken to provide a basis for designing new systems. The one-dimensional model is useful for discussing changes in R-value due to changes in system parameters such as non-parallel surfaces but fails to provide a direct link with laboratory measurements. A multi-dimensional model of reflective foil assemblies will be useful in discussing the

true potential of the assemblies as thermal barriers. Numerical calculations should also be undertaken to describe the behavior of low emittance surfaces used in combination with mass type insulations.

The modeling effort should include a critical review of recently published information about free convection in rectangular cavities. An increase in h_c used in REFLECT, for example, would have the effect of reducing the calculated R-values and bring calculated and experimental results into better agreement.

STUDY EFFECT OF EMITTANCE CHANGES ON REFLECTIVE INSULATION PERFORMANCE

A need exists to establish if aging affects the thermal performance of reflective insulations. A laboratory study of accelerated aging due to surface reactions in typical chemical environments should be undertaken. Means by which foil emittance can be maintained or improved should be sought.

STUDY THE EFFECTIVENESS OF LOW EMITTANCE FOILS USED WITH OTHER INSULATIONS

A laboratory study should be undertaken to determine the effectiveness of low emittance foils used jointly with mass type insulations. Additional work is needed to determine ways to combine the features of reflective insulations and mass insulations for use in attics, crawl spaces, and below floors.

ESTABLISH CRITERIA FOR SAFE USE OF METAL FOILS AS INSULATION

Safety factors associated with use of reflective foil assemblies as building insulation should be studied. The electrical properties and combustion characteristics of reflective foil assemblies should be determined in order to determine criteria for safe use.

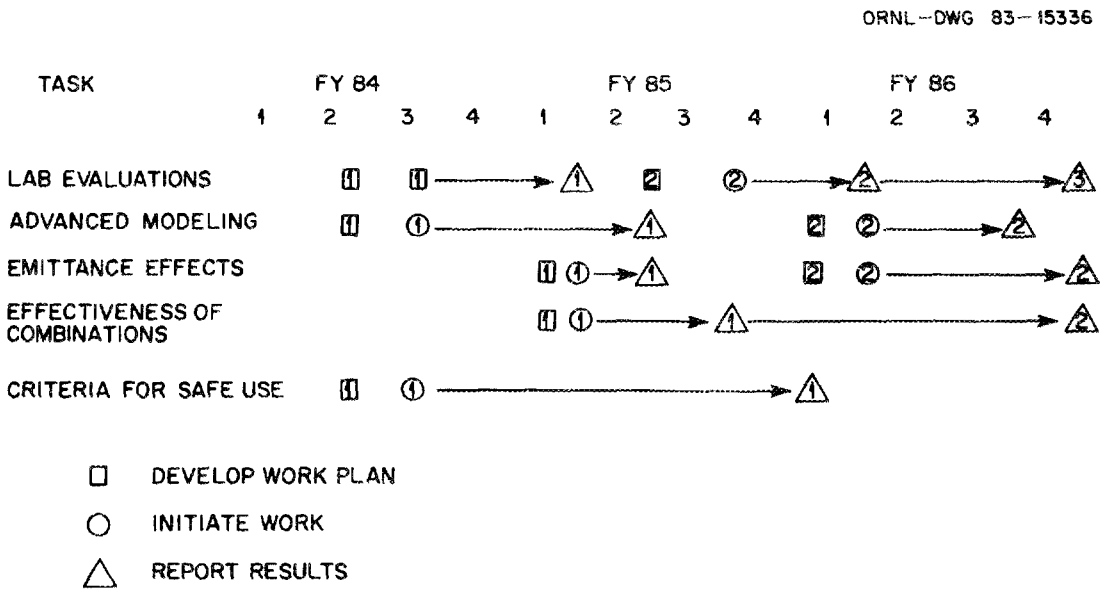

Figure 9. Reflective insulation project schedule.

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APPENDIX A

COMPANIES PRODUCING OR MARKETING REFLECTIVE INSULATIONS

1. AAE Systems, Inc., P.O. Box 20876, San Diego, California 92120
2. Alfol, Inc., P.O. Box 7024, Charlotte, North Carolina 28217
3. Aluminum Insulation Manufacturing Company, 5123 Brooks Street, Montclair, California 91763
4. Denny Corporation, Route 4, Noble Industrial Park, Caldwell, Ohio 43724
5. Energy Saver Imports (E.S.I.) Company, 8611 West 71st Circle, Arvada, Colorado 80004
6. Foilpleat Insulation, Inc., 2020 West 139th Street, Gardena, California 90249
7. Parsec, Inc., P.O. Box 38534, Dallas, Texas 75238
8. Reynolds Metals Co., Box 27003, Richmond, Virginia 23261
9. Roy and Sons, P.O. Box 5490, El Monte, California 91731
10. Superior Aluminum Insulation Inc. 6441 Roland St., Buena Park, California 90621

APPENDIX B

A CORRELATION FOR THE HEAT TRANSFER COEFFICIENT $h_{c(50)}$ FOR RECTANGULAR REGIONS USING POLYNOMIALS IN REGION THICKNESS AND TEMPERATURE DIFFERENCE

The heat transfer data of Robinson and Powell,[6] have been correlated in terms of gap thickness, ℓ, and the temperature difference across the gap, ΔT, using Equation (B-1) which is identical to Equation (7). The subscript k appearing on each of the

$$\begin{aligned} h_{c(50)k} = {} & a_{10k} + a_{11k}\ell + a_{12k}\ell^2 + a_{13k}\ell^3 + a_{14k}/\ell + \\ & (a_{20k} + a_{21k}\ell + a_{22k}\ell^2 + a_{23k}\ell^3 + a_{24k}/\ell)\ \Delta T + \\ & (a_{30k} + a_{31k}\ell + a_{32k}\ell^2 + a_{33k}\ell^3 + a_{34k}/\ell)\ \Delta T^2 + \\ & (a_{40k} + a_{41k}\ell + a_{42k}\ell^2 + a_{43k}\ell^3 + a_{44k}/\ell)\ \Delta T^3 \end{aligned} \qquad \text{(B-1)}$$

a_{ijk} values identify a heat flow direction. Equation (B-1) is a function of two variables once k is specified. The functions

$$h_{c(50)k} = b_{ok}(\Delta T) + b_{1k}(\Delta T)\ell + b_{2k}(\Delta T)\ell^2 + b_{3k}(\Delta T)\ell^3 + b_k(\Delta T)\ell \qquad \text{(B-2)}$$

$$b_{jk}(\Delta T) = a_{1jk} + a_{2jk}\Delta T + a_{3jk}\Delta T^2 + a_{4jk}\Delta T^3 \qquad \text{(B-3)}$$

$b_i(\Delta T)$ in Equation (B-2) were taken to be polynomials in ΔT as shown in Equation (B-3) and the coefficients a_{ijk} were obtained using the Method of Least Squares applied to coordinate pairs (ΔT, $b_{jk}(\Delta T)$) obtained by fitting (ℓ, $h_{c(50)k}$) data points read directly from the correlations published by Robinson and Powell.[6] Thus, an array of 309 data points were used to establish the coefficients in Equation (B-1).

The steps outlined above do not result in a true least square fit of the data set and was consequently checked by calculating $h_{c(50)}$ values to compare with the input data. Table B-1 summarizes the results of the calculation. The average value for the difference between calculated and input $h_{c(50)}$ values should be 0.0 for a least squares fit. The column headed Δ % contains the actual value for the average percent difference between calculated and input $h_{c(50)}$ for each heat flow direction. Table B-1 also contains an average value for the absolute value of the difference between calculated and input $h_{c(50)}$, Δ, for each heat flow direction in a column labeled $|\Delta|$ %. A 95% confidence interval for each set of $h_{c(50)}$ was calculated from the sample standard deviation of values for Δ. Figure B-1 shows the percentage differences between calculated and input $h_{c(50)}$ as a function of ℓ. Approximately 94% of the 309 of the calculated $h_{c(50)}$ are within $\pm$ 2% of the input values and 98% are within $\pm$ 3%. Table B-2 contains the a_{ijk} needed to calculate $h_{c(50)}$ using Equation (7) or Equation (B-1) and Table B-3 contains typical output for each heat flow direction. Table B-2 is followed by five figures that show calculated $h_{c(50)}$ values plotted on the curves published by Robinson and Powell.[6]

Table B-1. Summary of results obtained for the comparison of calculated and experimental $h_{c(50)}$

Heat Flow Direction	Number of Points	$\bar{\Delta}$ % (a)	$\overline{\lvert\Delta\rvert}$ % (b)	95% Confidence on Δ (%) (c)
UP	65	- .0015	0.24	0.62
UP @ 45°	70	.0150	0.92	2.60
HORIZONTAL	65	- .0990	1.26	3.14
DOWN @ 45°	65	.0080	0.39	1.02
DOWN	39	.0120	1.01	2.48

(a) $(h_{c(50)}(CALC) - h_{c(50)}(EXP)) \times 100 / h_{c(50)EXP}$

(b) $|(h_{c(50)}(CALC) - h_{c(50)}(EXP)) \times 100| / h_{c(50)}EXP$

(c) 2 times the sample standard deviation for the set Δ (%).

Table B-2. Coefficients a_{ijk} for Equation 7

k	Heat Flow Direction
1	up
2	45° up
3	horizontal
4	45° down
5	down

k=1

i/j	0	1	2	3	4
1	0.154033	0.128242	-0.672234E-1	0.103352E-1	0.449575E-1
2	0.261297E-1	-0.170819E-1	0.740205E-2	-0.106537E-2	-0.129284E-2
3	-0.543166E-3	0.484687E-3	-0.224020E-3	0.332463E-4	0.268733E-4
4	0.421073E-5	-0.427516E-5	0.205385E-5	-0.310975E-6	-0.122383E-6

k=2

i/j	0	1	2	3	4
1	-0.292974	0.439537	-0.155525	0.188638E-1	0.198930
2	0.248568E-1	-0.537916E-2	-0.247209E-3	0.207259E-3	-0.690024E-2
3	0.153549E-3	-0.536929E-3	0.260268E-3	-0.367985E-4	-0.197945E-4
4	-0.428586E-5	0.706284E-5	-0.308349E-5	0.412338E-6	0.104639E-5

Table B-2. (Continued)

k=3

i/j	0	1	2	3	4
1	-0.258489	0.147802	0.113648E-1	-0.762171E-2	0.260617
2	-0.163168E-1	0.386983E-1	-0.178151E-1	0.258329E-2	0.454289E-3
3	0.431892E-3	-0.746744E-3	0.330506E-3	-0.480532E-4	-0.470610E-4
4	-0.203963E-5	0.388716E-5	-0.175310E-5	0.2647107E-6	0.102102E-6

k=4

i/j	0	1	2	3	4
1	-0.578849E-1	-0.537902E-3	0.179100E-1	-0.227585E-2	0.205572
2	-0.336486E-2	0.827876E-2	-0.614257E-3	-0.257762E-3	-0.112611E-2
3	-0.277961E-3	0.329177E-3	-0.208731E-3	0.364642E-4	0.110325E-3
4	0.450468E-5	-0.528978E-5	0.272097E-5	-0.429814E-6	-0.149081E-5

k=5

i/j	0	1	2	3	4
1	0.874875E-2	-0.155474E-2	0.124601E-2	-0.242282E-3	0.166890
2	-0.212700E-2	0.286348E-2	-0.111934E-2	0.152577E-3	0.615557E-3
3	0.285561E-4	-0.329725E-4	0.126985E-4	-0.169089E-5	-0.800767E-5
4	0.0	0.0	0.0	0.0	0.0

Table B-3. Results for $h_{c(50)}$ obtained from Equation (7)

The following is a tabulation of $h_{c(50)}$ computed using the a_{ijk} values listed above:

k identifies the direction of heat flow:
1 = heat flow up
2 = heat flow 45° up
3 = heat flow horizontal
4 = heat flow 45° down
5 = heat flow down

DT identifies the temperature difference (°F) across a gap of width x inches. The units for $h_{c(50)}$ are BTU/ft²·hr·°F.

k = 1

DT = 10.00	$h_{c(50)}$
x = 0.500	0.432
1.000	0.391
1.500	0.369
2.000	0.353
2.500	0.341
3.000	0.332
3.500	0.330
DT = 20.00	
x = 0.500	0.526
1.000	0.476
1.500	0.448
2.000	0.429
2.500	0.416
3.000	0.406
3.500	0.400
DT = 30.00	
x = 0.500	0.587
1.000	0.535
1.500	0.505
2.000	0.483
2.500	0.468
3.000	0.457
3.500	0.450
DT = 40.00	
x = 0.500	0.630
1.000	0.578
1.500	0.546
2.000	0.523
2.500	0.506
3.000	0.494
3.500	0.488
DT = 50.00	
x = 0.500	0.669
1.000	0.613
1.500	0.581
2.000	0.557
2.500	0.538
3.000	0.526
3.500	0.519
DT = 60.00	
x = 0.500	0.717
1.000	0.651
1.500	0.616
2.000	0.592
2.500	0.574
3.000	0.560
3.500	0.550

Table B-3. (Continued)

k = 2			k = 3		
DT =	10.00	$h_{c(50)}$	DT =	10.00	$h_{c(50)}$
x = 0.500		0.363	x = 0.500		0.340
1.000		0.317	1.000		0.222
1.500		0.317	1.500		0.230
2.000		0.311	2.000		0.245
2.500		0.298	2.500		0.251
3.000		0.289	3.000		0.248
3.500		0.294	3.500		0.244
DT =	20.00		DT =	20.00	
x = 0.500		0.422	x = 0.500		0.349
1.000		0.397	1.000		0.278
1.500		0.390	1.500		0.301
2.000		0.378	2.000		0.314
2.500		0.365	2.500		0.311
3.000		0.356	3.000		0.305
3.500		0.361	3.500		0.310
DT =	30.00		DT =	30.00	
x = 0.500		0.470	x = 0.500		0.362
1.000		0.454	1.000		0.323
1.500		0.439	1.500		0.354
2.000		0.425	2.000		0.365
2.500		0.414	2.500		0.355
3.000		0.409	3.000		0.344
3.500		0.412	3.500		0.353
DT =	40.00		DT =	40.00	
x = 0.500		0.511	x = 0.500		0.378
1.000		0.497	1.000		0.360
1.500		0.474	1.500		0.394
2.000		0.458	2.000		0.401
2.500		0.451	2.500		0.388
3.000		0.450	3.000		0.373
3.500		0.450	3.500		0.380
DT =	50.00		DT =	50.00	
x = 0.500		0.547	x = 0.500		0.394
1.000		0.530	1.000		0.393
1.500		0.503	1.500		0.426
2.000		0.487	2.000		0.430
2.500		0.483	2.500		0.414
3.000		0.483	3.000		0.396
3.500		0.480	3.500		0.401
DT =	60.00		DT =	60.00	
x = 0.500		0.583	x = 0.500		0.411
1.000		0.563	1.000		0.423
1.500		0.535	1.500		0.454
2.000		0.520	2.000		0.456
2.500		0.514	2.500		0.439
3.000		0.512	3.000		0.421
3.500		0.504	3.500		0.426

Table B-3. (Continued)

k = 4			k = 5		
DT =	10.00	$h_{c(50)}$	DT =	10.00	$h_{c(50)}$
x = 0.500		0.346	x = 0.500		0.345
1.000		0.191	1.000		0.179
1.500		0.166	1.500		0.125
2.000		0.168	2.000		0.098
2.500		0.176	2.500		0.082
3.000		0.181	3.000		0.071
3.500		0.180	3.500		0.064
DT =	20.00		DT =	20.00	
x = 0.500		0.344	x = 0.500		0.347
1.000		0.217	1.000		0.182
1.500		0.211	1.500		0.130
2.000		0.221	2.000		0.103
2.500		0.229	2.500		0.087
3.000		0.230	3.000		0.077
3.500		0.224	3.500		0.071
DT =	30.00		DT =	30.00	
x = 0.500		0.348	x = 0.500		0.349
1.000		0.241	1.000		0.185
1.500		0.248	1.500		0.134
2.000		0.261	2.000		0.108
2.500		0.265	2.500		0.092
3.000		0.262	3.000		0.082
3.500		0.256	3.500		0.077
DT =	40.00		DT =	40.00	
x = 0.500		0.354	x = 0.500		0.351
1.000		0.263	1.000		0.188
1.500		0.277	1.500		0.137
2.000		0.289	2.000		0.112
2.500		0.289	2.500		0.096
3.000		0.282	3.000		0.086
3.500		0.279	3.500		0.082
DT =	50.00		DT =	50.00	
x = 0.500		0.361	x = 0.500		0.353
1.000		0.284	1.000		0.191
1.500		0.301	1.500		0.140
2.000		0.312	2.000		0.114
2.500		0.308	2.500		0.099
3.000		0.298	3.000		0.089
3.500		0.295	3.500		0.086
DT =	60.00		DT =	60.00	
x = 0.500		0.365	x = 0.500		0.355
1.000		0.302	1.000		0.193
1.500		0.322	1.500		0.142
2.000		0.331	2.000		0.116
2.500		0.326	2.500		0.101
3.000		0.314	3.000		0.091
3.500		0.308	3.500		0.088

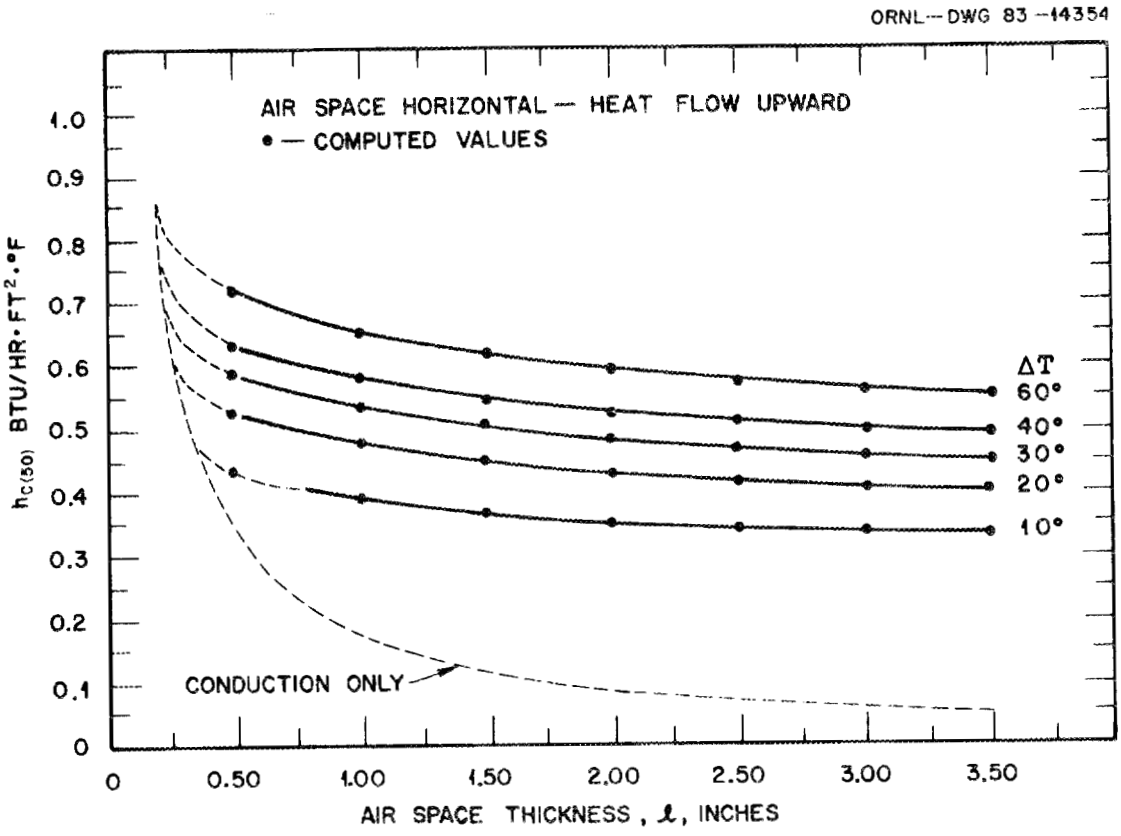

Figure B.1. A comparison of calculated and experimental $h_{c(50)}$ for heat flow upward.

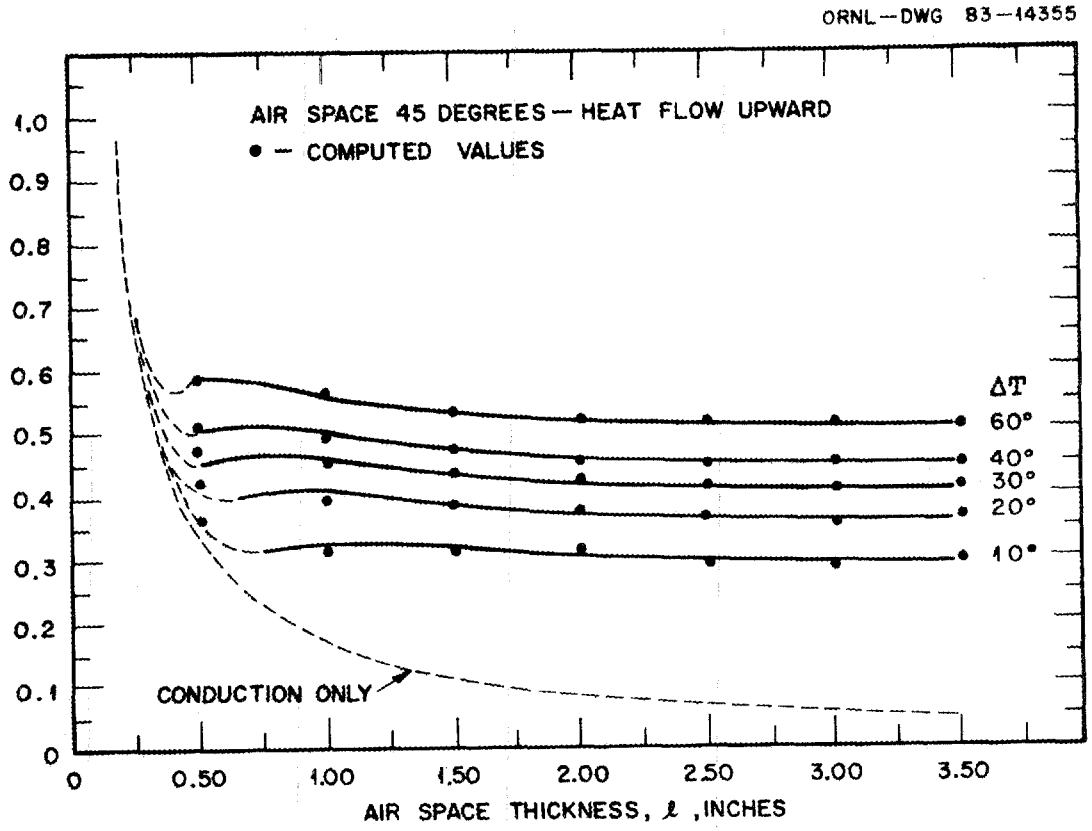

Figure B.2. A comparison of calculated and experimental $h_{c(50)}$ for heat flow upward at 45 degrees.

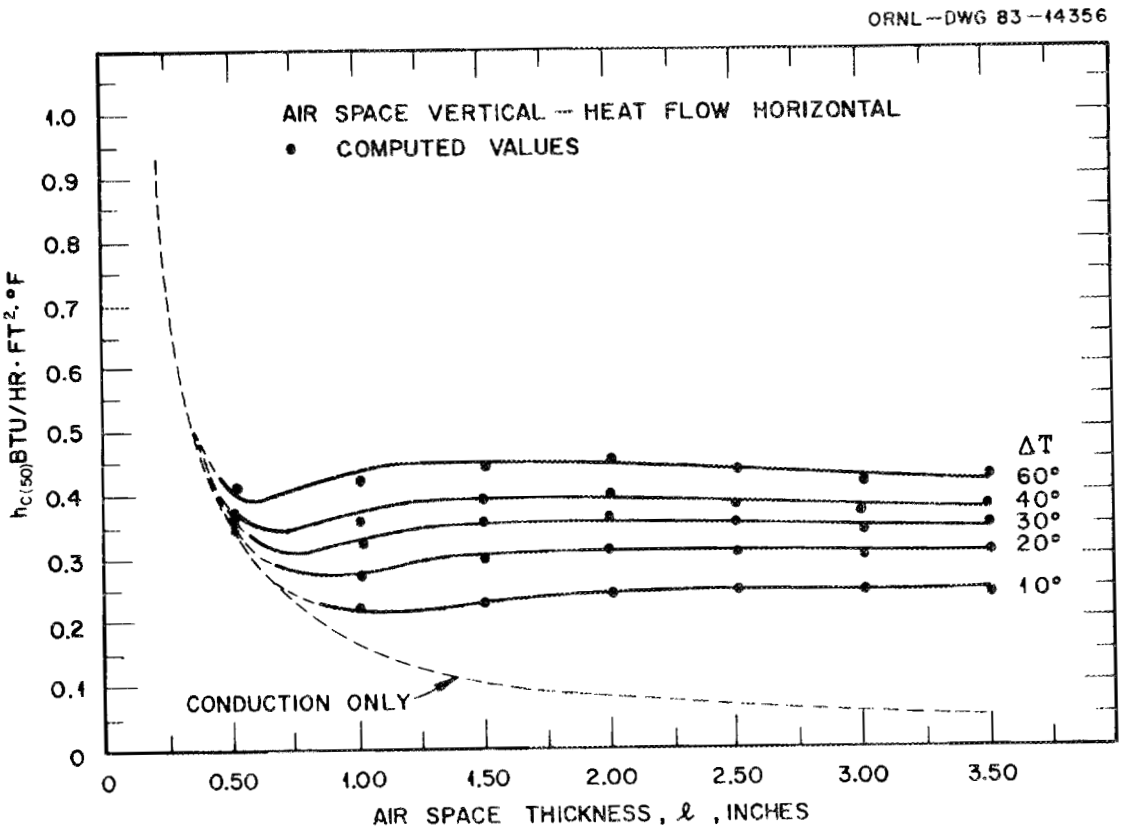

Figure B.3. A comparison of calculated and experimental $h_{c(50)}$ for heat flow horizontal.

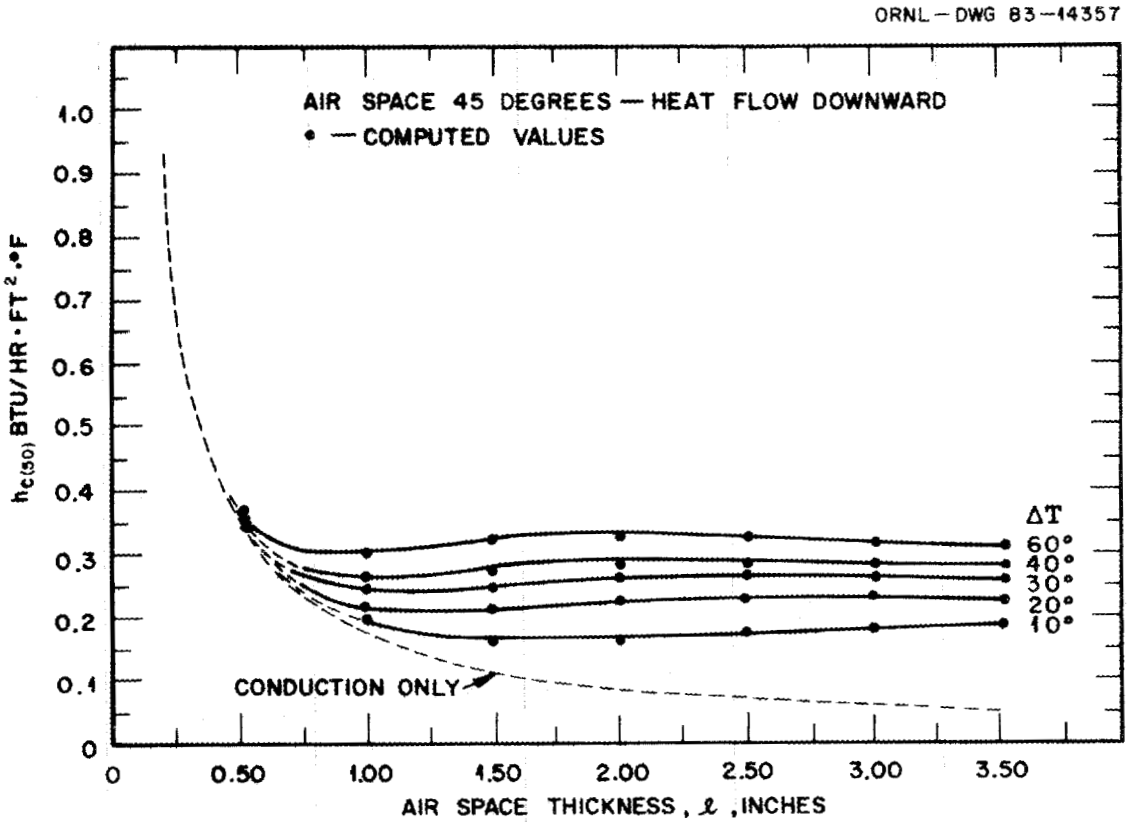

Figure B.4. A comparison of calculated and experimental $h_{c(50)}$ for heat flow downward at 45 degrees.

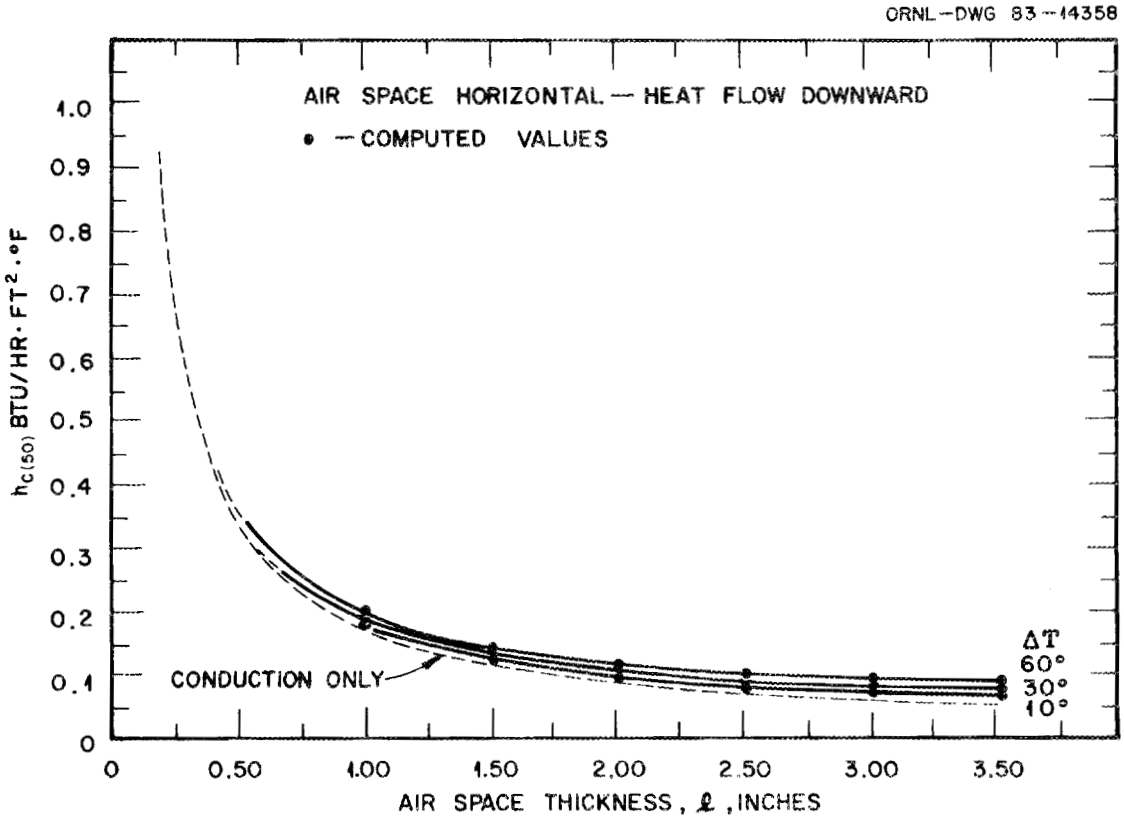

Figure B.5. A comparison of calculated and experimental $h_{c(50)}$ for heat flow downward.

APPENDIX C

FORTRAN PROGRAM FOR THE CALCULATION OF EFFECTIVE R-VALUE FOR A SERIES OF PARALLEL REFLECTIVE AIR GAPS

Contents

C.1 Program description

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C.3 Program output

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C.7 Example output for REFLECT version 2

C.1 Effective R-Value Calculation

The Fortran program "REFLECT" listed in this appendix can be used to calculate an effective R-value for a series of parallel air gaps positioned between isothermal planes. The steady-state one-dimensional calculation includes heat transfer by radiation and convection-conduction. Convective heat transfer coefficients are taken from the data of Robinson et al.[6] using the constants listed in Appendix B.

C.2 The Program Requires the Following Input

Item	Program Variable
(a) Heat flow direction	K
(b) Number of air gaps	N
(c) Thickness of gap I (inches)	X(I)
(d) Emissivities for the two surfaces of gap I	SE(I,1), SE(I,2)
(e) Temperatures of the isothermal boundaries (°F)	T(1,1), T(NP,1)

C.3 The Program Outputs the Following Information

(a) Heat flow direction and number of air gaps

(b) Thickness and E for each gap

(c) Temperatures on the boundaries of each gap

(d) Effective R-value for each air gap

(e) Effective R-value for the total system

C.4 Listing of Program REFLECT

```
C         PROGRAM REFLECTIVE R
          DIMENSION X(10),E(10),T(11,2),DT(10),TM(10),R(10),
     &    SE(10,2),TS(10)
          COMMON A(4,5,5)
          DATA A / 0.154033  ,0.261297E-1, -0.543166E-3,0.421073E-5,
     &     0.128242   ,-0.170819E-1, 0.484687E-3,-0.427516E-5,
     &    -0.672234E-1, 0.740205E-2,-0.224020E-3, 0.205385E-5,
     &     0.103352E-1,-0.106537E-2, 0.332463E-4,-0.310975E-6,
     &     0.449575E-1,-0.129284E-2, 0.268733E-4,-0.122383E-6,
     &    -0.292974   , 0.248568E-1, 0.153549E-3,-0.428586E-5,
     &     0.439537   ,-0.537916E-2,-0.536929E-3, 0.706284E-5,
     &    -0.155525   ,-0.247209E-3, 0.260268E-3,-0.308349E-5,
     &     0.188638E-1, 0.207259E-3,-0.367985E-4, 0.412338E-6,
     &     0.198930   ,-0.690024E-2,-0.197945E-4, 0.104639E-5,
     &    -.258489,   -.163168E-1,  .431892E-3,-.203963E-5,
     &     0.147802   ,.386983E-1,-.746744E-3, 0.388716E-5,
     &    0.113648E-1, -.178151E-1,0.330506E-3,-0.175310E-5,
     &    -0.762171E-2,0.258329E-2,-0.480532E-4,0.2647107E-6,
     &    0.260617   , 0.454289E-3,-.470610E-4,0.102102E-6,
     &    -0.578849E-1,-0.336486E-2,-0.277961E-3, 0.450468E-5,
     &    -0.537902E-3, 0.827876E-2, 0.329177E-3,-0.528978E-5,
     &     0.179100E-1,-0.614257E-3,-0.208731E-3, 0.272097E-5,
     &    -0.227585E-2,-0.257762E-3, 0.364642E-4,-0.429814E-6,
     &     0.205572   ,-0.112611E-2, 0.110325E-3,-0.149081E-5,
     &     0.874875E-2,-0.212700E-2, 0.285561E-4, 0.000000   ,
     &    -0.155474E-2, 0.286348E-2,-0.329725E-4, 0.000000   ,
     &     0.124601E-2,-0.111934E-2, 0.126985E-4, 0.000000   ,
     &    -0.242282E-3, 0.152577E-3,-0.169089E-5, 0.000000   ,
     &     0.166890   , 0.615557E-3,-0.800767E-5, 0.000000   /
888       CONTINUE
          WRITE(5,100)
          WRITE(5,101)
          READ(5,200)    K
          WRITE(5,102)
          READ(5,200)    N
          NP=N+1
          WRITE(5,103)   K,N
          WRITE(5,104)
          DO 1 J=1,N
          READ(5,201) I,X(I),SE(I,1),SE(I,2)
          E(I)=1.0/(1.0/SE(I,1)+1.0/SE(I,2)-1.0)
1         CONTINUE
          WRITE(5,105)
          WRITE(5,106) (J,X(J),E(J),J=1,N)
          WRITE(5,107)
          READ (5,202)   T(1,1),T(NP,1)
          T(1,2)=T(1,1)
          T(NP,2)=T(NP,1)
          XT=T(NP,1)-T(1,1)
          XS=0.0
```

```
      DO 2 I=1,N
      XS=XS+X(I)
2     CONTINUE
      DO 3 I=2,N
      T(I,1)=T(I-1,1)+XT*X(I-1)/XS
3     CONTINUE
222   CONTINUE
      SR=0.0
      DO 4 I=1,N
      TM(I)=0.5*(T(I+1,1)+T(I,1))
      DT(I)=ABS(T(I+1,1)-T(I,1))
      HR=E(I)*0.00686*((TM(I)+460.0)/100.)**3
      R(I)=1.0/(HR+HC(K,X(I),DT(I),TM(I)))
      SR=SR+R(I)
4     CONTINUE
      DO 5 I=2,N
      T(I,2)=R(I-1)*XT/SR+T(I-1,1)
      TS(I)=ABS(T(I,2)-T(I,1))
5     CONTINUE
      DO 6 I=1,N
      IF ( TS(I) .GT. 1.E-4 ) GO TO 333
6     CONTINUE
      WRITE(5,108)
      WRITE(5,109)
      WRITE(5,110) ( I,T(I,1),I=1,NP)
      WRITE(5,111)
      WRITE(5,112) ( I,R(I),TM(I),I=1,N)
      WRITE(5,113) SR
      WRITE(5,114)
      GO TO 888
333   CONTINUE
      DO 7 I=2,N
      T(I,1)=T(I,2)
7     CONTINUE
      GO TO 222
100   FORMAT(2X,'PROB. TYPE 1=UP,2=45/UP,3=HOR,4=45/DOWN,5=DOWN')
101   FORMAT(2X,'INPUT PROBLEM TYPE (I2) ')
102   FORMAT(2X,'INPUT NUMBER OF AIR GAPS (I2)')
103   FORMAT(2X,'HEAT FLOW TYPE',I2,' WITH',I3,' GAPS')
104   FORMAT(2X,'INPUT GAP NO. (I2),WIDTH (F10.3),SIDE 1 EM (F10.3)
     &,SIDE 2 EM (F10.3)',/)
105   FORMAT(2X,' GAP NUMBER   WIDTH          E VALUE',/)
106   FORMAT(2X,I6,4X,F10.3,4X,F10.4)
107   FORMAT(2X,'INPUT TEMP LT SUR. (F10.3), RT SUR. (F10.3)',/)
108   FORMAT(2X,'CONVERGENCE HAS BEEN ACHIEVED ')
109   FORMAT(2X,' BOUNDARY TEMPERATURES (F)',/)
110   FORMAT(2X,I5,5X,F10.2)
111   FORMAT(2X,' GAP NUMBER  R OF GAP     T MEAN')
112   FORMAT(2X,I5,5X,F10.3,1X,F10.1)
113   FORMAT(2X,' TOTAL R-VALUE FOR THIS CASE IS ',F10.3,/)
114   FORMAT(2X,'************ END OF CALCULATION ************',//)
200   FORMAT(I2)
```

```
201       FORMAT(I2,3F10.3)
202       FORMAT(2F10.3)
999       CONTINUE
          END
C         EFFECTIVE R-VALUE FOR A SERIES OF REFLECTIVE AIR GAPS
          FUNCTION HC(K,X,DT,TM)
          COMMON A(4,5,5)
          IF ( X .GE. 0.5 ) GO TO 1
          HC=0.159*(1.0+.0016*TM)/X
          RETURN
1         HC=0.0
          DO 2 J=1,4
          DO 2 I=1,4
          HC=HC+A(I,J,K)*X**J*DT**I/(X*DT)
2         CONTINUE
          DO 3 I=1,4
          HC=HC+A(I,5,K)*DT**(I-1)/X
3         CONTINUE
          C=0.159*(1.0+0.0016*TM)/X
          W=(HC-C)*100/C
          IF ( W .GT. 10.0 ) GO TO 4
          HC=HC*(1.0+0.0017*(TM-50.0))
          RETURN
4         HC=HC*(1.0+0.0010*(TM-50.0))
          RETURN
          END
```

C.5 Example Output for REFLECT

```
PROB. TYPE 1=UP,2=45/UP,3=HOR,4=45/DOWN,5=DOWN
INPUT PROBLEM TYPE (I2)
1
INPUT NUMBER OF AIR GAPS (I2)
3
HEAT FLOW TYPE 1 WITH 3 GAPS
 INPUT GAP NO. (I2),WIDTH (F10.3),SIDE 1 EM (F10.3) ,SIDE 2 EM
  (F10.3)

1  3.75      .80       .05
2  1.0       .80       .05
3  .75       .05       .80
 GAP NUMBER    WIDTH          E VALUE

     1         3.750        0.0494
     2         1.000        0.0494
     3         0.750        0.0494
INPUT TEMP LT SUR. (F10.3), RT SUR. (F10.3)

49.9       100.1
 CONVERGENCE HAS BEEN ACHIEVED
 BOUNDARY TEMPERATURES (F)

    1          49.90
    2          68.57
    3          84.70
    4         100.10
 GAP NUMBER  R OF GAP     T MEAN
    1          2.266       59.2
    2          1.958       76.6
    3          1.869       92.4
 TOTAL R-VALUE FOR THIS CASE IS      6.093

************ END OF CALCULATION ************
```

C.6 Listing of REFLECT Version 2

The version of REFLECT listed below has been constructed to calculate R-values for k = 1, 2, 3, 4, and 5 for a given set of input values for N, gap widths, emissivities, and total temperature difference across the assembly. The function HC called by this version is the same as HC in the preceding program.

```
C         PROGRAM REFLECTIVE R
          DIMENSION X(10),E(10),T(11,2),DT(10),TM(10),R(10),
     &    SE(10,2),TS(10)
          COMMON A(4,5,5)
          DATA A / 0.154033  ,0.261297E-1, -0.543166E-3,0.421073E-5,
     &     0.128242   ,-0.170819E-1, 0.484687E-3,-0.427516E-5,
     &    -0.672234E-1, 0.740205E-2,-0.224020E-3, 0.205385E-5,
     &     0.103352E-1,-0.106537E-2, 0.332463E-4,-0.310975E-6,
     &     0.449575E-1,-0.129284E-2, 0.268733E-4,-0.122383E-6,
     &    -0.292974   , 0.248568E-1, 0.153549E-3,-0.428586E-5,
     &     0.439537   ,-0.537916E-2,-0.536929E-3, 0.706284E-5,
     &    -0.155525   ,-0.247209E-3, 0.260268E-3,-0.308349E-5,
     &     0.188638E-1, 0.207259E-3,-0.367985E-4, 0.412338E-6,
     &     0.198930   ,-0.690024E-2,-0.197945E-4, 0.104639E-5,
     &    -.258489,   -.163168E-1,  .431892E-3,-.203963E-5,
     &     0.147802   ,.386983E-1,-.746744E-3, 0.388716E-5,
     &    0.113648E-1, -.178151E-1,0.330506E-3,-0.175310E-5,
     &    -0.762171E-2,0.258329E-2,-0.480532E-4,0.2647107E-6,
     &    0.260617   , 0.454289E-3,-.470610E-4,0.102102E-6,
     &    -0.578849E-1,-0.336486E-2,-0.277961E-3, 0.450468E-5,
     &    -0.537902E-3, 0.827876E-2, 0.329177E-3,-0.528978E-5,
     &     0.179100E-1,-0.614257E-3,-0.208731E-3, 0.272097E-5,
     &    -0.227585E-2,-0.257762E-3, 0.364642E-4,-0.429814E-6,
     &     0.205572   ,-0.112611E-2, 0.110325E-3,-0.149081E-5,
     &     0.874875E-2,-0.212700E-2, 0.285561E-4, 0.000000   ,
     &    -0.155474E-2, 0.286348E-2,-0.329725E-4, 0.000000   ,
     &     0.124601E-2,-0.111934E-2, 0.126985E-4, 0.000000   ,
     &    -0.242282E-3, 0.152577E-3,-0.169089E-5, 0.000000   ,
     &     0.166890   , 0.615557E-3,-0.800767E-5, 0.000000   /
888       CONTINUE
          WRITE(5,100)
          WRITE(5,102)
          READ(5,200)    N
          NP=N+1
          WRITE(5,104)
          DO 1 J=1,N
          READ(5,201) I,X(I),SE(I,1),SE(I,2)
          E(I)=1.0/(1.0/SE(I,1)+1.0/SE(I,2)-1.0)
1         CONTINUE
```

```
      WRITE(5,105)
      WRITE(5,106) (J,X(J),E(J),J=1,N)
      WRITE(5,107)
      READ (5,202)   T(1,1),T(NP,1)
      T(1,2)=T(1,1)
      T(NP,2)=T(NP,1)
      XT=T(NP,1)-T(1,1)
      XS=0.0
      DO 2 I=1,N
      XS=XS+X(I)
2     CONTINUE
      DO 10 K=1,5
      WRITE(5,103)K,N
      DO 3 I=2,N
      T(I,1)=T(I-1,1)+XT*X(I-1)/XS
3     CONTINUE
222   CONTINUE
      SR=0.0
      DO 4 I=1,N
      TM(I)=0.5*(T(I+1,1)+T(I,1))
      DT(I)=ABS(T(I+1,1)-T(I,1))
      HR=E(I)*0.00686*((TM(I)+460.0)/100.)**3
      R(I)=1.0/(HR+HC(K,X(I),DT(I),TM(I)))
      SR=SR+R(I)
4     CONTINUE
      DO 5 I=2,N
      T(I,2)=R(I-1)*XT/SR+T(I-1,1)
      TS(I)=ABS(T(I,2)-T(I,1))
5     CONTINUE
      DO 6 I=1,N
      IF ( TS(I) .GT. 1.E-4 ) GO TO 333
6     CONTINUE
      WRITE(5,108)
      WRITE(5,109)
      WRITE(5,110) ( I,T(I,1),I=1,NP)
      WRITE(5,111)
      WRITE(5,112) ( I,R(I),TM(I),I=1,N)
      WRITE(5,113) SR
10    CONTINUE
      WRITE(5,114)
      GO TO 888
333   CONTINUE
      DO 7 I=2,N
      T(I,1)=T(I,2)
7     CONTINUE
      GO TO 222
100   FORMAT(2X,'PROB. TYPE 1=UP,2=45/UP,3=HOR,4=45/DOWN,5=DOWN')
101   FORMAT(2X,'INPUT PROBLEM TYPE (I2) ')
102   FORMAT(2X,'INPUT NUMBER OF AIR GAPS (I2)')
103   FORMAT(2X,'HEAT FLOW TYPE',I2,' WITH',I3,' GAPS')
104   FORMAT(2X,' INPUT GAP NO. (I2),WIDTH (F10.3),SIDE 1 EM (F10.3)
     &  ,SIDE 2 EM (F10.3)',/)
```

```
105       FORMAT(2X,' GAP NUMBER    WIDTH          E VALUE',/)
106       FORMAT(2X,I6,4X,F10.3,4X,F10.4)
107       FORMAT(2X,'INPUT TEMP LT SUR. (F10.3), RT SUR. (F10.3)',/)
108       FORMAT(2X,' CONVERGENCE HAS BEEN ACHIEVED ')
109       FORMAT(2X,' BOUNDARY TEMPERATURES (F)',/)
110       FORMAT(2X,I5,5X,F10.2)
111       FORMAT(2X,' GAP NUMBER  R OF GAP     T MEAN')
112       FORMAT(2X,I5,5X,F10.3,1X,F10.1)
113       FORMAT(2X,' TOTAL R-VALUE FOR THIS CASE IS ',F10.3,/)
114       FORMAT(2X,'************ END OF CALCULATION ************',//)
200       FORMAT(I2)
201       FORMAT(I2,3F10.3)
202       FORMAT(2F10.3)
999       CONTINUE
          END
```

C.7 Example Output for Version 2 of REFLECT

```
PROB. TYPE 1=UP,2=45/UP,3=HOR,4=45/DOWN,5=DOWN
INPUT NUMBER OF AIR GAPS (I2)
2
 INPUT GAP NO. (I2),WIDTH (F10.3),SIDE 1 EM (F10.3)      ,SIDE 2 EM
  (F10.3)

1  1.75       .9        .05
2  1.75        .05       .90
 GAP NUMBER    WIDTH          E VALUE

     1         1.750        0.0497
     2         1.750        0.0497
INPUT TEMP LT SUR. (F10.3), RT SUR. (F10.3)

50.         100.
 HEAT FLOW TYPE 1 WITH  2 GAPS
  CONVERGENCE HAS BEEN ACHIEVED
  BOUNDARY TEMPERATURES (F)

    1          50.00
    2          75.35
    3         100.00
  GAP NUMBER  R OF GAP     T MEAN
    1          1.906       62.7
    2          1.853       87.7
  TOTAL R-VALUE FOR THIS CASE IS     3.760
```

```
HEAT FLOW TYPE 2 WITH  2 GAPS
 CONVERGENCE HAS BEEN ACHIEVED
 BOUNDARY TEMPERATURES (F)

    1          50.00
    2          75.37
    3         100.00
 GAP NUMBER  R OF GAP     T MEAN
    1          2.147       62.7
    2          2.084       87.7
 TOTAL R-VALUE FOR THIS CASE IS     4.232

HEAT FLOW TYPE 3 with  2 GAPS
 CONVERGENCE HAS BEEN ACHIEVED
 BOUNDARY TEMPERATURES (F)

    1          50.00
    2          75.37
    3         100.00
 GAP NUMBER  R OF GAP     T MEAN
    1          2.542       62.7
    2          2.468       87.7
 TOTAL R-VALUE FOR THIS CASE IS     5.010

HEAT FLOW TYPE 4 WITH  2 GAPS
 CONVERGENCE HAS BEEN ACHIEVED
 BOUNDARY TEMPERATURES (F)

    1          50.00
    2          75.42
    3         100.00
 GAP NUMBER  R OF GAP     T MEAN
    1          3.448       62.7
    2          3.334       87.7
 TOTAL R-VALUE FOR THIS CASE IS     6.781

HEAT FLOW TYPE 5 WITH  2 GAPS
 CONVERGENCE HAS BEEN ACHIEVED
 BOUNDARY TEMPERATURES (F)

    1          50.00
    2          75.70
    3         100.00
 GAP NUMBER R OF GAP      T MEAN
    1           5.964      62.8
    2           5.639      87.8
 TOTAL R-VALUE FOR THIS CASE IS    11.603

************ END OF CALCULATION ************
```

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