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**OAK RIDGE
NATIONAL
LABORATORY**

LOCKHEED MARTIN

**DEVELOPMENT OF METAL-CLAD
FILLED EVACUATED PANEL
SUPERINSULATION**

Final Report for CRADA Number ORNL 93-0192

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March 1997

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Metals and Ceramics Division

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TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT	1
1. OBJECTIVES OF CRADA	1
2. BENEFITS OF CRADA TO DOE	1
3. TECHNICAL DISCUSSION OF RESULTS	2
3.1 Direct Measurements of Cladding Thermal Conductivity	2
3.1.1 Measurement Method	2
3.1.2 Specimens	12
3.1.3 Electrical Resistivity Results	15
3.1.4 Total Hemispherical Emittance	23
3.1.5 Thermal Conductivity Results	30
3.2 Thermal Measurements on Evacuated Panels	40
3.2.1 Measurement Method	40
3.2.2 Test Panels	43
3.2.3 Heat Transmission Results	43
3.3 Refrigerator Simulations	48
3.3.1 Energy Savings Due to Evacuated Panels	48
3.3.2 Economic Analysis	51
4. INVENTIONS	56
5. COMMERCIALIZATION POSSIBILITIES	56
6. PLANS FOR FUTURE COLLABORATIONS	58
7. CONCLUSIONS	58
8. ACKNOWLEDGMENTS	59
9. REFERENCES	59

LIST OF FIGURES

1. Schematic of Apparatus for Thermal Conductivity Measurements	3
2. Temperature Profile from Experiment on Specimen 2 at 50°C	5
3. Temperature Profile from Experiment on Specimen 2 at 100°C	6
4. Temperature Profile from Experiment on Specimen 2 at 150°C	7
5. Temperature Profile from Experiment on Specimen 2 at 200°C	8
6. Temperature Profile from Experiment on Specimen 2 at 250°C	9
7. Geometry of Stainless Steel Specimens for Thermal Conductivity Measurements	14
8. Electrical Resistivity of 0.012 inch thick Type 304 Stainless Steel	16
9. Electrical Resistivity of 0.008 inch thick Type 304 Stainless Steel	17
10. Electrical Resistivity of 0.0035 inch thick Type 201L Stainless Steel	18
11. Electrical Resistivity of 0.003 inch thick Type 201 Stainless Steel	19
12. Electrical Resistivity of 0.003 inch thick Type 321 Stainless Steel	20
13. Electrical Resistivity of 0.002 inch thick Type 321 Stainless Steel	21
14. Emittance of 0.012 inch thick Type 304 Stainless Steel	24
15. Emittance of 0.008 inch thick Type 304 Stainless Steel	25
16. Emittance of 0.0035 inch thick Type 201L Stainless Steel	26
17. Emittance of 0.003 inch thick Type 201 Stainless Steel	27
18. Emittance of 0.003 inch thick Type 321 Stainless Steel	28
19. Emittance of 0.002 inch thick Type 321 Stainless Steel	29
20. Comparison of Measured Total Hemispherical Emittance with Total Normal Emittance Calculated from Electromagnetic Theory	31
21. Thermal Conductivity of 0.012 inch thick Type 304 Stainless Steel	32
22. Thermal Conductivity of 0.008 inch thick Type 304 Stainless Steel	33
23. Thermal Conductivity of 0.0035 inch thick Type 201L Stainless Steel	34
24. Thermal Conductivity of 0.003 inch thick Type 201 Stainless Steel	35
25. Thermal Conductivity of 0.003 inch thick Type 321 Stainless Steel	36
26. Thermal Conductivity of 0.002 inch thick Type 321 Stainless Steel	37
27. Arrangement of Heat Flux Meter Apparatus for Tests on Evacuated Panels	41
28. Arrangement of Heat Flow Meter Apparatus for Measurements on Evacuated Panels (top view)	42
29. Calculated Annual Energy Usage for Refrigerator with 0.5 Inch Thick Evacuated Panels	52
30. Calculated Annual Energy Usage for Refrigerator with 1 Inch Thick Evacuated Panels	53
31. Calculated Lifetime Value of Energy Savings for Refrigerator with 0.5 Inch Thick Evacuated Panels	54
32. Calculated Lifetime Value of Energy Savings for Refrigerator with 1 Inch Thick Evacuated Panels	55
33. Cost-benefit Relationship for One-Inch Thick Evacuated Panels with Stainless Steel Cladding and R-50 per Inch Filler Applied to Typical Refrigerator	57

LIST OF TABLES

1. Typical Composition of Stainless Steels	13
2. Characteristics of Stainless Steel Specimens	13
3. Location of Thermocouples Along Length of Specimens	15
4. Deviation (percent) between Measured Electrical Resistivity and CINDAS Recommended Values	22
5. Variation of Electrical Resistivity along Specimen Length	22
6. Deviation (percent) between Regression Curve for Measured Thermal Conductivity and CINDAS Recommended Values	39
7. Room Temperature (75°F) Thermal Conductivity from Direct Measurements	39
8. Characteristics of Evacuated Panels	44
9. Center-of-Panel and Filler Thermal Resistivities for Evacuated Panels	44
10. Center-of-Panel and Overall Panel Thermal Resistivities for Evacuated Panels	47
11. Results of Computer Program Simultaneous Estimation of Cladding Thermal Conductivity, Filler Resistivity and Overall Panel Resistivity	47
12. Characteristics of Refrigerator Used for Simulations of Energy Savings with Evacuated Panels	49
13. Changes Made to EPA Baseline Refrigerator Characteristics	50

DEVELOPMENT OF METAL-CLAD FILLED EVACUATED PANEL SUPERINSULATION

K. E. Wilkes, J. P. Strizak, F. J. Weaver, J. E. Besser, and D. L. Smith*

ABSTRACT

This Cooperative Research and Development Agreement (CRADA) was between Aladdin Industries, Inc. and Lockheed Martin Energy Research Corp. The purpose of the CRADA was to determine the thermal performance of various metal claddings used to encapsulate Filled Evacuated Panel (FEP) superinsulation and to optimize the cost versus thermal performance of the claddings. A FEP superinsulation is a new type of superinsulation with the potential for saving large amounts of energy in buildings, building equipment, transportation (refrigerated railcars and trucks), industrial applications, etc. The major disadvantage of metal claddings for FEPs is the heat loss through the cladding caused by the high thermal conductivity of most metals. In smaller FEPs, this heat loss can degrade the overall performance of the FEP by factors of two or more as compared with polymer-clad FEPs. On the other hand, metal claddings are essentially impermeable to ambient air, whereas polymer claddings are not. Thus, the longevity and reliability of metal-clad FEPs are much superior to polymer-clad FEPs. In addition, because of the very low vapor pressure of metals as compared to polymers, metal-clad FEPs can achieve and operate at lower internal pressures. These lower pressures allow use of less expensive and/or higher performance filler materials.

1. OBJECTIVES OF CRADA

The objective of the CRADA was to determine the effects of metallic claddings on the overall thermal performance of evacuated panel superinsulation, including the effects of different thicknesses and types of metal claddings. The impact of cladding design on energy savings due to application of evacuated panel superinsulations to refrigerators was also to be estimated.

2. BENEFITS OF CRADA TO DOE

A major part of the Building Materials Program, which is funded by the DOE Office of Buildings Energy Research, is the development of evacuated panels with higher thermal resistance, lower costs, and longer lifetimes. The procedures and technology learned in evaluating the heat losses due to conduction through stainless steel claddings will be of direct benefit to the R&D efforts of the Building Materials Program. ORNL will continue to develop the technology

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to optimize the cost-benefit relationships for evacuated panels for applications in both appliances and in the envelopes of buildings.

3. TECHNICAL DISCUSSION OF RESULTS

Results from this CRADA are organized into three sections. In the first section, results are given of direct measurements of the thermal conductivity of several types and thicknesses of stainless steel foils that were being considered for use in evacuated panel superinsulations. These measurements were undertaken to obtain data on the foils in the actual thicknesses and heat treatments that are being used in superinsulations. The second section gives results on measurements of the thermal resistance of several evacuated panels that were fabricated using different types and thicknesses of steel. The final section gives the results of simulations of the energy performance of refrigerators that would incorporate evacuated panels into their walls and doors. Energy savings are given for different thicknesses of stainless steel vacuum jackets used in conjunction with filler materials with different thermal resistances.

3.1 Direct Measurements of Cladding Thermal Conductivity

3.1.1 Measurement Method

The thermal conductivities of selected stainless steel foils were measured using a direct electrical heating method. The apparatus used for these measurements was an adaptation of an ASTM C 835 apparatus normally used for measurement of the total hemispherical emittance of metals. The apparatus is shown schematically in Figure 1.[1] A specimen in the shape of a dogbone was clamped between two water-cooled electrodes inside an evacuated chamber with water-cooled walls. The specimen was heated by passage of a direct electrical current to temperatures ranging from room temperature to 500°C. Eight platinum versus platinum-10 percent rhodium thermocouples, made from 0.003 in. diameter wire, were spot welded to the specimen at selected positions along its length. The two elements were welded separately to the specimen. In addition to providing a measurement of the temperature profile along the specimen, the platinum-10 percent rhodium thermoelements were used to measure the voltage drop along the specimen. The thermal conductivity was inferred from the measured temperature profile.

Thermocouples and
Voltage Taps

Figure 1. Schematic of Apparatus for Thermal Conductivity Measurements

This measurement gives the thermal conductivity in the direction parallel to the specimen surface. This is the direction of interest for applications as vacuum claddings for superinsulation, since the heat flow around the edges of vacuum superinsulations is in the plane of the metal.

Direct electrical heating methods have been used for nearly 100 years for measurement of the thermal conductivity of metals.[2,3] If the metal specimen has a large cross sectional area so that heat losses from the surfaces are negligible compared with conduction along the specimen, then the temperature profile will be a parabola. If this is the case, the thermal conductivity can be calculated from an algebraic equation using temperatures measured at the midpoint and at one other location (assuming symmetrical cooling of the ends). When heat losses from the surface become significant, the temperature profile is more complex and analysis of the data is more difficult. Figures 2 through 6 show measured temperature profiles for one of the specimens at a sequence of increasing temperature levels. [Note: In section 3.1, a mixed set of units is used. Inch units are used for specimen dimensions, while the SI units customarily used with C 835 are used for temperatures and thermophysical properties.] The shape of the temperature profile at the lowest temperature is approximately parabolic, but as the temperature is increased the profile becomes flatter in the middle and steeper at the ends. At very high temperatures, the heat generated by the electrical current is nearly equal to that radiated from the surface, heat flows by conduction are minimal, and the temperature profile is very flat, except at the very ends of the specimen.

An energy balance on a differential length of a thin specimen yields the following differential equation:

$$\frac{I^2 \rho}{A} - P \epsilon \sigma (T^4 - T_0^4) + A \frac{d}{dx} \left(k \frac{dT}{dx} \right) = 0 \quad (1)$$

where I = current

ρ = electrical resistivity

A = cross sectional area of specimen

P = perimeter of specimen

ϵ = total hemispherical emittance

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 2. Temperature Profile from Experiment on Specimen 2 at 50°C

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 3. Temperature Profile from Experiment on Specimen 2 at 100°C

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 4. Temperature Profile from Experiment on Specimen 2 at 150°C

**Type 304 Stainless Steel, 0.008 in. thick
Specimen 2**

Figure 5. Temperature Profile from Experiment on Specimen 2 at 200°C

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 6. Temperature Profile from Experiment on Specimen 2 at 250°C

σ = Stefan-Boltzmann constant

T = absolute temperature of specimen at position x

T_0 = absolute temperature of specimen surroundings

x = position on specimen

k = thermal conductivity

The first term in Equation 1 represents the Joulean heat generated by passage of the electrical current, the second term represents the heat lost by radiation, and the third term represents the heat conducted along the length of the specimen. Equation 1 assumes that the temperature of the specimen varies only in the length direction and not across the width or through the thickness. This assumption is justified for thin foils such as the ones used in the present study.

Equation 1 is highly nonlinear because of the T^4 radiation term and also because the three thermophysical properties (electrical resistivity, emittance, and thermal conductivity) may vary significantly with temperature. Because of the nonlinearities, an exact analytical solution to extract the thermal conductivity from measured quantities is generally not possible. Past studies using direct heating methods have resorted to various approximations to obtain thermal conductivity values; these are summarized by Flynn [4] and by Taylor [5]. For this project, we used computer methods to deduce the thermal conductivity from numerical solutions of Equation 1 without resorting to any approximations.

Reduction of experimental data consisted of three steps. In the first step, the electrical resistivity was obtained from the voltage drop, ΔV , between the two thermocouples that span the center 2 in. section of the specimen, using the following equation:

$$\rho = \frac{\Delta V}{\Delta L} \frac{A}{I} \quad (2)$$

where ΔL is the distance between the two thermocouples. The temperature assigned to the resistivity value is the average of the readings of the two center thermocouples. Since the center 2 in. section was usually very isothermal, the temperature that applies to the resistivity value is well defined. The resistivity values were then plotted versus temperature and the data were fitted

by the method of least squares to obtain a quadratic equation of the form:

$$\rho = a + b \cdot T + c \cdot T^2 \quad (3)$$

where a , b , and c are constants obtained from the fitting procedure. As will be seen, this equation gives very good representations of the data.

In the second step of data analysis, the total hemispherical emittance was calculated from the voltage drop (ΔV) between the two thermocouples that span the center 2 in. section and the average of the temperature readings of these two thermocouples, using the following equation

$$\epsilon = \frac{\Delta V \cdot I}{P \Delta x \sigma (T^4 - T_0^4)} \quad (4)$$

where again Δx is the distance between the two thermocouples. This equation assumes that the heat generated in the center section is exactly balanced by heat radiated from the surface of the specimen. This would be exact if there were absolutely no heat conduction along the length of the specimen. In reality, there is a small amount of conduction since the temperature profile is not exactly flat even over the center 2 in. section of the specimen. A correction was made to Equation 4 by fitting a cubic spline [6] to the temperature profile and calculating the conduction heat transfer at the ends of the 2 in. section. For these calculations, thermal conductivity values from the literature [7] for Type 304L stainless steel were used. Use of literature values for the thermal conductivity was justified since the correction was never greater than 3 percent, and was usually much less. The emittance versus temperature values were also fitted to an equation of the quadratic form. As will be seen, the data fit this form of equation very well.

In the third step of the data analysis, a special purpose finite difference computer program was written and used to solve for the thermal conductivity. The inputs to the computer program consisted of the geometry of the specimen (width, thickness, distance between each of the thermocouples), temperatures read by the thermocouples nearest the water-cooled ends, the electrical current, and the equations for electrical resistivity and emittance versus temperature. With this input, the computer program would assume a value for the thermal conductivity and then predict the temperatures at the locations of the other thermocouples. A systematic search

was used to find the value of the thermal conductivity that resulted in the least squares difference between the calculated and measured temperature profiles. Figures 2 through 6 show comparisons between the calculated (curves) and measured (symbols) temperature profiles. The temperature assigned to the thermal conductivity value was the average of the low and high temperatures along the specimen.

3.1.2 Specimens

Specimens of four stainless steel alloys (AISI Types 201, 201L, 304, and 321) were provided by Aladdin Industries. Nominal chemical compositions of the alloys are given in Table 1.[8] The major alloying elements are chromium, which imparts oxidation resistance, and nickel, which stabilizes the alloy in the austenitic phase. The basic alloy in the austenitic stainless steel family is Type 302, which contains about 18 percent chromium and 8 percent nickel (hence, 18-8 stainless steels). In Type 201, manganese and nitrogen partly replace the nickel. Type 201L is similar but has lower carbon content to provide improved corrosion resistance in welded structures. Type 304 is similar to Type 302, but has a lower carbon content also for better corrosion resistance in welded structures. Type 304L has an even lower carbon content. In Type 321, titanium is added to prevent chromium carbide precipitation and hence improve the resistance to intergranular corrosion.

Aladdin prepared specimens in the geometry shown in Figure 7. The specimens were in the shape of a dogbone with a 12 inch long section having a nearly uniform width of 0.5 inches. Specimen thicknesses ranged from 0.002 to 0.012 inches. The specimens and their measured thicknesses are identified in Table 2. Eight platinum versus platinum-10 percent rhodium thermocouples were spot welded to the uniform-width section of the specimens at the locations given in Table 3. Two of the thermocouples spanned the central 2 in. long section (locations of 5.0 and 7.0 inches). Thermocouples were placed within 0.25 in. of the ends of the uniform-width section, and the others were placed at intermediate locations to attempt to capture the shape of the temperature profile.

Table 1. Typical Composition of Stainless Steels

AISI Type	C	Mn	Si	Cr	Ni	P	S	Others
302	0.15	2.00	1.00	17.0-19.0	8.0-10.0	0.045	0.03	
201	0.15	5.5-7.5	1.00	16.0-18.0	3.5-5.5	0.06	0.03	0.25 N
304	0.08	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	
304L	0.03	2.00	1.00	18.0-20.0	8.0-12.0	0.045	0.03	
321	0.08	2.00	1.00	17.0-19.0	9.0-12.0	0.045	0.03	5× % C min Ti

Note: compositions are given in weight percent.

Source: Metals Handbook [8]

Table 2. Characteristics of Stainless Steel Specimens

Specimen	Type	Thickness, inches
1	304	0.01215
2	304	0.00823
3	201L	0.00349
4	201	0.00305
5	321	0.00311
6	321	0.00208

Note: not to scale

Figure 7. Geometry of Stainless Steel Specimens
for Thermal Conductivity Measurements

Table 3. Location of Thermocouples Along Length of Specimens

Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6
0.5	0.25	0.25	0.25	0.25	0.25
2.0	0.75	0.5	0.5	0.5	0.75
3.5	1.75	1.0	1.0	1.0	1.75
5.0	5.0	5.0	5.0	5.0	5.0
7.0	7.0	7.0	7.0	7.0	7.0
8.5	10.25	11.0	11.0	11.0	10.25
10.0	11.25	11.5	11.5	11.5	11.25
11.5	11.75	11.75	11.75	11.75	11.75

Note: locations are distances (in inches) from the top of the 12 inch long uniform width section.

3.1.3 Electrical Resistivity Results

Results of the electrical resistivity measurements from the central 2 in. section of the specimens are given in Figures 8 through 13. The lines through the data points were calculated from the least squares fit, and the equations and coefficients of determination (r^2) are also given in the figures. In all cases, the coefficients of determination were greater than 0.9998, indicating that the quadratic equation gives the correct variation of resistivity with temperature. Data were taken as the specimen was heated up to 500°C (called Run 1), and then as the specimen was cooled back to room temperature (called Run 2). No evidence of hysteresis was observed, indicating that the microstructural aspects of the specimens that affect the electrical resistivity were stable at least up to 500°C over the duration of the test. Table 4 compares the present results with the values recommended by CINDAS^{**}. [9,10] The present values for Specimens 1 and 2, which were made of Type 304, are within ± 2 percent of the CINDAS values. The data for Specimen 3, which was made of Type 201L, are within 0.5 percent of the CINDAS values, while

^{**}CINDAS is the Center for Information and Numerical Data Analysis and Synthesis at Purdue University, and is recognized as an international authority on thermophysical properties.

Type 304 Stainless Steel, 0.012 in. thick
Specimen 1

Figure 8. Electrical Resistivity of 0.012 inch thick Type 304 Stainless Steel

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 9. Electrical Resistivity of 0.008 inch thick Type 304 Stainless Steel

Type 201L Stainless Steel, 0.0035 in. thick
Specimen 3

Figure 10. Electrical Resistivity of 0.0035 inch thick Type 201L Stainless Steel

Type 201 Stainless Steel, 0.003 in. thick
Specimen 4

Figure 11. Electrical Resistivity of 0.003 inch thick Type 201 Stainless Steel

Type 321 Stainless Steel, 0.003 in. thick
Specimen 5

Figure 12. Electrical Resistivity of 0.003 inch thick Type 321 Stainless Steel

Type 321 Stainless Steel, 0.002 in. thick
Specimen 6

Figure 13. Electrical Resistivity of 0.002 inch thick Type 321 Stainless Steel

Table 4. Deviation (percent) between Measured Electrical Resistivity and CINDAS Recommended Values

Temperature, °C	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6
25	-0.8	1.9	-0.5	+4.7	-0.8	1.6
100	-0.7	1.9	-0.5	+4.1	0.2	2.1
200	-0.6	1.9	-0.5	+3.5	1.2	2.6
300	-0.7	1.8	-0.4	+3.1	2.0	2.8
400	-0.7	1.6	-0.3	+2.8	2.5	2.8
500	-0.9	1.4	-0.2	+2.6	2.9	2.7

Table 5. Variation of Electrical Resistivity along Specimen Length (Normalized to Resistivity of Center Section)

Section	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6
1	1.00325	1.00376	1.01110	1.02153	1.01592	-
2	1.00197	0.99892	1.00288	1.01765	1.01245	1.00401
3	0.99884	0.99711	1.00221	1.00680	1.00200	1.00105
4	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
5	1.00003	1.00681	1.00286	1.00543	1.00419	1.01132
6	0.99946	1.01515	1.01114	1.00844	1.00748	1.01132
7	1.00064	1.00465	1.01042	1.01399	1.01348	1.01132

those for Specimen 4, which was made of Type 201, are 3 to 5 percent higher. The data for Specimens 5 and 6, which were made of Type 321, are within ± 3 percent of the CINDAS values. Considering the small thickness of the present specimens, this level of agreement is considered to be very good. For example, the measured values of resistivity are proportional to the specimen thickness, and an error of 3 percent in the thickness of Specimen 5 could be due to a thickness uncertainty of less than 0.0001 in.

Another result of the electrical resistivity measurements was that they could be used to quantify variations in the width of the specimens. Electrical resistivities were calculated for each section between adjacent thermocouples. Resistivity data at low temperatures showed systematic variations along the length of the specimen. Generally, the measured electrical resistivity was larger near the ends of the specimen than in the center. This is shown by the data in Table 5, where the seven segments correspond to the spaces between the eight thermocouples. Since the temperature variations were small at low temperatures, these variations were not due to the temperature dependence of the resistivity. Rather, these systematic variations appear to be due to the specimen being wider at the center than at the ends. This was confirmed by direct measurements of the specimen width. The variation may be due to the clamping arrangement that was used in fabricating the specimens. If the ends were held fixed by pins through the two holes, then the middle might flex under the action of the cutting tool, allowing the middle to be wider. Even though these variations in width were small, it was found to be necessary to include this factor in the analysis for thermal conductivity.

3.1.4 Total Hemispherical Emittance

Results of the total hemispherical emittance measurements are given in Figures 14 through 19. Run 1 corresponds to data obtained upon heating the specimen up to 500°C, and Run 2 corresponds to cooling back to room temperature. In all cases, the emittance for Run 2 was slightly lower than that for Run 1. Since the emittance depends on the condition of the specimen surface, it is possible that heating the specimens to 500°C in vacuum drove off some surface contamination or changed the thickness of the protective oxide film, resulting in a lower emittance.

Type 304 Stainless Steel, 0.012 in. thick
Specimen 1

Figure 14. Emittance of 0.012 inch thick Type 304 Stainless Steel

Type 304 Stainless Steel, 0.008 in. thick
Specimen 2

Figure 15. Emittance of 0.008 inch thick Type 304 Stainless Steel

Type 201L Stainless Steel, 0.0035 in. thick
Specimen 3

Figure 16. Emittance of 0.0035 inch thick Type 201L Stainless Steel

Type 201 Stainless Steel, 0.003 in. thick
Specimen 4

Figure 17. Emittance of 0.003 inch thick Type 201 Stainless Steel

Type 321 Stainless Steel, 0.003 in. thick
Specimen 5

Figure 18. Emittance of 0.003 inch thick Type 321 Stainless Steel

Type 321 Stainless Steel, 0.002 in. thick
Specimen 6

Figure 19. Emittance of 0.002 inch thick Type 321 Stainless Steel

Data from Run 2 for the six specimens are compared in Figure 20 with predictions from electromagnetic field theory. The Schmidt-Eckert equation [11] relates the total normal emittance (ϵ_n) to electrical resistivity (ρ) and absolute surface temperature (T_s) through

$$\epsilon_n = 0.576 \sqrt{\rho T_s} - 0.124 \rho T_s \quad (5)$$

where ρ is in ohm-cm and T_s is in degrees Kelvin. The CINDAS recommended electrical resistivity curve for Type 304 was used to calculate the theoretical curve in Figure 20. Figure 20 shows that the emittances of Specimens 2 through 6 are very similar and their variation with temperature parallels the theoretical curve. The emittance for Specimen 1 is considerably higher, but still has the same basic variation with temperature. The difference between the experimental and theoretical curves can be attributed to two factors. The first is that the experimental data are total hemispherical emittances (i.e., for radiation that is emitted in all directions from the surface), while the theoretical curve is for the total normal emittance (i.e., the radiation emitted only in a direction perpendicular to the surface). For perfectly flat, clean surfaces, electromagnetic theory predicts that the total hemispherical emittance will be about 20 percent larger than the normal emittance for the magnitude of emittances typical of stainless steel. This factor explains half or more of the difference between the theoretical curve and the data for Specimens 2 through 6. The other factor not included in the theoretical curve is surface contamination, oxide films, and surface roughness, which usually make the emittance higher than the value obtained from electromagnetic theory. It appears that the surface condition of Specimen 1 was significantly different from that of the other five specimens, possibly because of a different mill finish.

3.1.5 Thermal Conductivity Results

Thermal conductivity results for Specimens 1 through 6 are given in Figures 21 through 26. The thermal conductivity values are given in units of W/cm²°C; to convert to Btu·in./h·ft²·°F units, multiply by 693.3, and to convert to Btu/h·ft·°F, multiply by 57.78. The data were fitted to equations linear in temperature by the method of least squares, and the resulting equations and coefficients of determination are given on the figures. As with the electrical resistivity, there was

Comparison of Measured Emittance with Schmidt-Eckert Theory

Figure 20. Comparison of Measured Total Hemispherical Emittance with Total Normal Emittance Calculated from Electromagnetic Theory

Type 304 Stainless Steel, 0.012 in. thick
Specimen 1

Figure 21. Thermal Conductivity of 0.012 inch thick Type 304 Stainless Steel

Type 304 Stainless Steel, 0.008 in. thick Specimen 2

Figure 22. Thermal Conductivity of 0.008 inch thick Type 304 Stainless Steel

Type 201L Stainless Steel, 0.0035 in. thick Specimen 3

Figure 23. Thermal Conductivity of 0.0035 inch thick Type 201L Stainless Steel

Type 201 Stainless Steel, 0.003 in. thick
Specimen 4

Figure 24. Thermal Conductivity of 0.003 inch thick Type 201 Stainless Steel

Type 321 Stainless Steel, 0.003 in. thick
Specimen 5

Figure 25. Thermal Conductivity of 0.003 inch thick Type 321 Stainless Steel

Type 321 Stainless Steel, 0.002 in. thick
Specimen 6

Figure 26. Thermal Conductivity of 0.002 inch thick Type 321 Stainless Steel

no discernible difference between the thermal conductivity values obtained upon heating to 500°C (Run 1) and those obtained upon cooling back to room temperature (Run 2).

The thermal conductivity data are less precise than either the electrical resistivity or emittance data. The resistivity and emittance data were obtained from measurements on the nearly isothermal central section of the specimen. Calculation of the thermal conductivity relies upon having accurate data for the resistivity and emittance, and on having accurate knowledge of the temperature profile. At the lower temperatures, the temperature profile was measured accurately, but the emittance data had less accuracy than at higher temperatures. Because of the lower accuracy of the emittance data, valid thermal conductivity data were obtained only above about 50°C. At the higher temperatures, the emittance values were more accurate, but the temperature profile became less well known as the profile became flatter in the middle and steeper at the ends. Because of the lower accuracy in defining the temperature profile, valid conductivity data could only be obtained up to about 250 to 350°C. Only a limited amount of thermal conductivity data were obtained for Specimen 6. This was due to difficulties in welding thermocouples to this very thin specimen (the thermocouple wires were 0.003 in. diameter, making them 50 percent larger than the specimen thickness). As a consequence, several of the thermocouples became detached from the specimen during the measurements.

The present data are compared with the CINDAS recommended values in Figures 21-26, and percentage differences between the regression curves and the CINDAS values are given in Table 6. For Specimens 1 and 2 (Type 304), the present values are 13 to 14 percent lower than the CINDAS value near room temperature and are within 7 percent at 300°C. For Specimen 3 (Type 201L), the present values are within 5 percent of the CINDAS values, while those for Specimen 4 (Type 201) are about 20 percent lower than the CINDAS values. For Specimen 5 (Type 321), the present values are within 1 percent of the CINDAS values from room temperature to 300°C. For Specimen 6 (also Type 321), the present values are within 7 percent over the limited temperature range for which we could obtain data. Except for Specimen 4, this level of agreement is considered to be very reasonable, considering the difficulties in making these measurements on specimens with such small thicknesses and also given that CINDAS estimated that their recommended values have an uncertainty of about ± 5 percent. In addition, the

Table 6. Deviation (percent) between Regression Curve for Measured Thermal Conductivity and CINDAS Recommended Values

Temperature, °C	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6
25	-13.2	-14.4	-4.9	-18.8	-1.0	-6.3
100	-11.4	-12.4	-3.1	-19.4	-0.9	-5.5
200	-9.0	-9.8	-0.8	-19.8	-0.4	-4.7
300	-6.6	-7.2	+1.7	-19.7	0.2	-4.3

Table 7. Room Temperature (75°F) Thermal Conductivity from Direct Measurements

Specimen	Alloy	Thermal Conductivity		
		W/cm·°C	Btu·in./h·ft ² ·°F	Btu/h·ft·°F
1	304	0.129	89.2	7.44
2	304	0.127	88.0	7.34
3	201L	0.141	97.9	8.16
4	201	0.121	83.6	6.97
5	321	0.140	96.8	8.07
6	321	0.134	92.7	7.72
Average		0.132	91.4	7.62

CINDAS values are for the solution annealed condition, whereas the present specimens probably have some degree of cold-work. Cold-worked material would be expected to have a somewhat lower thermal conductivity than material in the solution annealed condition.

Room temperature thermal conductivity values in several units of interest are summarized in Table 7, where values were calculated from the regression equations. The average conductivity is 0.132 W/cm·°C, and the conductivities of the six specimens are within about ± 8 percent of this value. These results show that there is not a great deal of variation of the room temperature thermal conductivity with either alloy type or foil thickness.

3.2 Thermal Measurements on Evacuated Panels

3.2.1 Measurement Method

Thermal measurements were made on steel-clad evacuated panels using a heat flow meter apparatus that conforms to ASTM C 518.[12] The method consists of sandwiching a flat specimen between two isothermal plates that are held at constant, but different, temperatures (usually 55°F and 95°F). The heat flux through the specimen is measured using calibrated heat flux transducers. The thermal resistance, R , is then calculated from

$$R = \frac{\Delta T}{q} \quad (6)$$

where ΔT is the temperature difference across the specimen and q is the heat flux (i.e., the heat flow per unit area).

Measurements on evacuated panels were made by sandwiching them within sheets of semi-rigid fiberglass insulation, as shown in Figure 27. A recess was cut into the middle sheet to accept the evacuated panel. Thermocouples were taped near the center of the top and bottom surfaces of the evacuated panel. Heat fluxes were measured using an array of four-inch-square heat flux transducers (HFTs) placed on the bottom plate of the apparatus. The arrangement of the heat flux transducer array with respect to the hot plate and the evacuated panel is shown in Figure 28.

Figure 27. Arrangement of Heat Flow Meter Apparatus for Tests on Evacuated Panels. The hot and cold plates are 24 inches square. The total insulation thickness is 2.5 inches.

Hot and cold plates,
24 in. sq.

Heat flux transducers,
4 in. sq., each

Evacuated panel,
14 in. sq.

Figure 28. Arrangement of Heat Flow Meter Apparatus for Measurements on Evacuated Panels

3.2.2 Test Panels

Aladdin furnished seven evacuated panels for this phase of the program. Characteristics of the panels are given in Table 8. All panels were about 14 inches square, exclusive of the flange on the flat side. The average panel thickness, based on measurements at 12 locations over the surface of the panel, ranged from 0.37 to 0.56 inches. The pan-shaped sides of Panels 18 and 20 were greatly distorted, giving very nonuniform thicknesses, especially near the edges. The pan-shaped sides of all panels were made of stainless steel, using either Type 304, 201, or 201L at 0.003 to 0.008 inches thick. For all panels except 18 and 20, the flat-side cladding was made of the same alloy and thickness as the pan-shaped side. For Panel 18, the flat side was made of 0.012 inch thick Type 304, and for Panel 20, the flat side was made of 0.017 inch thick cold-rolled steel. Three types of fillers (unspecified) were used for the panels, as shown in Table 8.

3.2.3 Heat Transmission Results

The results of tests in the heat flow meter apparatus are given in Table 9. The quantities labeled "center-of-panel" were obtained by using the temperature difference measured across the evacuated panel and the heat flux measured over the central 4 inch by 8 inch area (i.e., HFTs 15 and 16). This corresponds to the traditional method for reporting center-of-panel resistances for evacuated panel insulations. The center-of-panel resistivities ranged from a low of 15 $\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}\cdot\text{in. (R/in.)}$ for Panel 20 to a high of 58 R/in. for Panel 138. Panels with Filler Type C all had resistivities between 44 and 58 R/in. With exception of Panel 20, resistivities for the other four panels were clustered around 23 to 25 R/in.

Aladdin made heat transmission measurements using a 1-1/2 in. diameter gauge that was developed in-house. Center-of-panel values measured with the gauge were within ± 17 percent of the heat flow meter apparatus results. Since the Aladdin gauge was designed to provide rapid determinations of relative panel performance rather than absolute values, the level of agreement with the heat flow meter results is considered to be reasonable.

Because of heat conduction around the edges of the panel through the stainless steel cladding, the overall panel resistivity will not be the same as the center-of-panel value. Also, because of the relatively small size of the panels, the measured center-of-panel value will be

Table 8. Characteristics of Evacuated Panels

Panel	Panel Thickness, in.	Pan-Shaped Cladding		Flat Cladding		Filler
		Thick., in.	Alloy	Thick., in.	Alloy	
18	0.406	0.004	304	0.012	304	Type A
20	0.423	0.004	304	0.017	Cold-rolled	Type B
24	0.373	0.008	304	0.008	304	Type A
26	0.400	0.008	304	0.008	304	Type B
138	0.535	0.004	304	0.004	304	Type C
155	0.562	0.003	201	0.003	201	Type C
222	0.512	0.0035	201L	0.0035	201L	Type C

Note: All panels were approximately 14 inches square, exclusive of welding flange on flat side.

Table 9. Center-of-Panel and Filler Thermal Resistivities for Evacuated Panels

Panel	Measured Center-of-Panel, R/inch	Calculated Filler R/inch		Percent Difference, (Filler/Center-1) $\times 100$
		2 HFTs	20 HFTs	
18	24.1	29.3 ± 1.5	36.8 ± 3.2	15 - 66
20	15.3	20.2 ± 0.8	27.8 ± 2.0	27 - 95
24	25.3	30.6 ± 1.2	36.8 ± 3.0	16 - 57
26	23.1	28.0 ± 1.1	32.6 ± 2.4	16 - 52
138	57.6	73.0 ± 4.1	83.1 ± 11.3	20 - 63
155	43.6	49.2 ± 1.2	52.3 ± 3.8	10 - 29
222	53.9	66.6 ± 2.8	70.0 ± 7.1	18 - 43

Note: Range of filler resistivities results from calculations with stainless steel thermal conductivity ranging from 6.4 to 8.6 Btu/h $\cdot$ ft $\cdot$ °F (0.11 to 0.15 W/cm $\cdot$ °C)

somewhat less than the value that would be obtained for a very large panel where the edge conduction effects would not influence the heat flow in the center. The effects of edge heat conduction were analyzed using a special purpose finite difference heat conduction computer program. The computer program uses knowledge of the specimen assembly geometry, boundary temperatures, and the thermal conductivities of the cladding, filler, and surrounding material to calculate the heat flux distribution at the locations of the heat flux transducers. The thermal conductivity of the filler material will generally not be known, and the thermal conductivity of the cladding may or may not be known. Starting with initial estimates for the unknown thermal conductivities, the computer program systematically varies these conductivities and searches for the values that give the best match (in the least squares sense) between the calculated and measured heat flux distributions.

As the first step in this analysis, the program was used to estimate the thermal resistivity of the filler material. Since the resistivity of the filler material will be the same as the center-of-panel resistivity for a very large panel, the difference between the estimated filler material and the measured center-of-panel values is an indication of the loss in thermal performance because of heat conduction through the cladding material. For these calculations, the thermal conductivity of stainless steel was taken to be 7.5 ± 1.1 Btu/h·ft·°F (0.13 ± 0.02 W/cm·°C). The value of 7.5 Btu/h·ft·°F corresponds to the average thermal conductivity measured in Section 3.1, while ± 1.1 Btu/h·ft·°F represents the range of uncertainty in the measured values. The thermal conductivity of cold-rolled steel was taken to be 26.2 Btu/h·ft·°F.[13] Results of these calculations are given in Table 9. Two values are given for the calculated filler R/in. For one calculation, the computer program tried to match the heat fluxes measured with only the two center heat flux transducers (HFTs 15 and 16). For the other calculation, the program tried to match all twenty heat flux transducers that were under the evacuated panel (HFTs 2-5, 8-11, 14-17, 20-23, and 26-29). The last column gives the percentage difference between the calculated filler resistivity and the measured center-of-panel value. These calculations indicate that a very large panel would have a resistivity 10 to 95 percent larger than the measured center-of-panel values. This indicates that there is a significant effect of edge conduction on the heat flow over the center 4 inch by 8 inch area that is used for determining the measured center-of-panel values. The large range of

percentage differences is caused by a combination of the uncertainty in the cladding thermal conductivity and the different values obtained by using different areas for the calculations. In general, the effect of different calculation areas is largest for those panels that have the most nonuniform thicknesses, i.e., Panels 18 and 20.

Of more practical interest is the calculated overall panel thermal resistivity, which is given in Table 10. The format for this table is the same as for Table 9. The effects of uncertainty in cladding thermal conductivity and of different calculational areas are much less for the calculation of overall panel resistivity than for the estimation of the filler resistivity. These results show that heat conduction through the cladding is estimated to cause the overall panel resistivity to be as much as 58 percent less than the measured center-of-panel values.

The computer program was also used to try to estimate the cladding thermal conductivity as well as the filler resistivity. Results of calculations using the heat fluxes measured with the center six transducers (HFTs 9, 10, 15, 16, 21, and 22) are given in Table 11. The results for Panels 138, 155, and 222 are very reasonable. The cladding thermal conductivities for these panels were within less than 30 percent of the directly measured values; the filler resistivities were within 8 percent of those estimated in Table 9; and the overall panel resistivities were within 8 percent of those estimated in Table 10. Results for the other panels were less reasonable. For Panels 18, 24, and 26, the cladding thermal conductivity is less than one-half of the directly measured values, but the overall panel resistivities were within three to 14 percent of those estimated in Table 10. For Panel 20, the program would not run. Attempts were made to perform these same calculations using heat fluxes measured with more of the transducers. However, the calculated cladding thermal conductivities were even less reasonable, even for Panels 138, 155, and 222.

As might be expected, the computer model only works well when the geometry of the panel conforms to the regular rectangular geometry that is built into the model. Panels 18 and 20 had very nonuniform thicknesses. They also had very thick flat sides, and, in the case of Panel 20, the flat side was made of a much higher thermal conductivity steel. For Panels 24 and 26, the stainless steel was still fairly thick. Thicker claddings and high thermal conductivity materials lead to a more isothermal flat surface, and hence more uniform heat fluxes. The basis of the computer

Table 10. Center-of-Panel and Overall Panel Thermal Resistivities for Evacuated Panels

Panel	Measured Center-of-Panel, R/inch	Calculated Panel R/inch		Percent Difference, (1-Panel/Center) × 100
		2 HFTs	20 HFTs	
18	24.1	15.4 ± 0.2	17.5 ± 0.1	27 - 37
20	15.3	11.0 ± 0.2	13.2 ± 0.1	13 - 29
24	25.3	14.6 ± 0.4	16.1 ± 0.2	36 - 44
26	23.1	13.5 ± 0.4	14.7 ± 0.2	36 - 43
138	57.6	25.2 ± 1.1	26.2 ± 0.5	54 - 58
155	43.6	23.1 ± 0.9	23.7 ± 0.3	45 - 49
222	53.9	26.1 ± 1.0	26.5 ± 0.5	50 - 53

Note: Range of panel resistivities results from calculations with stainless steel thermal conductivity ranging from 6.4 to 8.6 Btu/h·ft·°F (0.11 to 0.15 W/cm·°C)

Table 11. Results of Computer Program Simultaneous Estimation of Cladding Thermal Conductivity, Filler Resistivity and Overall Panel Resistivity

Panel	Cladding Thermal Conductivity, Btu/h·ft·°F	Filler Resistivity, R/inch	Overall Panel Resistivity, R/inch
18	2.96	24.2	16.9
20	-	-	-
24	2.57	26.5	17.5
26	3.55	24.9	15.4
138	8.35	76.2	24.2
155	8.81	50.8	22.1
222	9.85	73.4	24.1

Note: Based on heat fluxes measured with central six heat flux transducers.

program is that it relies on heat flux variations to estimate the cladding conductivity. As these variations are reduced, the ability of the program to reliably estimate the cladding conductivity is reduced. From these results, the computer program appears to be useful for estimating the cladding conductivity when the panel has a uniform thickness, the cladding is fairly thin (i.e., around 0.004 in.), and the cladding on both sides of the panel is the same metal. However, directly measured values of the cladding thermal conductivity are to be preferred.

3.3 Refrigerator Simulations

3.3.1 Energy Savings Due to Evacuated Panels

The EPA Refrigerator Analysis (ERA) Program [14] was used to estimate the energy savings that could be expected due to the application of evacuated panel insulations in the walls and doors of refrigerators. The ERA program was designed to allow comparisons of the performance potential of alternate cabinet and cycle designs. It combines an analysis of the refrigerator load requirements of the cabinet with a simulation of the capacity and efficiency of the refrigeration cycle. One specific feature that was built into ERA was the capability of analyzing the effects of advanced insulation materials.

For a baseline, we used the 18 ft³, top mount refrigerator labeled 1993 Model A (typical), as described in Reference 15. An 18 ft³ top mount refrigerator was chosen for a baseline because it is representative of those currently available commercially. Approximately 40 percent of the market is for this size of refrigerator/freezer, and it is the most popular size purchased.[16] The specifications for this refrigerator were developed by EPA by modifying an actual 1991 model to meet the 1993 energy standards. Key characteristics of the 1993 model are given in Table 12.

The energy usage for this model as calculated by the ERA program is 650 kWh per year for the conditions of the DOE 90°F closed door test. This is below the 1993 DOE energy standard of 684 kWh per year. For the simulations reported here, we changed the ambient temperature to a more reasonable value to simulate the interior of a house, and added door opening schedules. The changes that were made are detailed in Table 13. Temperatures with the fresh food and freezer compartments were left unchanged at 38°F and 5°F, respectively. With these revised conditions, the annual energy usage was 671 kWh.

Table 12. Characteristics of Refrigerator Used for Simulations of Energy Savings with Evacuated Panels

Storage Volume:	17.7 cubic feet
Insulation R/inch:	8.0 for walls 7.4 for doors
Insulation Volume:	56% of Storage Volume
Cabinet Height	59.5 in.
Cabinet Width:	32.0 in.
Cabinet Depth:	27.8 in.
Outer Surface Area:	56.3 square feet
Compressor Design:	Reciprocating, 5.28 EER
Evaporator Area:	1.42 square feet per cubic foot
Condenser Area:	0.51 square feet per cubic foot
Fans:	28.0 watts
Anti-Sweat Heaters:	5.5 watts
Refrigerant Line Heat:	Vapor Line
System COP:	1.36

Table 13. Changes Made to EPA Baseline Refrigerator Characteristics

Item	EPA Report	Present Study
Ambient temperature	90°F	75°F
Temperature under cabinet	105°F	90°F
Temperature of air entering condenser	95°F	80°F
Door opening: Fresh food Freezer	0 0	2.5 per hour 1 per hour
Fresh food temperature*	38°F	38°F
Freezer temperature*	5°F	5°F
Total kWh/year	653	671

* Note, these items were not changed for the present simulation.

Refrigerator simulations were performed for a range of filled evacuated panel characteristics. Filler resistivities used were 25 R/inch and 50 R/inch (50 R/inch is the highest value that the program will allow at present). The thickness of the stainless steel cladding ranged from 0.002 to 0.012 inches, and its thermal conductivity was taken to be 0.11, 0.13, and 0.15 W/cm²°C. The value of 0.13 W/cm²°C corresponds to the average thermal conductivity measured in Section 3.1. The other two values are 15 percent higher and lower than the average, and represent the range of uncertainty in the measured values. Simulations were also performed for polymer-clad evacuated panels. Overall panel thicknesses were one-half inch and one inch, and the panels were assumed to cover 60 percent of the outside area of the refrigerator. A coverage of 60 percent is the value that has been estimated by the refrigerator industry as a practical limit

considering the other components that must be placed within the walls and doors. The remaining space within the walls and doors of the refrigerators was taken to be filled with polyurethane foam insulation with a R/inch of about 8.

Figures 29 and 30 show the calculated annual energy usage for the refrigerator when insulated with a combination of polyurethane foam and evacuated panels at one-half inch and one inch thicknesses. The energy usages for polymer-clad panels are shown on these figures at zero cladding thickness. The reference case with no evacuated panel is also shown. The results show the expected decrease in energy usage as the evacuated panel resistivity is increased, as the panel thickness is increased, as the cladding thickness is decreased, and as the cladding thermal conductivity is decreased. Figure 29 shows that the cladding thickness for a one-half inch thick stainless-steel-clad panel with R-50 per inch filler must be less than about 0.007 inches in order to have an energy usage lower than a polymer-clad panel with an R-25 per inch filler of the same thickness. Since R-25 per inch fillers, such as precipitated silica, can be encapsulated in polymer claddings, this result places an upper limit on the stainless steel thickness that can be used and still allow the steel-clad higher R-per-inch fillers to be competitive. For one inch thick panels, the limit on stainless steel cladding thickness is about 0.004 inches.

3.3.2 Economic Analysis

The annual energy usages were used in a life-cycle analysis to calculate the present value of the lifetime energy savings produced by addition of evacuated panels to the doors and walls of the refrigerator. These calculations were based on a 20 year lifetime, a national average residential electricity price of 8.4 cents per kilowatt-hour [17], projections of future price changes for electricity [18], and a real (i.e., exclusive of inflation) discount factor of 3.4 percent [18]. It is interesting to note that the price of electricity (exclusive of general inflation) over the next 20 years is projected to be no higher than the present price, and in some years to be one to two percent lower. Results of these calculations are given in Figures 31 and 32 for the one-half inch and one-inch thick evacuated panels. The present value of energy savings represents the benefit to the consumer, and places a limit on the extra price that a consumer should be expected to pay for a refrigerator that incorporates evacuated panels. This extra price is exclusive of any extra

Energy Usage of 18 Cubic Foot Refrigerator 0.5 Inch Thick Evacuated Panels at 60 percent Coverage

Figure 29. Calculated Annual Energy Usage for Refrigerator with 0.5 Inch Thick Evacuated Panels

**Energy Usage of 18 Cubic Foot Refrigerator
1 Inch Thick Evacuated Panels at 60 percent Coverage**

Figure 30. Calculated Annual Energy Usage for Refrigerator with 1 Inch Thick Evacuated Panels

**Lifetime Value of Energy Savings for 18 Cubic Foot Refrigerator
0.5 Inch Thick Evacuated Panels at 60 percent Coverage**

Figure 31. Calculated Lifetime Value of Energy Savings for Refrigerator with 0.5 Inch Thick Evacuated Panels

**Lifetime Value of Energy Savings for 18 Cubic Foot Refrigerator
1 Inch Thick Evacuated Panels at 60 Percent Coverage**

Figure 32. Calculated Lifetime Value of Energy Savings for Refrigerator with 1 Inch Thick Evacuated Panels

amount that a consumer might be willing to pay based on emotional or altruistic motivations due to factors such as contributing to reduction of greenhouse gases.

The present values of energy savings also can be used to estimate the additional material and manufacturing costs that can be allowed for the use of steel-clad, high-R-per-inch evacuated panels. As an example, we will take the case of one-inch-thick evacuated panels. For the 18 cubic foot refrigerator under study, the outside area is 56.3 square feet. With 60 percent coverage, 33.8 square feet of evacuated panels would be used. Waldron [19] estimated the incremental material and manufacturing costs for refrigerators insulated with polymer-clad, precipitated-silica-filled evacuated panels to be \$1.39 per board foot (i.e., one-inch thick and one square foot area) of panel. This figure includes the savings due to part of the polyurethane foam insulation being displaced by the evacuated panels. He estimated the cost of precipitated silica to be \$0.75 per board foot, while Aladdin estimates the cost of R-50 per inch fillers to be as low as \$1.25 per board foot. Waldron estimated that about 2.9 square feet of barrier would be used per board foot of panel and that the cost of polymer cladding would be about \$0.32 per board foot. We assume that 2.9 square feet of stainless steel will also be required per board foot of panel, and estimate the cost of stainless steel to be \$3.00 per pound.

We adjusted Waldron's figure of \$1.39 per board foot to account for the differences in filler and cladding costs and calculated the incremental cost of adding stainless steel clad evacuated panels with R-50 per inch fillers to the typical refrigerator. The incremental energy savings and incremental costs of metal-clad panels are shown in Figure 33. Figure 33 shows that the cladding thickness must be less than about 0.004 inches thick in order to be economical. If profit margins were included in the analysis, the economical thickness would be less.

4. INVENTIONS

No inventions were made as part of this CRADA.

5. COMMERCIALIZATION POSSIBILITIES

Superinsulations based on filled evacuated panels are presently being commercialized. Some refrigerator manufacturers are utilizing superinsulations in certain models of refrigerators.

Incremental Benefits and Costs of Stainless Steel Clad Evacuated Panels

Figure 33. Cost-benefit Relationship for One-Inch Thick Evacuated Panels with Stainless Steel Cladding and R-50 per Inch Filler Applied to Typical Refrigerator

It is expected that they will find use in other applications in the future, including other appliances such as water heaters and ranges, commercial ovens, building envelopes, refrigerated railcars and trucks, and industrial applications.

6. PLANS FOR FUTURE COLLABORATIONS

While there are no definite plans for future collaborations, ORNL and Aladdin will continue to interact as the technology of filled evacuated panels continues to be developed.

7. CONCLUSIONS

A direct electrical heating method was used to measure the electrical resistivity, emittance, and thermal conductivity of a series of austenitic stainless foils being considered for use as the cladding of evacuated panel insulations. The specimens had thicknesses ranging from 0.002 to 0.012 inches, and were made from AISI Type 201, 201L, 304, and 321 stainless steels. Measured thermal conductivities for Types 201L, 304 and 321 were within about 15 percent of values recommended in the literature, while the measured values for Type 201 were about 20 percent lower than the recommended values. At room temperature, the thermal conductivities of the various specimens varied by a total of ± 8 percent about an average value of $0.13 \text{ W/cm}\cdot^\circ\text{C}$. Based on these data, it appears that variations of thermal conductivity among various types and thicknesses of austenitic stainless steels are relatively minor.

Thermal resistances of seven steel-clad evacuated panels were measured in a heat flow meter apparatus. The panels had various fillers and had claddings made of different types and thicknesses of steel (stainless steel except for the flat side of one panel which was made of cold-rolled steel). Measured center-of-panel resistivities ranged from 15 to 58 R/inch ($\text{h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}\cdot\text{in.}$). A special purpose computer program was used to analyze the experimental heat flux data to estimate the resistivity of the filler material, the overall resistivity of the panel, and the cladding thermal conductivity. These calculations showed that heat conduction through the metal cladding has a large effect on the thermal performance of the panel. It was projected that a very large panel would have a thermal resistivity 10 to 95 percent higher than the center-of-panel values measured on the 14 inch square test panels. It was also projected that the overall

resistivity of the panels would be as much as 58 percent lower than the measured center-of-panel values. Attempts to estimate the thermal conductivity of the cladding from the measured heat flux data met with only limited success.

EPA's Refrigerator Analysis (ERA) computer program was used to estimate the energy savings that could be expected from the application of evacuated panel insulation to the walls and doors of a typical refrigerator. Energy savings were calculated for panels with different filler resistivities, cladding thicknesses and cladding thermal conductivities. Comparisons were made between stainless-steel clad panels with R-50 per inch fillers and polymer-clad panels with R-25 per inch fillers. The latter corresponds to silica filler which may be contained within polymer claddings. For one-half inch thick panels, it was estimated that the metal cladding would have to be thinner than 0.007 inches in order for the metal-clad panels to have greater energy savings than the polymer-clad panels. For one inch thick panels, the cladding would have to be less than 0.004 inches.

The calculated energy savings were used in a life-cycle economic analysis to examine the cost-benefit relationships for stainless-steel-clad panels. The incremental lifetime energy savings and incremental costs were calculated for stainless-steel-clad panels with R-50 per inch fillers. It was estimated that the cladding thickness would have to be less than about 0.004 inches to have a positive net benefit for one-inch-thick panels.

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