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Optimizing the Effective Conductivity and Cost of Gas-Filled Panel Thermal Insulations

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Optimizing the Effective Conductivity and Cost of Gas-Filled Panel Thermal Insulations

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ABSTRACT

Gas-Filled Panels, or GFPs, are an advanced thermal insulation that employ a low-conductivity, inert gas, at atmospheric pressure, within a multilayer reflective baffle. The thermal performance of GFPs varies with gas conductivity, overall panel thickness, and baffle construction. Design parameters of baffle constructions that have a strong effect on GFP thermal resistance are (1) cavities per thickness, (2) cavity surface emittance, and (3) conductance of the baffle materials. GFP thermal performances, where the above parameters were varied, were modeled on a spreadsheet by iterative calculation of one-dimensional energy balances. Heat flow meter apparatus measurements of prototype GFP effective conductivities have been made and are compared to results of the calculations. The costs associated with varying baffle constructions are estimated based on the prices of commercial material components. Results are presented in terms of cost per area per unit thermal resistance ($/Area·R-Value) and are useful for optimizing GFP designs for air, argon, or krypton gas fills and a desired effective conductivity and thickness. [1]

INTRODUCTION

Recent efforts to develop new high performance insulations are motivated by international concerns over ozone depletion, global warming, and energy efficiency. Insulations with low thermal conductivity facilitate the design of low conductance insulated systems. This enables consuming less energy in processes to condition temperatures within the insulated spaces. Ozone depletion concerns arise from the use of chlorinated fluorocarbons used to expand semi-rigid polymer foams. Such closed-cell insulations that retain expanded fluorocarbons obtain the lowest conductivities (about 0.02 W/m·K) of commonly used insulation materials. Global warming concerns arise from both the release of fluorocarbon blowing agents, which absorb in the infrared, and from the release of carbon dioxide associated with the energy consumed to condition the insulated spaces. Energy efficiency concerns arise

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for a variety of reasons including: capital requirements for infrastructure to increase energy supply, pollution, limited energy resources, and national security.

Research and development at Lawrence Berkeley Laboratory are directed at an alternative thermal insulation technology referred to as Gas-Filled Panels or GFPs [1,2]. At the time of this writing, GFP technology is experimental and no commercial products are available. GFPs are insulating systems that contain a low-conductivity gas at atmospheric pressure and employ a reflective baffle to suppress radiation and convection within the gas. A polymer barrier envelope is used to retain a high concentration of the desired fill gas. The reflective baffle in a GFP is assembled from metalized thin polymer films and papers. References herein to the thermal performance per unit thickness, or "thermal conductivity", of a GFP are actually an "effective thermal conductivity", or λ_e, because GFPs are inhomogeneous devices containing dissimilar material components and a strict definition of thermal conductivity as a material property does not apply.

Thermal conductivity and cost are important attributes to consider when comparing different insulation material technologies. While both low cost and high performance per unit thickness are desirable, the latter is usually accompanied by an increase in cost. A higher cost can be justified in some insulation applications where the thickness available for insulation is limited and a high resistance to heat flow is desirable for improved energy efficiency.

Effective conductivity and cost information for GFP insulators is especially complicated because of the wide range of values attainable with GFP technology. GFP effective conductivities can vary from 0.01 W/m·K to 0.1 W/m·K. GFP costs can vary from an estimated $0.50/m^2·cm to $20.00/m^2·cm. This paper attempts to clarify the conductivity capabilities of GFP technology by presenting the results of a simple calculational model that predicts GFP performance with varying designs. Results for air, argon, and krypton gas fills are presented. A GFP with a given thickness and gas fill can have a wide range of conductivities depending on the number of cavities in the baffle construction. Increasing the number of cavities yields a lower conductivity device (until gas volume is significantly displaced by solid baffle material) because of increased suppression of radiation and convection. Increasing the number of cavities, however, increases the cost of the device because more baffle material is required. This paper attempts to clarify the relationship between cost and thermal performance and shows a simple optimization for one type of baffle construction with argon, and krypton gas-fills.

HEAT FLUX CALCULATIONS

The effective conductivities of GFP insulators were modeled by calculating the heat flux through a gas-filled cavity in a baffle assembly subjected to a temperature difference. The simplified analysis is one-dimensional and neglects the effect of the barrier component on overall effective conductivity. Baffle λ_e is derived from one-dimensional heat flow analysis for one cavity located in the middle of the baffle assembly. Figure 1 is a schematic of the single cavity used for the calculations and shows the geometry, temperature, and heat flux terms.

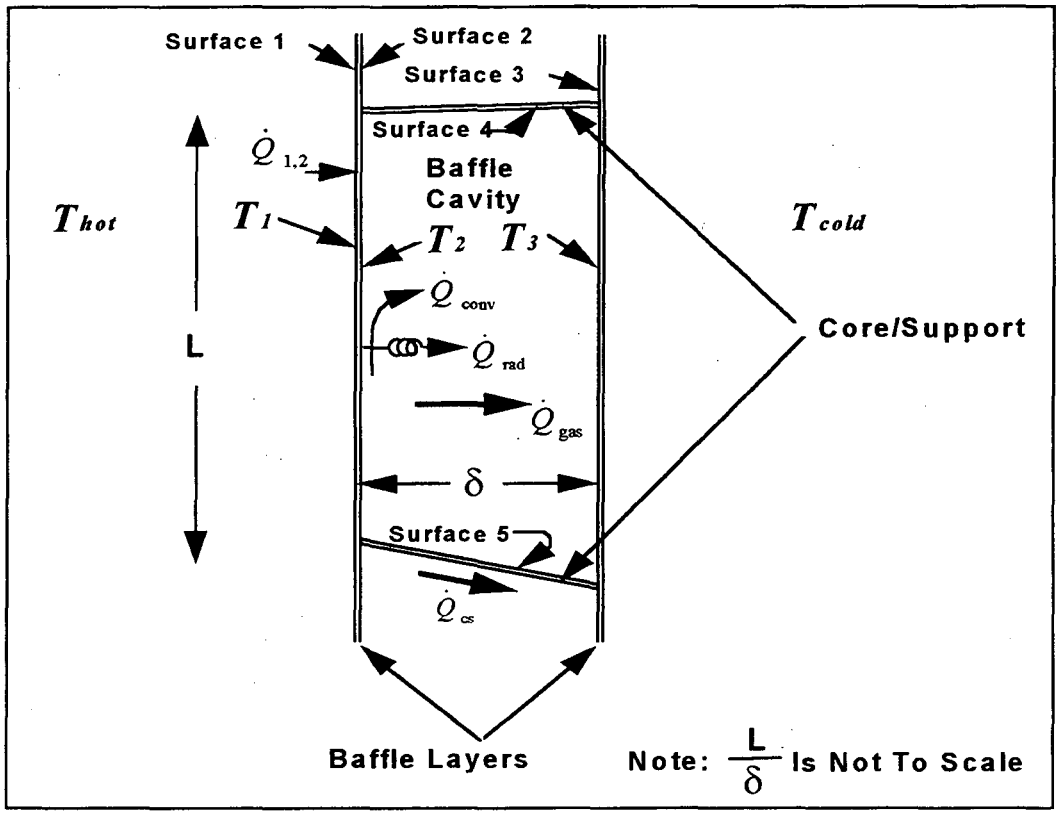

Figure 1: Cavity Geometry for Heat Flux Calculations

The total heat flux, $\dot{Q}_{2,3}$, across the cavity is calculated by Equation 1.

$$\dot{Q}_{2,3} = \dot{Q}_{rad} + \dot{Q}_{gas} + \dot{Q}_{conv} + \dot{Q}_{cs} \tag{1}$$

where,

$\dot{Q}_{2,3}$ = Total heat flux between cavity surface 2 and surface 3

$\dot{Q}_{rad}$ = Heat flux due to radiation

$\dot{Q}_{gas}$ = Heat flux through gas due to conduction

$\dot{Q}_{conv}$ = Heat flux through gas due to convection

$\dot{Q}_{cs}$ = Heat flux through core/support material due to solid conduction.

Heat flux through the baffle is driven by applying a temperature, T_{hot}, to one external surface of the baffle assembly, and a temperature T_{cold} to the other surface. T_m is the mean of T_{hot} and T_{cold}. The overall temperature difference across the baffle is $T_{hot} - T_{cold}$ or $\Delta T_{h,c}$. The temperature difference across the baffle cavity being analyzed is T_2 - T_3 or $\Delta T_{2,3}$. The solid conduction calculation is based on an area weighted one-dimensional heat transfer analysis. Three different components are treated separately, the baffle layers (which cover the whole area), the gas, and the core/support. The calculation assumes that the baffle layers have no temperature gradients in the plane of the baffle.

Radiative heat transfer across the cavity is calculated using Equation 2, a standard version of the Stefan-Boltzman law for two infinite planes with σ= 5.669 x

10^{-8}. The core/supports are assumed to have no influence on the radiation calculation so surfaces 4 and 5 are not included in the calculation. The characteristic cavity length, **L**, is typically greater than characteristic cavity gap width, δ, by a factor of 10 or more. The emittances of cavity surfaces 2 and 3 are ε_2 and ε_3, respectively. Cavity surfaces 2 and 3 are assumed opaque. A_{cavity} is the product of cavity length, **L**, and unit depth.

$$\dot{Q}_R = \frac{A_{cavity}\sigma}{\left(\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}\right)}\left[\left(T_3+\Delta T_{2,3}\right)^4-\left(T_3\right)^4\right. \tag{2}$$

Core/supports are used to locate or support the baffle layers to maintain cavity geometry. Heat flux due to solid conduction through this material is calculated using Equation 3. The length of the core/support varies with baffle design, so cavity gap width, δ, is adjusted to account for possible longer core/support length, δ_{cs}. The conductivity of the core/support material is k_{cs} and the conduction area A_{cs} is the product of thickness of the material and unit depth.

$$\dot{Q}_{cs} = \frac{k_{cs}}{\delta_{cs}} A_{cs}\Delta T_{2,3} \tag{3}$$

Heat flux due to simple conduction through the gas is calculated using Equation 4. This flux is governed by the ideal still gas thermal conductivity, λ. Values for gas properties are based on the average of the overall temperature difference. Gas property data for the model [3] uses a linear regression to yield values corresponding to the mean baffle temperature.

$$\dot{Q}_{gas} = \frac{\lambda}{\delta} A_{cavity}\Delta T_{2,3} \tag{4}$$

Additional heat flux through the gas is due to transport of gas within the cavity and its subsequent conduction. This convective heat transfer is calculated using Equation 5 where the characteristic length is cavity length, **L**, as for free convection from a vertical plate.

$$\dot{Q}_{conv} = \frac{\mathrm{Nu}\lambda A_{cavity}\Delta T_{2,3}}{\mathrm{L}} \tag{5}$$

The Nusselt number, **Nu**, is calculated using Eq. 6.

$$\mathrm{Nu} = \left[0.825+\frac{0.387\,\mathrm{Ra}^{1/6}}{\left(1+\left(0.492/\mathrm{Pr}\right)^{9/16}\right)^{8/27}}\right]^2\left(\frac{\log(\mathrm{L}/\delta)+0.53}{1.35}\right) \tag{6}$$

where,

$$\mathrm{Ra} = \mathrm{Pr} * \mathrm{Gr}$$

$$\mathrm{Gr} = \frac{g\beta\Delta T_{2,3}\delta^3}{\nu^2}$$

$$\mathrm{Pr} = \frac{\mu c_p}{\lambda}$$

Grasshof number, **Gr**, is calculated as for natural convection across a fluid layer using cavity gap width, δ, for characteristic length [4]. The **Nu** correlation is a literature correlation [5] for natural convection on a vertical plate that has been modified by the logarithmic term (in parenthesis) in Equation 6. This modification has the effect of increasing the calculated heat flux due to convection for typical baffles. This modified Nusselt correlation is presented solely for improving the accuracy and resolution of convective heat flux calculations for predicting GFP conductivities. This correlation is preliminary and is not intended for general use. This correlation has been developed for use with cavities having a characteristic length of 50 mm. The values 0.53 and 1.35 used in the logarithmic term were originally derived using a non-standard experimental technique employing infrared thermography. This preliminary work used single-cavity test baffles constructed from typical baffle materials that were heated on one surface with a uniform plate. Total heat flux was determined experimentally by measuring surface temperatures, relative to a reference emitter, and measuring the surface convection coefficient by reference to a test specimen with known thermal conductivity. The constants were then determined by regressing calculational results (from the present model) to experimental results.

The convection calculations used here do not use conventional literature correlations for natural convection in enclosed spaces because literature correlations were found to fail to resolve significant levels of convective heat flux in contradiction with observed convection in GFP baffles. The large body of literature (see for example [6]) on enclosed fluid layers does not adequately address the small-scale natural convection situation in a GFP baffle cavity. Rayleigh numbers, **Ra**, for baffle cavities are typically 5 to 20 which is an order of magnitude, or more, lower than **Ra** numbers of experimental measurements in the literature. Many literature correlations yield no convection for these low **Ra** numbers. The widespread notion that convection is thoroughly suppressed in cavities that have a gap width smaller than certain thresholds (depending on gas) has not been supported in our work on GFPs. We have observed surface temperature patterns, via infrared thermography, indicating convection is occurring in (air-filled) gap widths of 6 mm and less. Baffles having cavity gap widths of about 6 mm have also been measured using a heat flow meter apparatus (see below) at λ_e higher than can be explained without significant convection.

THERMAL PERFORMANCE MODEL

A spreadsheet based model was developed to predict the effective conductivity, or λ_e, of numerous variations on baffle construction. The calculated heat flux through one cavity equals the total heat flux and, and with the overall temperature difference, the λ_e of the entire baffle assembly can be predicted. Independent inputs to the spreadsheet model include, temperatures applied to the baffle (T_{hot} and T_{cold}), overall thickness of the baffle, number of cavities in the baffle, characteristic length of a baffle cavity, type of gas fill (mixture of two may be used), baffle material property data (thickness, k_{cs}, and ε), and the type of baffle design. Two types of baffle design were used in the model to determine geometry and baffle materials.

The first baffle design is a stiff construction which employs kraft paper laminated to thin metalized polyolefin film for baffle layers and kraft paper for core/supports. The second baffle design is a flexible construction which employs only thin metalized polyolefin film in a multilayer, partially bonded stack assembly.

Equations 1-6 can be used to calculate the heat flux once the temperature difference across the cavity, $\Delta T_{2,3}$, is known. The model assumes that the distributions of temperatures across cavity surfaces and cavity gap widths are uniform throughout the thickness of the baffle. Total heat flux across the cavity is calculated and equated to the total heat flux, $\dot{Q}_{1,2}$, through an adjacent baffle layer. This heat flux through the baffle layer generates a temperature difference, $\Delta T_{1,2}$, across the thickness of the baffle material. A new distribution of temperatures across cavity surfaces can be assumed based on the new value for $\Delta T_{1,2}$. The model iterates in this fashion until the temperature differences change by less than 0.0001° C. This iteration allows the inclusion of the effect of the high thermal conductivity of the baffle material which displaces gas fill. While this effect is typically small for flexible baffles, it becomes significant for stiff baffles using a large number of layers.

This simplified model is intended for use as a design aid in conjunction with a cost model, described below. The results for λ_e are believed to be accurate within 10% for high performance baffle designs. The model is less accurate for lower performance baffles, predicting a higher λ_e. The calculation results for specific prototype GFPs and baffles are compared to experimental test results in Table I.

EXPERIMENTAL TESTING OF PROTOTYPES

The performance of a number of prototype GFPs has been measured using a heat flow meter apparatus in conformance with standard procedures [7]. These tests were conducted independently by Oak Ridge National Laboratory [8]. Test specimens were a nominal 605 mm square, except for the 12.7 mm thick krypton-GFPs which were a nominal 305 mm square. The tests were conducted at a mean temperature of 23.89°C (±0.5°C) with a temperature difference of approximately 22.2°C. Results from these tests are given in Table I with the corresponding results from the calculational model discussed above.

CALCULATION RESULTS

The calculation model was used to characterize the relationship between effective conductivity and certain parameters of design for baffle constructions. The still gas thermal conductivity of the gas fill limits the λ_e attainable with a GFP; ideal gas values used in the model (with T_{hot}= 25°C and T_{cold}= 0°C) are 0.0252 W/m·K for air, 0.0170 W/m·K for argon, and 0.00906 W/m·K for krypton.

Varying the number of cavities in a baffle assembly is of interest because of its strong effect on both performance and cost. Figure 2 shows the relationship between GFP λ_e and the number of cavities for argon for three different overall thicknesses. Air and krypton have similar relationships for λ_e with values that approach their

TABLE I COMPARISON OF MEASURED AND CALCULATED GFP EFFECTIVE THERMAL CONDUCTIVITIES

Baffle thickness mm	Total number of cavities	Gas-Fill type (Approx. % of primary)	Experimental Tested λ_e (W/m·K)	Calculational λ_e (W/m·K)	Difference Calculation vs. Test
25.4	4	Air	0.0333	0.0367	10%
27.0	4	Argon (100%)	0.0227	0.0259	14%
25.6	8	Argon (98%)	0.0212	0.0210	-0.9%
70.4	19	Argon (99%)	0.0206	0.0211	2.4%
12.7	4	Krypton (100%)	0.0127	0.0130	2.4%
26.2	4	Krypton (100%)	0.0142	0.0153	7.8%
48.0	14	Krypton (100%)	0.0130	0.0127	-2.3%
44.5	16	Krypton (100%)	0.0116	0.0114	-1.7%

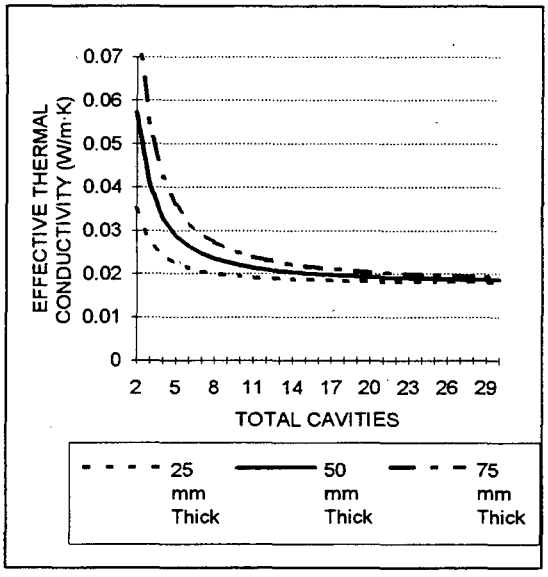

Figure 2: Argon-GFP λ_e versus total number of cavities for flexible baffles of 25, 50, and 75 mm total thickness

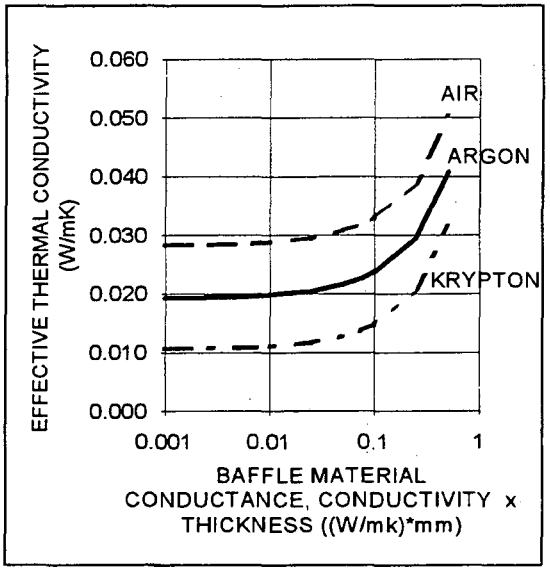

Figure 3: GFP λ_e versus the product of baffle material conductivity and material thickness, for air-, argon-, and krypton-filled stiff baffles, 50 mm thick, with 15 cavities.

ideal effective conductivity. These relationships are for one type of flexible baffle. The results are for temperature conditions T_{hot}= 25°C and T_{cold}= 0°C, and cavities of 50 mm characteristic length. The calculation uses baffle material conductivity, k_{cs}, of 0.36 W/m·K and a thickness of 0.0178 mm. Cavity surface ε were 0.04 and 0.25.

Baffle material conductance is of interest for stiff baffles because of its effect on overall thermal performance and the increased stiffness afforded by a higher conductance material. Baffle material conductance used here is defined as the product of the material conductivity, k_{cs}, and its thickness in millimeters. Figure 3 shows the relationship between GFP λ_e and baffle material conductance for stiff baffles with air, argon, and krypton. These results are for temperature conditions T_{hot}= 25°C and T_{cold}= 0°C, and cavities of 50 mm characteristic length. Both cavity surface ε were 0.04. Baffles in Figure 3 are 50 mm thick with a total of 15 cavities.

Because the calculation is one dimensional (assumes isothermal cavity surfaces), the results from solid conduction calculations are not expected to be very accurate and are presented only to show trends and the magnitude of the effect.

Baffle material emittance, or ε, is interesting because of its effect on overall performance and selection of baffle materials. Vacuum deposited aluminum coatings typically impart an ε of 0.03 to 0.05 to polymer films. Polyolefin films with significant infrared transmission can have ε of 0.25 to 0.35 on the surface opposite from an aluminum coating. Uncoated opaque surfaces typically have values of 0.90. Special coatings that transmit visible and solar radiation can be 0.10. Table II shows the calculated conductivities for different combinations of emissivities on 50 mm thick flexible baffles with 15 cavities. These results are for temperature conditions T_{hot}= 25°C and T_{cold}= 0°C, and cavities of 50 mm characteristic length. Baffle material conductivity is assumed 0.36 W/m·K and material thickness is 0.0178 mm.

COST MODEL

A cost model was developed to assess the marginal costs of varying baffle construction designs. This cost model uses the conductivity model, described above, to predict the thermal performance of the defined baffle assembly. The cost model sums the amount of gas, baffle material, and barrier material used in the design. Expected list prices for material components are inputted along with values for simple multipliers to adjust for other manufacturing expenses, such as adhesive, associated with using more or less of a material component. Factors can be applied to individual material components as well as to the overall total of material costs. Costs presented here are simply estimated cost-to-manufacture and do not necessarily correspond with expected prices for GFP insulators. These costs are meant to provide preliminary information for product design and its optimization. Analysis conducted with the model is divided into two areas. The first analysis is on the baffle component and gas fill as an independent filler material. This is interesting because it helps show the sensitivity of cost to the barrier component and is important because of the many different techniques, and associated costs, available

TABLE II: CALCULATED EFFECTIVE CONDUCTIVITIES FOR VARIOUS VALUES OF CAVITY SURFACE EMITTANCE

ε_2	ε_3	Air-GFP λ_e W/m·K	Argon-GFP λ_e W/m·K	Krypton-GFP λ_e W/m·K
0.04	0.04	0.02914	0.01982	0.01097
0.04	0.25	0.02942	0.02009	0.01125
0.04	0.35	0.02944	0.02012	0.01127
0.04	0.9	0.02949	0.02017	0.01132
0.1	0.1	0.02972	0.02040	0.01155
0.1	0.9	0.03056	0.02124	0.01239
0.25	0.25	0.03135	0.02203	0.01318
0.25	0.9	0.03316	0.02384	0.01500
0.9	0.9	0.04355	0.03423	0.02539

for the barrier component. The second analysis is for entire panels using one type of barrier envelope, a flexible, coextruded polymer barrier film.

Results from the cost model are presented as cost per unit of thermal resistance per square meter ($\$/m^2\cdot(m^2\cdot K/W)$). This value is referred to here as *specific cost* and is useful for comparing the costs of insulations with different levels of performance. This value is referred to as *filler material specific cost* for the first analysis on only the baffle and gas.

CONDUCTIVITY AND COST RESULTS

Results of the first analysis on the baffle component and gas fill are shown in Figures 4 and 5 where the relationship between λ_e and filler material specific cost is plotted. These results are for flexible baffles and do not include a barrier envelope. The baffle material, used for both the baffle layers and core/supports, is assumed to be a one-side-metalized polyolefin film, 0.0178 mm thick, priced at $\$0.086/m^2$. Gases are assumed to cost \$0.00/liter for air, \$0.002/liter for argon, and both \$0.30/liter and \$0.50/liter for krypton (the higher being current, high-purity product and the lower being an estimate for future, less-processed, product). The final total of simple material costs is increased by 20% and no factors are applied to individual material costs. The curves in Figures 4 and 5 are generated by varying the number of total cavities for the stated thickness. These results are for temperature conditions T_{hot}= 25° C and T_{cold}= 0°C, and cavity length of 50 mm. The calculation uses baffle material with assumed conductivity, k_{cs} = 0.36 W/m·K, thickness of 0.0178 mm, and surface ε of 0.04 and 0.25.

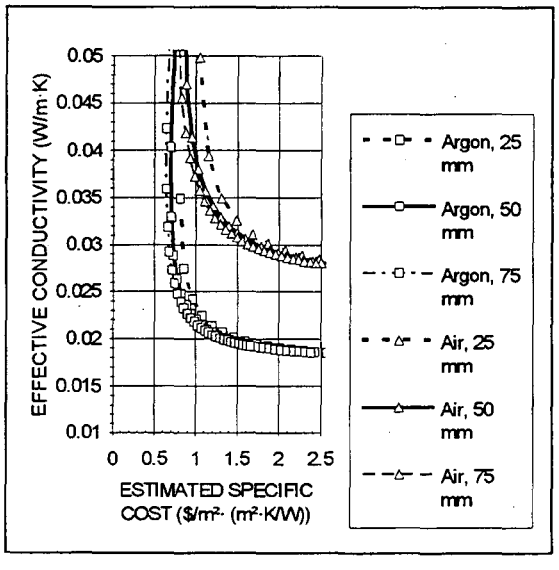

Figure 4: Air-Baffle and Argon-Baffle λ_e versus estimated Filler Material Specific Cost for flexible Baffles of 25, 50, and 75 mm total thickness

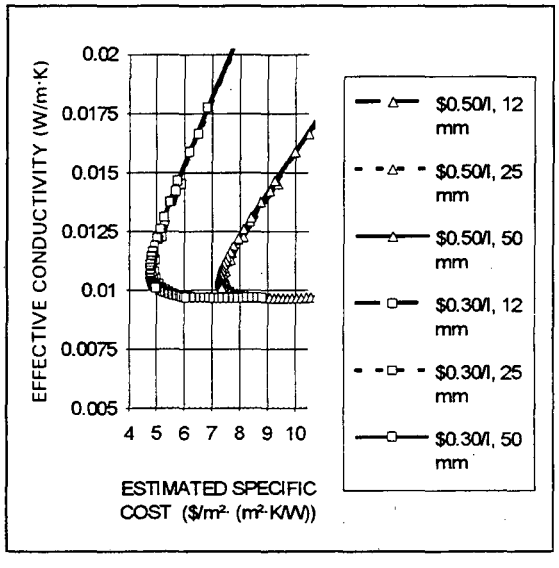

Figure 5: Krypton-baffle λ_e versus estimated Filler Material Specific Cost for flexible Baffles of 12, 25, and 50 mm total thickness and krypton at \$0.50/liter and \$0.30/liter

The results of the second analysis on entire GFPs are shown in Figures 6 and 7 where the relationships between effective conductivity and specific cost are plotted. These results are for barrier wrapped flexible panels having an area of 305 mm by 305 mm and the stated thickness. Baffle material and gas fill cost assumptions are as in the first analysis above. The barrier film for argon and krypton GFPs is assumed to be a multi-layer thermoplastic film, 0.1 mm thick, priced at $1.07/m^2. The barrier film for air GFPs is assumed to be a monolayer thermoplastic film, 0.1 mm thick, priced at $0.32/m^2. In addition to the simple overall 20% increase in final cost, as above, this second analysis uses additional factors that increase the estimated cost prior to the final total of material costs; baffle film is multiplied by 1.1, barrier film by 1.2, and an extra $0.005/liter is added to all gas types. These added factors are intended to account for marginal manufacturing costs. The curves in Figures 6 and 7 were generated by varying the number of cavities. These results are for temperature conditions T_{hot}= 25°C and T_{cold}= 0°C, and cavity length of 50 mm. The calculation uses baffle material with assumed conductivity, k_{cs} = 0.36 W/m·K, thickness of 0.0178 mm, and surface ε of 0.04 and 0.25.

Results shown in Figures 6 and 7 indicate that an interesting optimization can be performed on the number of cavities that will minimize specific cost. Table III lists λ_e and total cost for these optimized GFPs. Note that this optimization applies only to the cost analysis presented here; changes in component costs will alter the optimum number of cavities.

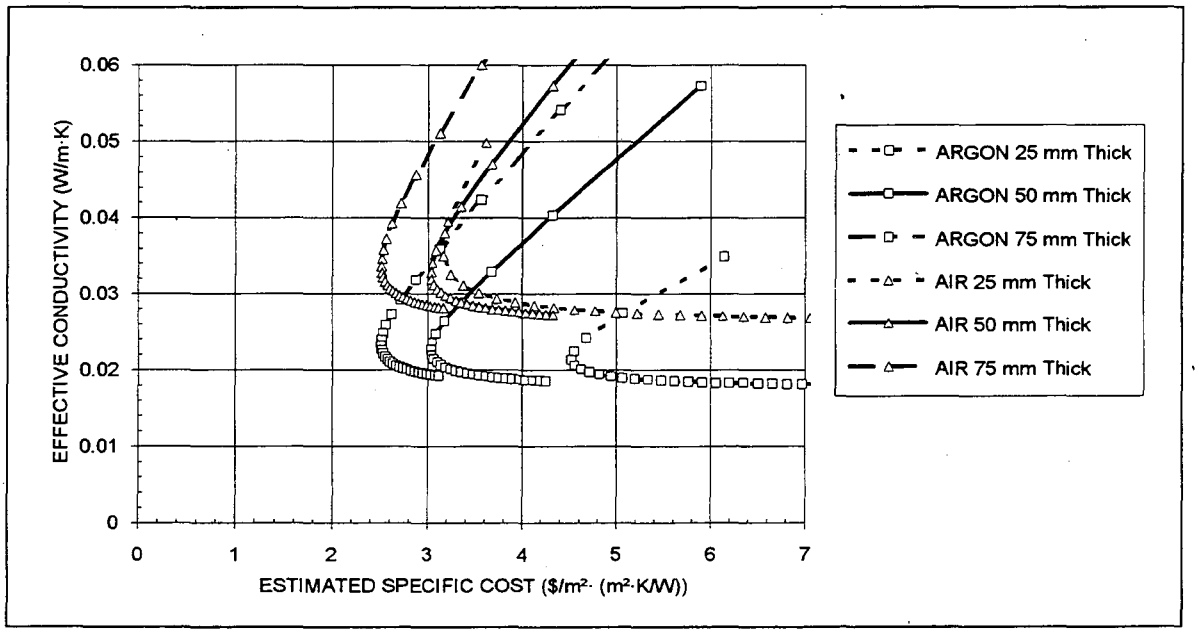

Figure 6: Air-GFP and Argon-GFP λ_e versus estimated specific cost for flexible GFPs of 25, 50, and 75 mm total thickness

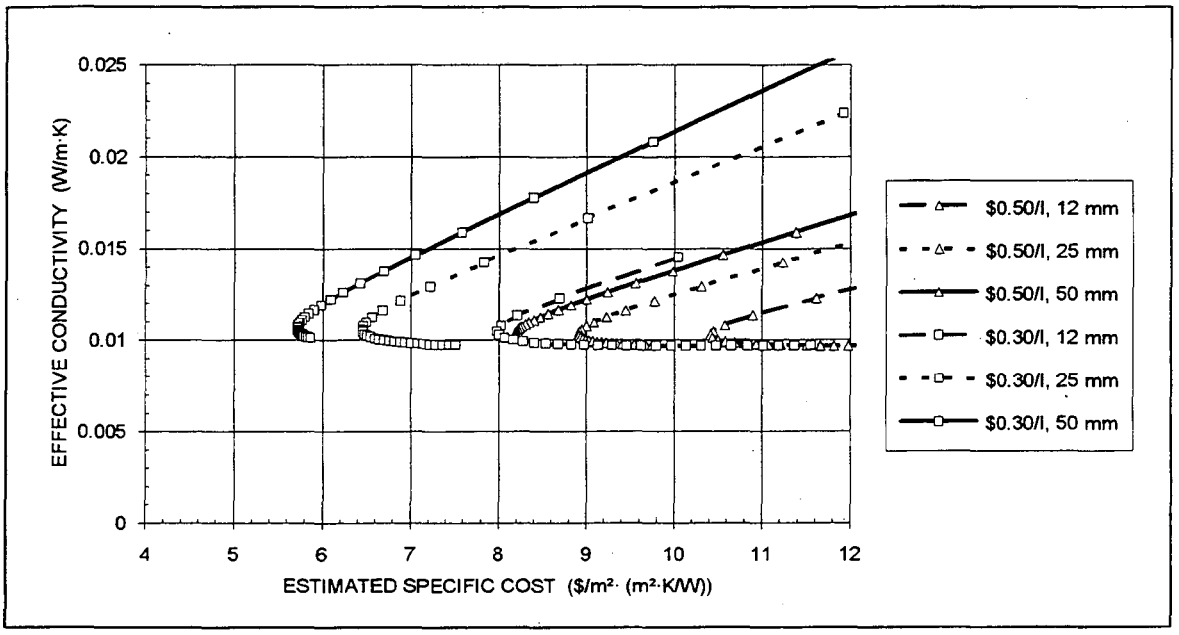

Figure 7: Krypton-GFP λ_e versus estimated specific cost for flexible GFPs of 12, 25, and 50 mm thickness for krypton at $0.50/liter and $0.30/liter

TABLE III: OPTIMUM NUMBER OF CAVITIES, λ_E, AND COST FOR MINIMUM SPECIFIC COST, PRESENT ANALYSIS ONLY

		Air	Argon	Krypton @ $0.30/l	Krypton @ $0.50/l
25 mm thick	Optimum cavities	4	6	12	13
	λ_e (W/m·K)	0.0350	0.0213	0.01057	0.01033
	Cost ($/m^2)	2.26	5.30	15.22	21.54
50 mm thick	Optimum cavities	6	9	20	24
	λ_e (W/m·K)	0.0380	0.0226	0.01064	0.01037
	Cost ($/m^2)	3.02	6.70	26.81	39.46

SUMMARY

A spreadsheet based model was developed which predicts the effective conductivity and sums the material component costs of insulating devices based on Gas-Filled Panel technology. This model calculates heat flux across a single cavity in the middle of the baffle using standard methods for radiation and conduction. Convective heat flux is calculated using a non-standard method because conventional correlations for enclosed fluid cavities failed to resolve convective effects in a GFP baffle. Experimental measurements of prototype GFP conductivities have been made and are compared to the results from the calculations. Cost estimates are based on the quantity and price of the material components in combination with simple multipliers to account for added manufacturing costs.

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