Methods to Enhance the Insulating Values of Closed-Cell Foam

L.R. Glicksman

ABSTRACT

Enhancement of the thermal behavior of foam insulation is required due to the need to limit or eliminate the blowing agents, which can be hazardous to the environment. Most replacement blowing agents have higher thermal conductivities than the current blowing agents. Several alternate techniques to improve the insulation characteristics of the foam are currently under investigation at our university. These techniques include the use of fine-cell foams to increase the surface area of struts and thus increase the infrared extinction coefficients of the foam. The use of opaque flakes to decrease the transmissivity of cell walls is also under examination. A third technique to improve the foam's insulating characteristics is the inclusion of small vacuum elements within the foam. These elements are filled with powder and enclosed in a very low-porosity, low-conductivity film.

INTRODUCTION

Closed-cell foam insulation blown with a refrigerant vapor has the lowest effective thermal conductivity, or the highest R per unit thickness, of any non-vacuum insulation currently available. With the advent of higher energy standards for buildings and appliances there is a need to improve the R-value even further.

Recently there has been concern that the CFCs used to blow the foams cause depletion of the ozone layer. Under international agreements the use of current day CFCs must be phased out. Recent measurements of ozone depletion in the northern hemisphere may accelerate the rate of CFC phase-outs. If replacement CFCs must be used, they by-and-large have a higher conductivity than the current CFCs. Thus, means must be developed to decrease other forms of heat transfer in foams just to retain present levels of R-values with the new CFCs.

There has been a research program on rigid foam insulation at the author's university for the past six years. The research has concentrated on developing fundamental models to understand and predict the effective thermal conductivity and aging of closed-cell foam insulation. Research recently under way focuses on identification and development of new techniques which will allow foams containing environmentally acceptable blowing agents to have effective conductivities equal to or less than present foams.

The present paper will review the fundamental models for the effective conductivity of foam insulation. These models will be used to predict the thermal degradation caused by alternate blowing agents. The models will also be used to identify and evaluate the benefits of techniques which have been proposed to improve the foam properties.

L.R. Glicksman is Professor of Thermal Science and Building Technology, Department of Architecture and Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

HEAT TRANSFER MECHANISMS

Heat transfer through the foam is due to three mechanisms, conduction along the struts and cell walls of the solid polymer, conduction through the gas within the cell, and thermal radiation. The total heat transfer can be predicted as the sum of the heat transfer by the three mechanisms considered separately.

The solid polymer in the foam forms a regular cellular structure. For polyurethane foam roughly 15% to 20% of the polymer is in thin walls separating the cells. The balance of the polymer is in struts, thick rod-like elements formed at the intersection of three cell walls.

For a foam which has both cells and struts, the overall contribution to the effective conductivity due to solid conduction is,

$$k_{cs} = (2/3 - f_s/3)\ (1-\delta)\ k_p \qquad (1)$$

where k_p is the conductivity of the solid polymer, f_s is the fraction of polymer in the form of struts, and $1-\delta$ is the volume fraction of polymer in the foam. For uniform isotropic foam, Equation 1 is accurate to ± 7%.

The conductivity of the solid polymers, k_p, has been recently measured; values of k_p in W/m°C (BTU/hrft°F) are: polyurethane: 0.262 (0.152); phenolic: 0.274 (0.158); polystyrene: 0.202 (0.117); and polyisocyanurate: 0.258 (0.149) Sinofsky 1984. The foam was compressed (roughly 30,000 psi) to form a solid block of polymer. The thermal conductivity was measured using a transient technique with a heat wire within the foam.

Heat is transferred across the cell by conduction through the gas within the cell as well as by thermal radiation. The cell interior comprises 95% or more of the total foam volume. It can be shown that conduction in the solid and gas are additive. The conduction through the gas is dependent on the local gas composition. The thermal conductivity of CFC-11 vapor is roughly one-third that of air. When the foam is exposed to air, the air will diffuse into the foam through the cell walls, increasing the gas conductivity and the effective foam conductivity. For unprotected polyurethane foam 5 cm thick this process may occur over several years. Over still longer periods, typically several decades or more, the refrigerant vapor will diffuse out of the foam, the gas concentration within the cells will have a higher percentage of air, and the overall conductivity will rise.

Measurements of foam transmissivity indicate that the mean distance between radiation emission and absorption in the foam is of the order of 1 mm or less. Since the mean distance is much less than the thickness of a foam board, the radiation heat transfer can be treated as a diffusion process. That is, the heat transfer is proportional to the local gradient of the absolute temperature to the fourth power and inversely proportional to the absorptive property of the foam, the extinction coefficient (Glicksman etal, 1987). Recent results have shown that the extinction coefficient for conventional rigid foams can be predicted by a simple model of the foam.

In the infrared wavelengths, transmission measurements have revealed that cell walls are about 90% transparent to infrared radiation. In the model, the cell walls are assumed to be transparent. Measurements of much thicker films, of the order of the strut thickness, have shown that these elements are essentially opaque. Thus the struts serve as the main barrier to thermal radiation through the foam.

The extinction coefficient is proportional to the total surface area of the strut per unit volume of the foam. Taking the cells as pentagonal dodecahedrons, and the struts as inscribed within equilateral triangles, the strut surface area can be shown to be proportional to the square root of the foam density and inversely proportional to the cell diameter (Glicksman and Torpey, 1987). The resulting expression for the extinction coefficient becomes:

$$K = 3.68 \frac{\sqrt{\rho_{foam}/\rho_{poly}}}{d} \tag{2}$$

where d is the cell diameter, ρ_{foam} if the foam density, and ρ_{poly} is the polymer density. Combining this with the equation for thermal radiation for the diffusion limit yields the following expression for the contribution to the effective foam conductivity due to radiation:

$$k_r = \frac{16\ \sigma\ T^3 d}{3\ (3.68)\ \sqrt{\rho_{foam}/\rho_{poly}}} \tag{3}$$

d is the average cell diameter, ρ_{foam} is the foam density, and ρ_{poly} is the density of the solid polymer. As the cell diameter is decreased at a fixed foam density, the number of struts, which inhibit the radiation, is increased. Similarly, as the foam density is increased, the thickness and surface area of the strut is increased, thus decreasing radiation heat transfer.

Samples of isocyanurate and polyurethane foams were obtained from several different sources. The extinction coefficient, given by Equation 2, was compared to values obtained from transmission measurements of the foams. The predicted and measured values are quite close, as shown in Figure 1. Recently, Cunningham and Sparrow measured the contribution of radiation heat transfer for foams with different cell size but approximately constant density. The radiation contribution was obtained by subtracting predicted solid conductivity contributions from the measured effective conductivity. Figure 2 shows a comparison of their experimental results vs. the prediction given by Equation 3. There is still a need to confirm these results for the smallest cell sizes, of the order of 0.1mm, where the experimental determination of k_r has the highest uncertainty.

Combining the effect of radiation through the foam with conduction through the gas and conduction through the polymer yields,

$$k_{eff} = \delta k_g + (2/3 - fs/3)(1 - \delta)\ k_p + \frac{16\ \sigma\ T^3 d}{3\ (3.68)\ \sqrt{\rho_f/\rho_p}} \tag{4}$$

For a polyurethane or polyisocyanurate foam with a density of 32 Kg/m^3 (2 lb/ft^3), and a mean cell diameter of 0.5 mm, freshly made, i.e., cells filled with pure CFC-11 and no broken cells, the effective thermal conductivity is .0176 W/m∘K at room temperature, 20°C; this corresponds to a thermal resistance, the inverse of the conductivity of 8.2 $(BTU\text{-}in/hrft^{2\circ}F)^{-1}$. Of the total conductivity, 50% is due to conduction through the vapor, 16% is conduction through the solid polymer in the foam of struts and cell walls, and 34% is due to radiation heat transfer through the foam.

INFLUENCE OF REPLACEMENT BLOWING AGENTS ON THE FOAM THERMAL CONDUCTIVITY

The theoretical models of the effective thermal conductivity can be used to predict how much the effective conductivity will increase when replacement blowing agents are used. The models will also be useful in identifying possible measures to restore the conductivity to its original level. Table 1 compares the conductivity of a fresh foam filled with CFC-11 to fresh foam filled with HCFC-123 and HCFC-141b, two possible alternate blowing agents with the same cell size, foam density, and percentage of polymer in the struts. The alternate blowing agents when available will cause about an 11% increase in the thermal conductivity if all of the other foam properties can be maintained constant. Shorter term solutions, which may involve partial or total substitution of CO_2 for CFC-11 can cause much larger changes. In addition, the aging phenomenon, the increase of thermal conductivity due to air diffusion into the foam, occurs more rapidly since there is less CFC-11 available to mix with the incoming increasing air. Small amounts of air diffusion cause the fraction of air to be increased when there is less CFC-11 present. Total substitution of CFC-11 with CO_2 causes the effective foam conductivity to rise by 44%.

TABLE 1

Effects of Various Blowing Agents on the Thermal Conductivity of Closed Cell Polyurethanes or Polyisocyanurate Foams

CELL GAS	FOAM EFFECTIVE CONDUCTIVITY W/m°C (BTU/hrft°F)
CFC-11	.0180 (.0104)*
HCFC-123	.0200 (.0116)**
HCFC-141b	.0197 (.0114)**
Air (100%)	.0364 (.021)
CO_2 (100%)	.0266 (.0154)
Air/CFC-11 (50/50) (mass fraction)	.0317 (.0183)
CO_2/CFC-11 (33/66)	.0227 (.0131)
CO_2/CFC-11 (50/50)	.0241 (.0139)

*Base line, assumed
**Based on measured vapor thermal conductivity (Shankin, I., Allied, 1988).

FOAM ENHANCEMENT: CELL SIZE REDUCTION

There are several modifications to the foam which will counteract the increased conductivity caused by the substitution of CO_2 for CFC-11. These modifications are directed at reducing the radiation heat transfer. When the average cell size is reduced while maintaining the density constant, the total length and surface area of the struts are increased. It has been found that the radiation component varies directly with the average cell diameter so halving the cell size should halve the radiation.

Since the foam density has an influence on both the radiation heat transfer and the solid conductivity, it is useful to look at the effect of foam density and cell size at the same time. Figure 3 shows the effective conductivity of a foam filled with pure CFC-11 for two different cell diameters and a range of foam densities. These results were obtained from Equation 4. For a fixed cell diameter the conductivity initially decreases as the density is increased due to the reduction in the radiation heat transfer. As the density is increased further, the conductivity begins to rise due to the increased heat transfer by conduction through the solid. The same behavior holds for smaller cell sizes, although the level of the effective conductivity is lower due to the lower radiation and the minimum point occurs at smaller densities.

Figure 4 shows similar results for a foam filled with pure CO_2. The magnitude of the effective conductivity is higher than that for CFC-11-filled foam but the advantages of using small cell sizes and modest densities remain. If the cell size of the 100% CO2-filled foam can be reduced to 0.1 mm (and the simple radiation model is still valid; this has yet to be experimentally substantiated) the R-value of the foam is predicted to be more than 7 (BTU-in/ft^2°F). This corresponds to an effective conductivity of 0.020 W/m°C, about the same as a HCFC-123-filled foam.

There are several important practical barriers to this solution: making fine-cell foam is difficult, especially for applications such as refrigerators. Additionally, an effective barrier must be designed to prevent CO_2 from diffusing out of the foam and to prevent air from diffusing into the foam. In a typical unprotected foam, CO_2 will diffuse out in a matter of days. Most, if not all, present foam products made as boards have inadequate adhesion between the facing material and the foam so that even if the facing is impermeable, air and CO_2 can easily move in a lateral direction under the interface from the edge to the center of the board. Figure 5 shows the predicted rate of conductivity increase for a board 122 cm (4 ft) wide initially filled with CO_2. The time for the conductivity change has increased substantially over an unforced foam because the time varies with the square of the characteristic thickness. In this simulation it is assumed that facing is impermeable and there isn't any lateral diffusion under the interface. Certainly in appliances, where it is possible to provide tight interfaces, a pure CO_2 filled foam with small cell sizes provides good performance if such a foam can be made to fully fill the wall cavity.

A second technique to reduce radiation heat transfer is to include opaque flakes in the polymer cell walls, making them less transparent. Figure 6 shows the increase in the radiative extinction coefficient as graphite and aluminum flakes are added to the foam. The extinction coefficient is calculated from transmissive measurements made over the infrared wavelengths where appreciable thermal radiation is emitted at room temperature. The radiation heat transfer, which varies inversely with the extinction coefficient, can be reduced by 15% to 20% by the use of the flakes. However, part of this improvement is offset by the increased solid conductivity of the polymer containing the metal flakes. This is shown in Figure 7, the effective conductivity of the foam decreases as flakes are added; a large amount of flakes causes the effective conductivity to increase. Present research has begun to find flakes which will minimize the increase in the solid conductivity.

The effective conductivity of foam-filled walls can be increased by using foams in conjunction with vacuum insulations. Flat evacuated panels containing fine particles encapsulated within flexible envelopes have demonstrated insulation levels three times higher than fresh CFC-11-filled foams of the same thickness. There are several issues to be addressed before these panels are commercially feasible. First, the flexible envelope must be impermeable enough to maintain the desired vacuum over the lifetime of the insulation. Evacuated panels commercially introduced into a line of Japanese refrigerators several years ago have been discontinued, presumably because of this problem. The envelopes cannot be made of heavy metal foil, which is a good gas barrier, because heat transfer around the circumference of the package will cause substantial thermal "short-circuiting" of the vacuum and severely increase the effective conductivity. If the panel is directly attached to a steel wall of an appliance, the steel wall acts as a short-circuiting element; this effect can be reduced by the use of a layer of foam insulation between the vacuum panel and the steel wall.

If suitable vacuum panel materials are found, a large-scale manufacturing process for the vacuum assembly is needed as well as means to protect the panel from punctures or other damage which will cause the envelope to leak.

Another vacuum insulation design has been proposed uses parallel metal panels separated by glass beads to create a hard vacuum. Radiation heat transfer is minimized by the use of high reflectivity coatings on the inside surface of the panels. Because the panel walls must be rigid they must be thicker. This can result in substantial heat transfer around the circumference of the panel, severely limiting the lower limit of the effective conductivity. For example, calculations were made by the author, assuming a panel with stainless steel walls of 0.2 mm (.008 in) thick, a 61 cm (24 in) panel width, 3.2 cm (1/8 in) panel thickness. Assuming only one-dimensional heat transfer through the panel gave a calculated resistance value of 45 (Btu/hr ft^2 $^oF)^{-1}$. However, when a more complete analysis is done, including the circumferential heat transfer along the steel walls of the panels, the overall resistance drops to 15 (Btu hr ft^2 $^oF)^{-1}$.

CONCLUSIONS

The use of environmentally safe blowing agents for closed-cell foam insulation result in a substantial increase in the effective conductivity of the foam and will cause increased energy consumption in appliances and buildings.

There are several techniques that could be used to recover all or some of the lost performance. Reducing the cell size of foams reduces the radiation heat transfer without influencing solid or gas conduction. The extent of this effect for very small sizes must be determined and means to form small cell sizes must be developed for commercial applications.

The inclusion of opaque flakes in the foams also reduces the radiation heat transfer; however, excessive amounts of flakes can cause the solid conductivity of the struts and cell walls to increase, negating some of the gains.

The use of vacuum insulation in combination with foams holds out the brightest hope for long-term improvement in insulating characteristics. An envelope material must be developed which will maintain an acceptable vacuum for the lifetime of the insulation while minimizing circumferential heat transfer.

Although there are several possible avenues to produce low conductivity in foams that use environmentally acceptable blowing agents, considerable research is required before these techniques can be useful in commercial products. The fact that such improvements are possible should serve as a stimulus to research and development.

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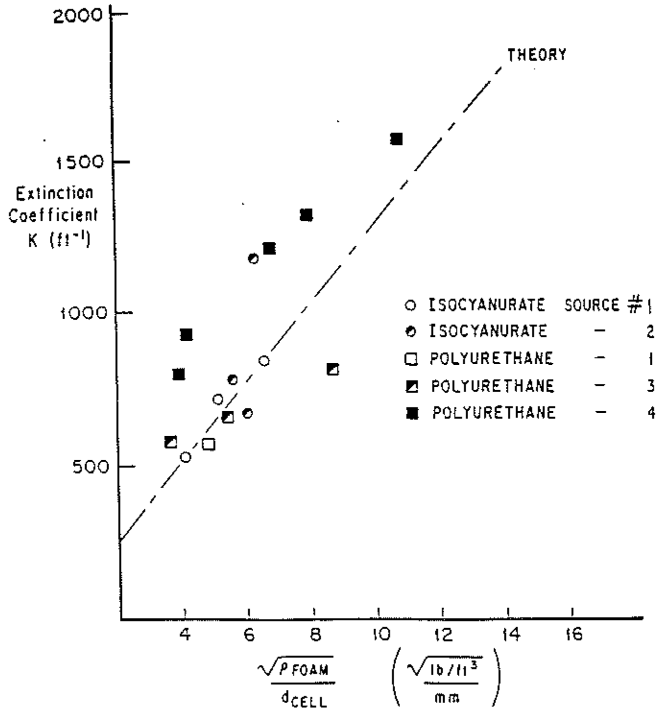

Figure 1. *Extinction coefficient of foam, the influence of foam density and cell diameter; measured extinction coefficients and theory based on opaque struts*

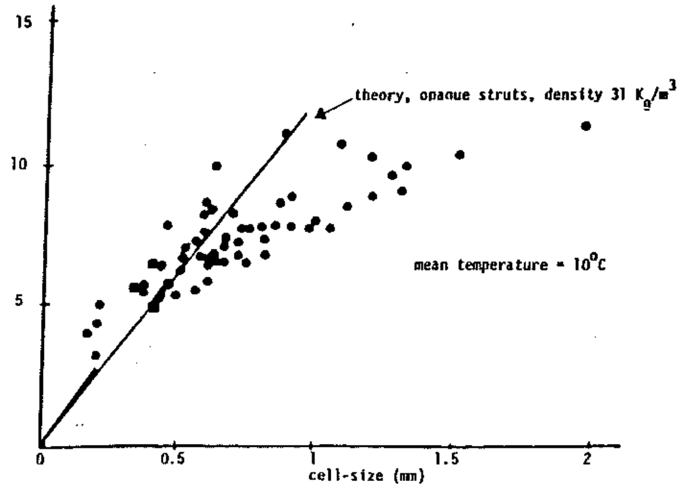

Figure 2. *Dependence of radiative heat transfer on cell size (Cunningham and Sparrow, Cellular Polymers 5, 1986)*

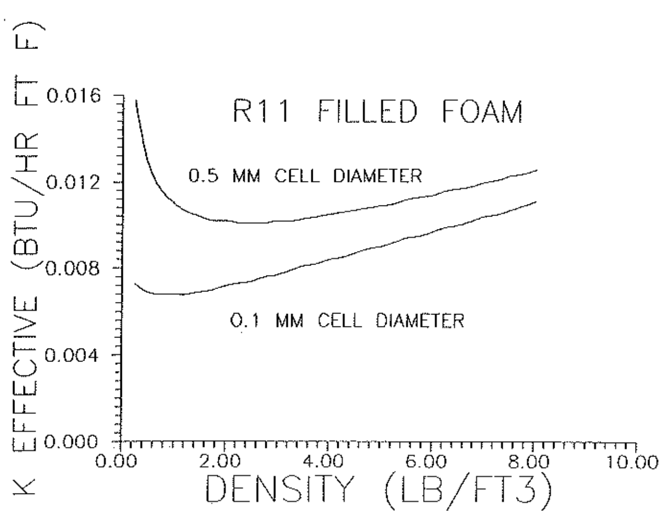

Figure 3. *Predicted dependence of R-11-filled foam on cell size and foam density*

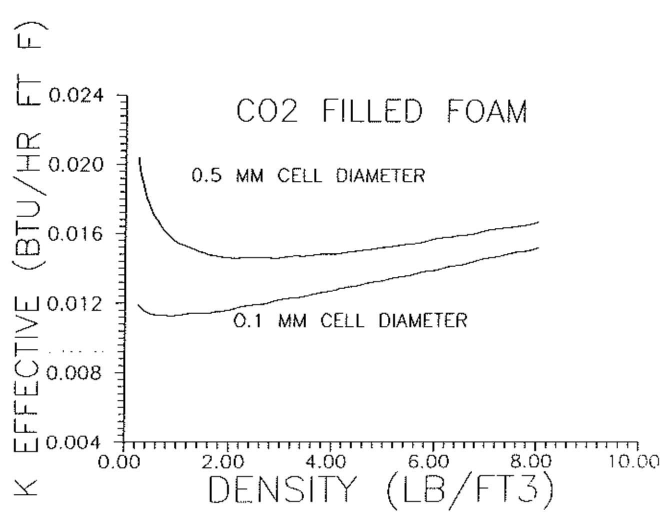

Figure 4. *Predicted dependence of CO_2-filled foam on cell size and foam density*

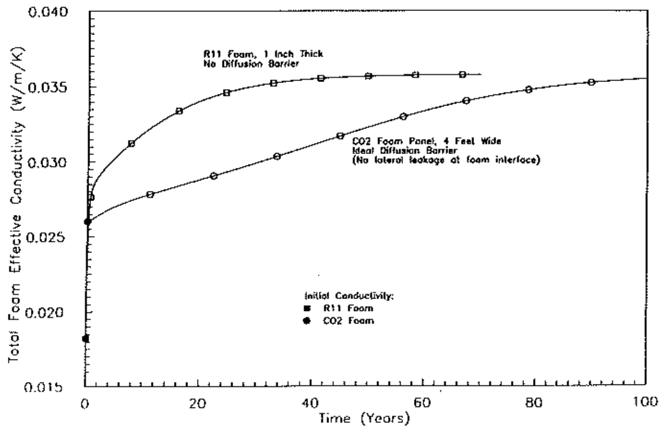

Figure 5. Effective conductivity of CO_2-filled foam with time, panel 4 ft. wide, assuming zero gas diffusion through faces and zero leakage laterally under the faces

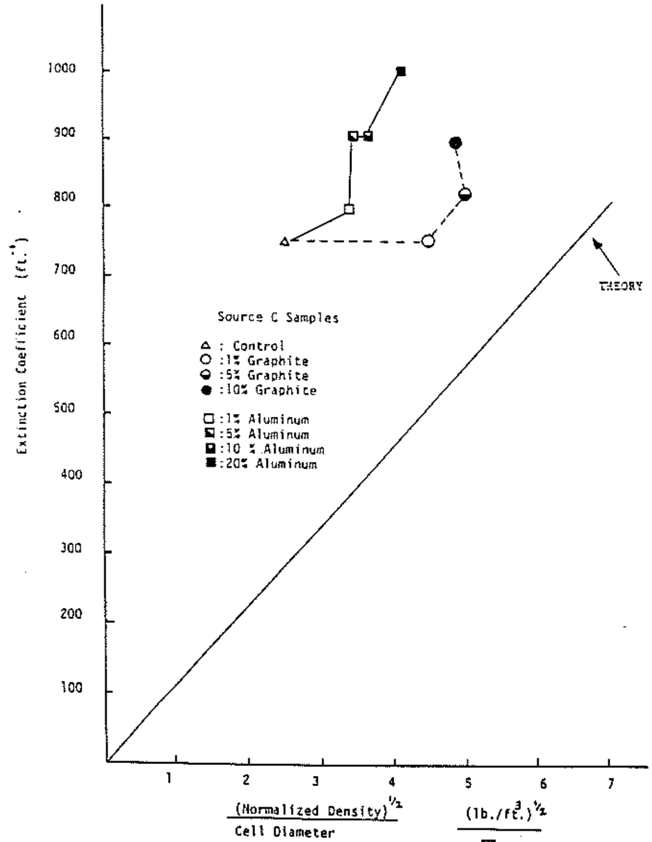

Figure 6. Measured extinction coefficients of foams filled with graphite or aluminum flakes; theory: equation 3 with no fillers

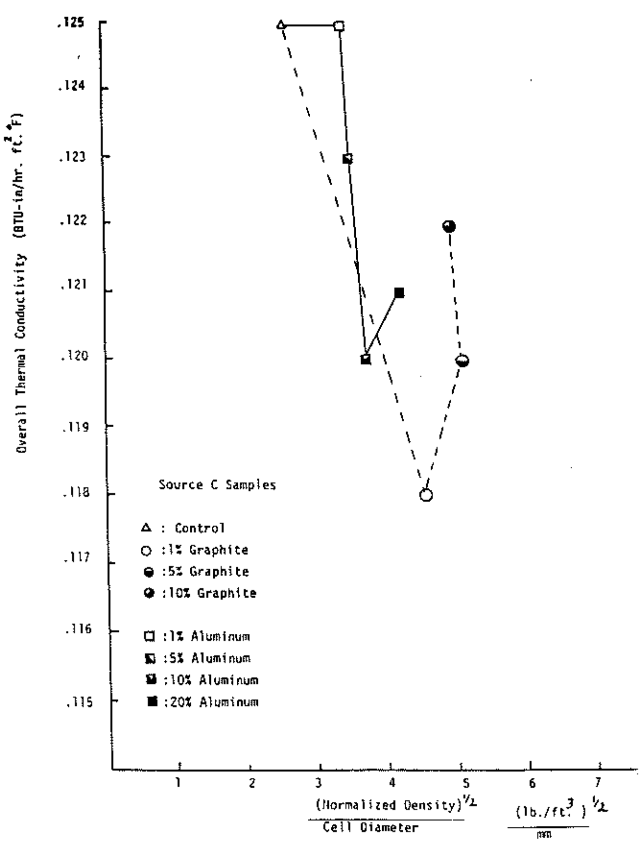

Figure 7. Measured effective thermal conductivity of foam filled with graphite or aluminum flakes