Factors Governing Heat Transfer through Closed Cell Foam Insulation*

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ABSTRACT: The factors governing the heat transfer through foam insulation are reviewed and a predictive model is presented. Heat transfer takes place by conduction through gas within the foam cell, by conduction through the solid polymer and by thermal radiation. The gas conductivity is a function of the local gas composition. A given volume of polymer in a cell wall transmits twice the heat as the same volume in a strut. Radiation can be accurately predicted by assuming the cell walls are transparent and the struts are opaque. The radiation heat transfer is proportional to the square root of the foam density and inversely proportional to the cell diameter to the first power. Addition of metal flakes to the polymer shows promise in reducing the transparency of the cell walls.

KEY WORDS: foam, heat transfer, conductivity, radiation.

INTRODUCTION

CLOSED CELL FOAM insulation blown with a refrigerant gas has the highest R value per given 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 R values even further.

Recently there has been concern that the CFCs used to blow foams may cause depletion of the ozone layer. If replacement CFCs must be used, they

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by-and-large have a higher conductivity than the current CFCs being used. 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 blowing agents.

There has been a program of research on rigid foam insulation at MIT for the past six years. This work has been supported by the Society of Plastics Industries, the Office of Buildings Energy Research and Development through Oak Ridge National Laboratory, Koppers Inc., Dow Chemical, Mobay Chemical and with the active cooperation and support from Jim-Walters Research Corp., and Owens-Corning Fiberglas.

The research at MIT has concentrated on developing fundamental models to understand and predict the aging effect and the R values of foam insulation. The present paper and the companion paper in this issue will review the models developed and present some of the recent results of this investigation. This paper will deal with the fundamental forms of the heat transfer which contribute to the overall k value of the foam.

Earlier work in the literature presented simple models of conduction, convection and radiation in foam. It is generally agreed that the cells are so small and the resulting temperature differences across each cell are so small that natural convection is negligible in the cell. Previous references have dealt with the conduction through the solid polymer making up the cell wall by using a simplified geometry; for example, several references assumed the cells form cubes which are in-line, Russell [1] and Doherty et al. [2]. Photographs of foams reveal that the cell geometry is much more complex than this. In addition, the solid polymer appears in both the cell wall and in the struts which form at the intersection of the cell walls.

Some references in the literature have also dealt with radiation heat transfer in and through the cell walls. In some cases, the cell walls were assumed to be opaque; the resulting radiation heat transfer was then calculated to be negligible, Skochdople [3] and Doherty et al. [2]. Other cases empirical results were derived for the radiation heat transfer. For example, Cunningham [4] has shown that radiation heat transfer decreases as the cell size is reduced but it was not clear what other parameters directly influenced the radiation and generalization of the results was difficult. Finally, a reasonable number of studies have reported on the overall effective k or R value as a function of the forming and aging conditions of the foam. Again, it has been very difficult to generalize these results and sort out the importance of the competing parameters.

In this paper the emphasis will be on fundamental models for each component of the heat transfer in generic closed cell foam. These heat transfer mechanisms include conduction through the solid polymer in the cell walls and the struts, conduction through the gas within the cell and radiation

within the foam. The paper will draw on the results of previous papers and thesis which deal with a particular part of the process in more detail.

Equally important as the model is the availability of accurate values of the thermophysical properties to be used with the model. Considerable effort has been expended in this program to measure those properties which were not confidently known. Thus, the models could be checked with the heat transfer measurements in the foam without the need to fit the constants.

CONDUCTION IN THE SOLID POLYMER

Photographs of foam, both with the use of optical microscopes and scanning electron microscopes reveal a rather complex foam structure. Figure 1 shows a two-dimensional SEM photograph obtained by Reitz et al. [5] by filling the cells with a resin which hardened and allowed thin sections to be obtained. Thin cell walls meet to form struts, the latter being probably the reservoir of material from which the cell walls are formed as the foam is blown. The cells in three dimensions are approximately in the form of pentagonal dodecahedrons. Reitz has found after studying several different foams that the majority of polymer material resides in the struts. Typically, 80 to 85 percent of the polymer is in the struts with the balance in the cell wall, see Table 1. Considering the collection of cell walls and struts, it is generally true that in a foam, unless a preferred rise causes the cell axis to be larger than the axes normal to the rise direction, the orientation of a given cell wall is in a random direction.

Considering the conduction in the cell walls first, given the complex geometry it is beyond reasonable efforts to develop an exact model to deal with the cell wall geometry. Rather than that, an upper and lower limit model has been developed to bracket the exact result. It will be seen that the difference between the upper and lower model is small enough to allow the conduction for the exact case to be predicted with good accuracy.

The upper limit model assumes that conductivity in the polymer in the directions normal to the temperature gradient are very large. Thus, the heat being transferred through the polymer can be distributed as it moves from one row of cells to the next to maximize the conduction heat transfer. The upper limit model was found to give the same results if the cell walls are assumed to be in-line, staggered, or in a random orientation [see Figures 2(a) and 2(b)].

The lower limit model assumes that the conductivity of the polymer is the same in the directions normal and parallel to the direction of heat flow. Further, the lower limit model assumes that the heat flow in the gas is always parallel to the temperature gradient; that is, heat flow from a cell parallel to

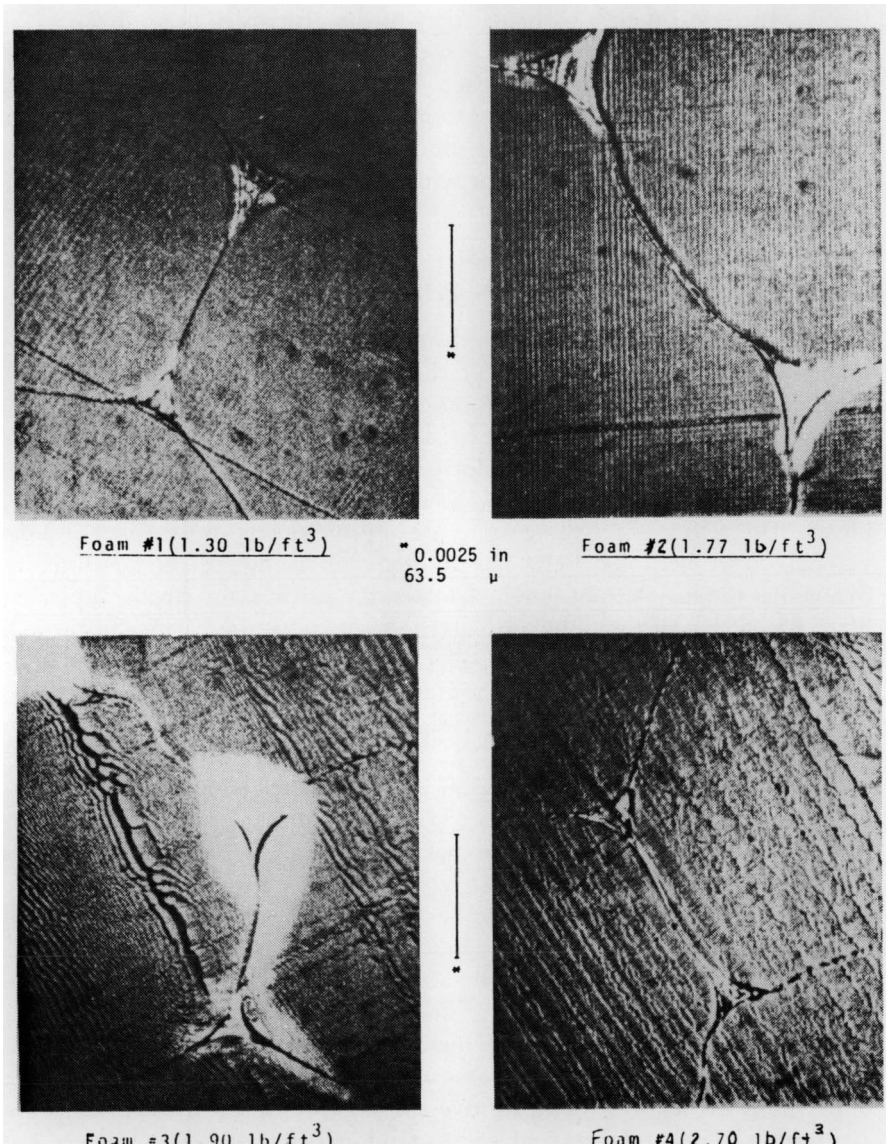

FIGURE 1.

Table 1. Comparison of five foam geometries.

Foam	Density (lb/ft³)	Approx. Cell Size (mm)	Average Wall Thickness (μ)	Average Strut Area (μ²)	Average % Wall/% Strut	Average % Wall/% Strut (50% Swell)
1 Unfaced Polyurethane Foam from Free Rise Bun (TDI)	1.30	0.51	0.30–0.37 (0.25–0.42)[a]	413 (344–561)[a]	17–20/80–83	11–13/87–89
2 Unfaced Polyurethane Foam from Partially Free Rise Bun (MDI)	1.77	0.51	0.35–0.57 (0.46–0.63)	525 (495–713)	20–21/79–80	13–14/86–87
3 Sprayed Polyurethane with Foil Facings (MDI)	1.90	0.43	0.70–0.78 (0.68–0.93)	423 (267–675)	28–31/69–72	19–21/79–81
4 Semi-Continuous Pour Polyurethane Foam with Metal Facings (MDI)	2.70	0.38	0.45–1.1	295 (234–381)	13–32/68–87	9–21/79–91
5 Sprayed Polyurethane Foam with Steel/Rubber Facings (MDI)	3.0	0.25	0.31–0.34 (0.25–0.42)	175 (102–242)	12–14/86–88	8–9/91–92

[a]Range of values.

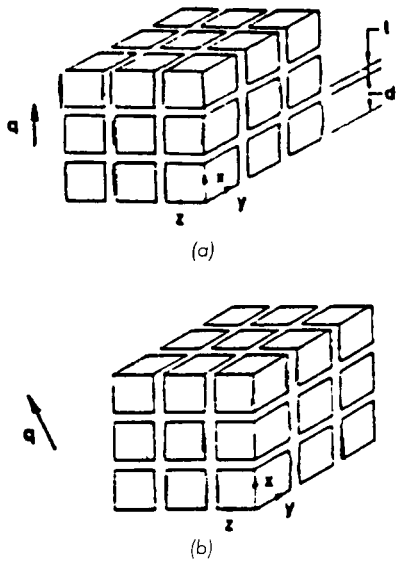

FIGURE 2. (a) In-line cubes with 100% membranes. (b) In-line cubes with 100% membranes. Cell orientation oblique to the heat flow direction.

the temperature gradient to a cell normal to the temperature gradient can not use the gas as a shortcut near the intersection of the two cells. For the most extreme case of staggered cubic cells, which gives the lowest conduction heat transfer, the lower limits predict a conduction through the solid which is only 15 percent lower than the upper limit model. Given that solid conduction is typically 25 percent of the total heat transfer through the foam, the difference between the upper and lower limits is negligible. Using the upper limit, the conduction heat transfer through the cell walls can be written as,

$$K_c = (2/3)(1 - \delta)K_p \tag{1}$$

where K_p is the conductivity of the solid polymer and δ is the volume fraction of cells in the foam. The factor 2/3 can be understood for the in-line cubic array where four out of the six cell walls transfer heat when the cube is parallel to the temperature gradient. Equation (1) is written when all the polymer is in the form of cell walls.

A similar analysis can be applied to the struts. The struts can be considered to form a series of in-line cubes, staggered cubes, or cubes whose sides are not parallel to the heat flow direction. Finally, the struts can be assumed to be aligned in random directions. In all of these cases the upper limit model

gives the same value for the thermal conductivity along the solid struts,

$$K_s = (1/3)(1 - \delta)K_p \tag{2}$$

The equation is similar to that for the cell walls but the coefficient has been reduced to 1/3. Only four of twelve struts in a cube take part in the conduction when the cube is aligned parallel to the temperature gradient.

For a foam which has both cells and struts, Equations (1) and (2) can be combined to give the overall solid conduction,

$$K_{cs} = (2/3 - f_s/3)(1 - \delta)K_p \tag{3}$$

where f_s is the fraction of polymer in the form of struts.

Equation (3) requires the value of the solid conductivity of the polymer. A review of the literature revealed a serious disagreement of the value of the thermal conductivity. To remedy this Sinofsky [6] measured the thermal conductivity of polymer in rigid foams. He crushed the foams around a thin wire. The transient temperature response of the wire for a given power input was used to determine the thermal conductivity of the compressed polymer. The applied pressure on the foam was increased until the results were independent of the pressure and all of the voids between the polymers were removed. The results of his measurements are summarized in Table 2. A large number of samples from different suppliers were tested. The variation in the value of the conductivity was found to be modest.

CONDUCTION IN GAS

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 percent or more of the toal foam volume. It can be shown by comparing the upper and lower cases for conduction in the solid that conduction in the solid and gas are additive.

Table 2. Measured conductivity of solids formed from compressed foams.

	Number of Formulations	Average Value of K_s Btu/h·ft²(F/in.)	Standard Deviation of K_s Measurement
Polyurethane	24	1.82	5.2%
Phenolic	3	1.90	5%
Polystyrene	3	1.40	7.7%
Poly-isocyanurate	5	1.79	10.4%

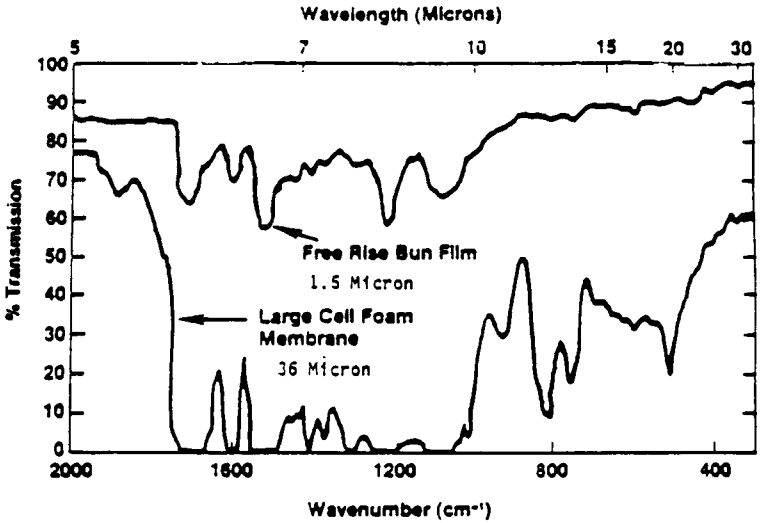

FIGURE 3. Transmission of radiation through a single polyurethane cell wall.

The conduction through the gas is dependent on the local gas composition. It has been shown that the Wassiljewa equation combined with the Lindsey-Bromley correlation, Reid [7] and Peters et al. [8], predicts the conductivity of a gas mixture to within 5 percent when the concentration of the constituents are known. The companion paper to this one deals with the prediction of the gas composition as the foam ages: as air diffuses into the foam and mixes with the blowing gas. Combining the solid and gas conduction yields the following form for the total conduction,

$$K_{cs} + K_{gas} = (2/3 - f_s/3)(1 - \delta)K_p + \delta K_g \qquad (4)$$

RADIATION HEAT TRANSFER

In order to determine if radiation heat transfer could be an important mechanism, measurements were made of the transmissivity of thin slices of foam and of thick cell walls. Figure 3 shows the measured transmissivity of a cell wall taken from a free rise bun. This has a wall thickness considerably greater than that of a conventional foam cell. Even with the exaggerated thickness, the transmissivity is seen to be above 90 percent over the wavelengths of importance for thermal radiation at room temperature (Schuetz and Glicksman [9]).

Measurements of foam transmissivity indicate that the mean distance between radiation emission and absorption in the foam is of the order of one

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.

Although the radiation interaction with the foam is a combination of absorption and scattering, it can be accurately represented by a single value of the extinction coefficient. The extinction coefficient is the sum of the absorption coefficient and a modified form of the scattering coefficient with accounts for non-isotropic scattering (Glicksman, Schuetz and Sinofsky [10]). Furthermore, the extinction coefficient can be determined from simple transmission measurements within an uncertainty of 10 percent or less.

Recent results have shown that the extinction coefficient for conventional rigid foams can be predicted by a simple model of the foam. The cells are assumed to be transparent and the struts are thick enough to be assumed to be opaque. Note that since the strut thickness can be of the same order as the wavelength of radiation, a more exact treatment would deal with the electromagnetic interaction, Mie scattering. Nevertheless, the opaque strut assumption yields valuable results.

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 [11]). The resulting expression for the extinction coefficient becomes,

$$K = 3.68 \frac{\sqrt{\varrho_f/\varrho_p}}{d} \tag{5}$$

where d is the cell diameter, ϱ_f is the foam density, and ϱ_p 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,

$$K_r = \frac{16\sigma T^3 d}{3(3.68)\sqrt{\varrho_f/\varrho_p}} \tag{6}$$

where T is the absolute temperature of the foam and σ is the Stefan-Boltzmann constant. Figure 4 shows a comparison of the extinction coefficient predicted by the opaque strut analysis and that determined from measurements of the foam transmissivity.

Current experiments have been aimed at decreasing the radiation heat

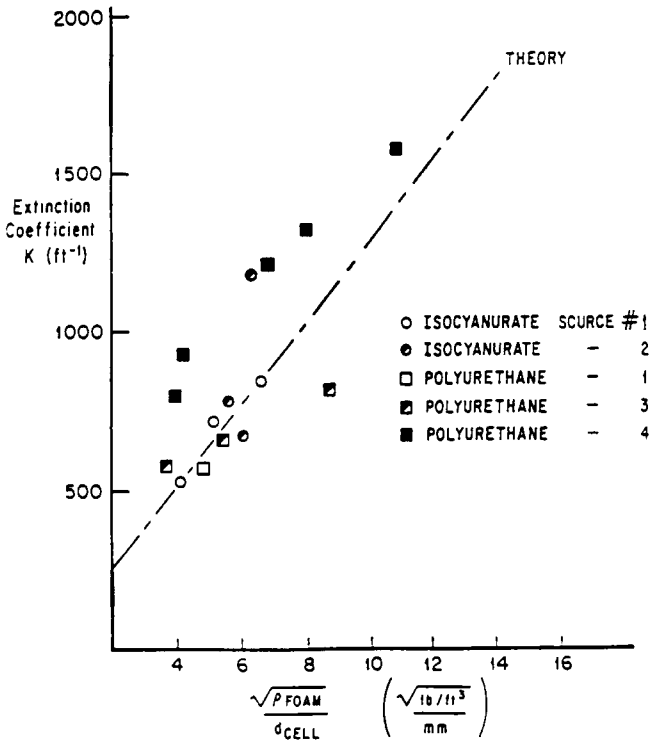

FIGURE 4. Extinction coefficient of foam, the influence of foam density and cell diameter measured extinction coefficient and theory based on opaque struts.

transfer through the foam by the addition of fine flakes of metal or graphite to the polymer. The flakes which end up in the cell wall should absorb or reflect radiation, reducing the transmissivity of the cell wall. Figure 5 shows some preliminary results of the increase of the extinction coefficient due to the addition of the flakes.

FINAL FORM OF THE HEAT TRANSFER EQUATION

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

$$K_{eff} = \delta K_g + (2/3 - f_s/3)(1 - \delta)K_p + \frac{16\sigma T^3 d}{3(3.68)\sqrt{\varrho_f/\varrho_p}} \qquad (7)$$

In this case, it is assumed that the cell walls are transparent.

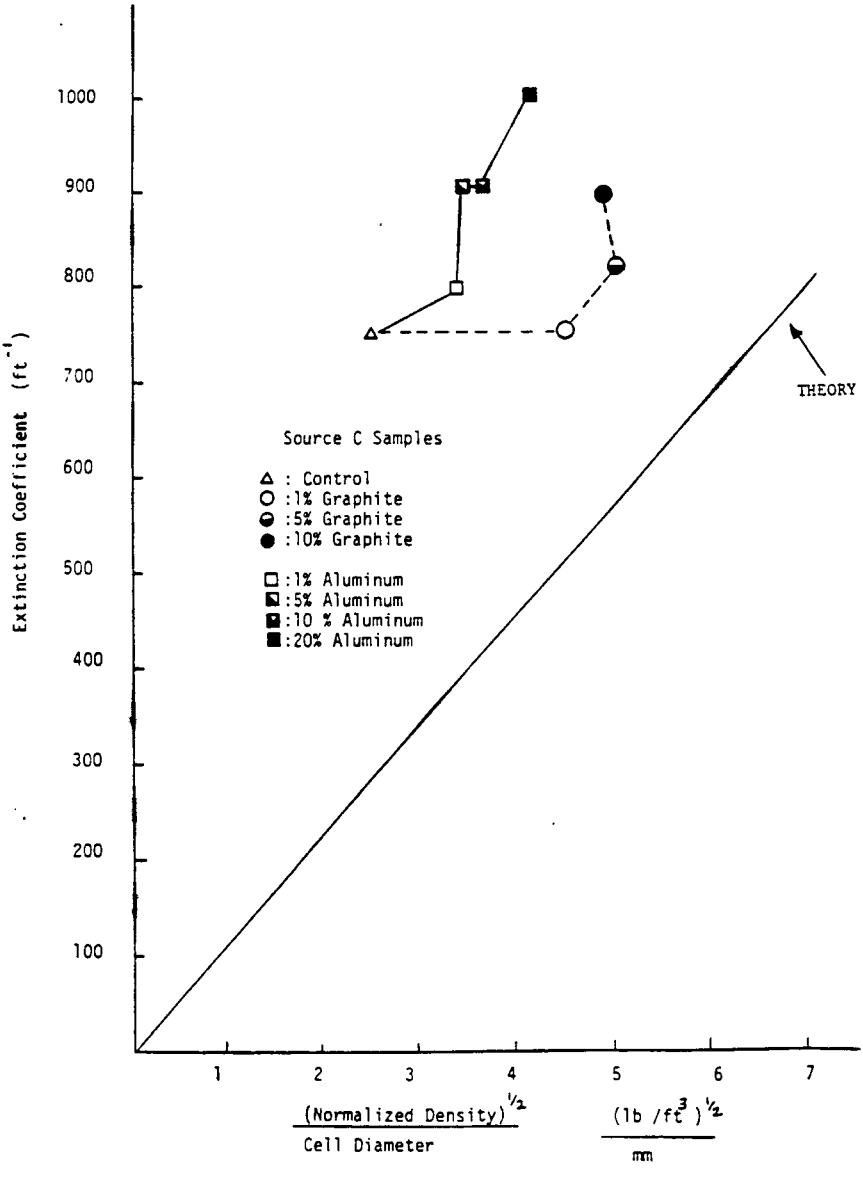

FIGURE 5.

CONCLUSIONS

Heat transfer through foam insulation takes place by conduction through the gas in the cells, by conduction through the solid polymer making up the cell walls and the struts, and by thermal radiation through the foam. The three forms of heat transfer can be found separately and then summed.

The gas conductivity is a function of the gas composition within the foam. This can be found from a solution to the gas diffusion equations through the foam and through the facing material.

Conduction through the cell walls and struts can be closely bracketed by simple upper and lower limiting solutions. The conduction heat transfer is a function of the volume fraction of polymer in the cell walls and the struts and the thermal conductivity of the solid polymer. The latter has been found to be insensitive to minor changes in the polymer composition. A given volume of polymer in a cell wall transmits twice as much heat by conduction than the same amount in a strut.

The cell walls are almost completely transparent to thermal radiation. A model assuming the struts are opaque and the cell walls completely transparent predicts experimental radiation heat transfer data quite closely. The radiation is found to be proportional to the square root of the foam density and inversely proportional to the cell diameter to the first power.

One means to reduce the radiation heat transfer is to make the cells opaque by the addition of metal or graphite flakes. Recent preliminary experiments using flakes have given encouraging results (Figure 5).

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