ADVANCED INSULATION FOR APPLIANCES

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ABSTRACT

This paper describes the energy-saving potential of using superior insulation in appliance walls, focusing on reducing energy use in refrigerators. The paper also describes a vacuum insulation concept now under development at the Solar Energy Research Institute (SERI). The heat transfer through the refrigerator shell is discussed and compared to other energy-using components. Alternative methods to reduce conductive and radiative heat transfer are described, including vacuum insulation, which is discussed with incremental strategies. Finally, costs and major balance-of-system modifications possible with superior insulation are briefly discussed, as well as efficiency contributions by other innovative components, such as desiccants and thermoelectric heat pumps that would be possible if shell losses were greatly reduced.

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INTRODUCTION

Appliance efficiency would clearly be improved if thermal processes, transport, and storage were further isolated from the immediate thermal environment. Cost, volume, and weight considerations have delayed the widespread introduction of such improvements even though "energy-conserving" models are now available for many appliances, and regulations that could increase efficiency have been proposed to upgrade insulation standards. Others (Goldstein and Miller, 1986) define the full range of efficiency improvements possible with refrigerator/freezers. We believe that improvements as great as those already seen (Hirst et al., 1986) are possible and would be cost-effective. In this report we consider the initial factors in support of developing a superior insulating material for appliances. We describe one application , the residential refrigerator/freezer, and the opportunities, risks, and strategies we encountered in defining our optimal research path.

Various sources agree that thermal transfer through the envelope (walls, top, bottom, and door) amounts to 50%-60% of the load for a refrigerator with a top freezer. Two methods for increasing the insulating value of the refrigerator shell exist. The most obvious and readily available method increases the thickness of existing insulation. This method results in larger outside dimensions if the useful internal volume is to remain the same. Thus, a practical size limit is reached that is determined by the dimensions of existing passageways and kitchen counter cut-outs. If the outside shell dimensions are kept constant, the interior volume of the refrigerator is reduced. The optimum in this case is determined by the reduction in storage volume. Figure 1 shows this relationship, though the optimum could shift with the details of a particular refrigeration system.

An alternative to increasing the thickness of existing insulation is to improve the R-value per inch thickness of the insulating material. To do this, we must address each of the modes of thermal transfer. These modes and means of reducing thermal transfer, are: radiation - provide multiple reflective surfaces, convection - remove gases or greatly slow their free motion within the insulation, and conduction - minimize the number and cross section of thermal paths through the insulation.

The "powder" and "vacuum" concepts are the two main approaches being investigated. Oak Ridge National Laboratory (ORNL) (McElroy, 1985) has been investigating using small-diameter (7-300 nm) silica powders to increase the R-value of insulation. The 7-nm powders yielded an R-7 value per inch in air,

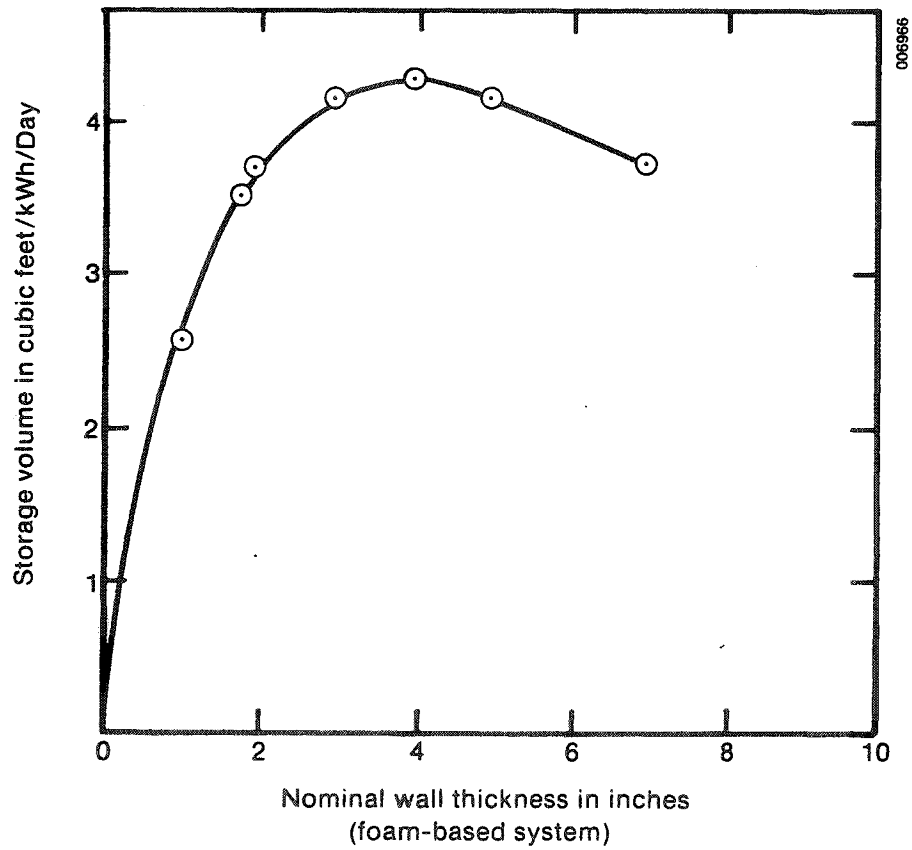

Figure 1. Energy factor (storage volume per kWh/day) versus nominal insulation system thickness based on ideal cube geometry of cabinet.

and an R-16 value in a partial vacuum. Larger powders (30-300 nm) had R-values of R-4 in air and R-32 in partial vacuum, respectively. Mixtures of the higher-cost, fine powders with the lower-cost, coarse powders resulted in even better performance, with an R-47 per inch reported at 13.3 Pa (0.10 atm) pressure. Insulation values decrease as the partial vacuum is lost; one panel under test for three years has now begun to lose its thermal resistance, probably as a result of gas permeating through the metallized polymer envelope.

ORNL also tested evacuated powder panels produced by Fujimori Kogyo, using fine perlite powders. These panels surround the freezer section and are foamed in place. The R-values of these production-line panels tested at 2.4 per inch in air and 44 per inch in 13.3-Pa (0.10 atm) vacuum.

SERI's "vacuum" approach differs from the partial vacuum approach for enhancing the performance of fine powders just described. Our experience in developing the vacuum window (Potter and Benson, 1986) in which a high vacuum (10^{-6} torr) reduces gas-phase conduction, led us to consider a similar approach for opaque insulation panels. In this discussion, we examine the opportunities of using insulation with an R-value of 150 per inch, costing

$2.00/0.1-in. layer/ft^2 to manufacture and install within a refrigerator shell.

The obvious effect of replacing 1.1-in. foam insulation with 0.1-in of new material is the increase in the refrigerated space. Calculations using the dimensions of a 17.3 ft^3 unit (which initially has 2.1 inches of foam) show a 3.5 ft^3 increase in refrigerated volume and a reduction in yearly energy use from 1764 kWh to 1095 kWh (a savings of 669 kWh, which at $0.06/kWh = $40.14). This savings occurs with no change in sizing or type of motor and compressor; part-load and cycling inefficiences were not considered in this gross analysis. Insulation manufacture and installation costs would be $84.20, which if passed on to the consumer, would equal a 2-year simple payback. In practice, typical mark-up of the incremental cost would result in a 4-6 year payback.

Hirst, et al. (1986) and others have shown that this range in simple payback may not be acceptable to residential refrigerator purchasers. Therefore, a value must be attached to the increased volume, thus decreasing payback time. Figure 2 compares volume and cost for the full range of models offered in a 1984 mass-merchandise catalog (Sears, 1984). From this comparison, a cubic foot of refrigerated volume can be estimated to be worth $30-$90 (less minimal balance-of-system manufacturing cost increments). This added value can reduce the simple payback considerably perhaps to within the range of efficiency-rebate incentives available in some locations.

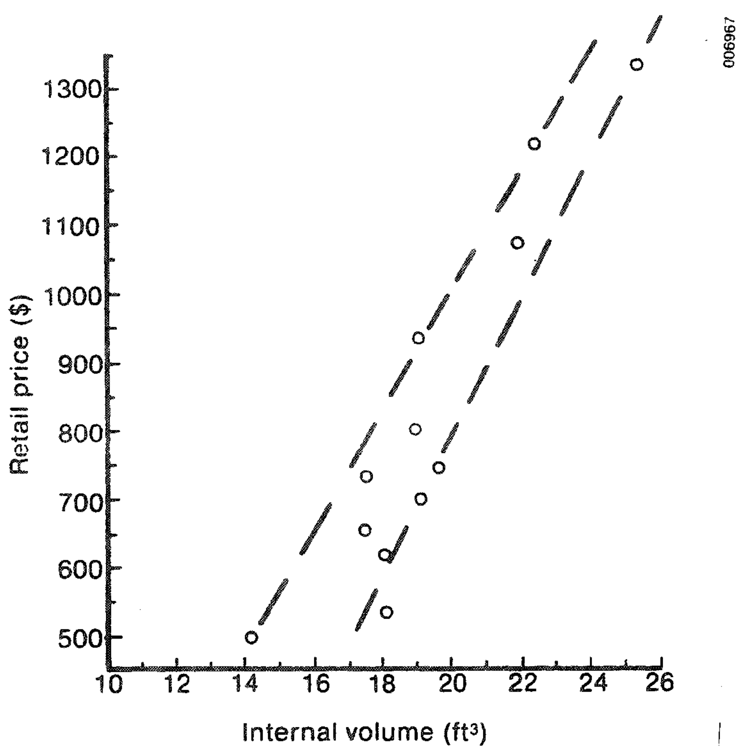

Figure 2. Relation between internal volume and retail price of 1984 Sears refrigerator-freezers

Although the consumer's interest is short payback time, the manufacturer's interest in such a unit could be that it would meet proposed stricter state or federal requirements for efficiency because the unit combines increased volume and decreased consumption.

In another case we examine using two layers of the new insulation and one inch of existing foam insulation as a fail-safe, back-up insulation (the redundancy practice now seen in the advanced Japanese refrigerators). In this case, we see minimal loss of volume (0.35 ft^3); however, now we can significantly down-size the motor and compressor if we can identify a "buffer" to allow rapid cool-down after door openings or other sensible or latent load impositions. While these are nontrivial engineering design issues, for our discussion we further assume that combining waste heat-regenerated desiccants (Maclaine-cross and Pesaran, 1986) and phase-change materials (Lane, 1983) serves our purpose. We can only calculate the cost of the insulation ($84.20) in this case because we do not know the amount of desiccant needed or the cost of the storage subsystems. In addition, the total cost would be offset by equipment size reductions.

With door seal and other improvements, we might consider adding a third layer of insulation. With a shell R-value of about 50, the function fulfilled by the "ice-box" could now be reexamined and the equipment could be completely redesigned. The possibility of using thermoelectric cooling (Goldsmid, 1964) with few or no moving parts is intriguing.

At SERI we will be building a vacuum welding oven capable of fabricating samples for testing the accuracy of thermal calculations. With a high-throughput manufacturing facility, using standard industry amortization figures, our preliminary analysis suggests that a square foot of such a product can be made with costs of $1.20 for materials, $0.10 for processing, $0.52 for overhead and profit, and $0.10 for installation--a total of $1.92/$ft^2$. Information from a confidential industry source disclosed that a square foot of refrigerator/freezer sidewall now costs the appliance manufacturer about $1.00, with $0.20 of that cost attributed to the foam insulation. Total costs of $2.00 per sidewall square foot would "perhaps be tolerable" according to the same source. Preliminary cost estimates of one layer (R-15) of this vacuum insulation material indicate an added cost nearly in the industry's "tolerable" range. If the concept proves technically viable, further incentive may still be necessary to encourage industry uptake, because of capital equipment requirements and reluctance to greatly change production methods.

CONCLUSIONS

This novel insulation concept, and other vacuum technologies related to it, show great promise for reducing energy use in building appliances. Questions of cost and durability remain unanswered.

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