The Effect of New Priorities and New Materials on Residential Refrigerator Design

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Increasing energy-efficiency requirements, combined with environmental considerations, have resulted in designs for domestic refrigerators that incorporate new thermal insulating materials. The first series of tests of these materials have been sufficiently promising that incorporation of vacuum insulations is likely within the next several years. Initial designs will probably use a combination of vacuum insulations and foam; in future designs, major parts consolidation will be possible using structural and other characteristics of the new panel assemblies.

Given optimization of the refrigerator thermal envelope according to life-cycle costs, energy use by refrigerators could be greatly reduced; refrigerators could lose their significance as a major component in residential energy-use. Possible forms in which these new materials will be used are discussed, including alternatives for composite assembly and requirements for reliability and durability.

Introduction

Importance of Refrigerator Energy Loads

There are about 125 million refrigerators, freezers, or combination refrigerator/freezers (as a class, referred to here as refrigerators) in the United States. In the average home, they are the largest consumer of electrical energy. They use 20%-25%, or more than 170 billion kWh/a, of the total electric load in the residential sector--an amount equal to the entire output of about 20 baseload power plants each rated at 1000 MW (Shepard and Houghton 1990).

In other industrialized countries, refrigerators also consume considerable amounts of electricity. In rapidly developing countries, growth in electrical demand is outstripping the capacity of electrical generation and distribution systems. As electrical lines are extended to residences, patterns of electricity use follow those seen in industrialized countries (Figure 1). The lessons learned in the current development of energy-efficient refrigerators could have large international consequences. For example, China, which manufacturing no refrigerators in 1980, made more than 8 million in 1990, with further increases planned. India projects that consumer use will grow from a current market saturation of perhaps 4% to 60% by 2015 (in a country with 250 million households).

As shown in Figure 1, electrical loads per refrigerator vary considerably around the world. In the United States refrigerator-freezers are quite large (about 20 ft^3 [560 l] refrigerated volume on the average) compared to other developed countries, where both refrigerator size (perhaps 12 ft^3 [340 l] on the average) and energy efficiency are moderate. In developing countries refrigerators are smaller (perhaps 7 ft^3 [200 l]) and very often single-door, and their energy efficiency is relatively low (Meyers et al. 1990).

Refrigerator energy use is growing at an accelerated rate in developing countries. Energy-use reductions that have been experienced in developed countries, where market saturation can be over 120% of the households, can be duplicated in those countries. But the per-unit savings could be more than offset by increased use in developing countries, without better transfer of the improved technologies. In developing countries, huge consumer markets are demanding increased access to a relatively inefficient product. Yet the refrigerator provides such a great improvement in the living standard that the consumer has little incentive to reduce energy use. Additionally, newer energy-conserving technologies may not be readily available.

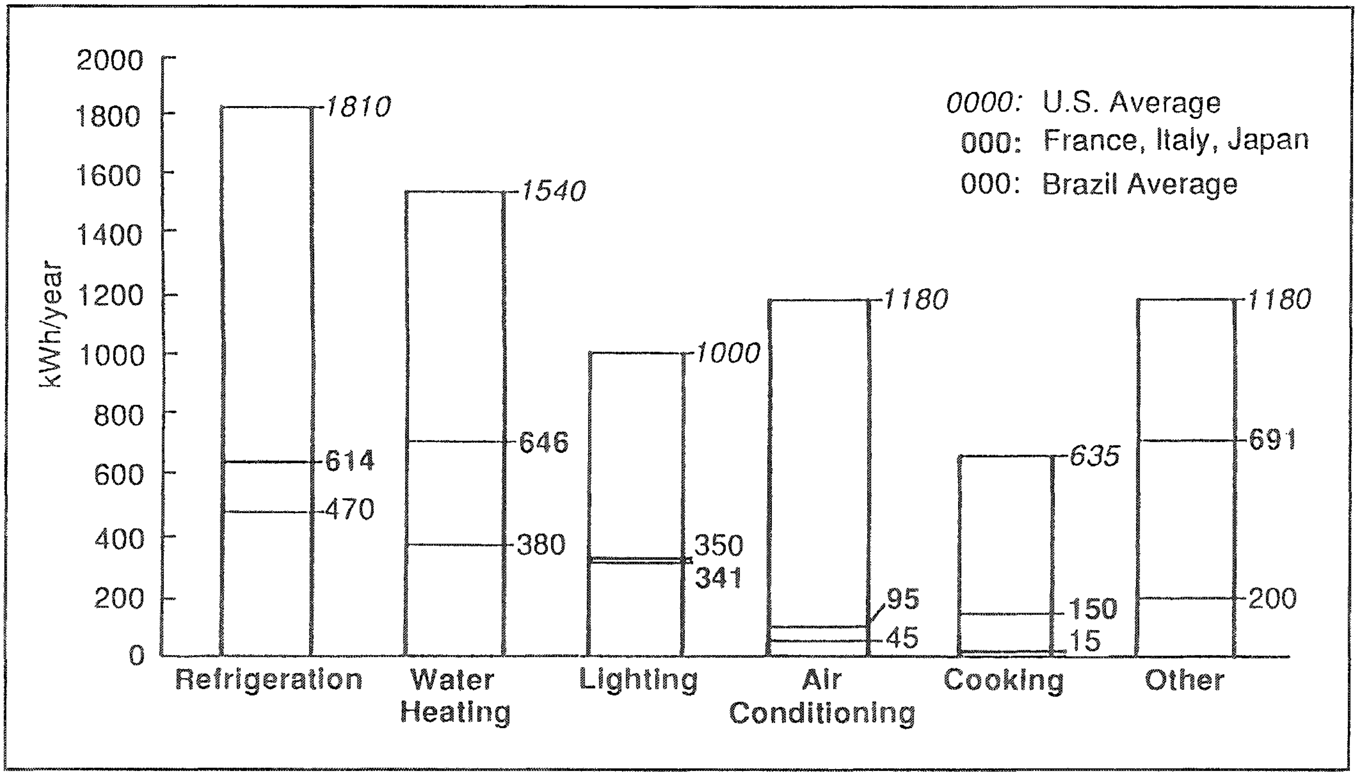

Figure 1. Average Residential Electricity Use in the United States, Brazil, and Three Industrialized Countries, Showing Great Similarities in End-Use Distribution. Organization of Economic Cooperation and Development (OECD) average is the mean of national averages from France, Italy, and Japan (Based on Reddy and Goldemberg 1990; and Schipper and Meyers 1989).

Importance of Thermal Insulation in Refrigerators

Contrary to popular opinion, the energy use of a household refrigerator is not closely related to the frequency of door openings or to the amount of food kept inside. Rather, even with improvements in insulation over the past 20 years, between 70% [2] and 95% (Anonymous 1988) of the electrical load, may still be directly related to the thermal performance of the insulated shell. The remaining load is caused mainly by thermal gains through gaskets, which also have great improvement potential, and from defrost or antisweat heaters. For that reason, improved insulation performance by itself can bring about significant overall energy savings by lowering the demand on the chiller subsystem.

The general observation that insulation values have not been optimized on a life-cycle or societal basis has been made often (see, for example, Potter and Christensen 1986; Potter, Benson and Smith 1988; Potter and Benson 1990). Calculations have also been published that show the specific benefits of higher insulating levels (Smith and Potter 1990). While not denying the potential for significant energy reductions obtainable through cycle improvements and other innovations, it is clear that insulation can be one of the most important determinants of refrigerator energy use.

In the following section, we examine the drivers for advanced refrigerator design and discuss insulation alternatives.

Analysis

Energy-efficiency as a Driver of Advanced Refrigerator Designs

In the United States, consumers demanded improved appliance efficiency after the 1970s oil price shocks. In response, industry reduced the annual energy use of refrigerator-freezers from an average of 1700 kWh in 1972 to 1200 kWh by 1980 (AHAM 1990). Since 1980, industry and government have agreed on an acceptable schedule for further reductions, codified most recently in the National Appliance Energy Conservation Act (NAECA, U.S. DOE 1989).

NAECA regulations require that annual energy use of the baseline refrigerator-freezer unit be further reduced to 950 kWh by 1990 and to 700 kWh by 1993. Figure 2 shows recent energy-use reductions and progress anticipated under the NAECA. Reductions are expected to continue as improved technologies become practicable. Proposed financial incentives for manufacturers, which are supported by many organizations including the U.S. Environmental Protection Agency (EPA, Hoffman 1990) might also contribute to reduced energy use.

According to opinion ventured by a wide range of industry observers, the 1993 NAECA standards can be met without resorting to vacuum insulations. A range of other technical "fixes," such as improved compressor efficiencies and alternative operating cycles, will reduce energy use to below the required level (which may be approximately 20% below the current average). However, these same observers, speaking confidentially, predict that vacuum insulation sidewalls will be offered as early as 1995-1996 on limited lines, in early anticipation of broader use by 1998.

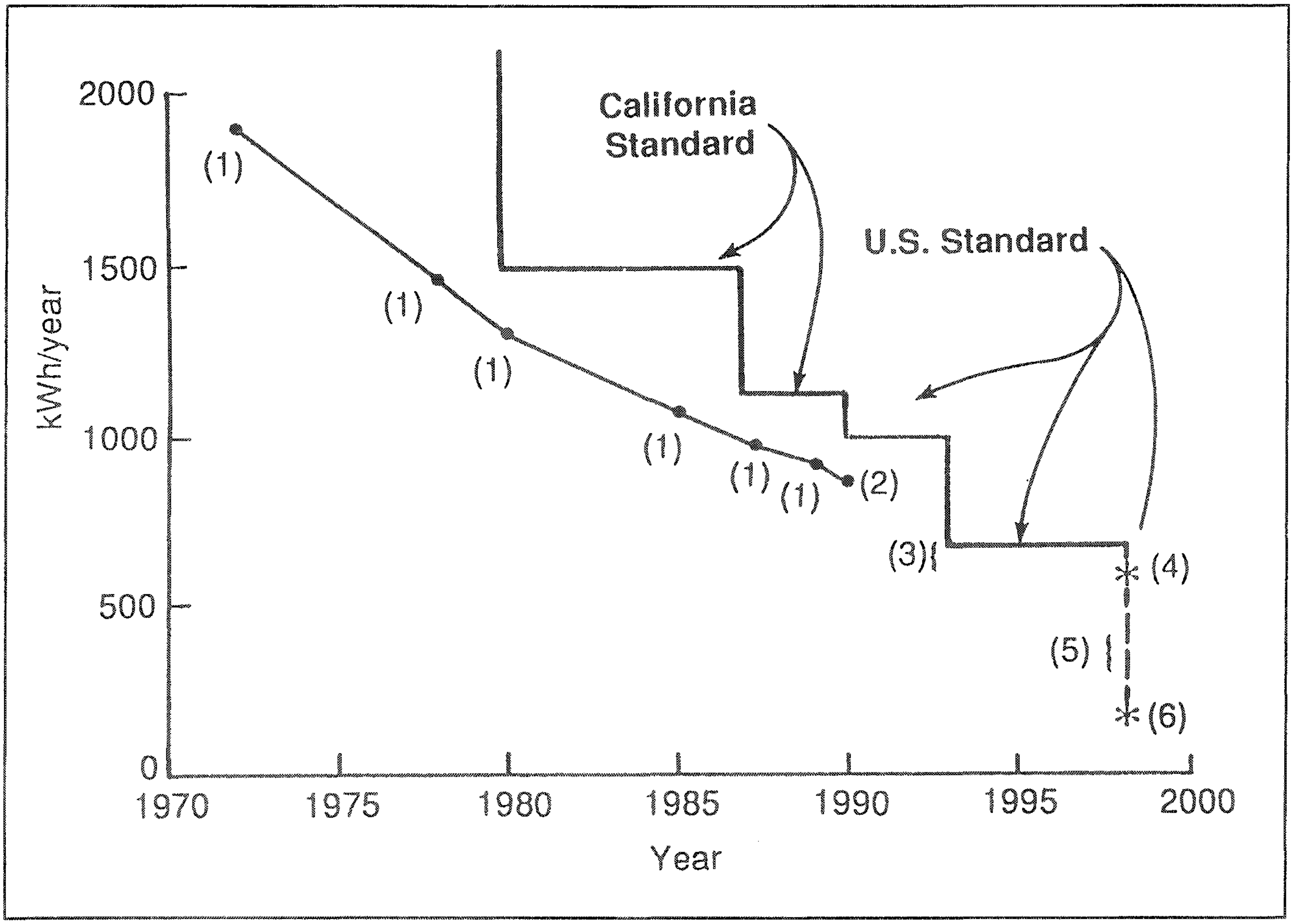

Figure 2. Actual and Projected Reductions in U.S. Refrigerator Use Over a 30-Year Period, Normalized to a 20-Cubic-Foot (Adjusted Volume) Top-Mount Refrigerator-Freezer. Based on shipment-weighted energy ratings from 1972 through 1990 (1--AHAM 1990, 2--AHAM 1991). The range projected for 1993 assumed performance as much as 50 kWh/yr, on the average, better than the 1993 standard level (3--[7]). The dotted line at 1996-1996 represents the energy level encouraged by the "Golden Carrots" incentives [3]. The vertical dashed line in 1998 indicates the effective year for the next standard level, not the level itself, which will be determined in about 1995 based on innovations then considered to be "technologically feasible." One projection for 1998 assumed no further change from 1993 than incorporation of evacuated insulation panels (4--Turiel 1991). Another projection for 1998 assumed a variety of technologies and incentives (5--Hoffman 1990) A third projection for 1998 assumed implementation of specific refrigerator modifications (6--Goldstein et al. 1990).

If these estimates of market readiness are accurate, the NAECA regulations for energy efficiency of 1998 models (to be compiled in 1995) may reflect the technical feasibility and cost effectiveness of vacuum insulations. This determination could, by itself, result in the reduction of refrigerator energy use to a relatively insignificant level by the end of the decade, as shown by the lower values in Figure 2.

These vacuum insulation concepts, several of which currently are being considered for refrigerator use, can easily be compared by examining their envelope and filler materials.

Details on Vacuum Insulation Designs. *The gas-impermeable envelopes can consist of polymer films, metal foils, or thicker sheet metal.* The performance of thin polymer films and foils in other thermal applications indicates that they may be suitable as multilayer vacuum-tight envelopes. Manufacturing ease and expense may not be a problem because the material is well characterized and in current wide use. Rapid, reliable joining and long-term gas impermeability are technical issues now being examined.

Monolithic thin metal envelopes can be vacuum-tight (similar to the common, thicker, all-steel vacuum bottles) and can be joined rapidly and hermetically. If methods can be developed to reduce their weight and cost, the envelopes might be used to enclose thin vacuum insulation panels.

Filler materials can include layers of polymer film, gels, powders, fibers, spacer arrays, or perhaps some combination of these. Materials that can be compressed for strength and that combine extremely small cell spaces with very long thermal conduction paths (thereby reducing convection and conduction) can fill either type of envelope. Powders, fibers, and aerogels, which can be specially formulated to reduce radiative heat transfer, are appropriate choices; work continues on low-cost and reliable fabrication techniques.

Discrete spacer arrays, while not compressible, provide only a limited number of contacts between envelope faces, and, therefore, very limited solid conduction paths. Rapid, reliable fabrication techniques also must be developed if this approach is to be practical.

Given the progress to date and that anticipated in the near future, further significant reduction in refrigerator energy use may not be practicable. Besides the suggested life-cycle optimization of vacuum insulation use, another possible step involves a change in cycle control, especially with regard to the defrost function.

With European experience as a guide, the elimination of a defrost cycle could possibly reduce refrigerator-freezer energy use by 15% to 20% (from a 1990 base [6]), depending on success in removing sources of excess moisture from the frozen-food section, where frost can affect chiller coil performance. Waste-heat regenerated desiccants could be used for removing this moisture [4].

After the defrost cycle energy reductions, further savings may come by improving the interface between the refrigerator and its thermal environment. Better use of appropriate outside temperatures and radiant heat sinks via a through-the-wall heat exchanger or heat pipe-based system (as previously sold with one line of extremely high-efficiency units [5]), could reduce energy use (Brackett 1991). Further net household energy reduction would also be technically feasible, though to this point impractical, if a better use could be found for the heat generated by the appliance. This has been suggested in some "integrated appliance" schemes, where waste heat from the refrigerator is intended for preheating domestic water.

Potential Driver: Environmental Consequences of Refrigerator Operation

In addition to energy efficiency, which has been the main driver toward improvements, environmental concerns are now important considerations in new refrigerator design. Initially, environmental concern was related to the manufacture and operation of refrigerators, and in particular to the immediate and lifetime losses of chlorofluorocarbons (CFCs). CFCs have been used as blowing agents in insulating foam and as the refrigerant working fluid. Fortunately, this situation has improved because revised field service practices greatly reduce those CFCs routinely emitted under some refrigerant recharging procedures.

With new refrigerators, the development of non-CFC chemicals with similar thermal properties holds great promise. Resolution of materials compatibility and long-term safety questions will likely result in the increasing use of these chemicals. They will substitute for the CFCs as foam-blowing agents and thermal working fluids, greatly reducing or eliminating the direct environmental consequences of refrigerator operation.

The vacuum insulations described previously constitute another non-CFC alternative for refrigerator insulation. As their cost and manufacturability issues are resolved, they may substitute for some or all of the insulating foam now used in refrigerators. In either case, the ultimate environmentally safe operation of advanced refrigerators, at least without consideration of the indirect effects of electricity use, will thus be ensured. Continued reduction of refrigerator electric energy use will reduce those indirect effects.

Other indirect environmental effects of wasteful refrigerator energy use abound. There appears to be an increasingly clear relation between power generation and global warming (Flavin and Lenssen 1990). From a regional perspective, utility planners in developing countries can see how growing electricity demand also worsens local air quality (Sathaye and Ketoff 1990) while undermining power grid reliability (Meyers et al. 1990). This results in power shortages in the critical commercial and industrial sectors (Jones et al. 1988) and increasing capital drain for power plant construction (Fickett et al. 1990).

Potential Driver: Refrigerator Life Cycle Environmental Consequences. Until recently the question of refrigerator life-cycle design has most often been encountered only when energy-efficiency options have been considered. In these analyses, the question was always: What is reasonable to consider for the payback of a new energy-saving feature? Less than a year, as apparently demanded by the consumer? Or over its lifetime, which could be less than the lifetime of the utility plant built to supply it with energy? Or somewhere in between? In this section we expand the life-cycle question beyond energy alone and also consider the recyclability of the appliance itself.

This life-cycle driver has two primary elements:

(1) Refrigerators account for a large number of the 32 million major appliances (weighing 2.8 million tons) discarded each year in the United States (EPA 1991). This land-fill burden looms larger in light of restrictions anticipated for the disposal of refrigerators, which, following the lead of Connecticut, Minnesota, Wisconsin, and Florida, could prohibit their disposal in landfills by 1998 [1].

(2) Refrigerators are not now designed to be easily disassembled, so parts or materials that could be recycled cannot be easily separated from other materials. For example, the sidewall is typically made of a thermoformed plastic inner liner and a prepainted metal outer shell, maintaining a cavity between them filled with expanded polyurethane foam. The presence of these three noncompatible materials, which also are not easily separable at disposal, results in close to 10 million North American refrigerators each year that are not recycled.

The life-cycle problem can be, ironically, further exacerbated by the improvement of energy efficiency if alternative chemical blowing agents are used within an expanded insulating polymer. An industry group has predicted sidewall R-values as high as 22 (ft^2-F-hr/Btu) by 1993 and 32 by 1998 (Solar Energy Research Institute, 1990). For these predictions to be realized with chemical-blown insulating foams, very thick polymer walls are predictable. Achieving an R32 with an R6 foam would result, for example, in a 5-inch-thick wall of blown polymer, well adhered for structural reasons to the outside steel wrapper and lined with a thermoformed polymer liner. Recycling this "Plastic A/Plastic B/Steel" assembly would be difficult with existing equipment and methods.

Research by the polymer industry is addressing the question of rigid foam recycling, with special attention to the hundreds of thousands of tons of CFCs still trapped in refrigerator sidewalls. Two recovery processes reported recently include separating the foam from the metal and plastic panels, then either pulverizing the foam under a solvent contained in a gas-tight container, or shredding the foam in a gas-tight system. The fluff is then compressed in a high-pressure chamber, yielding water and CFC-11. The resulting foam powder might be bonded to form panels similar to wood particle boards (Polyurethane Division 1991).

The use of vacuum insulations, especially those wrapped in steel, could lead to future recycling solutions that are more plausible. While allowing reasonable wall thicknesses, as shown in Figure 3, they would maintain the high insulating performance that energy-efficiency standards demand. The first-generation solution, in which a steel vacuum insulation is used to increase insulating value and a (non-CFC) foam insulation provides the familiar structural stiffness, may resemble Sketch C in Figure 3. Later, second-generation solutions could eliminate possible problems with less-compatible materials by better using the unique qualities of the steel. Such qualities as strength and stiffness could eliminate the need for structural foam and possibly permit further parts consolidation by substituting for some or all of the exterior shell of some refrigerators, as shown schematically in Sketch D of Figure 3.

In either of the steel vacuum insulation cases above, the design solutions allow a thin sandwich sidewall of superior insulating quality, with inside (food-quality) liner and outside (appearance) shell made of compatible,

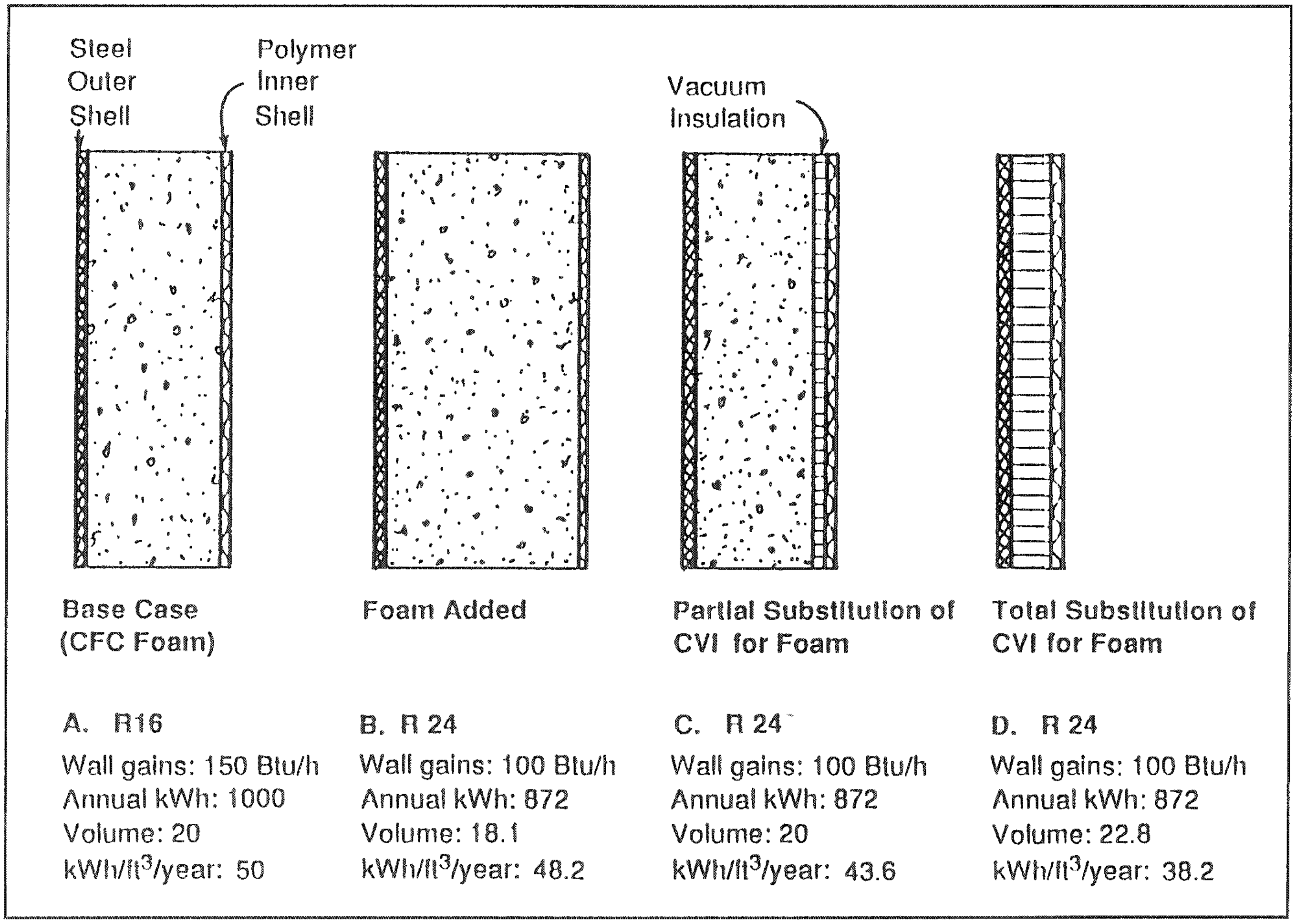

Figure 3. To-Scale Comparison of Options for Increasing Insulating Performance of Refrigerator Sidewalls. The insulating value of foam is assumed to be R8 in an inch; a hypothetical mid-performance-range vacuum insulation is assumed with an insulating value of R10 in 0.25 inch.

recyclable polymers. The "cavity" would be filled with the steel vacuum insulation panels (themselves composed of 60%-100% recycled, or "pre-cycled," steel content), with or without additional compatible foam [8]. Figure 4 is a sketch of one version of the concept.

This sandwich can be easily dismantled at disposal, with the selected polymers recompounded for 100% reuse and the steel insulation also shipped back for 100% reuse in another life-cycle (perhaps again as a vacuum insulation, or, after remelt, as any steel product).

Support for Improved Performance of Refrigerators

A number of market factors now encourage the use of better insulation in refrigerators. Perhaps the most pervasive in the United States, beyond efficiency standards, is the increasing influence of an ethic that encourages the purchase of refrigerators and other products that are more environmentally benign, even though they may be more expensive (Udall and Harvey 1990).

Many electric utility companies, acting on their identification of refrigerator electric loads as cost-effectively controllable from a systems perspective, offer a range of incentives for energy efficiency (EPRI 1987; Mataloni and DeVitto 1991). These incentives, aimed at purchasers of high-efficiency units, are mostly rebate programs that partly or completely offset extra consumer costs of improved models. Actively improving refrigerator efficiency with new non-CFC technologies can reduce major uncertainties about future electric energy and demand levels (Joyner 1989) by reducing an obvious component of residential consumption.

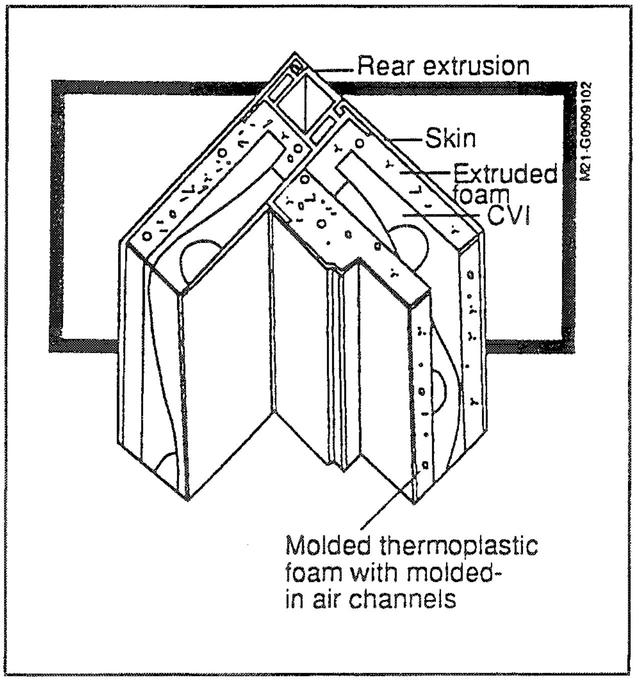

Figure 4. Detailed Sketch of Composite Refrigerator Wall Using Steel Vacuum Insulation. In this first-generation design, foam is retained mainly for structural purposes; it also insulates around the edges of early steel insulation panels, identified above as "CVI" (compact vacuum insulation)(Based on Fitch Richardson/Smith 1991 and [8]).

The "Golden Carrots" concept affects manufacturers even more directly. This type of incentive program proposes that utilities and other interested parties contribute to a fund that can be distributed among refrigerator manufacturers whose products surpass the energy-efficiency requirement of NAECA. An earlier precedent-setting program in Sweden--which sought refrigerators with efficiencies 30%-40% better than the best then on the market--apparently was successful (Morrill 1990). A large west-coast utility started a similar program in the United States, and other contributions should bring the fund to between $10 and $20 million within a short period of time (Nadel 1991).

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In developing countries, support is more likely to come from international public interests like the U.S. Agency for International Development programs and philanthropic foundations and from joint-venture private-sector interests that anticipate an expanding international market for improved refrigerator technologies. Governments will also help by purchasing energy-efficient models, strengthening standards, instituting testing and labeling programs, and negotiating with manufacturers for improved designs, components, and operating characteristics.

Other Appliance Applications

Vacuum insulations may be useful in appliances such as domestic water heaters, where utility demand-side control can use distributed thermal storage as an energy "peak leveler" and "valley filler." Such a scheme is more practical if the capacity for storage is large and the off-cycle losses are very low because of increased insulation levels. Yet larger water heaters, a natural result of both considerations, can be a problem with regards to delivery and siting within the building. The more compact vacuum insulations could provide increased thermal insulation, while allowing increased volume within the same outside dimensions, a desirable outcome for utility demand-side management.

The compactness and probable durability of the steel vacuum insulations may also make them useful as portable retrofits. Initial applications could be around refrigerators, where shorter compressor run-time could be expected.

Conclusions

Popular and institutional support is growing for improvements in the energy efficiency and environmental impact of household refrigerators. Technical and practical challenges face the developers of a number of vacuum insulation alternatives that promise to deliver the required performance improvements without CFCs. Accelerated commercialization, however, may require increased attention and assistance by government and industry; it is particularly important, for example, to improve and validate cost effectiveness so that these approaches will be broadly acceptable. Several of the vacuum insulation approaches will be on the market in several years; with continued optimization of their use, energy efficiency of refrigerators will become a much less serious conservation issue, and currently significant environmental impacts will be reduced.

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