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ABSTRACT

Recent developments in advanced insulations, such as powders under a soft vacuum (R=20 per inch), and hard-vacuum insulation with spacers (R=15 per 0.1 inch), merit evaluating their practical uses. Refrigerator/freezers (R/Fs) are well-suited for incorporating the new insulations for the following reasons: the energy consumption of R/Fs must be reduced to comply with the National Appliance Energy Conservation Act (NAECA) standards; the Montreal Protocol to Control Ozone-Depleting Substances calls for a reduction in chlorofluorocarbons (CFCs) that are now used in the insulative foams in R/F sidewalls; and both high R-values to minimize heat gain through the walls, and thin walls to maximize the interior volume, are desirable.

We selected two different R/F base-cases for this analysis, one had the typically used CFC foam (R=7.7 per inch), while the other featured non-CFC foam (R=5.3 per inch) in the exterior walls and doors. (In keeping with industry practice, both refrigerator doors were insulated with fiberglass.) Two simulated modifications of both of the base cases, based on the DOE closed-door test, included replacing part of the wall and door insulation with either 1 inch of powder or a 0.1 inch layer of hard vacuum/spacer insulation. Both of these modifications met the standard, even when the non-CFC foam base case was simulated.

Three other cases were tried, replacing the base design insulation with various thicknesses of the new insulations. When two layers of hard vacuum insulation are used, energy consumption is reduced by 44%, enabling it to meet the standard. A benefit of each of these configurations is that the interior volume of the R/F is increased (up to an additional 6 ft^3) thereby increasing the market value.

In general, savings of more than 50% in energy use appear possible. Associated increases in salable refrigerated volume may offset some or all of the anticipated cost of the improved insulation.

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INTRODUCTION

Technical advances in developing thermal insulating materials could result in large reductions in energy use and of ozone-depleting chemicals in refrigerators. In the last year, two significant events emphasized the importance of these advances. On March 17, 1987, the National Appliance Energy Conservation Act (NAECA) was signed into law. The first level of compliance will take effect on all refrigerator/freezers (R/Fs) sold in the United States after January 1990[1]. On September 16, 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was signed (and ratified by the Senate on March 14, 1988) that requires a time-phased decrease in the production of chlorofluorocarbons (CFCs) now used as the refrigerant working fluid and in the insulating polymer foam of R/Fs[2]. The protocol requires a 20% reduction from 1986 CFC production levels by 1993 and a 50% reduction from 1986 levels by 1998.

This combination of requirements has been called essentially contradictory by the industry, since reductions in energy use would be most easily accomplished by increasing insulation use. However, if a result of the CFC regulations is a non-CFC foam product that is not as thermally insulating, as nontoxic, as long-lived, or as available as that currently used, the former "easy fix" of increasing insulation is not appropriate. The importance of this conclusion is indicated by industry's estimate of a $600 million retooling effort necessary to satisfy NAECA[3,4]. As a result of the technical conflict and the financial issues, the Association of Home Appliance Manufacturers (AHAM) has asked DOE to maintain the established NAECA energy-use requirements in lieu of further reductions in 1993[3,4]. Solutions that address both energy efficiency and CFC-use requirements are urgently needed if these progressive measures are to be retained and energy conservation is to be improved significantly. Industry may find these solutions in chemical alternatives to CFC refrigerants and foaming agents. The purpose of this report is to describe numerous nonfoam insulation alternatives and their beneficial effects on R/F energy use.

ENERGY USE IN R/Fs

To put the potential energy impacts in perspective, in a typical house the third largest energy user is the R/F, after space and water heating. The U.S. market saturation of refrigerators is greater than 100%, which indicates that a measurable number of households have more than one unit. The national energy use of R/Fs is calculated to be about 2.5 quads, almost 5% of the total energy budget for buildings. While the average energy use of a new refrigerator has dropped from an average of about 2000 kWh/year in 1972 to today's shipment-weighted average of about 1100 kWh/year for the same sized unit, most of the decrease was accomplished before 1983, by which time expanded polymer insulating foam had replaced fiberglass in the sidewalls[5,6].

In this regard it is interesting to examine the range of existing non-CFC insulating products that could be used in R/F sidewalls. If volume were no issue, improved efficiency could be easily achieved by surrounding the refrigerated compartment with bulk insulation of the type used in insulating attics (where volume has little value). Cellulose, fiberglass, and rockwool materials, with R-values ranging from about 2 to about 4 per inch, are blown into these spaces in thicknesses mostly related to cost-effectiveness. That cost-effectiveness is defined by calculations that use the cost of the material, the cost of heating or cooling energy, and the climate-driven differences between inside and ambient temperatures over time (degree-days). Figure 1 illustrates the relation between degree-days and typical attic insulation R-values for buildings in three climates (Boston, Houston, and Madison, Wis.) with different annual degree-days. It is not conventional to apply the same calculational method to the thermal environment of an appliance, but it is technically accurate and instructive to do so. The results are sensitive to the cost of materials and required payback periods used, both of which are different between building shells and appliance shells. Figure 1 also shows the results of applying the same cost-effectiveness requirements to certain residential appliance sidewalls, given the same material and energy cost assumptions (assuming unconstrained volume). For appliances, degree-days are based on the temperature differences between indoor air and appliance storage (both are usually maintained by a thermostat). Figure 1 shows that the thermal transfer environment for an appliance is, on average, much harsher over the course of a year than that for a building. The projection of R=60 insulation for freezer sidewalls is surprising considering its contrast with existing levels (R=12).

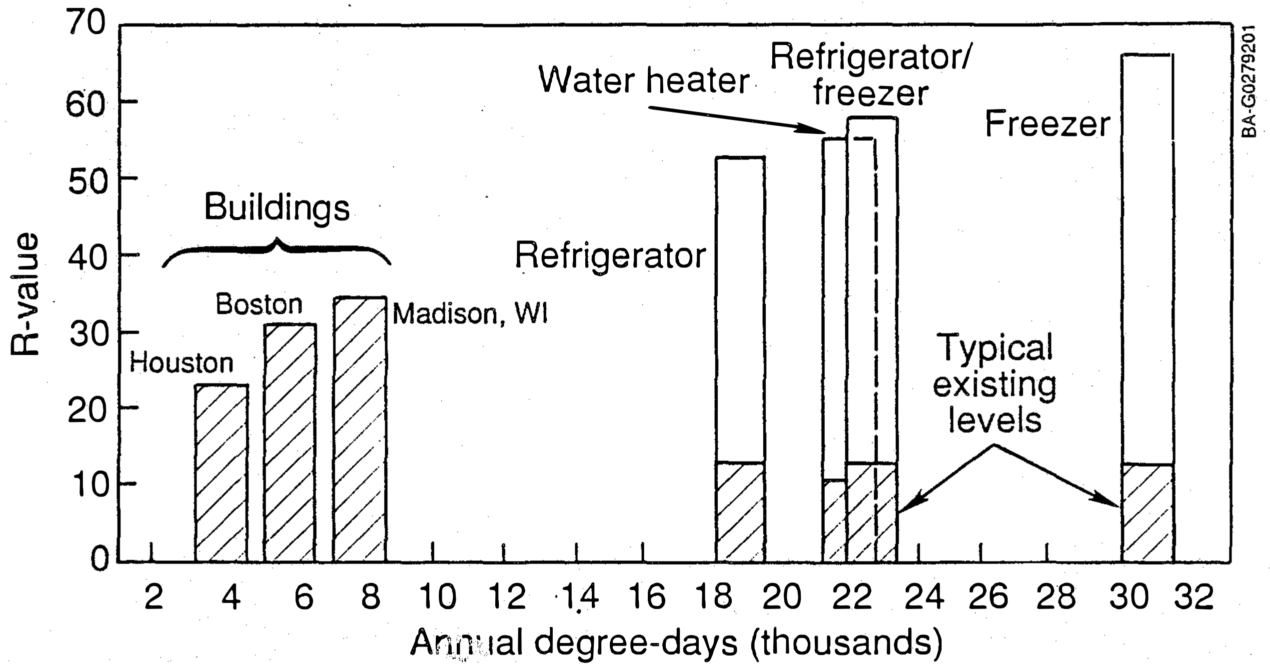

Figure 1. Extrapolated R-values, based on degree-days (assuming unconstrained volume)

Besides the appliances shown in the figure, a similar argument could be made for increasing the sidewall insulating values of other common convenience thermal storage containers, such as vending machines, water coolers, and ice machines. The reasons for sub-optimal insulation in their sidewalls are similar also, including increased initial costs, energy costs that are unnoticed or paid by others, and restrictions on exterior dimensions.

Volume has practical and marketing values in many appliance applications. For example, an R=60 sidewall (an optimum value for freezers given the base conditions of Figure 1) could be achieved with an R=3 per inch insulation, but would require 20 inches of thickness. Energy-saving solutions that maintain reasonable volumes within constrained outer dimensions are desirable. From a marketing perspective, we have showed previously that the retail price of a cubic foot of refrigerated space varies from $30 to $90[7]. The present use of foam rather than fiberglass in R/Fs could be considered further evidence of both the practical and marketing benefits of increasing the volume in a R/F.

CFC USE IN R/Fs

More of the CFCs in a R/F are found in the insulating foam (about 1 1/2 pounds), than in the refrigerant working fluid (about 1/2 pound). The best current insulations that are non-CFC and nonvacuum are in a range of R=4.5 to R=5.9. The lower figure is the R-value of dense fiberglass insulating board, R=4.5[8]. The higher value is that obtained from testing CFC-blown foams after the CFC gases have been lost, R=5.9[9]. If we de-rate the R=5.9 foam by 10% to R=5.3 per inch, to reflect difficulties in obtaining optimal thermal characteristics in a non-CFC foam, a value of R=60 can be obtained with 11 inches of sidewall containing such a material. In summary, the penalty of volume associated with insulating R-values in the 2 to 5 per inch range is clearly substantial in the drive for energy-efficiency without CFC-blown foam.

ADVANCED INSULATIONS

Limits may have been reached in the performance of nonvacuum insulating systems. Several vacuum approaches have shown promise as advanced insulations. Three such concepts now under development (ultrafine powders, silica aerogel, and hard vacuum/spacer are described below). Each of these could satisfy the requirements of greatly reduced R/F energy use and greatly reduced CFC use. Each type would provide more effective thermal insulation with less potential for environmental damage. They are also less flammable and produce safer by-products if melted or burned.

Ultrafine Powders

A silicon oxide powder mixture with optimized characteristics of particle size, opacity, and density could be an excellent thermal barrier[10]. Under a "soft" vacuum (for example, about 10^{-2} Torr) such an insulator could achieve R=50 per inch.

Numerous patents exist for powder insulation systems that include specifications for both the type of powder to be used (usually a form of silica or perlite), and for the type of material to contain the powder (usually an evacuated panel or bag). Fabrication can involve milling the powder particles to the desired size, or capturing them as a fumed or precipitated by-product, heating them to drive off surface water, compressing them to the desired density, and sealing them within a gas- and water-tight pouch of layered polymers and foils. After compression and evacuation, the gas barrier envelopes containing the powder take on an essentially board-like form.

The high R-values of powder insulations can be attributed to their ability to frustrate three mechanisms of heat transfer: solid conduction, gas-phase conduction, and radiation.

In powder insulations, the miniscule size and irregular shape of each solid particle makes the contact points between them microscopic, thus limiting solid conduction. Powder insulations inhibit gas-phase conduction in two ways. First, the pores between powder particles are so tiny as to create a barrier that impedes the movement of gas molecules. Second, the partial evacuation of the bags or panels that contain the powder reduces the overall number of molecules available to collide with each other. Tests show that powder insulations not employing a vacuum yield an R=7 per inch, while those using a vacuum yield up to R=47 per inch. The constituents of powder insulations tend to reflect or absorb thermal radiation, thereby retarding radiative heat transfer.

In Europe, evacuated powder insulation systems are sold by a German aerospace company. In the United States, research on powder insulation systems is proceeding at both private- and public-sector laboratories, including a large appliance manufacturer and the Oak Ridge National Laboratory in Oak Ridge, Tennessee. Inexpensive manufacturing processes are now being investigated.

Silica Aerogel

This material is extremely light, with 90%-95% micropore volume. It could be used as a solid or pellet filler in an insulating panel[11]. When sealed in a slightly evacuated container at 1/10 atmosphere (a gas pressure of 76 Torr), it has been tested at R=20 per inch.

The discovery of aerogels dates from the early 1930s when S. S. Kistler of Stanford University developed a method for drying gels without shrinking them. Normally, as a gelatinous substance dries at atmospheric pressure, it shrinks to approximately 10% of its original volume. As when a jellyfish dries on the sand, little collapsed tissue remains. Even after such dramatic shrinkage, such air-dried gels are still about 50% empty space. Kistler discovered that by extracting the fluid from a wet gel under increased pressure and high temperatures, he produced materials that were extremely light and up to 98% porous. It is the extreme porousness of dried or "aero" gels that accounts for their high thermal resistance. In Europe, silica aerogel pellets are sold as loose-fill insulation by a German chemical company. Silica aerogel is being investigated for its insulating properties by German university researchers, and by a private-sector U.S. firm working in collaboration with Lawrence Berkeley Laboratory in Berkeley, California. Researchers are investigating alternatives for producing large sections at low cost.

Hard Vacuum/Spacer

A vacuum insulation concept that features an extremely low gas pressure (about 10^{-6} Torr, often called a "hard" vacuum) within an edge-welded metal envelope has been considered a possibility, in some form, for application as an insulation[7]. The high vacuum eliminates significant gas-phase conductance through its thickness. The internal supports achieve low thermal conductance by the introduction of highly constricted heat flow paths through their thickness.

The envelope material of choice is a thin, low thermal conductivity metal such as stainless steel or a titanium alloy. The use of a low thermal conductance envelope is essential to prevent the faces of the envelope acting as lateral heat transfer "fins" and aggravating heat conduction around the vacuum panel, through the welded perimeter. The thickness of the envelope material is dictated by concerns of rigidity and the need to avoid bowing of the envelope material between spacers to the extent that additional solid conductance paths are created.

Preliminary analyses have been conducted for the simplest hard vacuum/spacer designs. High values of thermal resistance appear to be possible in a simple, very thin section insulation (e.g., R=15 in 1/10 inch). The performance of the assembly depends on obtaining and maintaining a high vacuum, on using internal supports with high thermal resistance, and on achieving low radiative heat transfer across the vacuum gap.

The hard-vacuum insulation will lose its highly insulating properties if the vacuum cannot be maintained. Any puncture of the stainless steel wall will allow air to enter the cavity and degrade the vacuum. Permeations caused by imperfections in the stainless steel or in the edge welds will also cause the vacuum to fail. Upon failure, the R value is calculated to be reduced by 86%, from R=15 in 1/10 inch to R=2.1 in 1/10 inch.

Researchers at the Solar Energy Research Institute are investigating the basic concept and its various applications. Again, as with the other two concepts, a manufacturing process that could produce an inexpensive and practical product is the key to widespread application.

APPLICATION TO REFRIGERATOR/FREEZERS (R/Fs)

To illustrate the energy-conserving effect of an ultrathin advanced insulation, calculations were made for several scenarios modifying a base-case R/F design defined by the Natural Resources Defense Council (NRDC)[12]. We made two modifications to the NRDC base-case design to represent existing R/F production more closely: 1) a larger capacity compressor was assumed, which raises the EER from 3.18 to 3.65, a minor improvement to reflect industry practice that includes many units with EERs greater than 5.0; and 2) the refrigerator door is insulated with 1.25 inches of R=3 fiberglass, rather than R=7.7 foam, reflecting the reality that a majority of refrigerator doors are not currently foamed. For the purpose of these calculations, we assumed that an evacuated powder insulation is available that measures R=20 in one inch, as well as an ultrathin vacuum insulation that measures R=15 in 1/10 inch, and that these add \$3.00/ ft^2 and \$2.00/ft^2 of insulated shell, respectively, to the retail cost of the R/F. It should be clear that general conclusions drawn for these hypothetical vacuum insulations are applicable to any other advanced concepts, the only difference being the thickness and costs required to achieve the listed R-value. We have compared energy use in these exercises to the California 1992 Appliance Energy Standards (CAES) since the second-level NAECA standards have not been published. The CAES guideline should be considered a worst-case (most stringent) scenario.

A note regarding the calculation procedures used here is appropriate. The standard DOE performance testing method for R/Fs is a "closed-door" test at 90°F; the higher temperature is intended to account for the effect of door openings and other service loads. We have generated data based on the DOE testing procedure, though it probably over-values improvements in sidewall efficiency. It is thought that greater than 80% of the thermal gains in a R/F are because of gradual heat gain through the shell, as opposed to latent and sensible gains from door openings and the introduction of warm, moist food products; the closed-door testing procedure (and calculations) attribute even more emphasis than that to shell characteristics. Especially at high R-value levels, where we could show energy use dropping to near-zero, it is clear that these calculations could be misleading compared to reality and to a hypothetically more realistic, balanced calculation procedure.

In this base-case design of existing R/F units, as Figure 2 shows, CFC-blown insulation, rated at R=7.7 per inch, is foamed between a steel outer case and a plastic inner liner. The prototype has a refrigerated volume of 16.7 cubic feet and uses 1080 kWh/yr, which gives it a figure of merit EE (kWh per cubic foot per year) of 64.6 as shown in Figure 2-A. Five configurations will now be described that maintain the same interior refrigerated volume, but use different insulations in the shell.

As the first modification example, in Figure 2-B we also examine the effect of 1 inch generic ultrafine powder insulation, an R=20 under "soft" vacuum pressure, replacing some of the foam. Energy use is calculated to drop dramatically to 607 kWh/yr, enabling it to comply with CAES. Because of the higher resistance to heat transfer through the sidewalls, a decreased internal heat load from condenser and mullion heaters was assumed, as in Goldstein[12]. With a net installation cost of \$118.00 [$(53.4\ \text{ft}^2 \times \$3.00/\text{ft}^2)-(53.4\ \text{ft}^2 \times \$0.79/\text{ft}^2)$, where \$0.79 is the cost per board foot of foam suggested by Goldstein[13]] simple payback to the consumer from the energy cost savings alone is about 3 years. Cost-of-saved-energy, an indicator that should be comparable to the costs of other electricity generating options, is \$0.017/kWh, and the unit would comply with the California 1992 Appliance Energy Standards (CAES).

Applying the R=15 "hard" vacuum insulation to the prototypical unit, in Figure 2-C we also schematically show and calculate the effects of placing the compact vacuum insulation next to the steel outer case and foaming as usual. This case, and that of the powder installation above, were configured to minimize production changes necessary to comply with CAES. In this scenario, a 45% reduction in energy use is calculated when we simulate the DOE test procedure. The reduced energy use (to 593 kWh/yr) also brings this unit into compliance with CAES for this size. The figure of merit EE is 35.5, also down 45% from the base case, and the cost to accomplish the change is estimated as \$102. The cost-of-saved-energy is \$0.014/kWh.

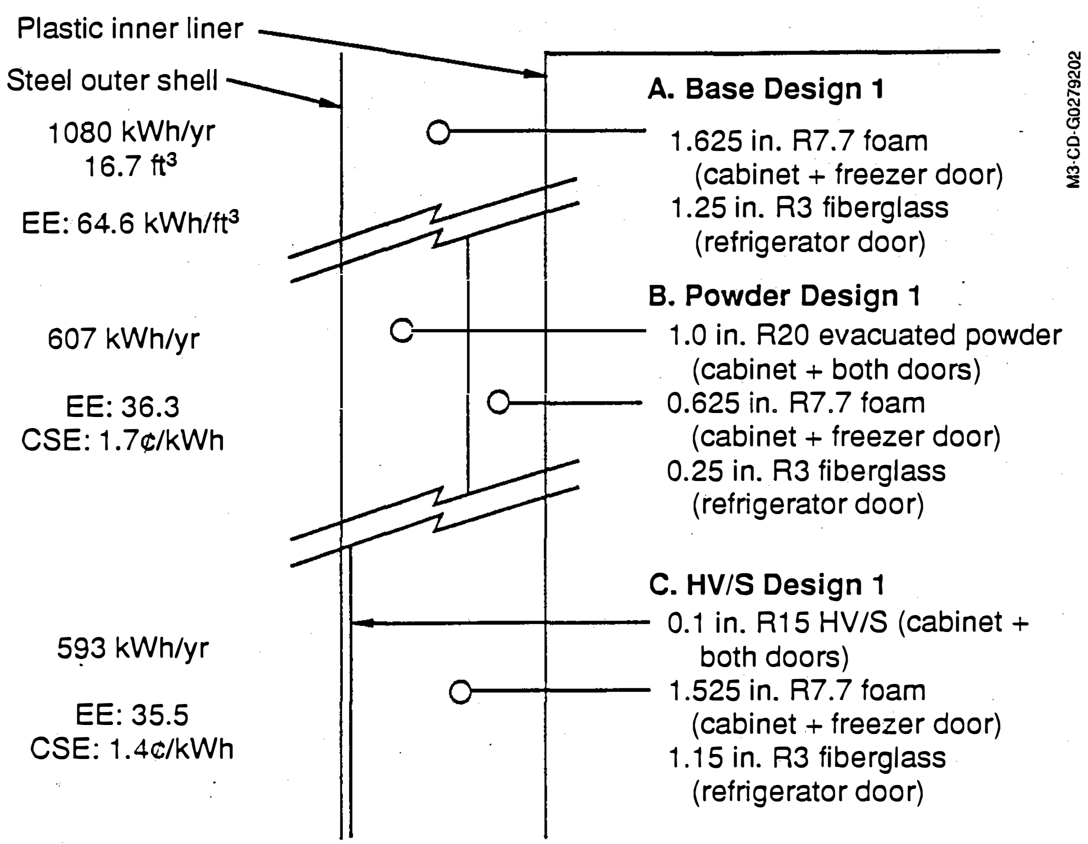

Figure 2. Base case and modified refrigerator sidewalls showing proposed application of advanced insulation and resulting energy use (to be compared to the CAES limit of 658 kWh for 16.7 ft^3)

An alternative base-case design was considered in Figure 3A. In this case, the previously used R=7.7 foam was replaced with an R=5.3 non-CFC foam. This design consumes 1276 kWh/yr compared to the 1080 kWh/yr represented in the previous example. The effects of replacing part of the non-CFC foam with either one inch of powder or one layer of compact vacuum insulation are shown in Figures 3-B and 3-C, respectively.

Figure 4-A shows the result of replacing all the foam with a one-inch layer of R-20 powder. This configuration adds more than 2 cubic feet to the interior volume, while significantly reducing the energy consumption. It consumes approximately 786 kWh/yr yet does not meet the CAES standard of 701 kWh/yr for its 19 cubic-foot volume. The marginal cost of this modification is an estimated $98 which results in $0.02/kWh cost-of-saved-energy.

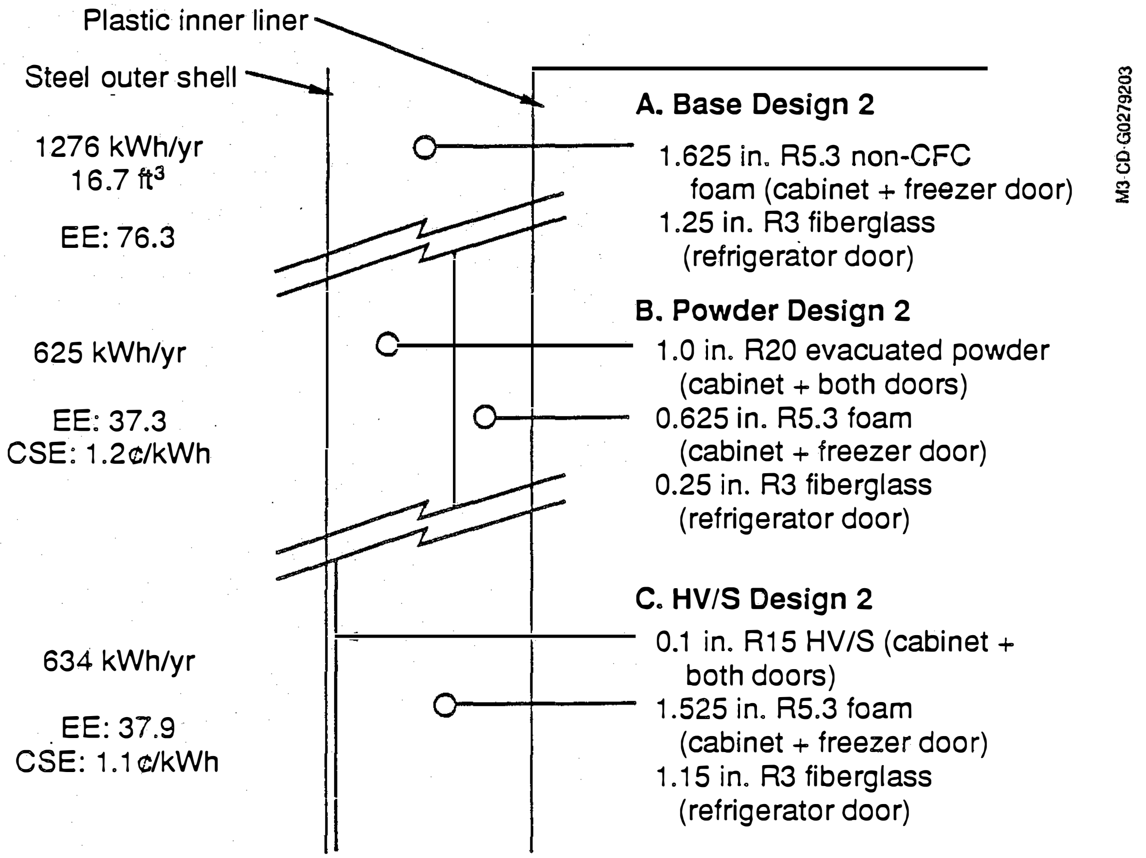

Figure 3. A base case with a hypothetical non-CFC (R=5.3) foam, and additions of advanced insulations, showing resulting energy use (to be compared to the CAES limit of 658 kWh for 16.7 ft^3)

Similarly, in Figure 4-B the compact vacuum insulation entirely replaces the base case foam, and the plastic inner liner is effectively expanded to include the 6 cubic feet previously filled with foam, increasing consumer amenity by increasing refrigerated storage space. In this case, the increased heat loss caused by the expanded interior shell slightly overcomes the decreased heat transfer attributable to an improved insulation, resulting in a yearly energy use of 1002 kWh. The figure of merit (EE) reflects the increase in volume despite the relatively unchanging energy use, dropping 31% from 64.6 to 44.3. The cost for this modification was calculated as only $45 (down from the previous case by the cost of the displaced foam). Cost-of-saved-energy is not appropriate here, since energy use was nearly unchanged; benefits were in CFC-avoidance and volume enhancement. However, this unit does not comply with CAES.

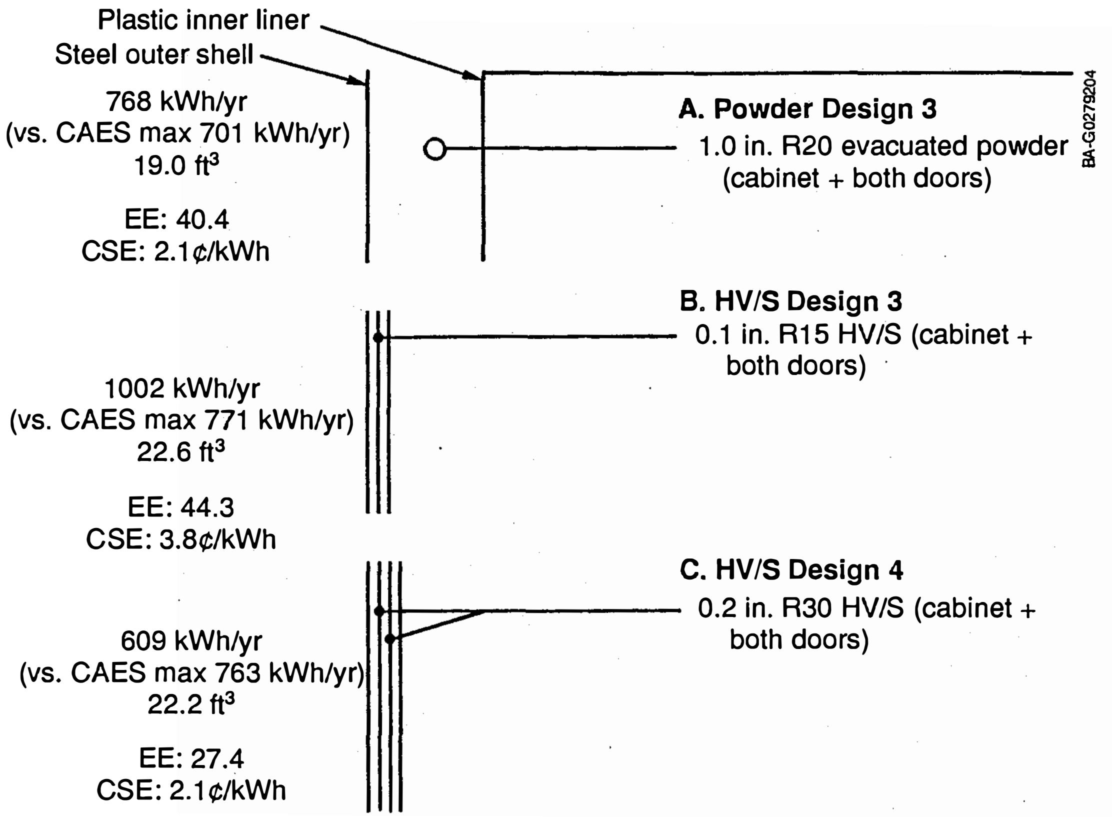

Figure 4. Advanced insulation replacement strategies showing effects on energy use and volume

In Figure 4-C we also show the effect of installing two layers of compact vacuum insulation to replace the foam insulation in the sidewalls. In this case, we benefit from both the higher volume and the lower energy use, now 22.2 cubic feet and 609 kWh/year, respectively. The figure of merit is 27.4, significantly down (58%) from the first base case, and the cost to accomplish this is calculated to be $150. Cost-of-saved-energy is $0.021/kWh.

To sum up the simulation exercises, we demonstrated that we could save enough energy to comply with CAES and eliminate more than half the CFCs when part of the existing insulation is replaced with either one inch of evacuated powder or one thickness of hard vacuum/spacer material. We gained volume at $8 per cubic foot when one thickness of the hard vacuum/spacer material was used, and we increased volume while meeting the standard using two thicknesses of the material. The energy use conclusions are summarized in Figure 5.

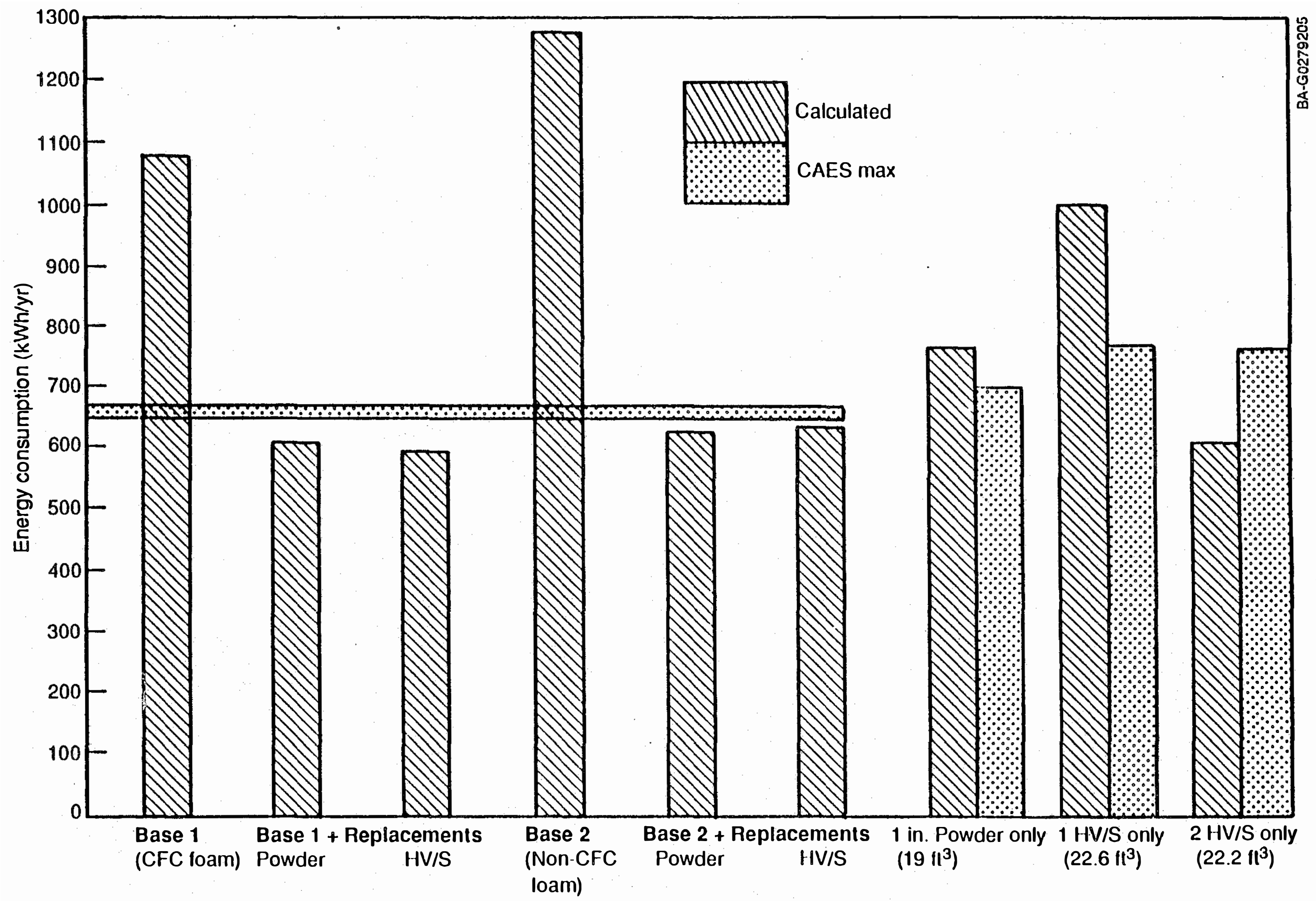

Figure 5. Summary of R/F Simulation Results: Calculated performance vs. CAES maximum

Several key issues must be addressed before we can bring any of these three advanced insulation technologies completely out of the laboratory and into widespread use. We must

- o prove the essential soundness of each technology, which includes defining the limits of materials, structures, and operating conditions
- o answer questions of durability and longevity
- o identify economical fabrication processes.

CONCLUSIONS

Significant and positive energy use and environmental impacts resulted from incorporating advanced insulations into R/Fs. Savings of more than 50% in energy use appear to be possible, with associated increases in salable refrigerated volume that may offset some or all of the anticipated cost of the improved insulation. Work to date on three vacuum alternatives supports continued optimism that solutions will be available for industry use in complying with energy efficiency and CFC-reduction requirements.

ACKNOWLEDGMENT

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