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DOMESTIC REFRIGERATOR/FREEZER APPLICATIONS FOR NEW TECHNOLOGIES

By

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ABSTRACT

This paper deals with the issues of meeting higher energy efficiency standards while phasing out CFC's in domestic refrigerator/freezer applications. An escalating social awareness, in addition to providing opportunity for new advertising strategies, improved market share and an enhanced replacement market through the early retirement of existing product in the field, is resulting in accelerating development schedules and an increased tax burden on the industry. Challenges facing the manufacturer do not present themselves without risk or without ramifications in many seemingly unrelated areas. Success in meeting these challenges will depend on the manufacturer's ability to implement new technologies without regard for corporate size or level of technical sophistication, while remaining within the constraints of capital limitations.

INTRODUCTION

The domestic refrigerator/freezer manufacturer is faced with a national appliance efficiency law that mandates significantly higher energy efficiency standards in 1993. The National Appliance Energy Conservation Act of 1987 established energy efficiency standards for a wide variety of consumer products. The products were segregated into separate classes to which different energy standards apply. Seven classes of refrigerator/freezers and three classes of freezers were specified.

In late 1989, the Department of Energy (DOE) issued a final rule on the 1993 refrigerator/freezer and freezer energy standards. Due to revisions in DOE's analysis, the final rule adopted levels of improvement that were significantly higher than expected or recommended in the Notice of Proposed Rulemaking. The DOE analysis was found to be flawed and though later amended for certain categories, remains flawed in other product categories. The final rule is based on DOE's assumption that CFC's will be available until 1996. Legislated schedules require the establishment of new energy efficiency standards again in 1998.

Within a similar time frame, the production of chlorofluorocarbons (CFC's) will be discontinued due to global environmental concerns. It has been fifteen years since CFC's were first implicated as a major contributor to the depletion of the ozone layer in the earth's stratosphere. Since then, as more data has accumulated, this assessment has become widely accepted by many in the scientific community. In early 1989, the Montreal International Protocol called for CFC production limits. To comply with this treaty, the United States Environmental Protection Agency (EPA) has proposed major reductions in the production of CFC's. In light of more recent data and the meeting of the European Environmental Ministers, it is anticipated that these reductions will be further accelerated.

The domestic refrigerator/freezer industry is affected in two areas. Polyurethane foam insulation utilizes a CFC blowing agent, CFC-11 (and a small amount of CFC-12), to maintain in-place densities. Proper density minimizes thermal conductivity, resulting in reduced cabinet heat leakage. Refrigerator/freezer sealed systems utilize a CFC refrigerant, CFC-12. Proper refrigerant selection and system design is critical to thermal performance and energy efficiency.

THE 1993 DOE REFRIGERATOR/FREEZER ENERGY STANDARD

The Final Rule

The DOE has determined that revised energy efficiency standards for refrigerators, refrigerator/freezers and freezers would result in significant conservation of energy and be economically justified. Therefore, on November 17, 1989, DOE issued The Final Rule amending Title 10, Part 430 of the Code of Federal Regulations to create new energy efficiency standards for these product categories. The new standards were established through simulations carried out using a computer model developed by Arthur D. Little. The A. D. Little steady-state energy model calculates heat leakage into a cabinet and then determines the energy needed by the refrigeration system to maintain interior temperatures as specified in the DOE test procedure.

The Final Rule defines seven classes of refrigerator/freezers and three classes of freezers. Energy standard equations were developed for each class. As the energy consumption of refrigerators, refrigerator/freezers and freezers depends on the fresh food (38°F) and freezer (0°F) compartment volumes, the standards were established in terms of adjusted volume (AV).

For refrigerators, which may include a freezer compartment for the storage of food above 8°F, the adjusted volume (R-AV) is defined as the fresh food volume (VFF) plus 1.44 times the freezer volume (VF):

$$\text{R-AV (CU FT)} = \text{VFF} + (1.44)\text{VF} \tag{1}$$

For refrigerator/freezers, the adjusted volume (R/F-AV) is defined as the fresh food volume (VFF) plus 1.63 times the freezer volume (VF):

$$\text{R/F-AV (CU FT)} = \text{VFF} + (1.63)\text{VF} \tag{2}$$

For freezers, the adjusted volume (F-AV) is defined as 1.73 times the freezer volume (VF):

$$\text{F-AV (CU FT)} = (1.73)\text{VF} \tag{3}$$

Corrections To The Final Rule

In 1990, representatives of refrigerator manufacturers and of the Association of Home Appliance Manufacturers (AHAM) informally approached DOE with concerns regarding the stringency of the energy standards for several product classes. Included, were the classes of Refrigerator and Refrigerator/Freezer-Manual Defrost (Class 1), Refrigerator/Freezer-Automatic Defrost with: Bottom-Mount Freezer w/o Through-the-Door Ice (Class 5) and Chest Freezer and All Other Freezers (Class 10). The DOE agreed to review design options considered in the engineering analysis and based upon their review, concluded that the energy standards were in error for these product classes. Action was taken to correct the standards, resulting in the energy standard equations appearing in Table 1.

To demonstrate the impact of The Final Rule, the Refrigerator and Freezer-Manual Defrost (Class 1) 1990 and 1993 energy standards have been plotted as functions of adjusted volume (Figure 1). As can be seen, legislated increases in energy efficiency originally ranged from 26.4 percent for larger units (17 CU FT AV) to 60.5 percent for compact units (2 CU FT AV). Corrected increases now range from 10.9 percent for larger units to 6.5 percent for compact units. Similar changes result from the corrected energy standard equations for the classes of Refrigerator/Freezer-Automatic Defrost with: Bottom-Mount Freezer w/o Through-the-Door Ice (Class 5) and Chest Freezer and All Other Freezers (Class 10).

PRODUCT CLASS	ENERGY STANDARD EQUATIONS (KWH/YR)	
	EFFECTIVE 1-1-90	EFFECTIVE 1-1-93
1. REFRIGERATOR AND REFRIGERATOR/FREEZER-MANUAL DEFROST	(16.3AV+316)	(13.5AV+299)
2. REFRIGERATOR/FREEZER - PARTIAL AUTO DEFROST	(21.8AV+429)	(10.4AV+398)
3. REFRIGERATOR/FREEZER - AUTO DEFROST WITH: TOP-MOUNT FREEZER W/O THROUGH-THE-DOOR ICE[1]	(23.5AV+471)	(16.0AV+355)
4. REFRIGERATOR/FREEZER - AUTO DEFROST WITH: SIDE-MOUNT FREEZER W/O THROUGH-THE-DOOR ICE	(27.7AV-488)	(11.8AV+501)
5. REFRIGERATOR/FREEZER - AUTO DEFROST WITH: BOTTOM-MOUNT FREEZER W/O THROUGH-THE-DOOR ICE	(27.7AV+488)	(16.5AV+367)
6. REFRIGERATOR/FREEZER - AUTO DEFROST WITH: TOP-MOUNT FREEZER WITH THROUGH-THE-DOOR ICE	(26.4AV+535)	(17.6AV+391)
7. REFRIGERATOR/FREEZER - AUTO DEFROST WITH: SIDE-MOUNT FREEZER WITH THROUGH-THE-DOOR ICE	(30.4AV+547)	(16.3AV+527)
8. UPRIGHT FREEZER - MANUAL DEFROST	(10.9AV+422)	(10.3AV+264)
9. UPRIGHT FREEZER - AUTOMATIC DEFROST	(16.0AV+623)	(14.9AV+391)
10. CHEST FREEZER AND ALL OTHER FREEZERS	(14.8AV+223)	(11.0AV+160)

[1] INCLUDING ALL REFRIGERATOR MODELS WITH AUTOMATIC DEFROST.

TABLE 1 : CORRECTED ENERGY STANDARD EQUATIONS FOR REFRIGERATORS, REFRIGERATOR/FREEZERS AND FREEZERS

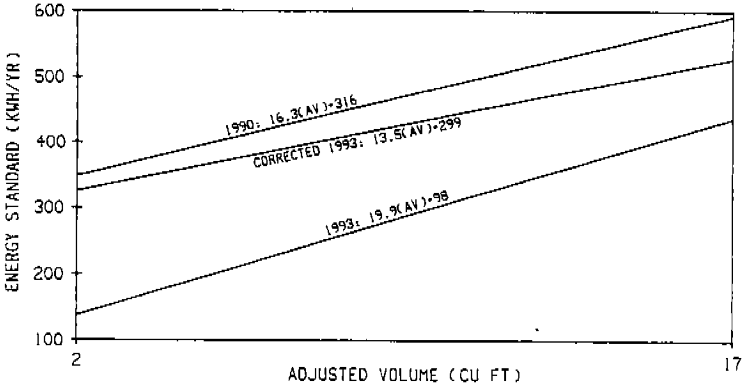

FIGURE 1 : CLASS 1 R/F WITH MANUAL DEFROST - 1990/1993 CORRECTED

Remaining Questions

The Final Rule was amended on October 24, 1990. However, remaining anomalies will result in a negative impact on consumers through higher product costs and the loss of specific refrigerator, refrigerator/freezer and freezer models.

As an example, Figure 2 depicts a comparison of the energy standard for manual defrost refrigerators to that for manual defrost vertical freezers as functions of adjusted volume. As can be seen in Figure 2, higher energy levels are permitted for refrigerators (38°F) than for vertical freezers (0°F). A similar relationship exists when compared as functions of AHAM (actual) volume.

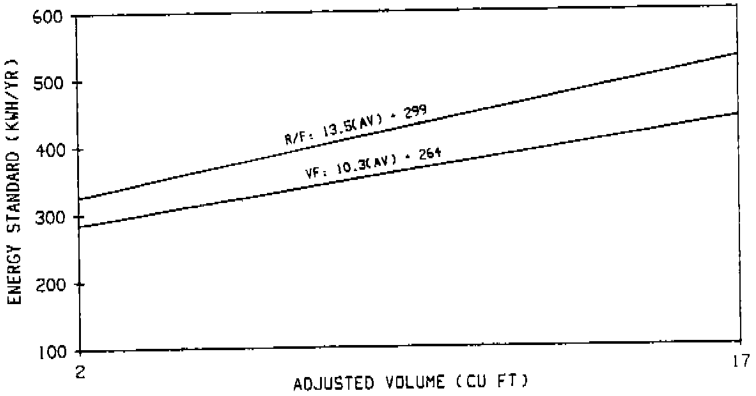

FIGURE 2 : CLASS I R/F VS CLASS 8 VF - 1993 CORRECTED

As flawed as the 1993 DOE Refrigerator/Freezer Energy Standard may be, it has been signed into law and becomes effective January 1, 1993. Furthermore, legislated schedules require the establishment of more stringent energy efficiency standards by 1998. If anticipated levels are adopted, the energy consumption of a typical refrigerator/freezer will have been reduced by nearly 90 percent between 1972 and 1998. However, to achieve the anticipated 1998 energy levels will require the implementation of new technologies while discontinuing the employment of CFC's currently being utilized as both sealed system refrigerants and polyurethane foam insulation blowing agents.

THE STATUS OF NON-CFC DEVELOPMENT

A History Of Refrigerants

The earliest attempts to transfer heat by means of mechanical refrigeration involved the use of volatile refrigerants, many of them toxic. Wide varieties of fluids have been considered as vapor compression refrigerants. Materials such as sulfur dioxide, methylene chloride and various forms of ether were actually used in commercial quantities. Ammonia is still being successfully used for many refrigeration applications.

CFC's were the result of a research effort to discover a new family of refrigerants that would be stable, non-toxic, non-flammable and possess ideal thermodynamic properties. Following their discovery in 1928, commercial production wasn't initiated until 1931. CFC's were first used in household refrigerators in 1933.

Depletion Of The Ozone Layer

Ozone, an oxygen molecule comprised of three oxygen atoms, is present in the earth's stratosphere at less than one part per million. However, the ozone layer shields the earth from much of the sun's cancer causing ultraviolet rays. Since 1977, atmospheric scientists have noted a severe depletion of ozone in the stratosphere over Antarctica. NASA has subsequently shown the depletion to include a much wider area. There are many theories as to the cause of ozone depletion, including those who believe it to be a natural oscillation of the weather systems or a result of volcanic activity. The most widely held view, however, is that chlorine, in the presence of sunlight and ice crystals, reacts to destroy ozone and that the source of chlorine in the earth's stratosphere is man's production of CFC's.

Although CFC's are non-toxic, non-flammable and possess ideal thermodynamic properties as refrigerants, it is their stability coupled with their chlorine content that has linked them to possible depletion of the ozone layer. CFC's regulated by the Montreal Protocol have been assigned an ozone depletion potential (ODP), a measure of the possible effect on the ozone layer of chlorine released from the compound, along with the estimated atmospheric lifetime of the compound. By definition, the ODP for CFC-11 is 1.0. The search for CFC substitutes has identified hydrofluorocarbons (HFC's) and hydrochlorofluorocarbons (HCFC's) as leading candidates. HFC's do not contain chlorine and therefore have zero ODP levels. In HCFC's, the presence of hydrogen reduces the stability of the molecule, allowing the chlorine to dissipate in the lower atmosphere and thereby resulting in a much lower ODP.

Present Status Of Non-CFC Alternatives

To maintain proper in-place densities and resulting thermal conductivities, polyurethane foam insulation systems have relied on CFC-11 as a primary foam expansion agent. As a blowing agent, CFC-11 is non-toxic, non-flammable, possesses a low vapor thermal conductivity and is compatible with ABS and certain grades of HIPS inner liner materials. The phaseout of CFC's is requiring an extensive search for effective, economical new blowing agents, with none of the leading candidates emerging as an ideal replacement.

PROPERTY	CFC-11	HCFC-22	HCFC-123	HCFC-141b
BOILING POINT (°F)	74.9	-41.4	82.2	89.6
OZONE DEPLETION POTENTIAL	1.00	0.05	0.02	0.15
GREENHOUSE WARMING POTENTIAL	1.00	0.34	0.02	0.15
VAPOR THERMAL CONDUCTIVITY (BTU/HR-FT-°F)	0.0054	0.0075	0.0080	0.0080
FLAMMABILITY LIMITS (%VOL)	NONE	NONE	NONE	7.3-16.0
TOXICITY AEL (PPM)	1000	1000	100	500
COMPATIBLE WITH ABS/HIPS	YES	MAYBE	NO	NO

TABLE 2: PROPERTIES OF ALTERNATIVE FOAM INSULATION BLOWING AGENTS

Presented in Table 2, is a comparison of pertinent physical properties for CFC-11 and probable alternative HCFC blowing agents. As can be seen from the data, there are no ideal alternatives for CFC-11. Although the HCFC's exhibit low potentials for ozone depletion, the greenhouse warming potential of HCFC-22 may eventually lead to its demise. All candidates appear to compromise thermal conductivity (although the likelihood of HCFC-22 being present only in the vapor phase, resulting in a lower thermal conductivity, suggests the need for further evaluation). The flammability limits of HCFC-141b may dictate suitability for certain applications. In light of the recent toxicity failures of HCFC-123, its future remains suspect. Furthermore, HCFC-141b is considered nearly as toxic as HCFC-123 (long-term toxicity testing remains incomplete, however). Although HCFC-22 shows promise with regard to its compatibility with ABS and HIPS, HCFC-123 and HCFC-141b will clearly require the development of new or revised inner liner materials.

For nearly sixty years, domestic refrigerator/freezer sealed systems have utilized a CFC refrigerant, CFC-12, to transfer heat. Proper refrigerant selection is critical to thermal performance and energy efficiency. The most likely sealed system refrigerant replacement for CFC-12 is HFC-134a, which has no potential for ozone depletion. Required revisions to compressor motor winding insulation and the development of compatible compressor lubricants appear to be nearing completion. Although HFC-134a is significantly less efficient than CFC-12 (a seven percent reduction in compressor EER under standard rating conditions), it is anticipated that proper system design can minimize the energy impact in application. The new refrigerant is commercially available and as production proceeds, cost increases are expected to stabilize.

Another HFC refrigerant, HFC-152a, is also being considered in certain applications. Although more efficient than HFC-134a, its flammability limits in air (3.9-16.9 percent by volume) make it an unlikely candidate for domestic refrigerator/freezer applications.

Due to the need for drop-in service replacements over the next several decades, it is anticipated that ternary mixtures (such as DuPont's HCFC-22/HCFC-124/HFC-152a blend) will also find a market.

APPLICATIONS FOR NEW TECHNOLOGIES

The clear objective in today's development strategies is to achieve high efficiency without the employment of CFC's. When evaluating domestic refrigerator/freezer applications for new technologies, it is convenient to consider separately, the cabinet side as the load source and the system side as the means through which the load is addressed. The load must be minimized at the source and that which remains must be transported in the most efficient manner achievable.

The Cabinet Side

It is estimated that approximately ten percent of cabinet heat leakage occurs through the door gasket areas, involving both the gasket cross section and the interaction between the gasket and adjoining surfaces. Figure 3 is a comparison of an existing door gasket configuration and a proposed design enhancement.

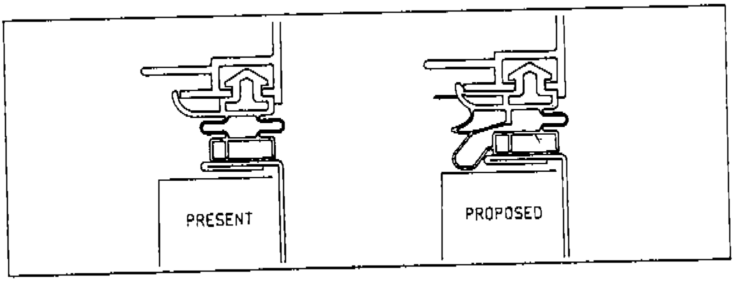

FIGURE 3: DOOR GASKET REDESIGN

As can be seen in Figure 3, several aspects of the door gasket design have been considered. In particular, the dead air space has been increased to reduce conduction of heat through the gasket area. In addition, several air baffles and balloons have been incorporated into the design in order to reduce air infiltration.

The greatest potential for cabinet heat leakage is through the composite walls and door assemblies. The formula for steady-state heat conduction in one dimension best approximates the heat transfer process:

$$\frac{Q}{A} = \frac{To-Ti}{\frac{1}{hi} + \frac{X1}{K1} + \frac{X2}{K2} + \frac{X3}{K3} + \cdots + \frac{1}{ho}} \qquad (4)$$

Where: Q/A = heat flow per unit area.
To-Ti = temperature difference between the room ambient and the refrigerated space.

hi,ho = inside, outside convection coefficients.
X1,X2,X3,... = individual layer thicknesses.
K1,K2,K3,... = individual conduction coefficients.

An analysis of Equation 4 identifies only the terms Xn and Kn as realistic opportunities for reducing cabinet heat leakage through the composite walls and door assemblies.

The most obvious approach to reducing heat leakage is to increase cabinet walls and door insulation thicknesses (Xn). However, disadvantages to this approach include the capital expenditure for retooling, increased material and shipping costs, a lower level of customer acceptance due to dimensional changes, and expanded foam insulation usage.

A better approach is to address the conduction coefficients (Kn). Most blowing agent candidates to replace CFC-11 appear to compromise thermal conductivity. Improvements may be realized with the development of superior blowing agents or by manipulating foam cell structure and uniformity through equipment changes. Additional opportunities may present themselves with the development of non-CFC vacuum insulations.

Vacuum insulations are compact panels comprised of an envelope under vacuum and an array of internal spacers to prevent collapse due to the differential between atmospheric pressure and the envelope's internal vacuum. They may or may not include filler materials. Issues such as envelope material and manufacturing processes, thermal conductivity of the spacers, spacer array, edge effects and filler material selection all impact performance, cost and resulting cost effectiveness.

Design criteria along with anticipated industry acceptance concerns regarding domestic refrigerator/freezer applications for non-CFC vacuum insulations have been summarized in Table 3. Perhaps the greatest challenge facing the emerging compact vacuum insulation industry is the manufacturability of the panel sections. The processes are complex and must be consistent in order to provide for repeatability and to permit multiple sourcing. Durability of the panel sections must result in their safe arrival at the refrigerator/freezer assembly line and their survival of the assembly process. Furthermore, the panels must be testable and reasonable test procedures must be developed for the design approval, receiving inspection and audit functions. The domestic refrigerator/freezer industry is in general agreement that line reject rates and in-warranty field failure rates cannot exceed 0.5 percent. It is imperative that the effect of failure be non-catastrophic. Therefore, it appears likely that the insulation system will be a composite of vacuum and polyurethane foam insulations, resulting in thermal conductivities ranging from R-30 to R-40. Additional weight should not exceed 30 pounds per refrigerator/freezer. To be competitive with polyurethane foam insulation, material and installation (labor) costs should not exceed 0.15$/SF-R.

DESIGN CRITERIA	INDUSTRY ACCEPTANCE CONCERNS
MANUFACTURABILITY	MULTIPLE SOURCES. CONSISTENCY
DURABILITY	SHIPPING. PRODUCTION HANDLING
TESTABILITY	DESIGN APPROVAL. RECEIVING INSPECTION. AUDIT
LINE REJECT RATE	LESS THAN 0.5 PERCENT
FIELD FAILURE RATE	LESS THAN 0.5 PERCENT IN WARRANTY
EFFECT OF FAILURE	NON-CATASTROPHIC
THERMAL CONDUCTIVITY	R-15 to R-25 (R-30 to R-40 COMPOSITE)
WEIGHT	LESS THAN 30 POUNDS
COST	MATERIAL. LABOR LESS THAN .15 $/SF-R

TABLE 3: VACUUM INSULATION PANEL DESIGN CRITERIA

The System Side

In a typical domestic refrigerator/freezer application (depicted in Figure 4), refrigeration is accomplished by continuously circulating a refrigerant through a sealed system. The sealed system is comprised of four major components: the compressor circulates the refrigerant, discharging high pressure vapor to the condenser; the condenser removes heat from the refrigerant due to temperature differences and by liberating the latent heat of condensation; the expansion device (usually a capillary tube) delivers liquid refrigerant to the evaporator at a reduced pressure; and in the evaporator, the refrigerant absorbs heat due to temperature differences and by absorbing the latent heat of vaporization.

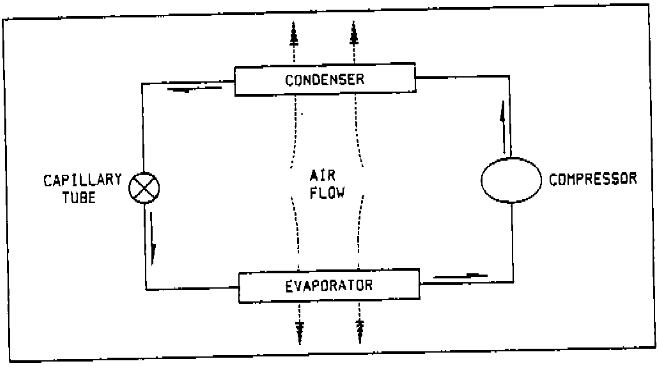

FIGURE 4: THE BASIC REFRIGERATION CYCLE

An analysis of the basic refrigeration cycle schematic identifies the compressor as the best opportunity for reducing energy consumption during the heat transport process. The fractional horsepower compressor industry has made great progress over the last decade in energy efficiency ratio (EER) enhancement. Although areas for improvement are becoming more difficult to identify, even with the introduction of less efficient non-CFC refrigerants, it is expected that for certain capacity ranges, compressor EER's will exceed 5.0 by 1993. By no means can it be assumed that these EER levels will be available for all capacity ranges. In particular, for smaller refrigerator/freezers, the correspondingly smaller compressors are less energy efficient. A more realistic expectation for compact applications is an EER level of 4.0.

The evaporator offers potential for energy improvement through enhanced refrigerant to air heat exchange, permitting the evaporator temperature to be raised and resulting in lower compressor energy consumption. This can be accomplished by redesigning primary (tube) and secondary (fin) profiles to provide for greater air flow (at acceptable sound levels), improved refrigerant flow, and increased heat exchange surface areas. Primary surfaces can be enhanced by adding internal grooves or other modifications. Secondary surfaces can be redesigned with various waffling configurations and by optimizing fin shapes and densities. Improvements in primary to secondary contact will also increase evaporator efficiency. Designing for ease of condensate disposal limits the defrost cycle, resulting in further reductions in energy consumption.

The opportunity remains for the development of more efficient refrigerants and refrigerant blends. HFC-152a, although flammable, is more efficient than HFC-134a, as are a number of binary and ternary mixtures. However, due to the wide array of required testing and the accelerating schedules, it is unlikely that refrigerants not yet identified could be commercially available in time to become a realistic part of the solution.

Other Considerations

Other areas of consideration also offer potential for energy improvement in domestic refrigerator/freezer applications. High efficiency evaporator and condenser fan motors lower energy consumption and (for the evaporator fan motor) reduce cabinet heat leakage. This can be accomplished without experiencing a loss in air flow and at moderate cost increases. Demand and adaptive defrost systems can reduce cabinet heat leakage by limiting unnecessary defrost cycles and can optimize performance by assuring a clear evaporator. Even selective feature levels can result in improvements in energy consumption when properly matched to the consumer's habits.

SUMMARY AND CONCLUSIONS

The domestic refrigerator/freezer industry has been heavily regulated in many areas and is being threatened with regulation in many new areas. As the federal government continues to legislate more stringent standards for energy efficiency, CFC's are being phased out on an alarmingly accelerating schedule. It is only through the development of new technologies that the domestic refrigerator/freezer industry will be able to achieve legislated levels of energy efficiency while phasing out CFC's.

An analysis of the cabinet side has identified door gasket redesign, potential for the development of improved foam insulation systems, and compact vacuum insulations as opportunities for non-CFC energy improvement. The application of vacuum insulations will require careful adherence to a difficult array of design criteria.

The system side analysis has identified continuing increases in compressor EER, new evaporator configurations, and the development of more efficient refrigerants and refrigerant blends as potential areas for improvement.

Other considerations include high efficiency evaporator and condenser fan motors, demand and adaptive defrost systems, and selective feature levels.

Success in meeting challenges facing the domestic refrigerator/freezer industry will depend on the manufacturer's ability to implement new technologies. There can be no consideration for corporate size or the level of technical sophistication. Although capital limitations may dictate the approach, legislation will assume that the entire industry possesses the technology necessary to meet stringent non-CFC energy efficiency standards.

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