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Chillers, Refrigerators, Supermarkets, Unitary Equipment

Global Warming Implications of Replacing Ozone-Depleting Refrigerants

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The past decade has been a challenging time for the HVAC&R industry worldwide. Provisions of the Montreal Protocol and its various amendments require the phaseout of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) compounds that have been used extensively as refrigerants in heat pumps, air conditioners and refrigeration systems. At the same time demands for increased energy efficiency and pressures from international competition have continued unabated.

A new international agreement—The Kyoto Protocol—has been initiated to reduce emission of greenhouse gases (GHGs) to reduce the potential risk of excessive global warming. More than 150 countries met last December in Kyoto and agreed to roll back emissions of carbon dioxide (CO_2) and five other GHGs, including hydrofluorocarbons (HFCs), by about 5.2% below 1990 levels by 2008 to 2012. Emissions targets were adopted for most developed countries. With CO_2 emissions tied directly to energy use, the pressures for further HVAC&R equipment efficiency improvements will increase in the early decades of the next century.

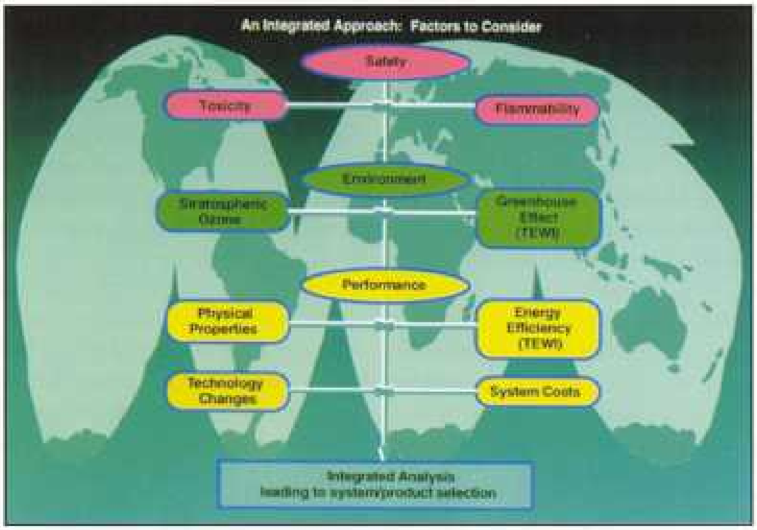

Figure 1: Factors to consider in selecting an optimum solution for a given heating, cooling or refrigeration requirement.

Many categories of HVAC&R equipment have been or are being redesigned to use HFCs or "natural" refrigerants* such as propane, ammonia and CO_2. As the transition from CFCs and HCFCs to HFCs progresses, issues are raised about whether a class of refrigerants exists that has a lower overall global warming impact on the environment. Are the worldwide efforts to solve one environmental problem—stratospheric ozone depletion—only exacerbating another—global warming? Should regulations restricting the use of flammable or toxic refrigerants be relaxed so they can be used in more applications because of their low global warming potential (GWP)? Can "high" GWP refrigerants be used prudently with a net environmental benefit?

The U.S. Department of Energy and AFEAS** jointly sponsored projects to identify the major applications of refrigerants worldwide and to examine the impacts of CFC and HCFC replacements on overall emissions of GHGs. The five major uses of refrigerants, based on refrigerant sales, are automobile air conditioning, supermarket refrigeration, unitary heat pumps and air conditioners, chillers for cooling large office and commercial buildings, and household refrigeration.

In 1991 and 1994, baseline and alternative refrigerants and technologies were examined for typical equipment in each of the five applications.[1, 2] Conventional systems for these applications all employ compressors, fans and maybe pumps to

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move heat either out of a cooled space or into a heated space. Consequently, these systems can lead to the emission of two different GHGs.

The energy consumed by the systems, in the form of electricity or the direct combustion of a fossil fuel, results in the release of carbon dioxide. Almost all of the refrigerants used in these applications are GHGs. If the refrigerant leaks out of the system during operation, is lost during maintenance or is not recovered when the system is scrapped, it contributes to global warming.

In 1997, the global warming impacts of alternative HFCs and natural refrigerants and new technologies that have a reasonable potential of becoming commercial products for these five applications before 2010 to 2015 were evaluated.[3] The study included applications in Europe, Japan and North America and used representative data for each region for equipment size and efficiency, weather and climate, and CO_2 emissions from power generation. This article summarizes results from that study with respect to four buildings' applications of HVAC&R equipment and systems.

Total Equivalent Warming Impact (TEWI)

The concept of Total Equivalent Warming Impact (TEWI) was developed to combine the global warming effects corresponding with the CO_2 released due to energy use over the lifetime of the system (indirect effect) with the effects resulting from lifetime refrigerant emissions (direct effect). TEWI makes use of GWPs for refrigerants relative to CO_2 published by the Intergovernmental Panel on Climate Change (IPCC).

Although TEWI is finding its way into common usage, it is probably best to spend a little time explaining the concept. *Figure 2* is a graph of the normalized radiative forcing (potential for temperature change) from the release of GHGs from two applications: (a) a "typical" low temperature refrigeration system in an American supermarket, and (b) a "typical" household refrigerator in North America. The vertical axes are dimensionless and represent theoretical radiative forcing of all GHGs emitted by the systems over their lifetime normalized to the radiative forcing of CO_2. Algorithms used for determing these theoretical values are described in the report issued from the original AFEAS/DOE global warming study.[1]

The supermarket and refrigerator examples were chosen to illustrate differences in warming impacts for systems with both large and small direct effects. The lower curves in each chart show how CO_2 from energy use accumulates in the atmosphere over the systems' lifetimes, and then how the CO_2 is gradually removed through natural processes (e.g. plants, ocean, rain water) in time. The upper curves illustrate the additional effect resulting from total refrigerant emissions from the systems and then its gradual decomposition in the atmosphere and removal.

The total effect from energy use and refrigerant emissions is proportional to the area under the curves; warming impact due to energy use corresponds to the area under the bottom curve and that from refrigerant emissions to the area between the curves. This total effect must be stated on the basis of some integration time horizon (ITH); i.e., how far out in time is the integration carried. Using a short period of time omits a great deal of the overall impact by leaving out much of the area under the curves. Using an extremely long period of time can understate the near term effects that these releases will have on climate change. A 100-year ITH is commonly used.

The computations required to estimate warming impacts using the theoretical radiative forcing curves (as in *Figure 2*) can be difficult, especially for applications where there are continuous low-level refrigerant emissions over the system lifetime.

The TEWI concept was developed as a simplified measure of lifetime total warming impacts. TEWI for a given application or system can be computed by estimating the total amounts of refrigerant and blowing agent (if applicable) released and the total energy used by the equipment being considered over its useful lifetime. TEWI is calculated by:

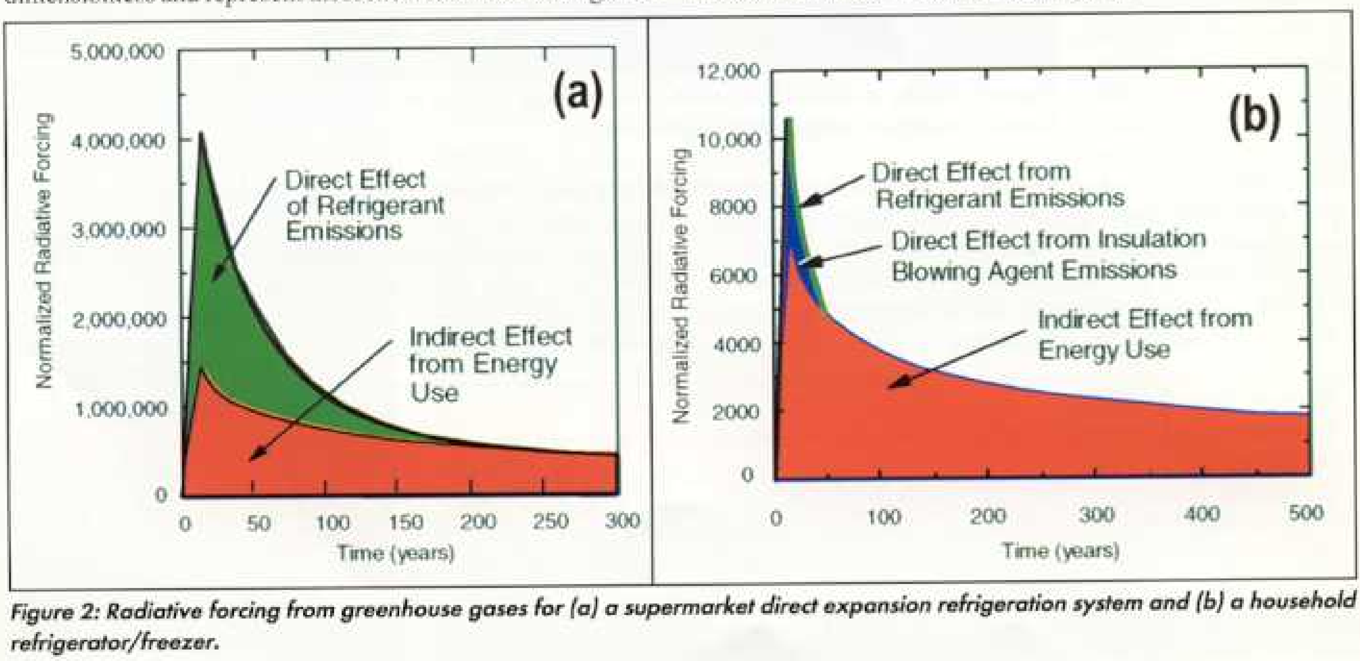

Figure 2: Radiative forcing from greenhouse gases for (a) a supermarket direct expansion refrigeration system and (b) a household refrigerator/freezer.

$$TEWI = MASS_{refrigerant} \times GWP_{refrigerant} + MASS_{blowing\ agent} \times GWP_{blowing\ agent} + \alpha \times E_{annual} \times L_{years}$$

The factor α is used to convert the annual energy use, E, and equipment lifetime, L, to the corresponding CO_2 emissions.

Results and Discussion

TEWI is useful for comparing the relative global warming impacts of alternative refrigerants or cooling technologies under a controlled set of assumptions. However, it is only one of many criteria that must be considered in making choices between HVAC&R options, as illustrated in *Figure 1*. Safety, health, other environmental concerns, owning and operating costs, ease of maintenance and energy sources are among other important factors that must be examined before choosing the most appropriate heating, air-conditioning or refrigeration option for any given application. Information developed in this study complements that of studies addressing many of these other issues to help industry, government and international policymakers reach sound decisions during the CFC and HCFC phaseouts and any GHG emissions rollback.

It is difficult to calculate an absolute value for TEWI. Uncertainties exist for all of the assumptions (many of which are estimates or averages) that enter into the TEWI calculations. Uncertainties in the direct effect include estimates of annual refrigerant leakage and end-of-life recovery rates as well as uncertainties in the GWP values themselves. The indirect contributions from energy use can be determined with less uncertainty (especially for specific local case studies where the fuel source can be characterized accurately), but these values are still not absolutely precise. These various uncertainties minimize the importance of small differences in TEWI comparisons between similar, established technologies that use the same energy source. When making such comparisons, if the TEWI differences are small, the technology that shows lower energy use might be preferable as long as safety and environmental considerations are adequately addressed and costs are reasonable. In some cases, a selection of the option with lowest energy consumption could result in choosing a technology with a calculated TEWI that is slightly greater than the minimum.

Supermarket Refrigeration. The display cases, walk-in coolers and refrigerated processing rooms in supermarkets are generally categorized as low temperature (frozen foods) and medium temperature (dairy, meat and fresh fish, and produce) systems. In large stores, these systems typically consist of racks of compressors in a back room connected to display cases on the sales floor by thousands of feet of field-erected refrigerant piping. The systems are designed for high dependability because of the value of the refrigerated inventory and ease of maintenance to minimize disruptions to customers and store operation. Very large amounts of refrigerant are required because of the high internal volumes of the piping. Historically, the systems have had high leakage rates.

Refrigerant emissions are being reduced as a result of changes in the costs of refrigerants as well as environmental concerns. There is a greater emphasis on preventive maintenance to locate and fix leaks, changes from quick disconnect couplings to brazed connections between piping and the display cases and changes in display cases to use continuous tubing instead of soldered return bends in the heat exchangers. Several supermarket chains and some major independent stores have shown that emission rates can be reduced to 10% of the charge per year.[4] European manufacturers and the U.S. Air-Conditioning and Refrigeration Institute (ARI) have estimated emissions for current systems ranging from 10% to 15% annually.[5,6] ARI has projected target leakage rates for the future that are even lower, about 6%.[6]

Figure 3 illustrates some typical results for this application from the study—in this instance, low temperature refrigeration for a supermarket in North America. The top four bars show the TEWI for different HFC refrigerants in direct expansion systems (i.e. remote compressor room, long piping) using an average of current leak rate estimates. The bars show small differences from energy consumption that are not significant because of the simplifications made in estimating energy use. The graph also shows the large fraction of TEWI resulting from refrigerant emissions with some alternative refrigerants clearly better than others with regard to global warming. The second set of bars shows that significant reductions in TEWI could be achieved for all of the refrigerants by meeting the ARI estimates for leakage rates in the future.

The bottom two sets of bars in *Figure 3* represent the TEWI for two alternative technologies for providing supermarket refrigeration: secondary loops and "distributed" refrigeration systems. Secondary loop systems still consist of compressor racks in a machine room, but an intermediate heat transfer loop is introduced so a brine is chilled in the machine room and is then pumped to the display cases.

This approach eliminates most major sources of refrigerant leakage as well as greatly reducing the refrigerant charge. Since the refrigerant has been isolated in the machine room and does not enter the retail sales floor, toxic or flammable refrigerants can be considered. Ammonia (R-717), which has zero GWP, is

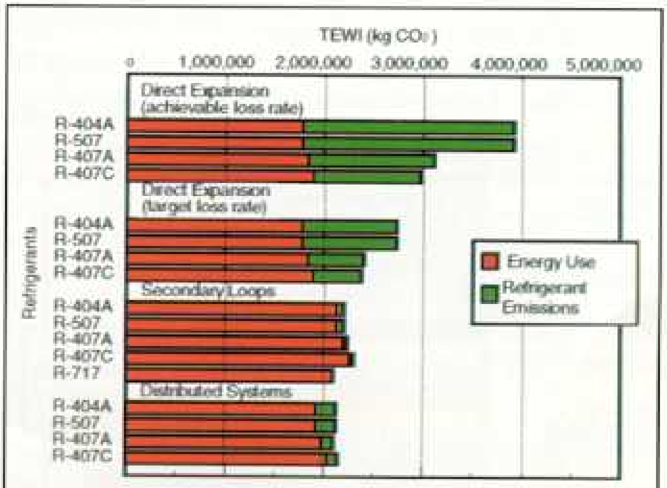

Figure 3: TEWI for low-temperature supermarket refrigeration in North America.

shown as one of the alternative refrigerants for secondary loop systems. These five bars show an increase in energy use compared to the alternatives above them, due to the pumping power required to circulate the brine and thermodynamic losses resulting from the intermediate heat exchanger. They also show lower TEWI than both baseline systems (at the top) and the alternatives with reduced leak rates.

Distributed systems rely on locating compressors close to the display cases they service (e.g. on the sales floor, on the roof, on top of walk-in coolers). For this study, a water loop for condenser heat rejection was assumed to transfer the heat removed from the display cases to a cooling tower or air-cooled heat exchanger on the roof. This imposed a pumping power requirement and a thermodynamic penalty on the refrigeration system similar to but smaller than that for the secondary loop systems. TEWI for the distributed systems are very similar to those for secondary loops with slightly lower energy use and slightly higher refrigerant emissions.

The TEWI for low temperature and medium temperature supermarket refrigeration systems in North America, Japan and Europe all show similar comparisons. Significant reductions in TEWI could be achieved through further improvements in leak reduction or by using either secondary loops or distributed refrigeration systems. With both secondary loop and distributed systems, there are only small differences in TEWI between the alternative refrigerants.

Unitary Space Conditioning. Heat pumps and air conditioners are commonly used in North America and Japan. In North America, these are frequently window mounted or through-the-wall packaged units or central "split systems" with the compressor and one heat exchanger mounted on a cement pad outside the building and another heat exchanger in the central air duct for the building. Systems in Japan commonly use a central compressor and outdoor heat exchanger with refrigerant pumped to individual heat exchangers in several different rooms in the building. Heat pumps are not as widely used in Europe, and many systems are heating-only types with hydronic distribution systems (secondary loop).

The TEWI for ducted, split-system, electric heat pumps is shown in *Figure 4* using residential building heating and cooling

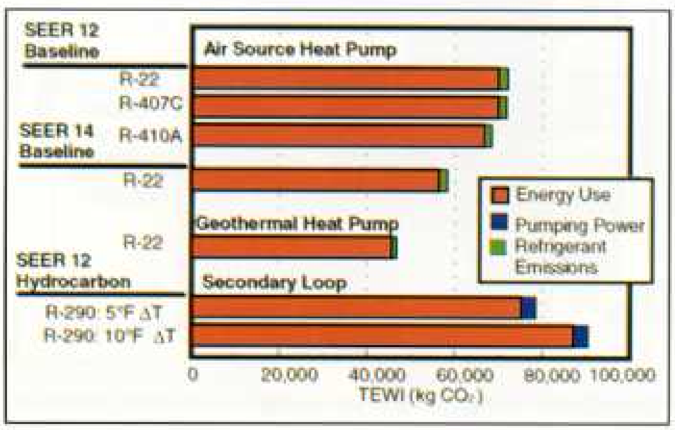

Figure 4: TEWI for heat pumps in Atlanta.

loads for Atlanta. R-407C and R-410A are shown as alternative refrigerants in comparison to standard and high efficiency R-22 air-source heat pumps. R-407C and R-410A are both mixtures of HFCs that are being developed to replace R-22. The bars for the high efficiency R-22 heat pump and geothermal (ground source) heat pump clearly show that reductions in TEWI can be achieved by efficiency gains that exceed the direct effects on global warming from refrigerant losses.

The bottom two bars illustrate a problem in using flammable refrigerants in residential and commercial applications. These bars correspond to heat pumps using propane (R-290) as the refrigerant with a secondary loop between the outdoor equipment and the air ducts in the house. The secondary loops are essential components in providing user safety by isolating the refrigerant outside the building where it can safely disperse in case a leak develops. Without the secondary loop, the hydrocarbon system (propane in this case) has efficiencies that are virtually identical to those of R-22 (top bar).

The secondary loop increases energy use because of the temperature difference between the refrigerant and the brine and the pumping power required to circulate the brine. As mentioned earlier, connecting a heat pump to a hydronic distribution system, as is done in Europe, would mean that the same ΔT and pumping power would be experienced with all refrigerant options and TEWI estimates would be essentially identical.

Gas engine-driven heat pumps are on the market and advanced gas absorption heat pumps are being developed with a market entry target of about 2000. These are evaluated for residential heating/cooling application in the full report.[3] They show potential to reduce TEWI for locales dominated by heating requirements.

Chillers. Chillers are efficient machines for cooling water that is circulated to fan coil units in large commercial buildings. Chillers use a variety of different types of compressors depending on the design cooling load; reciprocating, screw, scroll, and centrifugal chillers are all common as are gas-fired absorption chillers. The focus of this article is on centrifugal chillers because they dominate the market in North America in terms of installed capacity. There are also a great many low capacity reciprocating chillers in use in North America. Absorption chillers dominate the market in Japan.

Historically, production of centrifugal chillers was divided between low-pressure machines using R-11 and high-pressure systems using R-12. R-123 and R-134a have been phased in to replace R-11 and R-12, respectively. Very large capacity centrifugal chillers have used R-22. The phase-out of HCFCs mandated by the Montreal Protocol has resulted in efforts to identify replacements for both R-123 and R-22, although there are no clear alternatives at this time. At least one independent source has suggested that perhaps an exemption for R-123 could be considered (if no acceptible alternative can be found) due to its very low GWP and the high energy efficiency (e.g., low CO_2 emissions) of machines that utilize it.[7] Ammonia is being used in some systems. There are safety issues and regulations affecting the use of both ammonia and hydrocarbons in large systems in residential and commercial areas because of the large refrigerant charges, so it will be difficult for ammonia to be used as a substitute in all chiller applications and unlikely that hydrocarbons will be used outside of industrial applications.

There is some disagreement about what assumption for refrigerant loss rates due to leakage, purging (air must be purged from low pressure systems for proper operation), and maintenance best represents the current population. Prior to the Montreal Protocol refrigerant loss rates were fairly high. New chillers are significantly tighter and high efficiency purge units have reduced emissions considerably.

ARI estimated emission rates of 0.5% to 2% annually,[6] and 4% was used in the first two TEWI studies.[1,2] *Figure 5* shows the TEWI for 3500 kW (1,000 ton) chillers in Atlanta for several different refrigerants and a range of refrigerant loss scenarios. The direct global warming effect from refrigerant losses is a small fraction of the TEWI at all the emission rates analyzed, particularly for R-123 machines. Results for ammonia (R-717) are for screw chillers, as are the results for R-22. The results for R-123 and R-134a are for centrifugal chillers.

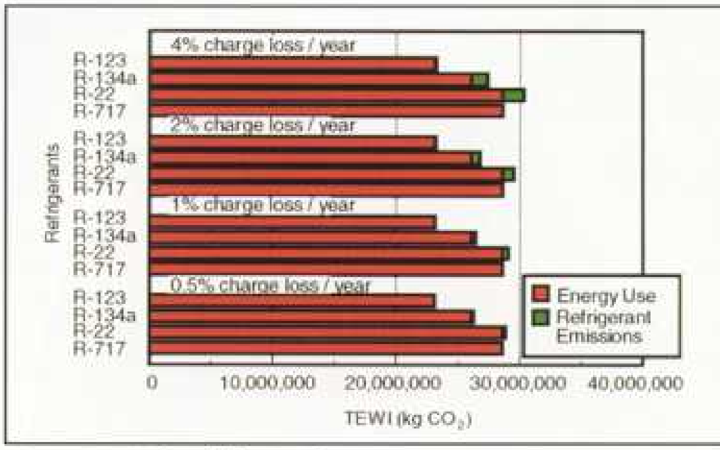

Figure 5:* *TEWI for chillers in Atlanta.

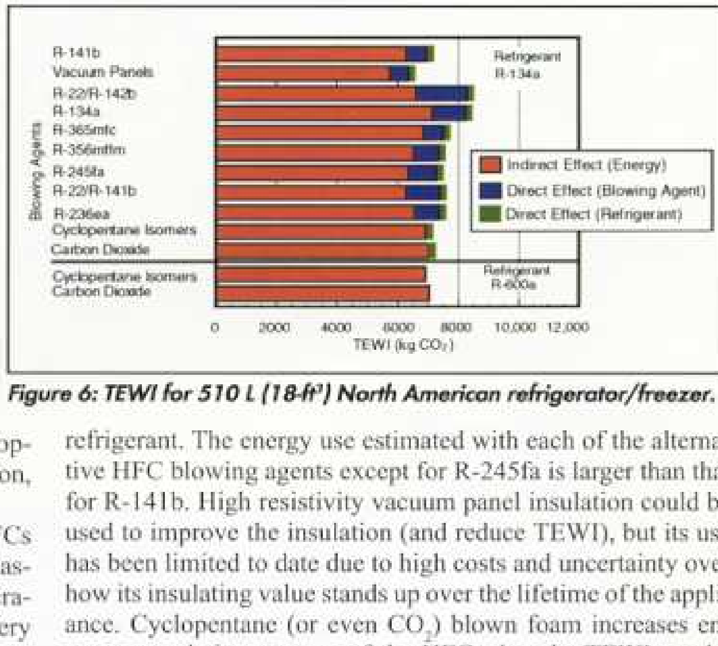

Figure 6:* *TEWI for 510 L (18-ft³) North American refrigerator/freezer.

TEWI for this class of equipment has fallen 25% to 30% since the early '90s for new chillers. Significant improvements in equipment efficiency, replacement of CFC refrigerants with HCFC and HFC alternatives and reductions in refrigerant loss rates are the principal reasons for the lower TEWIs. The choice of refrigerant makes only a minor difference in direct TEWI in new chillers. Differences in efficiencies for various refrigerant options have a significant impact on the indirect contribution, however, which is dominant in this application.

Household Refrigerators. Refrigerators have used CFCs as refrigerants since the 1950s and as blowing agents for plastic foam insulation since the early 1970s. Both the refrigeration systems and the insulation have been developed to be very efficient, first with R-12 and R-11 for the refrigerant and blowing agent and then with R-134a and R-141b in North America, Japan and parts of Europe.

Many European products now use isobutane as the refrigerant and cyclopentane or various pentane isomers as the blowing agent. Alternative blowing agents are needed to replace R-141b in the U.S., which is due to be phased out by 2003. Many different HFCs have been considered to fill this role, but manufacturers and suppliers have not yet settled on the best replacement.

Estimated TEWI for a 510 L (18 ft³) North American refrigerator are shown in *Figure 6*. The energy use segments of the bars are based on the best U.S. DOE 90°F (32°C) closed-door test results available on refrigerator cabinets containing foam formulations using these chemicals as blowing agentslisted.[8] Further development of foam formulations with the alternative HFC blowing agents is expected to reduce their energy use.

The bars in *Figure 6* have segments for the energy use, direct effect of the blowing agent, and direct effect from the refrigerant. The energy use estimated with each of the alternative HFC blowing agents except for R-245fa is larger than that for R-141b. High resistivity vacuum panel insulation could be used to improve the insulation (and reduce TEWI), but its use has been limited to date due to high costs and uncertainty over how its insulating value stands up over the lifetime of the appliance. Cyclopentane (or even CO_2) blown foam increases energy use relative to most of the HFCs, but the TEWI can be lower. The HFC refrigerant adds a small contribution to TEWI.

Conclusions

The concept of total equivalent warming impact, or TEWI, was developed as a comparative index of global warming impacts of competing options for meeting a given end use application. Examples have been shown for four different heating, cooling and refrigeration applications. In most of these, the CO_2 emissions resulting from energy use dominate the results. Efforts to improve system efficiency and reduce CO_2 emissions will yield the greatest reduction in global warming impact.

For supermarket refrigeration, however, the level of refrigerant emissions is relatively high and changes in design or technology that reduce these emissions can make significant reductions in TEWI. Secondary loops or distributed systems have the potential to greatly reduce TEWI for supermarket systems using either fluorocarbon or natural refrigerants.

The TEWI index provides a useful tool in the assessment of competing technologies that could be used as chemical compounds are phased out under the Montreal Protocol. However, it is only one of many factors that must be considered in evaluating the "best technology" for any given application. Other factors include safety, health, costs, reliability, ease of maintenance and regional energy sources.

Notes

* "Natural" refers to something that occurs naturally in the biosphere, and it is used here with some reluctance. The term implies connotations of being better or safer than something that is "manufactured," while in truth special considerations are needed to accommodate the flammability or toxic nature of some "natural" compounds when they are used as refrigerants.

** The Alternative Fluorocarbons Environmental Acceptibility Study, an international consortium of fluorocarbon manufacturers created to evaluate the environmental acceptability (exclusive of toxicity, which is evaluated by separate consortia) of fluorocarbon refrigerants, foam insulation blowing agents and solvents.

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