TEWI Analysis: Its Utility, Its Shortcomings, and Its Results

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Abstract:
The past decade has been a challenging time for the refrigeration and air conditioning industry worldwide. Provisions of the Montreal Protocol and its amendments require the phaseout of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) compounds that have been used extensively as insulating foam blowing agents and refrigerants in refrigeration systems, heat pumps, and air conditioners. In response, hydrofluorocarbon (HFC) compounds were proposed, developed, and are starting to be used as the primary alternatives to CFCs and HCFCs. However, in 1997 under the Kyoto Protocol, industrialized nations have agreed to roll back emissions of HCFCs, carbon dioxide (CO_2), and four other greenhouse gases which threaten to cause excessive global warming. The U.S. Department of Energy and the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) jointly sponsored research projects to identify the major applications of CFCs, HCFCs, and HFCs and to examine the impacts of these compounds and the energy use of applications employing these compounds on global warming. The five major uses of fluorocarbons based on sales were automobile air conditioning, supermarket refrigeration, unitary heat pumps and air conditioning, chillers for cooling large office buildings, and household refrigeration. Almost all of the refrigerants used in these applications are global warming gases, and if the refrigerant leaks out of the system during operation, is lost during maintenance or is not recovered when the system is scraped, it contributes to global warming. But, it is also true that the energy consumed by refrigeration and air conditioning systems, in the form of electricity or the direct combustion of fossil fuel, results in the release of CO_2, the primary cause of atmospheric global warming.

The concept of Total Equivalent Warming Impact (TEWI) was developed to combine the global warming effects of CO_2 released to the atmosphere due to energy used over the lifetime of a system (indirect effect) with the effects resulting from refrigerant and blowing agent emissions (direct effect). TEWI serves as a comparative index of global warming impacts of competing options for meeting a given end use application. For automotive air conditioning and supermarket refrigeration of refrigerant emissions are relatively high and changes in design or technology that reduce these emissions or use of alternative, non-fluorocarbon technologies can make significant reductions in TEWI. In the other three applications studied, the CO_2 emissions resulting from energy use dominate the results. In these applications, efforts to improve system efficiency and reduce CO_2 emissions will result in the greatest reduction in global warming impact. While the TEWI index provides a useful tool in the assessment of competing technologies that could be used as alternatives to those using fluorocarbons, it is only one of many factors that must be considered in choosing the "best technology" for any given

application. Other factors include safety, costs, reliability, ease of maintenance and regional energy sources.

Introduction

Many categories of HVAC&R equipment have been, or are being, redesigned to use HFCs or "natural" refrigerants[1] such as propane, ammonia, and carbon dioxide. As the transition from CFCs and HCFCs to HFCs progresses, issues are raised about whether a class of refrigerants exists that has lower overall impact on the environment, particularly with regard to 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[2] jointly sponsored projects at Oak Ridge National Laboratory (ORNL) to identify the major applications of refrigerants worldwide and to examine the impacts of CFC and HCFC replacements on overall emissions of greenhouse gases. The five major uses of refrigerants, based on magnitude of refrigerant sales, were found to be 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 (Fischer, et al, 1991; Fischer, et al, 1994). Conventional systems for these applications all employ compressors, fans, and maybe pumps to move heat either out of a cooled space or into a heated space. Consequently these systems can lead to the emission of two different greenhouse gases. The energy consumed by the systems, either 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 also greenhouse gases. If the refrigerant leaks out of the system during operation, is lost during maintenance, or is not recovered when the system is scrapped, it also contributes to global warming. The concept of Total Equivalent Warming Impact (TEWI) was developed to combine the global warming effects corresponding to the carbon dioxide 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 carbon dioxide published by the Intergovernmental Panel on Climate Change (IPCC).

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[1] "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.

[2]The Alternative Fluorocarbons Environmental Acceptability 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.

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 (Sand, et al, AFEAS 1997). 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 carbon dioxide emissions from power generation. This article summarizes results from that study.

TEWI

Although TEWI is finding its way into common usage, it is probably best to spend a little time explaining the concept. Figure 1 is a graph of the normalized radiative forcing (potential for temperature change) from the release of greenhouse gases (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 determining these theoretical values are described in the report issued from the original AFEAS/DOE global warming study (Fischer, et al, 1991). 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 carbon dioxide from energy use accumulates in the atmosphere over the systems' lifetimes, and then how the carbon dioxide 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); 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 a lot 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 1) 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:

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

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

Results and Discussion
The TEWI concept is a useful technique 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 2, 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.

Automotive Air Conditioning. Three fundamentally different cooling systems were considered for automobile air conditioning; a conventional HFC-134a based system, an HC-290 based system, and a transcritical vapor compression system using CO_2 as the refrigerant. The analysis for the hydrocarbon system included losses associated with using a secondary heat transfer loop to isolate the flammable refrigerant (propane – HC-290) outside the passenger compartment. This safety feature reduces the cycle efficiency relative to direct expansion systems, adds parasitic energy consumption due to the fluid pump, and increases overall system weight.

The 1997-analysis included much more detailed information than previous studies. It used the same approach of evaluating energy use for operating and transporting the air conditioner and the direct contribution of refrigerant emissions. Results were computed for thirteen different countries. Figure 3, shows the results for the hottest climates in each region of Japan, Europe, and North America. Each bar in Figure 3 contains five segments (some are too small to show up on the graph):

- a segment for the CO_2 from the energy used to power the air conditioner (indirect),
- a segment for the CO_2 from energy used to transport the air conditioner (indirect),
- a segment for the direct effect of refrigerant emissions under a minimum loss scenario (direct),

and

- two segments for the incremental effect of higher refrigerant loss rates (losses requiring 2 service visits during the lifetime of the vehicle with additions of refrigerant equaling 40% of the original charge and 1½ service visits).

Two different bars are shown for the transcritical CO_2 cycle (R-744); (A) assuming only equivalent total cooling load and (B) assuming equivalent total cooling load and evaporator exit air temperature (which affects passenger comfort). Depending on the climate and refrigerant emissions, the alternative systems show potential for lower TEWI than the HFC-134a system. This potential must be weighed against the cost, reliability, service and maintenance considerations, and passenger comfort and safety. More extensive prototype development and field trial testing are needed to determine the viability of both the hydrocarbon and transcritical CO2 systems in consumer products and whether or not these potential reductions are achievable at reasonable cost.

The direct effect of refrigerant emissions for HFC based automobile air conditioners is a significant part of the TEWI. The automobile manufacturers have responded aggressively with efforts to reduce charge size and emissions. Research and laboratory development of air-conditioning systems based on transcritical CO_2 compression show a potential to reduce TEWI for this application. Estimated TEWIs for CO_2 and hydrocarbon systems are lower than those for HFC-134a systems in regions with cool climates as shown more clearly in the full report (Sand, et al, 1997); TEWI are comparable to higher in climates with high cooling loads as shown in Figure 3. Energy consumption estimates for HFC systems are consistently lower than those for CO_2 and hydrocarbon systems.

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 and 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 (Richey 1995). European manufacturers and the U. S. Air-Conditioning and Refrigeration Institute (ARI) have estimated emissions for current systems ranging from 10% to 15% annually (Haaf 1996 and Hourahan 1996). ARI has projected target leakage rates for the future that are even lower, about 6% (Hourahan 1996).

Figure 4 illustrates some typical results for this application from the ORNL 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 Fig. 4 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, a toxic or flammable refrigerants can be considered. Ammonia (R-717), which has zero GWP, is 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 our 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.

While only one set of results is shown, 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 *from the best attainable in 1997* through further improvements in leak reduction or by employing either circulating brine in secondary loops or using 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 5 using residential building heating and cooling 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 one of the problems 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 adds a thermodynamic loss because of the temperature difference between the refrigerant and the brine circulated to the house 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 now and advanced gas absorption heat pumps are being developed with a market entry target of around 2000. These are evaluated for residential heating/cooling application in the full report (Sand, et al, 1997). They show some 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 certain alternatives at this time. At least one independent source has suggested that perhaps an exemption for R-123 could be considered (if no acceptable 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 (Anderson and Morehouse, 1997). 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 ½% to 2% annually (Hourahan 1996) and 4% was used in the first two TEWI studies (Fischer, et al, 1991, 1994). Figure 6 shows the TEWI for 3500 kW (1000-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.

TEWI for this class of equipment has decreased 25% to 30% since the early 90's 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 chlorofluorocarbons as refrigerants since the 1950s and as blowing agents for polymer 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. because it 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 typical 510-liter (18 ft^3) North American refrigerator are shown in Figure 7. The energy use segments of the bars are based on U. S. DOE 90 F closed-door test results on refrigerator cabinets containing foam formulations using these chemicals as blowing agents (Haworth 1996). Results for the alternative HFC blowing agents are based on the best results obtained in 1997. Further development of foam formulations with these blowing agents is expected to reduce energy use.

The bars in Fig. 7 have segments for the energy use, direct effect of the blowing agent, and direct effect from 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 five different heating, cooling, and refrigeration applications. In most of these, the CO_2 emissions resulting from energy use dominate the results; and efforts to improve system efficiency, and reduce CO_2 emissions, will yield the greatest reduction in global warming impact. For automotive air conditioning and supermarket refrigeration, however, the level of refrigerant emissions remains relatively high and changes in design or technology that reduce these emissions can make significant reductions in TEWI. Use of a transcritical CO_2 cycle for automotive air conditioning results in lower direct effects from refrigerant emissions and has the potential to reduce TEWI despite a lower cycle efficiency. 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 (safety, health, costs, reliability, ease of maintenance, and regional energy sources are among the others.).

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Figure Captions

Figure 1 Radiative forcing from greenhouse gases for (a) a supermarket direct expansion refrigeration system (b) a household refrigerator/freezer

Figure 2 Factors to consider in selecting an optimum solution for a given heating , cooling, or refrigeration requirement.

Figure 3 TEWI for automobile air conditioners.

Figure 4 TEWI for low temperature supermarket refrigeration in North America.

Figure 5 TEWI for heat pumps in Atlanta.

Figure 6 TEWI for chillers in Atlanta.

Figure 7 TEWI for 510 liter (18 ft^3) North American refrigerator/freezer.

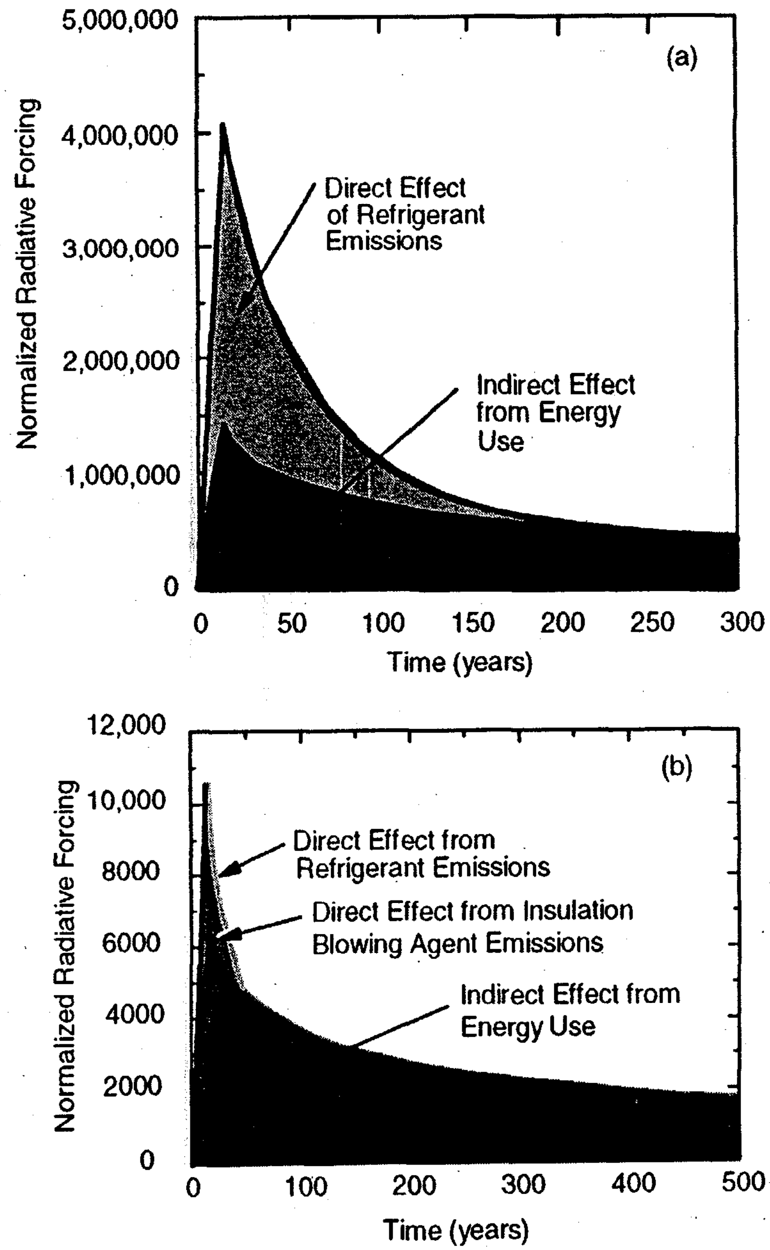

Figure 1. Radiative forcing from greenhouse gases for (a) supermarket direct expansion refrigeration system and (b) a household refrigerator/freezer

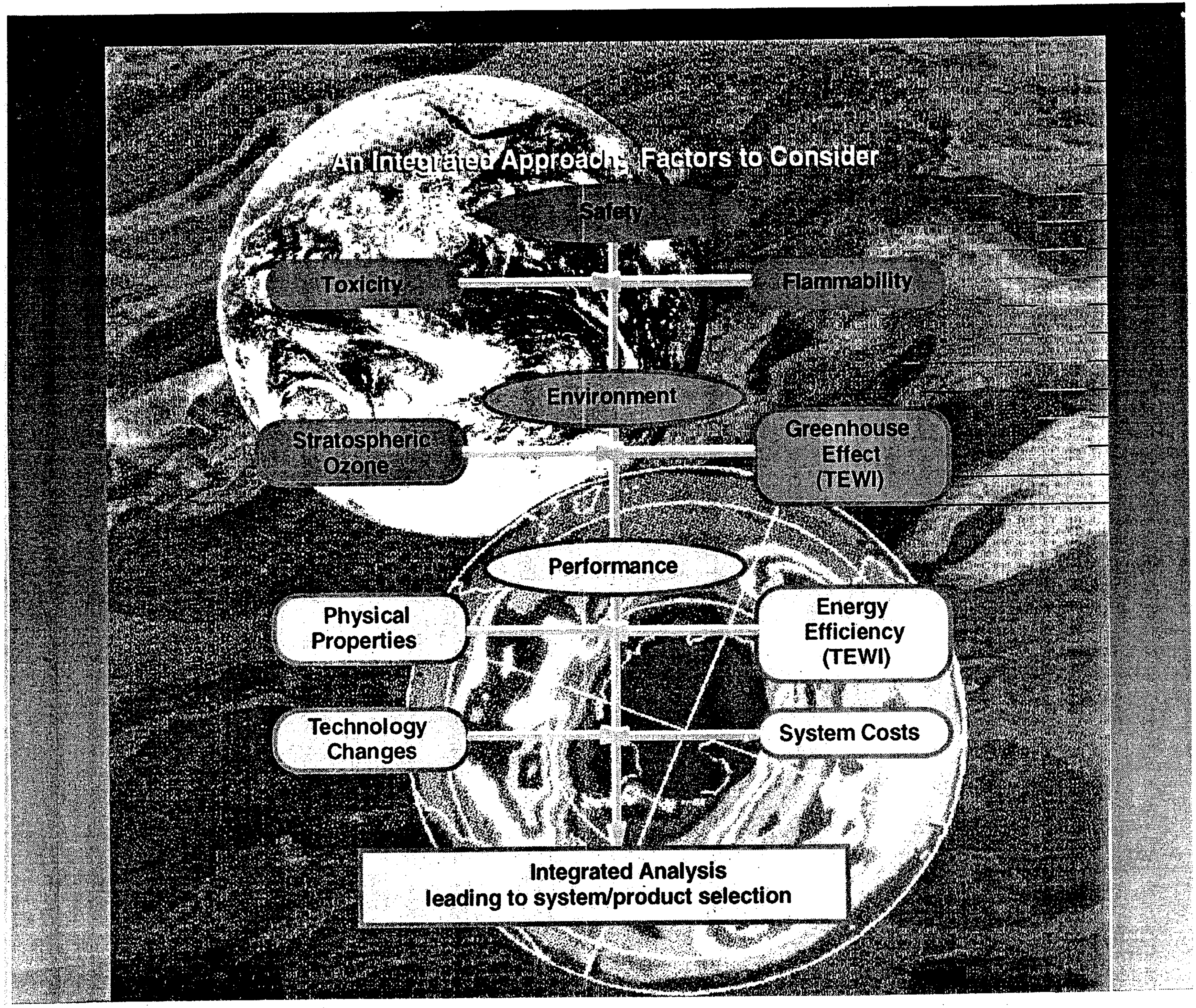

Figure 2 Factors to consider in selecting an optimum solution for a given heating, cooling, or refrigeration requirement.

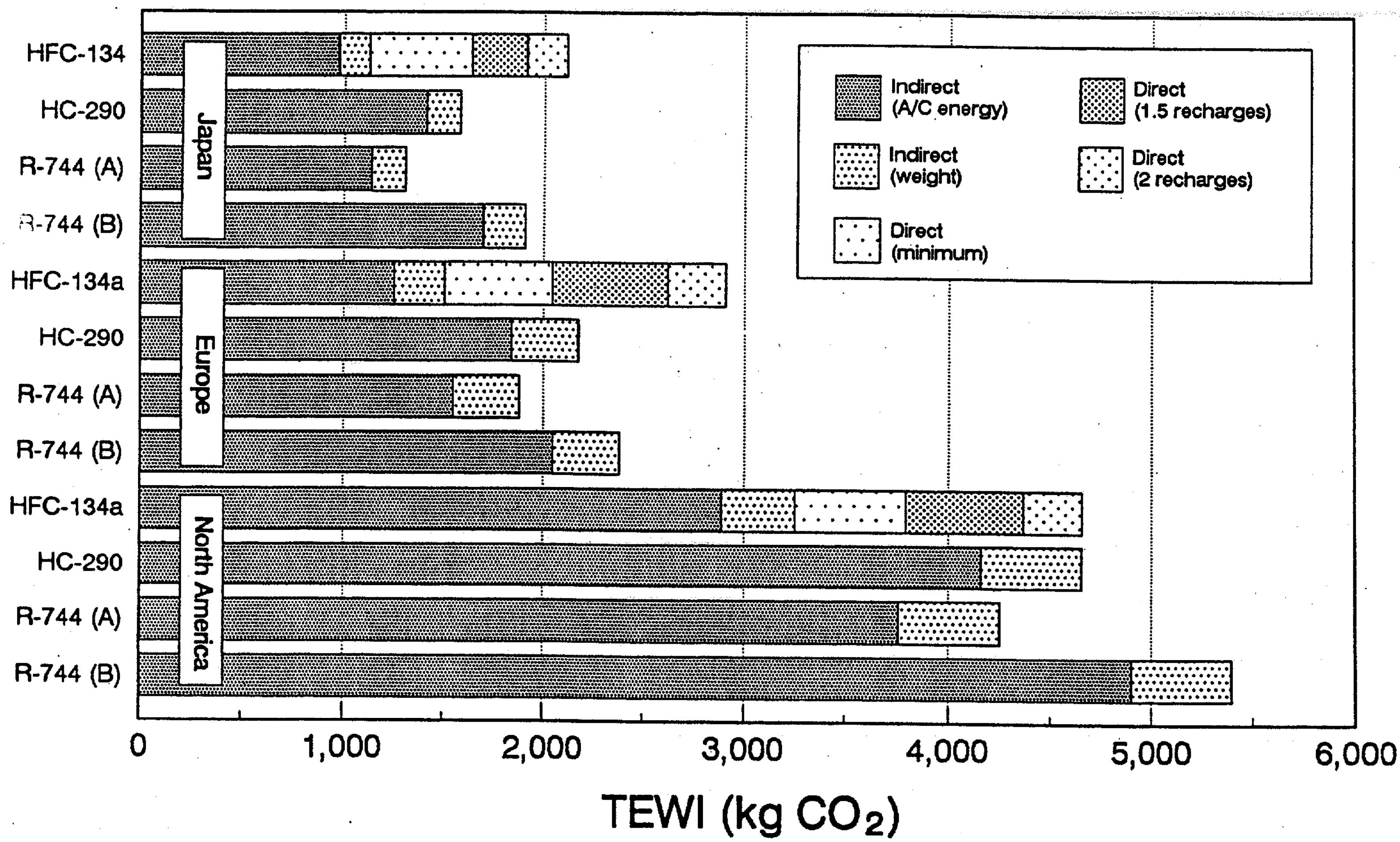

Figure 3 TEWI for automobile air conditioners.

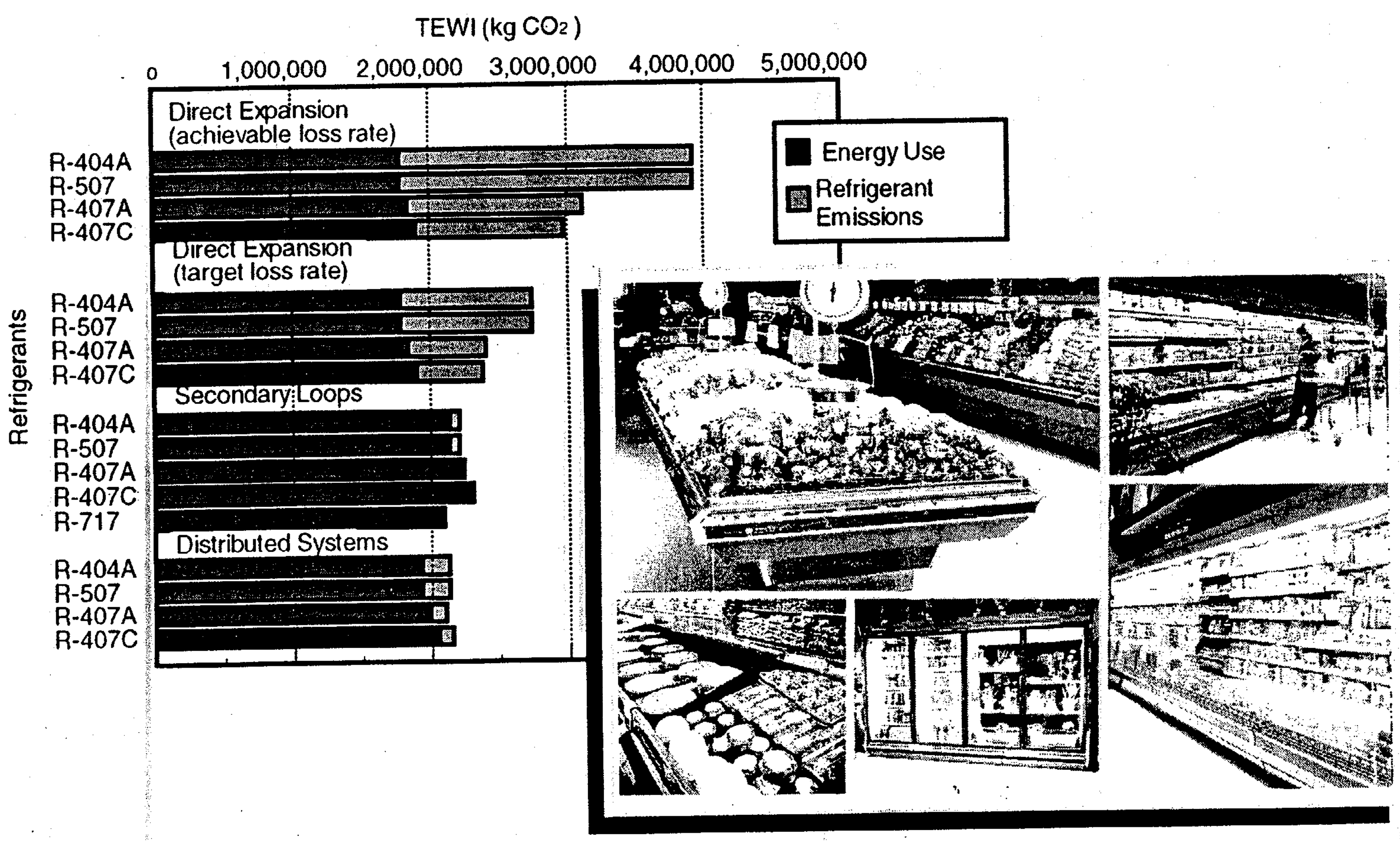

Figure ~~3~~ 4. TEWI for low temperature supermarket refrigeration N orth America

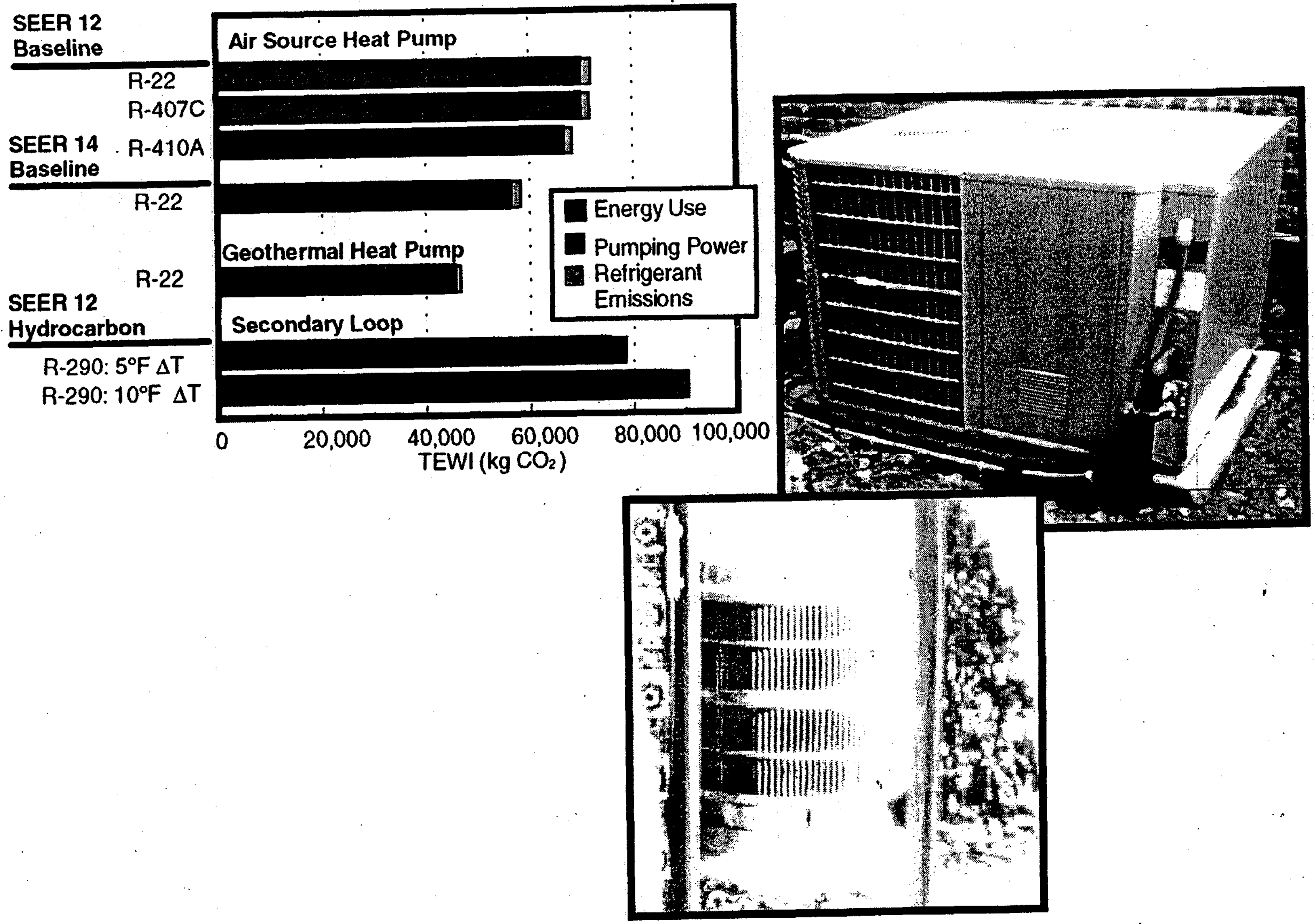

Figure ~~4~~ 5. TEWI for split system heat pumps in Atlanta

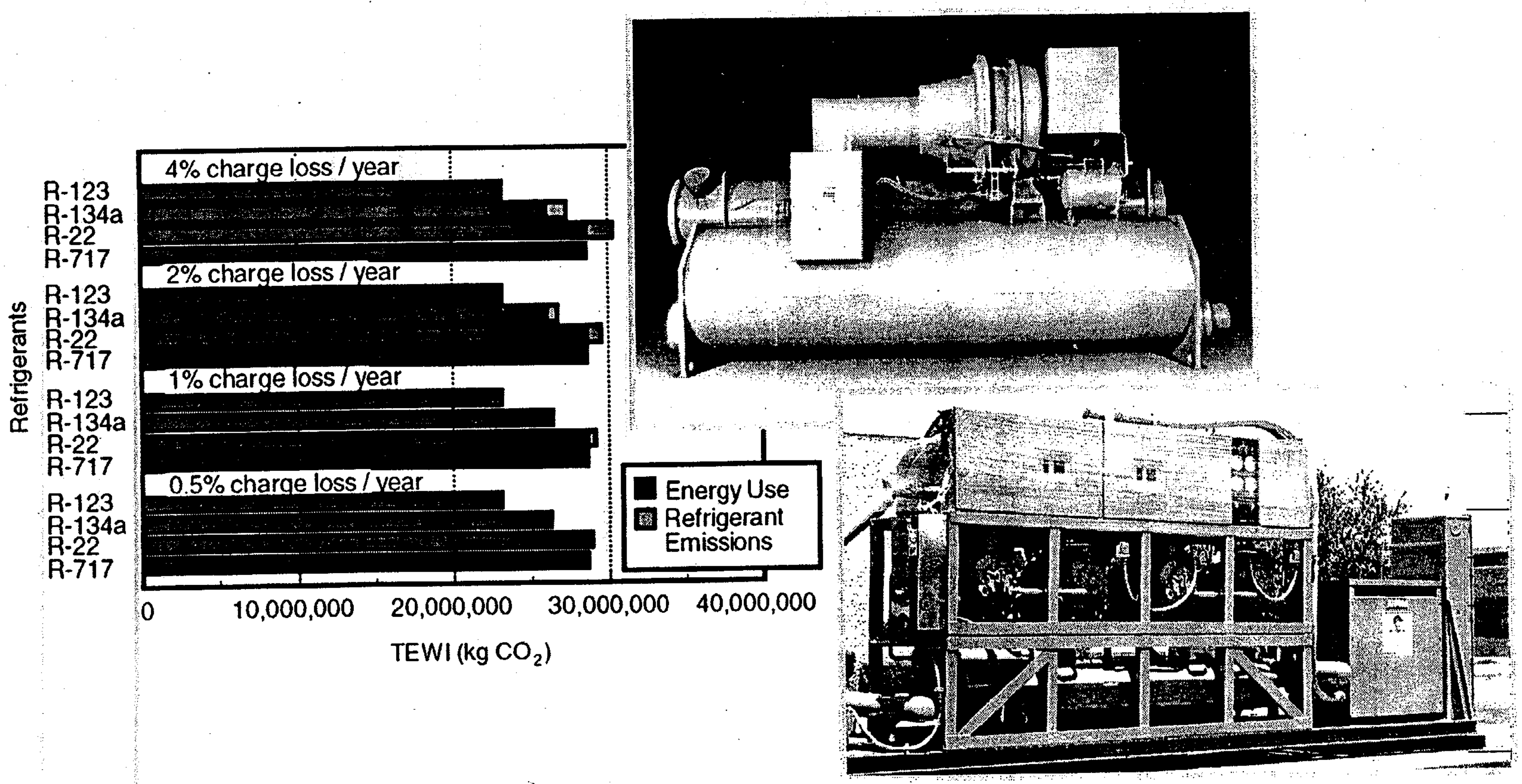

Figure 6. TEWI for chillers in Atlanta

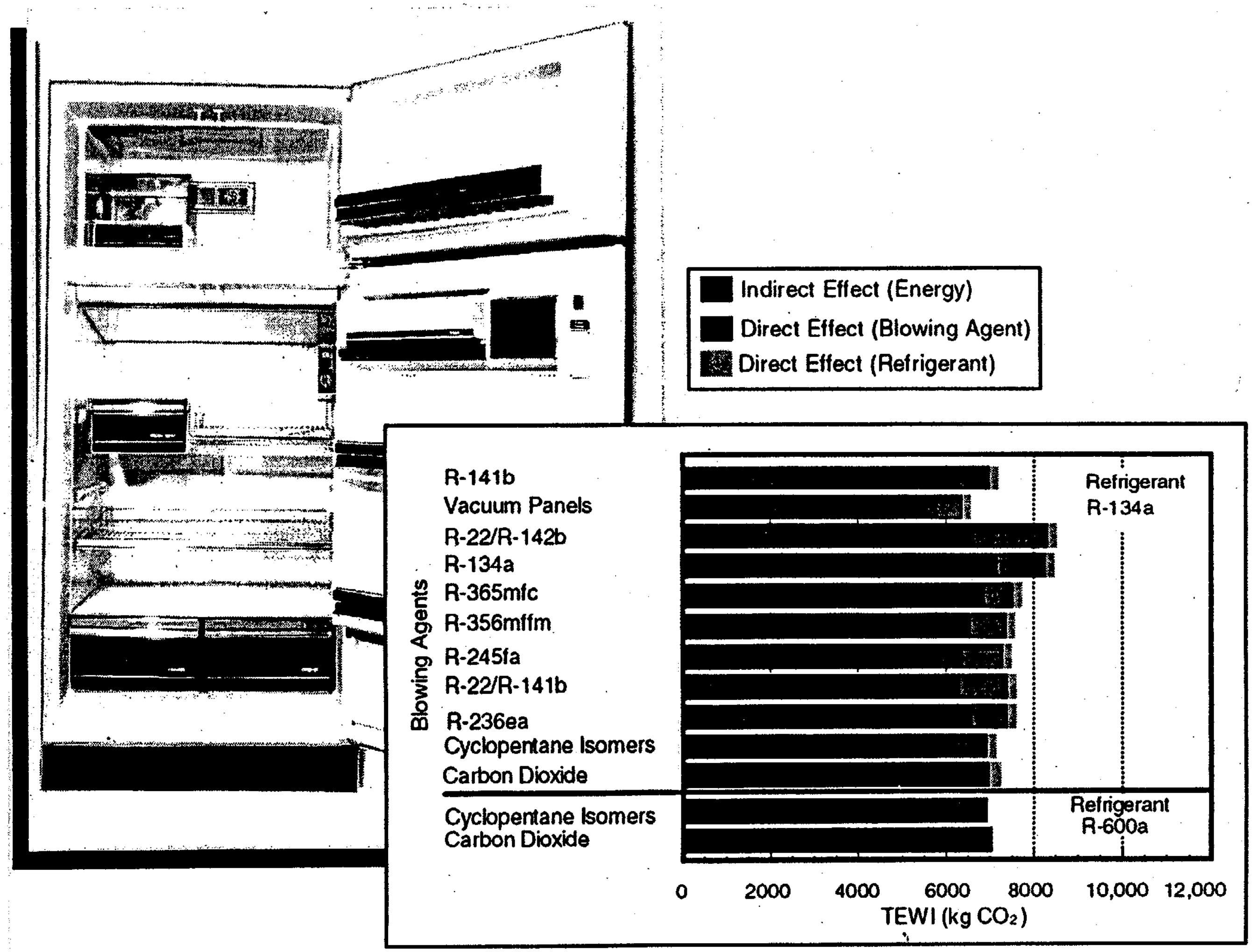

Figure 7. TEWI for 510 liter (18ft³) North American refrigerator/freezer