GLOBAL WARMING IMPLICATIONS OF NON-FLUOROCARBON TECHNOLOGIES AS CFC REPLACEMENTS

CONF-931121--40

S. K. Fischer
J. J. Tomlinson
Oak Ridge National Laboratory

To be presented at the
1993 ASME Winter Annual Meeting
New Orleans, Louisiana
November 28-December 3, 1993

Research sponsored by the Office of Building Technologies, U.S. Department of Energy under contract No. DE-AC05084OR21400 with Oak Ridge National Laboratory, managed by Martin Marietta Energy Systems, Inc.

GLOBAL WARMING IMPLICATIONS OF NON-FLUOROCARBON TECHNOLOGIES AS CFC REPLACEMENTS

Steve K. Fischer
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

John J. Tomlinson
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Chlorofluorocarbons (CFCs) are rapidly being phased out of production and use due to their role in stratospheric ozone depletion, which prompted the international Montreal Protocol agreement and related national implementation timetables. As new fluorocarbon alternatives have been identified and as climate change has emerged as the other major global environmental issue, there has been increased attention on the global warming potential (GWP) of these replacement compounds as greenhouse gases. Greenhouse gas emissions stemming from energy use (primarily carbon dioxide), often referred to as *indirect* emissions, have been shown for many CFC applications to be an even more important environmental consideration than the refrigerant (or blowing agent) *direct* emission and GWP (Fischer 1991). A study was conducted in cooperation with a consortium of chemical manufacturers, AFEAS, and the U.S. Department of Energy (DOE) to address these combined global warming effects. A concept of Total Equivalent Warming Impact (TEWI) was developed for combining the *direct* and *indirect* effects and was used for evaluating CFC-replacement options available in the required CFC transition time frame. The study involved extensive interaction with both CFC-user industries and the chemical producers throughout North America, Europe, and Japan, and the findings were used in the United Nations Environment Programme (UNEP) recent reassessment of the Montreal Protocol. Analyses of industry technology surveys as well as measurements in our own laboratories at ORNL indicate that CFC-user industries have made substantial progress toward near-equal energy efficiency with many of the HCFC and HFC alternatives.

A supplementary effort has been undertaken to systematically examine more non-fluorocarbon (e.g., absorption, desiccant) and emerging next-generation technologies and to evaluate their comparative energy efficiency and TEWI relative to the replacement fluorocarbon options. This paper reviews selected results for these technologies in commercial refrigeration and residential heating and cooling applications. Alternatives for supermarket refrigeration and residential space conditioning are evaluated and discussed.

GLOBAL WARMING IMPLICATIONS OF NON-FLUOROCARBON TECHNOLOGIES AS CFC REPLACEMENTS

Steve K. Fischer
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

John J. Tomlinson
Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Chlorofluorocarbons (CFCs) are rapidly being phased out of production and use due to their role in stratospheric ozone depletion, which prompted the international Montreal Protocol agreement and related national implementation timetables. As new fluorocarbon alternatives have been identified and as climate change has emerged as the other major global environmental issue, there has been increased attention on the global warming potential (GWP) of these replacement compounds as greenhouse gases. Greenhouse gas emissions stemming from energy use (primarily carbon dioxide), often referred to as *indirect* emissions, have been shown for many CFC applications to be an even more important environmental consideration than the refrigerant (or blowing agent) *direct* emission and GWP (Fischer 1991). A study was conducted in cooperation with a consortium of chemical manufacturers, AFEAS, and the U.S. Department of Energy (DOE) to address these combined global warming effects. A concept of Total Equivalent Warming Impact (TEWI) was developed for combining the *direct* and *indirect* effects and was used for evaluating CFC-replacement options available in the required CFC transition time frame. The study involved extensive interaction with both CFC-user industries and the chemical producers throughout North America, Europe, and Japan, and the findings were used in the United Nations Environment Programme (UNEP) recent reassessment of the Montreal Protocol. Analyses of industry technology surveys as well as measurements in our own laboratories at ORNL indicate that CFC-user industries have made substantial progress toward near-equal energy efficiency with many of the HCFC and HFC alternatives.

A supplementary effort has been undertaken to systematically examine more non-fluorocarbon (e.g., absorption, desiccant) and emerging next-generation technologies and to evaluate their comparative energy efficiency and TEWI relative to the replacement fluorocarbon options. This paper reviews selected results for these technologies in commercial refrigeration and residential heating and cooling applications. Alternatives for supermarket refrigeration and residential space conditioning are evaluated and discussed.

INTRODUCTION

By now it is well known that CFCs will be phased out by January 1, 1996 as a result of the Montreal Protocol and that equipment using alternative refrigerants will need to be designed and marketed. Hydrochlorofluorocarbons (HCFCs) such as R-22 also face a limited lifetime under the terms of the Clean Air Act in the U.S. and similar policies in other countries. Hydrofluorocarbons (HFCs) also face regulation and possible phase-out even though they have no impact on stratospheric ozone; HFCs are being challenged because they are greenhouse gases and contribute to global warming. However, these compounds can function as very efficient refrigerants and their efficiency results in lower energy use than some alternative refrigerants and refrigeration processes. Consequently, their use can lead to lower CO_2 emissions and less global warming.

The Total Equivalent Warming Impact (TEWI) was developed as a measure of the contribution to global warming which combines the direct warming effect of the refrigerant after it is released into the atmosphere and the indirect effect of carbon dioxide emitted as a result of the energy used by a piece of equipment during its useful lifetime. It should be noted that TEWI is application specific. A joint project was undertaken between the Department of Energy and AFEAS (Alternative Fluorocarbon Environmental Acceptability Study) to examine the total impacts of new emerging technologies, not-in-kind substitutes for CFCs and HCFCs in refrigeration and air-conditioning applications.

Many radically different technologies are being proposed as alternatives to the more conventional vapor compression systems as CFCs and HCFCs are phased out and for consideration if

HFCs are regulated out of use. Among these are the following:

- absorption air conditioning
- desiccant cooling systems
- adsorption technologies
- metal hydride air conditioning
- evaporative cooling
- hydraulic refrigeration
- magnetic refrigeration
- thermoelectric refrigeration
- acoustic compressors and thermoacoustic cooling systems
- Stirling cycle refrigeration

Hydrocarbons (i.e., propane) are also attracting serious attention, particularly in Europe, as refrigerants in conventional compression equipment. It has been shown fairly conclusively that in almost all applications the predominant contributions to the TEWI are the result of energy use (Fischer 1991) and that these next generation technologies will have to have better energy efficiencies than compression systems with fluorocarbon refrigerants to have lower overall impacts on global warming.

Effort was directed toward compiling consistent and comparable information on these emerging technologies, particularly in regard to energy efficiency at the same operating conditions, in an attempt to evaluate their potential role in end-use applications. A major part of this information gathering effort was a series of workshops where technical experts in each of these fields presented information and answered questions with regard to the following:

- the current stage of development of the technology (e.g., commercially available, laboratory prototype, system design only),
- most appropriate applications,
- actual and theoretical system efficiency,
- both technical and market-based obstacles delaying or preventing commercialization of the technology, and
- potential market share.

The information presented was reviewed by a panel of authorities with representatives from academia, environmental public interest groups, government regulatory agencies, and HVAC/R manufacturers. These individuals synthesized the material from all of the presentations and compiled a summary of the status and future prospects for each technology. The panel members provided the following summaries.

HYDROCARBON REFRIGERATION

Domestic refrigerators using hydrocarbons as refrigerants and foam insulation blowing agents have already been commercialized in Europe. It is questionable if a significant market potential will develop for hydrocarbon refrigerators in either the U.S. or Japan because of the concerns raised about using a flammable refrigerant. The market potential throughout Europe and in developing countries is considered to be high. The principal advantage of these refrigerators is that they are viewed as environmentally friendly because they use refrigerants and foam insulation blowing agents with essentially zero GWP and zero ozone depleting potential. The energy efficiency of refrigerators using hydrocarbons is more or less the same as that of a refrigerator using HFC-134a. Conflicting claims are made by the advocates and opponents of hydrocarbons, but no conclusive data from directly comparable tests appear to be available.

STIRLING CYCLE REFRIGERATION

Several research and development companies and appliance manufacturers are investigating application of the Stirling refrigeration cycle to refrigerator/freezers because the Stirling cycle is inherently more efficient than the Rankine cycle in high temperature lift applications and because Stirling cycle equipment would use helium as the refrigerant (environmentally benign). Different developers use different approaches in the drive mechanism (free-piston and kinematic drives) and ways to achieve low friction losses within the systems (e.g. gas bearings and flexural bearings). Two free-piston systems have demonstrated energy efficiencies that are comparable with conventional refrigerators in the 200 W range and down-sized units would have superior efficiency in the 50 W range.

Unfortunately, the market potential of Stirling refrigerators appears to be severely limited because they have only demonstrated efficiencies that are comparable to conventional refrigerators using HFCs (Berchowitz 1993, Riggle 1993). There may be potential in the U.S. and Japan if international agreements force the use of non-fluorocarbon refrigerants with essentially zero GWP, and manufacturers in those countries insist on non-flammable working fluids (that is not the case in Europe and most developing countries).

A kinematic Stirling cycle refrigeration system (rhomboidal crank drive mechanism) has been developed for supermarket display cases (Miniatt 1993). These crank driven systems will only be feasible for the very low temperature freezer cases because the efficiency advantage of the Stirling cycle at these conditions is needed to offset the additional friction and adiabatic losses with the kinematic drive and high speeds. This product exists only at the design stage and the efficiency has not been demonstrated with a prototype system. The Stirling cycle requires a secondary heat transfer loop because of the small local heat transfer area at the head of the Stirling machine. Consequently, there may be no efficiency advantage over conventional compression equipment using ammonia or hydrocarbons, and the need for a secondary heat transfer loop to keep the hazardous refrigerants out of the retail area of the store. Only a low market potential is foreseen for Stirling cycle refrigeration in commercial applications. The technology could compete successfully in niche markets for even lower temperature applications where vapor compression cascade systems currently dominate and where there are essentially no available non-flammable refrigerants to replace the CFCs and HCFCs used today.

COMPRESSION/ABSORPTION HYBRID HEAT PUMP CYCLES

A laboratory demonstration unit of a hybrid compression/absorption heat pump has been developed in the United States and could be brought to market in about three years; similar systems using ammonia/water have already been built commercially in Europe for heat pump applications. These systems need an oil-free compressor in order not to contaminate the heat and mass transfer surfaces in the heat exchangers with oil. Presently only niche applications appear possible in the market for substitution of HFCs. The efficiency of compression/absorption hybrid cycles may be superior to conventional compression systems because of the gliding temperatures in the heat exchangers (Radermacher 1993). There are safety concerns about using ammonia in domestic applications, but systems with a water solution in the heat exchangers seem to drastically lower the danger of releasing ammonia to the ambient air. The hybrid system can also use fluids in their supercritical state by dissolving them into the solution and it seems to have a long-term potential as an energy efficient substitute for larger sized vapor compression systems using an HFC.

AMMONIA COMPRESSION

Past technologies on using ammonia as a refrigerant in chillers are being reviewed and developments are being pushed with an aim to establish highly reliable ammonia compression systems. Ammonia is both toxic and flammable in a narrow concentration range so restrictions on installation methods pose obstacles to the promotion of ammonia equipment, especially in the U.S. and Japan. Research is being carried out on improving heat exchangers in order to reduce the volume of ammonia used and to make the systems more compact. Efficiency is seen to be the same as that of fluorocarbon compression systems, but with improvements in heat exchangers it is possible that ammonia compression can be superior to that of fluorocarbons.

Supermarket refrigeration systems using ammonia are already commercialized in Europe, but they are still in the evaluation stage in the U.S. and other countries. It will be necessary to set up safety measures to protect against both the toxicity and flammability of ammonia. Secondary brine loops may be required to isolate the ammonia from the customer area of the stores, in which case the energy efficiency will be slightly reduced.

ABSORPTION

A small number of ammonia/water unitary air conditioners and heat pumps are being manufactured worldwide. The major technical issues facing absorption air conditioners include improvement of operating efficiency, reliability of solution pumps, development of corrosion-free materials, and development of a system control technology; reductions in the sizes of the absorber and generator would also be desirable. An enhancement of the standard Absorber-Heat-Exchange (AHE) absorption cycle known as the Generator-Absorber-heat-eXchanger (GAX) cycle has been recommended for future applications because it has a potential for higher energy efficiency. Several units have been built and demonstrations of the operation of the GAX cycle are being conducted. The market potential for absorption air conditioners and heat pumps will be affected by equipment costs relative to standard equipment, relative costs of natural gas and electricity, and also by the availability of natural gas.

Absorption cycle chillers have a long history of being manufactured worldwide. One of the key benefits of absorption chillers is to provide commercial building space cooling which would otherwise be supplied by electric chillers. This use of gas for cooling provides a valley-filling load for gas utilities and suppresses the peak electricity consumption during the summer months and reduces electric utility demand charges. In the past the double-effect chiller was developed to improve upon the energy efficiency of the single-effect system, and now there are several efforts underway to develop triple-effect systems for further efficiency gains. The high initial costs of absorption chillers limit the market potential of these systems, however this cost premium may be less (to society) than the alternatives in areas with electric capacity constraints.

EVAPORATIVE COOLING

Direct evaporative cooling has been widely used in arid climates for many years and indirect evaporative cooling can be used in more humid areas. Efficiency is superior with energy use typically less than half of that of conventional air-conditioning systems. Market potential is large in dry climates where evaporative cooling can match comfort levels found with mechanical cooling. Limited markets are possible even in humid areas in locations such as factories and farms with less stringent cooling requirements. Besides climate limitations, barriers to greater use of evaporative cooling include reluctance of designers to specify a different technology. Water availability is rarely a problem in the United States, but it could be a barrier in areas such as the Middle East that have severely limited water supplies.

Evaporative cooling has also been applied successfully for air conditioning of transit buses in the United States, and these systems for vehicles are already in commercial production. They should save a significant amount of energy compared to conventional air conditioning and eliminate the need for a refrigerant. Institutional reluctance to change air conditioning specifications for purchasing new equipment appears to be a major barrier to increased use of evaporative cooling for public transportation. While evaporative cooling works best in dry climates, indirect cooling systems should be able to provide acceptable comfort in much of the United States with the exception of the humid southeastern region.

DESICCANT COOLING

Liquid desiccant systems use a salt spray to dehumidify air and can be combined with evaporative cooling for air-conditioning purposes. A boiler drives the excess water out of the salt solution. With a single-effect boiler, the efficiency of the system is relatively low. Multiple effect boilers can improve efficiency but increase both the cost and complexity of the system. Solar-driven systems are also possible. This technology is currently in limited commercial production.

Another variation of desiccant cooling combines evaporative cooling with heat wheels and solid-desiccant wheels to create a heat-driven (i.e., natural gas or waste heat as opposed to electric-driven) cooling system. Manufacturers are working to develop proprietary desiccant materials which should substantially reduce the source temperatures needed to run the systems. The typical application uses natural gas as the energy source to drive the system, although electric heat-pump systems are also possible. The energy efficiency of gas-powered systems is comparable to that for conventional electric cooling when power plant and transmission losses are included. Desiccant systems can provide superior efficiency in areas where evaporative cooling can be used for much of the year. Solar-driven systems are also a possibility for improving efficiency but at additional cost. Some companies are planning field tests for as early as 1994. This technology is in small-scale commercial production. Full-scale production requires participation of a larger manufacturer; the absence of a major manufacturer to produce and distribute the product is a significant barrier facing desiccant cooling systems.

ADSORPTION COOLING

Several companies are pursuing the development of adsorption cooling systems based on the Joule-Thompson cooling of gases where low pressure gases are physically adsorbed onto or chemically adsorbed into a solid at near room temperature conditions. When the solid is heated the gases are desorbed at a high pressure, and when precooled and expanded through an orifice they provide net cooling. The fluids after expansion are boiled at low temperature and readsorbed to continue the cycle. One particular organization has designed a system that uses multiple canisters of activated carbon that use heat to pump the refrigerant to a higher pressure. This technology is in the laboratory demonstration phase with field tests scheduled for 1995. Another developer is in the early stages of developing a prototype and has a field test planned for 1996. The cooling efficiency of both these systems is lower than that for conventional electric cooling systems based on source fuel use, although computer predictions for system modifications indicate that efficiency levels could be comparable or better than vapor compression cooling. The heating efficiency should be superior to conventional electric systems. The relative prices of electricity and natural gas will be an important factor in determining the market for adsorption cooling systems.

ACOUSTIC COMPRESSION AND THERMOACOUSTIC COOLING

Sonic and thermoacoustic cooling devices present an appealing elegance and simplicity, and unlike some technologies do not require development of advanced materials. The compressor could use fluorocarbons, ammonia, or hydrocarbons, depending on choices by industry.

A laboratory proof of concept device exists, and initial obstacles of noise and oil free valve operation are solved in principle. There is manufacturer involvement in development, and theoretically the efficiency could be higher than vapor compression with a confirmed EER between 7 and 8 at standard refrigerator/freezer test conditions. The first prototype completed in May 1993 delivered 372 to 852 Btu/h which is similar to domestic U.S. refrigerator values, but this unit has not yet been instrumented to measure energy efficiency.

The thermodynamics of acoustic compression and thermoacoustic cooling have been demonstrated, as well as primary heat exchange within the engine at the 100 W level. Efficient, low cost generation of acoustic power as well as efficient coupling of the cooling engine to the intended load will be the key to realizing energy efficiency for refrigerator size uses. Future applications could include the kilowatt to several tons of cooling range for domestic air conditioning.

MAGNETIC REFRIGERATION

Magnetic refrigeration technology remains in the proof of concept or demonstration phase, and a retail size refrigeration system remains in concept/design phase. Obstacles to the technology are the need for cryogenic cooling of the superconducting system, development of low cost superconducting magnets and low cost materials. The high projected initial investment cost of a retail-size system may not be counteracted by the projected lifetime return on investment.

The energy efficiency is not demonstrated, but a modeled COP of 5 is reported for the retail-size system. A demonstration prototype of a refrigerator scale magnetic cooling device is being built with U.S. DOE support to validate the model. Magnetic cooling might find support from the electric power industry as an alternative to emerging competitive gas-fired systems for retail/supermarket cooling and dehumidification applications, particularly if HFC refrigerants are limited or regulated.

METAL HYDRIDES

Metal hydrides have the potential of being incorporated into cooling systems for vehicular air conditioning. Right now this technology is at the laboratory demonstration stage in the U.S. and another three to five years would be required before a commercial product could be available. The major obstacles for employing this technology are the cost and flammability of the materials. The system efficiency is low, although it can operate on waste heat (alternatively an additional burner would be required).

THERMOELECTRIC COOLING

Thermoelectric cooling based on the Peltier Effect is in one sense a mature technology; it is already available in some consumer and specialty products and could be used in additional applications in one year or less. A major breakthrough in thermoelectric materials is needed, however, to achieve an energy efficiency 90% that of compression cooling systems at low ΔT's; energy efficiency at high ΔT's is a major obstacle for developing this technology. Market potential is believed to be limited to specialty niche applications in cooling elements on electronic circuit boards, military applications, and convenience consumer products.

ANALYSIS

Two examples have been selected for analysis in this paper; the first is a supermarket refrigeration system that employs a secondary heat transfer loop and the second is an adsorption heat pump. Conventional supermarket refrigeration relies on direct heat transfer and frequently employs thousands of feet of piping with the refrigerant circulated between an isolated machine room, display cases on the sales floor, and condensing units on the roof or at ground level behind the building. These systems have very large refrigerant charges and traditionally have required large additions of refrigerant to replace emissions from leaks and servicing. An alternative design was studied which employs a secondary heat transfer loop so refrigerant is contained within the condensing unit (compressors and condensers). Using a secondary loop reduces efficiency because another ΔT is introduced and power is required for pumping a brine solution to the display cases. A secondary loop also reduces the necessary refrigerant charge, has fewer refrigerant leaks, and could serve to isolate flammable or toxic refrigerants from the retail area of the store.

Figure 1 shows the direct and indirect impacts of five hypothetical supermarket refrigeration systems on global warming. The vertical bar on the left represents a large supermarket using R-502 for both the low and medium temperature freezers and display cases and CFC-12 for the high temperature display cases and prep rooms (Fischer 1991). The heavily shaded portion at the bottom of the bar is an estimate of the CO_2 released to the atmosphere from generating electricity to power the refrigeration system for 20 years, and the lightly shaded region at the top is the CO_2 equivalent of the estimated refrigerant losses during the system's lifetime (Fischer 1991). The second bar from the left represents the same supermarket after the equipment was modified to use HCFC-22 for all of the high, medium, and low temperature applications; there is an insignificant change in the contribution from energy use but a substantial reduction in the direct effect of refrigerant emitted to the atmosphere.

The three sets of bars on the right of Fig. 1 represent the TEWI for redesigned refrigeration systems using secondary heat transfer loops; one bar based on HCFC-22 as the refrigerant, one bar with ammonia, and one with HFC blends developed for supermarket applications. These calculations are based on results from a study in Germany which found that energy use for a refrigeration system using HCFC-22 with a secondary know loop would be 10% higher than the energy use for an HCFC-22 system with direct heat transfer (Kruse, 1993) That study also found that a secondary loop with ammonia as the refrigerant would have a 7% energy penalty and one using HFCs, a 10% energy penalty. There are substantial reductions in the direct effects of refrigerant emissions due to small refrigerant charges (Kruse 1993) and an assumed reduction in loss rates. All three of the indirect systems have the potential for noticeably lower TEWI than the refrigeration systems currently used in supermarkets, but the differences between these three are probably not significant and should not be used to select one refrigerant over another.

Figure 2 illustrates the results of TEWI calculations for three different technologies for residential heating and cooling of a typical single-family home in Pittsburgh, Pennsylvania. The calculations are for a high efficiency (SEER 12), 10.6 kW (36,000 Btu/h) central air conditioner and gas furnace (90% efficient), a solid adsorption heat pump ($COP_{thermal}$= 1) (Ryan 1993), and a state of the art variable speed electric heat pump (SEER=16, HSPF=8.7) (Rice 1993). Each of these three systems are evaluated using three different assumptions on CO_2 emissions; the U.S. average emissions of 0.672 kg CO_2/kWh delivered (weighted average of coal, oil, and gas generated electricity with hydroelectric and nuclear power generation based on installed generating capacity), the peak emissions from a coal fired power plant of 1.215 kg/kWh, and the emissions of a gas combined cycle power plant of 0.704 kg/kWh (Cool Times 1993). Emissions for natural gas are based on 53.9 g CO_2/ 1000 Btu of energy input (Fischer 1991).

The heavily shaded portion at the bottom of each bar in Fig. 2 indicates the lifetime emissions of CO_2 from burning natural gas for heating or cooling, the lightly shaded region corresponds to CO_2 emissions resulting from electrical power consumption, and the small very lightly shaded portion at the top is the CO_2 equivalent of the lifetime refrigerant losses for the central air conditioner and electric heat pump. In each scenario shown, the lowest total impact is for the adsorption system even though it has a cooling efficiency significantly lower than either the central air conditioner or the electric heat pump (Ryan 1993). The higher heating efficiency offsets any disadvantage in cooling. Based on analytical evaluations at one laboratory, system modifications could increase heating and cooling efficiencies of adsorption heat pumps (Jones 1993), although the efficiencies of both the baseline and modified systems need to be demonstrated in actual equipment before drawing any conclusions about adsorption heat pumps.

CONCLUSION

Many technologies are available that could be developed for use in place of conventional compression systems for refrigeration and air conditioning. Comparisons of the global warming impacts using TEWI can be used to identify alternatives that have the potential for lower environmental impacts than electric-driven vapor compression systems using HCFCs and HFCs. Some options, such as the use of secondary heat transfer loops in commercial refrigeration systems to reduce refrigerant charge and emission rates, could be useful in reducing the losses of refrigerants to the atmosphere. The use of ammonia instead of a fluorocarbon in a system with a secondary loop offers only a small potential for decreasing TEWI. The lower TEWI may not be sufficient to warrant the increased complexity and risks of using ammonia in a retail sales environment. A few technologies, such as adsorption heat pumps, have predicted or demonstrated efficiency levels that show reduced TEWI levels compared to conventional and state of the art compression systems; further development of these systems could result in an even more

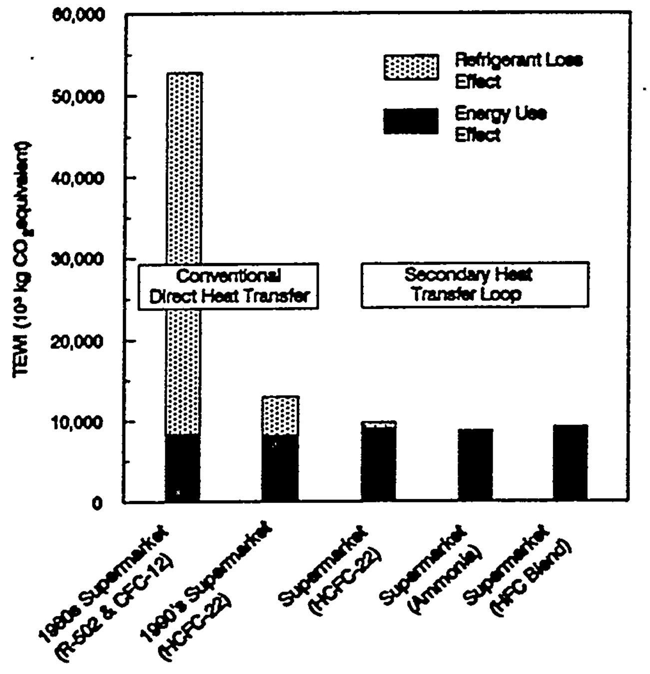

FIGURE 1. TOTAL EQUIVALENT WARMING IMPACTS OF SUPERMARKET REFRIGERATION SYSTEMS WITH DIRECT AND INDIRECT HEAT TRANSFER.

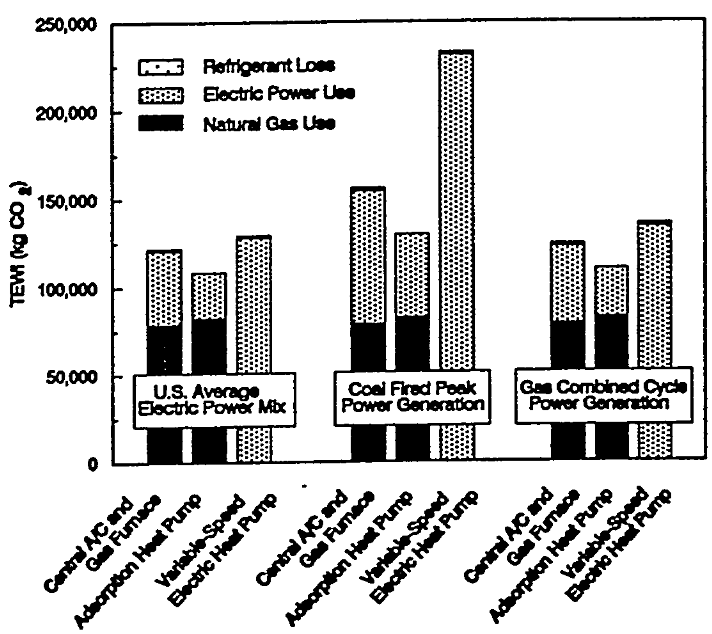

FIGURE 2. TOTAL EQUIVALENT WARMING IMPACT OF RESIDENTIAL HEATING AND COOLING SYSTEMS FOR THREE CO_2 EMISSIONS SCENARIOS.

favorable comparison based solely on TEWI. The health and safety risks of the alternative technologies or the materials they employ must also be considered and should not be significantly different from the risks associated with the technologies they would displace.

REFERENCES

Cool Times: News Digest of the American Gas Cooling Center, June/July 1993, Vol. 4, No. 3.

Berchowitz, D. 1993. *Free-Piston Stirling and Rankine Cooling*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Fischer, S., Hughes, P. J., Fairchild, P. D. 1991. *Energy and Global Warming Impacts of CFC Alternative Technologies*, AFEAS/DOE.

Jones, J. 1993. *Adsorption Heat Pump Development at JPL*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Kruse H. 1993. *European Research and Development Concerning CFC and HCFC Substitution*, Proceedings of the ASHRAE/NIST Refrigerant Conference: R-22/R-502 Alternatives, August 19 & 20, 1993, Gaithersburg, MD.

Lewis, P. ed 1993. Proceedings of the 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Miniatt, E. 1993. *STM4-120RF As Refrigerator For Supermarkets*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Rice, K. 1993. Personal communication on heat pump efficiencies.

Radermacher, R. 1993. *Vapor Compression Cycle with Solution Circuit*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Riggle, P. 1993. *Stirling Cycle Refrigeration*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.

Ryan, W. 1993. *CFC-Free Chemisorption Heat Pumps and Refrigeration*, 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, CO. June 23-25.