Energy and Global Warming Impacts of CFC Alternative Technologies

AFEAS
Alternative Fluorocarbons Environmental Acceptability Study

U.S. DEPARTMENT OF ENERGY

Energy and Global Warming Impacts of CFC Alternative Technologies

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15. CONCLUSIONS

None

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TABLE OF REFRIGERANTS/BLOWING AGENTS AND CHEMICAL SYMBOLS

Refrigerant number	Acronym	Chemical formula	Name
11	CFC-11	CCl_3F	trichlorofluoromethane
12	CFC-12	CCl_2F_2	dichlorodifluoromethane
22	HCFC-22	$CHClF_2$	chlorodifluoromethane
113	CFC-113	CCl_2FCClF_2	trichlorotrifluoroethane
114	CFC-114	$CClF_2CClF_2$	dichlorotetrafluoroethane
115	CFC-115	$CClF_2CF_3$	chloropentafluoroethane
123	HCFC-123	CF_3CHCl_2	dichlorotrifluoroethane
134a	HFC-134a	CF_3CH_2F	tetrafluoroethane
141b	HCFC-141b	CCl_2FCH_3	dichlorofluoroethane
142b	HCFC-142b	CH_3CClF_2	chlorodifluoroethane
152a	HFC-152a	CH_3CHF_2	difluoroethane
290	*	C_3H_8	propane
717	*	NH_3	ammonia
744	*	CO_2	carbon dioxide
50	*	CH_4	methane
502	HCFC-502	refrigerants 22 and 115 (48.8/51.2% by weight)	

ABBREVIATIONS/ACRONYMS/DEFINITIONS FOR TECHNICAL TERMS

Terms Related to Global Warming and Ozone Depletion

CFC	chlorofluorocarbon, molecules composed of chlorine, fluorine, and carbon atoms
GWP	global warming potential
HC	hydrocarbon, molecules composed of hydrogen and carbon atoms
HCFC	hydrochlorofluorocarbon, molecules composed of hydrogen, chlorine, fluorine, and carbon atoms
HFC	hydrofluorocarbons, molecules composed of hydrogen, fluorine, and carbon atoms
IR	infrared
ITH	integration time horizon of global warming potential (GWP) values
ODP	ozone depletion potential
radiative forcing	factors that can perturb the radiative balance of the Earth-atmosphere system
uv	ultraviolet

Terms Related to the Global Warming Analysis

DIRECT	equivalent CO_2 effect as a result of chemical emission
heat rate	energy content of primary energy consumed by a power plant per kWh_e generated at the bus bar
INDIRECT	CO_2 emissions as a result of energy use
kWh_e	kilowatt hours (electric)
kWh_t	kilowatt hours (thermal)
lifetime or service life	assumed number of years that equipment or building components remain in service
MPG	miles per gallon
per unit basis	basis for analysis of energy use and emissions, where unit is defined as a representative "system" (e.g., per refrigerator, per building) or other appropriate measure (e.g., unit capacity or unit throughput)

ABBREVIATIONS/ACRONYMS/DEFINITIONS FOR TECHNICAL TERMS (Continued)

Terms Related to the Global Warming Analysis (Continued)

TEWI	total equivalent warming impact, the sum of the DIRECT equivalent (chemical emissions) and the INDIRECT (energy use) global warming effects
tonne	metric tone, 1000 kg (2200 lb)
NIK	not-in-kind alternative, i.e., non-fluorocarbon options to replace CFCs

Terms Related to Refrigeration

AC	air-conditioner (cooling-only device)
charge	mass of refrigerant required in a vapor compression refrigerating device
chillers	air conditioning devices with water-cooled evaporators and an intermediate chilled water loop
COP	coefficient of performance, the useful refrigerating effect of a thermodynamic process divided by the electrical or mechanical energy input to the process (dimensionless)
EER	energy efficiency ratio
GSHP	ground-source heat pump
hermetic	air-tight (welded, soldered, etc.) system
HHV	high heating value
HP	heat pump (heating and cooling device)
HSPF	heating seasonal performance factor, total heating delivered over the heating season by a heat pump divided by electric energy consumed (Btu/Wh)
HVAC	heating, ventilating, and air conditioning
IPLV	integrated part-load value, a seasonal performance factor for chillers
OEM	original equipment manufacturer
PTHP	packaged terminal heat pump
PTAC	packaged terminal air conditioner
refrigerant	the working fluid in a thermodynamic cycle

ABBREVIATIONS/ACRONYMS/DEFINITIONS FOR TECHNICAL TERMS (Continued)

Terms Related to Refrigeration (Continued)

RT	refrigeration tons (3.516 kW, 12,000 Btu/h)
SEER	seasonal energy efficiency ratio
semi-hermetic	system with shaft or other mechanical penetrations that require seals
unitary equipment	broadly defined here as space conditioning devices with air-cooled evaporators (condensers in heating mode of heat pump)
vapor compression cycle	thermodynamic cycle in which mechanical energy is used to compress vapor
WLHP	water-loop heat pump

Terms Related to Insulation

aged k	thermal conductivity of foam insulation that has been aged (definitions and test procedures vary)
aged R/thickness	inverse of aged k
air-filled foam	foam insulation composed of cells filled with air due to the diffusion of gases into the foam and total depletion of the blowing agent from diffusion out of the foam
average k	time averaged k over a specified period of time, usually the service life of the foam insulation
average R/thickness	inverse of average k
blowing agent	chemical used form foam insulation, often selected for its low gaseous thermal conductivity and low rate of diffusion through the foam solid
blowing efficiency	volume of foam insulation produced at a specified density divided by the mass of blowing agent used, frequently used as "relative blowing efficiency" to relate the amount of an alternative blowing agent required to amounts of CFC-11 or CFC-12 that were historically used
EIFS	exterior insulation and finish system, a method of insulating masonry walls
evacuated panels	insulating panels formed with an impermeable plastic or metal membrane containing a vacuum that achieve a low to very low thermal conductivity; panels may contain porous filler material

Terms Related to Insulation (Continued)

fresh foam	foam insulation immediately after it has been manufactured and before there has been any significant diffusion of gases into the foam or diffusion of blowing agent out of the foam
impermeable facing	material bonded to the surface of foam insulation that is impervious to gaseous molecules (molecules from the air and foam blowing agent cannot readily diffuse through the facing)
IPC	isopropylchloride, also known as 2-chloropropane and by the registered tradename of LBL_2
k	thermal conductivity of insulation
k-factor	natural logarithm of 100-k where k is the thermal conductivity of foam insulation
MEPS	molded expanded polystyrene foam insulation (bead board)
permeable facing	material bonded to the surface of foam insulation that is permeable to gases (gaseous molecules from the air and the foam blowing agents can diffuse through the facing
PFA	perfluoroalkanes, specifically perfluoropentane and perfluorohexane
PIR	polyisocyanurate foam insulation
PMR	protected membrane roofing system, or method of roofing where the insulation is above the membrane
PUR	polyurethane foam insulation
R or R-value	thermal resistance, inverse of the thermal conductance
R/thickness	thermal resistance per unit thickness, inverse of k
sheathing	material added to the outside of wood frame construction beneath the exterior surface either to provide mechanical support or to provide additional insulation to the building
U or U-value	thermal conductance, k times thickness
UAΔT	thermal conductance of an envelope section (building, wall or roof, or appliance cabinet) times the area of the section times the difference in temperature from one side of the section to the other

ABBREVIATIONS/ACRONYMS/DEFINITIONS FOR TECHNICAL TERMS (Continued)

Terms Related to Insulation (Continued)

weight percent percentage of the mass of fresh foam that is due to the foam blowing agent, equal to the parts per hundred (pph) of blowing agent in the foam formation

XEPS extruded polystyrene foam insulation

Terms Related to Solvent Cleaning

MC methyl chloroform (see TCA)

No Clean refers to soldering operations that do not require a cleaning procedure to remove the soldering flux

O-A organic aqueous fluxes used in soldering

PCB printed wire circuit boards

PCE perchloroethylene

PWA printed wire assemblies

SAQ semi-aqueous cleaning

SIR surface insulation resistance

SMT surface mount technology

TCA 1,1,1 trichloroethane, also known as methyl chloroform (see MC)

TCE trichloroethylene

terpenes a number of cyclic hydrocarbons used as solvents

ABBREVIATIONS/ACRONYMS FOR ORGANIZATIONS, ASSOCIATIONS, AND CONSORTIA

ADL	Arthur D. Little, Inc.
AFEAS	Alternative Fluorocarbons Environmental Acceptability Study, a consortium of chemical manufacturers formed to investigate the potential environmental effects of CFC alternatives
AHAM	Association of Home Appliance Manufacturers
ANSI	American National Standards Institute
ARI	Air-Conditioning & Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
DOE	U.S. Department of Energy
EIA	Energy Information Administration, U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FMI	Food Marketing Institute
GM	General Motors Corporation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change, part of the World Meteorological Organization
JAMA	Japanese Automobile Manufacturers Association
MVMA	Motor Vehicle Manufacturers Association
NAECA	National Appliance Energy Conservation Act
NIST	National Institute of Standards & Technology (formerly National Bureau of Standards)
ORNL	Oak Ridge National Laboratory, research facility of the U.S. Department of Energy in Oak Ridge, Tennessee, managed by Martin Marietta Energy Systems
PAFT	Programme for Alternative Fluorocarbon Toxicity Testing
PIMA	Polyisocyanurate Insulation Manufacturers Association
SPI	Society of Plastics Industries
UNEP	United Nations Environment Programme

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

Chlorofluorocarbons (CFC s) have been the subject of worldwide attention due to the stratospheric ozone issue and the related landmark international agreement on control measures for ozone protection known as the Montreal Protocol. Review provisions of this Protocol have established the phaseout deadline for the controlled CFCs by the year 2000, except for a delay of 10 years for developing countries. Some European community and other countries are adopting even stricter timetables with phaseout ranging from 1995 to 1997. Research, engineering development, and manufacturing investment decisions are underway throughout the world to achieve an orderly transition from CFCs to suitable and environmentally acceptable chemical substitutes or alternative technologies within the timeframes cited.

In addition to their role in ozone depletion, CFCs are among the "greenhouse gases" in the atmosphere that contribute to future global warming. Figure 1.1 illustrates the proportional contribution of various greenhouse gases to calculated global warming.

As shown in Fig. 1.1, the contribution of CFCs to global warming in the last decade is second only to carbon dioxide (CO_2). CFCs are much more potent on a per molecule basis than CO_2 and some other greenhouse gases, even though the emissions of those gases are larger than CFC emissions by several orders of magnitude.

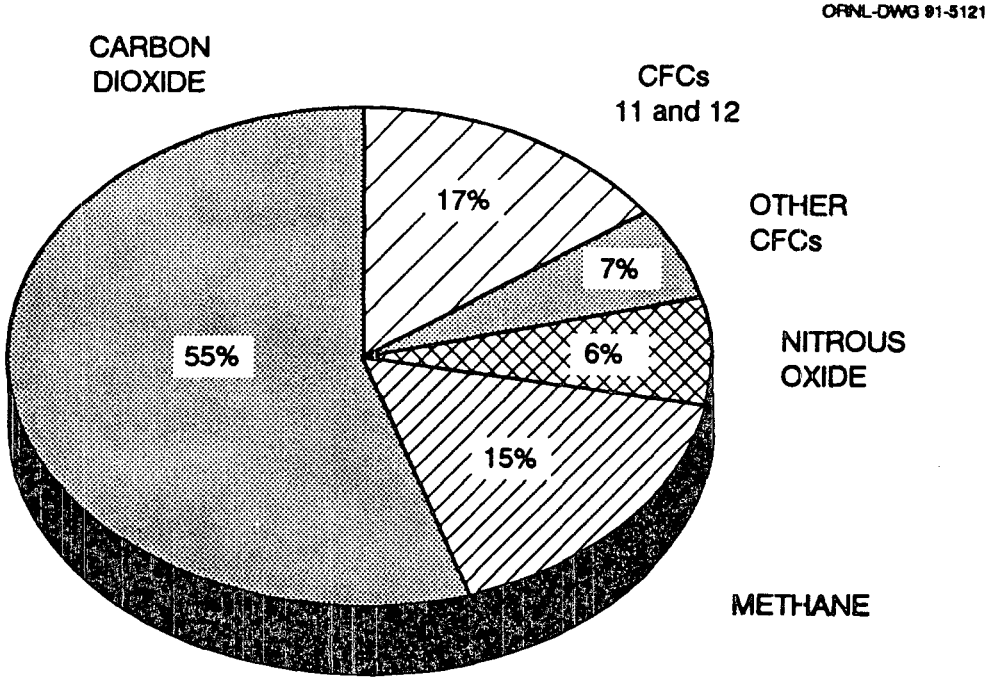

Fig. 1.1. Relative contributions of greenhouse gases to change in radiative forcing from 1980 to 1990 (Source: IPCC "Climate Change", 1990).

By simply replacing the CFCs with hydrochlorofluorocarbons (HCFCs) or hydrofluorocarbons (HFCs), the proportional global warming impact of these chemical emissions in the future would change as represented in Fig. 1.2.

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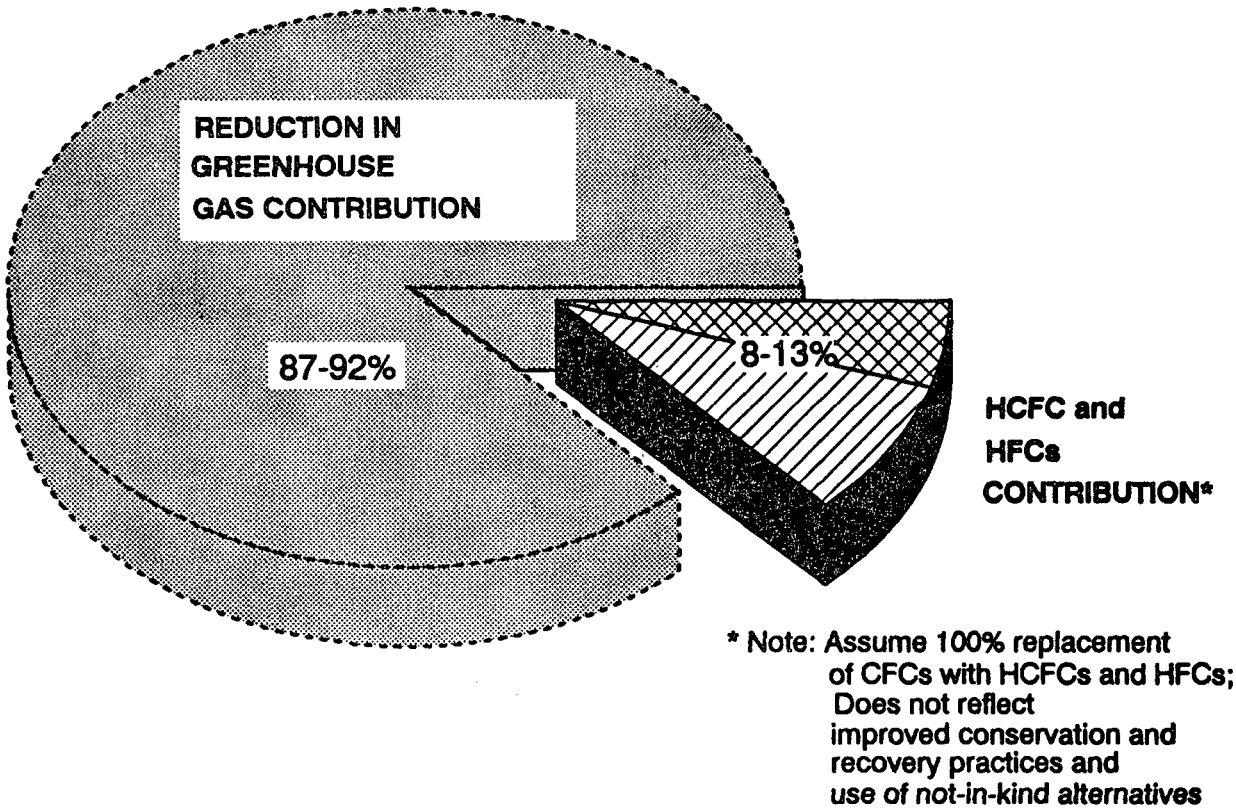

(The total pie represents contribution that would have resulted by continued use of CFCs.)

Fig. 1.2. Reduction in relative contribution of HCFCs and HFCs as greenhouse gases compared to CFCs.

However, CFCs (and their alternatives) function in energy-dependent systems or processes, and energy consumption in each of these specific applications can also affect CO_2 emissions linked to electricity or fossil fuel use. The DIRECT chemical greenhouse gas emission effect must be seen therefore, not in isolation, but together with the INDIRECT energy-related CO_2 emissions of the systems in which they are used.

It should be noted that new scientific data (WMO/UNEP, 1991) indicate that observed stratospheric ozone losses could be decreasing the global warming forcing by an amount that at least partially offsets that caused by the increased infrared trapping of CFCs. Although this indirect effect may decrease the GWPs of CFCs, it does not change the main conclusions of this study. Rather, the new information increases the importance of a systems analysis and the need to account for carbon dioxide emissions resulting from the energy requirements of a system.

For convenience in combining these effects, the DIRECT (chemical emission) effect is expressed as equivalent carbon dioxide, consistent with the Global Warming Potential (GWP) indexing approach of IPCC (explained further in Section 1.3). This equivalent CO_2 DIRECT effect can readily be

combined with the INDIRECT (energy-related) CO_2 emissions. The combined or total effect is termed the Total Equivalent Warming Impact or TEWI.

This concept is illustrated in Fig. 1.3 for replacement of CFCs in a household refrigerator.

In this example, the TEWI - represented by the comparative area of the two "pies" - is reduced by 18% in the transition from CFCs to the HCFC and HFC alternatives. This improvement is due to the reduction in DIRECT (emission-related) impact from 20% to 2% combined with no change in INDIRECT (energy-related) impact. An evaluation of this combined impact for the various alternatives to CFCs in a number of specific end-use applications is the purpose of this study.

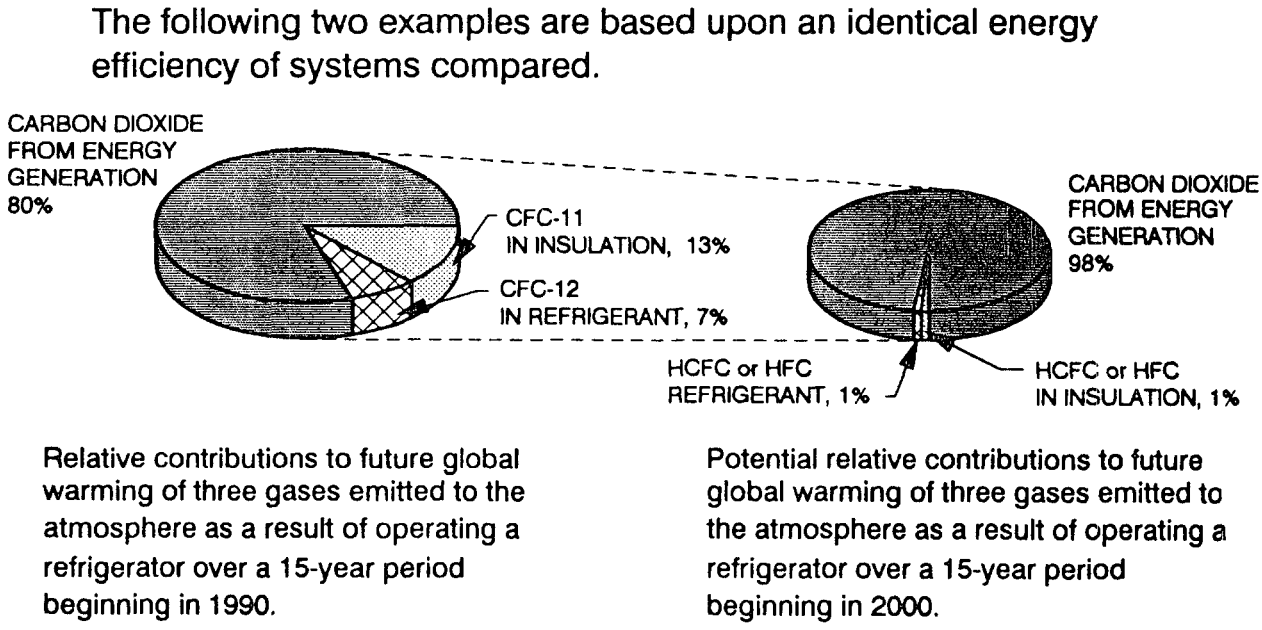

Fig. 1.3. Example of Total Equivalent Warming Impact from replacing CFCs with alternative fluorocarbons.

1.2 PURPOSE AND SCOPE

The primary objective of this study is to develop representative indications of the relative energy use, associated CO_2 emissions, and total equivalent warming impact (TEWI) of viable options to replace CFCs in their major energy-related application areas. It was motivated, in part, by a concern that most attention to date has focused on the DIRECT global warming effect of CFC's and their alternatives, with inadequate attention being paid to the INDIRECT effect of the CO_2 emissions arising from the differences in energy consumption by systems using different alternatives. The DIRECT and INDIRECT contributions are combined in this analysis to determine the TEWI of the various technical options. The study is international in scope and takes into account significant differences in present CFC end-use practices, sources of energy, and other societal factors between Europe, Japan, and North America.

Information developed in this report complements on-going studies to assess other environmental effects, safety, toxicology and costs. It will assist government, industry, and international policy-makers in making sound decisions from the options available to meet future societal needs - in the developed and in the developing world - in view of the CFC phaseout.

This study should be considered an overview of key issues. It relied largely on readily available information and focused on first generation CFC replacement technologies. The study is not comprehensive in its coverage of all CFC applications, technical options, and geographic regions, nor is the level of analysis undertaken exhaustive or technically detailed. However, the study did adequately assess, in the judgment of knowledgeable experts, alternatives that could reasonably be expected to be available for commercialization over the next decade. Simplifications were necessary in order to complete the study within the time and budget available. Also, the shorter, simplified approach seems more suited to the rapidly changing CFC transition situation underway now than a more lengthy, exhaustive study.

The analysis addresses CFCs as well as alternative chemicals and technology alternatives in uses such as refrigeration, foam insulation, and metal and electronic cleaning and drying processes. The major refrigerant applications covered in the analysis include:

- household refrigerators/freezers
- commercial refrigeration
- chillers (water-cooled, air-cooled)
- unitary space conditioning equipment
- automotive air-conditioning

The major applications of foam insulation include:

- commercial building roofs and walls
- residential wall sheathing
- insulation for household refrigerators

The major applications of solvents include:

- in-line and batch electronics cleaning processes
- in-line and batch metal cleaning processes

Table 1.1 lists the alternatives considered for each of these applications.

The study involved experts from industry, government, and academia around the world in the above applications to characterize existing CFC practices or baseline technology and to identify the technology options for the various applications and geographic regions. The focus of the technical analysis is on energy-use comparisons of the technology options and associated per lifetime equivalent CO_2 emissions, together with estimated emissions of the refrigerant, blowing agent, or cleaning solvent, all on a per unit basis. Electricity end-uses of energy are referenced back to the power plant, with regionally specific proportions of various fossil and other source energy, for purposes of estimating CO_2 emissions per unit of energy delivered. After extensive review of the findings to assure an objective and thorough evaluation, the report was made available to the Technology Options Assessment Panel of the United Nations Environment Programme (UNEP) for their use in the Montreal Protocol reassessment process, and to the global climate change Intergovernmental Negotiating Committee for the 1992 United Nations Conference on Environment and Development (UNCED).

Table 1.1. Matrix of applications and alternatives considered in the study

Household Refrigeration		Commercial Refrigeration	Air-Conditioning, Chillers, Heat Pumps	Automotive Air-Conditioning	Residential and Commercial Building Insulation Materials	Metal and Electronic Cleaning / Drying
Insulation Blowing Agent or Alternative Technology	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Insulation Blowing Agent or Alternative Technology	Solvent or Alternative Process
CFC-11	CFC-12	CFC-12	*Chillers*	CFC-12	*PIR / PUR*	CFC-113
CO_2/CFC-11 (part water blown)	HFC-134a	R-502	CFC-11	HFC-134a	CFC-11	1,1,1 Trichloroethane
HCFC-123	Ternary blend	HCFC-22	CFC-12	Ternary blend	HCFC-123	Trichloroethylene
HCFC-141b	Absorption	Two-stage multiplexed HCFC-22	HCFC-22	HFC-152a	HCFC-141b	Semi-aqueous
Isopropylchloride	HCFC-22/HCFC-142b dual evaporator	HFC-134a	HCFC-123	Propane	Isopropylchloride	Aqueous
CO_2 (with additive perfluoroalkane cell modifiers)	HFC-152a	Ammonia vapor compression	HFC-134a	Brayton cycle	*Extruded Polystyrene*	HCFC-123
100% CO_2 (water blown)	Stirling cycle (freezers only)	HFC-32 blend	Absorption (LiBr–water)	Stirling cycle	CFC-12	HCFC-141b
Evacuated (vacuum) panels			Ammonia vapor compression		HCFC-142b	No-clean
Perfluoroalkanes (blowing agent)			*Unitary*		HFC-134a	HCFC-225ca/cb
			HCFC-22		HCFC-124	
			HFC-134a		*Alternative Building Insulation Materials*	
			Absorption (ammonia water)		Glass fiber	
					Mineral fiber	
					Expanded polystyrene beadboard	

1.3 GREENHOUSE WARMING POTENTIAL INDEX

Considerable uncertainty exists about the climate change responses to greenhouse gas emissions due to an incomplete understanding of sources and sinks of greenhouse gases, clouds, oceans, polar ice, and interactive climate feedback mechanisms. "Radiative forcing" (factors that can perturb the radiative balance of the Earth-atmosphere system) or direct heat trapping effect involves less uncertainty and is used by atmospheric scientists to assess relative impacts of different gases.

Many of the indices that have been used as measures of relative contributions of the various greenhouse gases are based on past concentration changes in the atmosphere. An index termed the Global Warming Potential (GWP) has been developed which provides a simplified means of describing the relative ability of each greenhouse gas emission to affect future radiative forcing and thereby global climate change. The GWP, as developed by atmospheric scientists follows from the concept of relative Ozone Depletion Potential (ODP). The ODP, an integral part of the Montreal Protocol process for protection of stratospheric ozone, has been adopted by the Intergovernmental Panel on Climate Change (IPCC) and by AFEAS. The GWPs used throughout this report are relative to carbon dioxide, consistent with the IPCC indexing approach.

Global Warming Potential Relative to Carbon Dioxide

The extent to which a greenhouse gas contributes to calculated global warming depends on the amount of it that is emitted, the length of time which elapses before it is purged from the atmosphere and the infrared energy absorption properties of the gas. In this report, for each application, the amounts of gases emitted have been calculated explicitly, from estimates of either DIRECT fluorocarbon emissions or the quantities of carbon dioxide associated with energy usages. The other important factors are parameterized in Global Warming Potentials (GWPs). GWPs enable chemical emissions to be converted to their equivalent emissions of carbon dioxide so that there is a common basis for comparing impacts.

Carbon dioxide, CFCs, HCFCs and HFCs are purged from the atmosphere at very different rates. This is illustrated in Fig. 1.4a which shows that 100 years after a single emission of a representative HFC, almost none remains in the atmosphere. After the same interval, however, 41% of an emission of carbon dioxide would remain and, even after 500 years, 19% survives (Maier-Reimer, 1987). Therefore, the potential for an emission of carbon dioxide or other longer-lived greenhouse gases to warm the atmosphere exists for more than 500 years.

The GWP of a gas is calculated from its energy absorbing properties together with the amount present in the atmosphere over a specified length of time (i.e., the area under the curve for an individual gas as shown in Fig. 1.4). The computation is referenced to the same set of values for carbon dioxide. The specified period of time is the Integration Time Horizon, as described in IPCC (1990). If the time horizon is set at 100 years, the whole of the potential effect of a short-lived HCFC or HFC would be counted, but a substantial part of the effect of carbon dioxide – the hatched area in Fig. 1.4b – would be excluded. Thus, the 100-year time horizon does not give a true measure of the equivalence between any other gas and carbon dioxide. The situation is worse at the 20 year time horizon when, although 71% of the effect from the HFC has been counted, substantially less than 10% of the effect of carbon dioxide is included.

This report uses GWPs at the 500-year time horizon as listed in Appendix Table A.1, but the Executive Summary and Section 14 also contain representative calculations at the 100 year integration time horizon (IT) to illustrate the effect of the ITH on the conclusions. These values represent the nearest approach to a true means of equating emissions of CFCs, HCFCs and HFCs to each other

and to carbon dioxide. The effect of carbon dioxide after 500 years is highly uncertain and is neglected.

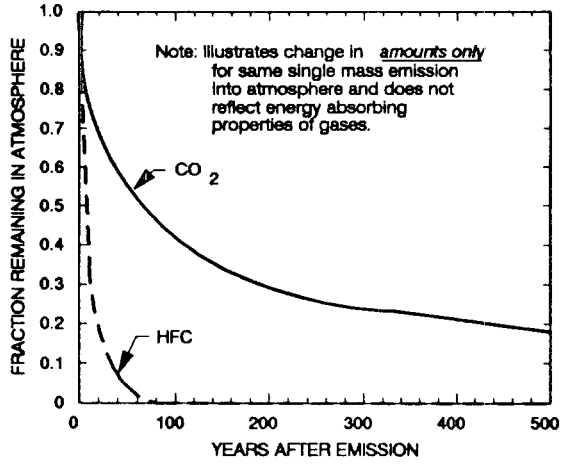

Fig. a. CO_2 and representative HFC purged from atmosphere at different rates.

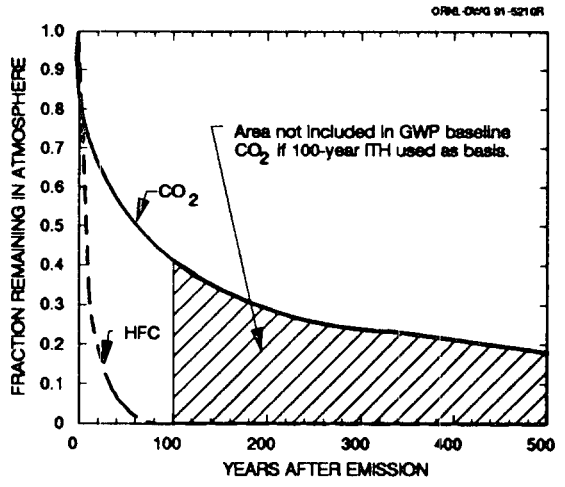

Fig. b. 500-year ITH for CO_2 selected as basis for GWP equivalence of fluorocarbons.

Fig. 1.4. Illustration of greenhouse gas purging rates in atmosphere and effect of Integration Time Horizon (ITH) on GWP values.

1.4 METHODOLOGY

The general approach employed in all cases consisted of the following steps:

- Development of appropriate engineering parameters to characterize the baseline technology and algorithms for calculating energy use in each application
- Identification of alternatives to replace the use of CFCs in the existing applications
- Collection and compilation of user industry data on comparative engineering parameters and physical properties to characterize the technology option(s)
- Calculation of energy use and an estimated lifetime equivalent carbon dioxide (CO_2) emissions (INDIRECT effect) from unit lifetime estimates and regional fuel utilization or electric power generation mix
  - for solvent these calculations were done on the bases of unit throughput
- Calculation of equivalent CO_2 emission of greenhouse gas content or loss (DIRECT effect), if applicable, for each option using the GWP index values.
- Combination of the INDIRECT and DIRECT global warming effects and comparison of the total equivalent global warming impact among technology options

"Current Generation" and "Next Generation" Alternative Technologies

New systems, materials, and processes that represent potential CFC replacement technologies are being developed rapidly. Technology options already available or identified by the user industries as their primary development focus for first generation replacement of CFCs, whether fluorocarbon or not-in-kind (non-fluorocarbon) alternatives, were given first consideration with regard to quantitative analysis of their DIRECT and INDIRECT effects and their TEWI. These are referred to as "current generation" alternative technologies in this report and are distinguished from "next generation" alternative technologies.

The emerging or potential "next generation" alternative technologies have also been evaluated, where adequate information on such options was available, to provide a more complete picture of future possibilities. These "next generation" options are not likely to be sufficiently well developed or available in the time frame of the commercial transition away from CFCs in the 1990s.

The development and commercial implementation of cleaning system technology options (solvent, aqueous, and semi-aqueous) is occurring at a more accelerated pace; therefore, the technology categories are defined somewhat differently. Currently sold and manufactured machines for major user markets are defined as "baseline" technology. Technology developed and likely to be increasingly practiced is defined as "best available current technology."

1.5 MAJOR FINDINGS

The results of the quantitative analyses conducted for each of the applications are illustrated in a series of summary bar graph figures. These figures show the changes in TEWI of the various CFC alternatives relative to the baseline CFC technology for a range of refrigerant, insulation, and cleaning applications. The relative proportions of the DIRECT and INDIRECT effects on the TEWI for each of the various alternatives or technical options are also illustrated. Reference will be made to these figures as the major findings are highlighted and discussed below. The study findings are separated into major general findings and application-specific findings.

The major general findings that address all three major application areas include the following:

- Replacement of CFCs with suitable HCFCs or HFCs yields a dramatic benefit in reducing TEWI for all CFC end-use applications considered; reductions in TEWI range from 10% to 98%, depending on application. The TEWI improvements are most striking in relatively high-loss applications such as solvent cleaning, automotive air conditioning, and commercial building roof insulation, as shown in Fig 1.5, 1.6, and 1.7.

- There is a wide variation among applications with regard to the relative importance of the INDIRECT (energy use) effect and the DIRECT (chemical emission) effect of the HCFC/HFC alternatives; the DIRECT effect can range from 2% to 98%, for instance,

  - Refrigerators/freezers show only 2-3% DIRECT impact with a variety of HFC refrigerants and HCFC foam blowing agents

  - Open top equipment for batch electronic cleaning of electronic components may have as high as a 98% DIRECT impact

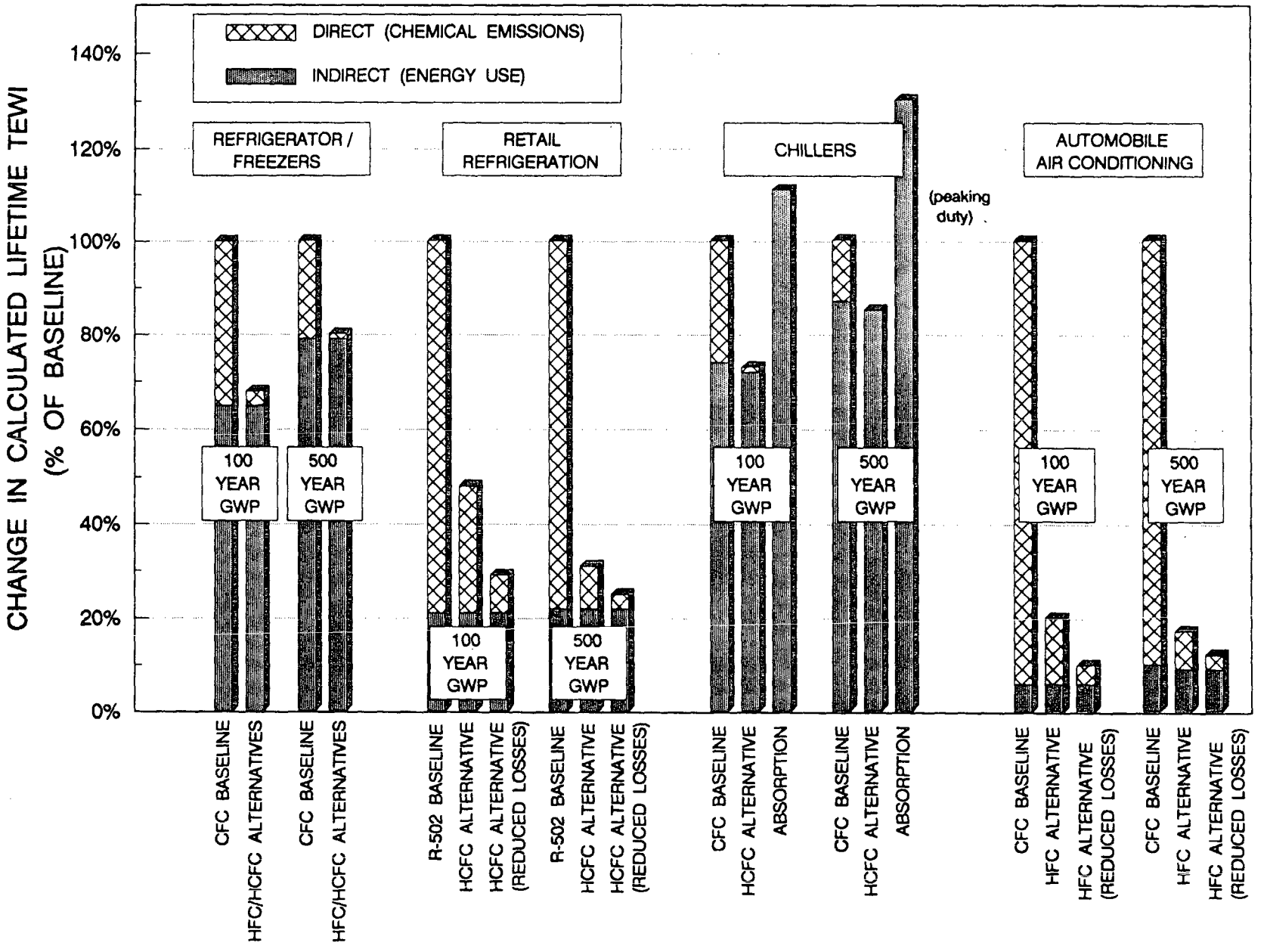

Fig. 1.5. Changes in TEWI relative to baseline CFC technology for selected refrigeration and air-conditioning applications.

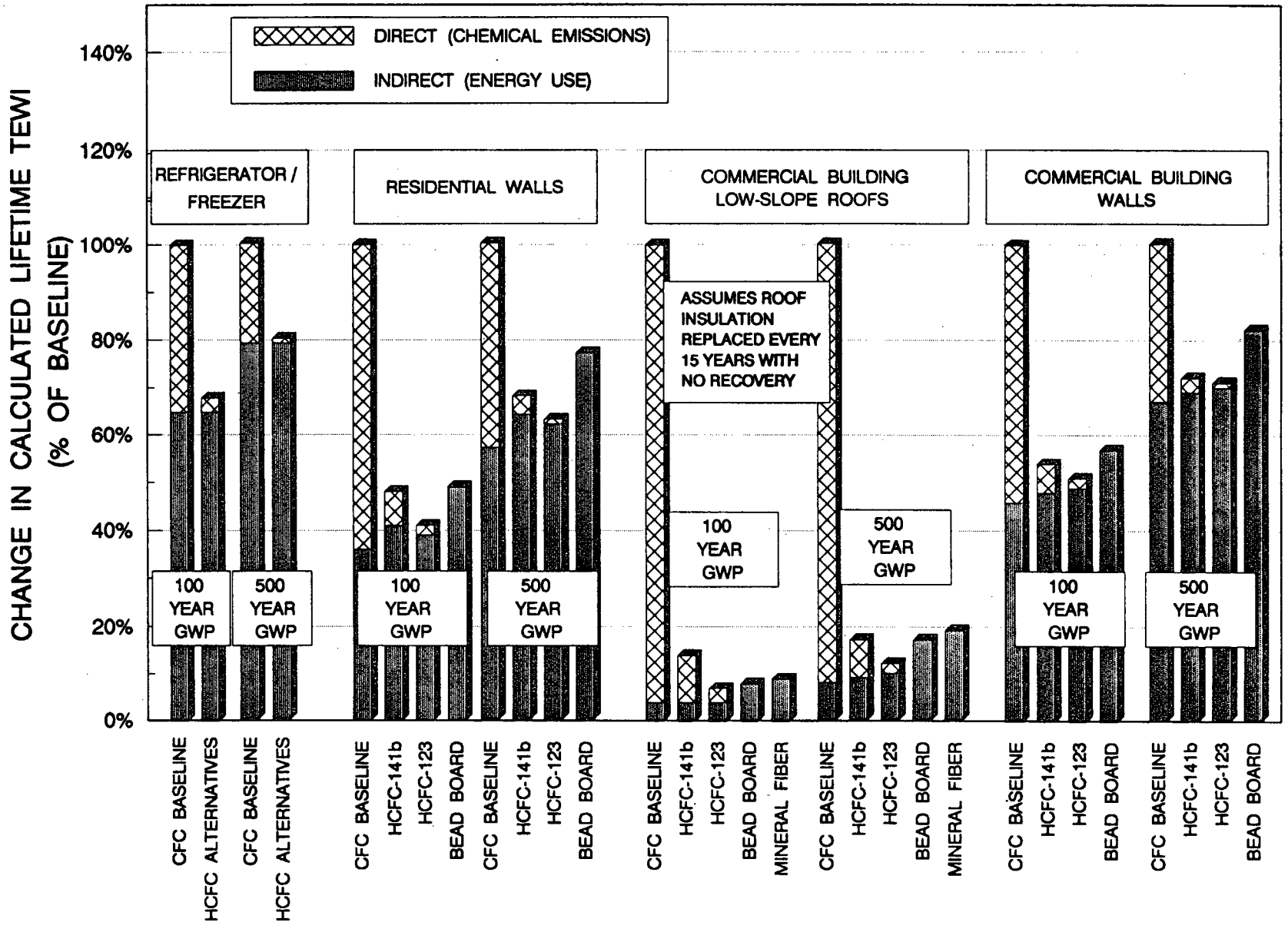

Fig. 1.6. Changes in TEWI relative to baseline CFC technology for selected insulation applications.

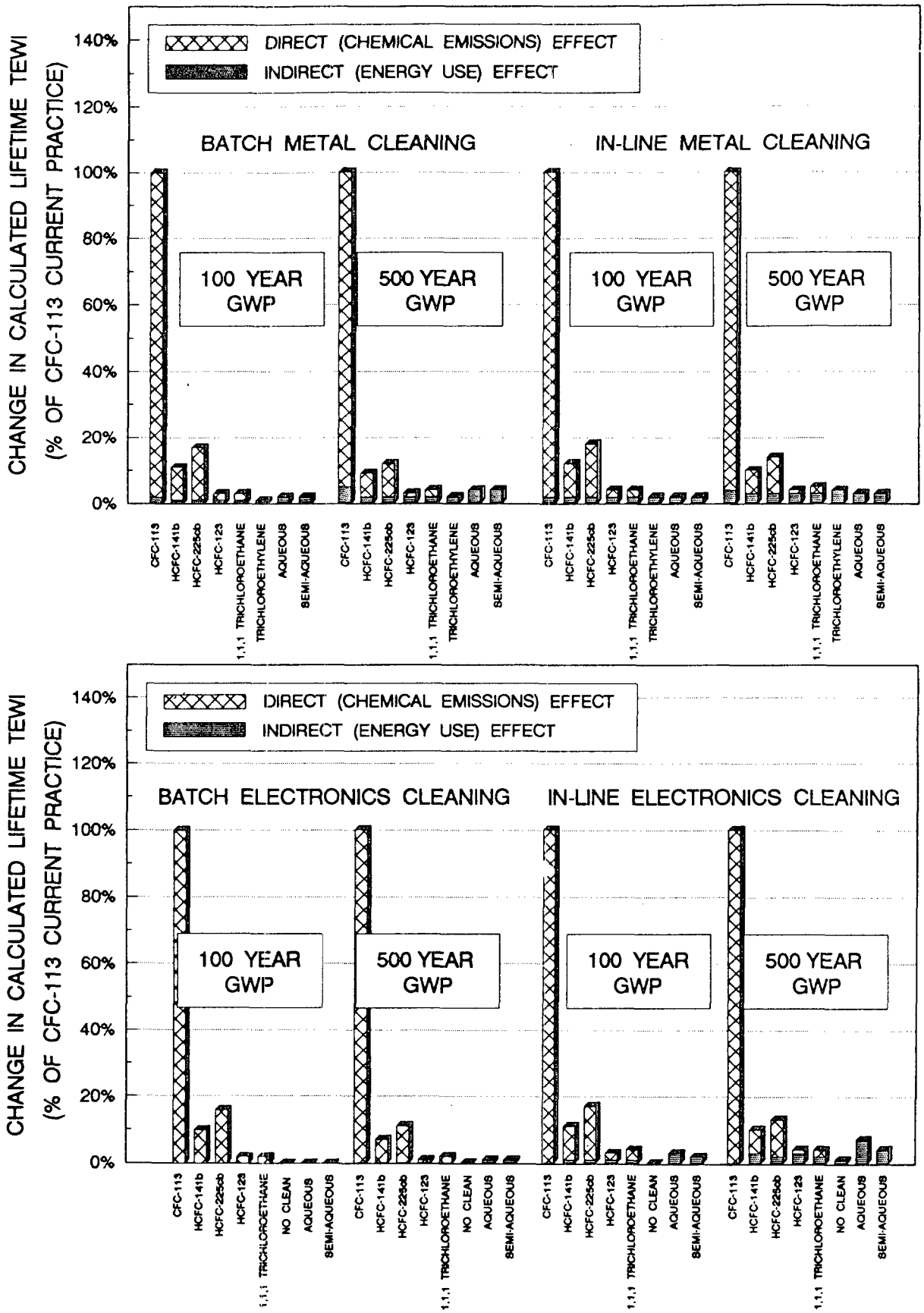

Fig. 1.7. Changes in TEWI relative to baseline CFC technology for current cleaning systems.

- Several alternative not-in-kind (NIK) technologies were evaluated or considered in each of the three major application areas, with results for some also showing reduced TEWI benefits.

  - Aqueous and semi-aqueous cleaning technologies are examples of NIK alternatives already in widespread use which exhibit a substantial reduction in TEWI relative to the baseline CFC cleaning technology (as shown in Fig. 1.7).

- Energy use for most of the available or current generation NIK options was found to be greater than for the HCFC/HFC technologies, as illustrated for insulation options (Fig. 1.6) and chillers* (Fig. 1.5). However, some next-generation NIK options such as evacuated vacuum panel insulation for appliances and "no-clean soldering" technology in the electronics sector show promise for future energy savings. Technical issues must still be successfully resolved before these options can be widely adopted.

SPECIAL NOTE: Improper conclusions can be drawn by comparing the TEWI shown in Figs. 1.5, 1.6, 1.7, and 1.11 using 100 year GWP values with those shown using 500 year values. For example, the 500 year TEWI show a higher percentage indirect effect, not a higher indirect effect than is shown for the 100 year GWP values. The indirect effect has the same magnitude in each case, the percentage increases because the total effect is smaller using the 500 year GWP values.

Figures 1.8, 1.9, and 1.10 focus on the fluorocarbon (HCFC and HFC) alternatives and illustrate the relative importance of their INDIRECT (efficiency-related) and DIRECT (emissions-related) effects. Most of the "current generation" HCFC and HFC technologies are still being optimized and, thus, the currently available data are not likely to represent the lowest cost effective energy consumption or the lowest losses/emissions achievable. Accordingly, these illustrations focus on identifying opportunities for further future reductions in the TEWI.

- For applications which are dominated by the INDIRECT (energy related) effect, insulation measures and efficiency improvements that are dependent on availability of suitable HCFC and HFC substitutes, represent the most effective, and in some cases, the only practical approach for achieving further substantial reductions in greenhouse gas emissions and TEWI.

- For applications in which the DIRECT effect of the chemicals represents a dominant or substantial proportion of the TEWI, such as solvent cleaning, automotive air conditioning, and retail refrigeration, further reductions in TEWI will be more dependent on low-loss concepts or new technology

  - These applications represent important target opportunities for developing and demonstrating new technology options aiming at substantially no-release equipment that could work with the most efficient substitutes (in-kind or not-in-kind) available in the long term.

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* NOTE: Absorption chiller results shown in Fig. 1.5 are representative of peaking duty for direct-fired double-effect equipment and are not directly comparable to the adjacent results for baseload duty of the CFC and HCFC/HFC chillers.

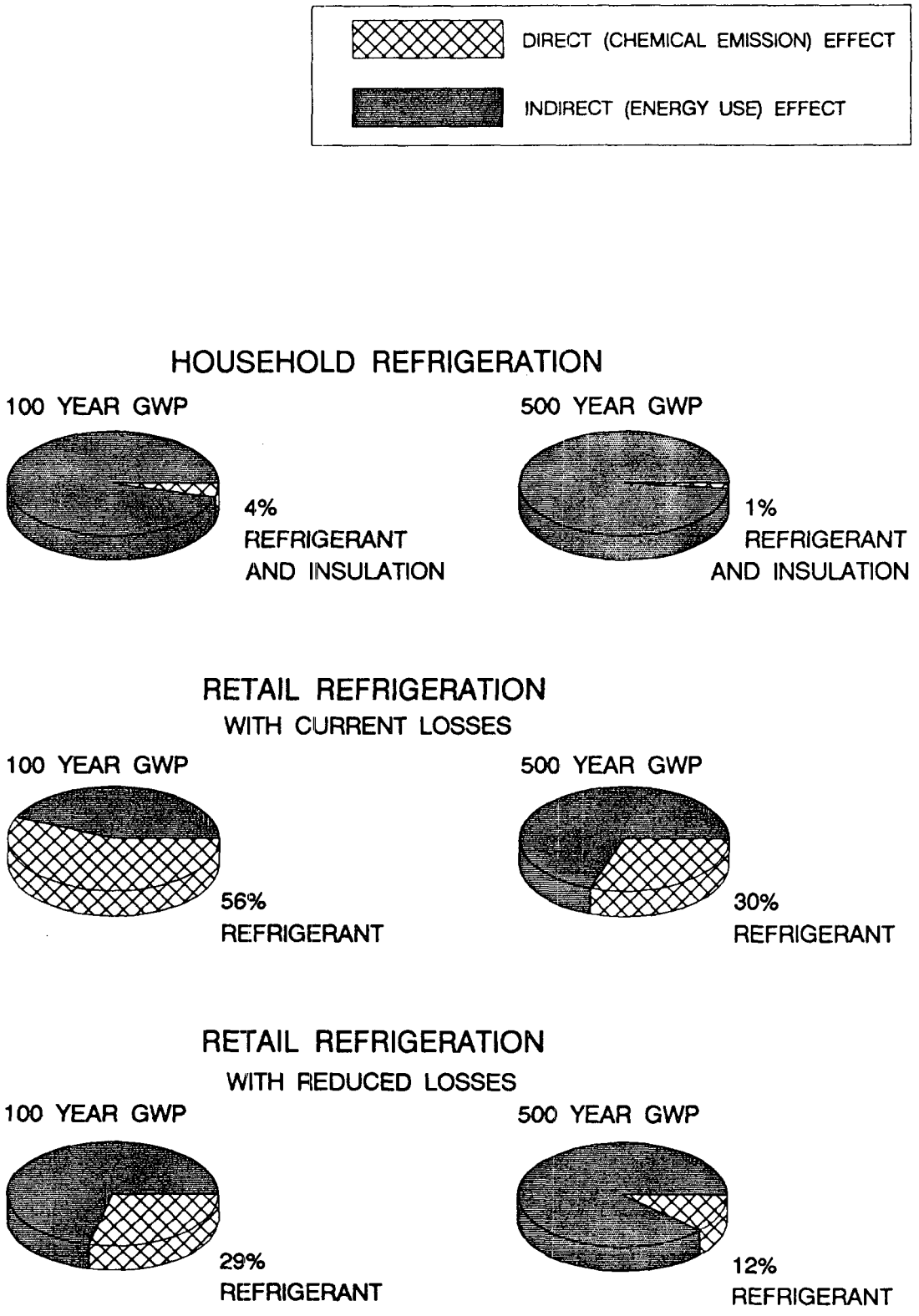


Fig. 1.8a. Relative proportion of DIRECT/INDIRECT effects to TEWI for selected refrigeration applications of HCFC and HFC alternatives.

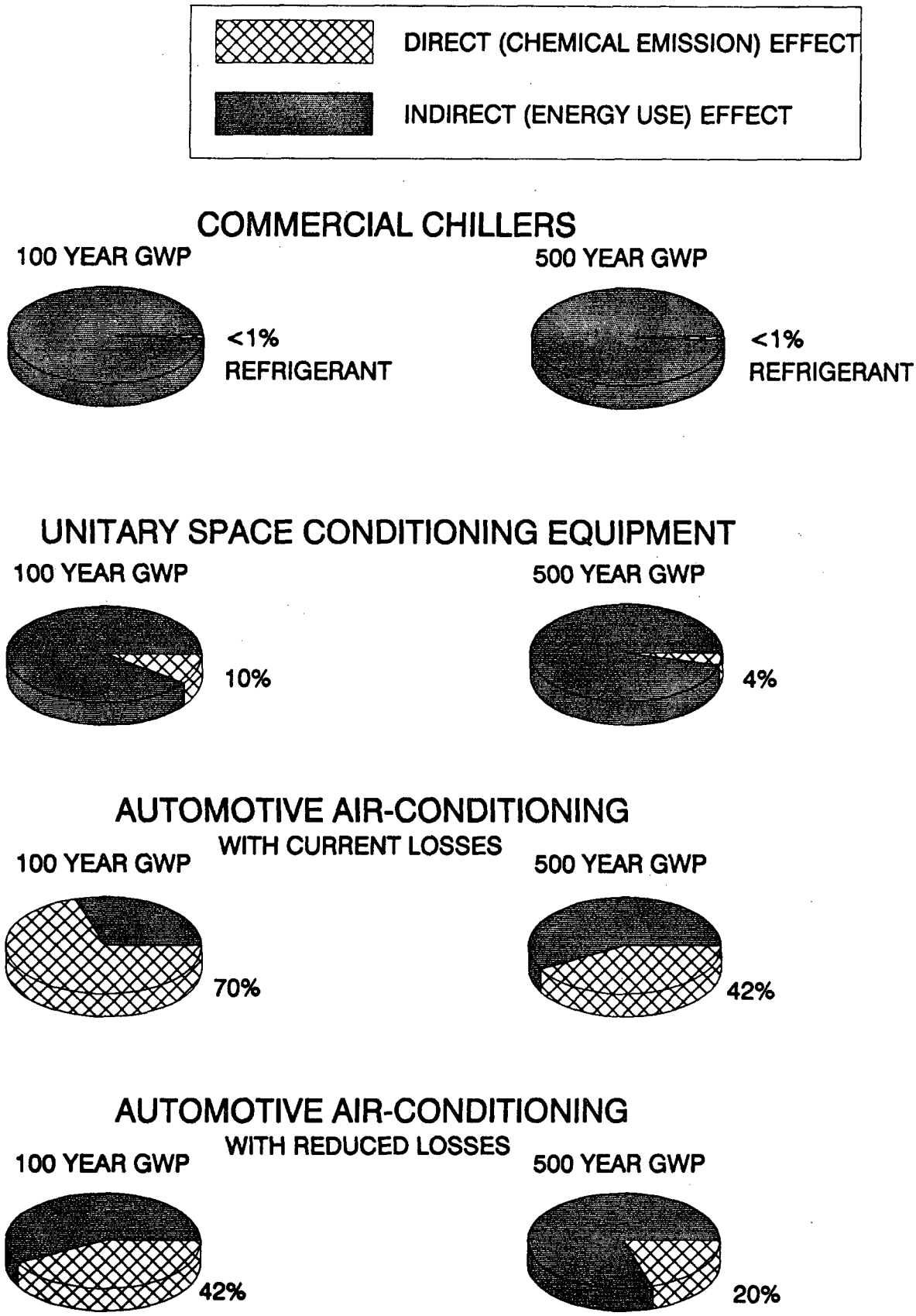


Fig. 1.8b. Relative proportion of DIRECT/INDIRECT effects to TEWI for selected air-conditioning applications of HCFC and HFC alternatives.

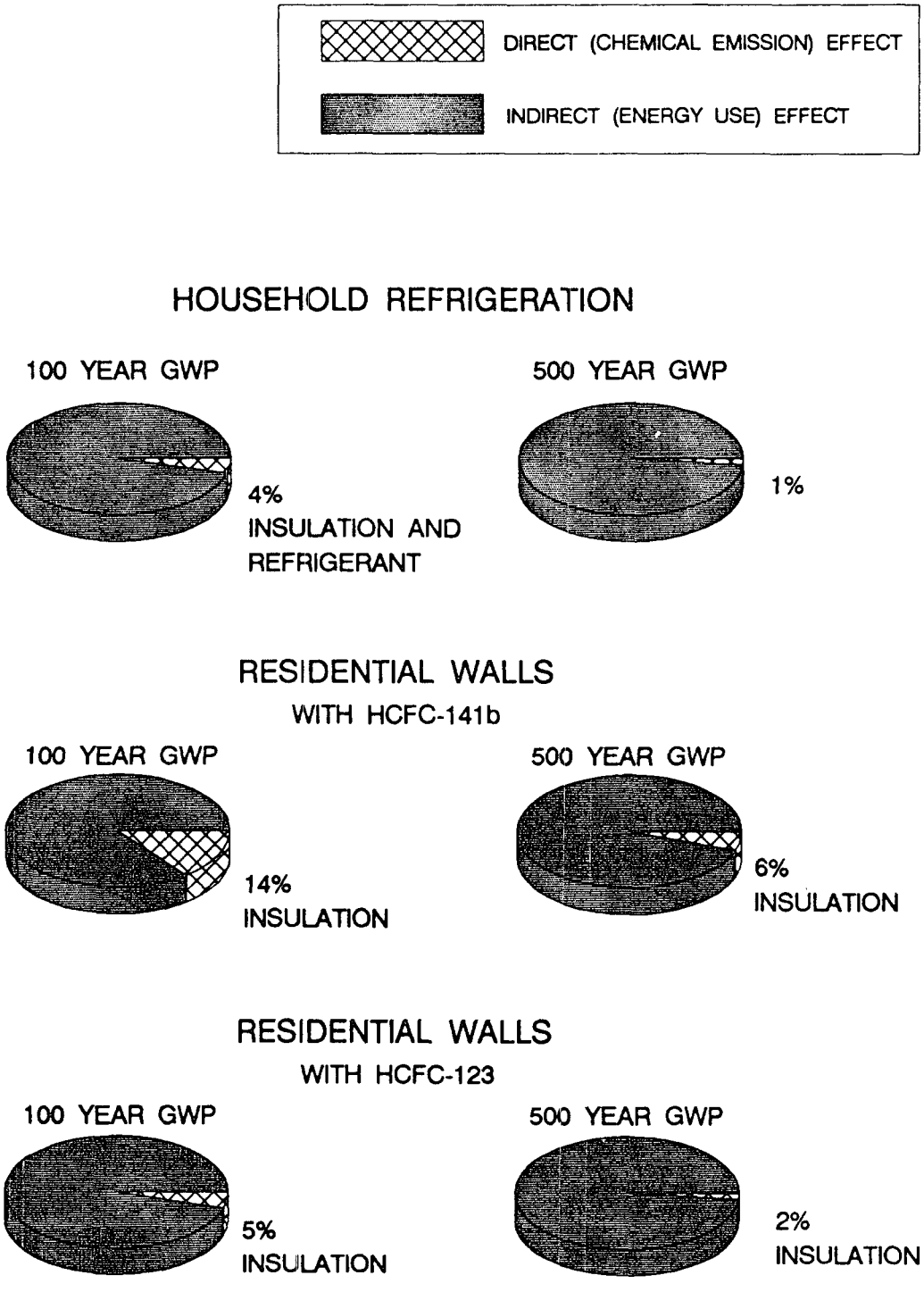


Fig. 1.9a. Relative proportion of DIRECT/INDIRECT effects to TEWI for selected insulation applications of HCFC alternatives.

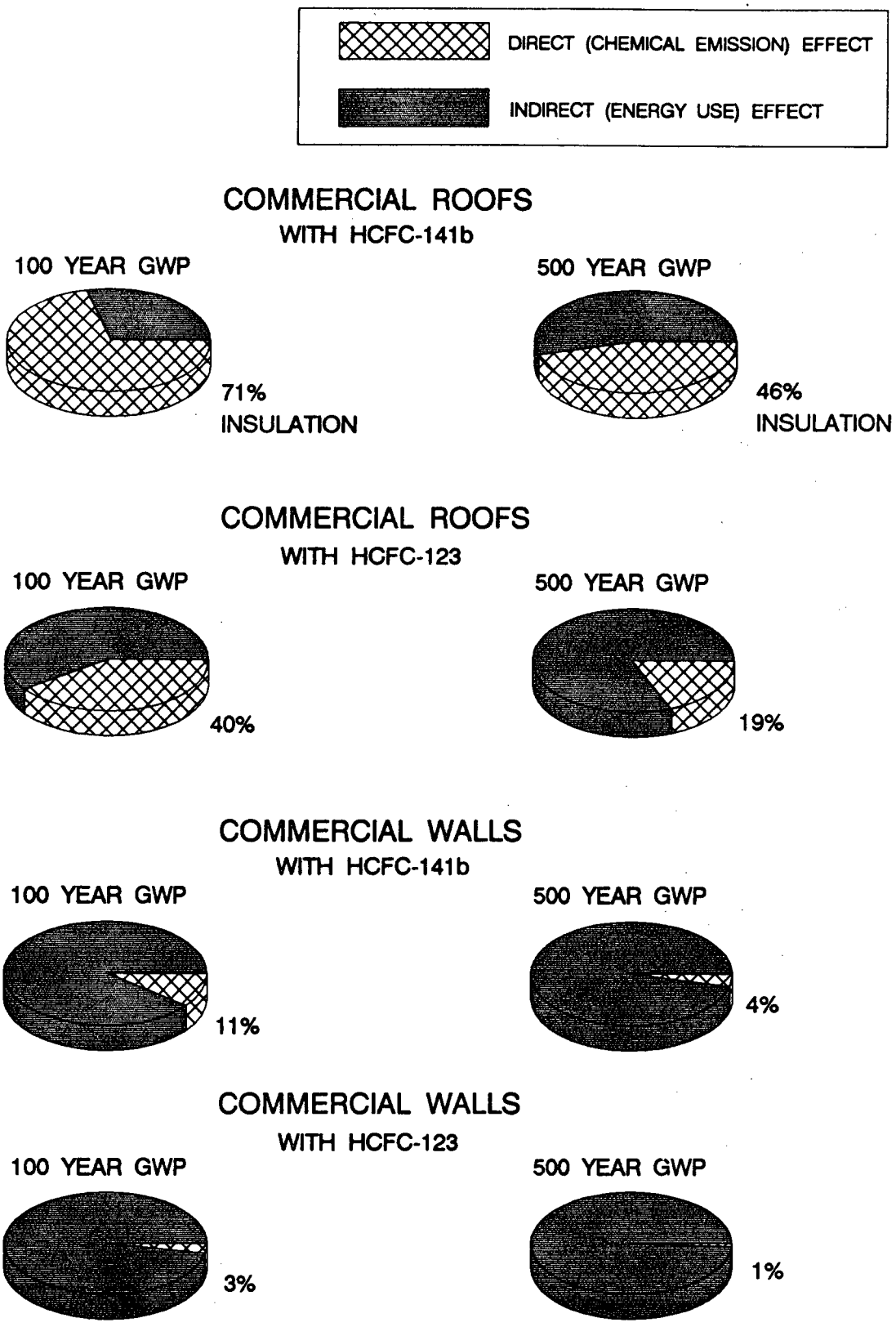


Fig. 1.9b. Relative proportion of DIRECT/INDIRECT effects to TEWI for selected insulation applications of HCFC alternatives.

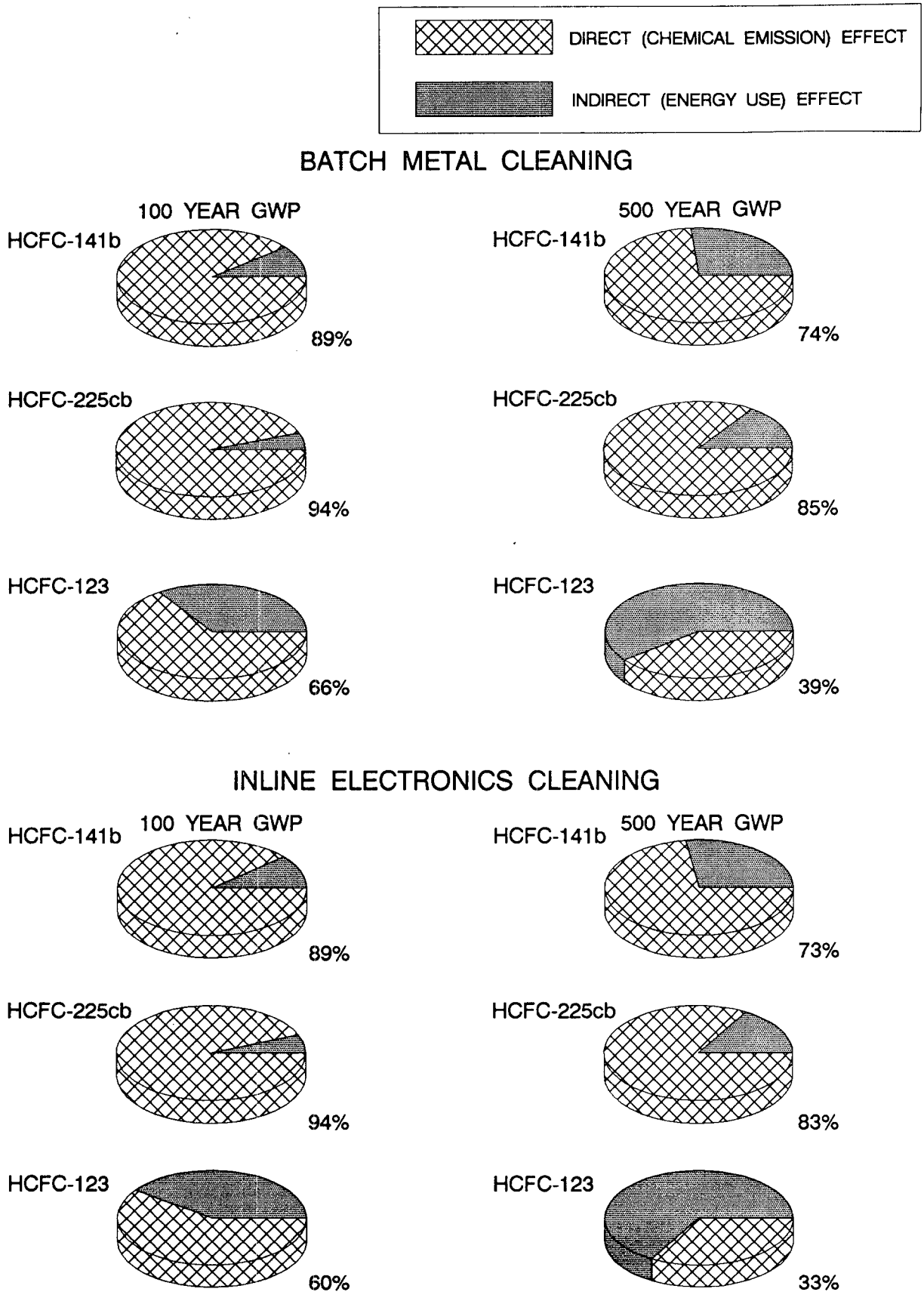


Fig. 1.10. Direct and indirect effects as proportion of TEWI for selected metal cleaning applications of HCFC alternatives (current cleaning technology, not BACT).

- Cleaning industries have generally identified and are already adopting or evaluating improved containment measures, technology to reduce energy consumption, and not-in-kind alternative options.

SPECIAL NOTE: The TEWI comparisons shown in Figs. 1.5, 1.6, 1.7, and 1.11 are valid only for different technology options within the same application. Different applications are combined on these figures only as a convenience in summarizing the results. It is important not to make comparisons between different applications; e.g., commercial roof insulation options should not be compared with household refrigerator insulation options with regard to TEWI differences.

1.6 APPLICATION SPECIFIC FINDINGS:

1.6.1. *CFC Refrigerant Alternatives*

- Energy efficiency/energy use differences are small between CFC baseline refrigerants and HCFC or HFC alternatives (Fig. 1.5).
  - Early published test data indicate small penalties for substitutes, but recent industry data show near equal refrigerant performance as achievable
    - -- with new lubricants
    - -- with optimized engineering design
- The small differences in lifetime energy use projections and associated INDIRECT CO_2 contributions among the HCFC and HFC options do not allow a meaningful ranking of the options at this time.

1.6.1.a For household refrigerators/freezers and building air-conditioning equipment dominated by INDIRECT (energy-related) effects:

- Once HCFC/HFCs have replaced CFCs, the only way to effect further significant reductions in TEWI is through energy efficiency improvements, whether with
  - conventional vapor compression cycle technology with HCFC/HFCs or other suitable working fluids, or
  - alternative cycles or processes

1.6.1.b The DIRECT (chemical-related) effect is a substantial proportion of the TEWI for automotive air conditioning and retail refrigeration HCFC/HFC applications (Fig. 1.8b).

- For these applications especially, improvements and/or projected improvements in service recovery practices and reduced losses from the piping systems can have a major influence on DIRECT effects and TEWI.
  - Further containment, new equipment design configurations and/or cycles/processes are longer term options for further reducing the TEWI for these applications.

1.6.2. *CFC Blowing Agents or Insulation Alternatives*

- Differences between "aged" thermal conductivity values for CFC-blown and HCFC-blown polyisocyanurate/polyurethane foam insulation materials are small; therefore, energy use and INDIRECT CO_2 emission differences are minor (Fig. 1.6).

- Differences in foam insulation thermal conductivity values and energy use between the leading HCFC blowing agents, 123 and 141b, are also small.

- Energy use for non-fluorocarbon foam insulation or fiber insulation is greater than for HCFC-blown foam insulation (Fig. 1.6); but, in some cases, the TEWI's are essentially equal, due to difference in DIRECT (chemical emission) effect of longer-lived HCFC's.

1.6.2.a For appliance insulation and residential/commercial wall insulation dominated by INDIRECT (energy-related) effects:

- Once HCFCs are used to replace CFCs, the primary avenue for further reducing TEWI is through more or better thermal insulation via

  - improved thermal resistance foam and advanced manufacturing processes with HCFCs (or other suitable low-conductivity gases or blowing agents),

  - thermal envelopes with higher insulation levels in buildings, or

  - next-generation insulation materials such as evacuated panels for some applications.

1.6.2.b The most significant DIRECT impact from HCFC-blown foam is associated with commercial roofing and re-roofing (Fig. 1.9).

- This finding is linked to current service life of commercial building roofs, which could possibly be extended by future improvements in construction and maintenance practices.

- The significance of the DIRECT impact is critically dependent on the atmospheric lifetime, and hence, the GWP of the HCFC used in these applications.

1.6.3. *CFC Alternatives for Metal and Electronic Cleaning and Drying*

- All alternatives examined provide a dramatic improvement in TEWI compared with the current CFC-113 use (Fig. 1.7).

- All metal and electronic cleaning systems examined showed energy use for solvent systems are either comparable to or significantly less than for aqueous and semi-aqueous systems.

- Unless solvent losses from the cleaning equipment are carefully controlled, the DIRECT impact of solvents with the longer atmospheric lifetimes will be the predominant factor in the total equivalent warming impacts (Fig. 1.10).

- Although for most uses "no clean" technologies are not yet viable, should they emerge in the future, then further reductions in TEWI levels may be possible.

- Technologies are available but not widely practiced as yet to reduce the TEWI of both solvent systems and aqueous or semi-aqueous systems. Examples include:

- use of control systems (e.g., "economizers") can reduce the distillation rates in the idling mode by 67%.
- use of heat pumps in low boiling solvent based systems that can reduce energy requirements by as much as 75%.
- use of closed loop systems and/or heat exchangers for aqueous or semi-aqueous cleaning with potential savings of approximately 30 to 35%.
- better control of emissions of solvents, especially in batch metal and electronic cleaning. With moderate increases in equipment costs, emissions from these systems can be reduced by 80% or more; reductions in excess of 90% are possible with more advanced systems. For example, systems are available to control solvent emissions from 0.5 kg/m^2 for batch systems down to 0.02 kg/m^2 of printed circuit boards cleaned.
- much of this technology can be retrofitted to existing equipment.

An estimate of the impacts of systems using the best available current technology is shown in Fig. 1.11. This figure shows that the TEWI for CFC-113 using the best available current technology is only about 20% of the TEWI for CFC-113 current practice (as shown in Fig. 1.7) and the TEWIs of the alternatives with BACT are even less. When widely adopted, the TEWI of solvent systems will be comparable or less than aqueous or semi-aqueous systems.

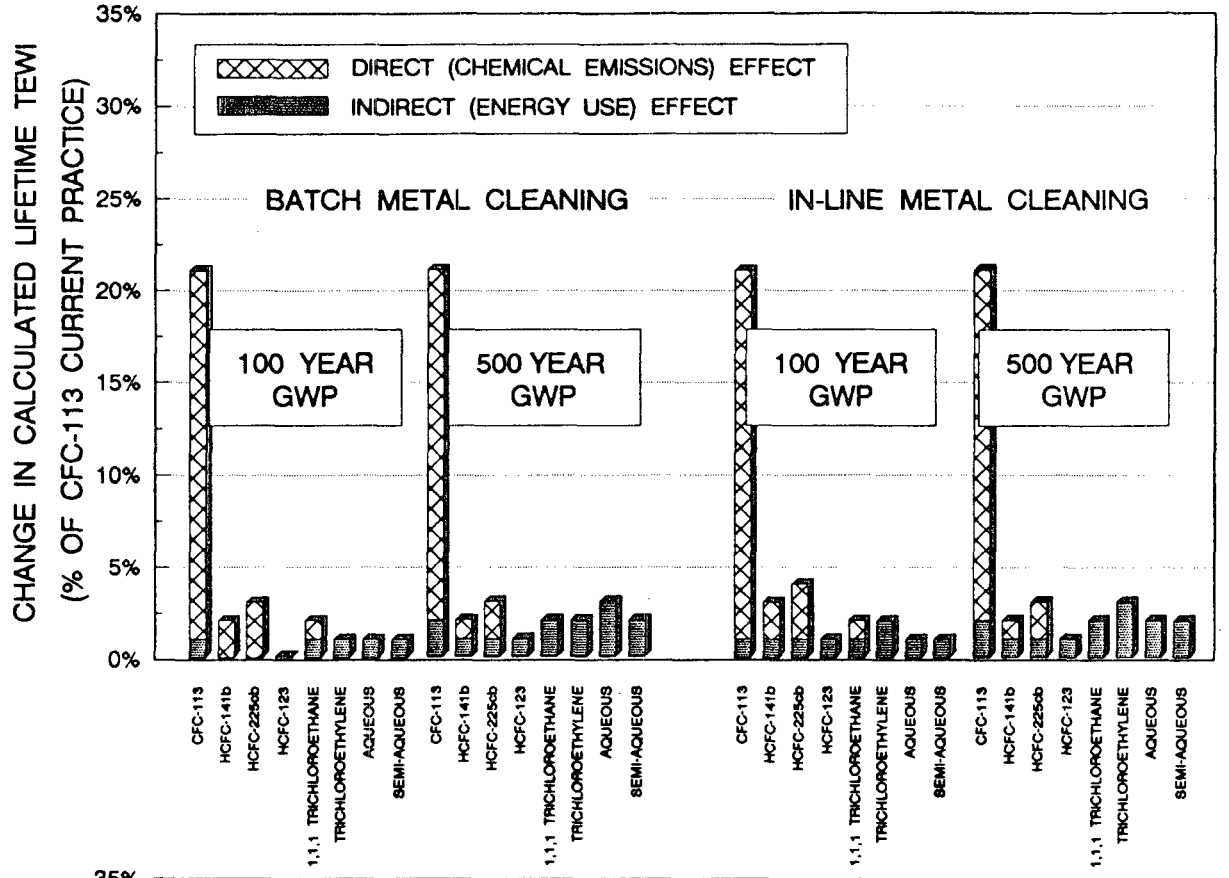
1.7 CONCLUSIONS

The potential changes in CO_2 emissions related to energy use of CFC replacement technologies (i.e., the INDIRECT effects) were found to be relatively small due, in part, to the emphasis placed on energy efficiency by the user industries. Therefore, the ten-fold reduction in DIRECT effects resulting from replacing CFCs depicted in Fig. 1.2 will yield a substantial reduction in TEWI and, hence, in contributions to future global warming in the industrialized countries by the end of the 1990s. This conclusion assumes that the options considered in this study are available and otherwise acceptable for the CFC transition.

Effects of not-in-kind replacement technologies and improved conservation/containment and recovery of the replacement fluorocarbons should further reduce the DIRECT effects and provide added reductions in the TEWI. The IPCC report (1990) and industry estimates (Gidunal, 1991) suggest that the future demand for HCFCs and HFCs may only be 40% of that for CFCs (based on projections from demand in late 1980's), due to the effects of reduced emissions and use of non-fluorocarbon alternatives. If this occurs, a twenty-fold reduction in DIRECT effects from fluorocarbon applications could be realized.

There is ample evidence from the user industry inputs to this study that conservation efforts are receiving increased attention for controlling current CFC emissions. The improved containment and recovery practices and technological solutions generated by these efforts should be readily adopted for the alternative fluorocarbons. On the other hand, not-in-kind (NIK) alternative technologies are generally not receiving major research attention in the refrigeration, air conditioning and insulation user industries, for a variety of valid business, technical, and time-related reasons.

The potential importance of these NIK options in the longer-term is acknowledged. The study has included some examples; although many more are under development. These options should be considered more fully, but information and verifiable data on many of these options are fragmented and difficult to interpret and compile. It is also difficult to assure comparability of available data on developmental technology with commercial or near-commercial technology. Misleading or speculative conclusions could be reached, perhaps to the detriment of the new or unconventional technology.



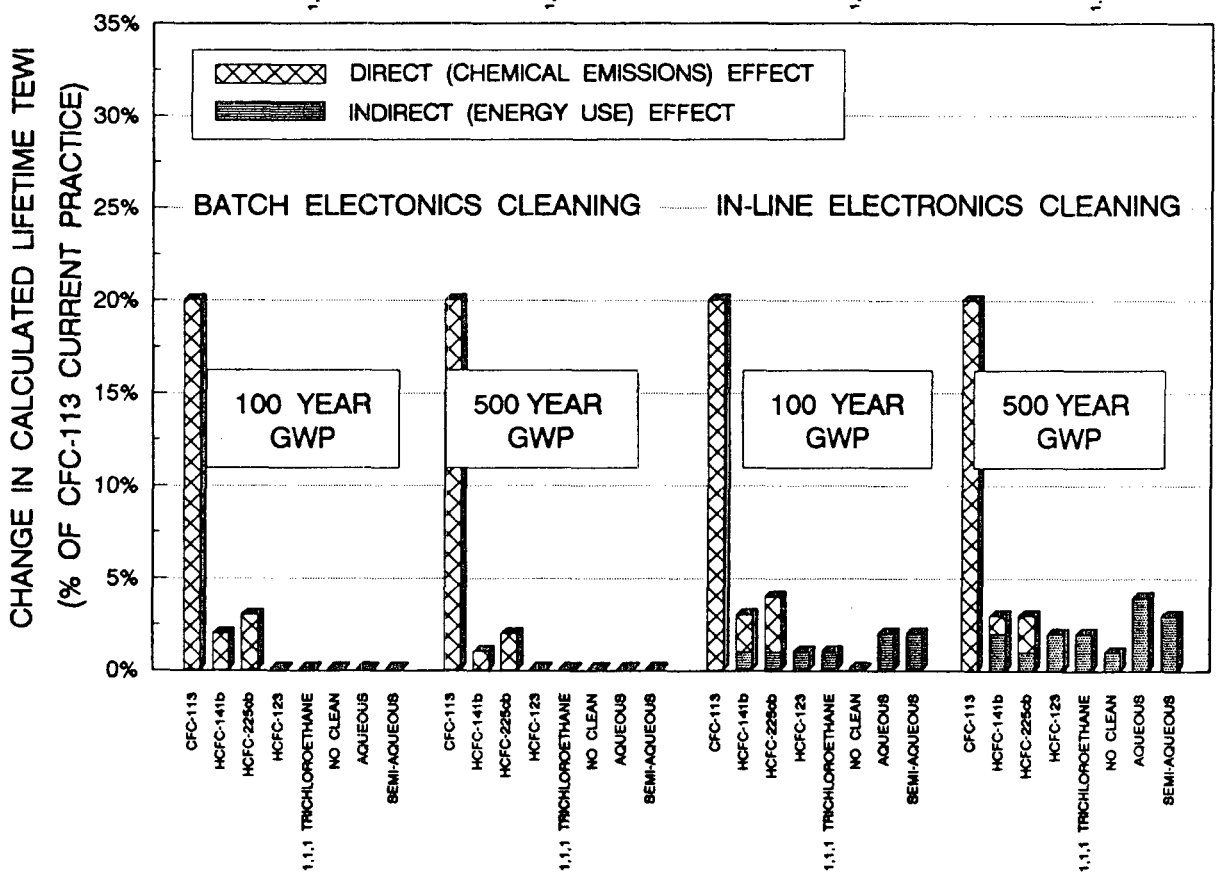


Fig. 11. Changes in TEWI relative to baseline CFC technology for Best Available Current Technology cleaning systems.

At a later stage, when these technologies reach a more mature state of development, further analysis should be attempted.

It was judged most important in this initial assessment to focus on "current generation" technology options and to reflect the thinking and planning of the user industries mainstream. The impacts of their preferred options represent the most likely outcome for the immediate CFC transition in the 1990s. The analysis and findings point out and highlight those applications in which the opportunities for NIK options may be the greatest, that is, in applications for which substantial HCFC/HFC DIRECT (emissions-related) effects remain. In the other applications in which the INDIRECT (energy-related) effects dominate, the NIK technologies would essentially have no significant TEWI advantage over fluorocarbon technologies unless they also offered lower energy use. A change of only 2 to 5% in efficiency would have a greater impact on TEWI than completely eliminating the direct (fluorocarbon-related) effect. NIK technologies would therefore have to be developed that are equal (or better) in energy efficiency and comparable in cost to the HCFC/HFC options to offer a TEWI reduction benefit in these applications.

Prior to the October, 1991 release of the UNEP/WMO Scientific Assessment Summary it was believed that replacing CFCs was the most important single near-term step that could be taken toward reducing future global warming impacts. However, since ozone depletion, linked to CFCs, appears to lead to a reduction in radiative forcing and hence the global warming impact of these gases, the net reduction to future global warming due to CFC elimination is uncertain. Because of the world's dependence on fossil fuels for primary energy needs and the predominant contribution of CO_2 to future global warming forcing, energy efficiency will be critical in limiting CO_2 emissions.

Finally, it is well recognized that the needs of the developing countries must be considered. The industrialized nations must be sensitive to the applicability, adaptability, and appropriateness of our technological solutions in those regions, where, for example, refrigeration needs are increasing dramatically. These global environmental issues such as ozone depletion and global warming require near complete participation worldwide if the solutions are to be effective. The energy and CFC replacement technology choices made by the developing nations will be crucial in determining how well we do overall in minimizing contributions to these issues.

2. INTRODUCTION

2.1 BACKGROUND

In addition to their more publicized role in ozone depletion, chlorofluorocarbons (CFCs) are among the "greenhouse gases" in the atmosphere that contribute to future global warming.

The contribution of CFC emissions to global warming in the last decade is second only to carbon dioxide (CO_2). It is understandable, therefore, that to date most attention has been focused on the DIRECT global warming effects of CFCs, as greenhouse gases, and on their relative GWP (or global warming potential) values.

The GWP index, developed through international cooperation among the world's atmospheric scientists, provides a simplified means of estimating the relative strength or potency of each CFC, alternative fluorocarbon, or other greenhouse gas. Hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are among the options available as CFC replacements. HCFCs and HFCs are also greenhouse gases, but because of their relatively short atmospheric lifetimes, their potential to contribute to global warming — their GWP — is much smaller than the potential of CFCs.

GWP by itself, however, is an incomplete measure of the potential global warming impact, because it does not account for a major INDIRECT effect — the CO_2 (greenhouse gas) emissions associated with energy use implications of CFC replacement technologies. Most of the controlled CFCs have important energy-related applications.

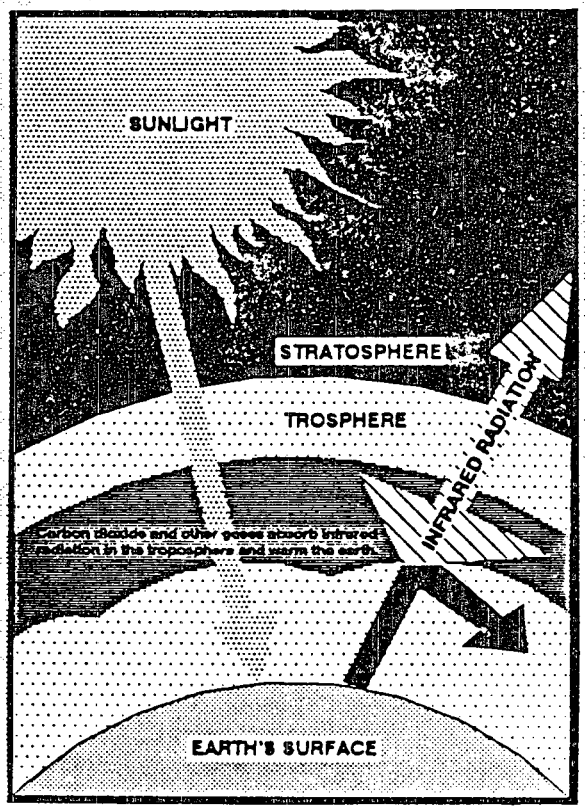
These include the use of CFC-12 as the refrigerant (or working fluid) in commercial and household refrigeration and in automotive air-conditioning, the predominant use of CFC-11 in centrifugal chillers for cooling large commercial buildings, and the use of CFC-115 as the major component in the R-502 azeotropic mixture used in low-temperature frozen food systems (retail and cold storage). Both CFC-11 and CFC-12 are used as "blowing agents" in producing a variety of foam insulation materials (polyisocyanurate, polyurethane, and extruded polystyrene) used in commercial and residential buildings and household appliances. These are all energy-intensive applications and, for most, energy efficiency or thermal performance is a prime consideration of the user industries in developing and quantitatively evaluating their CFC replacement options. Although not usually quantified, the technology options for replacing CFC-113 solvent cleaning agents can also involve significant inputs of energy for functions such as pumping, drying, and creation of artificial atmospheres.

In most cases, the energy associated with these CFC uses is provided by combustion of fossil fuels (at point-of-use or at electric power plant), resulting in the release of CO_2 to the atmosphere. These energy-related CO_2 emissions or INDIRECT effects may be comparable to or larger in their global warming impacts for some CFC replacement options than the combined DIRECT and INDIRECT effects of other options. Consequently, the systems approach of considering both DIRECT and INDIRECT sources of greenhouse gases seems appropriate and necessary to develop sound decision-making information.

To translate the results of the study into real world acceptance by industry and governments, other considerations–in addition to global warming–must also be taken into account. These include ozone depletion, toxicity, flammability, tropospheric ozone (photo-chemical smog) formation and tropospheric decomposition products. Many of these topics are addressed in other parts of the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) or the Program for Alternative Fluorocarbon Toxicity Testing (PAFT).

The Greenhouse Effect

The "Greenhouse effect" refers to the trapping by the atmosphere of a portion of the infrared radiation normally emitted back into space and the resultant warming of the earth's climate. The major constituents of the earth's atmosphere, nitrogen and oxygen, are essentially transparent to the radiation from the sun and to the lower frequency infrared heat radiation that is emitted by the warmed earth outward toward space. As illustrated conceptually in the figure below, minor constituents in the atmosphere, notably carbon dioxide and water vapor, absorb infrared radiation (IR) and reradiate only part of it outward to the colder temperature of space, leading to a net trapping of IR energy within the atmosphere. The long-term climate is governed by this energy balance between the absorbed solar radiation and the net emitted IR, along with the processes of convection and evaporation/condensation of moisture within the atmosphere.



Without the atmospheric capacity provided by the natural IR absorbing gases, the earth's equilibrium temperature would be about 30-35 degrees C (54-63 F) colder than it is now (Perry, 1986). Therefore, naturally occurring greenhouse gases keep the Earth warm enough to be habitable. However, emissions from human activities are capable of raising the "global temperature" (i.e., that global average annual-mean surface temperature) by increasing the concentration of natural gases like CO_2 or by adding new greenhouse gases like CFCs. This "enhanced" greenhouse effect is popularly referred to as global warming. The issue of concern, therefore, is not the greenhouse effect but the potential for accelerated global climate change that could be induced by man made changes to the earth's atmospheric IR absorption characteristics.

While the theory of global warming linked to atmospheric CO_2 concentrations is not new, the importance of other trace gases was not recognized until recently (1970's). These other trace gases include methane, nitrous oxide, tropospheric ozone, and the CFCs. As shown in the table below, the concentrations of all these gases are increasing, and it is generally conceded that the changes can be attributed to human activities (Ramanathan, 1988).

GREENHOUSE GASES AND CONCENTRATION CHANGES OVER TIME

GAS	CONCENTRATIONS			% Increase (1975-85)
	PRE-1850	1975	1985	
Carbon Dioxide (CO_2)	275 ppmv	330 ppmv	345 ppmv	4.6
Methane (CH_4)	0.7 ppmv	1.5 ppmv	1.7 ppmv	11.0
Nitrous Oxide (N_2O)	0.285 ppmv	0.294 ppmv	0.304 ppmv	3.5
CFC-11	0	0.11 ppbv	0.22 ppbv	103
CFC-12	0	0.19 ppbv	0.38 ppbv	101
Methyl Chloroform (CH_3CCl_3)	0	0.05 ppbv	0.13 ppbv	155
Carbon Tetrachloride (CCl_4)	0	0.097 ppbv	0.12 ppbv	24

The rising CO_2 concentration is associated with the widespread use of fossil fuels such as coal, gas, and oil and with the earth's reduced capacity to absorb CO_2 due to deforestation. Use of these fossil fuels is, in turn, directly linked to our energy needs and what technology we employ to meet those needs. Much of that technology in the residential, commercial, transportation, and industrial sectors is directly or indirectly related to use of CFCs and other substances controlled under the Montreal Protocol.

2.2 OBJECTIVES

The primary objective of this study is to develop representative quantitative indications of the relative energy use and associated INDIRECT CO_2 emissions, together with the DIRECT (chemical-related) equivalent* emission effect of viable options to replace CFCs in their major energy-related application areas. Both INDIRECT and DIRECT effects are taken into account to determine the combined global warming impact of the system, material application, or process being evaluated. The sum of these two types of emissions represents the total equivalent warming impact (TEWI)*, a concept which is used for comparative assessment of the various technical options.

The evaluation emphasizes those CFC replacement technologies that can be implemented on a global scale over the next ten years, including HCFC–and HFC–based options and other "not-in-kind" (non-fluorocarbon) technologies under development by the user industries.

This global warming information should be an important addition to other data and assessments of other environmental effects, health and safety aspects, and costs to allow industry, international policy-makers, and governments to make sound decisions for the future among the options available to meet societal needs in the developed and in the developing world in view of the CFC phaseout.

2.3 OVERALL APPROACH AND METHODOLOGY

This study uses a systems approach to provide an initial assessment of the total equivalent warming impact of systems using CFC alternative technologies. The study is international in scope and takes into account significant differences in present CFC end-use practices, sources of energy, and other societal factors between Europe, Japan, and North America.

The study involved experts from industry, government, and academia around the world in refrigeration, thermal insulation, and solvent cleaning to characterize existing CFC practices or baseline technology and to identify the technology options for the various applications and geographic regions. Therefore, much of the initial scoping work prior to the start of the impacts analysis can be viewed as a survey of the user industries concerning their candidate options to replace CFCs. The analysis was based on updated thermal properties, energy efficiency, and emissions data and other technology information from a wide array of experts in the user industries and other sources in Europe, Japan, and North America. The cooperation of these experts has been vital for the success of the study.

This study should be considered an overview of key issues. It relied largely on readily available information and focused on first generation CFC replacement technologies. The study is not comprehensive in its coverage of all CFC applications, technical options, and geographic regions, nor is the level of analysis undertaken exhaustive or technically detailed. However, these simplifications

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* Explanatory Note: For convenience in combining these effects, the DIRECT (chemical emission) effect is expressed as equivalent carbon dioxide, consistent with the Global Warming Potential (GWP) indexing approach of IPCC (explained further on p. 1.6 of the Executive Summary). This equivalent CO_2 DIRECT effect can readily be combined with the INDIRECT (energy-related) CO_2 emissions. The combined or total effect is termed the Total Equivalent Warming Impact or TEWI.

were judged by knowledgeable experts to be reasonable and appropriate for the type of impact assessment results sought and were necessary in order to complete the study within the time and budget available. Also, the shorter, simplified approach seems more suited to the rapidly changing CFC transition situation underway now than a more lengthy, exhaustive study.

The analysis addresses CFCs (baseline) as well as alternative chemicals and "not-in-kind" technology alternatives in uses such as refrigeration, foam insulation, and metal and electronic cleaning and drying processes. The focus of the technical analysis is on energy use comparisons of the technology options and associated service lifetime equivalent CO_2 emissions, together with estimated emissions of the refrigerant, blowing agent, or cleaning solvent, all on a per unit bases. Electricity end-uses of energy are referenced back to the power plant, with regionally specific proportions of various fossil and other source energy, for purposes of estimating CO_2 emissions per unit of energy delivered.

The general approach employed in all cases consisted of the following steps:

- Development of appropriate engineering parameters to characterize the baseline technology and algorithms for calculating energy use in each application

- Identification of alternatives to replace the use of CFCs in the existing applications

- Collection and compilation of user industry data on comparative engineering parameters and physical properties to characterize the technology option(s)

- Calculation of energy use and calculation of estimated lifetime equivalent carbon dioxide (CO_2) emissions (<u>INDIRECT</u> effect) from unit lifetime estimates and regional fuel utilization or electric power generation mix

  - for solvent these calculations were done on the bases of unit throughout

- Calculation of equivalent CO_2 emission of greenhouse gas content or loss (<u>DIRECT</u> effect), if applicable, for each option using the greenhouse warming potential (GWP) index values.

- Combination of the INDIRECT and DIRECT global warming effects and comparison of the total equivalent global warming impact (TEWI) of HCFCs, HFCs, and other technology options

This general methodology is adapted, as appropriate, for each specific application area, as described in the individual sections that follow.

Extensive review and revision of the draft application-specific analyses and preliminary results, coupled with meetings, correspondence, and discussions with users and other experts have preceded this version of the report to assure an objective and thorough evaluation of the findings and their basis.

The final report will be made available by the sponsors during Fall 1991 to the Technology Assessment Panel of the United Nations Environment Programme (UNEP) for their use in the Montreal Protocol reassessment process, and as input to the 1992 UN Conference on Environment and Development (UNCED).

2.4 APPLICATION AREAS AND TECHNOLOGIES CONSIDERED

The scope of applications encompasses refrigeration and space conditioning systems, building and appliance insulation materials, and metal and electronic cleaning/drying processes. Alternative fluorocarbons (HCFCs, HFCs) and other non-fluorocarbon ("not-in-kind") technology options were considered for each of these application areas.

The major refrigerant applications covered in the analysis include:

- household refrigerator/freezers
- commercial refrigeration
- chillers (water-cooled, air-cooled)
- unitary space conditioning equipment
- automotive air-conditioning

The major applications of foam insulation include:

- commercial building roofs and walls
- residential wall sheathing
- insulation for household and commercial refrigeration

The major applications of solvents include:

- in-line and batch electronics cleaning processes
- in-line and batch metal cleaning processes

"Current Generation" and "Next Generation" Technologies

New systems, materials, and processes that represent potential CFC replacement technologies are being rapidly developed. Technology options already available or identified by the user industries as their primary development focus for first generation replacement of CFCs, whether fluorocarbon or not-in-kind (non-fluorocarbon) alternatives, were given first consideration with regard to quantitative analysis of their DIRECT and INDIRECT effects and their TEWI. These are referred to as "current generation" technologies in this report and are distinguished from "next generation" technologies.

The emerging or potential "next generation" technologies have also been evaluated, where adequate information on such options was available, in order to provide a more complete picture of future possibilities. These "next generation" options are unlikely to be sufficiently well developed or available in the time frame of the commercial transition away from CFCs in the 1990s.

The development and commercial implementation of cleaning system technology options (solvent, aqueous, and semi-aqueous) is occurring at a more accelerated pace; therefore, the technology categories are defined somewhat differently. Currently sold and manufactured machines for major user markets are defined as "baseline" technology. Technology developed and likely to be increasingly practiced is defined as "best available current technology."

Table of Alternative Technologies

Table 2.1 lists the alternatives considered for each of the above-listed applications. The baseline or reference CFC and the alternatives considered for each application area are aligned in columns with the baseline CFC listed first (above dashed line). The leading candidate options, as identified by the

industry experts, are listed next, followed by other "current generation" options and then the longer-term, potential "next generation" options. An exception appears in the building insulation materials column. The alternative materials ("not-in-kind" options) are listed separately from blowing agent alternatives for polyisocyanurate/polyurethane (PIR/PUR) and extruded polystyrene foam insulations only as a simplification in constructing the table. The alternative insulation materials are all commercially available now and, dependent on the specific application, could be used to replace either PIR/PUR or extruded polystyrene insulation.

Comments and Caveats

The current CFC transition has triggered an outpouring of proposed "solutions" from researchers, entrepreneurs, and others, some of which may eventually prove to be viable commercial technology. The need to find replacement refrigerants, for example, has generated interest in revisiting some classic non-fluorocarbon refrigerants such as ammonia, hydrocarbons, water, and air. Ammonia is an efficient refrigerant and, of these non-fluorocarbons, is probably the most widely used today, notably in vapor compression systems serving refrigerated and frozen food storage facilities (cold storage) and in smaller absorption systems. Air, employed in a modified Brayton cycle, is used for air-conditioning on some aircraft; where the advantages of the readily available bleed air and lightweight, compact equipment often outweigh its low efficiency. Certain hydrocarbons are also efficient refrigerants and can be used safely in some industrial plants where the entire plant is geared to handle flammable chemicals.

These and other niche market commercial technologies — such as evaporative cooling, desiccants, microcell foams, heat pumps for low boiling solvent-based cleaning systems, and indirect systems to reduce refrigerant charge/losses or to isolate hazards — could possibly play an expanded future role in many applications that now rely more on CFCs. Also, a wide array of new technologies are now in various stages of development, research, or evaluation — such as near-azeotropic and zeotropic refrigerant blends and associated cycle innovations, new foam polyols and processes compatible with low GWP HFCs, advanced absorption cycle heat pumps/chillers, Stirling cycle refrigeration/cooling, vacuum panel insulation, and superconducting magnetic heat pump technologies. At least some of these new technologies should also lead to commercial future products with a potential for reducing global warming impacts.

From this extensive list of potential future options, which could no doubt be expanded, a few examples were evaluated. The limited analysis of "next generation" technology in selected, generally "best suited," applications, is intended to provide representative examples of longer-term possibilities.

Data and information on the "current generation" options is relatively complete and reliable, whereas less data/information are available on the emerging or "next generation" technologies considered or evaluated quantitatively. These differences and uncertainties are noted and explained in the specific application chapters. Also, in recognition of the difficulties in assuring comparability of available data on future advanced technology with commercial or near-commercial technology, findings and conclusions involving comparisons between "current generation" and "next generation" options are generally avoided.

To reiterate, this study is not comprehensive in its coverage of all CFC applications or technical options. It does treat a sufficient number and variety of options to provide representative indications of the comparative TEWIs and the relative DIRECT/INDIRECT contributions to global warming, consistent with the primary objective of the study.

Table 2.1. Matrix of applications and alternatives considered in the study

Household Refrigeration		Commercial Refrigeration	Air-Conditioning Chillers, and Heat Pumps	Automotive Air-Conditioning	Residential and Commercial Building Insulation Materials	Metal and Electronic Cleaning/Drying
Insulation Blowing Agent or Alternative Technology	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Refrigerant or Alternative Cycle	Insulation Blowing Agent or Alternative Technology	Solvent or Alternative Process
			Chillers		*PIR/PUR*	
CFC-11	CFC-12	CFC-12	CFC-11	CFC-12	CFC-11	CFC-113
CO_2/CFC-11 (part water blown)	HFC-134a	R-502	CFC-12	HFC-134a	HCFC-123	1,1,1, TCA
HCFC-123	Ternary blend	HCFC-22	HCFC-22	Ternary blend	HCFC-141b	Trichloroethylene
HCFC-141b	Absorption	Two-stage multi-plexed HCFC-22	HCFC-123	HFC-152a	Isopropylchloride	Semi-aqueous
Isopropylchloride	HCFC-22/ HCFC-142b dual evaporator	HFC-134a	HFC-134a	Propane	*Extruded Polystyrene*	Aqueous
CO_2 w/additive perfluoroalkane cell modifiers)	HFC-152a	Ammonia vapor compression	Absorption (LiBr-water)	Brayton cycle	CFC-12	HCFC-123
100% CO_2 (water-blown)	Stirling Cycle (freezers only)	HFC-32 blend	Ammonia vapor compression	Stirling cycle	HCFC-142b	HCFC-141b
Evacuated (vacuum) panels			*Unitary*		HFC-134a	No-clean
Perfluoroalkanes (blowing agent)			HCFC-22		HCFC-124	HCFC-225ca/cb
			HFC-134a		*Alt. Bldg. Insulation Materials*	
			Absorption (ammonia water)		Glass fiber	
					Mineral fiber	
					Expanded polystyrene beadboard	

Rationale for Focusing on "Current Generation" Technologies

Research, engineering development, and manufacturing investment decisions are currently underway throughout the industrialized countries in preparation for an orderly transition from CFCs to suitable and environmentally acceptable replacement chemicals or alternative technologies by the year 2000. Some European community and other countries are adopting even stricter timetables (phaseout by 1995-1997).

It was therefore judged most important, in view of these schedules, for this initial assessment of global warming impacts to focus on "current generation" technology and on the thinking and planning of the user industries' "mainstream." The study results should provide these user industries with the information on potential global warming impacts most relevant to their upcoming choices. Also, the estimated impacts for their leading candidate options represent the most likely range of energy and environmental outcomes for the immediate CFC transition in the 1990s.

2.5 ORGANIZATION OF REPORT

This report begins with a brief review of the uses of CFC-11, -12, -113, -114, and -115 and recent consumption levels among the various applications. Also, as a prelude to the application-specific chapters that follow, the bases for converting estimates of chemical (fluorocarbon) emissions and energy usage into a common CO_2 effect is explained.

Each of the Chapters 4 through 11 that follow examines a specific energy-related application of CFCs and potential alternatives. For each application, a representative system (or other characteristic "unit") is described and used to calculate explicitly the amounts of greenhouse gases emitted, from estimates of either DIRECT fluorocarbon emissions or the quantities of carbon dioxide associated with energy use (INDIRECT emission). Significant differences in present CFC end-use systems or "units" between Europe, Japan, and North America are also described in these application-specific chapters.

The overall findings and conclusions, reported in Chapters 12 and 13, are derived from the application-specific results and findings. They focus on comparison of the total equivalent warming impacts (TEWI) among the CFC replacement options for the immediate CFC transition and identification of potential avenues for achieving further reductions in TEWI beyond that transition period.

3. APPLICATION-DEPENDENCE OF GLOBAL WARMING IMPACTS

3.1 INTRODUCTION

In evaluating the combined global warming impact, the applications which warrant the greatest attention are those which use the largest share of the fluorocarbon chemicals and those which have the largest energy use or potential influence on future energy use. From a previous analysis of energy-use impacts of CFC alternatives for the U.S. only (Fischer, 1989), it is known that the applications of importance from an energy viewpoint often do not coincide with the high chemical consumption (emissions) applications. For example, the energy use and potential energy impacts in household refrigeration can be much larger than for automotive air-conditioning, yet the CFC consumption level in the automotive application is about twelve times higher (see Fig. 3.3). The applications selected for evaluation in the chapters that follow have thus been selected to represent a range of consumption (emission)-dominated and energy-dominated applications.

3.2 USAGE OF CFCs BY APPLICATION

Future levels of alternative fluorocarbon consumption and emissions are expected to be substantially lower than past CFC consumption. However, it is still appropriate to review the end-use consumption patterns of the baseline CFCs briefly to provide a perspective on the relative importance of various applications to overall fluorocarbon usage in the areas examined.

As shown in Fig. 3.1, although refrigerant uses constitute the largest of the three major end-use application areas evaluated in this study, all three are major uses. The CFCs which must be replaced are the fully halogenated compounds, namely CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115. CFC-113 is the only CFC solvent, and its use can be linked almost exclusively to metal and electronics cleaning (degreasing) and drying-applications. CFC-114 and CFC-115 are likewise used almost exclusively as refrigerants; however, their level of use/consumption is relatively minor compared to the other CFCs. CFC-11 and CFC-12 have the greatest diversity in use and also the highest level of consumption among the CFCs.

The common CFC-blown insulation materials used in buildings and appliances are polyisocyanurates (PIR) and polyurethanes (PUR), both blown with CFC-11, and extruded polystyrene (XEPS), produced using CFC-12. As shown in Fig. 3.2, the PIR/PUR insulations dominate this sector, with building insulation and appliance insulation as the major applications.

Figure 3.3 shows the major refrigerant uses, illustrating the dominant role of CFC-12 overall and the importance of automotive air-conditioning as an application, followed by commercial refrigeration (retail plus cold storage and transport refrigeration). It should be noted that the major use of CFC-115 is as the major component of R-502, which is widely used in low-temperature commercial refrigeration systems. (R-502 is an azeotropic mixture of 51.2% CFC-115 and 48.8% HCFC-22). CFC-11 use as a refrigerant is linked primarily to centrifugal chillers used in air-conditioning of large buildings.

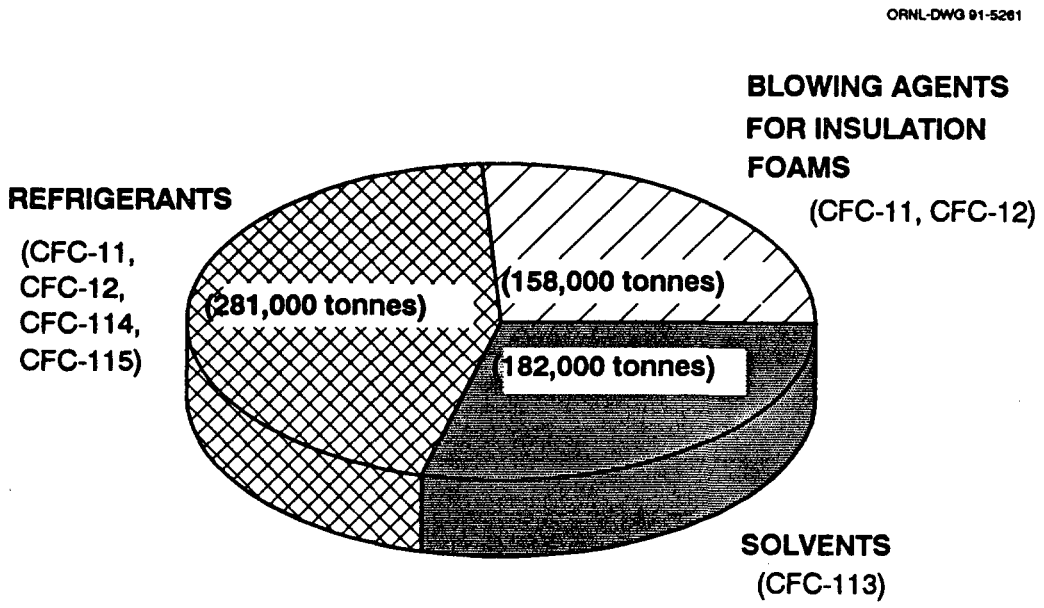

Fig. 3.1. World consumption of CFCs in major energy-related applications evaluated (Source: values are for 1986, estimated on the basis of UNEP Technical Options Reports, 1989).

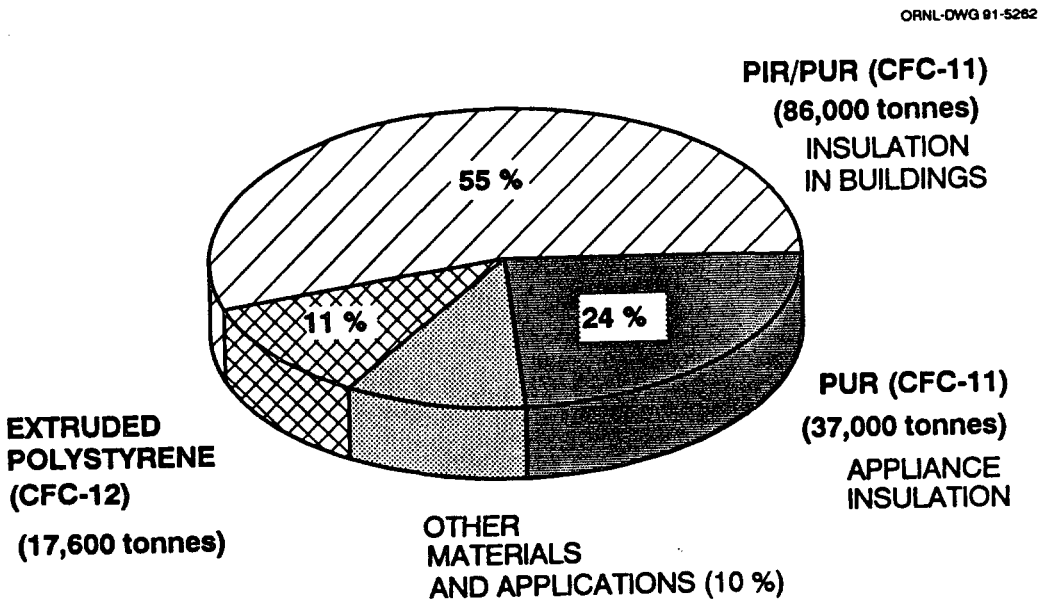

Fig. 3.2. Estimated 1986 world use of CFCs in insulation applications (Source: UNEP Technical Options Reports on Foams, 1989, and Chapter 9, "Commercial Building Insulation").

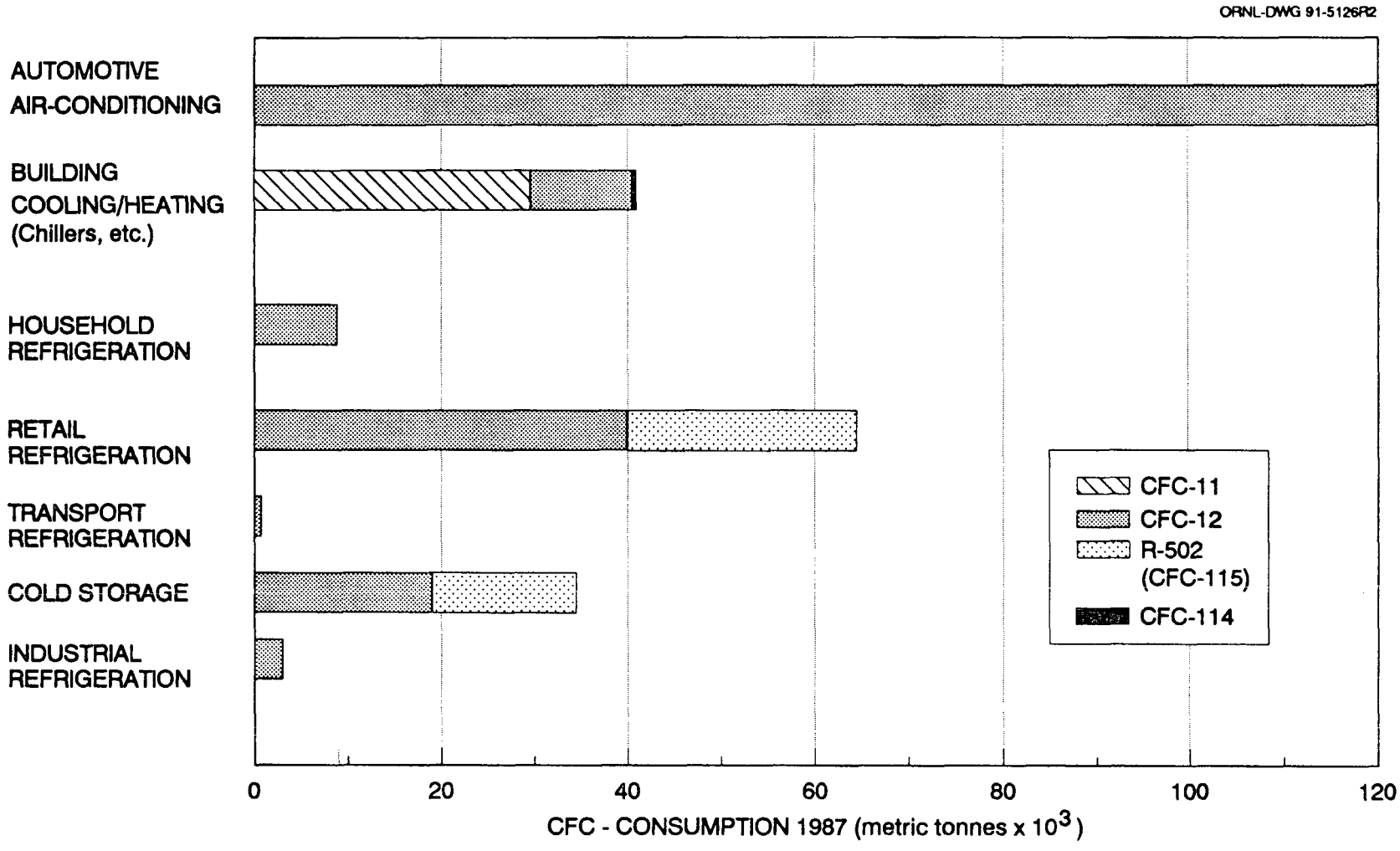

Fig. 3.3. Global consumption of CFCs in the different refrigeration/air-conditioning/heat pump sectors (Source: UNEP Technical Options Report, 1989).

3.3 GWP: EQUIVALENT CO_2 EFFECT OF FLUOROCARBON EMISSIONS*

Introduction and Summary

The extent to which a greenhouse gas can influence the earth's climate depends on the amount of the gas emitted, the length of time which elapses before it is purged from the atmosphere, and the radiative properties (the energy absorption) of the gas. One way to characterize the global warming impact associated with a particular application in refrigeration or insulation is to specify the amount of materials emitted (both the chemicals from the foam insulation and the refrigerant plus the CO_2 associated with energy use) and then explicitly calculate the radiative forcing and temperature response due to the emitted gases as long as they persist in the atmosphere. However, this is a complicated calculation and it is more practical in the analysis of an engineering system if the greenhouse impact of a material emitted can be equated to an equivalent amount of CO_2 at the point of emission.

This approach, while desirable, is not straight forward because CO_2, CFCs, HCFCs, and HFCs are purged from the atmosphere at very different rates. As a result, the time evolution of the radiative forcing and temperature response could be very different for different gases. Previous studies (IPCC, 1990) suggest using the time-integrated forcing as a measure of the greenhouse effect. The ratio of time integrated forcing of a gas to that of the same amount (by mass) of CO_2 is defined as the Global Warming Potential (GWP) for the gas. It can then be argued that one kilogram of gas emitted is equivalent to the GWP kilograms of CO_2. However, because of the different time evolution of the forcings, the value of GWP depends on the choice of the integration time period (the integration time horizon or ITH).

Definition of Global Warming Potential and its Dependence on Choice of Integration Time Horizon

Normalized values are used in this report, and elsewhere, rather than using the actual radiative forcing for each gas. The instantaneous radiative forcing for 1 kg of CO_2 dispersed throughout the atmosphere is set equal to one and the radiative forcing for the other gases are specified relative to CO_2. The instantaneous relative forcing factors (R) for gases used in this report are given in Table 3.1 (from IPCC).

Table 3.1. Instantaneous radiative forcing for 1 kg of gases in the atmosphere. The unit is normalized to 1 for CO_2

Gas	Radiative Forcing (R)
CO_2	1
CFC-11	3970
CFC-12	5750
CFC-113	3710
HCFC-123	2860
HFC-134a	4130

* Section 3.3 was written by Malcolm Ko, Nien Dak Sze, and Karen Orth of Atmospheric & Environmental Research, Inc.

Once an amount of gas is emitted into the atmosphere, it is removed at a rate according to its atmospheric lifetime. For most gases that are removed by photochemical reactions, such as CFCs and other halocarbons, the atmospheric content will decay with a constant exponential lifetime. Values for five halocarbons are given in Table 3.2.

Table 3.2. Atmospheric lifetimes for selected halocarbons

Gas	Lifetime (years)
CFC-11	60
CFC-12	130
CFC-113	90
HCFC-123	1.6
HFC-134a	16

For a gas that decays with a constant exponential lifetime, the forcing and integrated forcing can be expressed in analytic form. Consider a gas with a lifetime τ and radiative forcing per kilogram of R. If one kilogram is released into the atmosphere at time t=0, the abundance, A(t), at any later time t is given by:

$$A(t) = \exp(\frac{-t}{\tau}) \tag{3.1}$$

The behavior of A(t) for gases with lifetimes of 16 years, 60 years, and 130 years is illustrated in Fig. 3.4. The radiative forcing of a gas in the atmosphere has the same behavior as illustrated in Fig. 3.4 and is given by:

$$RF(t) = R \times A(t) = R \times \exp(\frac{-t}{\tau}) \tag{3.2}$$

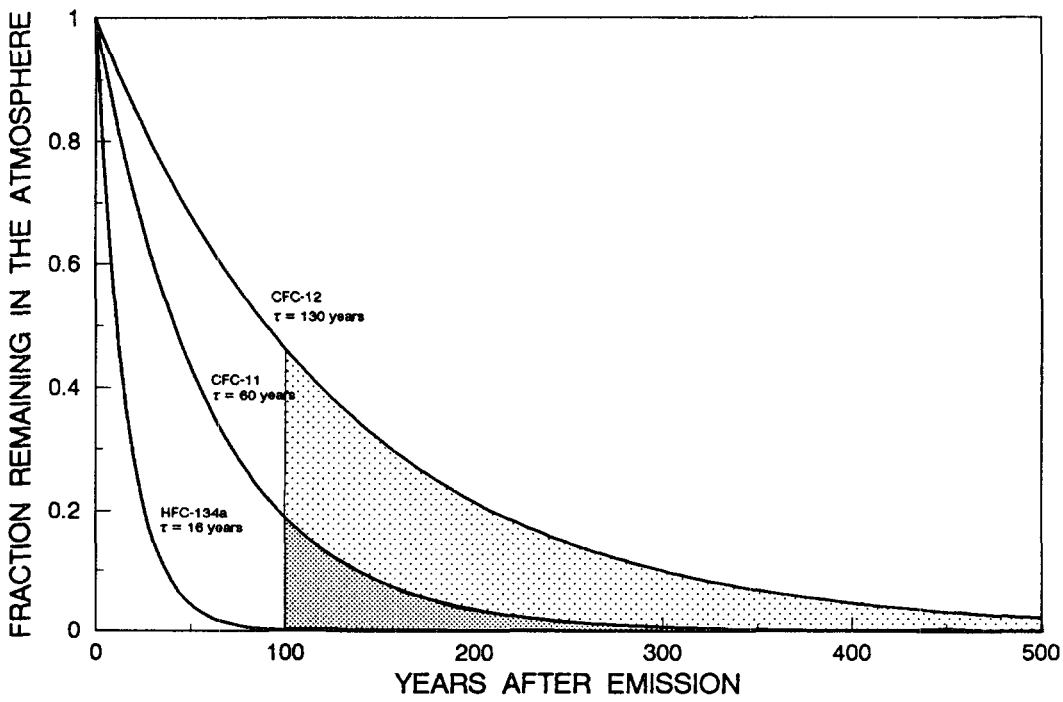

Fig. 3.4. Fraction of the gases remaining in the atmosphere after the initial emission.

The integrated forcing evaluated at t=ITH is given by IF(ITH):

$$IF(ITH) = \int_0^{ITH} R \times \exp(\frac{-t}{\tau}) = R\,\tau\left[1-\exp(\frac{-ITH}{\tau})\right] \tag{3.3}$$

Note that the integrated forcing is proportional to the area under the curves in Fig. 3.4 and has a finite value of $R\tau$ as $ITH \rightarrow \infty$. This limiting value represents the cumulative radiative forcing throughout the lifetime of the emitted gas. Table 3.3 shows the values of IR(ITH) for gases with various lifetimes.

As is evident from Fig. 3.4, HFC-134a is effectively all purged from the atmosphere after 100 years, and there is no additional contribution to the integrated forcing after the first 100 years. In contrast, 19% of the CFC-11 and 46% of the CFC-12 still remain in the atmosphere after 100 years. Their presence will continue to contribute to radiative forcing. The numbers in Table 3.3 indicate that 18% and 46% of the integrated forcing is left out if ITH=100 years is chosen for CFC-11 and CFC-12 respectively.

Table 3.3. Values of integrated forcing as functions of integration time horizon for gases with various lifetimes. The lifetimes are shown in parentheses. R values for the compounds are given in Table 3.1.

ITH	HFC-134a (16 years)	CFC-11 (60 years)	CFC-12 (130 years)
20 years	$11 \cdot R_{HFC\text{-}134a}$	$17 \cdot R_{CFC\text{-}11}$	$18 \cdot R_{CFC\text{-}12}$
50 years	$15 \cdot R_{HFC\text{-}134a}$	$34 \cdot R_{CFC\text{-}11}$	$42 \cdot R_{CFC\text{-}12}$
100 years	$16 \cdot R_{HFC\text{-}134a}$	$49 \cdot R_{CFC\text{-}11}$	$70 \cdot R_{CFC\text{-}12}$
200 years	$16 \cdot R_{HFC\text{-}134a}$	$58 \cdot R_{CFC\text{-}11}$	$102 \cdot R_{CFC\text{-}12}$
300 years	$16 \cdot R_{HFC\text{-}134a}$	$60 \cdot R_{CFC\text{-}11}$	$117 \cdot R_{CFC\text{-}12}$
400 years	$16 \cdot R_{HFC\text{-}134a}$	$60 \cdot R_{CFC\text{-}11}$	$124 \cdot R_{CFC\text{-}12}$
500 years	$16 \cdot R_{HFC\text{-}134a}$	$60 \cdot R_{CFC\text{-}11}$	$127 \cdot R_{CFC\text{-}12}$
∞	$16 \cdot R_{HFC\text{-}134a}$	$60 \cdot R_{CFC\text{-}11}$	$130 \cdot R_{CFC\text{-}12}$

Description of the decay process for CO_2 is not as simple because the removal is due to more complicated processes involving interaction with the biosphere and ocean transport. Calculations using ocean models indicate that about 10 to 15% of the CO_2 emitted could remain in the atmosphere indefinitely. It should be noted, however, that the model results depend on the detailed parameterization of the feedbacks in ocean dynamics and the biosphere which are not well

understood. Models (IPCC, 1990) indicate that the decay rate in the first 300 years can best be described by multiple decay lifetimes:

$$A_{CO_2}(t) = 0.30 \times \exp(\frac{-t}{7.0}) + 0.34 \times \exp(\frac{-t}{71}) + 0.36 \times \exp(\frac{-t}{820}) \tag{3.4}$$

The behavior of $A_{CO_2}(t)$ is illustrated in Fig. 3.5.

The integral of Equ. 3.4 provides the integrated forcing for one kilogram of CO_2 (Table 3.4). Note that in Table 3.4, the integrated forcing for ITH=500 years is three times larger than the corresponding values for ITH=100 years. This shows that the integrated warming for ITH of 100 years does not represent the total warming due to emitted CO_2. To illustrate this point, the integrated radiative forcing for different gases are included in Table 3.5 for different ITHs expressed as a percentage of the integrated radiative forcing for ITH of 1000 years. While an ITH of 100 years captures the total effects of a chemical such as HFC-134a with a 16 year lifetime, a significant portion of the effect of the longer-lived species are left out. For example, an ITH of 100 years will capture only 54% of the warming effects for CFC-12 and only 22% of the total effects of CO_2.

The global warming potential, $GWP_Y(ITH)$, for a gas, Y, is defined as the ratio of the integrated forcing ($IF_Y(ITH)$) evaluated at t=ITH to the integrated forcing for a reference gas ($IF_{ref}(ITH)$), that is given by Equ. 3.5.

$$GWP_Y(ITH) = \frac{IF_Y(ITH)}{IF_{ref}(ITH)} \tag{3.5}$$

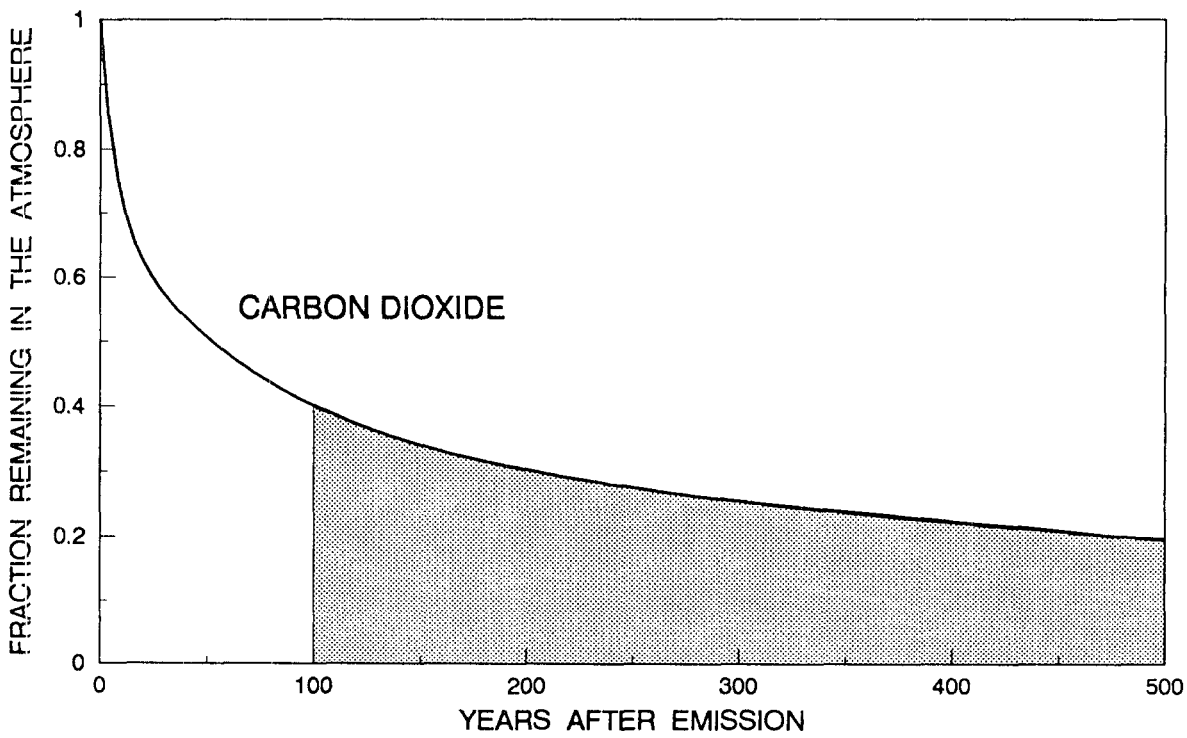

Fig. 3.5. The atmospheric decay of carbon dioxide as described by Equ. 3.4.

Table 3.4. Integrated forcing for 1 kg of CO_2 as a function of ITH

ITH (years)	$IR_{CO_2}(ITH)$
20	15
50	32
100	54
200	88
300	116
400	139
500	160

Table 3.5. Integrated radiative forcing for different gases for different integration time horizons expressed as a percentage of the integrated radiative forcing for an integration time horizon of 1000 years

ITH (years)	HFC-134a (16 years)	CFC-11 (60 years)	CFC-12 (130 years)	CO_2 Equ. 3.4†
100	100%	78%	54%	22%
200	100%	96%	79%	38%
500	100%	100%	100%	68%

† Note that the IPCC parameterization of CO_2 is only intended for ITH of about 300 years.

If the reference gas were to have a single exponential lifetime, then

$$GWP_Y(ITH) = \frac{R_Y \times \tau_Y \times \left[1 - \exp\left(\frac{-ITH}{\tau_Y}\right)\right]}{R_{ref} \times \tau_{ref} \times \left[1 - \exp\left(\frac{-ITH}{\tau_{ref}}\right)\right]} \tag{3.6}$$

Note the following limiting values:

$$GWP_Y(ITH) \rightarrow \frac{R_Y}{R_{ref}} \tag{3.7}$$

as ITH→0, and

$$GWP_Y(ITH) \rightarrow \frac{R_Y \times \tau_Y}{R_{ref} \times \tau_{ref}} \tag{3.8}$$

as ITH→∞.

When CO_2 is used as the reference gas, the forcing in the denominator has to be calculated using the integral of Equ. 3.4. The GWPs for 1 kg of several different gases relative to CO_2 are given in Table 3.6 as functions of ITH. The values for the numberator in Equ. 3.6 are obtained using Equ. 3.3 for the halocarbons in combination with the lifetimes, τ, and the radiative forcing, R, from Table 3.2 and Table 3.1, respectively. The values have been rounded off to two significant figures and differ from the actual computed values by up to 4%.

Table 3.6. GWP of several halocarbons relative to CO_2 for different ITH

ITH (years)	CFC-11	CFC-12	CFC-113	HCFC-123	HFC-134a
20	4500	7100	4500	310	3200
50	4200	7500	4500	140	2000
100	3500	7300	4200	85	1200
200	2600	6700	3400	52	750
300	2100	5800	2800	40	570
400	1700	5100	2400	33	480
500	1500	4500	2100	29	420

Definition of Total Equivalent Warming Impact

The scientific community is reaching agreemtent on the GWPs of many gases released into the atmosphere for different values of integration time horizons. There is no established procedure for determining the total contributions to radiative forcing from energy using equipment, however, such as systems like refrigerators that use CFCs in the foam insulation, as refrigerants, and also cause emissions of CO_2 due to the combustion processes used to generate electricity. These indirect emissions of greenhouse gases need to be considered also in evaluating alternative refrigerants, insulations, cleaning solvents, and new substitute technologies. The Total Equivalent Warming Impact (TEWI) can be defined as the equivalent amount of CO_2 that would give approximately the same integrated radiative forcing over a particular integration time horizon. Thus, TEWI depends on the choice of ITH. If we consider an appliance that emits X kg of CFC-11, Y kg of CFC-12, and indirectly emits Z kg of CO_2 from the energy consumed during its useful lifetime, the TEWI for ITH is given by:

$$TEWI(ITH) = X \times GWP_{CFC-11}(ITH) + Y \times GWP_{CFC-12}(ITH) + Z \tag{3.9}$$

Equation 3.9 provides a convenient algorithm for estimating the combined integrated radiative forcing for engineering systems, although it is not totally accurate. Ideally the integrations needed for Equ. 3.6 would include the production and emission of CO_2 from energy use spread over the lifetime of the system while Equ. 3.9 treats it as though the emission occurred all at once. The correct procedure can be used, but it is more difficult to perform than computing the TEWI with Equ. 3.9. Appendix B contains several comparisons of the TEWI with the more accurate integrated radiative forcing calculations to show that TEWI is a good approximation of the true warming impact of engineering systems. In general, the TEWI represents the total warming impact from emitted gases accurately if the integration time horizon is substantially longer than the atmospheric lifetimes of all of the emitted gases.

3.4 CO_2 EMISSIONS FROM FOSSIL FUELS AND ELECTRIC POWER GENERATION

The analysis of each application in this report eventually results in an estimate of annual fuel or energy use that must be converted to carbon dioxide emissions. This is straightforward for applications involving direct use of fossil fuels, such as natural gas and oil fired boilers for home heating and the combustion of gasoline for automobile air-conditioning. It is more complex, but also necessary for the systems using electricity generated by a mix of power plants burning fossil fuels and other plants using nonfossil sources (hydro, nuclear). Actual emissions will vary depending on the exact nature and grade of the fuel used and the operating efficiency or heat rate of the systems using it. Representative estimates (it is acknowledged that they are not precise) are derived in this section for use in the analyses described in the following chapters.

Electric-Powered Systems or Processes

A conceptual illustration of how electric end-uses of energy are converted to CO_2 is shown in Fig. 3.6. The basis for the cited values of kg CO_2 per kWh of electricity delivered is explained below for each of the three fossil fuel sources.

Coal Fired Electric Power Plants

Two different sources of information were used to estimate and verify the rate of CO_2 emissions from coal fired power plants. Marland (1983, p. 22) reported a United Nations coal equivalency value of 7000 Cal/kg (12,600 Btu/lb) which is equivalent to an energy content of 8.134 kWh_t/kg coal. Using a combined plant and transmission efficiency based on 3.37 kWh_t of energy input per kWh of electricity (kWh_e) delivered (11,500 Btu/kWh_e) results in 2.42 kWh_e of electricity delivered per kg of coal input. Marland also reported data from the United Nations for the mean carbon content of coal as 0.746 kg carbon/kg coal (1983, p.7), so there are 2.74 kg CO_2/kg coal assuming complete combustion (12 grams of carbon per 44 grams CO_2). Combining 2.74 kg CO_2/kg coal and 2.42 kWh electricity delivered per kg coal results in 1.13 kg CO_2/kWh_e (2.49 lb CO_2/kWh_e). These results were verified with data from a U.S. Department of Energy (DOE) publication on environmental pollution that reported 932 million kg CO_2 per billion kWh_e (0.3 million tons CO_2 per 10^{12} Btu produced) (DOE, 1983, p. 92) and a high-voltage transmission efficiency of 82% (DOE, 1983, p. 95). This is equivalent to 1.14 kg CO_2/kWh_e (2.5 lb CO_2/kWh_e).

Oil Fired Electric Power Plants

Data from the U.S. DOE report can also be used to compute CO_2 emissions for oil and gas-fired electric power plants. An oil-fired steam plant consumes 255,000 ℓ oil/million kWh_e produced on site (470,000 bbl/10^{12} Btu produced) (DOE, 1983, p. 114) or 0.311 ℓ/kWh_e delivered after including the

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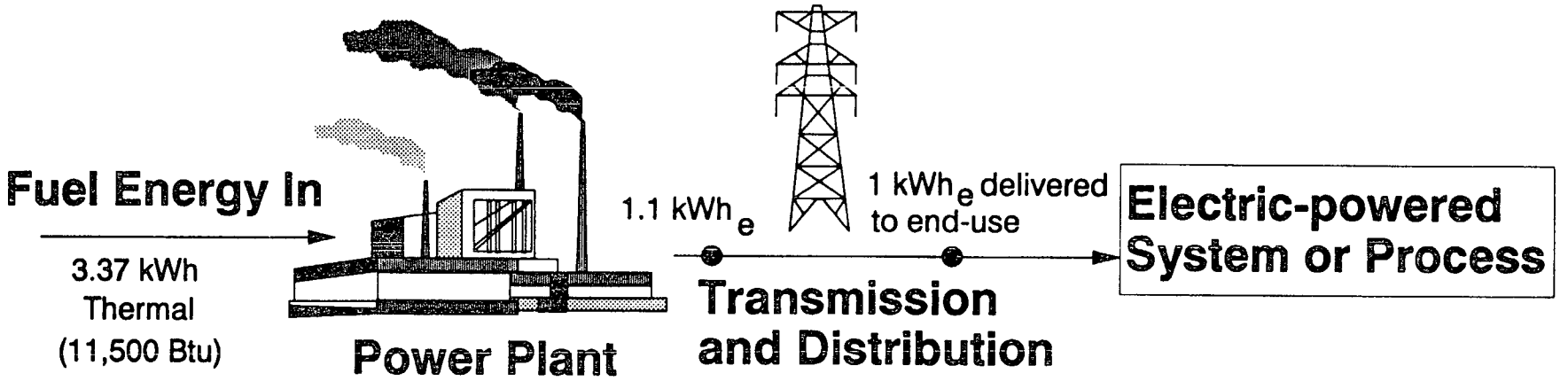
Electricity end- use energy is referenced back to the power plant for purposes of estimating CO_2 generation

1.14 kg CO_2 (2.5 lb) if coal
0.96 kg CO_2 (2.1 lb) if oil
0.58 kg CO_2 (1.3 lb) if natural gas
0 kg CO_2 if hydro or nuclear

} per kWh of electricity (kWh_e)



Thermal Equivalent assuming 33% plant efficiency

Fig. 3.6. Conceptual illustration of CO_2 emissions from electric end-uses of energy.

transmission efficiency. The density of residual fuel oil ranges from 0.97 to 1.01 kg/ℓ (8.05 to 8.45 lb/gal.) (ASHRAE, 1981, p. 15.5) and the carbon content is 0.85 kg carbon/kg fuel oil (Marland, 1983, p. 7). Together these result in a calculated 0.257 to 0.267 kg carbon emissions / kWh_e delivered or 0.942 to 0.980 kg CO_2/kWh_e (2.07 to 2.16 lb CO_2/kWh_e). The average value of 0.96 kg CO_2/kWh_e (2.11 lb CO_2/kWh_e) is used in this report.

Gas Fired Electric Power Plants

Similar calculations are performed using data for gas-fired power plants. DOE reports 255,000 $m^3/10^6$ kWh_e produced (2.64 x 10^9 ft^3 of natural gas/10^{12} Btu) (DOE, 1983, p. 134) and Marland cites a carbon content of 0.510 kg/m^3 for natural gas. Together, along with the transmission efficiency, these result in calculated emissions of 0.583 kg CO_2 / kWh_e (1.28 lb/kWh_e).

Regional Average CO_2 Emissions From Electric Power Generation

The calculated rates of CO_2 emissions for power generation by fuel source are used to estimate average emissions rates for Europe, Japan, and North America based on the regional fuel mix for electricity production. The International Energy Agency has published data on the electricity generating capacity of public and private utilities in many western countries by the particular fuel used. The information for countries in western Europe, regional data for North America, and national data for Japan is summarized in Table 3.7.

Table 3.7. Primary fuel sources for electric power generation (megawatts of generating capacity)

Country	Total	Coal	Oil	Gas	Nuclear	Hydro	Other
Austria	15,784	1,404	1,920	2,038	0	10,423	0
Belgium	14,137	2,434	2,805	2,061	5,511	1,327	0
Denmark	8,621	3,544	4,693	293	0	12	80
Finland	11,456	2,450	3,597	605	2,300	2,505	0
France	92,482	10,436	13,348	977	44,702	23,020	0
Germany	95,317	34,532	19,497	15,196	18,874	6,710	508
Greece	7,525	3,447	1,933	6	0	2,137	2
Iceland	949	0	151	0	0	756	42
Ireland	3,911	1,122	1,372	894	0	516	7
Italy	56,205	3,676	25,581	7,278	1,273	17,863	534
Norway	24,013	23	231	0	0	23,759	0
Sweden	33,100	1,197	6,235	203	9,648	15,813	5
Switzerland	15,210	0	750	0	2,950	11,510	0
United Kingdom	66,536	37,953	15,755	1,436	7,144	4,192	56
Total	445,246	102,216	97,867	30,985	92,402	120,543	1,234
	100%	23%	22%	7%	21%	27%	0%
Japan	173,735	13,865	76,550	21,560	25,846	35,697	216
	100%	8%	44%	12%	15%	21%	0%
North America	756,957	285,474	143,326	88,505	96,304	141,771	1,578
	100%	38%	19%	12%	13%	19%	0%

Source: Energy Statistics 1965-1986, International Energy Agency, Organization for Economic Co-operation and Development, Paris, 1988.

The overall percentage of capacity for each region by fuel source is used with the emissions rates of 1.14 kg CO_2/kWh$_e$ for coal, 0.96 kg/kWh$_e$ for oil, and 0.58 kg/kWh$_e$ for natural gas cited earlier and 0 kg CO_2/kWh$_e$ for nuclear generating plants and hydroelectric power (the secondary sources of CO_2 emissions from plant construction and the mining and transportation of fuels are neglected in this report, the averaged values prorated over the lifetime of a power plant are acknowledged to be a very small fraction of the emissions from the combustion of fossil fuels). This results in regional averages of 0.513 kg CO_2/kWh$_e$ emissions from electric power generation for Europe, 0.672 kg/kWh$_e$ for North America, and 0.581 kg/kWh$_e$ for Japan, as shown in summary Table 3.8.

Gas and Oil Boilers and Furnaces

The technical sections of this report on commercial and residential building insulation present data for energy requirements for gas and oil-fired space conditioning equipment and the CO_2 emissions from furnaces. The calculated building heating loads are converted to fuel use based on the high heating values of the fuels and eventually to CO_2 emissions. The heating values of natural gas vary but ASHRAE cites a range of 37,300 to 39,100 kJ/m^3 (1000 to 1050 Btu/ft^3) as being typical (ASHRAE 1981, p. 15.3). This report uses the average value of 38,200 kJ/m^3 (1025 Btu/ft^3). ASHRAE also gives a range of heating values for number 2 fuel oil of 39,520 to 38,180 kJ/ℓ (141,800 to 137,000 Btu/gal.) and this report uses the average value of 38,850 kJ/ℓ (139,400 Btu/gal.) (ASHRAE, 1981, p. 15.5). Values of 51.1 g CO_2/MJ fuel heating value (53.9 g CO_2/1000 Btu) for natural gas (Sand, 1991) and of 69.5 g CO_2/MJ heat value (73.3 g CO_2/1000 Btu) for fuel oil (Zurer, 1991) are also used.

Table 3.8. Electric power generating capacity by fuel source

Region	Nuclear	Hydro-Electric	Natural Gas	Fuel Oil	Coal	CO_2 Emissions	
						lbs/kWh$_e$	kg/kWh$_e$**
Europe	21%	27%	7%	22%	23%	1.13	0.51
North America	13%	19%	12%	19%	37%	1.48	0.67
Japan	15%	21%	12%	44%	8%	1.28	0.58

CO_2 Emissions from Gasoline

Chapter 8 of this report presents data for CO_2 emissions resulting from the use of automobile air-conditioners. The calculations required to derive this information are based on an estimate of the carbon dioxide emissions for the combustion of gasoline in terms of kg CO_2 per liter of fuel. The density of gasoline is approximately 0.739 kg/ℓ (6.160 lbs/gallon) at 16°C (60°F) (Baumeister, 1958) and Marland reported a carbon content of 86.9 kg C/kg gasoline (1990). There are then 0.64 kg of carbon per liter of gasoline, or 2.32 kg CO_2/ℓ of gasoline burned at a combustion efficiency of 99%.

**kWh$_e$ delivered

4. HOUSEHOLD REFRIGERATORS/FREEZERS

4.1 INTRODUCTION

Household refrigerators are an important end use of CFCs and the manner in which HFCs, HCFCs, and alternative technologies are employed in these domestic appliances could have a major impact on future worldwide energy demands. Approximately 58 million new refrigerator/ freezers are manufactured worldwide each year; and hundreds of millions are in use. There are about 130 million units in use in North America, 170 million in Western Europe (Bürgell,1988), 40 million in Japan, and 12 to 14 million in Australia and New Zealand (Roke, 1991). The potential for growth in the worldwide inventory of refrigerators is tremendous. Although there were only about 4 million refrigerators in China in 1985, this represents only 2% of the households in that country (Isaksen, 1990). It was estimated that by 1990 there would be 30 million refrigerators in China, 10% of the households. In 1989 there were an estimated 6 million refrigerators in India; this is predicted to increase to 20 million by 1996 and 78 million by 2010. There are also a substantial number of refrigerators elsewhere in Asia, South and Central America, and Africa. Refrigerators consume a significant portion of household energy use, as much as 30% in Europe (Jeffs, 1990) and 27% in Japan (Fujimoto, 1991), and the search for environmentally acceptable substitutes for the CFC-11 blown foam insulation and the CFC-12 operating fluid is an important challenge that must be met.

4.2 METHODOLOGY

The environmental impacts of alternatives for refrigerator/freezers depend on the direct effects of any chemicals that may be used and also on the energy consumed by the appliance over its useful life. Any evaluation of these impacts and a comparison of alternatives requires an algorithm for estimating the energy use of individual refrigerators. The analysis in this section is performed using an algorithm developed by W. David Lee of Arthur D. Little, Inc. for the U.S. Department of Energy (Lee, 1980):

$$\text{kWh per year} = \frac{24}{1000} \times \{ \%\ \text{on time} \} \times \{ \frac{\dot{Q}_{capacity}}{COP} + E \} \times 365 + \dot{Q}_{defrost} \tag{4.1}$$

where the percent, or fraction, on time is given by:

$$\%\ \text{on time} = \frac{\dot{Q}_{cabinet}}{\{\dot{Q}_{capacity} - I\}} \tag{4.2}$$

and the heat leakage into the cabinet, $\dot{Q}_{cabinet}$, compressor capacity, $\dot{Q}_{capacity}$, internal heat loads, I, and auxiliary energy use, E (e.g., fans), are all in watts and the annual energy use for an automatic defrost, $\dot{Q}_{defrost}$, is in kilowatt-hours. The steady-state energy consumption, in Watts, is given by the compressor energy use, $\frac{\dot{Q}_{capacity}}{COP}$, plus the auxiliary energy use, E. The daily energy use, in Watts, is

then the steady-state energy consumption times the percent on time times 24 hours/day. The percent on time is computed as the cabinet shell heat loss, $\dot{Q}_{cabinet}$, divided by the "useful" cooling available from the compressor, the capacity, $\dot{Q}_{capacity}$, less what is required to offset any internal heat loads, I. The heat leakage into the cabinet is determined using a UAΔT calculation that incorporates the approximate dimensions of the cabinet, the thickness and thermal conductivity of the insulation in the side walls, top, bottom, and door(s), and assumed temperature differences between the ambient air in the room and the temperatures in the storage compartments.

The efficiency of the compressor, COP, is to some extent dependent on the capacity of the compressor because it is more difficult to make a highly efficient small compressor than it is to make a larger compressor of the same efficiency. This is borne out in Fig. 4.1 which shows data from eleven different manufacturers for the efficiency and capacity of refrigerator compressors. The data from Fig. 4.1 have been used to set COPs for the analysis that follows.

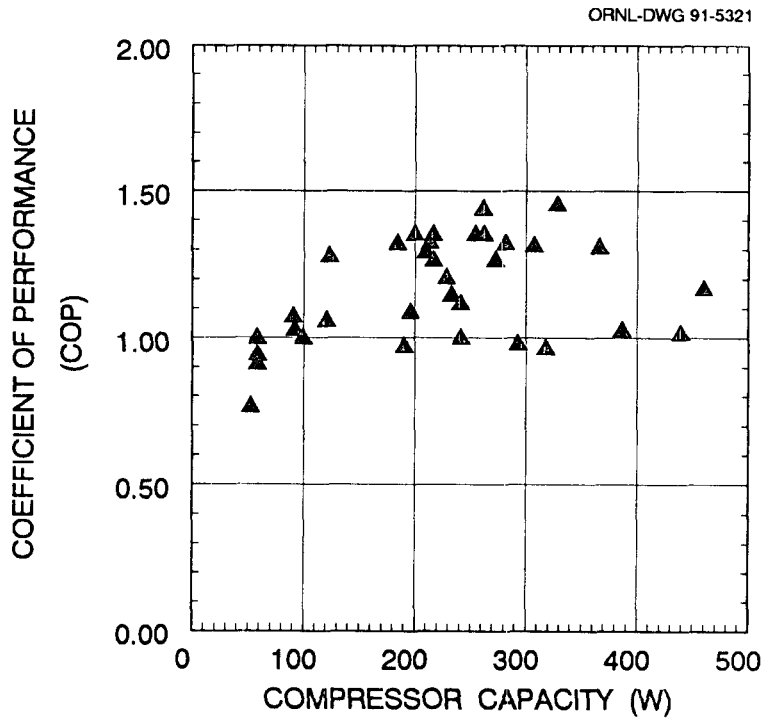


Fig. 4.1. Efficiency and capacity of compressors for refrigerator/freezers.

Compressor capacities needed to be selected in order to do the analysis for each refrigerator/freezer considered in this section. This selection is made by assuming that there is a fixed 50% on-time, in which case the compressor capacity can be determined from the cabinet heat gain and the internal refrigeration loads:

$$\dot{Q}_{capacity} = \frac{\dot{Q}_{cabinet}}{0.500} + I \tag{4.3}$$

4.3 BASELINE REFRIGERATOR DESIGNS

A broad selection of refrigerator/freezers are available to the consumers throughout the world, ranging from very small units of less than 100 liters (3.5 ft^3) to those with capacities higher than 700 liters (25 ft^3). Only a small number of refrigerators can be evaluated in this study, though, and consequently a single unit is considered for each of the three major geographic regions where a great many refrigerators are in use; North America, Europe, and Japan.

High efficiency refrigerator/freezers have been developed which rely heavily on CFC-11 blown plastic foam insulation because it has a very low thermal conductivity and is very effective in reducing heat leakage into the cabinet. The refrigeration system has consisted of a rotary or reciprocating compressor, static or fan cooled condenser outside of the cabinet, an evaporator inside of the refrigerated space, and CFC-12 as the working fluid.

There are basic differences between the appliances that are used in homes around the world that reflect the differences in lifestyle and national energy policies. Refrigerators in North America tend to be significantly larger than those used in Europe and Japan because of the larger homes in the U.S. and Canada and the shopping habits of the people there. Greater amounts of CFC-11 have also been used in the foam insulation in North America than elsewhere in order to meet U.S. minimum efficiency standards. Refrigerators in Europe are small and they are frequently built into the kitchen cabinetry. Also, the premium placed on space and energy in Japan has resulted in the development of foam insulation that has a very low thermal conductivity and so that thin walls can be used to increase the "volume efficiency".

Several specific assumptions are made for refrigerator/freezers in each of the major geographic regions in order to establish a baseline technology that can be used to evaluate the effects of alternative insulations and refrigerants on per unit energy use. These "baseline technologies" are then validated for conventional refrigerator/freezers with CFC-11 and CFC-12 by using Eq. 1 and published information about the annual energy use for a typical unit. This process of validation has required using slightly different assumptions for temperatures and internal loads to reflect the test and rating procedures used in each region. This is discussed in greater detail later.

Europe

The European refrigerator manufacturers have voluntarily reduced the use of CFC-11 in the foam insulation up to 50% by increasing the amount of water in the formulation; this foam is referred to as partially water blown or CO_2 blown foam (the water reacts with the isocyanate to form CO_2 in the foaming process). The data presented are for partially water blown foams containing 6% CFC-11 by weight. The thermal conductivities, or k-factors, for the foam insulation used in Europe range from 0.018 to 0.020 W/m·K (0.125 to 0.140 Btu·in./h·ft^2·°F) depending on the amount of CFC-11 used (Jeffs, 1991 and Sutej, 1989); the calculations are done using 0.020 W/m·K for partially water blown foam. Calculations are also presented for the same refrigerator as it would be with CFC-11 blown foam insulation with a k-factor of 0.018 W/m·K (0.125 Btu·in./h·ft^2·°F) and 12% CFC-11 by weight.

The typical refrigerator in Europe consumes about 500 kWh of electricity per year (UNEP, 1989). The calculations presented here are based on a 230 liter (8.1 ft^3) refrigerator with 55 mm of insulation in the freezer and 34 mm in the fresh food compartment (McGill, 1990). The annual energy use is estimated assuming an ambient room temperature of 25°C (77°F) and temperatures of -18°C (-0.4°F) in the freezer and 5°C (41°F) in the fresh food compartment. The auxiliary energy use is assumed to be 10 W during the off-cycle for defrost heaters (Roke, 1991).

There are 3.36 kg (7.39 lb) of foam insulation in this refrigerator and it contains an estimated 202 g (0.44 lbs) of CFC-11, which is very close to the values cited by Monaldi (1991) and Quast (1991). This refrigerator requires an estimated 140 g (4.9 oz) of CFC-12 (UNEP, 1989, and Monaldi, 1991).

North America

The baseline unit for North America is assumed to be an 522 l (18.4 ft^3) automatic defrost refrigerator with a top mounted freezer with an adjusted volume is 602 l (21.2 ft^3) (Norland, 1989) The wall thicknesses are:

- 49.8 mm (1.96 in.) in the freezer,
- 47.2 mm (1.86 in.) in the fresh-food compartment,
- 37.8 mm (1.49 in.) in the freezer door, and
- 36.1 mm (1.42 in.) in the door of the fresh-food compartment.

The auxiliary energy use includes 24.3 W for evaporator and condenser fans (Norland, 1989) and 90 Kwh per year for defrosting the evaporator (McMahon, 1987). The internal loads have been set to 56 W (192 Btu/h) to account for heat added to the cabinet from the defrost cycle (20.5 W), the evaporator fan (10.7), the hot wall condenser (12.5), and door closures (12.5) (Norland, 1989 and Lee, 1980). The refrigerator is assumed to have a 225 W compressor (775 Btu/h) with a COP of 1.37 (EER of 4.67 Btu/W·h) (Norland, 1989).

The calculated energy use of the North American baseline unit is validated against published information using temperatures specified in the U.S. DOE rating procedure (i.e., freezer temperature set at -15°C (5°F), the fresh-food compartment at 3.3°C (38°F), and an ambient room temperature of 32.2°C (90°F)). The baseline insulation is assumed to be CFC-11 blown polyurethane foam with a k-factor of 0.0173 W/m·K (0.120 Btu·in./h·ft^2·°F). The calculated energy use is 918 Kwh/year (2.52 kWh/day) which agrees well with data from Norland (1989) and UNEP (1989).

The refrigerator contains approximately 233 l (8.24 ft^3) of polyurethane foam insulation at an average density of about 30 kg/m^3 (2.0 lbs/ft^3), or about 6.75 kg (15 lbs) of foam. There are then 1060 g (2.34 lbs) of CFC-11 in the refrigerator (assuming 15.8 weight % CFC-11). The refrigerator contains approximately 170 g (6.0 oz) of CFC-12 (UNEP, 1989).

Japan

The sizes of the refrigerators marketed in Japan have changed dramatically since 1981. Information from the Japan Electrical Manufacturers Association show that between 1981 and 1987 the market share of 300 to 400 liter (10.6 to 14.1 ft^3) refrigerator/freezers grew from 1.5% to over 35%. During that same period the market share of refrigerators of less than 120 l (4.2 ft^3) grew modestly from 22% to 31%, while all other size classes lost market share (Fujimoto, 1989). The market has continued to change, and the Japan Air Conditioning, Heating, and Refrigeration News reported that during 1990 models larger than 400 l (14.1 ft^3) grew from only 2% of the market in 1988, to 7% in 1989, and to nearly 20% in 1990.

The baseline refrigerator/freezer chosen for Japan in this study is a 350 l (12.4 ft^3), automatic defrost model with an annual energy use of 600 kWh (Fujimoto, 1989). The cabinet is divided into three compartments; one for frozen foods, one for cold storage, and the third for produce and vegetables (approximately 25%, 50%, and 25% of refrigerated volume, respectively).

The Japanese test standard requires measurement of refrigerator energy use at two different ambient temperatures, 15°C (59°F) and 30°C (86°F), with freezer and fresh-food temperatures of -18°C

(-0.4°F) and 3°C (37.4°F), respectively, and includes a schedule of door openings and requirements for food in the freezer compartment (Alissi, 1988). According to Alissi the English translation of the procedure is not clear about the size of the load imposed on the freezer by the simulated food. The annual energy use is determined by prorating the energy uses based on 265 days of operation at 15°C and 100 days at 30°C.

Equation 4.1 was adapted for simulating the Japanese refrigerator test by computing daily energy use at the two required ambient temperatures and then assuming 265 days of operation at 15°C and 100 days at 30°C. The internal loads are set to 29 W (98 Btu/h) to account for frost formation and heat from the evaporator fan and an additional 56 W (191 Btu/h) are added to account for the door openings and the frozen food. The evaporator fan is assumed to draw 10 W and it is assumed that 55 kWh/year are required for defrosting.

The compressor is assumed to have a capacity of 175 W (600 Btu/h) and a COP of 1.20 at 54°C condensing (130°F), 23°C evaporating (-10°F), 32°C (90°F) suction gas and liquid line temperatures. The cabinet is foamed with 47 mm (1.85 in.) of CFC-11 blown foam in the freezer walls and door with an initial k-factor of 0.016 W/m·K (0.111 Btu·in./h·ft^2·°F) (McGill, 1990 and Sutej, 1990). The walls and door of the fresh food compartments have 33 mm of insulation (McGill, 1990).

These assumptions result in a calculated energy use of 600 kWh per year which is typical of a unit of this capacity (Fujimoto, 1989). An additional check was made by analyzing the energy use for the Japanese baseline refrigerator/freezer using the U.S. DOE test procedure. This results in an estimated annual energy use of 746 kWh which is approximately 24% higher than the estimated energy use with the Japanese procedure (600 kWh). This difference is of the same magnitude as the 27% increase observed by Alissi at Ray Herrick Laboratories in testing a refrigerator/freezer under the U.S. and Japanese test procedures (Alissi, 1988).

Refrigerators are manufactured in Japan with three different "types" of CFC-11 blown foam insulation; a low k-factor foam containing 15 to 16% CFC-11, a partially water blown foam in which water is added in order to reduce the amount of CFC-11 by 30%, and a very low thermal conductivity microcell foam using almost 16% CFC-11 by weight. The baseline 350 l refrigerator in this analysis is estimated to contain 129 l (4.56 ft^3) of foam insulation, and approximately 673 g (1.48 lbs) of CFC-11 (assuming a foam density of 33.0 kg/m^3, (2.06 lbs/ft^3) (Sutej, 1990), and a CFC content of 15.8 weight percent). This mass agrees reasonably well with the average CFC content provided by Fujimoto. The foam has a k-factor of 0.016 W/m·K (0.111 Btu·in./h·ft^2·°F). Calculations are also performed for the partially water blown foam and for the microcell foam insulation. The typical Japanese refrigerator also contains 137 g (4.83 oz) of CFC-12 (Fujimoto, 1991).

4.4 ALTERNATIVE REFRIGERANTS

Any analysis of alternative refrigerants requires some means of evaluating their performance either in absolute terms or relative to the performance of CFC-12. This comparison could be done in any of several ways, each of which has its drawbacks and pitfalls. The easiest and most simplistic is to attempt to rank the refrigerants based on their theoretical coefficients of performance (COP) in an ideal reversed Rankine cycle using fixed operating conditions (i.e., condensing and evaporating temperatures, the degrees of superheat and subcooling). These calculations appear to show some differences between the refrigerants, but it should be noted that there are several important departures from an ideal cycle in a refrigerator, such as liquid suction heat exchange, superheat, etc. that could affect the ranking. A calculation including these non-idealities may give a completely different ranking of refrigerants from that obtained using the ideal cycle (McLinden, 1990).

A closer approximation of refrigerant performance can be achieved with computer models that include the deviations from simple cycle operation. These models take into account that:

- compressor efficiency depends on the compressor size (displacement), the bounding pressures, pressure ratios, pressure differences, lubricity of oils, and the refrigerant density.
- the heat exchanger pressure drops and heat transfer coefficients depend on the refrigerant's transport properties and mass flow rates for given tubing geometry.
- the capillary tube/suction line heat transfer affects the cycle COP and cooling capacity, and in turn is affected by the refrigerant's transport properties and, especially, by the liquid and vapor specific heats.

In addition the refrigerator energy use is affected by the refrigerant/oil solubility because the solubility adds to the compressor cycling losses (Jaster, 1991). An analysis of the performance of each refrigerant would require identifying the best design for that particular refrigerant, within fixed price/performance constraints, as well as identifying the detailed information listed above. A rigorous comparison of refrigerants on this basis is a major design project that is clearly beyond the scope of this work.

A comparison could also be done strictly using compressor calorimeter data. This approach, however, does not take into account any of the minor design changes that could be made to enhance the overall system performance of a particular refrigerant. Modifications to the evaporator, capillary tube, and suction to liquid line heat exchanger can result in differences in energy use that are not apparent in calorimeter tests.

Finally, the analysis could be based on laboratory testing of refrigerators using alternative refrigerants. That is the approach taken here. The data used in this analysis are from tests of refrigerators that have been modified for use with a particular alternative refrigerant. Compressor and appliance manufacturers, chemical manufacturers, and research laboratories have devoted extensive effort toward determining the best alternatives to CFC-12 in refrigeration applications, including household refrigerators. The first tests that were conducted for refrigerator/freezers in which compounds were used simply as "drop-in" replacements for CFC-12 showed increases in energy use of 10 to 15%. Work since that time has shown that refrigerators with proper design and choice of lubricant can achieve the same or even better energy efficiency with an alternative refrigerant than comparable refrigerators with CFC-12.

Figure 4.2 shows laboratory data from Danfoss (Hansen, 1991), The Association of Home Appliance Manufacturers (AHAM, 1991) in the U.S., Oak Ridge National Laboratory (Vineyard, 1991), Xi'an Jiaotong University (Tan, 1990), and W. C. Wood (1991) for several possible alternative refrigerants. The measured energy use for refrigerators operating with the alternatives are plotted against the energy use for a comparable refrigerator using CFC-12. Any data points plotted above the heavy dotted line represent an increase in energy use relative to CFC-12, and points below the line represent a decrease in energy use. The conclusions are that:

- refrigerators using HFC-134a used from ½% less energy than one using CFC-12 to 6.9% more energy,
- refrigerators using a blend of HCFC-22 (36%), HFC-152a (24%), and HCFC-124 (40%) used from ½% less to 5.8% more energy than CFC-12, and
- refrigerators with HFC-152a used from 4% less energy to 2.7% more.

The measurements for HFC-152a are consistent with analytical modeling by L. Kuijpers of Philips Research Labs in The Netherlands which concluded that HFC-152a should be about 4% more efficient than CFC-12 (Kuijpers, 1988).

A blend of HCFC-22 and HCFC-142b is also considered as an alternative to CFC-12. L. Roke of Fisher & Paykel Refrigeration Division in New Zealand reported a 2½% increase in energy use for a dual evaporator refrigerator/freezer using a this blend when equal provision temperatures were achieved (+3°C, 37°F); but with a 4% decrease in energy consumption when equal freezer compartment temperatures were achieved (-15°C, 5°F) (Roke, 1991).

A pitfall in relying on data for existing equipment is that these data represent what has been done up until a particular point in time and do not necessarily show what a final efficiency comparison could be. The results based on comparable data that were available two years ago would give substantially different results than calculations based on the data available in 1991. Results two years from now, likewise, could be quite different than those obtained today. These data do show what efficiencies have been demonstrated, though, and future developments are not likely to do any worse than what is shown here.

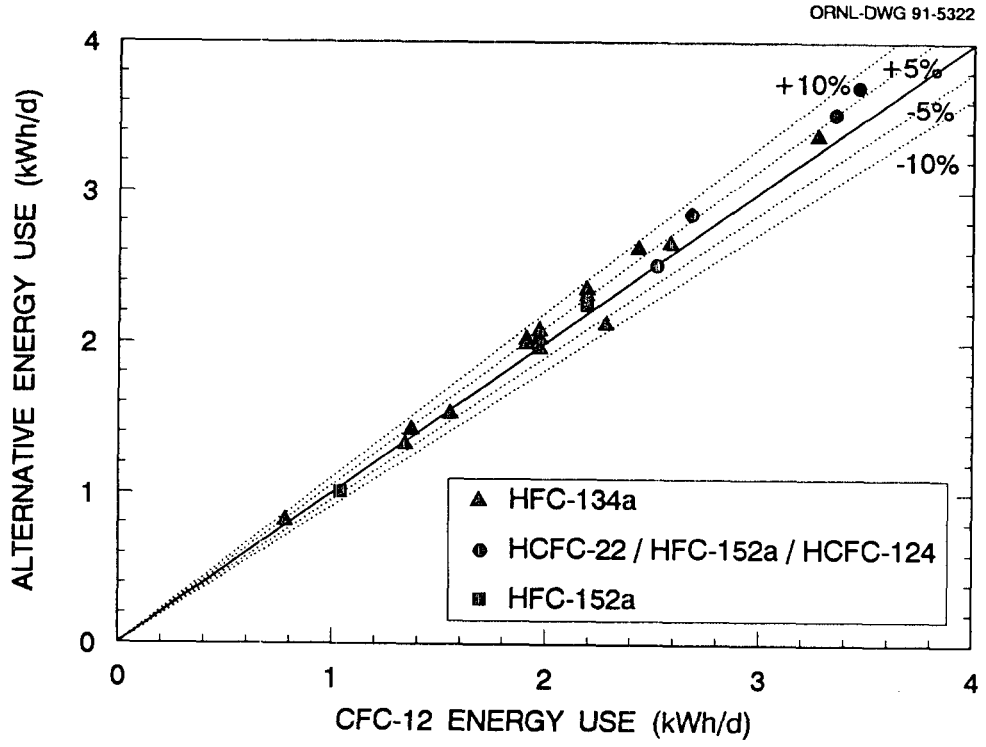


Fig. 4.2. Daily energy use for CFC-12 alternatives in a refrigerator/freezer.

4.5 ALTERNATIVE INSULATING MATERIALS

Extensive effort has also been devoted to developing substitutes for CFC-11 in the polyurethane foam insulation used in refrigerator/freezers. Ideally the replacements would have the same or better thermal properties than foam blown with CFC-11 as well as having comparable structural properties

and being compatible with all of the materials used in the refrigerator cabinet. These three properties are so important that they are considered by manufacturers to be essential attributes of any alternative insulation material; same or better k-factor, same or better structural properties, and compatibility with other materials of construction (particularly plastic liners). These conditions are being approached but have not yet been reached. Much of the initial testing of alternative foams was performed on samples that were prepared with a minimum of modification from the formulations and procedures developed for CFC-11 blown foam. For the most part surfactants and catalysts were changed to achieve the same foam density and the formulations were not optimized to give comparable or lower thermal conductivity. Intensive effort has gone into refining those formulations to narrow the differences between the mechanical and thermal properties of the alternative foams and of foam blown with CFC-11. Recent results are showing foams blown with alternative gases that have comparable thermal properties to those blown with CFC-11 used in many refrigerator/freezers.

Most of the effort in developing alternative blowing agents has gone into adapting polyol blends to use HCFC-123 or HCFC-141b in place of CFC-11, and results with these two compounds have been promising. Data for the k-factor of appliance foam insulation are shown in Fig. 4.3 for several formulations of foam using CFC-11 and for foams using HCFC-123 and HCFC-141b. The solid line indicates how the k-factor of CFC-11 blown foam decreases as the weight percent of the blowing agent increases; data for the European partially water blown foam are shown on the far left and the single point on the far right is for a very low k-factor foam used in Japan. The large "cross" near the center of the graph shows the ranges of weight percents and k-factors that were typically found in European refrigerator insulation before they started using partially water blown foams. The solid triangles and circles show that foams have been made and tested using HCFC-123 and HCFC-141b that have k-factors comparable to what was used in Europe and are even lower than the reduced CFC-11 blown foams used today. A short vertical line near the right side of Fig. 4.3 shows the range of k-factors typically used in North America and Japan. There are data points for both HCFC-123 and HCFC-141b that are at the top end of this range, however none have been reported thus far that are as low as the bottom end of the range. The same changes that have been made to reduce the k-factors of alternative foams could also be used with CFC-11 blown insulation, and these advanced CFC-11 foams outperform anything produced with alternative gases and represent a lost opportunity resulting from the necessity of eliminating CFCs.

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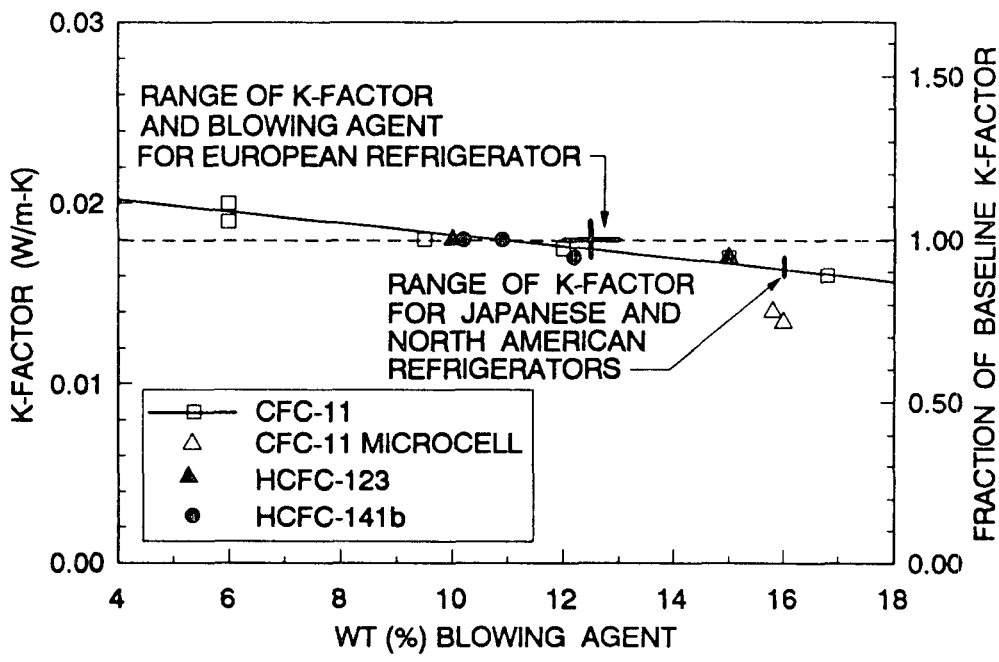

Fig. 4.3. K-factors of foam insulation using CFC-11 and HCFC blowing agents.

Neither HCFC-123 nor HCFC-141b is chlorine free, however, and consequently they each have some, albeit small, ozone depleting potential. Each of them, consequently, could possibly be phased out of production in the future. Papers have been published concerning 100% CO_2 blown polyurethane insulation as a chlorine free substitute for CFC-11. Foam blown entirely with CO_2 is considered as one of the alternatives to CFC-11 blown polyurethane in this analysis. The k-factor for CO_2 blown foam insulation varies from 0.022 W/m·K for freshly blown foam to 0.033 W/m·K for fully aged foam (0.153 to 0.230 Btu·in./hr·ft^2·°F) (Dietrick, 1989 and Krueger, 1990). It is known that "unprotected" foam blown with CO_2 (without an impermeable membrane facing) ages very quickly, but it is uncertain how quickly the k-factor of foam in a refrigerator cabinet will change.

Another chlorine-free alternative that is being considered by some appliance and foam manufacturers is the use of perfluoropentane or perfluorohexane in polyurethane foam. These materials can be used as the sole blowing agent, at about 6% by weight, and can achieve foam k-factors of 0.018 W/m·K (0.125 Btu·in./hr·ft^2·°F) (Jeffs, 1991). More recent work has been focusing on the use of these compounds in small quantities as surfactants in forming a very small cell structure in CO_2 blown foam. In this case from ½% to 2% by weight of the perfluoroalkane is used and the foam has a k-factor of 0.018 W/m·K (0.125 Btu·in./hr·ft$_2$·°F) (Jeffs, 1991).

The final alternative foam blowing agent considered in this analysis is isopropylchloride. This material is reported to have an ozone depleting potential of 0.003 relative to CFC-11 and a global warming potential of less than 1% that of CFC-11 (Creyf, 1991). Foams blown with isopropylchloride contain 8% of the blowing agent by weight and have a k-factor of 0.020 W/m·K (0.139 Btu·in./hr·ft$_2$·°F) (Jeffs, 1991).

The analysis does not incorporate the effects of aging of the insulation except for those calculations pertaining to CO_2 blown foam. A special task force for the Society of Plastics Industries (SPI) reported in 1988 that early testing of polyurethane insulated refrigerator/freezers basically showed no change in k-factor of the foam after ten years (SPI, 1988). In the absense of hard data on alternative foams, it has been assumed that foams manufactured with the substitute blowing agents would not age any differently than CFC-11 blown foam in an appliance (sealed between the steel cabinet wall and the plastic inner liner).

4.6 RESULTS

Annual Energy Use

The energy use algorithm defined by Equ. 4.1 is used to estimate the energy use for the North American, European, and Japanese baseline refrigerator/freezer using each combination of alternative refrigerants and blowing agents listed above. Some of the results from these calculations for pure refrigerants and a blend of HCFC-22, HFC-152a, and HCFC-124 are listed in Table 4.1 below.

Global Warming Potential

The TEWI is determined for the baselines and each of the alternatives by adding the individual contributions from the refrigerant, blowing agent, and energy use over the lifetime of the refrigerator. Data for the refrigerants and blowing agents are used to determine the direct effect due to the chemicals themselves. Tables in Appendix C contain information on the mass of refrigerants and blowing agents used in each case and global warming potentials for each of the compounds.

The direct effects are combined with indirect CO_2 emissions from power use based on data for the estimated annual energy consumption and the regional estimate of CO_2 emissions per kilowatt-hour delivered. As an example, the baseline European refrigerator with CFC-12 and CFC-11 blown foam contains approximately 140 g of refrigerant, 202 g of blowing agent, and consumes 485 kWh per year for approximately 15 years. CFC-12 has a global warming potential of 4,500 kg CO_2 / kg of CFC-12, CFC-11 has a global warming potential of 1,500 kg CO_2 / kg CFC-11, and the mix of coal, gas, oil, nuclear, and hydro power generation in Europe results in approximately 513 g of CO_2 emissions per kWh delivered. Consequently the "equivalent CO_2 emissions" for the European baseline are

Table 4.1. Annual energy use for baseline refrigerators using HFC refrigerants and HCFC foam insulation* (kwh/year)

Refrigerant	Foam Blowing Agent	North America	Europe	Japan
CFC-12	CFC-11	920	500	600
HFC-134a		910 - 970	500 - 540	600 - 640
Ternary Blend		910 - 960	500 - 530	600 - 630
HFC-152a		890 - 940	490 - 510	580 - 620
HCFC-22/HCFC-142b		890 - 940	490 - 510	580 - 610
CFC-12	HCFC-123	920	490	600
HFC-134a		910 - 970	480 - 520	600 - 640
Ternary Blend		910 - 960	480 - 510	600 - 630
HFC-152a		890 - 940	470 - 500	580 - 620
HCFC-22/HCFC-142b		890 - 940	470 - 500	580 - 620
CFC-12	HCFC-141b	920	490	600
HFC-134a		910 - 970	480 - 520	600 - 640
Ternary Blend		910 - 960	480 - 510	600 - 630
HFC-152a		890 - 940	470 - 500	580 - 620
HCFC-22/HCFC-142b		890 - 940	470 - 500	580 - 620
CFC-12	Perfluoroalkanes	960	490	630
HFC-134a		960 - 1020	480 - 520	630 - 670
Ternary Blend		960 - 1010	480 - 510	630 - 660
HFC-152a		940 - 990	470 - 500	610 - 650
HCFC-22/HCFC-142b		940 - 980	470 - 500	610 - 640
CFC-12	Isopropylchloride	1070	520	660
HFC-134a		1060 - 1130	520 - 560	650 - 700
Ternary Blend		1060 - 1120	520 - 550	650 - 690
HFC-152a		1030 - 1090	500 - 530	630 - 670
HCFC-22/HCFC-142b		1030 - 1090	500 - 530	630 - 670

* data derived from information in Figs. 4.2 and 4.3 and listed in Tables C.1 and C.4 in Appendix C rounded to the nearest 10 kWh/year

- the mass of CFC-12 times the GWP for CFC-12 plus
- the mass of CFC-11 times the GWP for CFC-11 plus
- the lifetime of the refrigerator times the annual energy use times the average CO_2 emissions per kWh delivered for Europe:

$$CO_2 = 0.140 \times 4{,}500 + 0.202 \times 1{,}500 + 15 \times 485 \times 0.513 = 4{,}665 \text{ kg} \quad (4.4)$$

The optimal refrigerant charge for each of the alternatives to CFC-12 is estimated from the baseline CFC-12 charge by using the ratio of the liquid density of the alternative to the density of CFC-12. The masses of the alternative foam blowing agents are estimated by using the relative blowing efficiencies for HCFC-123 and HCFC-141b and known weight percent of blowing agent for the perfluoroalkanes and isopropylchloride. The calculation in Equ. 4.4 assumes that all of the refrigerant and blowing agent are eventually released to the atmosphere and obviously the CO_2 calculation could be modified to reflect recovery by reducing the first term or first two terms by specified percentages.

Figures 4.4 to 4.6 contain the results for all of the combinations of current generation refrigerants and insulations for each region. The heavily shaded region at the bottom of each bar represents the estimated CO_2 emissions from energy use over the lifetime of the refrigerator. The middle section of each bar corresponds to the direct equivalent CO_2 emissions from the refrigerant and blowing agent, and the lightly shaded area at the top represent uncertainties due to the ranges of efficiency loss in the refrigeration system and the insulation. Tabulations of these results are provided in the Appendix (Tables C.5 to C.7)

These data are computed assuming a 15 year lifetime for each refrigerator and by using a regional average of 0.672 kg of CO_2 per kWh delivered for North America, 0.513 kg CO_2 per kWh for Europe, and 0.581 kg CO_2 per kWh for Japan.

Absorption

Absorption cycle refrigeration is a viable alternative to compression systems in refrigerator/freezers and there are consumer products available based on the principle of absorption. Absorption refrigeration relies on a mixture of ammonia-water-hydrogen as the working fluid and can use either an electric heater or natural gas combustion as the energy source instead of a motor driven compressor. This technology is employed in North America primarily for special niche market refrigerator applications such as in recreational vehicles where efficiency is not a critical product attribute. Efficiency improvements have been made in household absorption refrigerators in Europe, however, and these products have enjoyed modest sales in Europe within the recent past. This is the only refrigeration alternative that can be characterized as a commercially available not-in-kind substitute for CFC based vapor compression refrigeration.

Small absorption refrigerators consume 1¾ to 2 times the site energy as electric driven compression refrigerators with similar cabinet load characteristics [Lazarov, 1977 and Hofstetter, 1990] and as a result electrically heated absorption refrigerators have 75 to 100% higher indirect CO_2 emissions than comparable compression refrigerators. The primary energy consumption of the absorption could be less than that of vapor compression refrigerators if the absorption systems are heated with high efficiency natural gas burners. This conclusion, however, is limited to units similar to those reported by Lazarov and Hofstetter. Unlike compression refrigerators, the efficiency and energy use of absorption refrigerators depend on the balance of the cooling loads for the freezer and refrigerator compartments. The efficiency is at its highest at a particular ratio of cooling loads and units with relatively larger freezers will have lower efficiencies than those with the optimum ratio of loads. Consequently absorption units with small freezers could have lower CO_2 emissions than comparable compression refrigerators if very high burner efficiencies can be achieved, but similar reductions may be impossible for other sizes and styles such as those common in North America. A detailed evaluation would need to be done in order to identify the models and sizes of absorption refrigerators where CO_2 reductions are possible and to quantify what those reductions could be. Such a study is beyond the scope of this project. If it is done, such an evaluation would also need to compare other

factors affecting consumer preferences and satisfaction such as the refrigerator pull-down time and the cost and convenience of installation (e.g., outside venting of gas appliances).

4.7 CONCLUSIONS

The first conclusion to draw from the bar charts in Figs. 4.4 to 4.6 is that the small differences between the Total Equivalent Warming Impact (TEWI) of the leading candidate HFC/HCFC refrigerants and HCFC blowing agents are not significant. There is such an overlap in the uncertainties for these cases that no single combination can be picked out as the definitive best pair of refrigerant and blowing agent. Replacement of CFC-11 and CFC-12 with any of the leading candidate HCFC blowing agents and HCFC/HFC refrigerants would yield a significant reduction in TEWI, ranging from 18% in Europe and Japan (where use of partially water-blown CO_2/CFC-11 foam by many appliance manufacturers has already reduced potential CFC-11 emissions to some extent) to 20% in North America.

The refrigerator/freezer application is dominated by the INDIRECT (energy-related) effects, with results showing that the DIRECT effect constitutes only 2 to 3% of the TEWI for the HCFC and HFC alternatives. Refrigeration efficiency and insulation improvements represent the most effective means of achieving further substantial reductions in the TEWI, since the remaining DIRECT effect is so small and therefore reducing it to zero would yield at best a 2 to 3% improvement benefit. The improvements may be achieved via evolution of conventional technology with environmentally acceptable fluorocarbons or via alternative cycles or insulation materials/systems.

The charts do show that the use of perfluoroalkanes as the sole blowing agent have a significantly higher TEWI than do HCFC-123 or HCFC-141b with any of the refrigerants considered. The same statement can be made about the use of perfluoroalkanes as surfactants and isopropylchloride *at the k-factors that have been achieved to date*. The use of 100% CO_2 blown foam without additives to enhance its k-factor result in TEWI that are significantly higher than any of the other blowing agents considered even though the direct effect of the blowing agent is less than one kilogram. Finally, none of the refrigerants considered has a decided advantage over any of the others on a global warming basis in this application.

4.8 NEXT GENERATION TECHNOLOGIES

While the focus of this study and the preceding quantitative analysis is on the current generation of alternative technologies and efficiency levels likely to replace CFCs first in commercial products during the 1990s, there are other emerging or potential "next generation" technologies which are also evaluated in order to provide a more complete picture of future possibilities. Two of these alternatives which are not-in-kind technologies that might find application in household refrigeration are evacuated panel insulation and Stirling cycle refrigeration. These next generation options are unlikely to be sufficiently well developed or available in the time frame of the transition away from CFCs in the 1990s, and while some analysis has been performed for these alternatives it is difficult to assure comparability of available data on these advanced technologies with commercial or near commercial technologies such as some of the HFC and HCFC alternatives.

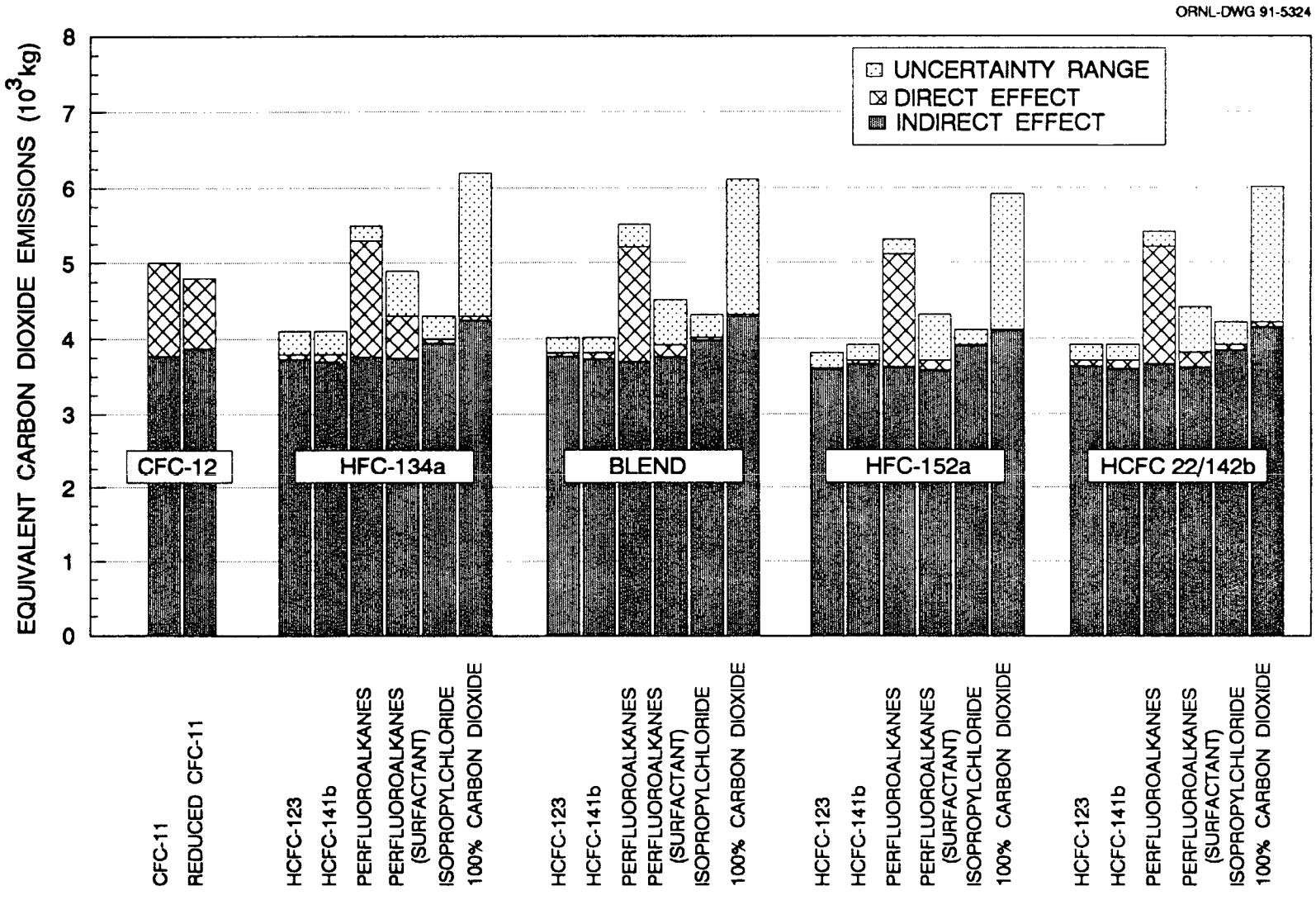

Fig. 4.4. Total equivalent warming potentials for CFC alternatives in European refrigerator/freezers.

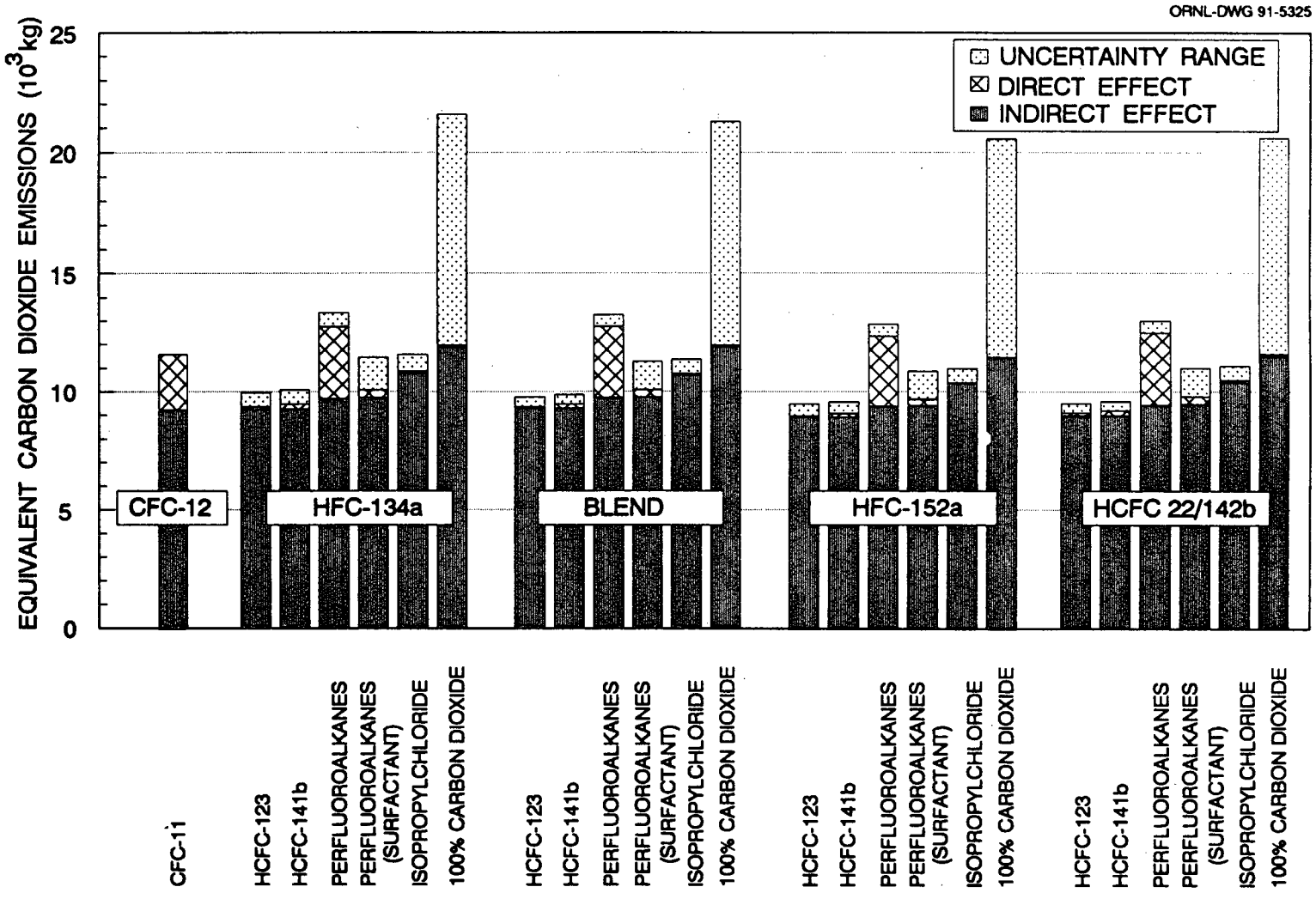

Fig. 4.5. Total equivalent warming potentials for CFC alternatives in North American refrigerator/freezers.

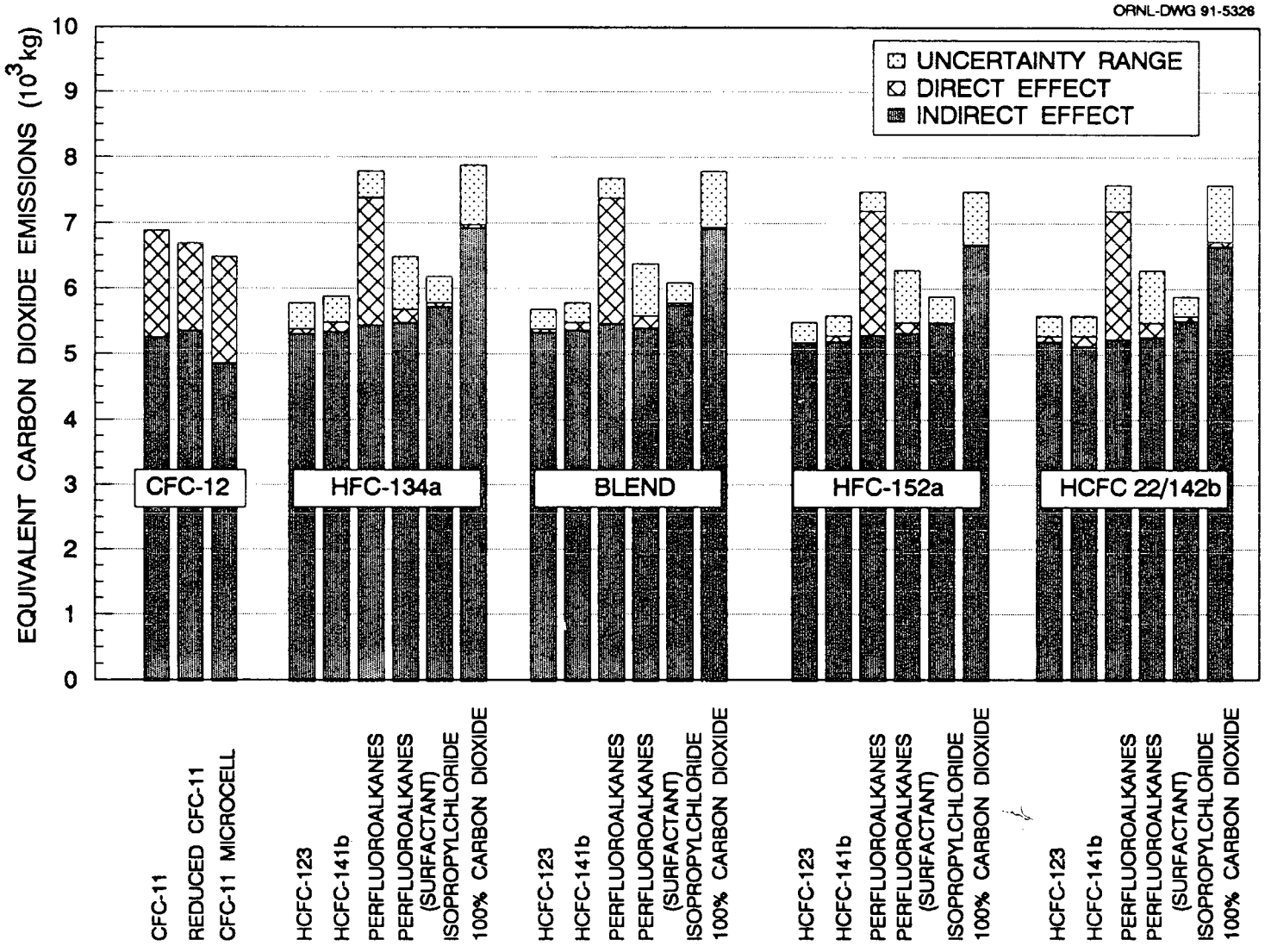

Fig. 4.6. Total equivalent warming potentials for CFC alternatives in Japanese refrigerator/freezers.

Evacuated Panel Insulation

Evacuated panels would achieve very low thermal conductivities by reducing the conduction and radiation components of heat transfer through the panel; the proposals for this type of insulation range from rigid metal panels containing a "hard" vacuum of only a few microns to an impermeable plastic membrane containing a filler material under a "soft" vacuum. A lot of debate in the appliance industry has focused on what materials should be used to manufacture evacuated panels and whether or not the panels would retain their very low thermal conductivity for the many years needed for a refrigerator cabinet. No effort in this project has been put into answering any of these concerns. The analyses that are performed are all based on the assumptions that panels of a specified k-factor could be developed and successfully integrated into a commercial product.

Calculations have been performed for a single refrigerator cabinet using evacuated panel insulation under two scenarios; assuming in the first case that 50% of the wall area is covered with evacuated panels, and that 80% coverage is used in the second. It is acknowledged that these scenarios are simplifications and that if these materials are ever commercialized they will probably be used selectively in only specific locations in the cabinet wall. The calculations have only been done for a 522 l (18.4 ft^3) refrigerator as is used in North America. This cabinet has the highest shell heat gains of any of the three baseline refrigerators used in the preceding analysis and consequently has the greatest potential energy savings through the use of evacuated panels.

Analyses have been performed assuming that panels could be manufactured which have a thermal resistance of 3.53 $K \cdot m^2/W$ (20 $h \cdot ft^2 \cdot {}^\circ F/Btu \cdot in.$) and that the thermal resistance of panels used in a refrigerator would not change during the 15 year lifetime of the appliance. The results are accurate only if these assumptions are valid. It has also been assumed that the panels are 25.4 mm (1 in.) thick and that they are embedded in a foam insulation when they are used in a refrigerator.

The results shown in Table 4.2 show the expected decreases in indirect warming potential resulting from the lower energy use for refrigerators with evacuated panel insulation, but the decreases of 14 to 20% are not as dramatic as may be expected. This is in part because the cabinet is not completely covered with the panels, but it is also the result of two other factors. First, there are only incremental improvements in the thermal integrity of the cabinet because the very low conductivity evacuated panels are replacing the foam insulation which already had a low thermal conductivity. Second, no effort has gone into reducing heat losses around the freezer and fresh food door gaskets or the defrost and fan powers; these losses have remained essentially constant. Data are not available to compare the possible manufacturing energy requirements of evacuated panels with the energy requirements for forming foam insulation. There would probably be a higher "embedded" energy in the evacuated panels, although it is unlikely that it would be so large as to be noticeable on the scale of Table 4.2. The limited analyses that has been performed indicates that evacuated panel insulation could be an effective means of reducing energy use and CO_2 emissions.

Stirling Cycle Refrigeration

Stirling cycle refrigeration is a next generation technology that is frequently mentioned as an alternative to the conventional vapor compression cycle for household refrigerators and freezers, and at least one appliance manufacturer is looking at the use of Stirling cycle refrigeration in household freezers. The discussion and evaluation of Stirling cycle refrigeration in this report is limited to its use in household freezers.

Table 4.2. Total equivalent warming impact of next generation technologies

Application and technology level	Direct Effect (kg CO_2)	Indirect Effect (kg CO_2)	TEWI (kg CO_2)
Refrigerator/Freezer			
Conventional refrigerator/freezer with HFC refrigerant and HCFC blown foam insulation	130	8950 - 9750	9080 - 9880
Conventional refrigerator/freezer with HFC refrigerant and evaculated panel insulation			
50% wall coverage	60	7700 - 8100	7760 - 8160
80% wall coverage	50	7250 - 7600	7300 - 7650
Freezers			
Conventional vapor compression cycle HFC/HCFC current technology	40 - 200	6600 - 6900	6640 - 7100
Stirling cycle current technology	35 - 130	7600 - 8700	7635 - 8830

De Jonge and Kuijpers estimated the COP of a Stirling cycle with an optimum design to be 1.19 at an evaporating temperature of -30°C (-22°F) and a condensing temperature of 35°C (95°F) after taking into account electric motor and mechanical drive efficiencies and parasitic effects such as heat conduction, regeneration losses, and deviations from ideal thermodynamics (Kuijpers, 1991). Comparable COPs from calorimeter testing for current technology high efficiency vapor compression systems average around 1.32 after discounting the superheat enthalpy which cannot be used effectively. This simplistic comparison implies that there is only a 10% lower efficiency for an optimum design of a Stirling cycle system, but this is a comparison between predicted Stirling performance and actual performance of vapor compression systems. Actual COPs of Stirling cycle systems realized in practice are certainly somewhat lower and a 15 to 20% difference relative to vapor compression is more realistic (Kuijpers, 1991).

Table 4.2 shows results for a 450 ℓ (16 ft^3) household freezer in North America for a vapor compression system using HFC-134a or HFC-152a as the refrigerant and either HCFC-123 or HCFC-141b blown foam insulation relative to a Stirling cycle freezer using Kuijpers estimate of 10% to 15% lower COP and the same foam blowing agents. The Stirling calculations, though, are based on low heat and regeneration losses (Kuijpers, 1991) and realistic motor and mechanical efficiencies. Predictions of future Stirling cycle efficiencies are higher than the COP used here, but they must be compared with vapor compression systems of the future that are being driven to lower energy use by efficiency standards[1]. The key point to note in Table 4.2 is the very small difference in direct effect between HFC compression systems and Stirling cycle refrigerators, and the conclusion to draw is that next generation technologies like Stirling cycle will have to compete with traditional technologies with HFCs and HCFCs in terms of efficiency and reliability on a nearly level playing field. There is not a significant inherent advantage to systems that do not use greenhouse gases because of the very low GWPs of some HFCs and HCFCs.

[1] The efficiencies shown in Table 4.2 are representative of what may be available during the time period of CFC phaseouts and no effort has been directed in this study toward predicting future efficiencies for either Stirling or advanced vapor compression technology.

Table 4.2 also shows the equivalent lifetime carbon dioxide emissions for a household freezer operating either with an HFC refrigerant in a vapor compression system or with a Stirling cycle refrigeration system. Data are shown which represent the current state of compression technology and also the future state where both technologies have been improved with further development of their efficiencies. The direct equivalent warming potential of the compression systems is due almost entirely to the blowing agent in the foam insulation with an imperceptible contribution from the small refrigerant charge. The direct effect for the Stirling cycle systems is due entirely to the blowing agent because the assumed working fluid, helium, does not contribute directly to global warming. It is important to note that the development of either vapor compression or Stirling technology to the point where it achieves 45 to 50% of Carnot efficiency represents a significant decrease in energy use and reduction in the indirect effects on global warming.

5. COMMERCIAL REFRIGERATION

5.1 INTRODUCTION

Commercial refrigeration is an important application of CFCs in Europe, North America, and Japan and it is an essential component of the food distribution system in those regions. The extension of refrigerated transport, food processing and storage, and retail sales into the developing countries is also vitally important to improving the health and overall standard of living of the people in those areas. It is very important that use of refrigeration expand into these regions and that viable replacements for CFCs are developed for food preservation before hydrofluorocarbon refrigerants are phased out.

Commercial refrigeration consumes a great deal of energy and the system efficiency is an important consideration for the companies and individuals that use these systems, but minor incremental efficiency improvements are not immediately accepted by the industry. The value of the refrigerated inventory, whether it is food or perishable medicines, frequently outweighs the value of the energy savings and consequently improvements must not jeopardize system reliability. Besides having high reliability, commercial refrigeration systems must operate within fairly narrow temperature range limits so as not to damage the product, and they must be easy to service so that emergency repairs can be performed easily by trained service personnel. Efficiency improvements are accepted by the industry only after they have proven their acceptability on these other criteria. Since the retail sales is such a dominant part of this industry, it is the only system analyzed in this section; refrigerated transport and food processing plants for the preparation and storage of perishable foods and pharmaceuticals are also important segments of this industry, but the quantities of CFCs and energy used in these applications are dominated by the CFC and energy use in retail sales.

Retail refrigeration systems rely almost exclusively on the Rankine vapor compression cycle and use hermetic, semi-hermetic, or open compressors with air-cooled or evaporative condensers. The evaporator and expansion valve are mounted inside the display case for retails sales equipment, and the evaporator is commonly defrosted with electric heat or with hot gas bypass from the compressor. Single compressor and multiplexed compressor systems are both common and each has its unique advantages relevant to initial cost, operating expense, and ease of service.

5.2 METHODOLOGY

Considering the diversity as well as the complexity of available options for these refrigeration systems, it is very difficult to arrive at meaningful estimates of annual energy use. This is true even for the well known systems currently operating with CFC-12, HCFC-22, and R-502* and any calculations performed would be for a very specific design and installation. The energy use modeling of these large parallel systems is further complicated by their use of multiplexed compressors, the optimization of run time using electronic controllers, heat reclaim, gas defrosting, and the like. The detailed analysis required to make a meaningful energy evaluation of this application is beyond the scope of this work. The uncertainties in evaluating energy use even for a baseline system with a simpler

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* the designation R-502 is used for refrigerant 502 because it does not fit neatly into any of the CFC/HCFC/HFC classifications because it is a mixture of HCFC-22 and CFC-115.

analysis far exceed the differences that might be discerned between possible alternative refrigerants. What follows is more of a qualitative assessment that helps identify where improvements need to be made to reduce overall net equivalent CO_2 emissions rather than a comparative analysis that tries to determine the strengths and weaknesses of alternative refrigerants and technologies. The data presented later in this section are specific to a particular system installation.

5.3 BASELINE SYSTEMS

The vast majority of retail refrigeration systems are used in sales of frozen as well as non-frozen perishable foods and beverage grocery items. The display cases are categorized by their air temperatures into three operational ranges for refrigeration; high temperature for fresh produce; medium temperature for fresh meats and dairy products; and low temperature for frozen meats, vegetables, and ice creams. These are summarized in Table 5.1. The market for new equipment using CFC-12 and R-502 is shifting very quickly to HCFC-22 because of the phaseout of CFCs scheduled by the Montreal Protocol. The shift to HCFC-22 increases the difficulty in establishing a baseline system because of the rapid design changes that are currently evolving to work around the very high compressor discharge temperatures associated with HCFC-22 in very low evaporating temperature applications.

Table 5.1. Retail refrigeration equipment

Temperature Category	Application	Refrigerants Used	Evaporator Exit Air Temperature
High Temperature	fresh produce	CFC-12 and HCFC-22	10°C (50°F)
Medium Temperature	meats and dairy	CFC-12 and HCFC-22	-2° to 7°C (28° to 45°F)
Low Temperature	frozen foods and ice cream	R-502 and HCFC-22	-18° to -32°C (0° to -25°F)

The food marketing industry is divided between very large stores that use refrigerated display cases connected to a remote condensing unit and compressor rack and small specialty markets that handle a single type of product (e.g., meat, fish, produce) and convenience stores. Many small stores rely on medium and low temperature self-contained display cases that house the evaporator, condenser, compressor, and expansion device. The large convenience stores frequently have additional self-contained display cases for sandwich products and processed meats and also use a walk-in cooler with shelves for milk and beverages that can be accessed through glass doors from the front and can be stocked from the rear. These units typically have the (compressor) condensing unit mounted on the roof or at ground level outside the building.

Although refrigerated display cases can use CFCs in foam insulation, this use is insignificant compared to the CFCs used in the refrigeration system. Only about 5% of the refrigeration load of open display cases is due to heat conduction through the walls, most of the load is due to radiation and air infiltration. The use of foam insulation in place of fiberglass can reduce the load of open cases by only about 2%; the absolute savings (computed on product load) that are possible for enclosed cases is of about the same magnitude as the savings for open cases, although the percentage is higher because of the lower overall load for an enclosed display case.

Remote Compressor and Condenser Units

Centralized refrigeration connected to one or more common condensers employing a remote machine room containing the rack(s) of semi-hermetic compressors have become the standard refrigeration system for large supermarkets in North America, Japan, and the United Kingdom. There are approximately 30,750 supermarkets in the U.S. using central refrigeration systems. These types of stores may be less common in Europe and Japan where smaller specialty shops are used for selling fresh meats, fish, produce, and dairy products. Where they are used, these systems can become very large and complex. During the 1980's the average supermarket in the United States had 46 display cases operating from the central refrigeration system, and this number is expected to go up to 80 cases with the development of "hyper" markets in the 1990's (Rugh, 1990). An average supermarket built in the late 1980's has as much as 25,000 m (82,000 ft) of copper tubing in refrigerant lines, heat exchangers, and pressure sensing lines, and 16,000 solder joints, fittings, and tube connections. It has 210 lineal meters (690 lineal ft) of display cases and 415 m^2 (4,469 ft^2) of walk-in coolers and freezers (Ares, 1989). The total refrigerating capacity of the compressor system would be approximately 135 kW (180 hp), and about one third of that would be for the low temperature display cases and freezers and the rest for the medium and high temperature cases and coolers. The refrigeration system alone would require about 570,000 to 640,000 kWh per year with a monthly utility bill on the order of $5,650 at typical 1990 U.S. electric rates (Ares, 1991, and Oas, 1991).

Similar systems are known to be used in the United Kingdom and in Japan. The Food Marketing Institute (FMI) has identified the "typical" supermarket for the United States and enumerated the types of refrigerated display cases that would be used in such a store. These data are listed in Table 5.2 below. Peter Cooper (1991) of Sainsbury's also provided ranges for the number of display cases found in stores in the United Kingdom and ranges on the lengths and capacities of each case. Composite values (average number of cases per store times the average length of case) are also listed in Table 5.2 for the U.K. This is a simplistic use of Cooper's data, and does not identify a typical supermarket, but it does indicate refrigeration systems that are roughly comparable to those in the United States in terms of size and complexities. More specifically, these data show a heavy use of frozen foods and meats in the United States and the United Kingdom and also comparable levels of refrigeration for dairy products. Data obtained for Japan provided a breakdown between medium temperature (i.e., fresh meats and dairy products) and frozen foods, but they are not as specific as those for the U.S. or the U.K. Roughly 90% of the commercial refrigeration in Japan is for dairy and fresh meat products and only 10% for frozen foods. The Japanese make much less intensive use of retail refrigeration; Japanese supermarkets typically have twenty display cases, 18 for medium and high temperature and two for low temperature, with a total installed capacity of 26 kW (35 hp) (Taguchi, 1991). The annual energy use for refrigeration is approximately 115,000 kWh.

Refrigerant charge and leakage

The use of remote compressors and condensing units in their current state of design necessitates that they have a very large refrigerant charge; a rule of thumb in the refrigeration industry in North America is that a supermarket will generally require 0.49 kg/m^2 (1 lb/10 ft^2) (Ares, 1991). Consequently, the average 3,700 m^2 (40,000 ft^2) supermarket has a refrigerant inventory of approximately 1,800 kg (4,000 lb). Systems in the U.K. may differ in design from those in North America, but they still use large refrigerant charges. One store in the U.K. has a refrigerant charge of 3,300 kg (7,300 lb). These large refrigeration systems can also be notoriously leaky, although that is a consequence of their use and not through careless design or installation. One of the most frequent sources of leaks is at the threaded connections within the low temperature display cases.

Table 5.2. "Aisle length" of refrigerated display cases in the U.S. and the U.K.

Type of Display Case	United States (m)	United States (ft)	United Kingdom (m)	United Kingdom (ft)
Dairy Product	30.5	100	41	135
Fresh Meat	59.1	194	21	69
Produce	46.3	152	no data	no data
Frozen Food	74.4	244	78	255
Total	210	690	140	459

These connections experience frost formation while the case is running and thermal stresses during the case defrost and refreeze cycles. The fittings are usually designed for the convenience of quick servicing on the sales floor and they will eventually work loose due to the frosting/defrosting transients in the refrigeration system; consequently they begin to leak (Ares, 1991). Leaks can also occur at the fittings and joints around the compressor rack; this is particularly true in older equipment which experience much greater magnitude and duration of vibrations than do the state-of-the-art compressor racks that came on the market in the late 1980's. Certain older compressor designs have measured vibration as much as 19 mm (0.75 in.) on the racks, causing pipe connections to leak refrigerant into the atmosphere. Compressor manufacturers and system installers have diligently worked on improving their systems and newer installations run much more smoothly, vibrating .05 to .07 mm (0.002 to 0.003 in.), and generally no longer add to the problem of refrigerant leakage in the machine room (Ares, 1991).

The combination of a very large refrigerant charge and a potentially leaky system warrants implementation of a rigorous program of preventive maintenance. One chain of grocery stores was very pleased when they instituted a robust preventive maintenance program and brought their usage rates for the refrigeration system and air-conditioning down to 17 kg/month (37 lb/month) per store; rates had been "much higher" under the previous maintenance program (Jirel, 1990). Typical loss rates in the United States have been quoted as high as 33% of the charge each year (Ares, 1991), but little documentation is ever made available on such errant job sites. Although the main problem may be with the low temperature equipment using R-502, losses of CFC-12 in medium and high temperature equipment can be significant. The "stationary aftermarket" for CFC-12 in supermarkets in the U.S. is 40 million kg/year (90 million lb/year) out of a total annual production of 140 million kg (310 million lb) (Lawson, 1990). This is second only to the aftermarket for automobile air-conditioning which requires 50 million kg (110 million lb) annually. It is widely believed that these large refrigeration systems can be brought to the point that leakage is almost insignificant just by good systematic preventive maintenance. Supermarket refrigerant loss in Europe is about 45 kg (100 lb) per year, while the leakage for a comparable system in the U.S. is 300 to 360 kg (700 to 800 lb) (EPRI, 1991).

Self-Contained Units

Small specialty shops selling fresh meat, fish, or produce and convenience stores are more accommodating to the use of self-contained refrigeration equipment than they are to a remote

compressor and condensing units. There are approximately one million low temperature display cases and 1.8 million medium and high temperature cases in Japan's convenience stores (Taguchi, 1991). There are 57,000 convenience stores in the United States that also use some self-contained display cases (Progressive Grocer, 1990) and 59,000 other small shops selling food that may or may not use refrigeration. Overall, the proportions of convenience store refrigeration are similar to those in Japan; one-third low temperature and two-thirds medium and high temperature.

Low temperature self-contained cases in Japan use R-502 and CFC-12 (Taguchi, 1991), while those in the U.S. use CFC-12 almost exclusively (ADL, 1989). All such cases have much smaller refrigerant charges than the centralized systems and also have lower leakage rates. The low temperature cases in Japan have a 300 g (10 oz) charge of CFC-12 or R-502, and the medium temperature cases use 400 g (15 oz) of CFC-12. The display cases in the U.S. use 200 to 400 W (¼ to ½ hp) compressors (ADL, 1989); those in Japan average 300 W (0.4 hp). Convenience stores in the U.S. also have walk-in coolers with remote condensing units so that the overall refrigeration system is larger than that reported for Japan; the walk-in's installed capacity averages 5.6 kW (7½ hp) with a charge of 23 to 34 kg (50 to 75 lb) of CFC-12 (Ares, 1991). Refrigerant leakage for self-contained display cases is practically zero, and that for the walk-in cooler is approximately 20% that of a walk-in for a large supermarket system. Total leakage is less than 6% of the total store refrigeration charge per year. Data were not obtained on the numbers and sizes of comparable display cases in Europe.

5.4 ALTERNATIVE REFRIGERANTS

The commercial refrigeration industry is rapidly moving forward in its efforts to totally eliminate the use of CFC-12 and R-502 in new equipment, and has made significant progress in this regard. The substitute refrigerant of choice, however, is exclusively HCFC-22. There have been some initial efforts at evaluating the performance of HFC-134a in high and medium temperature applications, and some analytical work has also been done on HFC-32 and HFC-32 blends for low temperature (EPA, 1991). Work with these refrigerants is in the very early stages, though, and is a long way from being reduced to practice and commercialized. Work is also being performed with HCFC blends for both low and medium temperature applications. In the meantime HCFC-22 is being used increasingly in new medium and high temperature display cases and condensing units with little or no difference in efficiency from comparable cases using CFC-12. HCFC-22 is also being used in low temperature applications, but this use necessitates some major design changes and there may or may not be a gain or a loss in efficiency when all of the system design improvements have been completed.

The primary difficulty in using HCFC-22 in low temperature applications is that the compressor discharge temperature exceeds 135°C (275°F) when the condensing temperature is at its normal level for high outdoor ambient conditions. High discharge temperatures can lead to a thermal breakdown of the lubricant, creating acids that attack the insulation on the motor windings and lead to compressor failure, and also leading to carbonization of the lubricating oil, which in turn creates crank-case sludge that ruins bearings. Design changes can work around this difficulty, at a cost, and at a possibly significant change in operating efficiency.

Single-stage compression can be adapted for low temperature applications using HCFC-22 by using refrigerant liquid or two-phase injection to keep the compressor cylinder head temperature down. This technique developed a bad reputation when it was first used in the late 1950's because it was suspected as the cause of a lot of compressor failures; recent experience with liquid injection has been more successful. Electronic sensors are now used to detect high head temperatures and liquid is injected into the compressor shell only when it is needed to cool the compressor discharge gas. This controlled system has proven to be reliable and is a viable means of using HCFC-22 in low

temperature applications where there are moderate ambient conditions. Liquid injection can lead to a 15 to 20% loss in capacity and 5 to 12% reduction in efficiency (Tollar, 1990) during high head pressure steady-state operation, but this does not necessarily translate into proportional increases in annual energy use. The decrease in compressor efficiency when the liquid is injected happens only at very high outdoor temperatures and may affect a very low number of operating hours in the year. One compressor manufacturer estimated that the steady-state efficiency of a single-stage compression system with demand cooling will vary from a little better than a conventional R-502 system to a little worse, and that over a typical operating season it will average 5 to 10% less efficient than the R-502 system (Muir, 1989). Single-stage liquid injected compressors with HCFC-22 are gaining acceptance as the preferred alternative to R-502 in the northern latitudes where the ambient temperatures remain fairly low.

Two-stage compression of HCFC-22 with inter-stage cooling is becoming the preferred alternative to single-stage compression of R-502 for low temperature refrigeration in the southern United States and other regions where there are a large number of operating hours at high ambient temperatures. Currently all of these systems are externally compounded where two or more compressors work together either as a dedicated pair or on a rack of multiplexed compressors; several compressor companies are working to develop a wide range of internally compounded compressors where the two-stage compression and inter-stage cooling are all done within a single compressor housing. The key design change in each case is the use of some means of cooling the discharge gas of the first stage of compression before it is used as the suction gas of the second stage. The cooling can be accomplished through any of several means including liquid injection from the mechanical subcooler, suction to liquid line heat exchangers, and desuperheaters for heating water. Externally compounded, two-stage compression systems are inherently more complicated than the single-stage R-502 systems that have been used in the past, thus they require a higher degree of service technology. The added complexity is an important factor in delaying or preventing the acceptance of this technology by stores outside of major metropolitan areas where it may be difficult to find qualified service personnel. Future use of internally compounded two-stage compressors should be easier to service than externally compounded compressors and consequently require less highly skilled service technicians.

Higher system efficiencies are possible with the two-staged compression concept, but a lot depends on the design and maintenance of the system. This view is not universally accepted, however, and data are presented in the literature which can show a well designed supermarket refrigeration system with single compressors having a higher overall system efficiency than a multiplexed system (Adams, 1990). The design of the multiplexed system must do a very good job of managing the suction lines so as to avoid unnecessary pressure reduction valving and the system must also be well maintained to realize any potential efficiency advantage. Compressor manufacturers cite potential efficiency advantages of up to 15% (Muir, 1989), 10 to 15% (Tollar, 1990), and 0 to 8% (Copeland, 1990). In the near future, it will be the design and maintenance of the refrigeration system that determines if actual energy savings occur when single-stage R-502 systems are replaced with two-stage HCFC-22 multiplex systems.

5.5 RESULTS

As explained earlier, a detailed analysis of the energy use in supermarket systems is too complicated to perform for this study and the available data on baseline and alternative systems is too imprecise to make the results of such an evaluation widely applicable at this point. What is presented instead is an evaluation of the energy use and direct refrigerant emissions for a very specific baseline system (Oas, 1991) and four evolutionary steps toward phasing out CFCs in an improved refrigeration system, all based on an existing supermarket in the U.S. The results shown in Fig. 5.1 are for:

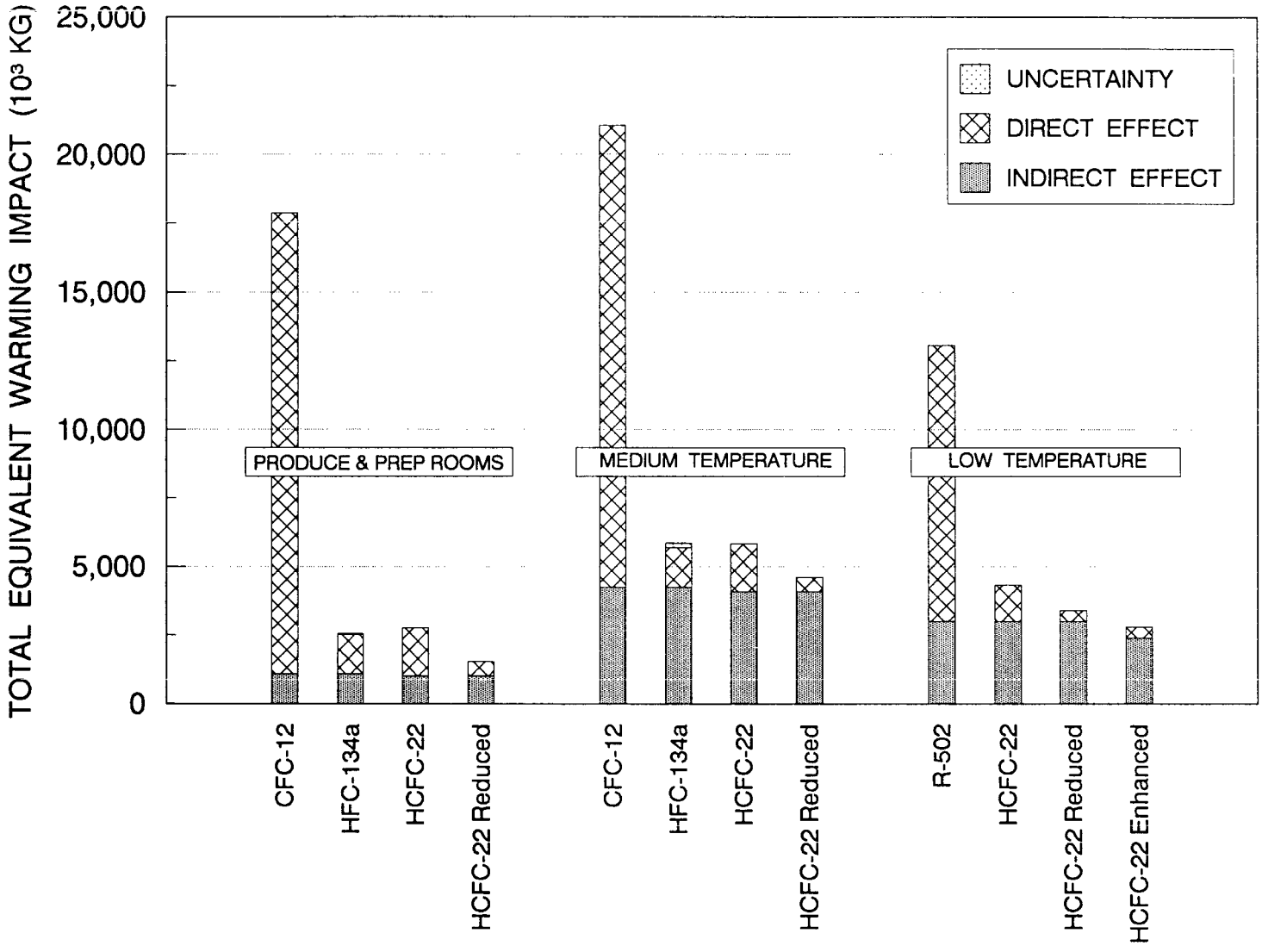

Fig. 5.1. Total equivalent warming impact of refrigerants for retail refrigeration display cases.

- an early to mid-1980's baseline refrigeration system; using R-502 for low temperature refrigeration and CFC-12 for medium and high temperature, 122 kW (163.5 hp) of installed capacity, and 620,000 kWh annually for refrigeration, 33% of the 1500 kg (3340 lb) refrigerant charge lost annually to leaks and service (labeled CFC-12 and R-502 in Fig. 5.1),

- a 1990 refrigeration system; using R-502 for low temperature refrigeration and HCFC-22 for medium and high temperature, 112 kw (150 hp) of installed capacity, and 602,000 kWh annually for refrigeration (223,000 for low temp), 33% of the 1500 kg (3340 lb) refrigerant charge lost annually to leaks and maintenance (HFC-134a),

- the conversion of the entire low temperature system in this store to HCFC-22 so that all temperature ranges use HCFC-22 without any changes in efficiency or leakage rates (HCFC-22),

- improved service schedules and maintenance practices of the converted HCFC-22 system so that only 10% of the charge is lost annually (HCFC-22 Reduced), and

- an arbitrary 20% improvement in energy efficiency for the low temperature refrigeration system in addition to the conversion to HCFC-22 with reduced leakage rates (HCFC-22 Enhanced).

Each of the five cases evaluated assumes that 100% of the refrigerant is recovered when the store is finally closed after 20 years of operation and the refrigeration system is retired from use.

5.6 CONCLUSIONS

Several interesting conclusions can be made from a projection of the results. They are:

- there are significant drops in the direct equivalent CO_2 emissions by switching from CFC-12 or R-502 to either HFC-134a or HCFC-22 in the medium and high temperature systems and HCFC-22 in the low temperature refrigeration systems,

- this is no significant difference between the TEWIs for HFC-134a and HCFC-22 in the high and medium temperature systems,

- the direct equivalent CO_2 emissions from refrigerant losses are still a significant fraction of the TEWI after converting to HFC-134a or HCFC-22 even assuming a decreased refrigerant loss rate (10% vs. 33%), and

- efficiency improvements in the low temperature systems are important, but the majority of storewide energy use for refrigeration is in the high and medium temperature systems and efficiency improvements are also needed in these systems to reduce storewide TEWI further.

The low temperature application has received much more attention in converting from CFCs than have medium and high temperature display cases, but cycle and efficiency enhancements are needed for these other two classes of display cases in order to make further large reductions in overall system emissions. Changes in case design, and their acceptance by customers and retailers, could also make significant reductions in refrigeration load and CO_2 emissions. The replacement of open "coffin cases" and old technology glass door cases with large anti-sweat heaters with new super-efficient glass

door cases can make a significant reduction in the refrigeration load. In large part old technologies with unnecessarily wasted energy are perpetuated to suit the customers' convenience.

5.7 NEXT GENERATION TECHNOLOGY OPTIONS

Research and development effort is also being directed toward other alternative refrigerants for commercial refrigeration systems. HFC-32 blends or ammonia are two options that could be used in place of R-502 or HCFC-22, but the refrigeration system would require substantial design changes. Work is also being done to identify high and medium pressure refrigerant blends that could be used in retail refrigeration systems with only evolutionary changes in compressor and case design.

Ammonia is widely used in other parts of the food industry, especially in processing and storage facilities. These uses include chilling of meat, poultry, fish, and perishable fruits and vegetables; refrigeration in the dairy and beverage (e.g., beer, wine) industries; freezing of ice cream and numerous other types of foods; the manufacture of ice; and warehousing of both refrigerated and frozen products. The International Institute of Ammonia Refrigeration (IIAR), in evaluating potential opportunities for expanded use of ammonia vapor compression beyond these current food and other process/industrial applications, has suggested that chillers could be the first target application, followed by retail refrigeration (IIAR, 1989).

The retail refrigeration application would involve an indirect system in which the ammonia refrigerant would cool a brine or antifreeze solution, which is then circulated to the refrigerated display. A secondary heat transfer loop is used to keep the refrigerant outside of the building and to keep any accidental releases of refrigerant away from the customers. A project is underway in Germany to design and test such a supermarket refrigeration system using ammonia and to compare its operation with a baseline system with HCFC-22. This is an interesting concept, which has the potential of significantly reducing the refrigerant charge as well as permitting the use of flammable or toxic refrigerants safely. It is not evaluated quantitatively in this chapter, however. Ammonia is analyzed quantitatively for the proposed chiller application in the following Chapter (see p. 5.5-5.12). A review of the pertinent codes and standards for ammonia application is provided in that section, together with a summary of technical issues and estimates of refrigerant performance.

There is a growing interest in the use of refrigerant mixtures using either HFC-32 or HFC-125 in low temperature refrigeration. Analytical work at the U.S. EPA has looked at the use of non-flammable blends of HFC-32 in low temperature systems and azeotropic mixtures have been identified which compare favorably with R-502 in terms of efficiency and capacity (Gage, 1991). Similar work has been performed considering blends of refrigerants with HFC-125. These refrigerant mixtures have potential as chlorine free alternatives for refrigeration systems that currently use R-502 or HCFC-22 and further work is needed in these areas. The blends are not included in the analysis presented in this report due to the time limitations of this study and the preliminary nature of the analytical findings for the blends.

Work is being done with HCFC blends which show promise as refrigerants in commercial refrigeration systems without the design adaptations that would be required for ammonia or flammable HFCs. At least one compressor manufacturer is working with a chemical company to identify refrigerant blends that have substantially lower GWPs than CFC-12 and R-502 and also higher efficiencies in medium and low temperature (medium and high pressure) applications (Sundaresan, 1991). The medium pressure blends of HCFC-22, HFC-152a, and HCFC-124 (undisclosed proportions) could reduce the direct effect of the refrigerant by an estimated 93 to 94% (relative to CFC-12, based on 500 year GWP values) with a 5 to 6% efficiency improvement. There

are two low temperature blends (high pressure) being considered which consist of HCFC-22, propane (HC-290), and either HFC-125 or FC-218. These blends could reduce energy use by 12% or more while reducing the direct effect of the refrigerant by 85 to 90% (relative to R-502, based on 500 year GWP). Further analysis and testing are required to develop any of these blends and to demonstrate their acceptability in commercial refrigeration equipment, but they have the potential of substantially reducing the TEWI of retail refrigeration systems.

6. COMMERCIAL CHILLERS

6.1 INTRODUCTION

Air conditioning in large multi-story buildings and very large single-story buildings is commonly provided by water chillers (water-cooled evaporators). Table 6.1 summarizes the world-wide installed capacity of water chillers. Approximately 211×10^6 kW (60×10^6 refrigeration tons, RT) of chillers requiring the use of CFC and HCFC refrigerants are in operation (ECI, 1990; Legin, 1991; Taguchi, March 8, 1991; UNEP, 1989). Of that, about 134×10^6 kW (38×10^6 RT) operate in North America, 39×10^6 kW (11×10^6 RT) in Japan, and 23×10^6 kW (6.6×10^6 RT) in Europe.

Table 6.1. Installed chillers capacity

Region		Capacity ($\times 10^6$ kW_t)	Capacity ($\times 10^6$ RT)
North America		134	38
Japan		39	11
Europe		23	6.6
Rest of World		15	4.4
Total Installed Capacity		211	60
Centrifugals	70% of total	148	42
Centrifugals on CFCs	80% of Centrifugals	118	33.6
on CFC-11	67% of Centrifugals	99	28.1
on CFC-12	12% of Centrifugals	18	5.0
Note: RT = refrigeration tons = 12000 Btu/h = 3.516 kW			

Centrifugal chillers represent 70% of the total with the rest having reciprocating, screw, or scroll compressors that primarily use HCFC-22 (Appendix E, Table E.9). CFCs that cannot be produced after the year 1999 are used in about 80% of operating centrifugal chillers; 67% with CFC-11 and 12% with CFC-12 (Clark, 1991; Appendix E, Table E.9). Consequently about 118×10^6 kW (33.6×10^6 RT) of centrifugal chillers are operating with refrigerants soon to be in short supply. Centrifugal chillers have had historical annual shipments that are cyclical with a generally increasing trend (Pietsch, 1989). Since average service life is about 30 years, more than two-thirds of these chillers are likely to be in service in the year 2000 if premature equipment retirements can be avoided.

Industry has taken a number of steps to prepare for this rapid transition away from CFCs. Acceptable near-term alternative HCFC and HFC refrigerants were found and production facilities were built or are under construction for making them available in commercial quantities. The technology to recover and recycle or reclaim CFCs was developed and commercialized so that CFC-conservation could play a role in minimizing premature equipment retirements. New chillers that were developed to be compatible with CFCs and their alternatives and commercialized so that chillers placed in service in the short-term could be field-converted at low-cost once the alternative refrigerants became available in commercial quantities. The technology to field-convert existing CFC-based chillers to operate with the alternative refrigerants was made available so that building owners would have an alternative to premature equipment retirement of the equipment as the cost of CFCs

to service existing chillers becomes excessive. New HCFC-22 chillers were also developed and commercialized to cover a broader capacity range.

The CFC phase-out was in response to measured and anticipated ozone depletion. Industry has invested tremendous resources to respond to this recognized environmental need. The selected near-term alternative refrigerants (HCFC-22, HCFC-123, and HFC-134a) for chiller service were evaluated to determine their contribution to global warming. This section documents an analysis of the lifetime total equivalent warming impact (TEWI), including DIRECT (refrigerant loss) and INDIRECT (energy use) contributions, resulting from the replacement of CFCs in chillers with HCFCs/HFCs. One not-in-kind (NIK) alternative was also evaluated, direct gas-fired double-effect absorption chillers, as an alternative to electric-driven vapor compression technology. Lastly, two next generation technologies were evaluated; ammonia as an alternative refrigerant for electric-driven vapor compression machines and advanced cycle absorption chillers.

The global warming analysis was limited to North America, Japan, and Europe where over 90% of the existing chiller capacity is installed. The analysis was simplified by assuming the same chiller annual load factor and seasonal performance factors for all locations. Estimates of chiller refrigerant loss rates vary widely so several different loss rates were considered.

6.2 METHODOLOGY

DIRECT and INDIRECT global warming contributions are calculated and combined to estimate TEWI. The analysis assumptions used to estimate DIRECT and INDIRECT emissions are summarized in Tables 6.2 and 6.3, respectively. The rationale to support the assumptions is provided below. The resulting approach is straight-forward and at a level of precision that is appropriate for the input data.

Chiller Categories

Four chiller equipment categories related to capacity in refrigeration tons (RT) are considered: 100 RT air-cooled, 300 RT water-cooled, 1000 RT water-cooled, and 3000 RT water-cooled. This enables an assessment of the dependency of emissions on refrigerant and chiller size class. 100 RT air-cooled chillers are primarily positive displacement machines using reciprocating, screw, or scroll compressors. 300 RT water-cooled chillers are primarily centrifugal machines, except for those using HCFC-22 that may be screw-type. For this study 1000 RT and 3000 RT chillers are exclusively centrifugal although screw-type machines are available up to the 1000 RT size range.

The rationale for selecting these chiller categories was as follows (Calm, April 1991). Enough air-cooled chillers existed to justify a category. Air-cooled chillers tend to be small hence the 100 RT size. Air-cooled chillers also require a high pressure/temperature lift due to operating conditions and typically employ positive displacement compressors (reciprocating, screw or scroll) and high-pressure refrigerants (HCFC-22). The few centrifugals in this category use medium or high-pressure refrigerants (e.g., CFC-12 or HCFC-22). The 300 RT water-cooled category represents the low-pressure centrifugal mass market. Approximately 67% of the existing centrifugal chiller capacity in the world is low-pressure using CFC-11 (Table 6.1). The 1000 RT water-cooled category represents the upper end of the low-pressure market with medium or high pressure refrigerants becoming predominant at about this size. The 3000 RT category is predominantly a high pressure refrigerant market. The number of units is modest but capacity is significant and chillers in this category are the only practical technical option for district or campus chilled water plants, or for chiller plants for very large facilities.

Table 6.2. Analysis assumptions for estimating the DIRECT contribution to TEWI as a result of operating chillers with various refrigerants over their lifetime

Equipment Categories:	100 RT air-cooled 300 RT water-cooled 1000 RT water-cooled 3000 RT water-cooled (Note: RT = capacity in refrigeration tons = 12000 Btu/hr = 3.516 kW_t)						
			R-11	R-12	R-22	R-123	R-134a
Refrigerant Charge (kg/RT): (*-denotes midpoint of range in Table E.2)	100 RT air-cooled		---	---	0.74	---	0.72
	300 RT water-cooled		0.91	1.24	0.9*	0.8*	1.1*
	1000 RT water-cooled		1.0*	1.33	1.6*	1.05	1.3*
	3000 RT water-cooled		---	1.2*	1.05*	---	1.05*
Refrigerant Loss Rates (%/yr):	parametric variation of % of charge lost per year... 0, 4, 8, 12, and 16 %						
				100 RT	300 RT	1000 RT	3000 RT
Refrigerant Options:	CFC, HCFC or HFC vapor compression			R-22 R-134a	R-11 R-12 R-22 R-123 R-134a	R-11 R-12 R-22 R-123 R-134a	R-12 R-22 R-134a
	Next generation ammonia vapor compression				ammonia	ammonia	
	NIK and next generation absorption				W/LiBr	W/LiBr	
Chiller Life:	100 RT--reciprocating, screw, scroll (all refrigerants)					23 years	
	300 RT--centrifugal and screw (all refrigerants)					30 years	
	1000 RT--centrifugal (all refrigerants)					30 years	
	3000 RT--centrifugal (all refrigerants)					30 years	
DIRECT CO_2 Emissions Analysis:	Charge x Loss Rate x Life x GWP = CO_2 emissions (kg/RT) x (% / yr) x (yr) x (kg CO_2/kg) = kg CO_2 /RT						
Global Warming Potential (GWP) Values (kg CO_2/kg):		ammonia	W/LiBr	R-11	R-12	R-22	R-123	R-134a
	500 yr	0	0	1500	4500	510	29	420

Refrigerant Charge

Refrigerant charge can vary by chiller size, refrigerant, vintage, compressor type, manufacturer, heat exchanger selections and a host of other variables. The refrigerant charge data available at the time of this study are summarized in Appendix E (Table E.1). The reported charge data varied widely and reflected chiller designs prior to CFC regulation. As a result, a new survey was performed (Calm, June 1991) that was consistent with the 1995 time-frame chillers used for the performance analysis (Calm, April 1991; Appendix F). The survey results are presented in Appendix E (Table E.2) and the assumptions used in this study are presented in Table 6.2.

Table 6.3a. Analysis assumptions for estimating the INDIRECT contribution to TEWI as a result of operating electric-driven vapor compression chillers with various refrigerants over their lifetime

Equipment Categories:	same as Table 6.2										
Refrigerant Options:	same as Table 6.2										
Chiller Life:	same as Table 6.2										
Chiller Annual Load Factor:	0.20 (Note: defined as annual load divided by (8760 x RT))										
Chiller Performance:	$(kW_e/RT)_c$ values approximating seasonal performance (See Table 6.4)										
Heat Rejection Performance: (water-cooled chillers only)	$\left[\text{Cooling Load} + \text{Chiller Heat Rejection}\right] \times \text{Tower/Pump Factor} = \text{Tower/Pump Power}$										
	$\left[3.516 + (kW_e/RT)_c\right] \times .0319 = \text{Tower/Pump Power}$										
	$kW_t/RT \times kW_e/kW_t = (kW_e/RT)_{tp}$										
INDIRECT CO_2 Emissions Analysis:	8760	x	Load Factor	x	Performance	x	Life	x	Regional Electric Conversion	=	CO_2 emissions
	(hr/yr)	x	(-)	x	$[(kW_e/RT)_c + (kW_e/RT)_{tp}]$	x	(yr)	x	(kg CO_2 /kWh_e)	=	kg CO_2 /RT
Conversion Factors:	Regional average electric conversion:						North America 0.672 kg CO_2/kWh_e Europe 0.513 kg CO_2/kWh_e Japan 0.581 kg CO_2/kWh_e				

Table 6.3b. Analysis assumptions for estimating the INDIRECT contribution to TEWI as a result of operating direct gas-fired absorption chillers over their lifetime

Chiller Annual Load Factor:	0.05 (Note: defined as annual load divided by (8760 x RT))												
Chiller Gas Performance:	gas COP values approximating seasonal performance (See Table 6.4)												
Gas INDIRECT CO_2 Emissions Analysis:	8760	x	Load Factor	x	3.516	x	1/gCOP	x	Life	x	Gas to CO_2 Conversion	=	CO_2 emissions
	(hr/yr)	x	(-)	x	$\left(\frac{kWh_t}{hr\text{-}RT}\right)$	x	(-)	x	(yr)	x	$\left(\frac{kg\ CO_2}{kWh_t}\right)$	=	kg CO_2 /RT
Chiller Electric Performance:	$(kWe/RT)_c$ values (solution pump, etc.) approximating seasonal performance (See Table 6.4)												
Heat Rejection Performance: (water-cooled chillers only)	$\left[\text{Cooling Load} + \text{Chiller Gas Heat Rejection} + \text{Chiller Electric Heat Rejection}\right] \times \text{Tower/Pump Factor} = \text{Tower/Pump Power}$												
	$\left[3.516 + 0.9\left(\frac{3.516}{gCOP}\right) + \left(\frac{kW_e}{RT}\right)_c\right] \times .0319 = \text{Tower/Pump Power}$												
	$kW_t/RT \times kW_e/kW_t = (kW_e/RT)_{tp}$												
Electric INDIRECT CO_2 Emissions Analysis:	8760	x	Load Factor	x	Performance	x	Life	x	Regional Electricity Conversion	=	CO_2 emissions		
	(hr/yr)	x	(-)	x	$[(kW_e/RT)_c + (kW_e/RT)_{tp}]$	x	(yr)	x	(kg CO_2 /kWh_e)	=	kg CO_2 /RT		
Conversion Factors:	Regional average electric conversion:		North America 0.672 kg CO_2/kWh_e Europe 0.513 kg CO_2/kWh_e Japan 0.581 kg CO_2/kWh_e				Electric conversions by fuel:		Coal 1.134 kg CO_2 / kWh_e Oil 0.957 kg CO_2 / kWh_e Gas 0.580 kg CO_2 / kWh_e				
	Gas conversion: 0.184 kg CO_2 / kWh_t (53.9 kg CO_2 / 10_6 Btu)												

For a given chiller category and refrigerant, charge increases with relative cost and efficiency (Table E.2). In this study, annual refrigerant loss is estimated simplistically as charge times loss rate. Using the same loss rates for all relative costs would unfairly penalize the more costly (and efficient) systems having larger charges. In reality, refrigerant loss is not directly related to charge. Chillers at all relative costs have the same capacity, purge unit, fittings, etc., and would be expected to lose the same amount of refrigerant per year regardless of charge. Consequently, for the purpose of estimating annual refrigerant loss, the base cost charge data (Table E.2, Table 6.2) were used for all cost levels.

Refrigerant Loss Rate

Refrigerant loss rate (percent of charge lost per year with full recovery of charge upon chiller retirement) can vary by the quality of field installation and service received as well as by chiller size, vintage, compressor type, refrigerant, manufacturer, etc. The refrigerant loss rate data available at the time of this study are summarized in Appendix E (Table E.3). The reported loss rate data varied so widely that parameterization was necessary as indicated in Table 6.2. Two independent sources provided evidence of higher loss rates for chillers using refrigerants with sub-atmospheric evaporator pressures such as CFC-11 that require purge units (Hummel, 1991; Miyasaka, 1989). The parameterization of loss rate enables comparisons of refrigerants at the same loss rates or at different rates.

The available loss rate data are historical and not indicative of the new industry emphasis on refrigerant recovery and recycling or reclamation and on the improved designs for new chillers. World-wide legislation and the predicted future CFC shortages and high prices have caused the development of acceptable practices to reduce loss rates (ASHRAE Guideline 3-1990) and the commercialization of hardware, tools, and training to implement the practices (McCain, 1991; Powell 1991; Gilkey, 1991). The desire to avoid premature equipment retirements provides strong motivation for the widespread implementation of improved practices and the newly available high-efficiency purge units, off-cycle pressurization systems, recover/recycle/reclaim systems, and leak-detection devices make it possible.

A loss rate range of 0% to 16% of charge per year was selected for this study. Equipment manufacturers project that loss rate will fall from the current level of approximately 8% to around 4% in the near-term and may eventually approach 0% per year (Calm, May 9, 1991). Sixteen percent (16%) per year represents the high end of previous loss rate assumptions if it is assumed that refrigerant is reclaimed upon chiller retirement (UNEP, 1989; Carrier, 1990; Miyasaka, 1989). In the USA, the 1990 Clean Air Act Amendments prohibit refrigerant venting as of July 1992, and other countries have enacted similar or more stringent requirements. In chiller applications, the size and value of the charge, the technical skill levels, the available tools, and the legislative mandates all suggest that full recovery of charge upon chiller retirement is a reasonable assumption.

Refrigerant Options

The refrigerant options for each chiller category are listed in Table 6.2 and include the CFC refrigerants that have dominated the applications in the past (see Appendix E, Table E.9) and the near-term HCFC/HFC alternatives. Also included are the ammonia vapor compression next generation alternative and the direct gas-fired absorption lithium-bromide-water (w/LiBr) NIK alternative (double-effect) and next generation alternative (advanced cycles).

Chiller Life

The chiller life assumption impacts the estimate of DIRECT equivalent CO_2 emissions because refrigerant loss is expressed as the percent of charge lost per year. Chiller life also impacts

INDIRECT CO_2 emissions resulting from the fossil energy consumption required to generate the electricity to operate the chiller over its life or to directly fire the chiller in the case of absorption. The chiller life assumption will not influence the relative importance of the terms but only the absolute values as long as the full refrigerant charge is recovered when the equipment is retired from service. The calculations presented in this section assume full refrigerant recovery and the assumptions on chiller lifetime are included only to maintain consistency with other sections of this report where product lifetime affects both absolute and relative values. Reported chiller life data available at the time of this study are summarized in Appendix E (Table E.4). Evidence exists that chiller life is really longer than previously accepted handbook values (ASHRAE, 1987). In this study 23 and 30 year lives were assumed for 100 RT (positive displacement) and 300/1000/3000 RT (centrifugal, screw, and absorption) chillers, respectively.

DIRECT (Refrigerant Loss) Equivalent CO_2 Emissions Estimate

Table 6.2 concludes by defining the calculation performed to estimate DIRECT CO_2 emissions. The calculation is a straight multiplication of refrigerant charge, annual refrigerant loss rate, chiller life, and refrigerant global warming potential or GWP (IPCC, 1990). Refrigerant charge varies with chiller category and refrigerant. Percent of refrigerant charge lost per year is parametrically varied from 0 to 16% in all chiller categories. Chiller life can vary between chiller categories but is the same for all options within a category. The calculations can be performed for refrigerant GWPs integrated over various time horizons, but the analysis here is based on 500 years.

Table 6.3 summarizes analysis assumptions for the INDIRECT CO_2 emission calculations. Several assumptions are required in addition to those for the DIRECT calculation. Also, the calculations are somewhat different for electric-driven vapor compression chillers (Table 6.3a) versus direct gas-fired absorption chillers (Table 6.3b).

Chiller Annual Load Factor

Chiller annual load factor is defined as the annual refrigeration load met by the chiller divided by the hours in a year (8760) times the chiller capacity. Load factor has a large impact on estimated INDIRECT CO_2 emissions. Reported load factor data available at the time of this study are summarized in Appendix E (Table E.7). The desired value would be an average across a region's chiller stock. A past study assumed a load factor of 0.3 for the world's chiller stock (Fischer, 1989). A detailed simulation study addressing 9 non-residential building types and 5 U.S. climates found a .024 to .474 load factor range (Patel, 1989). These results were used to derive a weighted average for the 1986 U.S. non-residential building stock of 0.17 (EIA, 1988). An estimated load factor range of 0.2-0.25 was derived from a sample of 35 chillers (Hummel, 1991). A compromise value of 0.20 was selected for this study and used for North America, Japan, and Europe.

The assumed load factor roughly corresponds to assumptions used in the U.S. centrifugal/screw chiller certification rating procedure to estimate the integrated part-load value (IPLV) or seasonal performance factor (ARI 550-90). The IPLV calculation assumes that when the chiller is active it spends 10% of the time at 75-100% capacity, 50% of the time at 50-75% capacity, 30% of the time at 25-50% capacity, and 10% of the time at 0-25% capacity. This corresponds to an active-period load factor of about 52.5% (.875 x .1 + .625 x .5 + .375 x .3 + .125 x .1 = .525). In applications where the active or occupied period is 11 hours per day and 6 days per week that corresponds to an annual load factor of 0.206.

Chiller Performance

Chiller operating efficiency is estimated with seasonal performance factors. For electric-driven chillers a seasonal value of kW_e /RT is used. For gas-fired absorption chillers seasonal values of both kW_e/RT (for solution pumps, controls, etc.) and gas COP are used. Gas COP is defined as the delivered cooling effect divided by the heat content (HHV) of the gas consumed. The chiller performance factors used in this study are described in greater detail in the next section and are presented in Table 6.4. It should be noted that the data in Table 6.4 are the results of an industry-wide survey and that some manufacturers have optimized designs of chillers using alternative fluids that match or surpass the efficiencies of the CFC chillers they are replacing.

Table 6.4. New chiller seasonal performance factors for alternative refrigerants at various cost levels (kW_e /RT or gas COP*)

Chiller Category	Refrigerant	Chiller relative cost levels[a]:				
		1.0 = Base	A	B	C	D
100 RT air-cooled	HCFC-22	1.00	0.93	0.83	--	--
	HFC-134a	1.04	1.00	0.93	--	--
300 RT water-cooled	CFC-11	0.67	0.64	0.53	--	0.50‡
	CFC-12	0.67	0.66	0.59	--	--
	HCFC-22	0.68	0.65	0.54	--	0.50‡
	HCFC-123	0.69	0.67	0.58	--	--
	HFC-134a	0.68	0.66	0.58	--	--
	W/LiBr (NIK)	--	--	--	--	0.95*†
	W/LiBr (NIK)	--	--	--	--	0.035
1000 RT water-cooled	CFC-11	0.66	0.59	0.51	< 0.50‡	< 0.44‡
	CFC-12	0.65	0.62	0.57	--	--
	HCFC-22	0.60	0.55	--	< 0.44‡	< 0.39‡
	HCFC-123	†	†	0.56	--	--
	HFC-134a	0.64	0.61	0.56	--	--
	W/LiBr (NIK)	0.65	0.61	--	1.00*†	1.25*†
	W/LiBr (NIK)	--	--	--	0.023	0.023
3000 RT water-cooled	CFC-12	0.74	0.66	--	--	--
	HCFC-22	†	†	--	--	--
	HFC-134a	0.66	0.60	--	--	--
		0.73	†			
		†	0.66			
			†			

Notes:
*-denotes gas COP, all other values are kW_e /RT.
†-denotes the midpoint of a range offered in the source (Calm, May 28, 1991).
‡-denotes an understated asymptote of the COPs (Hickman, 1991).
[a]-Relative cost refers to costs of fabrication normalized to those of a selected (representative) reference system (Calm, April 1991). A, B, C, and D are the same for refrigerant options within a chiller category but differ by chiller category. As a guide, Base < A < B < C < D, but increments between cost levels are not necessarily the same.

INDIRECT (Energy Use) CO_2 Emissions Estimate for Electric-Driven Chillers

Table 6.3a concludes by defining the calculations performed to estimate INDIRECT CO_2 emissions for electric-driven chillers. The calculation is a straight multiplication of hours per year, annual load factor, performance factor, life, and the appropriate regional factor to estimate CO_2 emissions from electricity consumption. The performance factor includes terms to account for the chiller (from Table 6.4) and, if water-cooled, for condenser pumps and cooling tower fans and spray pumps. The latter term is estimated from the cooling tower heat rejection rate and equals approximately 20% of the chiller term for 300 RT chillers using CFC-11 (Redden, 1987; EPRI, 1990).

INDIRECT (Energy Use) CO_2 Emissions Estimate for Direct Gas-Fired Absorption Chillers

Table 6.3b concludes by defining the calculations performed to estimate INDIRECT CO_2 emissions for direct gas-fired absorption chillers. Emissions are estimated separately for gas and electric consumption and summed to obtain the total. Gas consumption to operate the chiller is estimated using the seasonal gas COP from Table 6.4. Electric consumption derives from the Table 6.4 performance factor accounting for chiller auxiliaries (solution pump, controls, etc.) and from an estimate of power to operate condenser pumps and cooling tower fans and spray pumps that is consistent with the approach for electric-driven chillers. It is assumed that 90% of the heat content of the gas enters the absorption machine generator and is ultimately rejected through the cooling tower.

6.3 CHILLER PERFORMANCE ASSUMPTIONS

Common-basis seasonal performance factors were needed for each refrigerant option in a chiller category. Care was taken to avoid invalid comparisons. The issues involved in arriving at a common basis global warming analysis to support policy toward alternative refrigerants are reviewed below.
Before the ozone issue arose 100 RT air-cooled chiller designs had been optimized for HCFC-22 and water-cooled centrifugal designs had been optimized for CFC-11 in the small-to-medium sizes, CFC-12 in the medium-to-large sizes, and HCFC-22 in the large sizes. After ozone, CFC-11 and 12 chillers were redesigned to be compatible with the original refrigerants and with the accepted near-term replacements of HCFC-123 and HFC-134a respectively. This flexibility was required so that chillers could go into service with available refrigerants, yet be converted to HCFC-123 and HFC-134a inexpensively when those refrigerants become available in commercial quantities. These chillers had to function with two refrigerants and could not be optimized for both.

Likewise the designs that have been developed to field-convert CFC-11 and 12 chillers to HCFC-123 and HFC-134a may not result in optimized operation with the new refrigerants. These designs are intended to provide an economic alternative to premature chiller retirement when the cost to service existing chillers with CFC-11 and 12 becomes prohibitively high. The objective in field-conversions is to provide a chiller system that can be operated reliably with the new refrigerant for the balance of the chiller service life while meeting capacity and other application requirements.

Reported performance and capacity impacts of converting from CFC-11 to HCFC-123 and from CFC-12 to HFC-134a that were available at the time of this study are summarized in Appendix E (Tables E.5 and E.6). Reported performance and capacity impacts varied widely and some of the information sources did not specify the type of conversion being addressed (e.g., field-converting

existing chillers originally designed for CFC-11 or 12 to HCFC-123 or HFC-134a, or field-converting recently installed chillers originally designed to be compatible with both refrigerants and to meet application requirements with both refrigerants).

This wide variation was to be expected since both types of conversions are application-specific. If the existing chiller was originally designed for CFCs the change in efficiency and capacity when converted depends on factors such as existing chiller vintage and compressor selection (open or hermetic configuration, single or multi-stage, etc.) and on whether various component changes are included in the conversion (new impeller, new gear set, etc.). The major O.E.M.s have the technology to evaluate the application and recommend the best conversion package for the situation, but the resulting performance and capacity impacts will vary from application to application. If the existing chiller is a recently installed dual-compatibility model it was initially selected to meet the application requirements with either refrigerant, but again performance and capacity impacts when the conversion is actually made will vary from application to application.

To avoid these application dependencies it was decided to base the performance analysis on new chiller designs optimized for each alternative refrigerant and having equal capacities and equipment manufacturing costs. Since the designs for these mid-1990 chillers are not public knowledge, a request was made to an industry trade association (Air-Conditioning & Refrigeration Institute, ARI) to provide the necessary performance factors while protecting proprietary information and avoiding violations of anti-trust provisions (Calm, April 1991). Data from Japan (Taguchi, March 8, 1991; Taguchi, March 25, 1991) and Europe (Legin, 1991) were used to independently corroborate the North American performance data supplied by ARI to the extent possible.

Electric-Driven Chillers with CFC/HCFC/HFC Refrigerants

The performance factors used in this study for electric-driven chillers with fluorocarbon refrigerants are summarized in Table 6.4. Within each chiller category performance data were made available for chillers optimized for each refrigerant at the same capacity and at three different cost levels (Calm, May 28, 1991). The cost levels are not necessarily the same across chiller categories therefore only performance factors within a chiller category are directly comparable. Also the costs were not disclosed and the cost increments from Base to Level A and from Level A to Level B are not necessarily the same. It is known however that the Level B cost exceeds Level A, which exceeds the Base.

The performance factors reported in Table 6.4 are seasonal performance factors derived from IPLVs and COPs defined in the appropriate certification testing standard for reciprocating chillers (ARI 590-86) or screw and centrifugal chillers (ARI 550-90). These factors are consistent with the other analysis assumptions to the extent possible and enable the estimation of annual energy requirements to operate the various chillers as defined in Table 6.3a. North American, Japanese, and European certification testing standards for chillers are similar (Phillips, 1991) and it is believed that use of the performance factors in Table 6.4 is justified in all locations.

Use of the Table 6.4 performance factors is most appropriate for single chiller applications as this most closely relates to the IPLV calculations in the standards. Multi-chiller plants may impose significantly different duty on individual chillers, depending on whether they are connected in parallel or series-connected, whether primary and backup chillers are periodically reversed, etc.

The use of the same performance factors in North America, Japan, and Europe is reasonable because chiller operating conditions do not vary widely. Most machines are installed in chilled water applications that deliver water at about 6.7°C (44°F). In water-cooled applications, the condenser water spends most of its time between 15.5–29.4°C (60-85°F) so the variation in overall temperature

lift across the chiller is modest and about the same world-wide. Lift variation in air-cooled machines would be slightly more location-dependent but the weighting of operating conditions used in the standards to estimate IPLV is fairly representative for most applications and weather.

The use of equal cost is a necessary condition to obtain common-basis performance factors. Manufacturing cost was used because it could be directly related to the optimized chiller designs for each refrigerant. Ideally equal manufacturing cost would imply equal installed cost to the building owner, but this is not the case for several reasons. First of all, possible end-user costs are bounded at the low end by manufacturing cost and at the high end by value in the application, and market prices fall somewhere in-between. As a result, premium products that provide high application value command premium prices (Calm, April 1991). Second, the application of chillers with some refrigerants may involve additional costs to meet various codes and standards.

As an example of the latter case, HCFC-123 may have different application rules than the other new refrigerants considered here when the appropriate standards are updated (ANSI/ASHRAE 34-89; ANSI/ASHRAE 15-89) because its toxicity threshold limit value (TLV), when established, may be less than 400 ppm. Although the application rules are not yet final, HCFC-123 may require a refrigerant detector and alarm in the machinery room rather than an oxygen sensor and alarm. HCFC-123 may also require machinery room mechanical ventilation, but this requirement is also being recommended for all other refrigerants. Current rules allow natural ventilation for some other refrigerants under some circumstances, but effectiveness is apparently uncertain given that the commonly used refrigerants are all heavier than air and most machinery rooms are located in basements. (Burgett, 1991; Smithart, 1991).

At this time, it is believed that equal manufacturing cost is the most appropriate common-basis for performance factors and the analysis of global warming. After application rules are finalized for the various refrigerants, it may be appropriate to consider adjustments so that end-user cost is the common-basis for the global warming analysis.

Direct Gas-Fired Double-Effect Absorption Chillers as a Not-in-Kind Alternative

Direct gas-fired double-effect absorption technology based on water and lithium bromide (w/LiBr) as the fluid pair accounts for approximately 33 percent of the installed chiller capacity in Japan (Taguchi, March 8, 1991). An analysis was performed to determine if this technology is a viable not-in-kind alternative to HCFC/HFC vapor compression technology in North America.

The performance factors for direct-fired double-effect absorption chillers are listed in Table 6.4 for the 300 RT and 1000 RT water-cooled categories where they are available. This technology has significantly higher manufacturing costs, therefore performance is reported at cost levels C and D along with performance for CFC-11 and HCFC-22 vapor compression machines. The electric chiller performance stated for cost levels C and D are lower bounds that reflect extrapolations well beyond both the source data and conventional designs. Moreover, the extrapolated lower bounds were deliberately understated in some cases to avoid disclosure of the asymptotic limits (Calm, April 1991). As such, the direct comparison of double-effect absorption and vapor compression machines at equal chiller manufacturing costs may slightly favor absorption. Centrifugal chillers providing the base load should not be compared directly with absorption chillers used only for peak shaving because of the significant differences in the load factors. This kind of comparison is handled rigorously by Occhionero and Hughes (1991).

The manufacturing cost advantage of conventional chillers over double-effect absorption may be partly related to volume, but absorption machines are fundamentally more expensive to build because of their greater heat exchange area (DeVault, June 1991). However, absorption chillers have greater

value in use because of their ability to lower electric utility peak demand charges assessed to building owners, and therefore are able to command higher prices. A full analysis of end user cost/performance is beyond the scope of this study, however, industry experience indicates that direct-fired double-effect absorption chillers supplement electric-driven centrifugals by providing a means of electric load peak-shaving in multi-chiller plants. In those applications, the centrifugals are typically base-loaded (Schmitt, 1991). Thermal storage (ice or brine) is an alternative means of all-electric peak shaving that is not considered here.

Electric-Driven Ammonia Vapor Compression as a Next Generation Technology Alternative

Ammonia has been suggested as a next generation technology alternative to fluorocarbon refrigerants in chiller systems (this entire section borrows heavily from Stoecker, 1989; other references are cited specifically). Ammonia is a high-pressure refrigerant that would logically compete primarily with HCFC-22 in water-cooled screw chillers below about 1200 RT in capacity. The technical issues surrounding the application of ammonia are briefly reviewed and performance factors for a preliminary analysis offered.

The primary advantages of ammonia versus HCFC-22 in chiller applications are as follows:

- zero ozone depletion potential (ODP),
- zero global warming potential (GWP),
- lower cost of refrigerant,
- better cycle efficiency,
- higher refrigerant-side heat transfer coefficients,
- self-alarming leak detection, and
- better tolerance of water and air contamination.

The principal disadvantages of ammonia are as follows:

- toxic,
- moderately flammable,
- requires a different approach to handling oil,
- incompatible with copper and copper-bearing alloys,
- compatible heat exchanger tubes have poorer thermal conductivity than tubes that can be used with HCFCs and HFCs, and
- relatively high compressor discharge temperatures at typical chiller water evaporator temperatures.

Toxicity is the major disadvantage of ammonia with moderate flammability in the range of 15-28 percent by volume in air the second most important. These characteristics place constraints on the use of ammonia in chiller systems in the form of codes and standards (for example in North America–ANSI/ASHRAE Std.34-89, ANSI/ASHRAE Std. 15-89, BOCA, ICBO). The refrigerant sections of these codes and standards are under revision, but it is anticipated that application rules such as the following will continue:

- no use in direct systems with the possible exception of configurations with water jackets between ammonia evaporator tubes and conditioned air that are vented to the atmosphere,
- maximum charge limitations in indirect systems (in the past 227-454 kg (500-1000 lb) depending on occupancy),
- machine room mechanical ventilation and isolation from occupied spaces,
- automatic ammonia detection and alarm, and
- provision for service venting to atmosphere or into a vessel of water.

The last three disadvantages are relatively minor but influence the ammonia-based equipment configurations most likely to be successful in the chiller market. Oil recovery and return to the compressor is a necessity of all vapor compression systems regardless of refrigerant. In ammonia systems, since oil and ammonia are virtually immiscible, oil must be automatically pumped back to the compressor from an oil collector located in the evaporator. Although ammonia cannot be used with copper, it is compatible with carbon steel and aluminum, and systems can be built from these materials so long as open drives are used to isolate the copper-based electrical components.

High compressor discharge temperatures in the chilled water application can be accommodated with specific compressor or system design features that are also influenced by the application rules resulting from toxicity and flammability. As a general rule, replacement technologies are most successful when they can be configured as closely as possible to the systems they are replacing. The level of machine room sophistication and isolation required for ammonia most closely approximates current practice in large water-cooled chiller applications. Therefore, ammonia is more likely to be successful in relatively large water-cooled applications. However, if application rules continue to limit total ammonia charge at current levels, very large applications may be excluded. Consequently, the 300 RT and 1000 RT water-cooled categories were chosen for the analysis.

As a high-pressure refrigerant competing with HCFC-22 in the 300 RT and 1000 RT water-cooled chiller categories, the logical ammonia-based configuration would be the water-cooled open-drive screw machine. In ammonia systems serving industrial plants, evaporative air-cooled condensers are common because they maintain lower condenser temperatures that help offset the high discharge temperature characteristic of ammonia. But, evaporative condensers have shorter service lives, require extra maintenance, and are not common in chiller applications. In screw compressors, oil is used for sealing the space between the rotors, and this oil absorbs some of the heat of compression to moderate discharge temperature and make the combination of water-cooled condenser and cooling tower practical.

Based on the characteristics of ammonia and HCFC-22, it is expected that ammonia systems would have a performance advantage of about three percent due to better cycle efficiency plus perhaps another three percent due to better heat transfer coefficients, for a total of six percent at the shaft. In addition, open drives are generally regarded as more efficient than hermetics (of course the HCFC-22 machine could be open drive also). The oil recovery pump would introduce an additional auxiliary necessary for the ammonia system. Based on these considerations, it was assumed that ammonia would have a five percent performance improvement over HCFC-22. This performance improvement does not account for differences in heat transfer that could force evaporator and condenser temperatures further apart for ammonia compression than they are for HCFC-22, increasing compressor work.

It is not clear how the systems would compare on cost. In refrigerated warehouses, where the application rules are less stringent, ammonia systems have both better performance and lower installed cost (ASHRAE, 1990). It was assumed here that ammonia and HCFC-22 could be compared at the same relative cost for equipment fabrication. More stringent application rules may make ammonia chiller systems more expensive on an installed cost basis. Also, recent trends in product liability and tort law, and resulting insurance costs, have so far discouraged major manufacturers from pursuing the ammonia option.

Advanced Absorption Technology as a Next Generation Alternative

In recent years the program of the U.S. Department of Energy has been responsible for the invention of several new multi-effect absorption cycles suitable for application in chillers (DeVault, 1990). One of these cycles has been licensed to a major North American HVAC equipment manufacturer, and

a program to reduce it to practice is underway (GRI, 1990). If developments are successful, an absorption chiller with a seasonal gas COP of about 1.5, the same electric auxiliaries (solution pump, controls, etc.), and the same manufacturing cost may be available as a next generation alternative. These assumptions are used to evaluate this option. The advanced absorption cycles are capable of higher performance factors and improvements up to approximately a seasonal gas COP of 1.8 would be possible in subsequent products if the initial development is successful.

6.4 RESULTS

TEWI results including DIRECT and INDIRECT component breakouts are tabulated in Appendix G for electric-driven chillers with fluorocarbon refrigerants assuming 500 year GWP and 20% load factor for all regions, cost levels, and refrigerant loss rates. A subset of these results (base cost, 8 and 4 percent loss rates) are presented graphically in Figs. 6.1 through 6.3 for North America, Europe and Japan, respectively.

The formats of Figs. 6.1 through 6.3 are identical. Results of all refrigerant options in each chiller category are presented at the left for the current refrigerant loss rate of 8 percent per year, and at the right for the future refrigerant loss rate of 4 percent. Within each loss rate grouping, a column exists for each refrigerant option in each chiller category. The refrigerant options are identified with labels across the bottom. Groups of columns in the same chiller category are identified with word boxes spanning the columns.

The heavily shaded area at the bottom of each column in Figs. 6.1 through 6.3 represents the INDIRECT (energy related) component of TEWI. The other area represents the DIRECT (refrigerant loss) component. The total column height represents TEWI. The INDIRECT, DIRECT, and TEWI values are expressed as millions of grams of equivalent CO_2 emissions per RT over the service life of the chiller (23 years for 100 RT air-cooled, 30 years for other chiller categories).

All columns within a chiller category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided because relative cost levels and performance factors are not consistent and service lives may differ. Figs. 6.1 through 6.3 indicate little relative difference in results due to region. Since over 60 percent of the existing world chiller capacity is in North America (Table 6.1), the remaining analysis uses that basis.

6.5 CONCLUSIONS

In chiller applications once HCFC/HFCs replace CFCs, the differences in chiller TEWI due to refrigerant are minor. This point is illustrated in Fig. 6.4 where the change in calculated TEWI relative to the historical base refrigerant is presented for selected refrigerant options. The reason is that differences in performance factors between refrigerant options are relatively small, making INDIRECT term differences relatively minor. Since the INDIRECT term is dominant in this 23-30 year service life application, the TEWI differences are also minor. This is particularly true for the future loss rate of 4%/yr, but also true for the current loss rate of 8%/yr.

One has to look very closely at the tabulated chiller results in Appendix G to discern any differences between HCFC-22, HCFC-123, and HFC-134a. The following generalizations are offered from this exercise. In the 3000 RT category, and in the 1000 RT category at loss rates below about 4%,

HCFC-22 is preferred. As refrigerant loss rates increase, HCFC-123 is preferred; on the other hand, as a low pressure refrigerant in a machine with a purge unit, HCFC-123 may experience greater loss rates in the field than HCFC-22 or HFC-134a. In the 300 RT category, at loss rates below about 4%, HFC-134a is as good an alternative as HCFC-22 or HCFC-123. Also, in the 100 RT air-cooled category, the currently used HCFC-22 maintains an advantage over HFC-134a.

The analysis of direct gas-fired w/LiBr double-effect absorption technology as a not-in-kind chiller alternative in North America is presented in Fig. 6.6. It is clear that TEWI provides no motivation to use this technology in base load applications in place of centrifugal chillers. However, in peaking duty, depending on the fuel for electric generation, TEWI of double-effect absorption is similar to centrifugals at very high efficiencies consistent with equal chiller manufacturing cost. In practice, double-effect absorption competes with lower efficiency and lower cost centrifugals because of its greater value in peaking duty resulting from lower peak demand charges.

6.6 NEXT GENERATION TECHNOLOGIES

The analysis of advanced absorption technology as a next generation alternative to centrifugal chillers in North America is presented in Fig. 6.6. In this case, absorption has equivalent or lower TEWI with coal or oil generation without modifying HCFC-22 centrifugal performance factors to their base cost values. Such a change would indicate that absorption may also be competitive from the global warming point of view in some base load applications, particularly those with modest load factors.

The analysis of ammonia as a next generation alternative to HCFC/HFC refrigerants in chiller applications in North America is presented in Fig. 6.7. The comparison is made at 4%/yr and 0%/yr refrigerant loss rates to recognize that the level of containment necessary for ammonia would also translate into low loss rates for the HCFC/HFCs. TEWI values for HCFC/HFCs and ammonia are similar, with ammonia values slightly lower due to the assumed efficiency advantage of 5% relative to HCFC-22.

Ammonia has been available to the chiller industry from the beginning, but business risk associated with toxicity and moderate flammability have made CFCs preferable in the past. The transition from CFCs to HCFC/HFCs provides an opportunity for ammonia because new refrigerants will need to be deployed in chillers. Industrial concerns will individually evaluate the risk/return tradeoffs of participating in the chiller industry with products based on the available refrigerants. Whether ammonia is among the refrigerants selected remains to be seen. A public policy mandate does not seem appropriate because ammonia systems are expected to be more expensive on an installed cost basis due to application rules. This extra investment could just as well be utilized for higher efficiency (and cost) HCFC-22 chillers. Table 6.4 indicates an efficiency improvement of 4.4 to 8.3% at cost level A versus base cost for 300 RT and 1000 RT HCFC-22 chillers.

For the INDIRECT-dominated chiller applications, once HCFC/HFCs replace CFCs, the primary avenue for further reduction in TEWI is through the introduction of higher efficiency (and cost) chillers. Current generation double-effect absorption chillers are approximately TEWI-neutral in peaking duty, but have strong negative TEWI impacts in the base load chiller mass market. Next generation absorption chillers may broaden opportunities for TEWI reduction if successfully developed. Ammonia-based chiller technology may have a role depending on risk/return relative to the HCFC/HFCs.

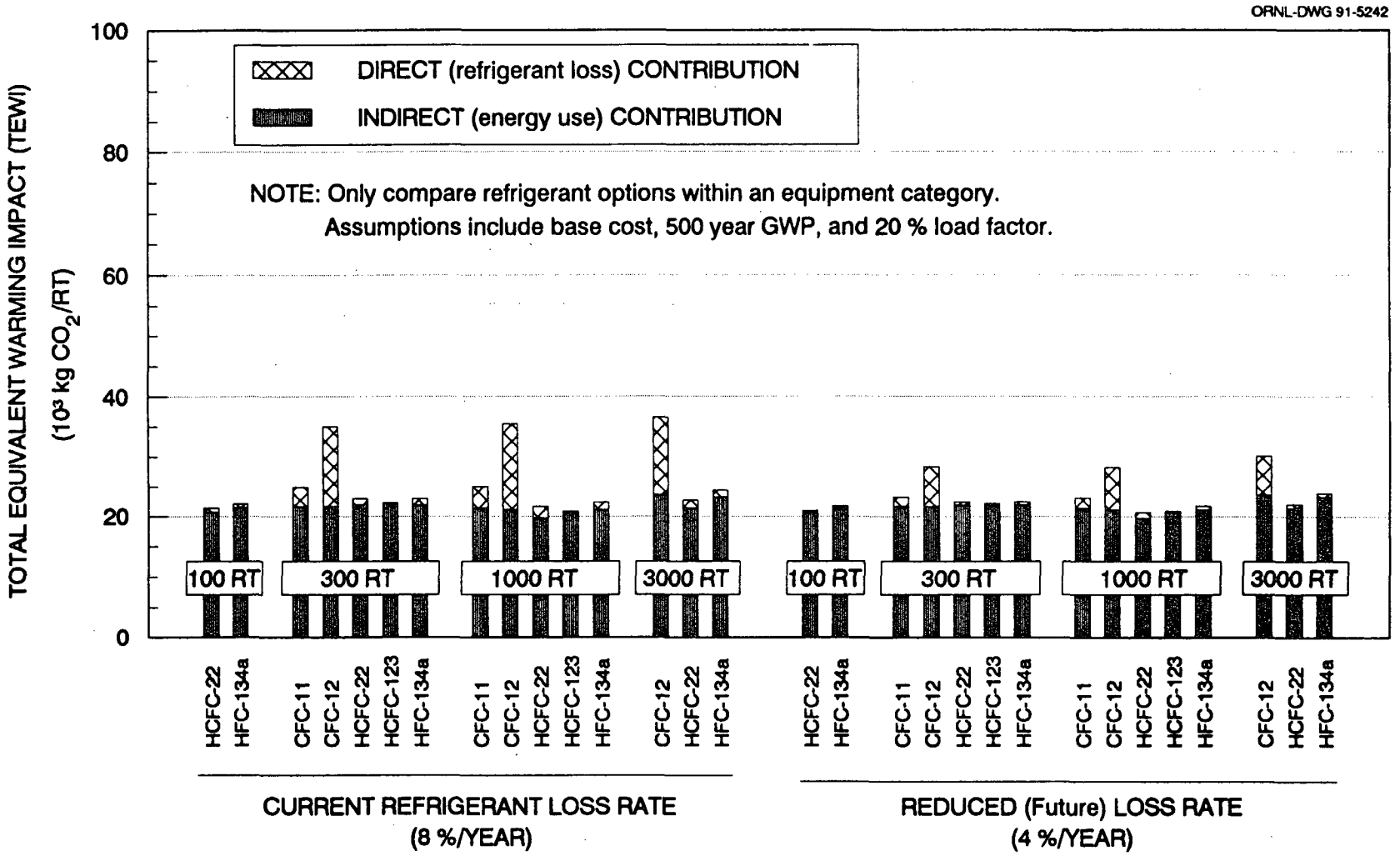

Fig. 6.1. DIRECT and INDIRECT equivalent lifetime CO_2 emissions of electric-driven chillers in Europe.

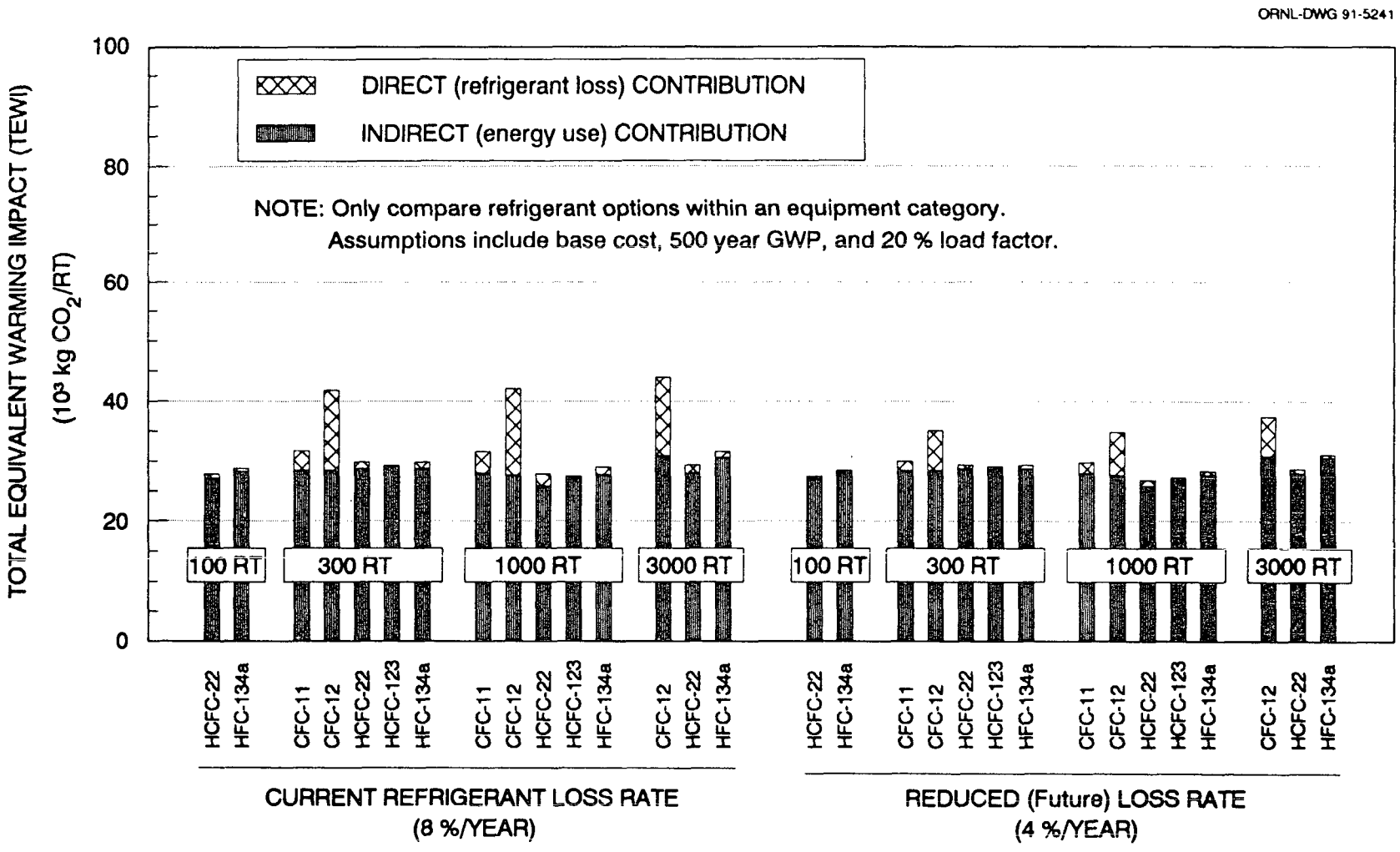

Fig. 6.2. DIRECT and INDIRECT equivalent CO_2 emissions of electric-driven chillers in North America.

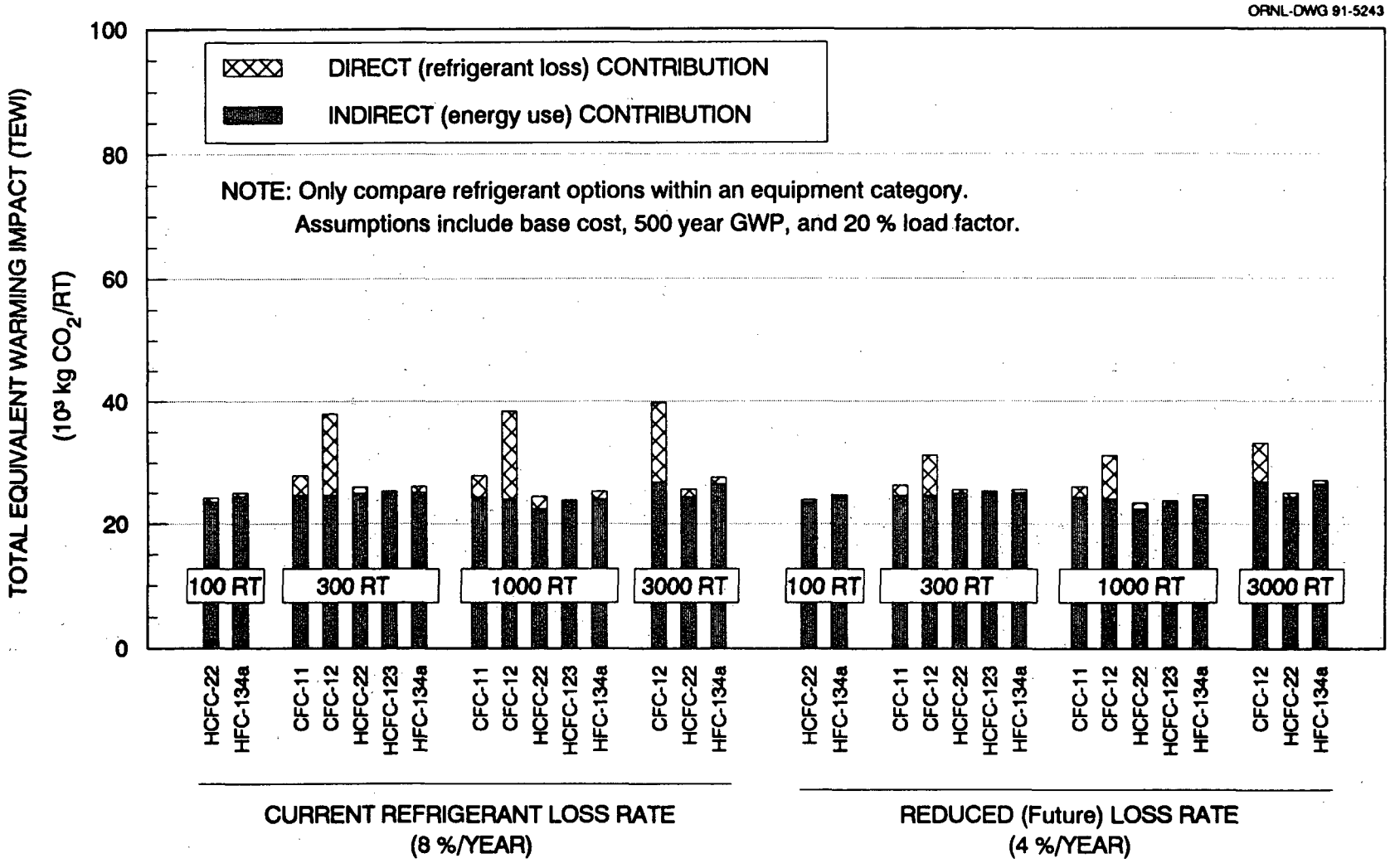

Fig. 6.3. DIRECT and INDIRECT equivalent lifetime CO_2 emissions of electric-driven chillers in Japan.

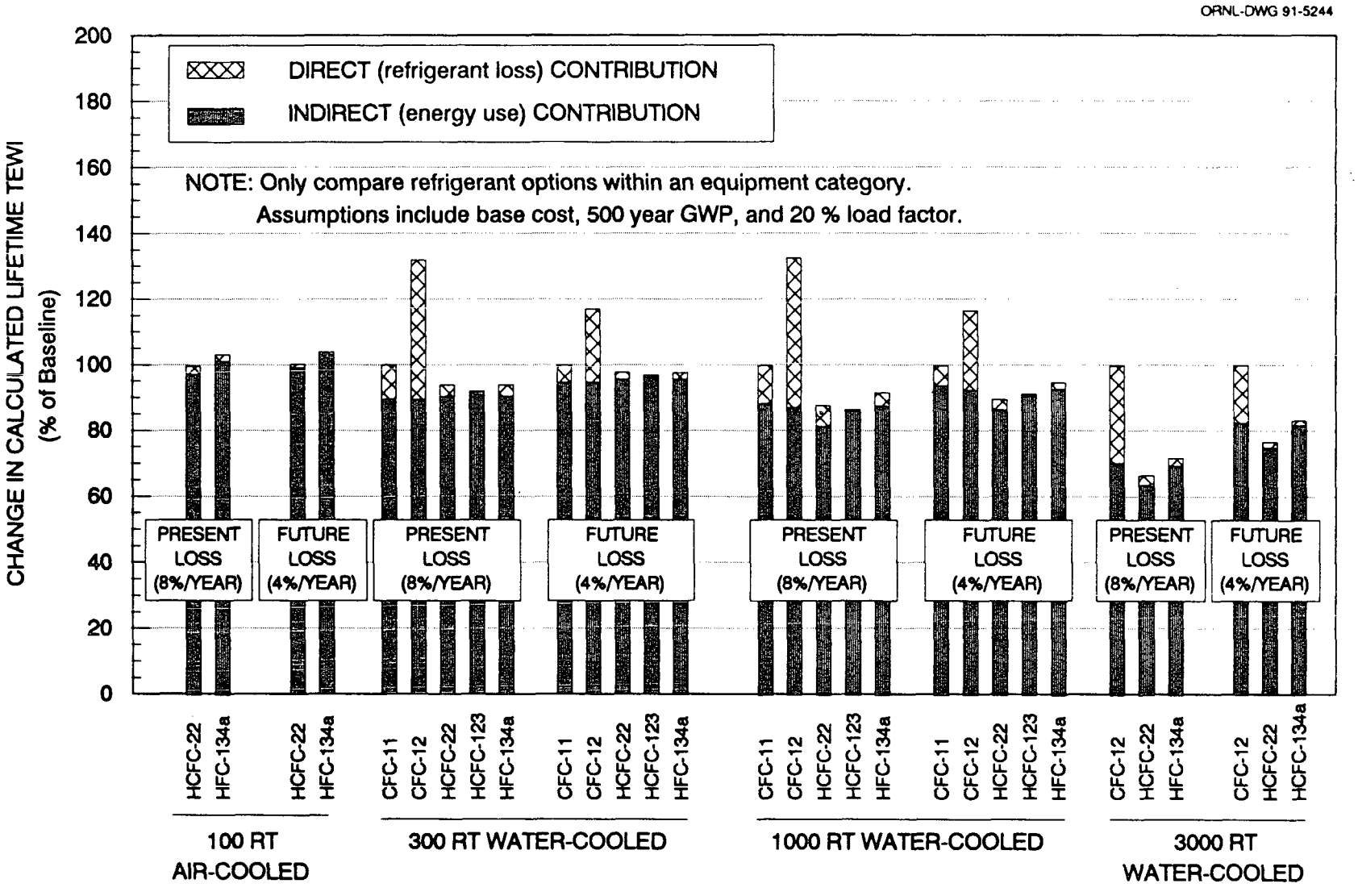

Fig. 6.4. Changes in net TEWI relative to baseline refrigerants for selected chiller cases in North America.

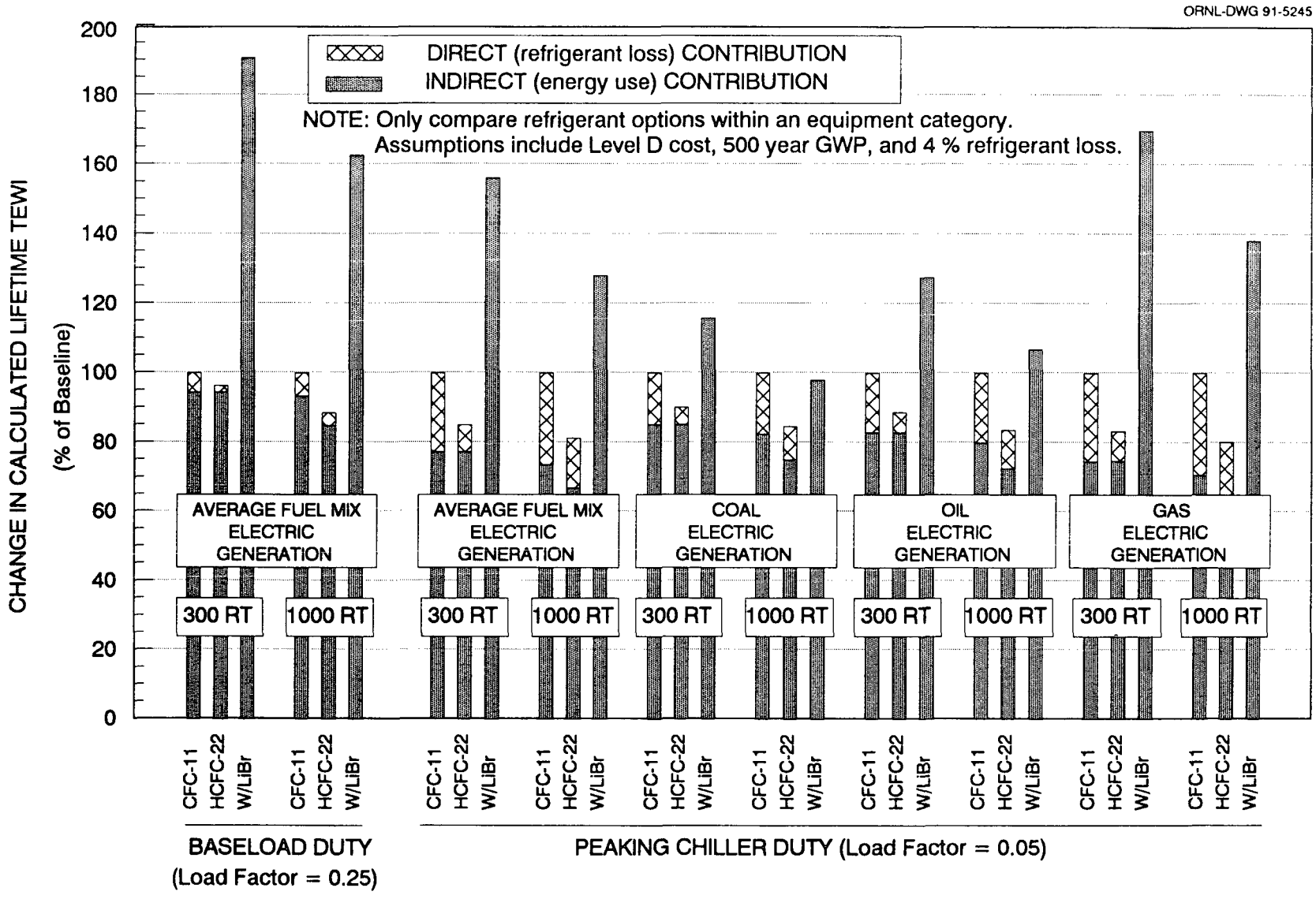

Fig. 6.5. Direct-fired double-effect absorption technology as a not-in-kind chiller alternative in North America.

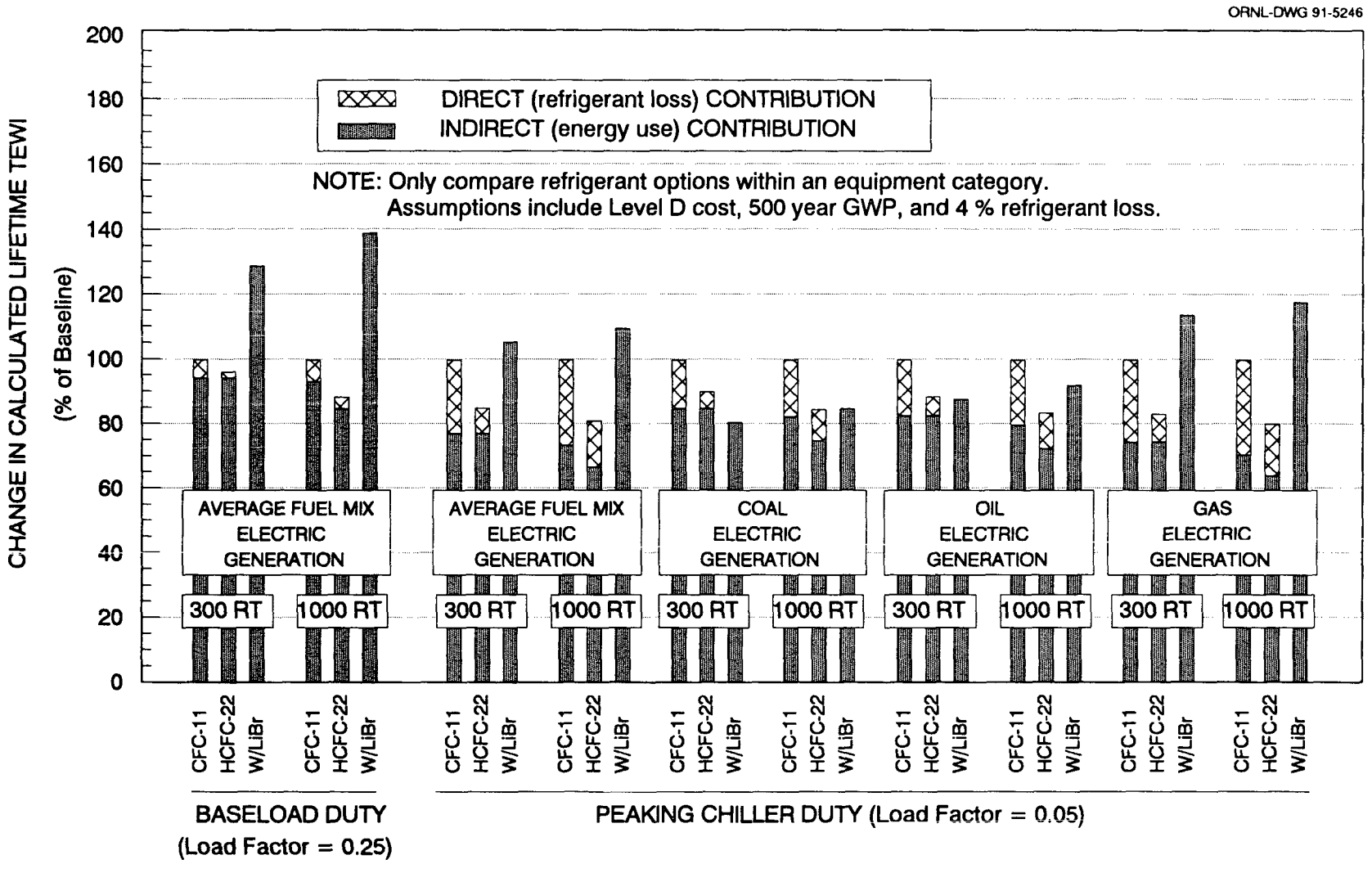

Fig. 6.6. Advanced absorption technology as a next-generation chiller alternative in North America.

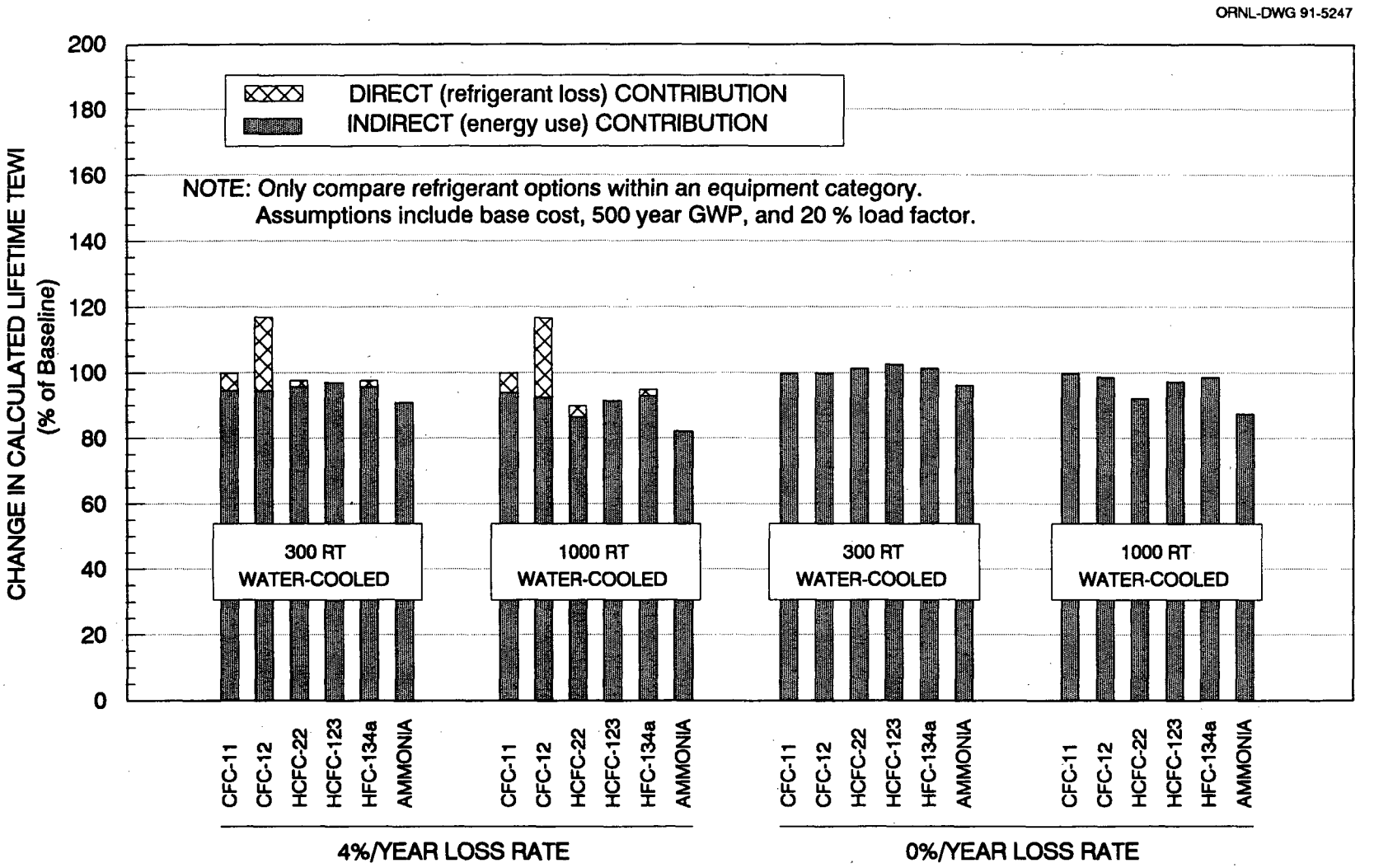

Fig. 6.7. Ammonia as a not-in-kind refrigerant alternative in North America.

7. RESIDENTIAL AND COMMERCIAL UNITARY HEATING AND COOLING EQUIPMENT

7.1 INTRODUCTION

Unitary equipment is broadly defined here to include all cooling devices that condition air via direct heat exchange with the evaporator rather than with the use of an intermediate chilled water loop (as with chillers). Some unitary devices (heat pumps) also provide heating. Fewer still provide heating but not cooling (heating-only heat pumps). Unitary equipment primarily serves residential and small-to-medium sized low-rise non-residential structures.

This broad definition of unitary equipment encompasses an extremely diverse set of configurations, including: room air conditioners (window units or portables), through-the-wall packaged terminal air conditioners (PTACs) or heat pumps (PTHPs), split-system air conditioners (ACs) and heat pumps (HPs) with unducted (and perhaps multiple) indoor units, split-system ACs and HPs with a single ducted indoor unit, ducted single-package AC and HP units (pad or roof-mounted), water-cooled indoor single-package units (water-loop HPs, floor-by-floor ACs, ground-source HPs), and many more. Most applications incorporate heating systems (gas, oil, electric resistance, propane, etc.) as the primary heating source with ACs or as a supplement with HPs. The primary or supplemental heating device may be incorporated into the unitary AC or HP package, or applied as a separate system.

Table 7.1 summarizes the estimated installed capacity of unitary equipment in North America, Japan and Europe. Approximately 763×10^3 kWt (217×10^3 RT) of unitary devices are in operation with a regional allocation of 71% in North America, 26% in Japan, and 3% in Europe (ECI, 1990, residential and commercial; Taguchi, March 25, 1991; Legin, 1991). This exceeds the installed chiller capacity of 195×10^3 kWt (55.6×10^3 RT) in these three highly developed regions of the world by almost a factor of four. Due to the relative costs and skill levels required to manufacture, install and maintain unitary devices versus chillers, it is believed that on a world-wide basis, unitary capacity exceeds that of chillers by more than a factor of four.

It is estimated that about 27% of the unitary devices in service are heat pumps that provide both heating and cooling (Table 7.1). The heat pumps are primarily in North America (about a 15% share in residential, ECI, 1990; and 13% in non-residential, Pietsch, 1989) and Japan (about a 53% share in residential and 74% in non-residential, Taguchi, March 25, 1991).

Unitary equipment uses HCFC-22 as the refrigerant almost exclusively. HCFC-22 has been viewed as part of the solution that will enable a rapid transition away from CFCs in the chiller and other applications, and finding an alternative to HCFC-22 in unitary equipment has not been a primary concern of industry to date. A transition away from HCFC-22 in existing unitary applications would be an enormous challenge.

The analysis of this section represents a first look at refrigerant alternatives to HCFC-22 in unitary equipment from the global warming point of view. A request to an industry trade association (Air-Conditioning & Refrigeration Institute, ARI) for performance data indicated that HFC-134a was the only refrigerant that has received sufficient attention as an alternative to HCFC-22 to enable a response in the required time frame for this study (Calm, April 1991). This section documents an analysis of the lifetime total equivalent warming impact (TEWI), including DIRECT (refrigerant loss) and INDIRECT (energy use) contributions, resulting from the replacement of HCFC-22 in unitary equipment with HFC-134a. One not-in-kind (NIK) alternative was also evaluated—direct gas-fired

Table 7.1. Installed capacity of unitary equipment

Region		Capacity ($x10^3$ kWt)	Capacity ($x10^3$ RT)
Residential air-conditioners (room, splits, 1-package, etc.)			
North America		323	92
Japan		63	18
Europe		11	3
Total		397	113
Residential heat pumps (splits, 1-package, etc.)			
North America		56	16
Japan		70	20
Europe		7	2
Total		134	38
Non-residential air-conditioners (splits, 1-pkg, room, PTAC, etc.)			
North America		144	41
Japan		18	5
Europe		--	--
Total		162	46
Non-residential heat pumps (splits, 1-pkg, PTHP, WLHP, etc.)			
North America		21	6
Japan		49	14
Europe		--	--
Total		70	20
Totals for all 3 regions			
Unitary AC	residential + nonresidential AC	559	159
Unitary HP	residential + nonresidential HP	204	58
All unitary	Unitary AC + Unitary HP	763	217
Chillers	chiller section, Table 7.1	195	55.6
Note: RT = refrigeration tons = 12000 Btu/h = 3.516 kWt			

absorption air conditioners as an alternative to electric-driven vapor compression technology. Possible next generation technologies are discussed but not evaluated.

The global warming analysis was limited to North America and Japan since Europe represents only about 3% of the operating unitary equipment in the three regions. Two widely-applied unitary equipment categories, split-system ACs and HPs (with single ducted indoor units), were selected to provide a representative evaluation. The analysis was simplified by selecting a Japanese location that would be expected to have similar equipment seasonal performance as the North American location

Table 7.2. Analysis assumptions for estimating the DIRECT contribution to TEWI as a result of operating unitary equipment with various refrigerants over the equipment lifetime

Equipment Categories:	2.5 RT unitary split system air conditioner (AC) 2.5 RT unitary split system heat pump (HP) (Note: RT = capacity in refrigeration tons = 12000 Btu/hr = 3.516 kWt)		
Refrigerant Options:	HCFC-22 and HFC-134a for all equipment categories		
Refrigerant Charge (kg/unit):		HCFC-22	HFC-134a
(* denotes midpoint of range in source (Calm, June 1991))	2.5 RT unitary split system AC	2.27	1.90
	2.5 RT unitary split system HP	2.75*	2.37*
Annual loss: End-of-life loss (%/yr:%)	parametric variation of (%/yr:%)... 0:0, 1:40, 4:40, and 8:100		
Equipment Life (yr):	2.5 RT unitary split system AC		20 yr
	2.5 RT unitary split system HP		20 yr
Global Warming Potential (GWP) Values ($kgCO_2/kg$):		HCFC-22	HFC-134a
	500 yr	510	420
DIRECT CO_2 Emissions Analysis:	(Charge x loss rate x life x GWP)+(Loss %) x charge x GWP = CO_2 emissions [(kg/unit) x (%/yr) x (yr) x ($kgCO_2/kg$)]+[(%) x (kg/unit) x ($kgCO_2/kg$)] = $kgCO_2$/unit		

where common-basis performance data were made available (Calm, April 1991). Although the equipment evaluated is suitable for both residential and non-residential service, in this first analysis, residential heating and cooling loads were applied.

7.2 METHODOLOGY

DIRECT and INDIRECT global warming contributions are calculated and combined to estimate TEWI. The analysis assumptions used to estimate DIRECT and INDIRECT emissions are summarized in Tables 7.2, 7.3, and 7.4, respectively. The rationale to support the assumptions is provided below. The resulting approach is straight-forward and at a level of precision that is appropriate for the input data.

Table 7.3. New Unitary Equipment Seasonal Performance Factors for Alternative Refrigerants at Various Cost Levels

(For HCFC-22 & HFC-134a: cooling-kW_e/unit, heating-seasonal COP (kWh_t/kWh_e))
(For ammonia/water: cooling electric-kW_e/unit, cooling gas-gas COP (kWh_t/kWh_t))

Equipment Category	Refrigerant	Unitary equipment relative cost levels[a]:			
		Base = 1.0	Level A	Level B	Level C
2.5 RT Split System AC - cooling	HCFC-22	3.00	2.70	2.49	1.95‡
	HFC-134a	3.41	3.00	2.70	---
	ammonia/water	---	---	---	0.45*†
	ammonia/water	---	---	---	1.17†
2.5 RT Split System HP					
- cooling	HCFC-22	3.00	2.38†	---	---
	HFC-134a	3.99†	3.00	---	---
- heating	HCFC-22	1.99	2.60†	---	---
	HFC-134a	1.55†	1.99	---	---

Notes:
*–denotes gas COP, all other cooling performance factors are kW_e /unit.
†–denotes the midpoint of a range offered in the source (Calm, May 28, 1991).
‡–denotes a maximum offered in the source (Calm, May 28, 1991).
[a]–relative cost refers to costs of fabrication normalized to those of a selected (representative) reference system (Calm, April 1991). A, B, and C are the same for refrigerant options within an equipment category but differ by equipment category. As a guide, Base < A < B < C, but increments between cost levels are not necessarily the same.

Unitary Equipment Categories

As mentioned previously, the broad definition of unitary equipment used here includes many diverse configurations and methods of integrating the heating function. In addition, unitary equipment may have reciprocating, scroll, rotary screw, or rolling-piston rotary compressors and either constant or variable-speed drives for the compressor and air moving devices. The common features across all unitary devices are air-cooled evaporators and the use of HCFC-22.

It was beyond the scope of this study to consider all unitary equipment categories. A request was made to ARI to provide common-basis performance information for three equipment categories (2.5 RT split-system ACs and HPs with single ducted indoor units, and 7.5 RT packaged air conditioners for pad or roof-mount) (Calm, April 1991). These categories are representative of about 75% of the North American installed base (Table 7.1; Pietsch, 1989; ECI, 1990) and over 55% of the installed base in North America, Japan, and Europe. The industry people were so strained by the effort to develop and introduce chillers with HCFC/HFC refrigerants that sufficient response to enable this lower-priority analysis was only received for the 2.5 RT AC and HP categories.

It is understood that these categories better represent unitary equipment in North America than in Japan. Typical North American and Japanese split systems differ significantly in several respects such as capacity, distribution (i.e., ducted versus ductless), compressor selection (i.e., reciprocating piston, scroll, and rolling-piston rotary versus dominantly rolling-piston rotary), and electrical power characteristics. Also, the newer Japanese products are primarily variable-speed inverter-driven systems while those in North America are single-speed, though variable-speed products are gaining in use (Calm, May 11, 1991). Nevertheless, for this first analysis of unitary heating and cooling equipment, the selected categories were judged to be sufficiently representative of Japanese equipment to warrant carrying through the analysis for Japan as well as for North America.

Refrigerant Options

The request to the USA industry association suggested that common-basis performance data be provided for HCFC-22, HFC-134a, and ammonia (Calm, April 1991). Only HCFC-22 and HFC-134a received sufficient response to enable the development of common-basis performance factors.

Refrigerant Charge

Refrigerant charge can vary by capacity, refrigerant, vintage, compressor type, manufacturer, heat exchanger selections and a host of other variables. The charge data available at the time of this study varied widely. As a result, a new survey was performed (Calm, June 1991) that was consistent with the mid-1990 unitary common-basis performance factors (Calm, April 1991). The charge assumptions used in this study are presented in Table 7.2. The base cost charge data were used for all cost levels to avoid unfairly penalizing the more costly (and efficient) systems (see Chiller section for discussion). The HCFC-22 charge compares well with an independent source (Taguchi, March 8, 1991).

Refrigerant Annual Loss Rate and End of Service Life Loss

No reliable data were found on refrigerant loss rates in unitary equipment. It is believed that historically unitary in-service loss rates (%/year) have been lower than those of chillers. Sub-atmospheric pressure refrigerants are not used, hence purge units are not needed. An eight percent annual loss would require service after a year or two due to poor performance. The leak would then be corrected, hopefully with the first repair, so it is unlikely that high loss rates would continue indefinitely. Many unitary devices are factory-sealed hermetic systems (window units, single-package units, PTACs, PTHPs, WLHPs, etc.) that have low losses. But even split-systems with improperly sealed tubing joints between the indoor and outdoor units would be corrected in a year or two.

End of service life loss is another matter. Historically there has been no economic incentive to recover refrigerant from units with small charges. Increasing refrigerant prices and the availability of recover/recycle/reclaim systems are factors that provide some incentive. Deliberate refrigerant venting will be illegal in some countries in the future (e.g., July 1992 in USA due to 1990 Clean Air Act Amendments), but unitary equipment technician skill levels may nonetheless prevent complete recovery. Based on these considerations, four loss scenarios were included in this study. The "annual loss: end-of-life loss (%/yr:%)" scenarios are as follows:

0:0	no losses (INDIRECT emissions only),
1:40	minimum in-service loss with projected E-O-L loss,
4:40	current in-service loss with projected E-O-L loss, and
8:100	extreme historic losses.

Equipment Life

The handbook values of 15 year service life for unitary split-system air conditioners and heat pumps (ASHRAE; 1987) are believed to be overly conservative for the mid-1990 equipment evaluated here. Evidence exists that historical service life has been closer to 20 years (Lovvorn, 1985; Pientka, 1986; Bucher, 1989; and Hiller, 1990). The 20-year value has been used in this study.

Global Warming Potential

Global warming potential values for the 500 year integration time horizon (IPCC; 1990) were used in this study as indicated in Table 7.2.

DIRECT (Refrigerant Loss) Equivalent CO_2 Emissions Estimate

Table 7.2 concludes by defining the calculation performed to estimate DIRECT CO_2 emissions. The calculation has an annual charge loss term and an end of life loss term that are summed to obtain the total. The annual charge loss term is a straight multiplication of refrigerant charge, annual refrigerant loss rate, unitary equipment life, and refrigerant global warming potential (GWP). The end of life loss term is the multiplication of the end of life loss, refrigerant charge, and GWP.

Table 7.3 summarizes the unitary equipment seasonal performance factors and Table 7.4 summarizes the remaining analysis assumptions required for the INDIRECT CO_2 emissions calculations. This information is discussed below.

Unitary Equipment Performance

Unitary equipment operating efficiency is estimated with seasonal performance factors. For electric-driven ACs and HPs in the cooling mode, a seasonal value of kW_e/unit is used. For electric-driven HPs in the heating mode, a seasonal value of COP (kWh_t/kWh_e) is used. For the cooling mode of direct gas-fired ammonia/water absorption air conditioners, a seasonal value of kW_e/unit is used for electric auxiliaries (indoor/outdoor fans, solution pump, chilled water pump) and a seasonal value of gas COP (kWh_t/kWh_t) is used for the primary fuel. The absorption performance factors are for existing technology. The vapor compression performance factors are for mid-1990s equipment designs optimized for each alternative refrigerant at equal capacities and at several manufacturing cost levels. Since the designs for these mid-1990 unitary devices are not public knowledge, a request was made to ARI provide the necessary performance factors while protecting proprietary information and avoiding violations of anti-trust provisions (Calm, April 1991). Data from Japan (Taguchi, March 8, 1991; Taguchi, March 25, 1991) were used to independently corroborate the North American performance data to the extent possible.

The performance factors used in this study are summarized in Table 7.3. The cost levels are not necessarily the same across unitary equipment categories, therefore only performance factors within an equipment category are directly comparable. Also, the costs were not disclosed and the cost increments between the various levels are not necessarily the same. It is known, however, that Base Cost < A < B < C.

Table 7.4. Analysis assumptions for estimating the INDIRECT contribution to TEWI as a result of operating unitary equipment with various refrigerants over their lifetime

	Pittsburgh, USA	Yamagata, Japan
2.5 RT Split System AC		
Cooling Annual Full-Load Hours	900	220
2.5 RT Split System HP		
Cooling Annual Full-Load Hours	900	220
Annual Heating Thermal Requirement (kWh_t/unit)	19,200	10,500

INDIRECT CO_2 Emissions Analysis for Electric AC or HP Cooling Mode Operation

Cooling Performance	x	Cooling Hours	x	Life	x	Regional Electric Conversion	=	CO_2 emissions
(kW_e/unit)	x	(hr/yr)	x	(yr)	x	($kgCO_2/kWh_e$)	=	kg CO_2/unit

INDIRECT CO_2 Emissions Analysis for Electric HP Heating Mode Operation

Heating Load	x	1/SCOP	x	Life	x	Regional Electric Conversion	=	CO_2 emissions
(kWh_t/unit)	x	(kWh_e/kWh_t)	x	(yr)	x	($kgCO_2/kWh_e$)	=	kg CO_2/unit

INDIRECT CO_2 Emissions Analysis for Ammonia/Water Absorption Cooling Mode Operation
NOTE: Total INDIRECT = gas term + electric term

$\frac{2.5\ (3.516)}{gCOP}$	x	Cooling Hours	x	Life	x	Gas to CO_2 Conversion	=	CO_2 emissions from gas
$\frac{kWh_t}{hr\text{-}unit}$	x	hr/yr	x	yr	x	$\frac{kgCO_2}{kWh_t}$	=	$kgCO_2$/unit
Cooling Performance	x	Cooling Hours	x	Life	x	Electric to CO_2 Conversion	=	CO_2 emissions from electric
$\frac{kW_e}{unit}$	x	hr/yr	x	yr	x	$\frac{kgCO_2}{kWh_e}$	=	$kgCO_2$/unit

Regional Average Electric Conversion Factors		Electric Conversion Factors by Fuel	
North America	0.672 kg CO_2/kWh_e	Coal	1.134 kg CO_2/kWh_e
Japan	0.581 kg CO_2/kWh_e	Oil	0.957 kg CO_2/kWh_e
		Gas	0.580 kg CO_2/kWh_e

Gas conversion factor: 0.184 kg CO_2/kWh_t (53.9 kg CO_2/mill Btu)

The performance factors reported in Table 7.3 are seasonal values for USA Region IV derived from SEERs and HSPFs defined in the appropriate certification testing standard (ARI 210/240-89). A comparison of the USA Region IV definition (ARI 210/240-89) with available by-city weather data (AFM-88-29) indicated that Pittsburgh, USA, is representative of Region IV. It was necessary to use these same seasonal performance factors in the other analysis location because they were the only common-basis values available. Consequently, a Japanese location (Yamagata) having heating and cooling degree-days similar to Pittsburgh was selected (AFM-88-29, 1978; Kuromoto, 1990). Residences in Pittsburgh and Yamagata have higher heating loads and lower cooling loads than residences where heat pumps and air conditioners are most widely applied. Consequently, the INDIRECT emissions estimates may understate the norm for air conditioners and overstate the norm for heat pumps.

The cooling mode calculations in Table 7.4 require cooling annual full-load hours. The heating mode calculations require the annual heating thermal requirement. The sources of these values are discussed below.

Cooling Annual Full-Load Hours

Cooling annual full-load hours (ASHRAE, 1985) were plotted versus cooling degree days (AFM-88-29, 1978; Kuromoto, 1990) to serve as one basis for estimating the appropriate annual full-load hour values for each location. These data were based on a survey of North American electric utility companies and on an indoor temperature of 23.9°C (75°F). A range of full-load hour data was available for 36 cities (ASHRAE, 1985) with the low end of the range applying to residential applications. The low values were used to construct the plot versus cooling degree days. The plot exhibited a broad band of scatter with a trend of increasing full-load hours with increasing cooling degree days. The scatter would be expected since cooling operation depends on wind velocity, humidity, solar input and occupancy effects as well as on outdoor dry-bulb temperature (the basis for cooling degree-days).

Cooling degree-days for the two locations range from 330-360°C-day (600-650°F-day). At this level of cooling degree-days, annual full-load hours ranged from about 200 to 900. A specific value of 900 hours was given for Pittsburgh (ASHRAE, 1985). Although this value is at the top of the range and appears high relative to the mid-range value of 550 hours, it compares well with the USA Region IV value of 800 (ARI 210/240-89). A value of 220 hours was selected for Yamagata. This roughly corresponds to the low end of the range and is consistent with typical full-load cooling hours from an independent source (Taguchi, April 11, 1991). These cooling full-load hour assumptions are summarized in Table 7.4.

Annual Heating Thermal Requirement

Annual thermal heating requirements for the two locations were estimated from heating degree-days using the modified degree-day method (ASHRAE, 1989). This method requires an estimate of the design heating load. Analysis in Boston, Massachusetts (Sarkisian, 1990) and field-test results in Syracuse, New York (Hughes, 1985) both indicate that residential design heating loads are about a factor of 1.67 higher than design cooling loads in those respective locations. Since Pittsburgh heating and cooling degree-days fall between those of Syracuse and Boston, this factor of 1.67 was used for Pittsburgh and Yamagata as well.

The annual heating requirement of 19200 kWh_t calculated in this manner for Pittsburgh was used directly. To verify this value, electricity consumption for heating was calculated using the HCFC-22 performance factor at base cost (Table 7.3) to obtain 9648 kWh_e. The same performance factor and Region IV heating hours of 2250 (ARI 210/240-89) results in an estimate of 9938 kWh_e, or 3%

higher. On this basis, it was determined that the modified degree-day method had sufficient precision for this analysis.

For Japan, the modified degree-day result for Tokyo was compared with the result of an equivalent full-load hour calculation using typical residential heating hours for Japan (Taguchi, April 11, 1991). The Tokyo comparison indicated that the typical heating energy usage is about 60% of that predicted by the modified degree-day method. The Japanese are less likely to condition residences when they are unoccupied and different comfort standards are generally accepted (Washington Post, 1991). Consequently, the 0.60 factor was applied to the modified degree-day result for Yamagata. The resulting annual thermal heating requirements are summarized in Table 7.4.

Cooling Mode INDIRECT (Energy Use) CO_2 Emissions Estimate

Table 7.4 defines the calculations performed to estimate INDIRECT CO_2 emissions in electric AC or HP cooling mode operation or in ammonia/water absorption air-conditioner operation. The electric energy calculation in all cases is a straight multiplication of seasonal performance factor, seasonal full-load hours, life, and the appropriate factor to estimate CO_2 emissions from electricity consumption. The gas energy calculation for the absorption air conditioner is a straight multiplication of capacity over gas COP, seasonal full-load hours, life, and the gas to CO_2 emissions conversion factor.

Heating Mode INDIRECT (Energy Use) CO_2 Emissions Estimate

Table 7.4 also defines the calculations performed to estimate INDIRECT CO_2 emissions in electric HP heating mode operation. The calculation is a straight multiplication of the heating thermal requirement, the inverse of the performance factor, life, and the appropriate regional factor to estimate CO_2 emissions from electricity consumption.

7.3 RESULTS

TEWI results including DIRECT and INDIRECT component breakouts are tabulated in Appendix H for 2.5 RT electric split-system ACs and HPs with HCFC/HFC refrigerants assuming 500 year GWP and 20 year life for all regions, cost levels, and refrigerant loss rates. A subset of these results (base cost) are presented graphically in Figs. 7.1 and 7.2 for North America and Japan, respectively.

The formats of Figs. 7.1 and 7.2 are identical with the exception of the vertical scale change between North America and Japan to enable accurate viewing of results. Air conditioner (AC) results are on the left and heat pump (HP) results on the right. All four refrigerant loss scenarios are displayed for both the AC and HP. Within each loss scenario grouping a column exists for HCFC-22 and for HFC-134a. The refrigerant options are identified with labels across the bottom. Pairs of columns with the same loss scenario are identified by the word boxes.

The heavily shaded area at the bottom of each column in Figs. 7.1 and 7.2 represents the INDIRECT (energy related) component of TEWI. The other area represents the DIRECT (refrigerant loss) component. The total column height represents TEWI. The INDIRECT, DIRECT, and TEWI values are expressed as thousands of kilograms of equivalent CO_2 emissions per unit (2.5 RT AC or HP) over the service life of the unit (20 years).

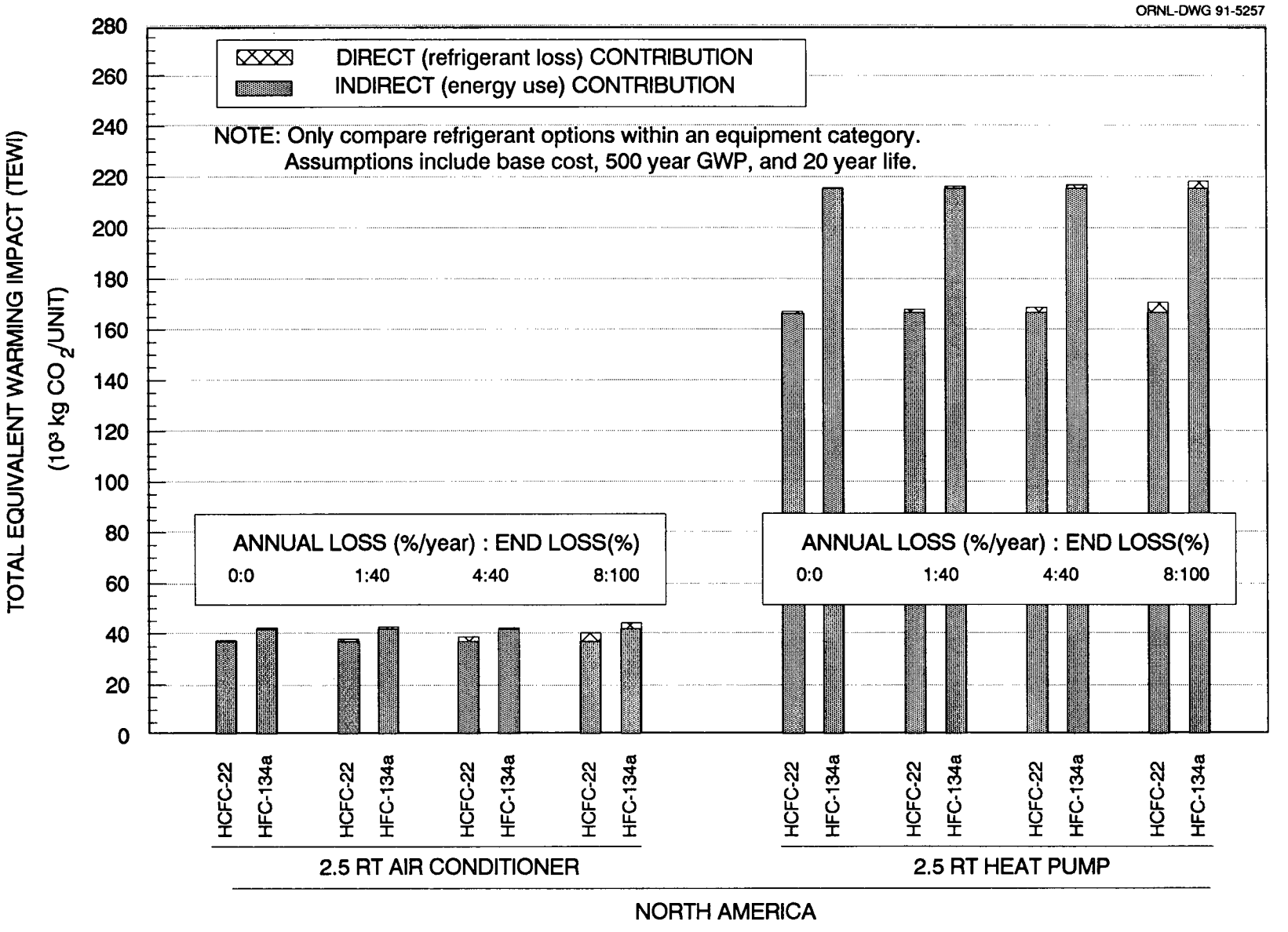

Fig. 7.1. DIRECT and INDIRECT equivalent lifetime CO_2 emissions of unitary air-conditioners and heat pumps in North America.

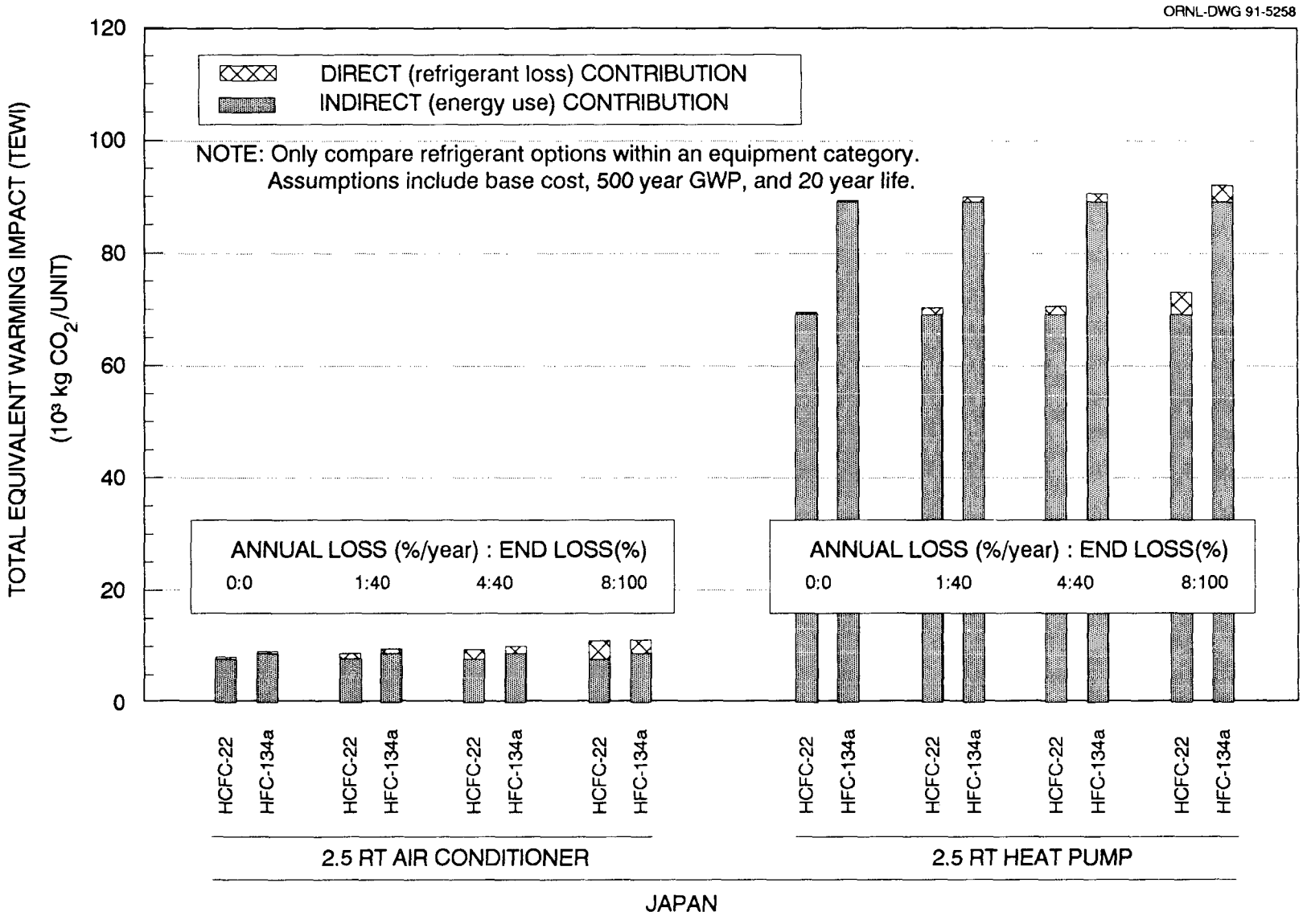

Fig. 7.2. DIRECT and INDIRECT equivalent lifetime CO_2 emissions of unitary air-conditioners and heat pumps in Japan.

All columns within an equipment category are on a consistent basis and can be compared directly. Comparisons between AC and HP categories should be avoided because relative cost levels and performance factors are not consistent, and the HP values include INDIRECT contributions from both cooling and heating (including electric resistance backup heat) modes of operation.

Figures 7.1 and 7.2 indicate a large difference between the corresponding INDIRECT terms in North America and Japan. This difference is primarily a result of lifestyle (Washington Post, 1991) but the regional average electric generation fuel mix is also a contributing factor.

The immediate observation from Figs. 7.1 and 7.2 is the overwhelming effect of energy use on the TEWI. Over 90% of the impact is due to heating or cooling energy except for a few sets of high loss assumptions, and then only for Japan.

7.4 CONCLUSIONS

Converting from HCFC-22 to HFC-134a in unitary equipment would result in a severe global warming penalty. This point is illustrated in Fig. 7.3 where the change in calculated TEWI resulting from a conversion to HFC-134a, relative to the HCFC-22 base refrigerant, is presented for the various equipment categories and loss scenarios in North America and Japan. The penalty is particularly large in heat pumping applications due to loss of efficiency and capacity relative to HCFC-22, but is also evident in air conditioning. HFC-134a only approaches parity with HCFC-22 in the highest refrigerant loss case for air conditioners in Japan. Since the selected analysis locations cause an understatement of INDIRECT emissions for air conditioning relative to the typical application, the above conclusion appears robust.

The analysis of direct gas-fired ammonia/water absorption air conditioners as a currently available not-in-kind (NIK) AC alternative in North America is presented in Fig. 7.4. It is clear that this technology results in a severe global warming penalty relative to HCFC-22 vapor compression systems regardless of electric generation fuel.

7.5 NEXT GENERATION TECHNOLOGIES

A variety of thermally-activated heat pump technologies (engine-driven, absorption, Stirling) are in various stages of development and may have global warming benefits relative to HCFC-22 based vapor compression machines in unitary applications (DOE, 1990; GRI, 1990). Although there may be a significant potential for future energy savings, it is unlikely that products using natural gas or other fossil fuels will have a significant impact in the time period corresponding to the CFC phaseout. The Office of Technology Assessment of the U.S. Congress has estimated that gas fired heat pumps may be introduced into the residential HVAC market as early as 1995, but they would achieve only a 10% market share by 2015 (OTA, 1991). Similar equipment for the commercial market would attain only a 2% market share by 2015.

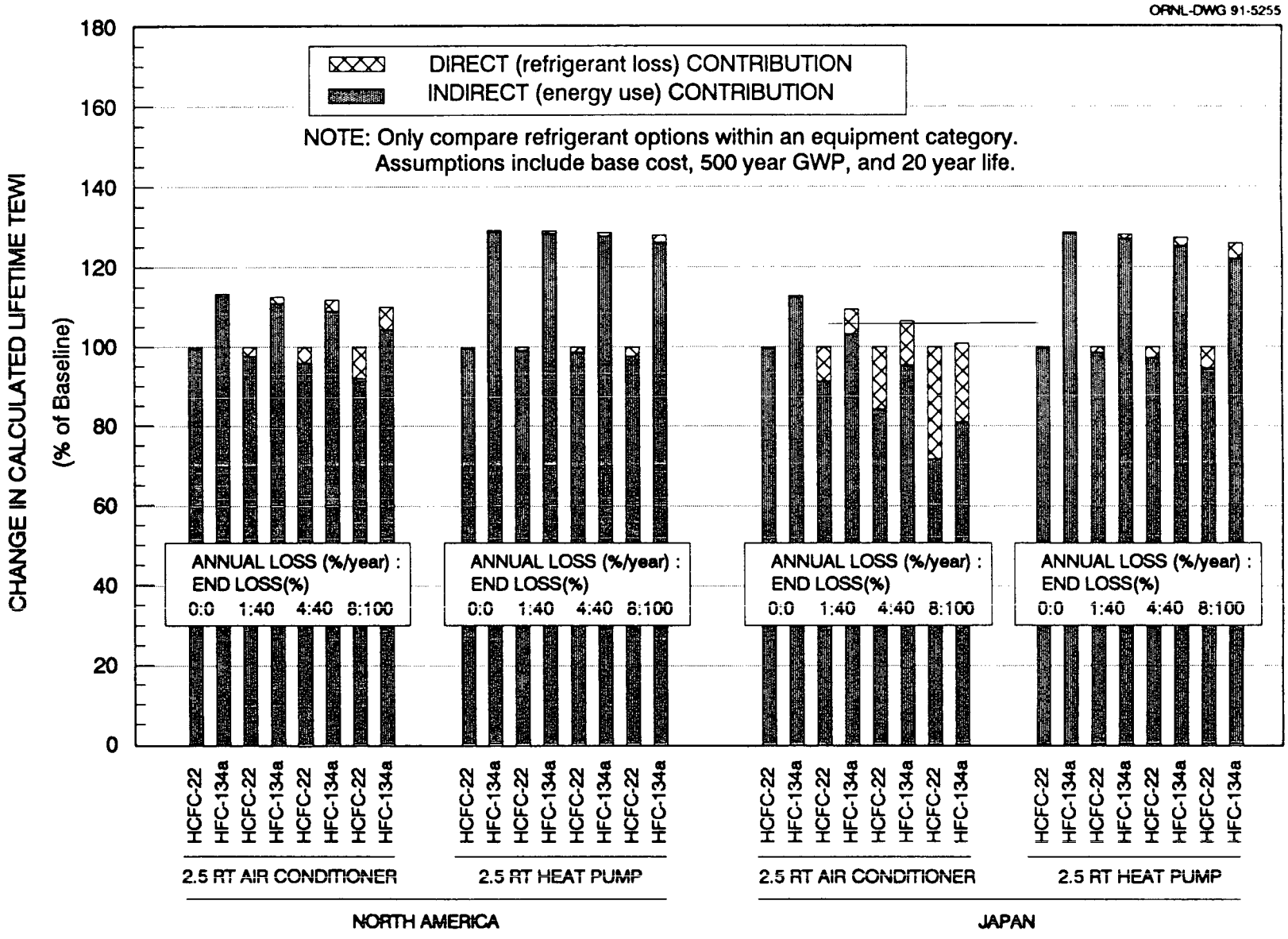

Fig. 7.3. Changes in net TEWI relative to baseline refrigerants for unitary cases in North America and Japan.

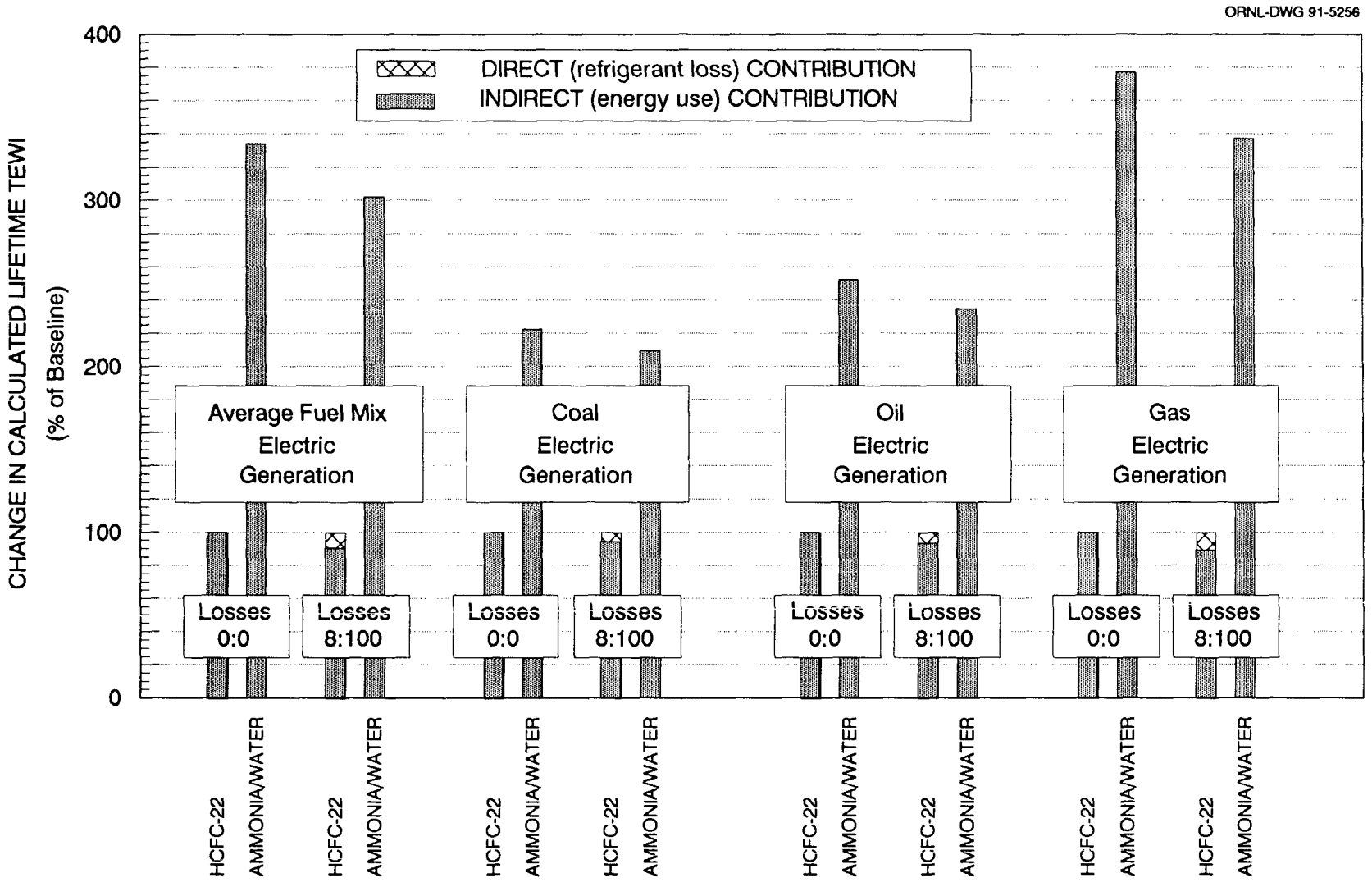

Fig. 7.4. Existing direct-fired absorption technology as a not-in-kind alternative for unitary air-conditioners in North America.

8. AUTOMOBILE AIR-CONDITIONING

8.1 INTRODUCTION

Automobile air-conditioning has become a very important application of CFC-12 because of the very large volumes of refrigerant used. Although not particularly common in Europe, auto air-conditioning (a/c) accounts for over 30% of all CFC-12 usage in Japan (Ushimaru, 1989) and 33% of all CFC-12 usage in the United States (Statt, 1988). As an indication of the rapid growth of mobile air-conditioning in these two countries, only 6% of the new cars sold in North America in 1960 were equipped with air-conditioning, but 78% of the cars sold in Canada and the United States in 1989 had air-conditioners. Out of approximately 55 million passenger vehicles in Japan, about 35 million are equipped with air-conditioners and fully 85% of the new cars sold in Japan in 1990, and 78% of all passenger vehicles, had factory or dealer installed air-conditioning (Taguchi, 1991). There is also a significant potential for growth in the automotive field as the use of private cars and trucks becomes more common in Asia, Africa, and South and Central America.

Although there are no statistics on the number of automobile air-conditioners in use, reasonable projections can be made from the number of vehicles registered worldwide and the statistics for air-conditioners installed in new vehicle sales. Data for the number of passenger vehicles registered in different regions of the world are listed in Table 8.1 using information from two different sources. The number of new vehicle sales and percentage of new vehicles with a/c are given in Table 8.2 for North America, Europe, Japan, and the rest of the world (UNEP, 1989). The known percentages of new vehicles with air-conditioning and the total vehicle registrations from Table 8.1 can be used to estimate future numbers of cars and trucks with air-conditioning because the useful lifetime of passenger vehicles is relatively short and a large fraction of the world fleet in 1990 will be replaced by 2000. The U.S. Environmental Protection Agency reports that the estimated useful life of a mobile air-conditioner is eleven years in a car and fifteen years in a truck (EPA, 1989). Similar data have been reported by Fiat (Gamarra, 1991).

8.2 BASELINE AIR-CONDITIONER

An automobile air-conditioner typically uses a belt driven compressor that is mounted on the engine block, flexible hoses to connect the compressor to a condenser that is located in front of the radiator, an evaporator inside the passenger compartment, and an expansion valve or orifice tube that is used to control refrigerant flow. The cooling capacity of these systems ranges from 3.5 to 5.8 kW (12,000 to 19,800 Btu/h) for Japanese cars (Ushimaru, 1989); capacities for the U.S. range up to 10.5 kW (36,000 Btu/h). The necessary cooling capacity is determined both by the desire to draw down the inside temperature quickly and also by the need to provide adequate cooling in the hot idle type of condition experienced in stop and go rush hour traffic in a hot, humid environment.

The refrigerant charge for an mobile air-conditioning system can range from 700 g (Taguchi, 1991) to as high as 1800 g (1.75 to 4.0 lbs) (Nonnemann, 1991) of CFC-12 for an automobile and 900 to 1500 g (2.0 to 3.3 lb) for a light-duty truck with the typical charges being around 1200 g (2.6 lbs) for an automobile and 1500 g (3.3 lbs) for a light truck (UNEP, 1989, p 88). Approximately one third of the refrigerant is lost annually through leaks and permeation through the hoses, losses during servicing, venting, accidents, and disposal at junk yards. Voluntary efforts and government regulations are being directed toward reducing these losses and recent experience by one U.S. manufacturer has been a usage rate of 10 to 20% of the refrigerant charge (Bhatti, 1991). The air-conditioning system

will also contain an accumulator and filter-drier to provide a reservoir for extra refrigerant and to remove particulates and moisture that may enter the system.

Table 8.1. World wide fleet of passenger vehicles (millions)

Region	1990 World Almanac	ORNL Transportation Data Book
Europe	156.7	110.2*
Eastern	14.6	
Western	142.1	110.2*
North America	196.2	200.3
Canada	14.1	15.9
Mexico	7.1	not given
United States	175.0	184.4
Japan	47.7	51.4
Africa	11.4	not given
South & Central America	25.5	not given
Asia (excluding Japan)	57.4	not given
Rest of the World	0.0	178.0
Total	494.9	539.9

Table 8.2. New vehicle sales and new vehicles with air-conditioning (A/C) (millions)

Region	1987 Car and Light-Duty Truck Sales	1987 Vehicles with A/C	Percentage of New Vehicles with A/C
Europe	13.9	1.3	9%
North America	17.0	11.3	78%
Japan	5.6	4.3	78%
Africa	0.5	0.3	60%*
South & Central America	1.5	0.9	60%*
Asia (excluding Japan)	2.4	1.3	54%
Rest of the World	0.6	0.4	66%*

Source: Technical Progress on Protecting the Ozone Layer: Refrigeration, Air Conditioning, and Heat Pumps Technical Options Report, UNEP, 1989.
* estimate by UNEP.

8.3 FUEL CONSUMPTION FOR INCREMENTAL VEHICLE WEIGHT CHANGES

Vehicle fuel use for air-conditioning depends on the efficiency of the air-conditioning system and also on the weight of the compressor, hoses, condenser, evaporator, etc. The heavier the system, the more fuel is required to carry it around. The Motor Vehicle Manufacturers Association (MVMA) in the United States and General Motors (GM) estimate that each 45.5 kg (100 lbs) that are added to the vehicle weight increases overall fuel use by 37.9 ℓ (10 gal) of gasoline for every 16,100 km (10,000 miles) driven (Halberstadt, 1991). This is equivalent to 57.1 ℓ / 100 kg / 10,000 km driven. Further information on Japanese made cars corroborates this estimate. Each 1% decrease in vehicle weight for Japanese cars improves vehicle fuel efficiency by ½ to 1% (Taguchi, 1991).

This rule of thumb can be used with vehicle sales information to derive an estimate in ℓ / 100 kg / 10,000 km. The sales weighted average curb weight for all light duty vehicles (cars and trucks) imported into the United States in 1989 was 1,122 kg (2,470 lbs) and the corresponding fuel economy was 12.1 km / ℓ (28.6 mpg) (Williams, 1990). This mileage figure is equivalent to 826 ℓ of fuel per 10,000 km (350 gal/10,000 miles). A 1% change in vehicle weight is 11.2 kg (24.7 lbs) and a ½ to 1% change in fuel use for 10,000 km is 4.1 to 8.3 ℓ (1.75 to 3.50 gal/10,000 miles). Combined, these data give an incremental fuel use of 36.6 to 73.2 ℓ / 100 kg / 10,000 km (7 to 14 gal / 100 lbs / 10,000 miles), which agrees very well with the MVMA data.

8.4 FUEL USE FOR AIR-CONDITIONING

MVMA and GM also estimated that the energy requirements for powering the air-conditioning system are approximately 47 ℓ of gasoline per 10,000 km driven (20 gal/10,000 miles) (Halberstadt, 1991). This estimate takes into account the compressor efficiency, air-conditioning blower, condenser fan, and the power transmission loss in the mechanical drive. European and Japanese manufacturers did not provide similar estimates for their products, but their system efficiencies are probably very close to those of air-conditioners manufactured for U.S. cars.

Both the fuel use for incremental weight changes and for powering the air-conditioner are expressed in terms of a standard driving distance. Davis and Hu (1991) have published data for the average annual number of miles driven per vehicle for the United States, Canada, Japan, and five European countries. These data are shown in Table 8.3. This information is used with the data on fuel use for incremental weight changes and the relative air-conditioning efficiencies for CFC-12 alternatives to evaluate the use of HFCs, HCFCs, and other refrigerants in automobile air-conditioning systems by using Eq. 8.1:

$$\text{fuel use} = \left[47\ \text{l} \times \frac{COP_{CFC\text{-}12}}{COP_{alt}} + 57.1\ \text{l} \times \frac{\text{weight of a/c}}{100\ \text{kg}}\right] \times \frac{\text{annual kilometers}}{10{,}000\text{km}} \qquad (8.1)$$

where COP_{alt} is the system efficiency of the alternative refrigerant and $COP_{CFC\text{-}12}$ is the baseline efficiency with CFC-12.

Table 8.3. Passenger vehicle use worldwide (distance per vehicle)

Region	Number of Vehicles (thousands)	Average Annual Driving		Regional Average	
		(miles)	(km)	(miles)	(km)
Western Europe				8,178	13,200
France	22,370	8,389	13,500		
Italy	23,500	6,214	10,000		
Sweden	3,483	7,768	12,500		
United Kingdom	20,923	9,102	14,650		
West Germany	26,288	9,072	14,600		
North America				10,165	16,400
Canada	11,900	10,715	17,250		
Mexico	no data	no data	no data		
United States	141,252	10,119	16,300		
Japan	30,776	6,274	10,100	6,274	10,100
Rest of the World	132,495	no data	no data	no data	no data

Source: Davis, S. and Hu, P., Transportation Energy Data Book: Edition 11, ORNL/66-49, January 1991.

8.5 ALTERNATIVE REFRIGERANTS

European, U.S., and Japanese manufacturers have firm plans to discontinue the use of CFC-12 in automobile air-conditioners as soon as they have proven designs, guaranteed supplies of an alternative refrigerant, and an acceptable lubricant for use with the new refrigerant. Some German manufacturers have already started producing systems using an alternative refrigerant, but for most of the companies this means beginning to convert to the use of HFC-134a in the 1993 or 1994 model year. The alternative designs are likely to include system enhancements to take advantage of the improved heat transfer characteristics of HFC-134a relative to CFC-12 in order to maintain adequate cooling capacity in a compact system. Other alternative refrigerants are mentioned for consideration either as medium or long term solutions to reliability, durability, flammability, and environmental concerns. These include blends of refrigerants (primarily HCFC-22, HFC-152a, and HCFC-124), propane, and HFC-152a. Both propane and HFC-152a are flammable and would require special design features, such as an intermediate heat transfer loop, to satisfy the product liability and safety concerns of the manufacturers and consumer safety advocates. There are industry concerns that non-flammable blends of refrigerants containing HFC-152a could also become flammable due to composition shifts from refrigerant losses.

HCFC-22 and other high pressure refrigerants are occasionally discussed as alternative fluids for mobile air-conditioning systems, but they are generally considered less suitable for this application than the alternatives listed above. HCFC-22 would operate at a much higher pressure than would the other refrigerants, and consequently has greater problems with refrigerant leakage through the hoses and seals. A proposed solution to this problem is to design a hermetically sealed, electrically driven system which could be located in the trunk of the car, away from the high temperatures in the engine compartment and hence at somewhat lower pressures. Thus far this solution has been viewed as an undesirable alternative to "conventional" designs using different refrigerants because of the lost storage space in the trunk and the increased size and weight of the alternator that would be needed to power a hermetic compressor. The size and weight problems are significant barriers to

implementing hermetic systems and make them unlikely substitutes for CFC-12 systems. It would also be very difficult for a hermetic system to compete with the efficiency of the semi-hermetic systems using CFC-12 alternatives because of the additional inefficiencies associated with converting from mechanical energy to electrical energy and then back to mechanical energy for cooling.

Data on the efficiencies and weights of air-conditioning systems using CFC-12 and substitute refrigerants are listed in Tables 8.4 and 8.5. The air-conditioner weights in Table 8.5 show increases for some of the alternatives that account for:

- improved condensing surfaces for the enhanced HFC-134a case to match the system head pressure of an air-conditioner using CFC-12 more closely, and
- a secondary heat transfer loop for air-conditioners using a flammable refrigerant (i.e., propane or HFC-152a) so the refrigerant is isolated from the passenger compartment.

The theoretical COPs in Table 8.4 have been computed using thermodynamic tables for CFC-12, HFC-134a, the ternary blend, HFC-152a, and propane. The COPs for the non-flammable refrigerants are calculated using a condenser temperature of 65.6°C (150°F), evaporator at 4.4°C (40°F), 11°C (20°F) of subcooling, and a return gas temperature of 4.4°C (40°F). The COPs for the two flammable refrigerants, HFC-152a and propane, are computed using the same condensing and liquid temperatures as for the non-flammable refrigerants, but the evaporating and suction temperatures are -1°C (30°F) to account for a secondary heat transfer loop to keep the flammable refrigerant out of the passenger compartment. The "Compressor COP" accounts only for the compressor losses and shows an isentropic efficiency of 65% while the "System COP" is 15% lower and includes the fan and blower powers and losses in the mechanical drive.

Table 8.4. Performance parameters for alternative mobile air-conditioning systems

Refrigerant	Theoretical COP	Compressor COP	System COP	Relative Performance
CFC-12	3.64	2.23	1.90	1.00
HFC-134a	3.54	2.16	1.84	0.97
HFC-134a (enhanced)	3.54	2.40	2.04	1.07
Ternary Blend	3.67	2.25	1.91	1.00
HFC-152a	3.22	2.09	1.78	0.94
Propane	2.93	1.90	1.62	0.85

Source: M. Halberstadt, Motor Vehicle Manufacturers Association, 1991. Personal communication.

The system COPs from Table 8.4 and the regional average vehicle use data from Table 8.3 are used with the estimated system weights in Table 8.5 to obtain estimates of the annual fuel use per vehicle for air-conditioning in North America, Europe, and Japan. These results are shown in Table 8.5.

Table 8.5. Fuel use for mobile air-conditioning in North America, Europe, and Japan

Refrigerant	Relative Efficiency	Weight (kg)	Fuel Use (ℓ /10,000 km)		Annual Fuel Use (ℓ)		
			A/C	Weight	North America	Europe	Japan
CFC-12	1.00	15.0	47.0	8.6	91.2	73.4	56.2
HFC-134a	0.97	17.3	48.5	9.7	95.5	76.8	58.8
HFC-134a (enhanced)	1.07	15.0	43.9	8.6	86.1	69.3	53.0
Ternary Blend	1.00	15.0	47.0	8.6	91.2	73.4	56.2
HFC-152a	0.94	21.8	50.0	12.6	102.7	82.6	63.2
Propane	0.85	21.8	55.3	12.6	111.4	89.6	68.6

The fuel requirements for air-conditioning listed in Table 8.5 are computed using Eq. 8.2:

$$\text{fuel use for a/c} = \frac{\text{47 liters}}{\text{relative efficiency}} \tag{8.2}$$

and the fuel requirements for carrying the air-conditioner around is calculated with Eq. 8.3:

$$\text{fuel use for weight} = \text{57.1 liters} \times \frac{\text{weight of a/c}}{\text{100 kg}} \tag{8.3}$$

The air-conditioning and weight requirements are then used with the regional average driving distances from Table 8.3 to arrive at data for annual fuel use for the air-conditioning systems for North America, Europe, and Japan.

$$\text{Annual Fuel Use} = [\text{ a/c + weight requirements}] \times \frac{\text{driving distance}}{\text{10,000 km}} \tag{8.4}$$

Significant work is being done to develop compact heat exchangers for auto air-conditioning,gases, particularly for use with HFC-134a, and it may be possible that systems can be built that are not any heavier than current air-conditioners for CFC-12.

8.6 GLOBAL WARMING IMPACT

The fuel use requirements for the operation and transport of the air-conditioner during its assumed useful life of eleven years are converted to CO_2 emissions based on 2.32 kg CO_2/ℓ (8.87 kg/gal). The vehicle emissions

also contain trace amounts of other greenhouse gases; specifically 0.08 g/ℓ (0.29 g/gal) of methane and 0.04 g/ℓ (0.15 g/gal) of nitrous oxide. These very low emissions rates are four orders of magnitude lower than that of CO_2 (note that these emission rates are in grams per liter and that for CO_2 is in kilograms per liter) and they are presumed to be insignificant relative to those for CO_2 and the direct equivalent warming impact from unavoidable emissions of the compression system refrigerants.

Besides the energy requirements for powering and carrying the air-conditioner, the environmental impacts of CFCs, HFCs, and HCFCs in automobile air-conditioners depend on how large of an initial charge is used in the system, how much of that is eventually recovered when the system is scrapped, how much refrigerant leaks out each year or is lost in servicing, and the ODP and GWP of the refrigerant that is used. The Japanese Automobile Manufacturers Association (JAMA) reported that current air-conditioning systems using CFC-12 require approximately 800 g (28 oz) of refrigerant for cars and 900 g (32 oz) for trucks. The industry target is to reduce these figures to 700 g (25 oz) and 800 g (28 oz) by 1993 (JAMA, 1990). Taguchi reported that current systems require 700 g of CFC-12 (1991). JAMA also estimated that a complete recharge of the system with refrigerant is required every 3 years and that this should be increased to 10 years between recharges by 1992. Halberstadt reported that current U.S. manufactured air-conditioners lose about 340 g (0.75 lb) of refrigerant annually due to leaks and servicing, and that this should be reduced to 113 g (0.25 lb) through improved procedures for handling the refrigerant and better system containment. According to the 1989 UNEP Technical Options Report, current automobile air-conditioners require 1.2 kg of CFC-12 for cars and 1.5 kg for trucks (1989). This is approximately the amount required for U.S. made systems. These data are shown in Appendix I. The masses of refrigerant charges for CFC-12 alternatives are estimated from the baseline CFC-12 charge based on their relative liquid densities.

8.7 RESULTS

Calculations were performed to estimate the lifetime equivalent CO_2 emissions for an automobile air-conditioner based on the eleven year useful life reported by the U.S. EPA. These results are shown in Fig. 8.1 assuming the target emissions rates listed above and with mandatory refrigerant recovery when a vehicle is scrapped. The uncertainty range for each refrigerant reflects the additional direct effects on global warming due to usage rates of 33% of the charge per year instead of the target rates of 10%.

8.8 CONCLUSIONS

The use of non-flammable fluorocarbon alternatives to CFC-12 will result in substantial reductions in direct global warming due to automobile air-conditioning with negligible changes in CO_2 emissions from energy use. This is shown in Fig. 8.1 where the direct effects from HFC-134a and the ternary blend are small fractions of the direct effect of CFC-12 with essentially the same indirect contributions from energy use. Energy use for air-conditioning using the flammable refrigerants is noticeably higher than that for either HFC-134a or the ternary blend, although the total equivalent warming impact for HFC-152a is essentially the same as for the non-flammable refrigerants. The direct effects of HFC-134a and the ternary blend are 10 to 25% of the TEWI (highest percentage in Japan where annual driving distance is smallest and lowest in North America where driving distances are high), and they are not negligible.

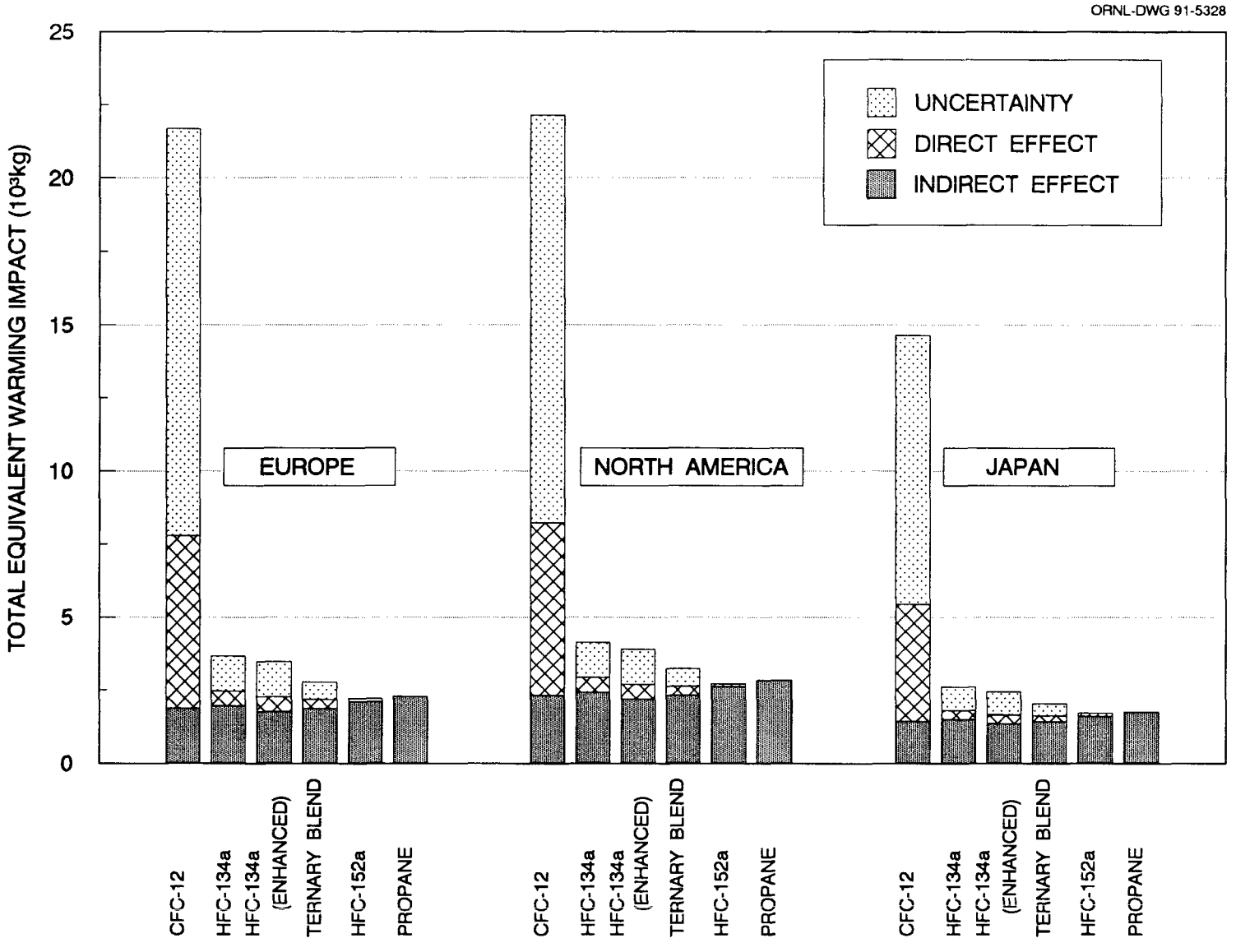

Fig. 8.1. Total equivalent warming impact of alternative refrigerants for automobile air-conditioning systems.

8.9 NEXT GENERATION TECHNOLOGY OPTIONS

Brayton cycle and Stirling cycle refrigeration are occasionally mentioned as viable environmentally safe alternatives to using fluorocarbons as refrigerants in compression systems for automobile air-conditioning. The Brayton cycle relies on air as the refrigerant and has been used successfully for air-conditioning the cockpits of military aircraft. The Stirling cycle uses helium as the refrigerant and is efficient in cryogenic work for liquefying gases; it is more efficient than compression systems in these "high lift" applications. Equipment has not yet been developed based on either one of these refrigeration cycles to the point where it is competitive with the conventional vapor compression systems for automotive air-conditioning in terms of cost, performance, or reliability. Further work could be done that might lead to a viable consumer product; that is not treated here.

The analysis performed on these cycles presumes that certain specified efficiencies could be achieved using the available information on system efficiency and weight and a comparison is made between the total equivalent warming impacts of these systems with compression systems using HFC-134a. This report does not delve into how these systems could be designed nor does it endorse any of the claims made by developers or proponents of this equipment. Both of these systems require extensive development of high performance components before they could be used in a viable air-conditioning system. The Brayton cycle has a realistic coefficient of performance of 1.4 at auto a/c operating conditions with a system efficiency between 0.8 and 1.7 (AiResearch, 1977); this gives the Brayton cycle a relative performance of 0.4 to 0.9 relative to CFC-12. The estimated weight of an automobile air-conditioner based on the Brayton cycle is 13.6 kg (30 lb) (Bhatti, 1991). Estimates for the system COP of an air-conditioner using the Stirling cycle range from 1.3 to 1.7 (STM) for a relative performance factor of 0.67 to 0.9 with a system weight of 31.8 kg (70 lb). These data are used to compute total equivalent warming impacts for these two systems in the same manner used to generate the data for Fig. 8.1 and Table I.1 in Appendix I. The results are shown graphically in Fig. 8.2.

Figure 8.1 shows large uncertainties in the TEWI for both the conventional vapor compression system using HFC-134a and the two potential next generation technologies. The uncertainty for the HFC-134a air-conditioner is due to the unknown rates for refrigerant leakage and service losses in the future. The very top of the bars for HFC-134a (including the lightly shaded uncertainty region) correspond to the TEWI based on refrigerant loss rates of one fifth of the charge lost annually through leakage, accidents, and service practices. The top of the cross-hatched portions of these bars correspond to the TEWI assuming that service practices are changed and systems are tightened up so that only 10% of the charge is lost each year. There are also broad ranges of uncertainty shown for the Brayton and Stirling cycle systems. The highest points on these bars are based on the best available information for system efficiency and weight, while the darkly shaded indirect effects alone (without the uncertainty ranges) correspond to the TEWI calculated using optimistic projections on system efficiency and weight. The most favorable assumptions for the Brayton and Stirling cycles result in TEWI's that are comparable to those calculated for the compression system with HFC-134a, but the region of uncertainty for them extends well above the TEWI for HFC-134a. Neither of these technologies would lead to a significantly lower overall contribution to global warming.

Research is underway at Lawrence Berkeley Laboratories in the U.S. and elsewhere on innovative technologies for reducing automobile cooling loads that would have an indirect effect on refrigerant emissions and energy use. Reductions in cooling requirements could lead to smaller and lighter air-conditioning systems using smaller refrigerant charges. Smaller systems would also be lighter and less energy would be required to transport the equipment. Smaller cooling loads could also make radically different refrigeration technologies employing waste engine heat feasible which simply are not practical for the current high loads. While recognizing the potential of these innovations, no effort has been direct toward a quantitative analysis of the effects of load reduction for this study. A

rigorous evaluation of equipment sizing including both the solar loads while the vehicle is not in use (that can be reduced by the technologies under development) and the latent loads encountered in humid stop and go city driving is beyond the scope of this study.

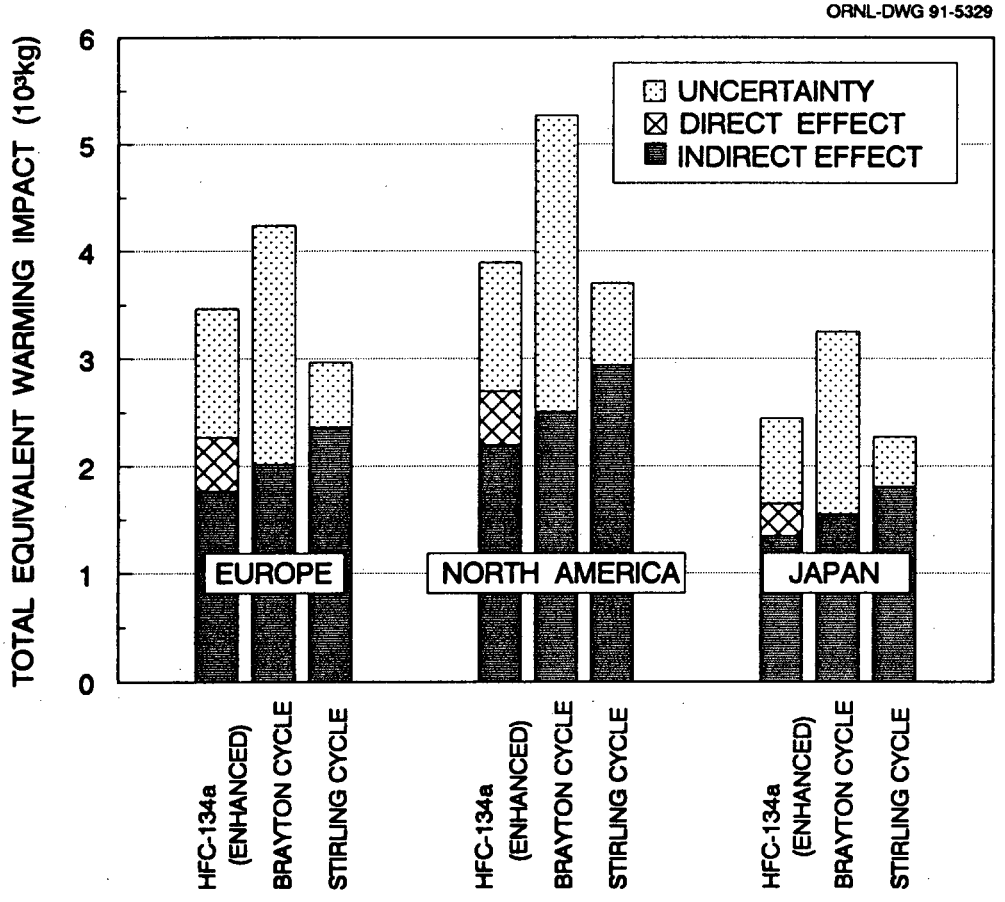

Fig. 8.2. Total equivalent warming impact of next generation technologies for automobile air-conditioning.

9. COMMERCIAL BUILDING INSULATION

9.1 INTRODUCTION

Commercial buildings are broadly defined here to include most non-residential and non-industrial process facilities such as places of commerce, warehouses, offices, schools, and hospitals. In 1989, over 430 million kilograms of polyurethane/polyisocyanurate (PUR/PIR) boardstock and laminate were used in commercial building applications (SPI-PD, 1990; Hagan, 1991; Jeffs, 1991; Cartmell, 1991). In the same year, approximately 100 million kilograms of extruded polystyrene (XEPS) were used in commercial applications (Baumann, 1991; Minsker, Mar. 1991; Minsker, Feb. 1991). Clearly, commercial building foam insulation blowing agent is a major end-use of CFCs and the manner in which alternative blowing agent technologies are employed could have a major impact on future ozone depletion and global warming.

This section documents an analysis of the lifetime total equivalent warming impact (TEWI), including DIRECT (blowing agent loss) and INDIRECT (energy use) contributions, resulting from the application of PUR/PIR and XEPS in commercial buildings. The primary analysis concerns PUR/PIR and XEPS blown with CFCs and alternative blowing agents. Not-in-kind (NIK) alternative types of insulation are also included as comparative references. No next generation technologies were evaluated for this application. The method of estimating TEWI has been simplified by focusing the analysis on two typical building types having three common foam board applications. The building types are a retail mall and a warehouse. The foam board applications are in low-slope roofs, masonry walls, and foam core metal panel walls. The analysis was also limited to two locations in each of North America and Europe.

9.2 BASELINE WALL, ROOF, AND BUILDING DESCRIPTIONS

DIRECT and INDIRECT global warming contributions are calculated and combined to estimate TEWI. Evaluation of the INDIRECT (energy-related) terms requires the use of a building energy analysis tool to estimate the energy consumption of baseline buildings. The baseline buildings and insulated wall and roof constructions are described in this section. The rationale for selection of walls, roofs, and buildings is also described.

The common CFC-blown insulations used in commercial buildings are PUR/PIR and XEPS. The allocation of PUR/PIR consumption to end-uses was used as the basis for selecting typical buildings because PUR/PIR is the dominant foam board insulation used in commercial buildings.

The 1989 world usage of PUR/PIR has been estimated by region and building end-use (Appendix J, Tables J.1-J.5; DPI-PD, 1990; EIA, 1988; PIMA, 1991; Hagan, 1991; Jeffs, 1991; Cartmell, 1991; Minsker, 1991; Galloway, 1991) and is summarized in Table 9.1. Over 80% of PUR/PIR used in all buildings and over 90% of PUR/PIR used in commercial buildings is applied in North America and Europe. Consequently resources were focused to define typical walls, roofs, and buildings for North America and Europe.

Commercial building characteristics surveys (EIA, 1988) and energy standards (ASHRAE/IES 90.1-1989) provide a relatively complete picture of commercial building construction practice in the U.S. Some insulation standards information was available for Europe but, with the exception of Great Britain, it pertained to residential construction (Jeffs; 1991). This same source also provided

some information on commercial building applications of PUR/PIR in Europe and commissioned a more detailed market survey (Galloway, 1991).

Table 9.1 Estimated 1989 world usage of PUR/PIR boardstock and laminate in building insulation million kg (million pounds) of boardstock/laminate

	North America	Europe	Japan	Rest Of The World	World Total
Residential					
walls: all types	44.0 (97)	17.2 (38)	20.4 (45)		
roofs: all types	---	33.7 (74)	---		
Non-residential					
roofs: low-slope	122.5 (270)	64.4 (142)	11.8 (26)		
walls: masonry (all types)	24.9 (55)	11.8 (26)	2.3 (5)		
wall/roofs: metal panels	12.7 (28)	155.4 (343)	---		
Total	204.1 (450) 36%	282.5 (623) 50%	34.5 (76) 6%	46.2 (102) 8%	567.3 (1251) 100%

The available North American and European data were used to select typical building types that use foam board insulation. U.S. usage of PUR/PIR by building type has been estimated for 1989 (Appendix J, Table J.6; EIA, 1988; DOE, 1983; EGI, 1980; ARS, 1985; PNL, 1985; UIC, 1988) and is summarized in Table 9.2. Nearly 65% of PUR/PIR is used in "mercantile + service," "office," and "warehouse" building types. The European data indicate an equal or larger representation by these building types (Jeffs, 1991; Galloway, 1991). In terms of energy intensity, the "office" category and some of the lessor categories in Table 9.2 are intermediate between "mercantile + service" and "warehouse." Consequently resources were focused to define typical walls and roofs for "mercantile + service" and "warehouse" buildings in North America and Europe.

The "mercantile + service" category includes retail and service buildings such as retail malls, shopping centers, stand-alone stores, and automobile service garages (EIA, 1988). Retail uses dominate floorspace in this category and retail mall building characteristics are a good compromise between large shopping centers and stand-alone stores. The retail mall with rows of stores with common walls was also thought to be more typical of European retail space.

The "warehouse" category includes warehouses of all sizes, shapes, styles, and vintages. A medium-sized, free-standing warehouse was thought typical for both North America and Europe.

Specific retail mall and warehouse buildings were required for the building energy analysis. The available information (Jeffs, 1991; Galloway, 1991; ASHRAE/IES 90.1-1989) indicated that North American and European building practices were similar enough to use common retail mall and warehouse building prototypes. ASHRAE/IES Standard 90.1-1989 and the Federal Commercial Buildings Energy Performance Standards (EGI, 1980) that preceded it were developed using reference buildings for each building type. The retail mall and warehouse reference buildings used for ASHRAE/IES and U.S. DOE commercial building standards development were used for this study because considerable resources had previously gone into selecting actual designs that were built and judged to be typical for their respective categories.

Table 9.2. Estimated 1989 distribution of usage of PUR/PIR boardstock and laminate among non-residential building types in the U.S. million kg (million pounds) of board/laminate

Building Type	Low-Slope Roof	Walls: Masonry	Walls: Metal Panels	Total	
assembly	8.7 (19.9)	4.0 (8.9)	1.3 (2.9)	14.0 (31.7)	10.0%
education	17.0 (37.4)	2.6 (5.7)	--- ---	19.6 (43.1)	13.5%
food sales	1.3 (2.7)	0.4 (0.8)	--- ---	1.7 (3.5)	1.1%
food service	1.8 (3.9)	0.6 (1.4)	0.3 (0.6)	2.7 (5.9)	1.9%
health care	5.5 (12.1)	0.6 (1.3)	0.2 (0.4)	6.3 (13.8)	4.3%
lodging	4.6 (10.0)	1.2 (2.6)	0.2 (0.4)	6.0 (13.0)	4.1%
mercantile+service	26.6 (58.6)	5.9 (13.0)	3.9 (8.7)	36.4 (80.3)	25.3%
office	21.3 (46.9)	3.4 (7.6)	1.2 (2.6)	25.9 (57.1)	17.9%
public order+safety	1.3 (2.9)	0.6 (1.3)	--- ---	1.9 (4.2)	1.3%
warehouse	22.1 (48.6)	3.4 (7.4)	4.2 (9.4)	29.7 (65.4)	20.6%
total	110.2 (243)	22.7 (50)	11.3 (25)	144.2 (318)	
	76.4%	15.7%	7.9%	100%	100%

The reference building prototype documentation includes definition of all building characteristics and operating procedures important to consider in building energy analysis (DOE, 1983). The wall and roof construction definitions were refined for this study. Construction details were desired that were typical for buildings using foam board insulation or that bounded the energy impact of foam board when a variety of construction practices were common.

A wide variety of wall construction is used in commercial buildings in North America including masonry veneer over wood frame, masonry frame, or steel frame; conventional siding over wood frame or masonry frame; and metal or concrete panels (EIA, 1988). The wall insulation R-values required by code for commercial buildings are modest relative to residential buildings because the larger ventilation and internal heat loads detract from the value of insulation. Buildings with wood and steel framing can typically achieve the required R-values with fiberglass batt insulation and conventional sheathing, furring, and siding in most areas. Some foam board sheathing over frame walls is used in cooler regions, but it is not considered a major use.

The most common commercial walls in North America using foam board are masonry over masonry frame, concrete panels, and metal panels. The first category includes concrete or masonry walls with foam board insulation on the inside or outside, and brick and block cavity walls with foam insulation in the cavity. Concrete panels include pre-cast load-bearing spandrels and non-load-bearing curtain-wall panels. The outside surfaces come in a variety of finishes, the cements come in a variety of pigments, and the foam insulation is typically site-applied on the inside surface. Metal panels include factory-sealed foam-core constructions with profiled galvanized steel, aluminized steel, or aluminum skins. The inside and outside skins come in a variety of baked enamel or anodized aluminum finishes. Profiled sheet steel with site-applied insulation is another technique, but this is not considered a major use of foam board.

The same commercial wall constructions using foam board have been identified in Europe, though the terminology differs somewhat (Jeffs, 1991; Galloway, 1991). The foam core metal panels are referred to as metal faced sandwich panels. Masonry walls with foam board insulated cavities were identified, as well as masonry insulated on the inside ("dry-lining" with foam/plasterboard composite) or outside (with cementitious overlayer).

Clearly a variety of wall construction practices in North America and Europe use foam board. Since it was beyond the scope to evaluate all options, two wall constructions were selected that bounded the energy impact of the foam insulation in single story retail malls and warehouses. A typical masonry wall is illustrated in Fig. 9.1 and a typical metal panel wall is illustrated in Fig. 9.2.

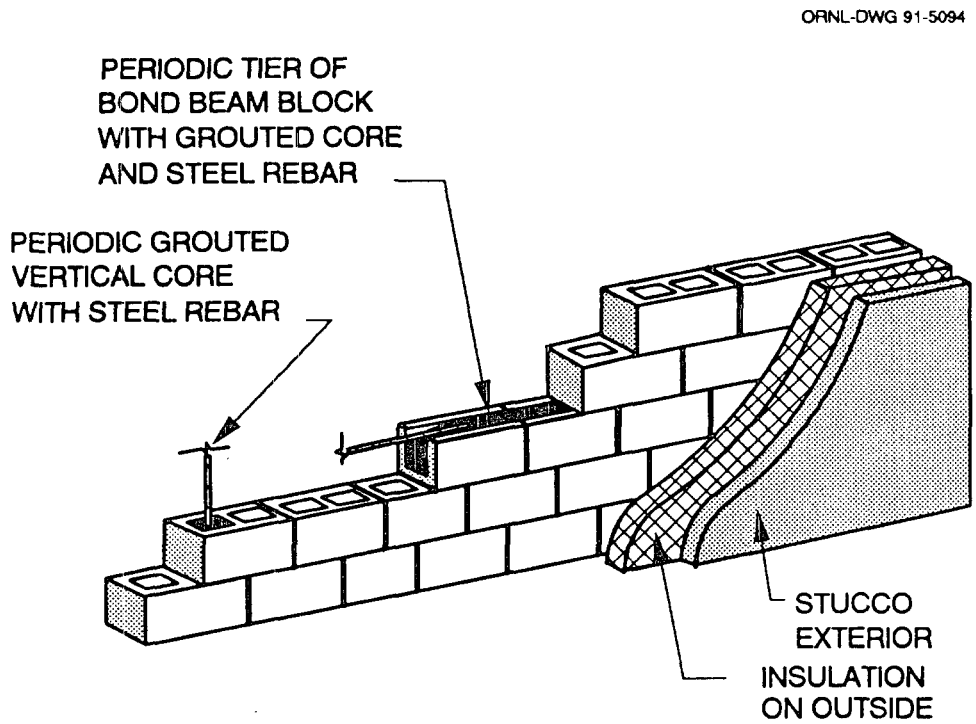

Fig. 9.1. Typical masonry wall in retail mall and warehouse.

The masonry wall of Fig. 9.1 consists of 203 mm (8 in) heavyweight concrete block partially filled with concrete, with foam board on the outside covered with a 12.7 mm (0.5 in) layer of stucco. The partial concrete fill is for reinforcement. Periodically, a tier of bond beam block is used for horizontal reinforcement, and a vertical core is used for vertical reinforcement. The concrete block is sealed and painted on the inside. In North America this wall system is often referred to as EIFS (exterior insulation and finish system).

The foam-core metal panel wall of Fig. 9.2 consists of profiled steel wraps or faces with factory-filled PUR/PIR foam cores. The steel has a baked enamel finish on both the inside and outside.

The two walls are typical constructions although not necessarily the most common. They were selected because they provide bounding conditions on the energy impact of foam board. The masonry wall has high thermal mass and placing the insulation on the outside maximizes the thermal mass effect. At the other extreme, the foam-core metal panel has very low mass.

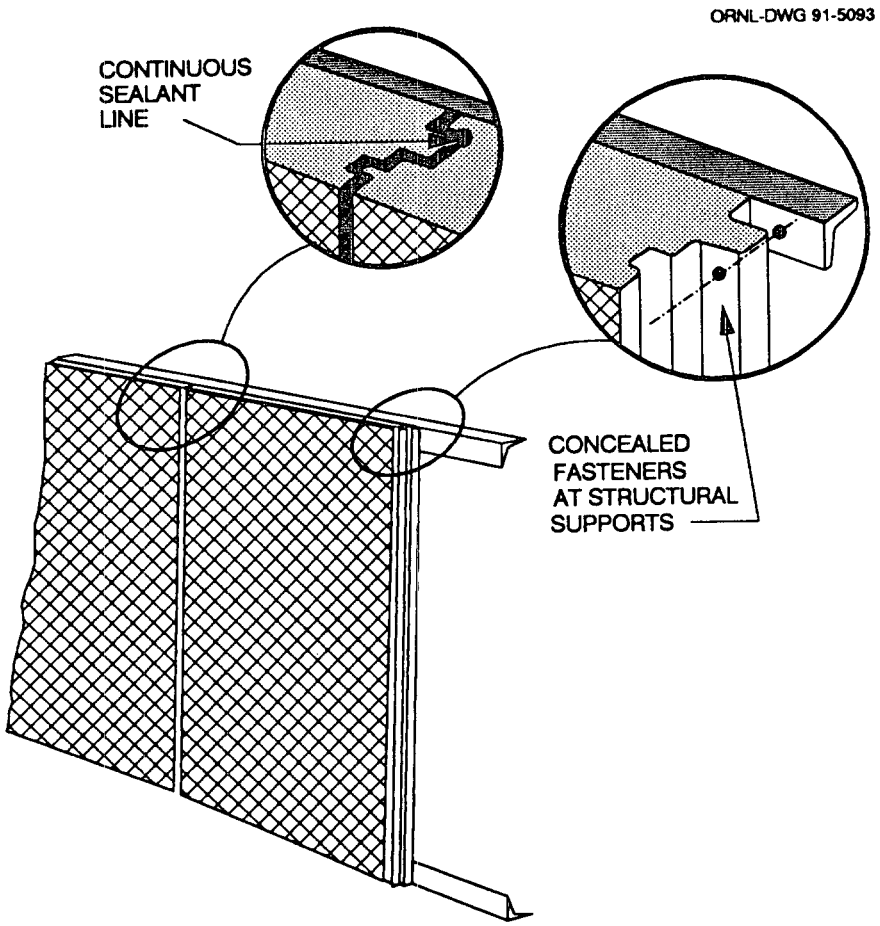

Fig. 9.2. Typical foam core metal panel wall in retail mall and warehouse.

Commercial roof constructions common in North America include sloped roofs with shingles, shakes, slate, or tile; and low-sloped roofs with a wide variety of alternate weather-sealing techniques such as built-up, synthetic or rubber (1-ply), and metal surfacing (EIA, 1988). Sloped roofs are typically insulated with fiberglass batts or blown insulation. Low-slope roofs are typically insulated with foam board, other boards, or combinations. Since the weather-sealing method has a negligible effect on thermal performance, one typical low-slope roof could be defined as illustrated in Fig. 9.3.

In Europe, there appears to be a greater variety of roof constructions using foam board (Galloway, 1991). Metal faced sandwich panel roof sheeting is commonly used on buildings with sandwich panel walls. Also common are foam board suspended ceilings and foam board under pitched roofs. However, the low-slope roof of Fig. 9.3 is also a common construction practice in Europe.

The low-slope roof of Fig. 9.3 has one minor variation to differentiate between retail mall and warehouse practice. Retail malls typically have dropped ceilings whereas the roof deck supports in warehouses are left exposed. A steel deck covered with insulation and then a built-up roofing weather seal was assumed. Depending on local fire codes, a sublayer between the foam board and metal deck may be required but was not considered here.

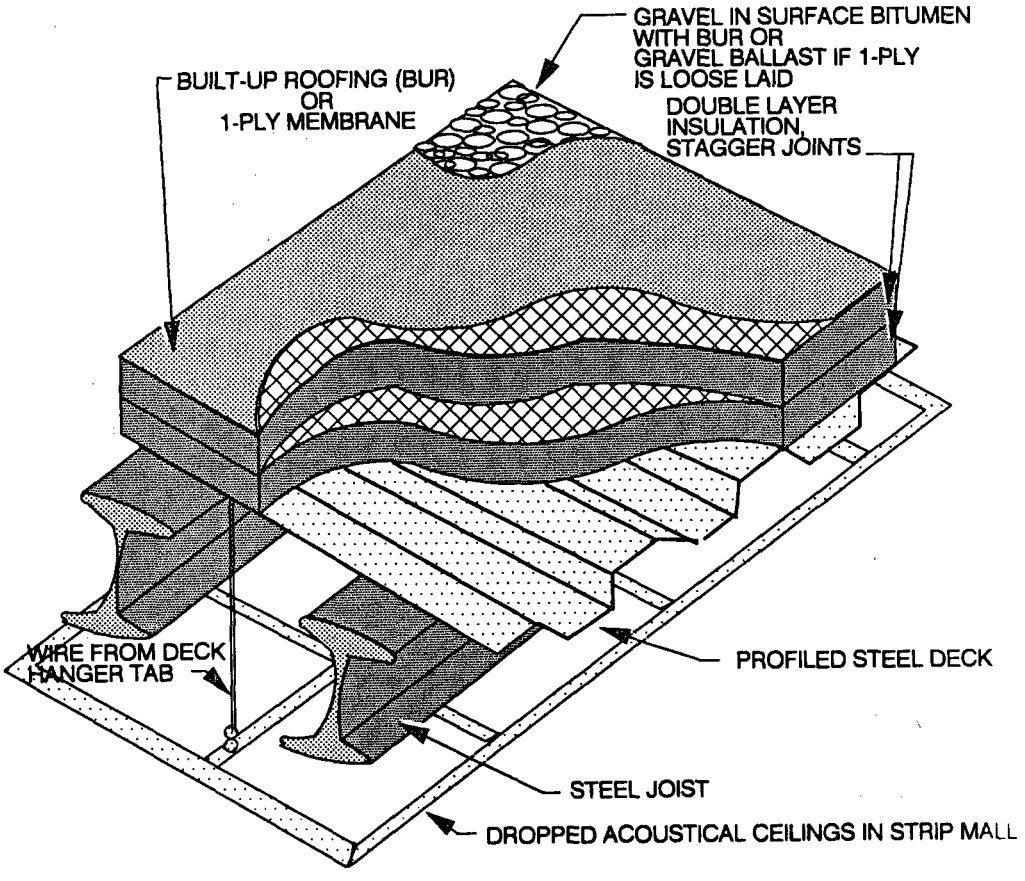

Fig. 9.3. Typical low-slope roof in retail mall and warehouse.

The retail mall and warehouse reference building characteristics are summarized in Table 9.3 and described in detail elsewhere (DOE, 1983). The retail mall prototype includes the end unit store and the next-to-end unit store. Other stores in the mall are similar and not included in the analysis. Adjoining stores have common walls. Walls are 4.9 m (16 ft) from floor to roof deck, with the dropped ceiling at the 3.7 m (12 ft) level. The stores have a modest amount of display glass in front. Each store has its own packaged rooftop unit for zone control. Air-side economizers are not common in this first-cost driven market and were not included. Over 80% of the retail floorspace in the 1986 U.S. commercial building stock was cooled (EIA, 1988) and cooling share in new construction and renovation markets is believed to be higher. European statistics were not available, but it was assumed that typical applications would be heated and cooled there as well.

The warehouse prototype includes a lunch room/locker area within the main warehouse and an office area centered on the long wall in the front of the warehouse. Only the warehouse and office area have external walls. The warehouse walls are 7.6 m (25 ft) from floor to roof deck. The office walls are 2.7 m (9 ft) from floor to roof deck with a dropped ceiling at the 2.4 m (8 ft) level. The warehouse has loading docks and doors but no windows. The office has typical window area.

The office and lunch/locker areas have their own packaged rooftop units for zone control. Warehouse floorspace in North America and Europe may or may not be cooled, so it was decided to evaluate both cases. When heated and cooled, the warehouse has packaged rooftop equipment.

Otherwise, it is heated with unit heaters and passively ventilated. None of the rooftop units have air-side economizers. The HVAC equipment efficiencies in both the retail mall and warehouse are based on the 1992 minimum efficiency levels in ASHRAE/IES Standard 90.1-1989.

Table 9.3 Retail Mall and Warehouse Building Characteristics

	Retail Mall heat/cool	Warehouse heat/cool	Warehouse heat/vent
Gross Floor Area - $m^2(ft^2)$	1093 (11760)	3786 (40752)	same
Length/Width- m(ft)			
End unit store	36.6/24.4 (120/80)		
Next-to-end unit store	16.5/12.2 (54/40)		
Warehouse gross area		98.1/36.6 (322/120)	same
Lunch/locker area (w/i warehouse)		22.8/9.1 (75/30)	same
Office area		20.1/4.8 (66/32)	same
Number of Floors	1	1	same
Floor-to-Floor Height - m(ft)			
Stores - full	4.9 (16)		
Stores - to dropped ceiling	3.7 (12)		
Warehouse		7.6 (25)	same
Office area - full		2.7 (9)	same
Office area - to dropped ceiling		2.4 (8)	same
Gross External Wall Area - $m^2(ft^2)$	648.1 (6976)	2107 (22676)	same
% windows, doors, etc.	16.4%	4.42%	same
Roof Construction	Low-slope (Fig. 9.3)	Low-slope (Fig. 9.3)	same
Wall Construction	Masonry (Fig. 9.1) or Metal Panel (Fig. 9.2)	Masonry (Fig. 9.1) or Metal Panel (Fig. 9.2)	same
Set Temperatures - •C (•F)			
Winter - occupied	21.1 (70)	20 (68)*	20 (68)*
Winter - unoccupied	12.8 (55)	12.8 (55)*	12.8 (55)*
Summer - occupied	24.4 (76)	25.6 (78)*	no control
Note: "*" indicates that lunch/locker and office area setpoints are same as for retail mall.			
HVAC Equipment			
Stores (separate units each)	packaged rooftop		
Warehouse		packaged rooftop	unit heaters
Lunch/locker		packaged rooftop	same
Office area		packaged rooftop	same
Heating Energy	gas,oil,or electric	gas,oil,or electric	same
HVAC Equip Efficiency			
Cooling EER - Wth/We (Btu/Wh)	2.61 (8.9)	2.49 (8.5)	—
Heating seasonal efficiency-electric	100%	100%	same
Heating seasonal efficiency-gas or oil	78%	78%	same

Table 9.3 Retail mall and warehouse building characteristics (continued)			
	Retail Mall heat/cool	Warehouse heat/cool	Warehouse heat/vent
INTERNAL LOADS			
Peak lighting load - $W/m^2(W/ft^2)$			
Stores	33.2 (3.08)		
Warehouse		5.2 (0.48)	same
Lunch/locker		16.1 (1.5)	same
Office area		32.3 (3.0)	same
Peak equipment plug load-$W/m^2(W/ft^2)$			
Stores	2.7 (0.25)		
Warehouse		1.1 (0.1)	same
Lunch/locker		8.1 (0.75)	same
Office area		8.1 (0.75)	same
Peak occupancy loads - $W/m^2(W/ft^2)$			
Stores (50% latent)	42.0 (3.9)		same
Warehouse (50% latent)		1.1 (0.1)	same
Lunch/locker (50% latent)		7.5 (0.7)	same
Office area (50% latent)		10.8 (1.0)	same
Note: Weekday, Saturday, Sunday/Holiday 24-hr diversity schedules as per ASHRAE/IES Standard 90.1-1989.			
Occupied Hours Per Year-hr	4140	2370	same

The baseline walls, roof, and buildings were selected to yield typical insulation-related heating and cooling energy consumptions for use in estimating INDIRECT contributions to global warming or various insulation options. Many commercial building types in addition to retail malls and warehouses use foam board, and many wall and roof cross-sectional designs are available in addition to the ones selected. The analysis was not intended to be all inclusive, only representative.

9.3 FOAM BOARD BENEFITS AND ALTERNATIVES

PUR/PIR Foam Boards

Benefits

PUR/PIR foams are light-weight, cost-effective, and have superior thermal properties. With foil, glass fiber, or rigid facer laminate PUR/PIR also has good-to-excellent compressive strength, rigidity, and moisture resistance, and excellent flammability characteristics.

All foam plastics are combustible and PUR/PIR is no exception. However, excellent flammability characteristics have been achieved with facer laminate and additive technology. For example certain PUR/PIR foams have passed tests allowing their direct use on metal roof deck constructions without the need for a separate thermal barrier. Also certain laminates can be directly sealed with hot bitumen when used on roofs.

Workmen are able to handle large sheets of PUR/PIR in most practical thicknesses in site-applied insulation applications due to its light weight. The much heavier mineral and glass fiber alternatives are also thicker for the same thermal value and must be handled in smaller sheets, increasing installation time and cost. In some applications the higher weights of these materials may also influence structural design and cost. Molded expanded polystyrene (MEPS), i.e.,beadboard, also is light and available in large sheets but is more prone to breakage and requires extra care and time in handling, transport, storage, and installation.

PUR/PIR foam boardstock exhibit excellent adhesion to a range of facing materials and it can be continuously laminated to various facing materials, such as aluminum foil, paper, glass roofing felts, and rigid steel and plasterboard. These processing characteristics make PUR/PIR foams uniquely suited to the cost-effective production of foam core products such as metal sandwich panels for walls and roofs, foam/plasterboard composites for masonry wall dry-lining, and foam/plasterboard sandwich panels for interior partitions. Factory-insulated building components save site-labor and overall cost, and improve quality control.

Benefits of Historical CFC Blowing Agent

Polyurethane (PUR) foams are formed by the reaction of a polyisocyanate with a polyol in the presence of a catalyst, surfactant, and blowing agent (Mann, 1988). Polyisocyanurate (PIR) foams are formed when excess polyisocyanate in the formulation reacts with itself to form trimer polyisocyanurate structures. North American boardstock is almost entirely PIR for its superior flammability performance. European boardstock is split between PUR and PIR (UNEP, 1989). Additives are often used to provide specific properties or processing advantages (e.g., fire retardants) and sometimes small amounts of CFC-12 have been used for processing reasons. Historically CFC-11 has been the blowing agent for PUR/PIR foam boardstock because of the following properties:

- non-toxic,
- nonflammable,
- nonreactive,
- noncorrosive,
- soluble in polyols (A) and polyisocyanate (B), i.e., complete freedom to distribute between A and B streams to optimize processing,
- lowers the viscosity of structurally desirable polyols enabling their use,
- enhances mixing via general viscosity reduction and compatibilizing effect,
- ideal boiling point,
- low gas thermal conductivity,
- low diffusion rate through resulting foam structure,
- low solubility in resulting foam structure solids, and
- provides a means of density control.

The heat generated by the exothermic reaction when the A and B streams mix converts the liquid CFC-11 to vapor causing the reaction mixture to foam and form a cellular structure. The CFC-11 gas is then encapsulated as the polymerization reaction proceeds to completion and the cell matrix solidifies. The amount of CFC-11 in the formulation controls the final density of the foam.

Once the foam is made it is the low gas conductivity of CFC-11 that contributes to the superior thermal characteristic of PUR/PIR foams. Other important properties of CFC-11 (i.e., low diffusion rate and low solubility in foam solids) enable PUR/PIR foams to retain excellent thermal properties for long periods of time.

Alternative Blowing Agents

The industry has been focusing its resources on the development of formulations that totally replace CFC-11 with HCFC blowing agents, or formulations that partially replace CFC-11 by using CFC-11/water mixtures. In the latter case, water reacts with polyisocyanate to generate CO_2 that acts as a blowing agent (Mann, 1988). In addition at least one other non-CFC, non-HCFC blowing agent technology has been commercialized (Creyf, 1991) and others are under investigation.

The CFC-11/water mixture approach may be able to displace 20% to 30% of the CFC-11 in PUR boardstock and 10% to 15% in PIR boardstock before other properties such as friability, adhesion, and flammability become unacceptable (Mann, 1988; UNEP, 1989). This approach may help decrease CFC-11 consumption in the short term, particularly in Europe where PUR is used extensively, but does not appear to be a viable alternative for the full replacement of CFC-11. Furthermore thermal properties, particularly in permeably-faced materials, would be significantly degraded.

The primary HCFCs under consideration are HCFC-123 and HCFC-141b. The extent to which these materials replicate the advantages of CFC-11 in the foaming process is still under investigation. The HCFCs are not drop-in replacements and formulations and processing will have to be optimized for each. Based on gas thermal conductivities it is clear that the HCFCs will not produce foams that match the thermal properties of CFC-11 foams unless cell size or other characteristics can be improved. However HCFC blown foams will be significantly better than CO_2-filled or air-filled foams.

A PUR/PIR foam has become commercially available that uses isopropylchloride (hereafter IPC) as the blowing agent (Creyf, 1991). IPC is neither a CFC nor an HCFC. Based on the gas thermal conductivity, the thermal performance of IPC foam is expected to be somewhat less favorable than that of the HCFCs.

Properties of PUR/PIR With Alternate Blowing Agents And Alternate Insulations

The properties of PUR/PIR with alternative blowing agents and of the identified not-in-kind alternative types of insulations are summarized in Table 9.4. It is widely known that the thermal properties of PUR/PIR boardstock vary with time and thickness. The service life of insulation in low-slope roofs is approximately 15 years (GSN, 1988; Aulisio, 1991). Insulation service life in walls can vary widely with the life of the building but here it is assumed to be 50 years. Table 9.4 presents average R/thickness values over these service lives at 2.54 cm (1.0 in), 5.08 cm (2.0 in), and 7.62 cm (3.0 in) insulation thicknesses.

The method used to estimate the average R/thickness values is presented in Appendix K, along with curves to estimate the values at any thickness. The values for PUR/PIR blown with CFC-11, HCFC-123, and HCFC-141b are based on laboratory measurements at 24° C (75° F) (McElroy, 1990; McElroy, March 1991) on materials with permeable facings. It is understood that the HCFC foams tested were early formulations that may not have been optimum. The engineering judgments made to estimate the values for impermeable facings (McElroy, May 1991), IPC blown PUR/PIR (Creyf, 1991; McElroy, May 1991), fresh foam, and air-filled foam are described in Appendix K.

The nominal density of 32 kg/m^3 (2.0 pcf) was assumed for all PUR/PIR materials to maintain consistency with the available thermal property data. It is understood that densities and thermal properties in some applications may differ somewhat; for instance 40 kg/m^3 (2.5 pcf) is more typical for foam core metal panels (Jeffs, February 1991). The blowing agent weight percent for CFC-11 is the historical typical value whereas the HCFC and IPC values are based on experience to date (Aulisio, 1991; Creyf, 1991).

Table 9.4. Properties of PUR/PIR with alternative blowing agents and of the identified not-in-kind alternative insulations

	nominal density kg/m³ (lb/ft³)	Wt. % Blowing Agent (%)	Average R/thickness over service life: 2.54 cm(1 in.)	5.08 cm(2 in.)	7.62 cm(3 in.)
			m²-K/W-cm for all 3 columns (ft²-h-°F/BTU-in for all 3 columns)		
PUR/PIR--15 Year Service Life (Roofs)					
(a) PUR/PIR materials with permeable facings					
PUR/PIR: CFC-11	32(2.0)	15.0	.420(6.06)	.450(6.49)	.466(6.73)
PUR/PIR: HCFC-123	32(2.0)	18.75	.392(5.66)	.414(5.98)	.428(6.18)
PUR/PIR: HCFC-141b	32(2.0)	12.75	.382(5.51)	.400(5.77)	.410(5.92)
PUR/PIR: IPC	32(2.0)	9.0	.342(4.94)	.362(5.23)	.373(5.39)
PUR/PIR: air	32(2.0)	--	.283(4.08)	.283(4.08)	.283(4.08)
(b) PUR/PIR materials with impermeable facings (40-50 micron aluminum foil)					
PUR/PIR: CFC-11	32(2.0)	15.0	.536(7.73)	.555(8.01)	.561(8.10)
PUR/PIR: HCFC-123	32(2.0)	18.75	.489(7.06)	.507(7.31)	.513(7.40)
PUR/PIR: HCFC-141b	32(2.0)	12.75	.464(6.69)	.479(6.92)	.484(6.99)
PUR/PIR: IPC	32(2.0)	9.0	.427(6.16)	.442(6.38)	.448(6.46)
PUR/PIR: air	32(2.0)	--	.283(4.08)	.283(4.08)	.283(4.08)
PUR/PIR--50 Year Service Life (Walls)					
(a) PUR/PIR materials with permeable facings (masonry wall only)					
PUR/PIR: CFC-11	32(2.0)	15.0	.379(5.47)	.424(6.12)	.442(6.38)
PUR/PIR: HCFC-123	32(2.0)	18.75	.361(5.21)	.395(5.70)	.409(5.90)
PUR/PIR: HCFC-141b	32(2.0)	12.75	.357(5.16)	.384(5.54)	.395(5.70)
PUR/PIR: IPC	32(2.0)	9.0	.316(4.56)	.345(4.98)	.357(5.15)
PUR/PIR: air	32(2.0)	--	.283(4.08)	.283(4.08)	.283(4.08)
(b) PUR/PIR materials with impermeable facings (40-50 micron aluminum foil) (both walls)					
PUR/PIR: CFC-11	32(2.0)	15.0	.505(7.29)	.539(7.78)	.550(7.94)
PUR/PIR: HCFC-123	32(2.0)	18.75	.461(6.66)	.492(7.10)	.503(7.26)
PUR/PIR: HCFC-141b	32(2.0)	12.75	.439(6.34)	.466(6.73)	.476(6.87)
PUR/PIR: IPC	32(2.0)	9.0	.403(5.81)	.430(6.20)	.439(6.33)
PUR/PIR: air	32(2.0)	--	.283(4.08)	.283(4.08)	.283(4.08)
(c) PUR/PIR--Sealed to Preserve Fresh Foam Insulating Values (metal panel wall only)					
PUR/PIR: CFC-11	32(2.0)	15.0	.574(8.29)	.574(8.29)	.574(8.29)
PUR/PIR: HCFC-123	32(2.0)	18.75	.525(7.57)	.525(7.57)	.525(7.57)
PUR/PIR: HCFC-141b	32(2.0)	12.75	.495(7.15)	.495(7.15)	.495(7.15)
PUR/PIR: IPC	32(2.0)	9.0	.458(6.61)	.458(6.61)	.458(6.61)
Not-In-Kind Alternative Types of Insulation					
(a) For low-slope roofs					
MEPS: pentane	16(1.0)	6.0	.263(3.80)	.263(3.80)	.263(3.80)
Glass fiber, organic bonded	186(11.6)	--	.273(3.94)	.273(3.94)	.273(3.94)
Mineral fiber, resin bonded	240(15.0)	--	.239(3.45)	.239(3.45)	.239(3.45)
(b) For EIFS masonry walls					
MEPS: pentane	16(1.0)	6.0	.263(3.80)	.263(3.80)	.263(3.80)

Handbook values were used for the properties of the not-in-kind insulation alternatives of MEPS (ASHRAE, 1989), organic-bonded glass fiber (NRCA, 1991), and resin-bonded mineral fiber (ASHRAE, 1989) with the exception of the R/thickness value for MEPS. This value was set equal to the R/thickness for air-filled XEPS derived as explained in Appendix K.

Applications of PUR/PIR and Alternative Insulations

The applicable insulation products for low-slope roofs are permeably-faced PUR/PIR made with various blowing agents, impermeably-faced PUR/PIR made with various blowing agents, MEPS, mineral fiber, and glass fiber. The analysis was also carried through for air-filled PUR/PIR as a reference to indicate thermal performance of permeably-faced water-reaction-CO_2 blown foam if a technique for making boardstock in this way is eventually found. Data were not available to estimate the performance of this hypothetical material with impermeable facers (i.e., CO_2-filled foam).

For EIFS masonry walls the same insulation products apply with the exception of mineral fiber and glass fiber. The latter materials are not suitable for this application because of their moisture characteristics.

Only PUR/PIR materials apply for foam core metal panel walls. By definition the metal panels have impermeable facings. In this application sealing may also be possible so that the fresh foam thermal properties are preserved over the service life of the building component. Therefore the analysis was carried through for both impermeably-faced and fresh foam materials properties.

Closed-cell phenolic foams are another class of foam insulation that historically used CFC-11, CFC-113, or mixtures of the two as the blowing agent (UNEP, 1989). Phenolics have many of the properties of PUR/PIR foams but are newer on the market, more expensive, and see much less use. As with PUR/PIR, HCFCs are being investigated as alternative blowing agents for phenolics (UNEP, 1989). But unlike PUR/PIR, phenolic chemistry is compatible with HFCs and HFC-based products are under development (Linger, 1991). If these developments are successful they may provide another insulation alternative, depending on cost and other characteristics. Data were not available to include this material in the analysis.

XEPS Foam Boards

Benefits

XEPS foams are light-weight, cost-effective, and have good thermal properties. XEPS also has outstanding resistance to moisture and freeze-thaw cycling in the presence of moisture, excellent compressive strength, and good handling characteristics. Flammability characteristics are good and certain XEPS foams have also passed tests allowing their direct use on metal roof deck constructions without the need for a separate thermal barrier.

XEPS can be used in most of the standard site-applied insulation applications in commercial buildings. However superior moisture resistance and compressive strength makes XEPS uniquely suited for use above waterproofing membranes in Protected Membrane Roof (PMR), roof terrace, plaza deck, and parking deck constructions. XEPS is also the material of choice for insulated foundations, basements, floor slabs, and earth-sheltered homes. In some northern countries the material is used beneath roads, railways, and pipelines to prevent frost-heave.

For site-applied insulation applications XEPS has the same advantages as were outlined previously for PUR/PIR, relative to the heavier mineral and glass fiber materials and to MEPS. Its light weight

and superior mechanical properties allow large boards to be handled without undue concern or care taken to prevent damage.

XEPS comes in two varieties, smooth-skinned and planed (cut-cell). The planed material provides grip for adhesive, plaster, and pour-in-place concrete applications. The planed material can be used to factory-assemble composites such as sandwich panels but not in a continuous process as with PUR/PIR.

Benefits of Historical CFC Blowing Agent

XEPS was first commercialized in the 1940s with methyl chloride as the blowing agent. CFC-12 was introduced as the blowing agent in the early 1960s enabling more structurally stable foam with improved thermal properties. CFC-12 was selected because of the following properties:

- non-toxic,
- nonflammable,
- nonreactive,
- noncorrosive,
- soluble in the molten polymer,
- ideal boiling point,
- low gas thermal conductivity, and
- low diffusion rate through resulting foam structure.

Molten polymer is mixed with additives and liquid blowing agent at high temperature and pressure to form a foamable gel. The gel is cooled and pumped through an orifice where the blowing agent vaporizes causing the polymer to expand, cool, and stabilize into a cellular structure. Auxiliary blowing agents or vacuum are often used to decrease the amount of CFC-12 required. The auxiliary blowing agents; typically methyl chloride, ethyl chloride, or hydrocarbons (butane and pentane); diffuse out of the foam in a relatively short period of time.

Once the foam is made it is the low gas conductivity of CFC-12 that contributes to the enhanced thermal characteristic of XEPS foams. Another important property of CFC-12, i.e., the low diffusion rate through the resultant foam, enables XEPS foams to retain excellent thermal properties for long periods of time.

Alternative Blowing Agents

The XEPS industry has aggressively embraced HCFC-142b as a replacement for CFC-12. Most producers are well on the way or have completed the conversion of production to HCFC-142b (Minsker, May 1991). Other alternative blowing agents that have received consideration include HCFC-124 and HFC-134a (UNEP, 1989).

Properties of XEPS With Alternate Blowing Agents And Alternate Insulations

The properties of XEPS with alternative blowing agents and of the identified not-in-kind alternative types of insulations are summarized in Table 9.5. As with PUR/PIR, the thermal properties of XEPS also vary with time and thickness. Table 9.5 presents average R/thickness values over the 15 year roof and 50 year wall service lives at 2.54 cm (1.0 in), 5.08 cm (2.0 in), and 7.62 cm (3.0 in) insulation thicknesses.

Table 9.5. Properties of XEPS with alternative blowing agents and of the identified not-in-kind alternative insulations

	nominal density kg/m³ (lb/ft³)	Wt. % Blowing Agent (%)	Average R/thickness over service life: 1 in.	2 in.	3 in.
			m²-K/W-cm for all 3 columns (ft²-h-°F/BTU-in for all 3 columns)		
XEPS--15 Year Service Life (Roofs)					
(a) XEPS materials--limited ORNL testing for thermal properties					
XEPS: CFC-12	32(2.0)	6.0	.288(4.15)	.321(4.63)	.333(4.81)
XEPS: HCFC-124	32(2.0)	6.7	.288(4.15)	.321(4.63)	.333(4.81)
XEPS: HFC-134a	32(2.0)	5.1	.288(4.15)	.321(4.63)	.333(4.81)
XEPS: HCFC-142b	32(2.0)	5.0	.288(4.15)	.321(4.63)	.333(4.81)
XEPS: air	32(2.0)	--	.283(3.80)	.283(3.80)	.283(3.80)
XEPS--50 Year Service Life (Walls)					
(a) XEPS materials--limited ORNL testing for thermal properties					
XEPS: CFC-12	32(2.0)	6.0	.268(3.87)	.293(4.23)	.313(4.52)
XEPS: HCFC-124	32(2.0)	6.7	.268(3.87)	.293(4.23)	.313(4.52)
XEPS: HFC-134a	32(2.0)	5.1	.268(3.87)	.293(4.23)	.313(4.52)
XEPS: HCFC-142b	32(2.0)	5.0	.268(3.87)	.293(4.23)	.313(4.52)
XEPS: air	32(2.0)	--	.283(3.80)	.283(3.80)	.283(3.80)
(b) XEPS materials--industry values for thermal properties					
XEPS: CFC-12	32(2.0)	6.0	.314(4.53)	.320(4.62)	.326(4.70)
XEPS: HCFC-124	32(2.0)	6.7	.314(4.53)	.320(4.62)	.326(4.70)
XEPS: HFC-134a	32(2.0)	5.1	.314(4.53)	.320(4.62)	.326(4.70)
XEPS: HCFC-142b	32(2.0)	5.0	.314(4.53)	.320(4.62)	.326(4.70)
XEPS: air	32(2.0)	--	.283(3.80)	.283(3.80)	.283(3.80)
Not-In-Kind Alternative Types of Insulation					
(a) For low-slope roofs					
MEPS: pentane	16(1.0)	6.0	.283(3.80)	.283(3.80)	.283(3.80)
Glass fiber, organic	186(11.6)	--	.273(3.94)	.273(3.94)	.273(3.94)
bonded	240(15.0)	--	.239(3.45)	.239(3.45)	.239(3.45)
Mineral fiber, resin bonded					
(b) For EIFS masonry walls					
MEPS: pentane	16(1.0)	6.0	.283(3.80)	.283(3.80)	.283(3.80)

Very little measured data are available on the thermal properties of XEPS with alternative blowing agents, and estimates are made from limited test data from the foam industry and ORNL. Industry has proposed a set of 50 year average R/thickness values for CFC-12 blown foam based on their own testing (Minsker, May 1991). These data were used in the analysis for wall insulation in the 50 year service life of masonry walls (the conclusions were also corroborated using aged foam R-values derived by McElroy in Appendix K). In this case XEPS blown with the HCFCs and HFCs were assumed to have similar behavior to XEPS blown with CFC-12. The method used to estimate the average R/thickness values for roof insulation is presented in Appendix K, along with curves to

estimate the values at any thickness. The values for XEPS blown with HCFC-142b are based on laboratory measurements at 24° C (75° F) (McElroy, March 1991). Since no data were available it was assumed that all of these materials would have similar thermal behavior. Average service life R/thickness values for XEPS only exceed air-filled values by at most 25%, compared to 100% for PUR/PIR. This means that the impact of alternate XEPS blowing agents on INDIRECT global warming estimates should be about a factor of four smaller than the impact of alternate PUR/PIR blowing agents. It was reasoned that since the latter impact was small, the assumption that alternate XEPS blowing agents had no impact on INDIRECT global warming was within the precision of the analysis. The air-filled foam value is derived as described in Appendix K.

The nominal density of 32 kg/m^3 (2.0 lb/ft^3) was assumed for all XEPS materials to maintain consistency with the available thermal property data. It is understood that densities and thermal properties in some applications may differ somewhat. The blowing agent weight percent for CFC-12 was assumed to equal the historical value. Weight percent values for the other blowing agents were estimated using the ratio of the molecular weights. This assumption was judged to be within the precision of the analysis (Minsker, May 1991). XEPS can be made with primary blowing agent only, or a combination of primary and auxiliary blowing agents. If only primary blowing agent is used, on the order of 10 weight percent of CFC-12 would be required (Shankland, 1991; MSDS, 1991). Historical production values are lower (Booth, 1991; Minsker, 1991).

Handbook values were used for the properties of the not-in-kind insulation alternatives of MEPS (ASHRAE, 1989), organic-bonded glass fiber (NRCA, 1991), and resin-bonded mineral fiber (ASHRAE, 1989) with the exception of the R/thickness value for MEPS. This value was set equal to the R/thickness for air-filled XEPS derived as explained in Appendix K.

Applications of XEPS and Alternative Insulations

For low-slope roofs the applicable insulation products are XEPS made with various blowing agents, MEPS, mineral fiber, and glass fiber. The analysis was also carried through for air-filled XEPS as a reference since XEPS can be, and in the past has been, made with blowing agents that do not remain resident in the foam to enhance thermal properties.

For EIFS masonry walls the same insulation products apply with the exception of mineral fiber and glass fiber. The latter materials are not suitable for this application because of their moisture characteristics. XEPS and its alternatives are not considered for the foam core metal panel end-use because it is not a significant market for XEPS.

The metal panel wall application was not judged to be a significant end-use for XEPS.

9.4 METHODOLOGY

This section describes the methods used to estimate the DIRECT and INDIRECT components of TEWI for the various insulation alternatives. The analysis compares PUR/PIR insulations made with the historical CFC-11 and alternative blowing agents, and also compares XEPS made with the historical CFC-12 and alternative blowing agents. Not-in-kind alternative types of insulation are also evaluated in the various PUR/PIR and XEPS end-uses for reference.

Three foam board end-uses have been identified for the analysis: low-slope roofs, masonry walls, and metal panel walls. The PUR/PIR alternatives are evaluated in all end-uses and the XEPS alternatives are evaluated in low-slope roofs and masonry walls. Comparisons are made for constant thicknesses

of insulation, and as a result calculations for alternative materials with lower thermal resistivity lead to higher energy use. Calculations for residential building insulation are performed assuming both constant insulation thickness and also assuming constant wall thermal resistance resulting from thicker layers of poorer insulating materials (see Sections 10.3 to 10.6). These simplifying assumptions lead to some important valid conclusions. A more rigorous analysis reflecting the actual decision making processes based on fluctuating material and labor costs is beyond the scope of this study and the results would be very sensitive to the unknown future prices.

DIRECT CO_2 Emissions

The calculations to estimate the DIRECT (blowing agent loss) component of TEWI are summarized in Table 9.6. Inputs to the calculation are the blowing agent weight percent (Tables 9.4 and 9.5), the 500 year GWP (IPCC, 1990), and the weight of foam insulation represented in the composite whole-building insulation end-uses for each region. For all foam insulations it is assumed that the blowing agent is lost to the environment either while in service or at retirement.

The composite whole-building insulation end-use weights are derived from the weight of insulation in those end-uses in specific buildings/locations using the weighting factors described in Appendix K, Table K.11. The resulting estimates of equivalent DIRECT CO_2 emissions are on the basis of the end-use in a typical composite whole-building application in the region. For example the DIRECT emissions for low-slope roofs in North America are a composite of DIRECT emissions for the low-slope roofs in the reference retail mall and the reference warehouse in Chicago and Atlanta. The composite building insulation weights, insulated areas, and insulation thicknesses are also provided in Table 9.6 for reference.

INDIRECT CO_2 Emissions

The calculations to estimate the INDIRECT (energy use) component of TEWI are necessarily quite involved and are explained in detail in Appendix K, Table K.10. The DOE-2.1D building energy analysis computer program (LBL, 1990) was used to estimate annual heating and cooling energy consumption for the retail mall and warehouse in the various locations. The insulation-related annual energies were isolated and multiplied by the appropriate insulation service life and converted to lifetime INDIRECT CO_2 emissions.

The thermal properties of foam boardstock vary with thickness and time. To account for thickness, reasonable values were selected for each building case by following the prescriptive guidelines of a widely recognized model building standard (ASHRAE/IES 90.1-1989). To account for time, average R/thickness values corresponding to the insulation thickness and service life were used in the building energy analysis.

The insulation-related annual heating energies and cooling electricity consumptions were accounted for separately. This enabled regional heating energy and power generation fuel mixes to be considered in the INDIRECT CO_2 emissions calculations.

The insulation-related annual heating and cooling energies are a subset of the total building heating and cooling energies (Appendix K, Table K.9). Heating energies related to insulation ranged from 10% to 30% for opaque walls and from 10% to 20 for low-slope roofs. Cooling energies related to insulation ranged from 0% to 10% for opaque walls and from 0% to 30% for low-slope roofs. The insulation-related energies are defined as the fraction of the heating and cooling loads met that are traceable to heat flows through the insulation. Additional simulations indicated that these energies

closely correspond to savings that could be achieved with adiabatic opaque walls or roofs. As an example, Fig. 9.4 illustrates where the rest of the annual total building heating energy goes in the reference retail mall and reference warehouse in Chicago.

Table 9.6. Summary of DIRECT lifetime equivalent CO_2 emissions calculation

Calculate Direct Emissions as...

Wt.% Blowing Agent	x	Global Warming Potential (GWP)	x	Composite Whole-Building Insulation Weight for End-Use	=	Equivalent Direct CO_2 Emission via Loss of Blowing Agent

$$\left(\frac{\text{kg B.A.}}{\text{kg ins.}}\right) \times \left(\frac{\text{kg } CO_2}{\text{kg B.A.}}\right) \times \left(\frac{\text{kg ins.}}{\text{comp. bldg.}}\right) = \left(\frac{\text{kg } CO_2}{\text{comp. bldg.}}\right)$$

PUR/PIR Composite Whole-Building Insulation Characteristics by End-Use...

	North America			Europe		
	Weight	Thickness	Area	Weight	Thickness	Area
	kg ins. / comp. bldg.	mm	m^2 / comp. bldg.	kg ins. / comp. bldg.	mm	m^2 / comp. bldg.
Low-slope Roof	4205	60.56	2170	4762	68.58	2170
Masonry Wall	966	26.68	1131	1010	27.92	1131
Metal Panel Wall	1576	43.54	1131	1839	50.80	1131
XEPS Composite Whole-Building Insulation Characteristics by End-Use...						
Low-slope Roof	5169	74.44	2170	5644	81.28	2170
Masonry Wall	1140	31.50	1131	1242	34.32	1131

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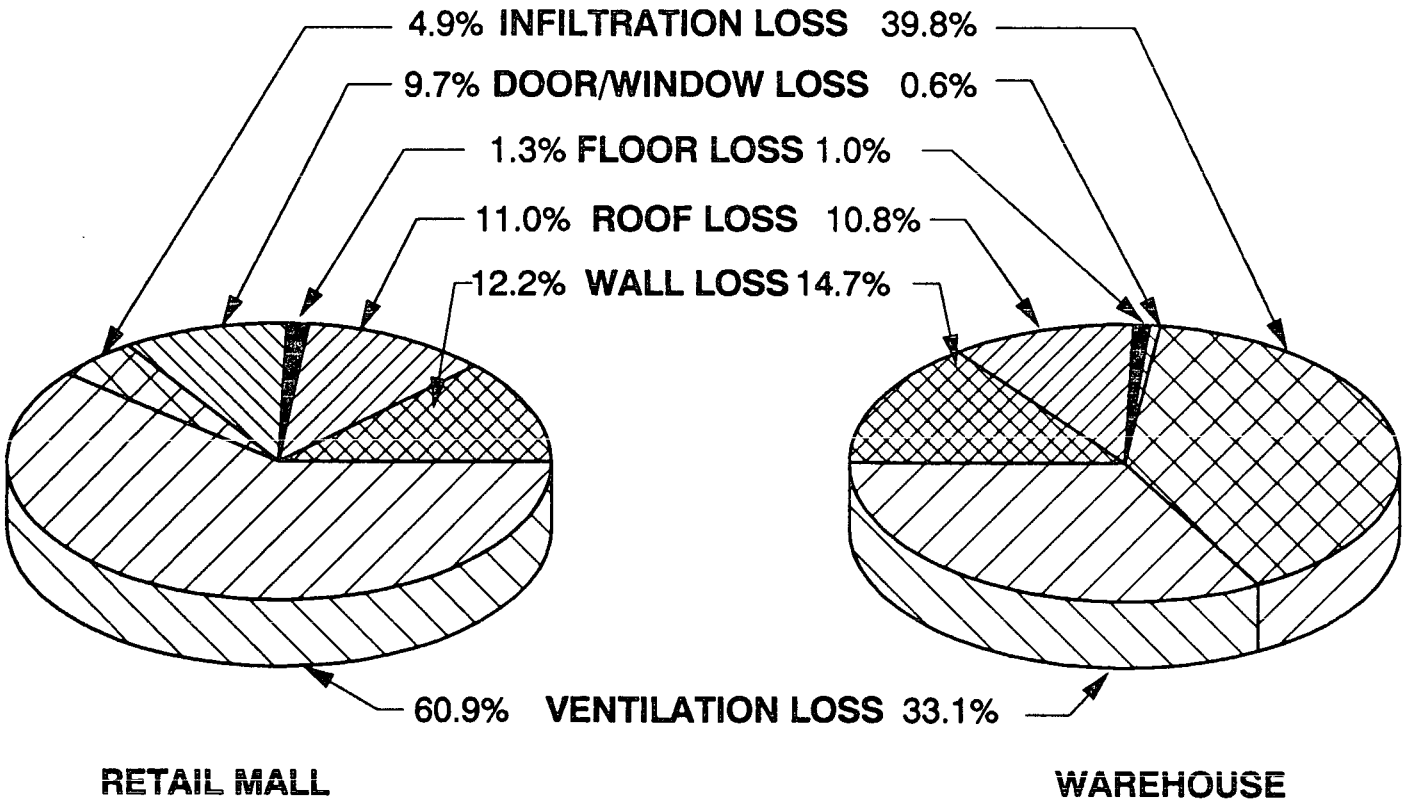

Fig. 9.4. Destination of heating energy delivered to masonry wall buildings in Chicago (roof and walls insulated with permeably-faced CFC-11 blown PUR/PIR).

The insulation-related annual energies are multiplied by insulation service life, converted to lifetime INDIRECT CO_2 emissions, and presented as emissions for composite whole-building insulation end-uses. The composite whole-building end-use values are derived using weighting factors as described in Appendix K. For example the INDIRECT emissions for low-slope roofs in North America are a composite of INDIRECT emissions for the low-slope roofs in the reference retail mall and the reference warehouse in Chicago and Atlanta.

9.5 RESULTS

TEWI results including DIRECT and INDIRECT component breakouts are tabulated for all foam insulation blowing agent alternatives and all not-in-kind (NIK) alternative types of insulation in Appendix L. These same results are presented graphically in Figs. 9.5 through 9.8 for North America and Europe respectively.

Figures 9.5 and 9.6 present the European results and Figs. 9.7 and 9.8 the North American results. For each region, the first figure (Figs. 9.5 and 9.7) contains results for the three PUR/PIR foam end-use applications and the second figure (Figs. 9.6 and 9.8) covers the two XEPS foam end-use applications. Within each end-use application, a column exists for each of the various foam insulation blowing agents or NIK alternatives. The blowing agent or NIK alternatives are identified with labels across the bottom. Groups of columns that are related are identified with word boxes spanning the columns. For example, foam insulations are distinguished from NIK alternatives, and foams with permeable and impermeable facings are differentiated.

The heavily shaded area at the bottom of each column in Figs. 9.5 through 9.8 represents the INDIRECT (energy-related) component of TEWI. The other area represents the DIRECT (blowing agent loss) component. The total column height represents TEWI. The INDIRECT, DIRECT, and TEWI values are expressed as thousands of kilograms of equivalent CO_2 emissions per composite building over the service life of the insulation (15 years in wall, 50 years in roofs). The reader can normalize these values per unit of insulation weight or per unit of insulated area by dividing by the composite building weights or areas provided in Table 9.6.

All columns within one of the three PUR/PIR or two XEPS end-use applications are on a consistent basis and can be compared directly. Comparisons across end-use applications should be avoided because of the different insulation services lives (15 years for roofs, 50 years for walls) and insulation thicknesses (PUR/PIR end-use thicknesses were based on a design value R/thickness of 0.433 m^2-K/cm(6.25 h-ft^2-°F/Btu-in); XEPS end-use thicknesses were based on 0.364 m^2-K/W-cm(5.0 h-ft^2-°F/Btu-in)). All foams and NIK alternatives within an end-use application were evaluated at the same insulation thicknesses.

9.6 CONCLUSIONS

In wall applications once HCFCs replace CFCs, the differences in foam insulation TEWI due to blowing agent are minor. This point is illustrated in Fig. 9.9 where the change in calculated TEWI relative to the CFC base is presented for selected alternatives in each wall end-use evaluated. The reason is that differences between average service life R/thickness values for CFC-blown and HCFC-blown foams are relatively small, making INDIRECT term differences relatively minor. Since the INDIRECT term is dominant in this 50-year service life application, the TEWI differences are also minor. For PUR/PIR foams, the NIK alternative has a significantly lower R/thickness value and a

TEWI value that is significantly higher than for the HCFC foams. This is also true for XEPS foams, although to a lesser extent.

In roof applications once HCFCs replace CFCs, the differences in INDIRECT emissions due to blowing agent are minor as in walls, but TEWIs can be significantly different because the DIRECT term is relatively more important in this 15-year service life application. This point is illustrated in Fig. 9.10 where the change in calculated TEWI relative to the CFC base is presented for selected alternatives in each roof end-use evaluated. The energy uses for NIK insulations are greater as in walls, but in some cases TEWIs are essentially equal to those of the HCFC foams due to the DIRECT term.

For the INDIRECT-dominated wall applications, once HCFCs replace CFCs, the primary avenues for further reductions in TEWI are more or better thermal insulation via improved R/thickness, higher insulation levels, or next-generation materials. The opportunities for NIK alternatives to reduce TEWI in the competitive marketplace may be limited since relatively larger thicknesses, weights, and installed costs would be required.

For roof applications where the INDIRECT term is still larger for HCFC foams but the DIRECT term is considerably more significant, there may be more of an opportunity for next generation foams or NIK alternatives to participate in the reduction of TEWI. This conclusion is linked to the current service life of commercial roofs, as illustrated in Fig. 9.11. Service life could possibly be extended by future improvements in construction and maintenance practices. As service life improves, the roof application also becomes INDIRECT-dominated. The PUR/PIR metal sandwich panel is an example of a roofing technology that extends insulation service life.

Several observations can be made in addition to the above major conclusions. For PUR/PIR foams, the difference between permeable and impermeable facings is minor in roof applications because of the 15-year service life and similar average service life R/thickness values at the relatively large insulation thicknesses typical for roofs. The value of impermeable facings is more evident in masonry walls where insulation thicknesses are modest and service life is longer. The true value of impermeable facings will remain uncertain until thermal properties based on experimental data become available. The thermal properties used here were based on engineering judgment.

The PUR/PIR foam core metal panels were evaluated as sealed systems that preserved fresh foam thermal properties, and as foam with impermeable facings. It made little difference which thermal property assumption was used because the R/thickness values were similar at the relatively large insulation thicknesses in metal panels.

For lack of better data, XEPS foams were assumed to have the same thermal properties regardless of blowing agent. The true thermal properties will remain uncertain until experimental data become available. In masonry walls, XEPS was evaluated with thermal properties based on limited ORNL testing and on industry testing. The results of these two cases may roughly establish the current level of uncertainty in properties. This uncertainty does not influence the major conclusions stated above.

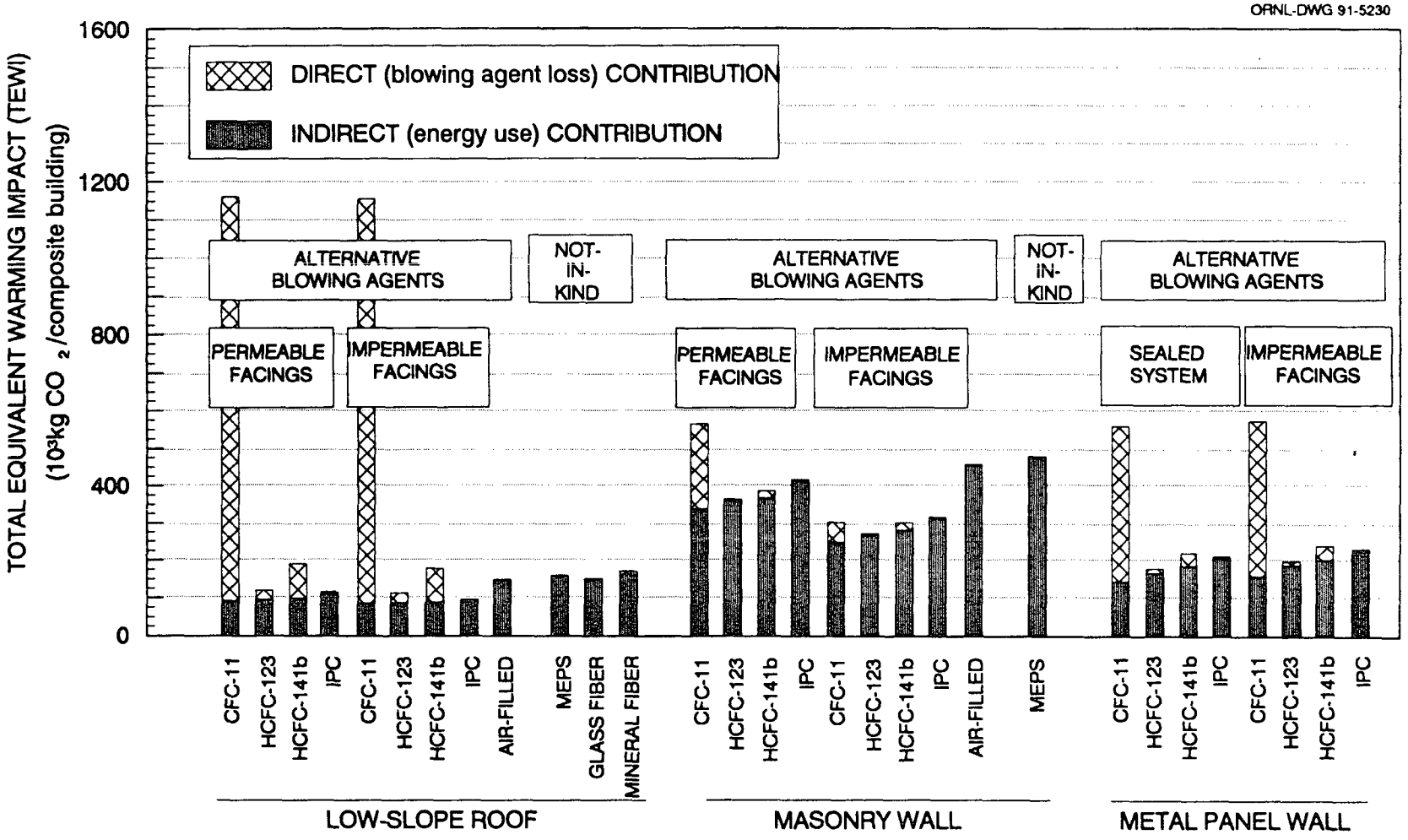

Fig. 9.5. DIRECT and INDIRECT equivalent lifetime CO_2 emissions for PUR/PIR foams with alternative blowing agents and for not-in-kind alternative insulations in Europe.

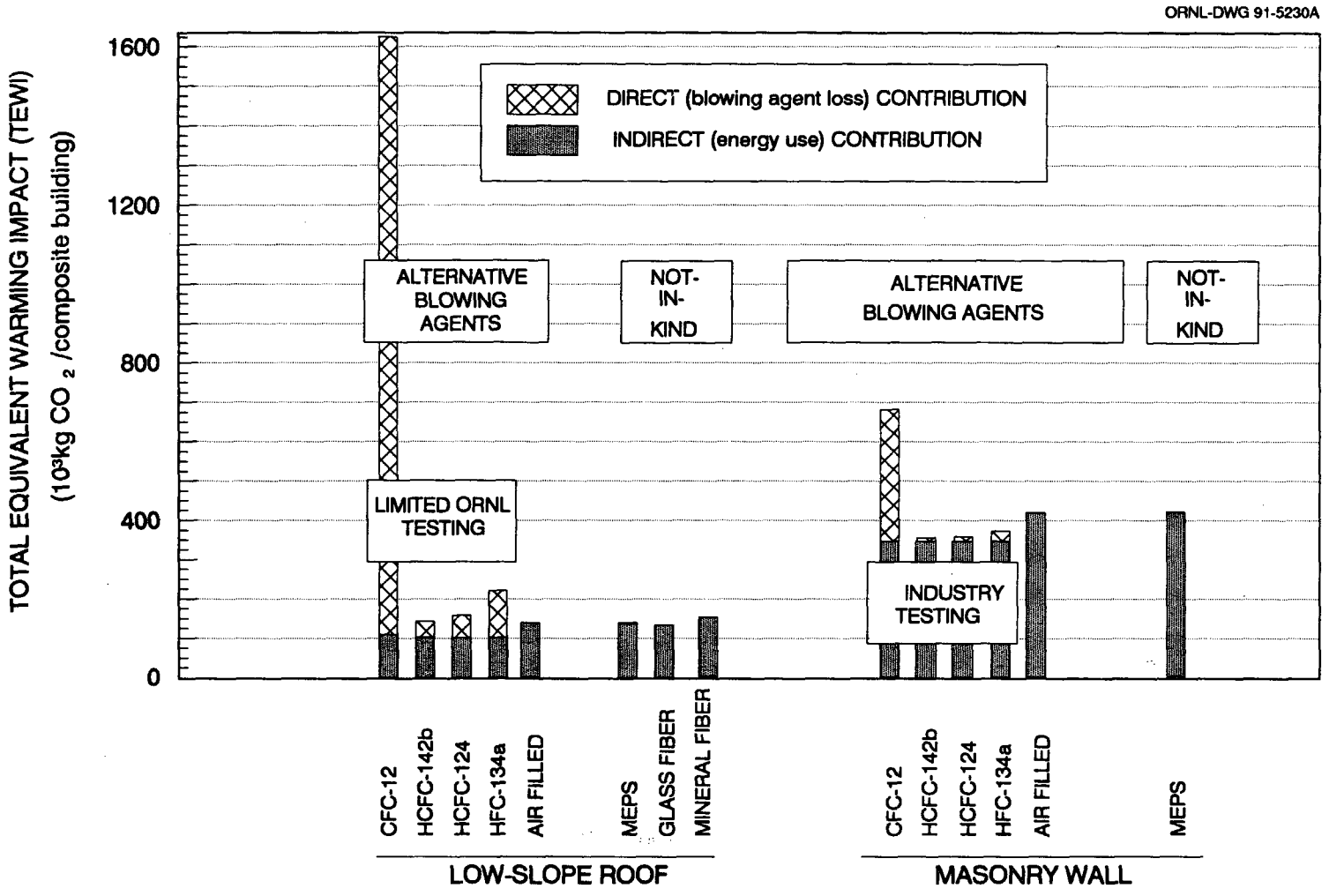

Fig. 9.6. DIRECT and INDIRECT equivalent lifetime CO_2 emissions for XEPS foams with alternative blowing agents and for not-in-kind alternative insulations in Europe.

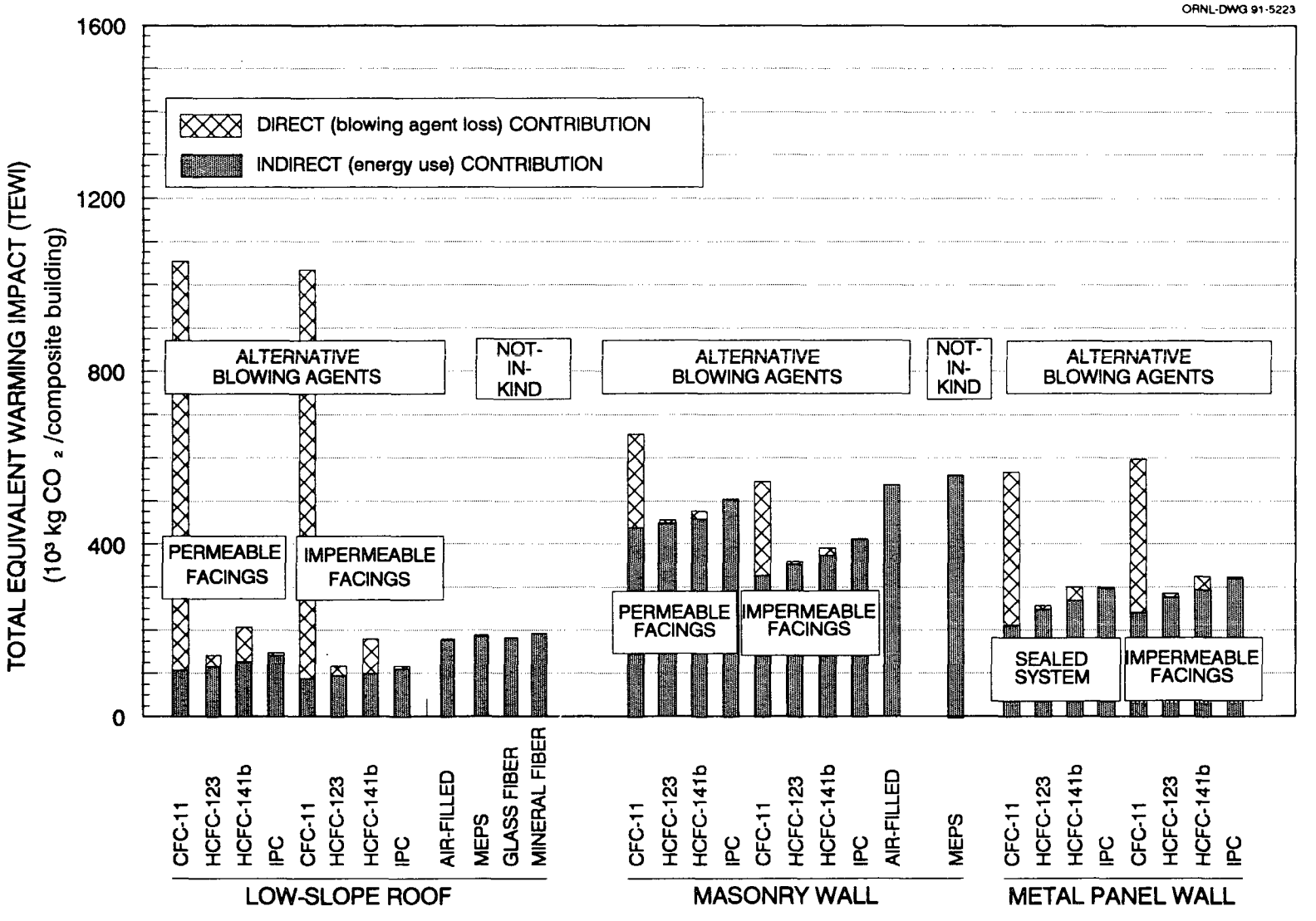

Fig. 9.7. DIRECT and INDIRECT equivalent lifetime CO_2 emissions for PUR/PIR foams with alternative blowing agents and for not-in-kind alternative insulations in North America.

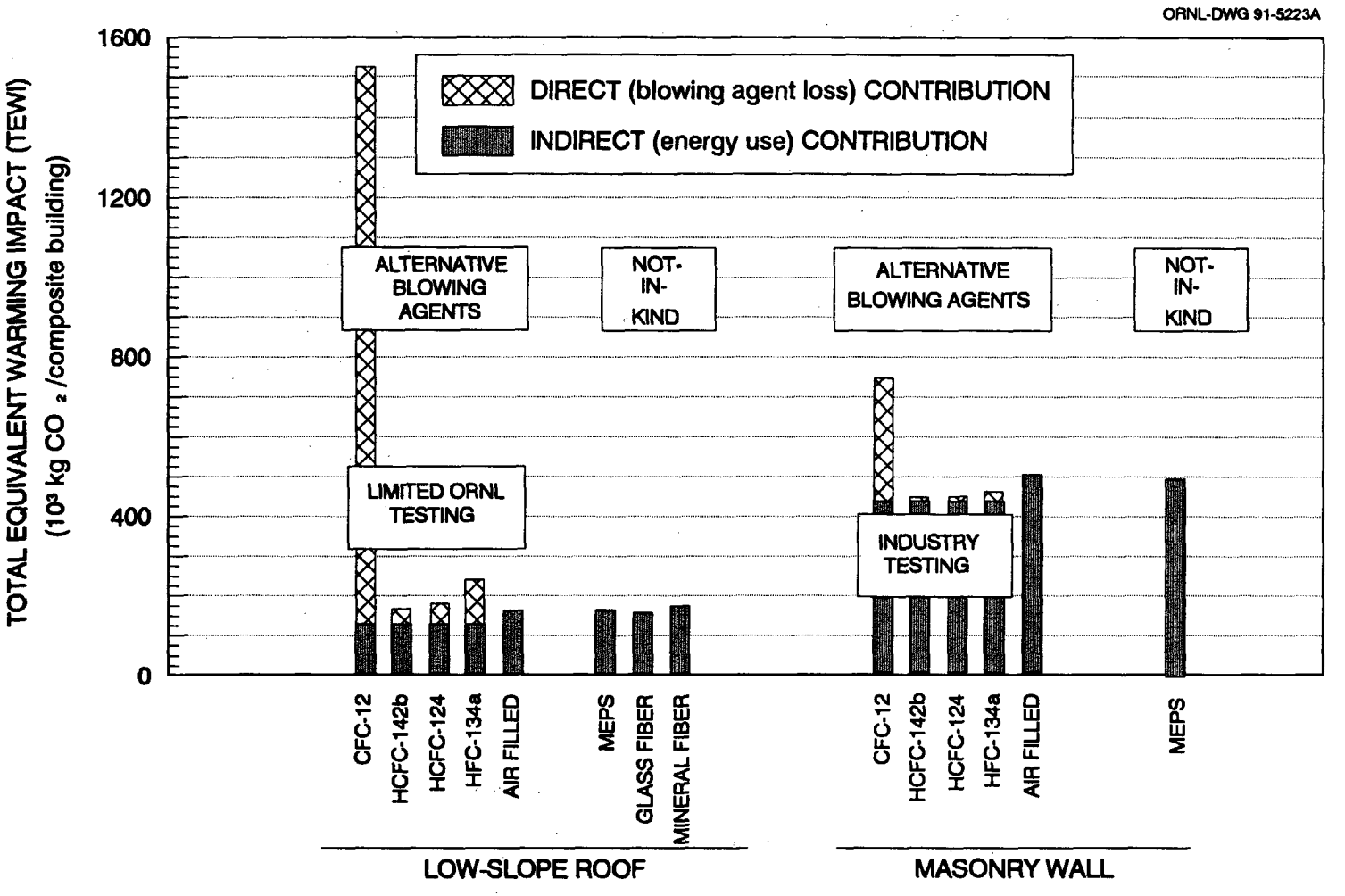

Fig. 9.8. DIRECT and INDIRECT equivalent lifetime CO_2 emissions for XEPS foams with alternative blowing agents and for not-in-kind alternative insulations in North America.

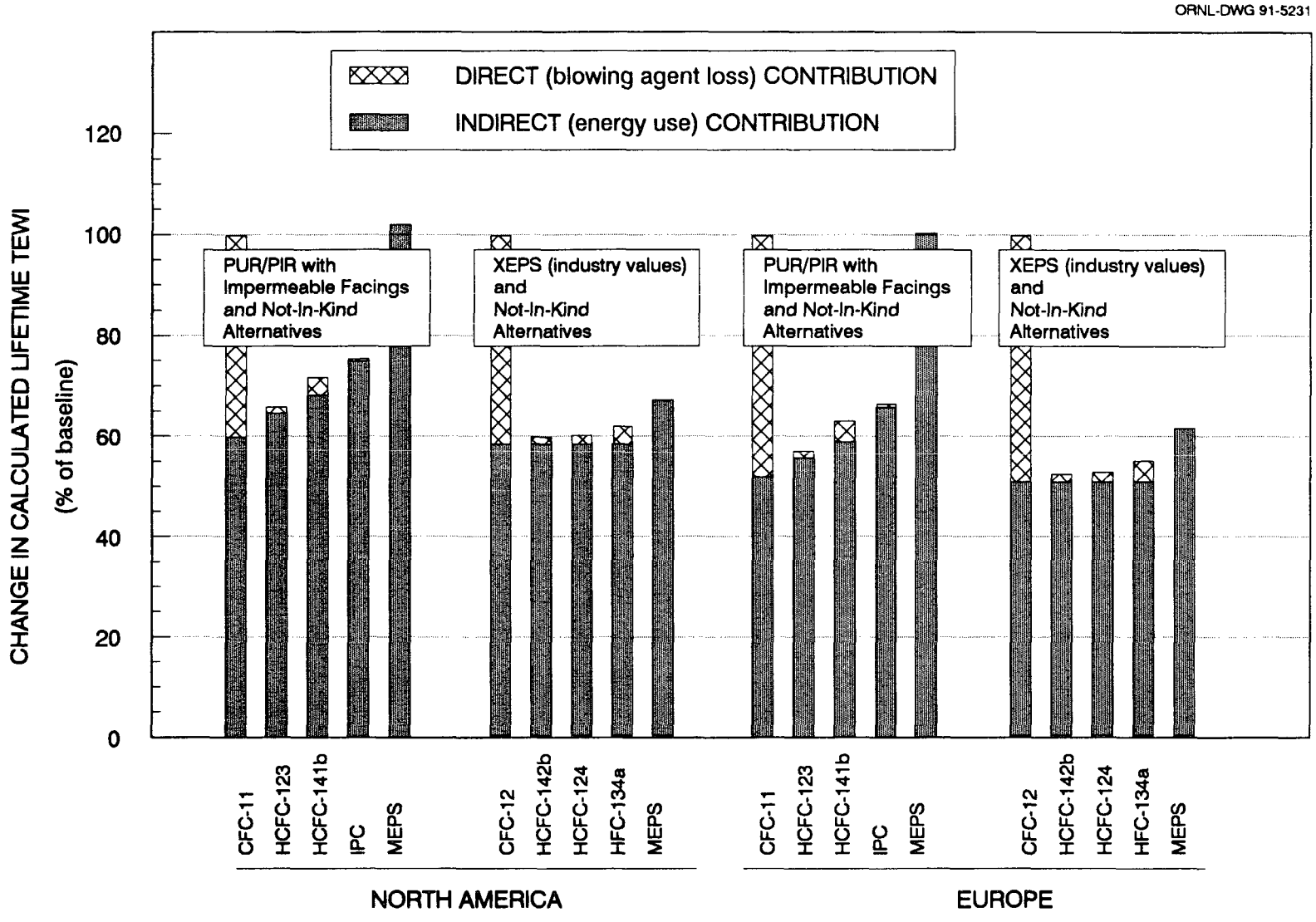

Fig. 9.9. Changes in net TEWI relative to baseline CFC technology for selected masonry wall insulation options.

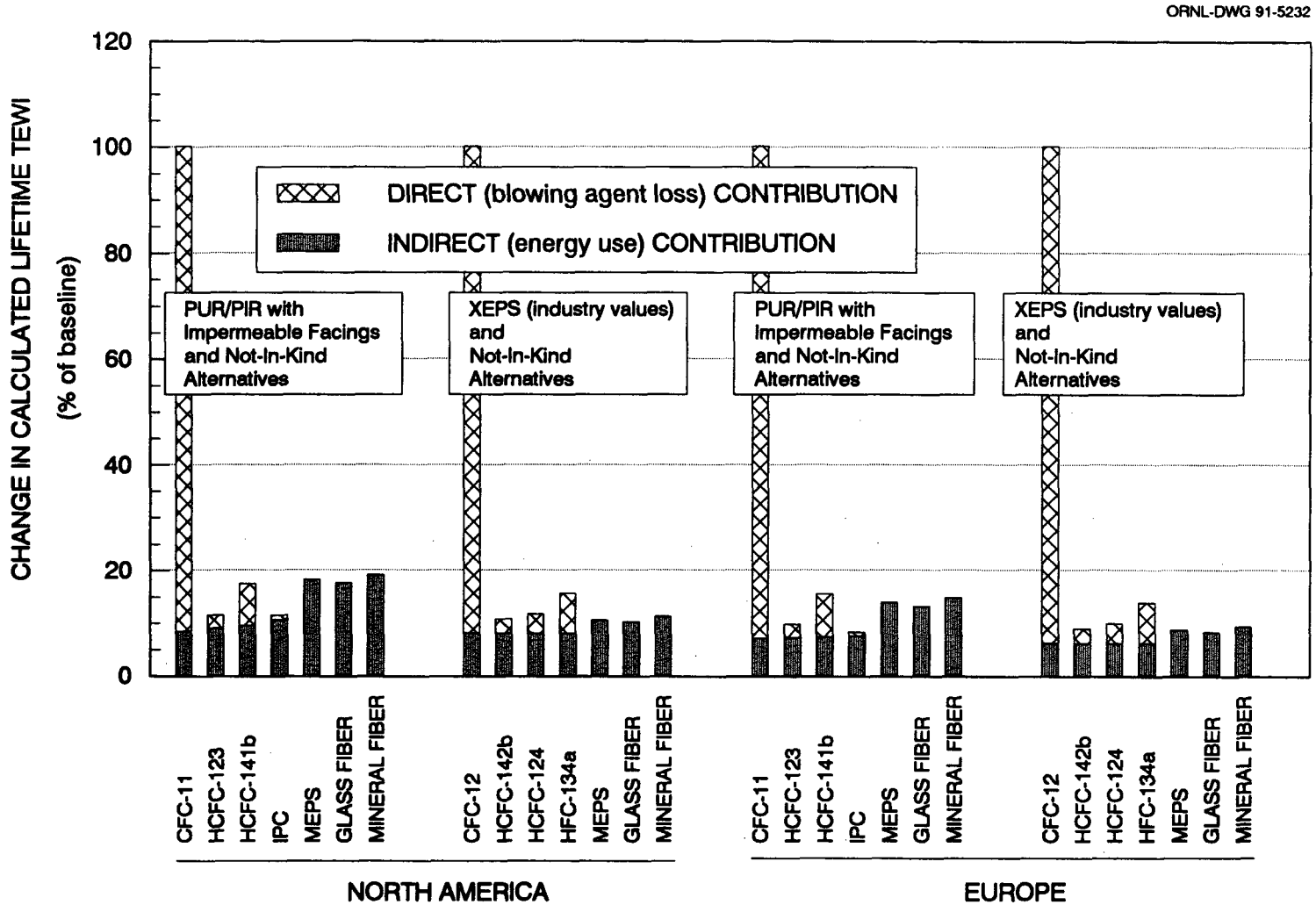

Fig. 9.10. Changes in net TEWI relative to baseline CFC technology for selected low-slope roof insulation options.

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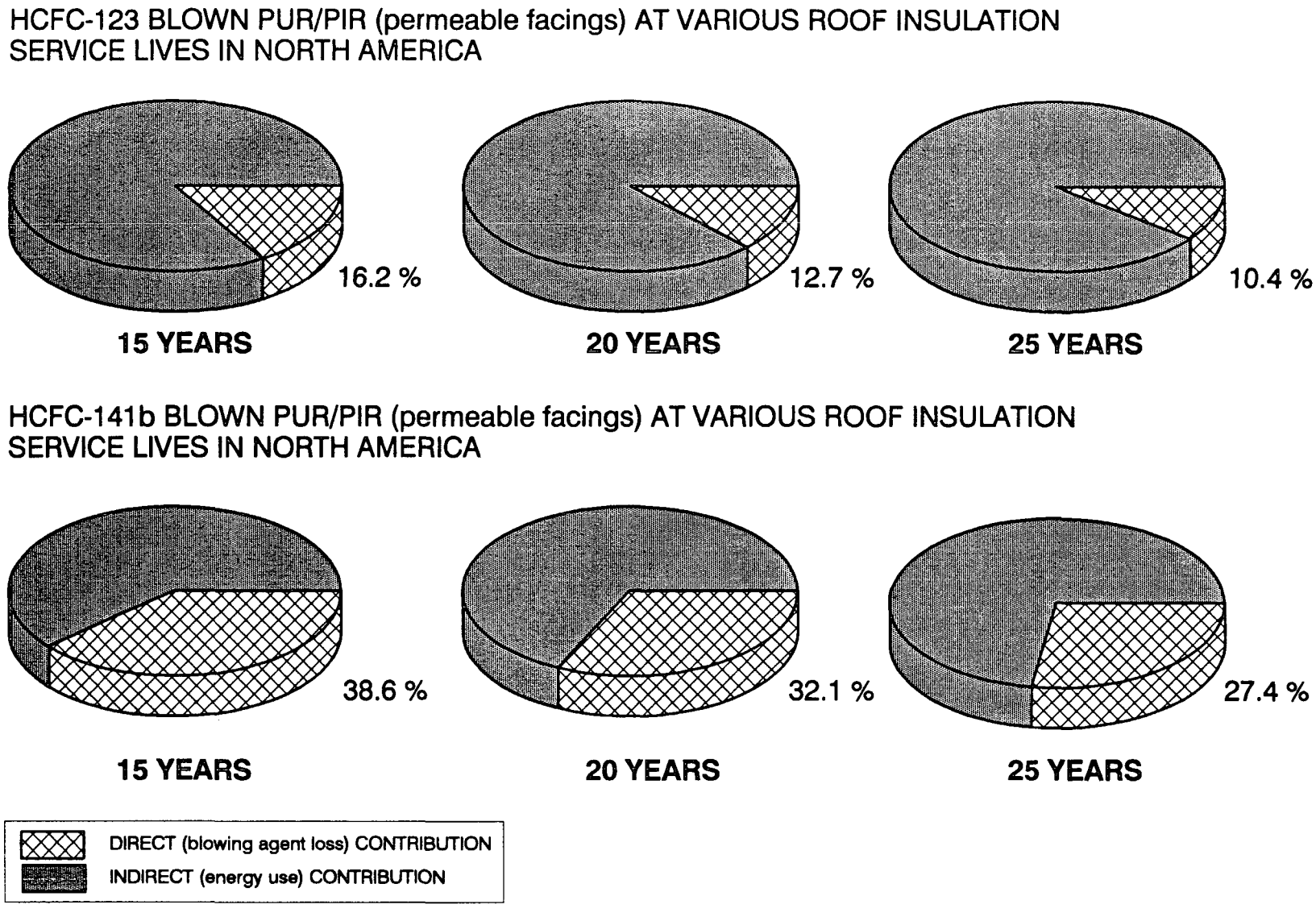


Fig. 9.11. Relative DIRECT and INDIRECT contributions to TEWI for HCFC-blown PUR/PIR with various service lives.

10. RESIDENTIAL BUILDING INSULATION

10.1 INTRODUCTION

Extruded polystyrene, laminated and non-laminated polyurethane and polyisocyanurate, and expanded polystyrene foam insulations are used as building insulation throughout the developed countries and there is a tremendous potential for expanding their use in Eastern Europe and Asia. Lichtenberg reported that 51,000 metric tonnes (112 million lbs) of laminated polyurethane boardstock alone were used worldwide in 1986, with 85% of this production coming from North America and Europe (East and West), with 5% from Japan, 7% from Australia, New Zealand, and the rest of Asia, and less than 4% from Africa and South and Central America (Lichtenberg, 1989). Foam insulation used in residences in North America is divided between three different types of materials; there were an estimated 37,500 tonnes (82.5 million lbs) of polyurethane/polyisocyanurate, 21,600 tonnes of extruded polystyrene (47.5 million lbs), and 14,400 tonnes (31.7 million lbs) of expanded polystyrene sheathing used in 1990 (Minsker, 1991). Minsker also reported that approximately 18,000 tonnes (39.6 million lbs) of polyurethane, 20,700 tonnes (45.6 million lbs) of extruded polystyrene, and 7,100 tonnes (15.7 million lbs) of expanded polystyrene were used in Japan.

All of these foams except expanded polystyrene are formed using either CFC-11 or CFC-12. It is important that alternative foam blowing agents or insulating materials are found as CFCs are phased out of production and that the new materials developed provide the same or better thermal performance than what is currently available with CFCs. An analysis is performed in this section to evaluate the overall effects of these foams on global warming. Representative single-family, detached homes in North America and Europe are used to evaluate the overall impact of foam insulations on building energy use and direct and indirect CO_2 emissions. The analysis does not extend to Japan because of the relatively low energy use for space conditioning in Japan compared to North America and Europe (EPA, 1990, Taguchi, 1991, and Washington Post, 1991).

10.2 BASELINE BUILDING DESIGN

Plastic foam boards are frequently used as part or all of the insulation in the walls of residential buildings. Masonry cavity walls can be constructed with an air gap between the two layers of masonry block (or brick), or the gap can be filled with polystyrene or polyurethane panels to insulate the wall from heat losses. Wooden frame construction used for cavity walls in North America and parts of Europe makes use of foam insulation as a layer of sheathing on the outside of the wall frame to augment the insulation provided by fiberglass batts in the wall cavity. In each case the foam insulation is an important component in the thermal structure of the wall.

Europe

Two baseline buildings are considered for Europe, one of a design corresponding to construction codes and practices in the United Kingdom and one appropriate for northern Europe. The first building is assumed to be a two story 83.6 m^2 (900 ft^2) (IEA, 1983 and UN, 1988), single-family home built using a cavity masonry construction with a 100 mm (4 in.) brick facade, 34 mm (1.3 in.) of expanded polystyrene insulation, a concrete block inner wall, and 13 mm (0.5 in.) of plasterboard on the inside. Figure 10.1 shows a cutaway drawing of the components of this wall system. The total opaque wall conductance is 0.45 $W/m^2 \cdot K$ (R-value of 12.6 $h \cdot ft^2 \cdot {}^\circ F/Btu$) (Jeffs, 1991). The ceiling is insulated to 0.25 $W/m^2 \cdot K$ (R-22.7) and the floor to 0.57 $W/m^2 \cdot K$ (R-10) (Jeffs, 1991). The

residence is assumed to be at the end of a row of homes so that there are three exterior walls. Approximately 15% of the exterior wall is comprised of double-glazed windows with an overall coefficient of heat transmission of 2.0 $W/m^2 \cdot K$ (0.35 $Btu/h \cdot ft^2 \cdot °F$) (Lee, 1990). The home is assumed to have a natural gas boiler with hot water radiators (IEA, 1984) with a fuel efficiency of 65%. Weather data for Mildenhall Royal Air Station is used for computing the building heating loads. The baseline heating load for the home is 6100 MJ (5800 KBtu), of which 30% or 1830 MJ (1740 KBtu) is lost through the walls.

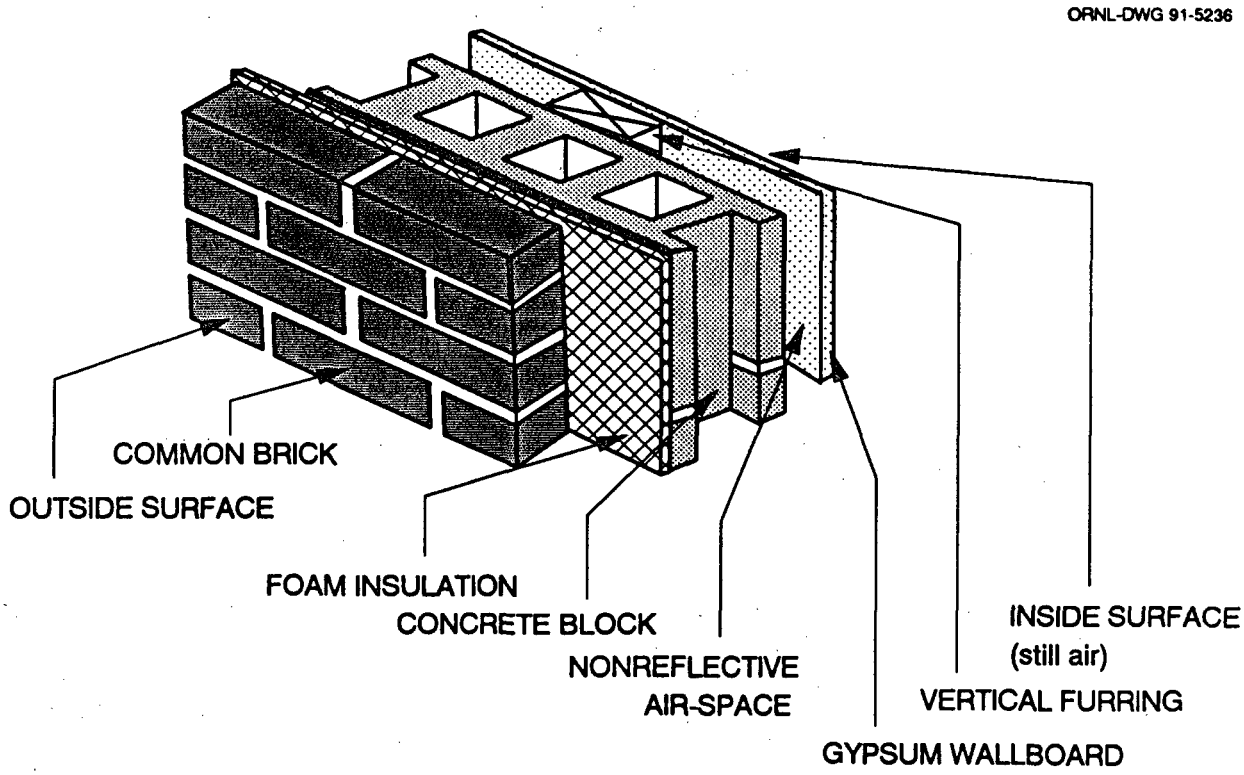


Fig. 10.1. Masonry wall construction for residential buildings in the UK.

The baseline home for northern Europe is assumed to be a two story, 130 m^2 (1,400 ft^2) (IEA, 1983 and UN, 1988) detached single-family home built of wood frame construction using 38 mm x 90 mm (2 x 4 in.) studs on 600 mm centers (24 in.). The outside of the wood frame is covered with 25 mm (1.0 in.) of foil-faced (impermeable) polyisocyanurate sheathing and 11 mm (0.4 in.) hardboard siding. The cavity between the studs is filled with fiberglass batts and the inside of the wall is covered with a 13 mm (0.5 in.) plasterboard finish as shown in Fig. 10.2. The total wall thermal conductance is 0.30 $W/m^2 \cdot K$ (R-19 $h \cdot ft^2 \cdot °F/Btu$) based on 12% of the wall surface containing studs and 88% containing the fiberglass batts (Jeffs, 1991). The assumptions on the windows are the same as for the home in the UK. The ceiling and floor thermal conductances are 0.20 $W/m^2 \cdot K$ (R-28) and 0.30 $W/m^2 \cdot K$ (R-20) (Jeffs, 1991). The home is assumed to be heated with a hydronic distribution system using a boiler burning #2 fuel oil (IEA, 1984). The boiler efficiency is assumed to be 65%. Weather data for Wiesbaden, Germany is used for calculating building loads. The heating load is 6000 MJ (5700 KBtu), of which 30% is assumed to be lost through the insulated portions of the walls.

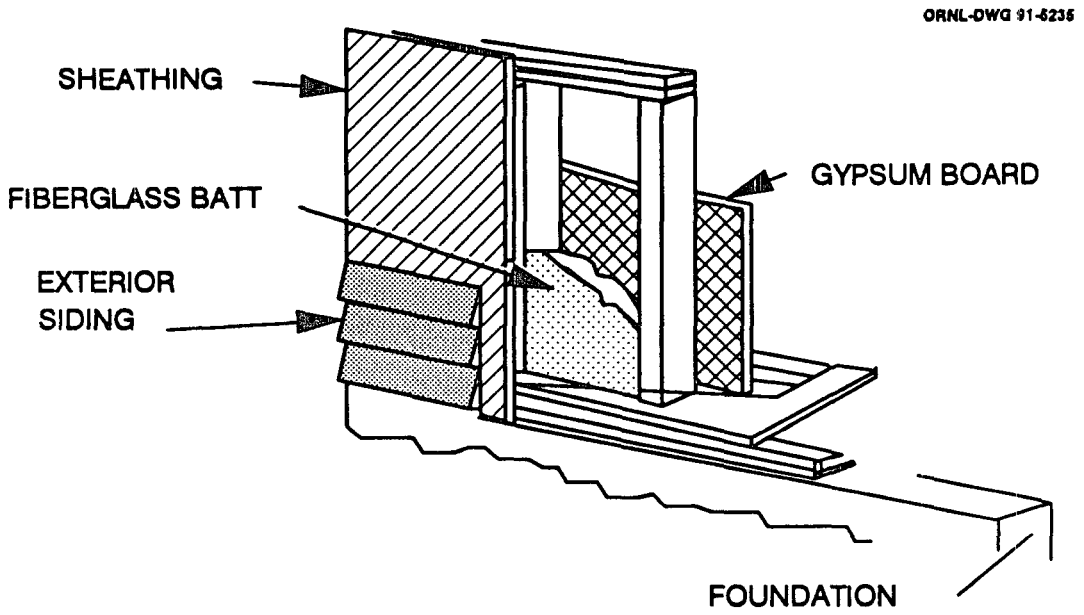


Fig. 10.2. Timber frame construction for residential buildings in northern Europe and North America.

North America

The baseline home for North America is assumed to be a two story, 186 m^2 (2,000 ft^2) detached single-family home also using wood frame construction of 38 mm x 90 mm (2 x 4 in.) studs on 400 mm (16 in.) centers. The outside of the home is covered with 21 mm (0.83 in.) of foil-faced (impermeable) polyisocyanurate foam sheathing and hardboard siding. Fiberglass batts are used in the cavity of the wall, and the inside is finished with 13 mm (0.5 in.) of plasterboard. The cavity portion of the wall has a thermal conductance of 0.30 $W/m^2 \cdot K$ (R-19 $h \cdot ft^2 \cdot {}^\circ F/Btu$) according to the 1989 Model Energy Code (Lee, 1990) and the total wall has a conductance of 0.31 $W/m^2 \cdot K$ (R-18.7) based on 15% of the wall occupied by the studs and 85% insulated with fiberglass batts. The window assumptions are the same as for the residences in Mildenhall and Wiesbaden. Analyses are performed for two locations in the United States; Chicago in the north and Atlanta in the south. The ceiling is assumed to be insulated to 0.15 $W/m^2 \cdot K$ (R-38) for Chicago and 0.19 $W/m^2 \cdot K$ (R-30) for Atlanta (Lee, 1990). The bottom floor of the building in each location is assumed to be insulated to 0.30 $W/m^2 \cdot K$ (R-19). The home in Chicago is assumed to have a high efficiency gas furnace (85%) (EPA, 1987) and a central air-conditioner with a cooling season coefficient of performance (COP) of 2.9 (seasonal energy efficiency ratio, SEER, of 10.0 Btu/Wh). The home in Atlanta is assumed to have an electric, air-to-air heat pump with a heating seasonal performance factor of 2.0 (HSPF = 6.8 Btu/Wh) and seasonal cooling COP of 2.9 (SEER = 10 Btu/Wh). The baseline heating load for Chicago is 29,600 MJ (28,100 KBtu) and that portion lost through the walls is 8900 MJ (8400 KBtu). The heating load for Atlanta is 11,100 MJ (10,600 KBtu) and 3300 MJ (3200 KBtu) is lost through the walls.

10.3 METHODOLOGY

Calculations are performed for two different assumptions concerning the baseline building design and how much of an alternative insulation is used in place of the CFC-11 or CFC-12 baseline. In one case the thermal resistance of the wall is held constant at a baseline value and the appropriate thickness of each alternative insulation is used in computing the volume of insulation and mass of blowing agent used. The building annual energy use does not change in this case. In the other case, the same thickness of insulation is used for each of the alternative materials and different heating and cooling loads are calculated for each of them. Very similar results are obtained for the two cases. The building load calculations include the effects of thermal "short circuiting" as would be caused by wooden studs in cavity walls. The building loads are calculated from data for a physical description of the building and binned weather data using a computer model developed at Oak Ridge National Laboratory for residential buildings (Ballou, 1981).

10.4 ALTERNATIVE INSULATING MATERIALS

Several alternative blowing agents are considered as substitutes for CFC-11 in polyisocyanurate and polyurethane and CFC-12 in extruded polystyrene insulation:

- HCFC-123, HCFC-141b, and isopropylchloride are included as substitutes for CFC-11 in polyisocyanurate foam, and pentane in expanded polystyrene bead board, and mineral fiber board are included as not-in-kind alternatives to CFC-11 blown polyisocyanurate,

- and HCFC-142b, HCFC-124, and HFC-134a, are included as substitutes for CFC-12 in extruded polystyrene, and pentane in expanded polystyrene bead board and fiber board are considered as not-in-kind alternatives to CFC-12 blown extruded polystyrene.

Time averaged thermal conductivities of foam insulation are used based on the thickness of the foam and the assumed building lifetime. The thermal conductivity of expanded polystyrene manufactured with pentane changes very rapidly after the foam is formed and its thermal properties are essentially those of air-filled foam. Foams formed with the other blowing agents age less rapidly because the blowing agents are retained in the foams for a longer time. Calculations of wall thermal conductances and building heating and cooling loads are computed using estimates for the integrated average K-factor of the foam over the assumed 50 year lifetime of the building (McElroy, 1991). Figure 10.3 shows the time-averaged K-factors for foam insulations using the alternative blowing agents as functions of the thickness, and Table 10.1 contains data for the thicknesses of each alternative insulation used in the calculations for constant wall thermal resistance for each city. The building heating and cooling loads are then determined using the average aged K-factors and the appropriate weather and building data.

10.5 RESULTS

Detailed results of the analyses are shown in a series of tables in Appendix M, and these numbers need to be studied to draw conclusions from this work. Portions of those tables have been extracted to illustrate points in the body of this section. The tables in Appendix M include:

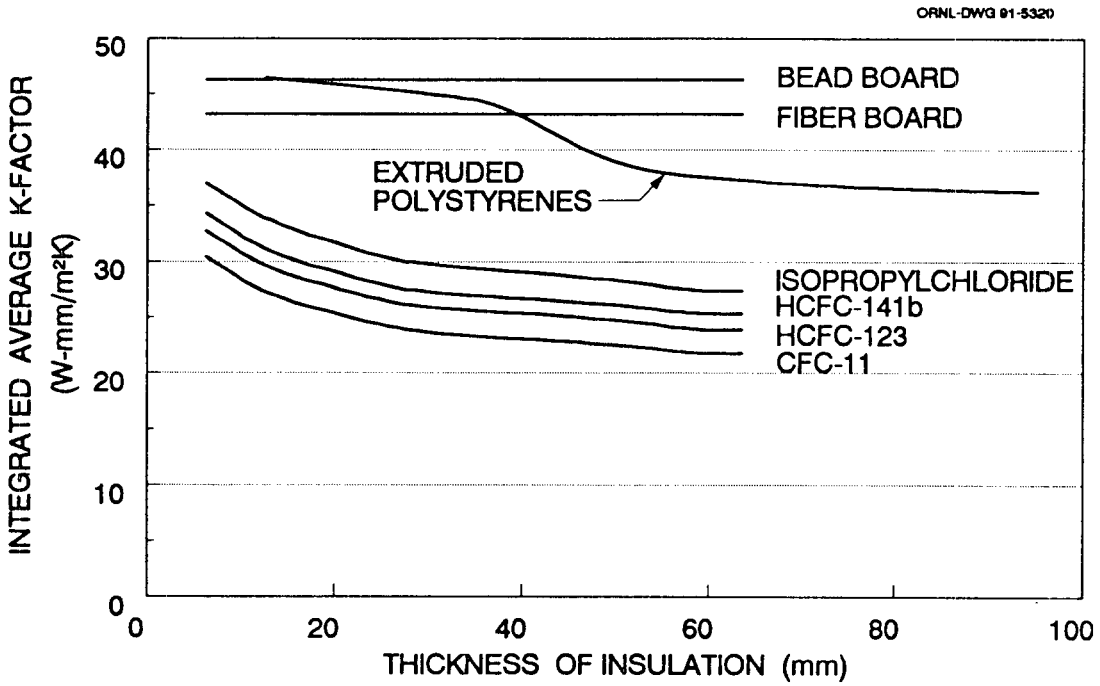


Fig. 10.3. Time-averaged (integrated) thermal conductivity (K-factor) for different thicknesses of insulating materials and foam insulations with alternative blowing agents.

- the annual heating load for each of the four baseline buildings (the estimated losses through the walls), the corresponding fuel use, and the CO_2 emissions from fuel use for the buildings with polyurethane, polyisocyanurate, and alternative materials (Table M.1) and extruded polystyrene and alternative materials (Table M.2),

- the volumes and masses of foam insulation, masses of blowing agents, and the net equivalent CO_2 emissions (GWP) values for the polyurethane alternatives (Table M.3) and the extruded polystyrene alternatives (Table M.4),

- the direct (chemical) and indirect (energy) lifetime equivalent CO_2 emissions for buildings using a constant thickness of foam insulation for each alternative; sized using CFC-11 blown polyurethane or CFC-12 blown extruded polystyrene (Tables M.5a and M.5b), and sized using pentane or CO_2 blown expanded polystyrene (Tables M.6a and M.6b)
  a. polyurethane alternatives
  b. extruded polystyrene alternatives

- the direct and indirect lifetime equivalent CO_2 emissions for buildings using a constant wall thermal resistance (Tables M.7a and M.7b).

Table 10.1. Thicknesses of insulation used for constant wall resistivity calculations

Alternative Insulating Materials	Mildenhall, UK (mm)	Wiesbaden, Germany (mm)	Chicago, US (mm)	Atlanta, US (mm)
Polyisocyanurate and Polyurethane				
CFC-11*	28	25	21	21
HCFC-123*	31	27	23	23
HCFC-141b*	32	28	24	24
Isopropylchloride*	34	30	26	26
Pentane (Bead Board)	53	47	39	39
Fiber Board	50	44	37	37
Extruded Polystyrene				
CFC-12	46	44	37	37
HCFC-142b	46	44	37	37
HCFC-124	46	44	37	37
HFC-134a	46	44	37	37
Pentane (Bead Board)	53	47	39	39
Fiber Board	50	44	37	37

* laminated foam board with an impermeable foil facing

Annual Energy Use

The primary interest in the analysis is that portion of the heating and cooling loads due to losses through the insulated portions of the exterior walls; the losses through the ceiling, floor, windows, infiltration, and heat gains from internal sources (e.g., people, cooking, laundry) are not affected by changes in the wall insulation and are not of particular interest. A detailed analysis of the baseline home for Atlanta showed that approximately 30% of the heat losses for a well insulated home are through the insulated walls with the balance coming from losses through the windows, roof, and from air infiltration. The assumption of double glazed, low emissivity windows is very important in this calculation; an even smaller percentage of the load is through the walls for single-glazed windows. This analysis also showed that only about 6% of the annual cooling loads are due to the walls. The primary factors affecting the cooling load are the heat gains through the windows and the internal heat sources from people, cooking, lights, and laundry. Consequently, further analysis is limited to only 30% of the calculated annual building heating load and the cooling load is not considered at all.

The calculated heat losses through the insulated walls of the four baseline residences are contained in Tables M.1 and M.2 in the appendix for the CFC blown foam insulations and with the alternative blowing agents. These results are assuming a constant thickness for the layer of foam insulation; the energy use for alternative walls with a constant thermal resistance is equal to the values shown for the buildings in Tables M.1 and M.2 for foams blown with CFC-11 or CFC-12. These tables also contain data for the annual fuel use for each building and the corresponding annual CO_2 emissions. The emissions are based on:

- 30.6 kJ/m^3 (1,025 Btu/ft^3) of natural gas and 51.1 g CO_2 / MJ (53.9 g CO_2 / 1,000 Btu) fuel heating value for gas (Sand, 1991),

- 38.8 MJ/ℓ (139,400 Btu/gal.) and 69.5 g CO_2 / MJ (73.3 g CO_2 / 1,000 Btu) of heating value for fuel oil (Zurer, 1991), and

- and CO_2 emissions of 0.672 kg/kWh for the U.S.

Global Warming Potential

Values for the GWP of the foam blowing agents are given in Appendix A.

Data for the masses of blowing agent and the corresponding net equivalent CO_2 emissions for each of the alternatives considered are contained in Tables M.3 and M.4 in Appendix M. The volumes of foam are computed from the dimensions of the residences and the thicknesses required for each particular case, the masses of foam are based on foam densities of 32 kg/m^3 (2.0 lb/ft^3). The masses of the blowing agents are based on 12.5% weight percent CFC-11 in polyisocyanurate foam, and relative blowing efficiencies of 75% and 115% for HCFC-123 and HCFC-141b based on theoretical predictions and the experience of some manufacturers (Shankland, 1991). It is assumed that foams manufactured with isopropylchloride use 8% blowing agent by weight. It is also assumed that the mass of CFC-12 in extruded polystyrene is 6% of the foam by weight, and that the masses of the CFC-12 alternatives will vary from that of CFC-12 in extruded polystyrene by the ratios of their molecular weights to that of CFC-12.

Data on the direct effects from the blowing agents and indirect lifetime (50 year) CO_2 emissions from fuel use are shown in Figs. 10.4a and 10.4b for constant thicknesses of polyisocyanurate and extruded polystyrene materials and alternatives in the four cities considered. Figures 10.5a and 10.5b contain the same information for the buildings assuming a fixed wall thermal resistance. More detailed information on the direct global warming contributions and indirect lifetime CO_2 emissions are shown in Tables M.5a and M.5b, M.6a and M.6b, and M.7a and M.7b in Appendix M. These results show the high emissions for foams blown with CFC-11 or CFC-12 in all four cities and the significant reductions possible with some of the alternative blowing agents. The relatively small differences between some of the alternatives, such as HCFC-123 and HCFC-141b in polyisocyanurate foam, are not significant considering the accuracy of the calculations and the overall scale of the results.

It should be pointed out that the results in Figs. 10.4a and 10.4b are not directly comparable. The difference can be illustrated by considering the use of fiber board sheathing in Atlanta as an example (the right-most bar in each of the two groups for Atlanta); the TEWI is about 22,000 kg for polyurethane/polyisocyanurate alternatives in Fig. 10.4a and 16,000 kg for extruded polystyrene alternatives in Fig. 10.4b. This is not an inconsistency between the results and it does not imply that in some way the extruded polystyrenes result in lower energy use. A relatively thin layer of sheathing is used in the polyisocyanurate alternatives based on the amount of CFC-11 blown foam that would be required to meet the building codes, while a thicker layer of sheathing is assumed for the extruded polystyrene alternatives as substitutes for CFC-12 foam. One of the hypothetical houses in Atlanta with fiber board sheathing has a thicker layer of insulation than the other one and consequently has a higher overall thermal resistance.

10.6 CONCLUSIONS

One important conclusion to draw from Figs. 10.4 and 10.5 is that only a small portion of the TEWI is due to the DIRECT effect of the chemical blowing agents. This is particularly true for the polyurethane/polyisocyanurate foam alternatives and for the extruded polystyrene alternatives where there are high winter heating loads, such as in Chicago. The alternative (NIK) insulation sheathing

materials show a higher calculated energy use effect for constant thickness insulation (Figs. 10.4a and 10.4b) and a higher TEWI than the foam insulations produced using the HCFC or isopropylchloride alternatives.

The results for the calculations assuming a constant wall thermal resistance in Fig. 10.5 are quite predictable; the compounds with the lowest direct global warming potentials also have the lowest overall lifetime emissions. Even though thicker layers of blown insulation are needed, the increase in the volume of foam and accompanying increase in mass of blowing agent required does not offset significant differences in the GWPs and relative foam blowing efficiencies for the different compounds.

There are a couple of limitations in this analysis that must be kept in mind. This analysis has not looked at the practicality of using thick layers of expanded polystyrene bead board or fiber board in some building applications; it simply may not be feasible to use these materials in some situations because of the thicknesses required. Unfaced or polyurethane/polyisocyanurate materials with permeable facings are also used in residential applications and they have not been evaluated in this analysis. These materials have been considered in the section of this report on commercial building insulation and they are compared with materials using impermeable facings in that section.

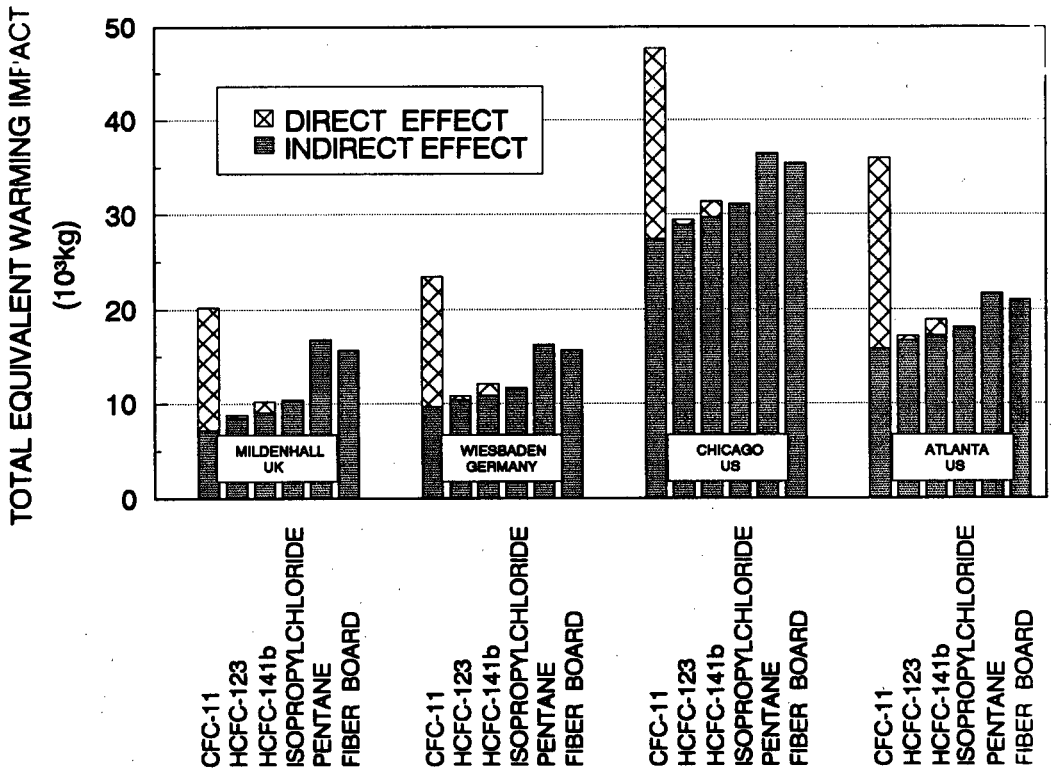


Fig. 10.4a. TEWI of residential buildings using polyurethane/ polyisocyanurate alternative materials with a constant thickness of insulation.

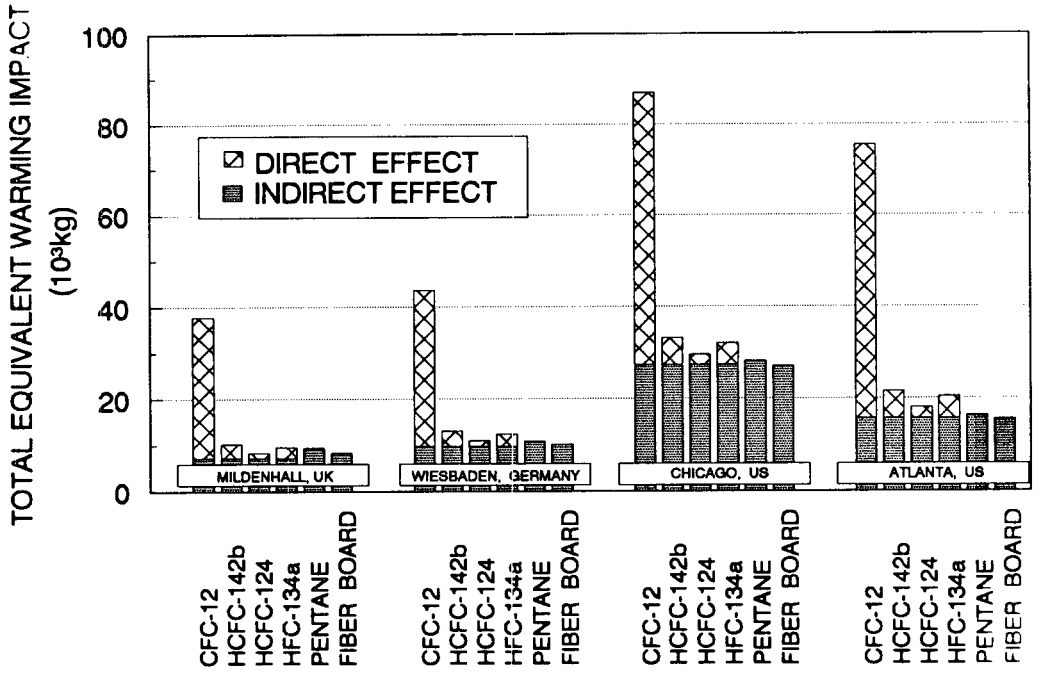


Fig. 10.4b. TEWI of residential buildings using extruded polystyrene alternative materials based on constant wall thickness.

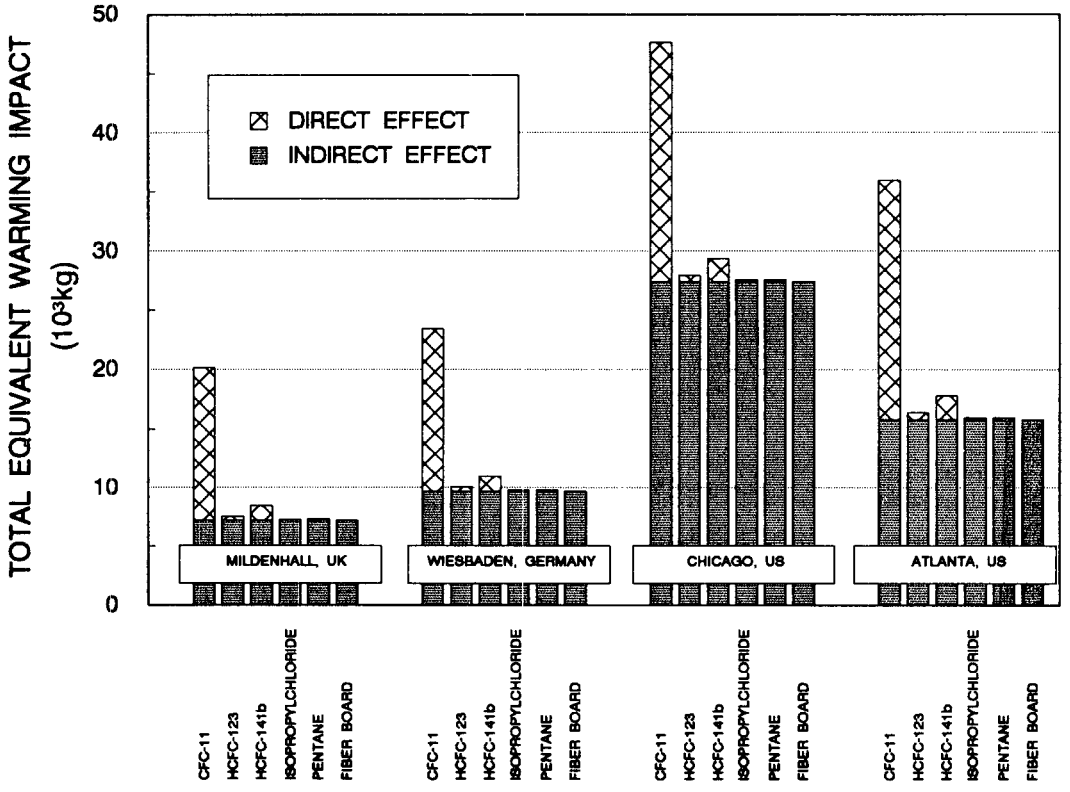


Fig. 10.5a. TEWI of residential buildings with polyurethane/ polyisocyanurate alternative materials with constant wall thermal resistance.

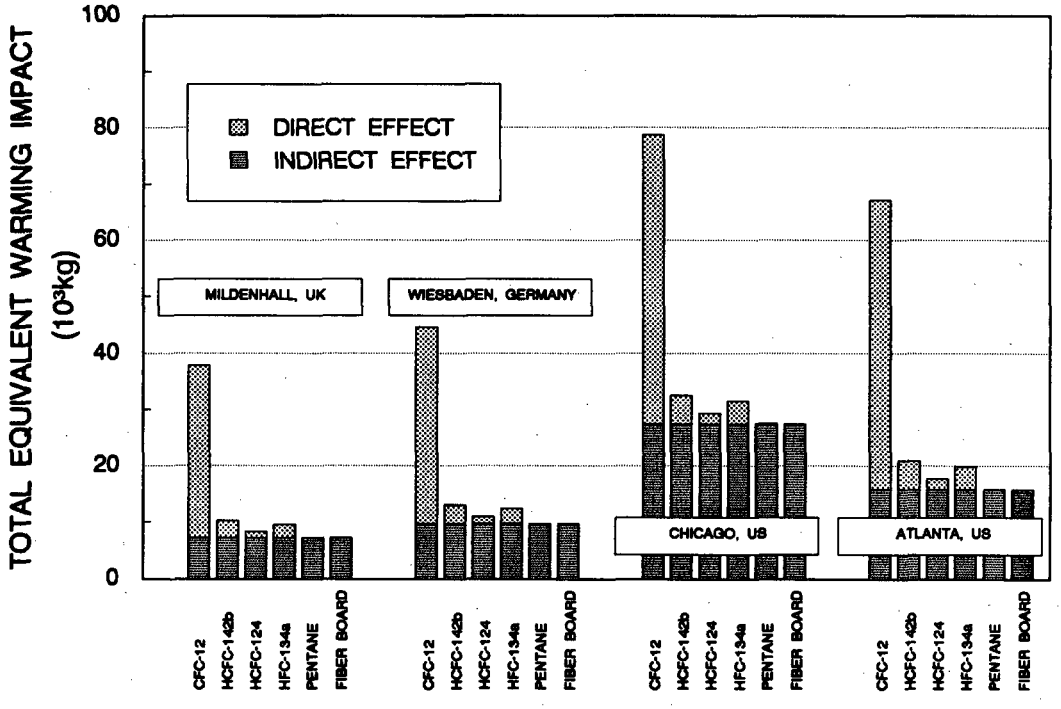


Fig. 10.5b. TEWI of residential buildings with extruded polystyrene alternative materials with constant wall thermal resistance.

11. METAL CLEANING: SYSTEMS AND RESULTS

11.1 INTRODUCTION

Many industries have relied heavily on CFCs for use in intermediate cleaning steps during manufacturing processes. CFC-113 has been particularly important for use in cleaning of precision metal parts and electronic circuit boards. The production controls of the Montreal Protocol will force a phaseout of CFC-113 and the various industries that have relied on it for their cleaning needs have been working diligently to find environmentally acceptable chemicals and processes that can achieve the same levels of cleanliness as was achieved with CFC-113. Several possible new technologies are becoming available (e.g., aqueous and semi-aqueous processes), but it is recognized that many of the systems being implemented based on these technologies are new, and often have not been optimized in an engineering sense for energy conservation or controlling solvent emissions. Furthermore, because systems are just being installed, few user measurements of solvent emissions or energy use have been made. As a result, this effort to quantify the total equivalent warming impact of alternative cleaning technologies represents the best available information that was readily available in the time frame of this study (January - August, 1991).

The scope of this study included major solvents and alternatives being used in state-of-the-art machines for cleaning metals and electronic printed wire circuit boards (PCB's). Cleaning systems included:

- Solvent based systems such as:
  - chlorofluorocarbons (CFC's)
  - hydrochlorofluorcarbons (HCFC's)
  - chlorinated hydrocarbons (CHC's)
- Aqueous systems with and without saponifiers
- Semi-aqueous systems in which an organic solvent is followed by an aqueous wash
- No clean technologies applicable to soldering operations which has the potential of eliminating the cleaning step of PCB assemblies (see Section 12).

Metals cleaning included both precision cleaning and metal degreasing. Systems evaluated included both batch and in-line (continuous) cleaning equipment that were being considered as replacements to CFC based cleaners. A number of other systems were identified (e.g. ice cleaning) but not considered because they were considered to be in the development phase or else having probably little impact over the next ten year time frame. An overview of the systems considered in batch and in-line cleaning is shown in Fig. 11.1.

11.2 CLEANING INDUSTRY

Broadly viewed, the cleaning industry is comprised of a diverse group of participants -- manufacturers of consumer products in a wide range of industries whose production processes include cleaning steps, the manufacturers of cleaning equipment, and producers of an array of cleaning solvents and other cleaning agents. Manufacturing industries where cleaning steps serve important functions include electronics, aerospace, automotive, and virtually all industries whose products utilize machined metal

parts. Cleaning equipment is available that ranges from manually operated dip tanks to fully automated conveyorized cleaning systems, designed to operate with specific cleaning agents, or a specific class of cleaning agents. Cleaning agents that traditionally have been used include organic solvents -- CFC's (primarily CFC-113), chlorinated hydrocarbons, hydrocarbons and derivatives (e.g., alcohols, esters, etc.) and a wide variety of aqueous and semi-aqueous systems incorporating acids, alkalis, saponifiers, builders, emulsions, and other chemicals. The number of product offerings runs in the hundreds.

		Continuous
		Batch
	Metal Cleaning	Electronic Cleaning
CFC (baseline)	x	x
HCFC	x	x
Chlorinated hydrocarbon	x	x
Semi-Aqueous	x	x
Aqueous	x	x
No Clean	NA	x

NA: Not Applicable

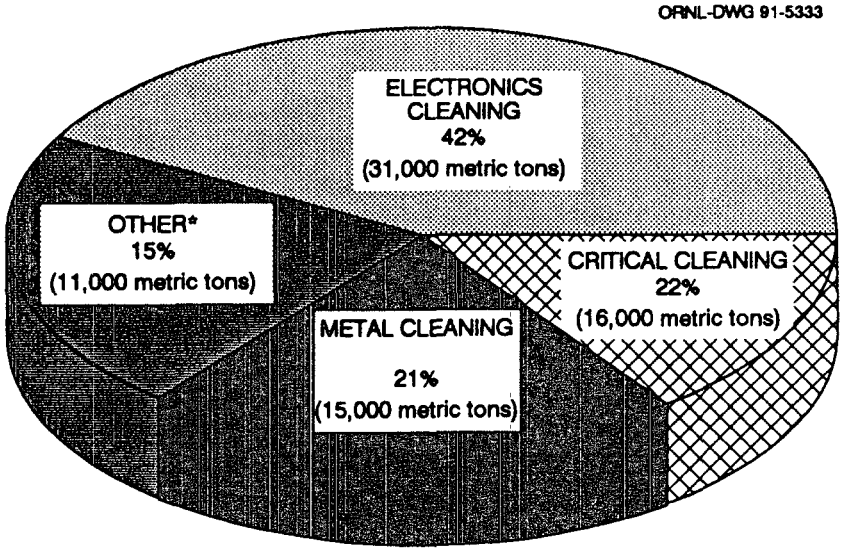
Fig. 11.1. Systems overview.

Figure 11.2 provides a breakdown of the usage of CFC-113 worldwide showing that general metal and precision cleaning and electronics cleaning use about equal amounts of CFC-113 (42-43% each) with the remainder accounted for in miscellaneous applications.

Metal Cleaning

Metal cleaning as a category includes a diverse range of types of parts and materials being cleaned, cleaning operations, and cleaning agents.

Applications/purposes for cleaning, a partial listing of which is presented in Table 11.1, range from cleaning and degreasing sheet metal coils, sheets, and parts prior to painting, to cleaning of machined parts. A significant portion of the machined parts are used in conventional, but nonetheless moderate to high precision, machinery having close operating clearances such as automobile engines and transmissions, hydraulic pumps, refrigerant compressors, and a wide variety of other mechanical products and equipment. For this type of equipment, cleaning serves the critical function of removing all particulate contamination, especially cuttings from machining operations, from the parts prior to assembly into a clean system, as required to obtain reliable, long life operation of the machinery.



*OTHER USES - REFRIGERANT, BLOWING AGENT, CHEMICAL INTERMEDIATE, DRY CLEANING SOLVENT
TOTAL CONSUMPTION: 73,000 metric tons
SOURCE: UCLA/NSF, 1988

Fig. 11.2. Breakdown of U.S. usage of CFC-113 by application.

Table 11.1. Metal cleaning applications

Industry	Examples of Parts Cleaned
Automotive	Engine parts
	Transmission parts
	Accessories (air-conditioner, power steering, etc.) parts
Bearing Industry	Bearing parts - balls, rollers, raceways, retainers
	Assembled bearings
HVAC/Refrigeration	Compressor parts
	Evaporator/condenser coils
Fluid Controls	Valve bodies and parts
Fluid Power	Hydraulic pump parts
	Valve and fitting parts

The CFC-113 consumed in metal cleaning is a modest portion of the total solvent use, less than 10% in the U.S. as shown in Table 11.2. For most oils and greases, chlorinated solvents such as trichlorethylene and 1,1,1 trichloroethane have proved to be more effective solvents than CFC-113.

Table 11.2. Summary of cleaning solvent usage in the U.S.A. by application category (1988). (10^3 metric tons)

Application	Solvent						
	CFC-113	1,1,1 Trichloro-ethane	Trichloro-ethylene	Perchloro-ethylene	Methyl Chloride	Oxygenated Hydro-carbons	Hydro-carbons
Metal Cleaning - Vapor	15	84	50	30	11		
Metal Cleaning - Cold	7	46	4	4	11	68	105
Precision Cleaning	20	26					
Electronic Cleaning	32	26*					
Subtotal	73	176					
Other Uses	12	104					
Total	85	280					

* includes manufacture of circuit boards
** alcohols are used in precision cleaning (Hey, 1991) but not reported in the source document
Source: Chem Systems 1990a

Even before the U.S. CFC excise tax resulted in significant increases in cost, the price of CFC-113 was considerably higher, approximately double, the price of chlorinated solvents and oxygenated hydrocarbon solvents such as alcohols, acetone and MEK. Given the higher cost and lower solvency of CFC-113 in comparison with chlorinated solvents, use of CFC-113 in metal cleaning has been limited to those applications where the specific advantages of CFC-113 are important.

There are considerable current and potential regulatory problems associated with the most commonly used chlorinated solvents. 1,1,1 trichloroethane (methyl chloroform) has a relatively high ozone depletion potential and, as a result, is being phased out over the medium term. Trichloroethylene, perchloroethylene, and methylene chloride have given rise to toxicological concerns as evidenced by low worker operator exposure limits (50 ppm in the U.S.). In response to this situation, many companies have adopted policies of almost total elimination of such solvent usage. The CFC-113 that has been used in metal cleaning applications in recent years has been used in roughly equal amounts in vapor degreasers, cold immersion cleaners, and for hand wiping. The features of CFC-113 (in comparison with chlorinated solvents) that are of value for metal cleaning are its low toxicity and lack of any residues, (arising from its stability, no need for stabilizers, and negligible breakdown products).

Precision Cleaning

Also referred to as "critical" cleaning, as a category distinct from metal cleaning and electronic cleaning, precision cleaning includes those cleaning processes and applications where virtually complete removal of contaminants, including submicron particles, surface residues, and adsorbed surface moisture is required. Examples of products requiring precision cleaning include computer disk drives, critical aerospace assemblies such as gyroscopes, precision electro-optical equipment, gas bearing assemblies, and high precision ball bearings.

Table 11.2 summarizes the solvents typically used for precision cleaning operations in recent years. In contrast to metal cleaning discussed above, CFC-113 has accounted for a relatively higher proportion (about 50% of the total) of the solvents used in precision cleaning operations. The valuable characteristics of CFC-113 are low toxicity, absence of residues, and chemical inertness.

The equipment used for precision cleaning is generally the same type of batch and in-line equipment used for metal cleaning, typically using one or more ultrasonic immersion steps to promote removal of surface films and particulates. The energy and solvent consumption is not readily distinguished from that associated with the cleaning of mechanical parts of similiar size and weight, so precision and metal cleaning have been treated as a single category in this study.

11.3 CLEANING AGENTS AND SOLVENTS USED

Solvents

Table 11.2 summarizes the annual usage in the U.S. for cleaning applications of the most commonly used solvents. Usage patterns are similar throughout the industrialized world. A brief description of the most important attributes of these solvents follows.

CFC-113 is used primarily as a solvent cleaning agent, with other use accounting for only about 15% of total usage. The primary attributes of CFC-113 as a cleaning agent are chemical inertness, low toxicity, compatibility with materials used in the parts to be cleaned, and reasonably good (though generally inferior to chlorinated solvents) solvency for oils, greases, and rosin flux residues. Azeotropic mixtures of CFC-113 with alcohols also are effective at removing ionic contamination as well as organics. CFC-113 is chemically stable, and used without the inhibitors and stabilizers that are needed with 1,1,1 trichloroethane.

HCFC solvents are intended as replacements for CFC-113. Commercialization of two low boiling HCFC's, HCFC-123 and HCFC-141b, is ongoing along with commercialization of several isomers of HCFC-225, whose boiling points are close to that of CFC-113.

Chlorinated solvents are often used in metal cleaning. In this class of solvents only 1,1,1 trichloroethane (methyl chloroform) is also used to some extent in PCB cleaning. Other chlorinated solvents include trichloroethylene (TCE), methylene chloride, and perchloroethylene, with TCE being in widespread use for metal cleaning applications.

Hydrocarbon solvents, and other derivatives used separately and with water in semi-aqueous cleaning, include aliphatic hydrocarbons, terpenes, alcohols, esters, and ketones. Alcohols are used both by themselves and blended with other solvents. In blends, alcohols provide solvency for ionic contamination.

Aqueous and Semi-Aqueous Cleaning Systems

New cleaning systems are being developed and put into use which do not use chemical solvents for removing grease and soldering rosens. Water with and without saponifiers: in some cases PCB cleaning in water alone is used; in other cases, saponifiers are used as for rosin based fluxes in PCB cleaning or oils in metal degreasing.

11.4 TYPES OF CLEANING EQUIPMENT

Cleaning equipment provides for the basic functions of handling the solvent/cleaning agent and the items to be cleaned, and contacting the two as appropriate. Most production cleaning processes employ a combination of solvency, surfactants and mechanical enhancement to remove contaminants from the parts being cleaned. To the extent that the contaminant is soluble in the cleaning agent or reacts with it, it will simply dissolve in the cleaning agent and be removed via drainage and subsequent dilution and drainage from the part during the rinse portion of the cleaning cycle. Mechanical enhancement in the form of mechanical agitation, ultrasonic agitation, submerged jets or high pressure jets, increases mass transfer rates (dissolving and dilution of soluble contaminants), penetrates small crevices, holes and other tight clearances, and provides for complete or partial removal of nonsoluble contaminants.

Table 11.3 summarizes the combination of system types and solvent or cleaning agents that were selected to represent the universe of CFC-113 based and replacement/alternative cleaning processes. Detailed descriptions of each system, and the basis for defining the system, are contained in Appendices T and V respectively.

Table 11.3. Summary of metal cleaning system types and solvent or cleaning agent combinations that were analyzed

Solvent/Cleaning Agent Classification	Batch	In-Line
High Boiling Temperature Solvent Vapor Degreaser	1,1,1 Trichloroethane Trichloroethylene	1,1,1 Trichloroethane Trichloroethylene
Low Boiling Temperature Solvent Vapor Degreaser	CFC-113 HCFC-141b HCFC-123 HCFC-225ca/cb	CFC-113 HCFC-141b HCFC-123 HCFC-225ca/cb
Semi-Aqueous	Hydrocarbon Wash/Water Rinse	Hydrocarbon Wash/Water Rinse
Aqueous	Detergent Wash/Water Rinse	Detergent Wash/Water Rinse

The overall intent of this analysis has been to define systems that are representative of currently available modern cleaning equipment alternatives that are both environmentally sound and effective cleaning systems, concentrating on those technologies which are most readily applicable to cleaning requirements which have been met with CFC-113 based systems. Both the batch and in-line systems that have been taken as representative are medium to large size systems that are produced as packaged equipment to a standardized (with options available) design. While these example systems

are representative of this class of cleaning equipment, it is recognized that there is a much wider diversity of cleaning equipment, cleaning solvents, and aqueous and semi-aqueous cleaning agents than are directly covered by the selected examples.

The aqueous system examples have assumed a detergent-based wash step; other cleaning agents that are used in an aqueous wash are saponifiers (strong alkali) and terpene emulsions. For the semi-aqueous system examples an immersion, wash in an aliphatic hydrocarbon (AHC) formulation, is assumed as discussed in Appendix T. Terpene immersion washing is also a viable alternative. For both types of system, the choice of cleaning agent does not significantly impact the energy inputs.

The same equipment used for general cleaning, with minor variations such as the addition of ultrasonic immersion steps, is used for most precision cleaning applications. Operating energy input levels are similar, but typical throughput rates are somewhat lower. For the purposes of comparing the equivalent CO_2 emissions of the alternative cleaning methods, the general metal cleaning results are applicable.

The scale of the example systems is near the medium size of all metal cleaning equipment. Mass production cleaning systems for relatively large parts -- refrigerant compressor bodies, automobile engine and transmission parts, air conditioning coils, etc. -- utilize considerably larger tanks, with correspondingly larger fluid inventories. At the small end of the scale, bench top ultrasonic cleaners and small vapor degreasers are in widespread use. The scale of equipment selected is in the most widespread use; and it is expected that the relative CO_2 emissions among solvent and aqueous alternatives is applicable to the broader range of equipment scale.

A major energy input to solvent vapor cleaners is the electric resistance heat input required to boil the solvent continuously, maintaining a stable vapor zone and providing a source of clean solvent for parts rinsing. Batch and in-line vapor cleaners are available that utilize a vapor compression cycle heat pump to both boil and condense the solvent vapor. As typically applied, the heat pump capacity is set to provide both a higher rate of solvent vapor generation and a lower electric power input. Because of the limited number of manufacturers of heat pump based vapor cleaners (e.g., Corpane Industries), heat pump based systems are noted as an important option, rather than the major technology used for vapor cleaning.

For each system type that was modelled, a representative configuration and a representative set of energy inputs was defined. In practice, the exact set of design features and cleaning techniques, and the corresponding energy inputs, are tailored to the particular cleaning application. As a result, a wide range of energy consumption occurs in practice. Important exceptions are noted in the material that follows in this section.

Depending on the solvents used and mechanisms to reduce solvent emissions, the CO_2 equivalent associated with solvent emissions may constitute a significant portion of the total equivalent warming impact of the solvent based cleaning processes, as discussed in Section 11.4. Solvent losses and dragout are discussed in Appendix Q. In general solvent vapor loss rates have been assumed representing typical modern machines for the baseline technology. In principle, techniques such as carbon adsorption and superheated solvent vapor drying, could be used to reduce dragout and emissions to near zero and various measures can be employed to control diffusion losses. Some of these techniques are old but have proved to be uneconomical, while others have only recently become practical in commercially produced equipment and are included as part of the best available current technology (BACT) scenario.

No inference should be drawn from the preceding statements that each of the defined example systems/solvents/ cleaning agents are equally well suited for cleaning all types of parts, oils, greases,

soils and other contaminants, or that comparable cleaning performance will result in all instances. Many users/operators of cleaning equipment have cited examples of processes where they could not readily replace solvent based cleaning processes with aqueous processes; for example:

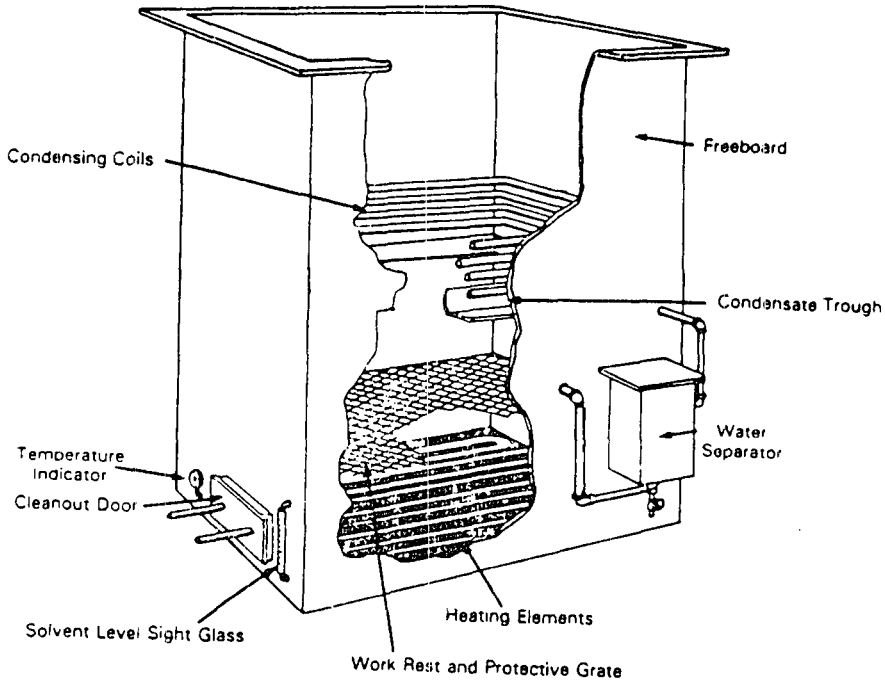
- honeycomb structures where it has proven difficult to obtain acceptable cleanliness in the deep narrow channels using alternatives,
- precision cleaning where small particulates down to the micron sized range need to be removed, and
- jet engine subassemblies where the rather benign CFC-113 has been difficult to replace because alternatives have not been entirely compatible when contacting insulating wires and other components.

Batch Solvent Vapor Cleaning System for Metals

Figure 11.3 shows a typical vapor cleaner for metal parts. In the basic vapor cleaning process, solvent is continuously evaporated from a boiling sump and condensed on coils above the surface of the boiling liquid solvent. The zone below the condenser coil and above the liquid contains saturated solvent vapor at ambient pressure. A part or basket of parts to be cleaned is lowered with an operator-controlled hoist into the saturated vapor zone, where the solvent vapors condense on the cooler parts, dissolving oils. The solvent and oils gravity drain off the parts and into the boiling sump. When the parts warm up, from the latent heat of the condensed vapors, solvent condensation stops, and the part is removed. Additional cleaning and rinsing steps can be added to the basic vapor cleaner, as indicated in Fig. 11.4. Immersion in circulating solvent or in an ultrasonically agitated tank are examples. The clean solvent condensed on the condenser coils may be used to provide a clean solvent rinse, as shown in Fig. 11.4, or returned directly to the boiling sump.

The space above the saturated vapor level that is enclosed by the sidewalls is called "freeboard", and is needed to minimize diffusion loss of the solvent. The treatment of the condensing coils and freeboard area varies depending on whether the solvent has a high boiling point (1,1,1, trichloroethylene) or a low boiling point (CFC-113, HCFC-141b, HCFC-123, HCFC-225ca/cb). For high boiling point solvents, the condensing coil is commonly water cooled, using tap water or a closed loop with a cooling tower, either being at temperatures well below the atmospheric boiling point of the solvent. A modest freeboard height, on the order of the inside width of the cleaner, is used. For very low boiling point solvents such as HCFC-123 and HCFC-141b, condensing coil temperatures of approximately 5°C (40°F), are needed to condense the solvent vapor. CFC-113 and HCFC-225ca or 225cb can have condensing coil temperatures up to about 16°C (60°F). The state of the art equipment that has been developed for the low boiling solvents employs two basic measures to control solvent losses, higher freeboard and low temperature freeboard chillers. Increased freeboard height lengthens the diffusion path for solvent molecules. The chiller, whose cooling coil is located at the bottom of the freeboard has the primary effect of condensing a major portion of the solvent vapors that diffuse above the saturated vapor zone, reducing the solvent vapor partial pressure at this level, for a reduced diffusion driving potential.

Calculations of the total equivalent warming impact from operation of a model batch solvent vapor systems have been carried out for the two high boiling and five low boiling solvents noted above. The detailed assumptions are discussed in Appendix T. The key assumptions are:



Source: Alternative Control Technology Document Halogenated Solvent Cleaners, 1989

Fig. 11.3. Batch solvent vapor cleaner for metal cleaning.

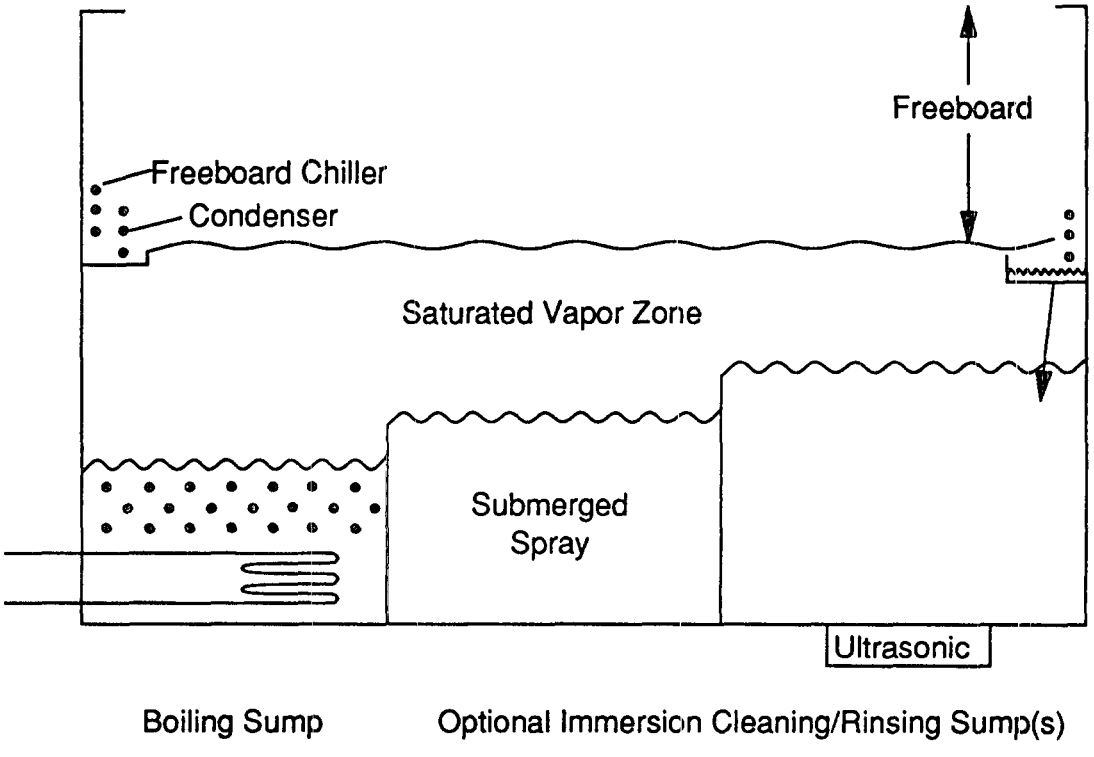


Fig. 11.4. Batch solvent vapor cleaning system with immersion steps.

- The energy input for boiling the solvent is provided by an electric resistance immersion heater, which is the most common practice with vapor cleaners. To provide for clean solvent, the volumetric "distillation" rate (e.g. gal/hr or liters/hr) has been kept constant to the primary condensing coils at a constant work throughput. Additional solvent condenses on the parts to be cleaned, requiring additional energy to raise the parts temperature. Heat losses have been estimated based on insulated machines.

- The low boiling temperature solvent cases include refrigeration energy requirements for solvent conservation.

- Ultrasonic modules and spray are employed.

- Solvent losses are based on modern machines, as discussed in Appendix Y. Total losses during operation were estimated at 0.75 kg/tonne metal cleaned and 0.5 kg/m^2 of printed circuit board for batch systems and 0.35 kg/tonne and 0.1 kg/m^2 for in-line machines (chiller temperatures will be different for the different solvent systems and this energy use is taken into account); lesser amounts lost during idling and downtime modes were calculated as shown in Appendix Q.

Several significant variations from this basic arrangement are also in practice but not part of the baseline technology; these are considered for machines installed as part of the scenario on future energy use using best available current technology (BACT, see Appendix AB).

- An "economizer" can be incorporated into the system to reduce the heat input when the system is idling or lightly loaded.

- The heat input for boiling the solvent can be supplied by a heat pump that also provides the cooling required by the solvent vapor condenser, significantly reducing the total electric power input. Savings of up to 75% can possibly be obtained (see Appendix AB).

- If highly purified solvent is required for cleaning, a solvent recovery still could be in continuous operation in parallel with the boiling sump of the vapor cleaner, providing continuous removal from the cleaner of the oils and other contaminants removed from the parts. The energy input to this still is primarily electric resistance heat to boil the solvent and is typically sized to be 50 to 100% of the heat input capacity to the heater in the boiling sump of the cleaner. Again, heat pumps can reduce energy consumption by up to 75% (The interested reader can calculate energy impacts from the information presented in Appendix Y).

- Different combinations of auxiliary cleaning enhancement (ultrasonics, spray rinses, etc.) can be utilized, all of which will have a second order impact on the energy input.

- More effective solvent vapor recovery systems.

Batch Aqueous and Semi-aqueous Cleaning Systems for Metal Cleaning

The general configuration of the open top batch type aqueous or semi-aqueous cleaning systems for general metal parts or precision parts is similar as pictured in Fig. 11.5. The equipment consists of a series of immersion tanks in which a sequence of washing, rinsing (one or multiple rinses), and drying steps are carried out.

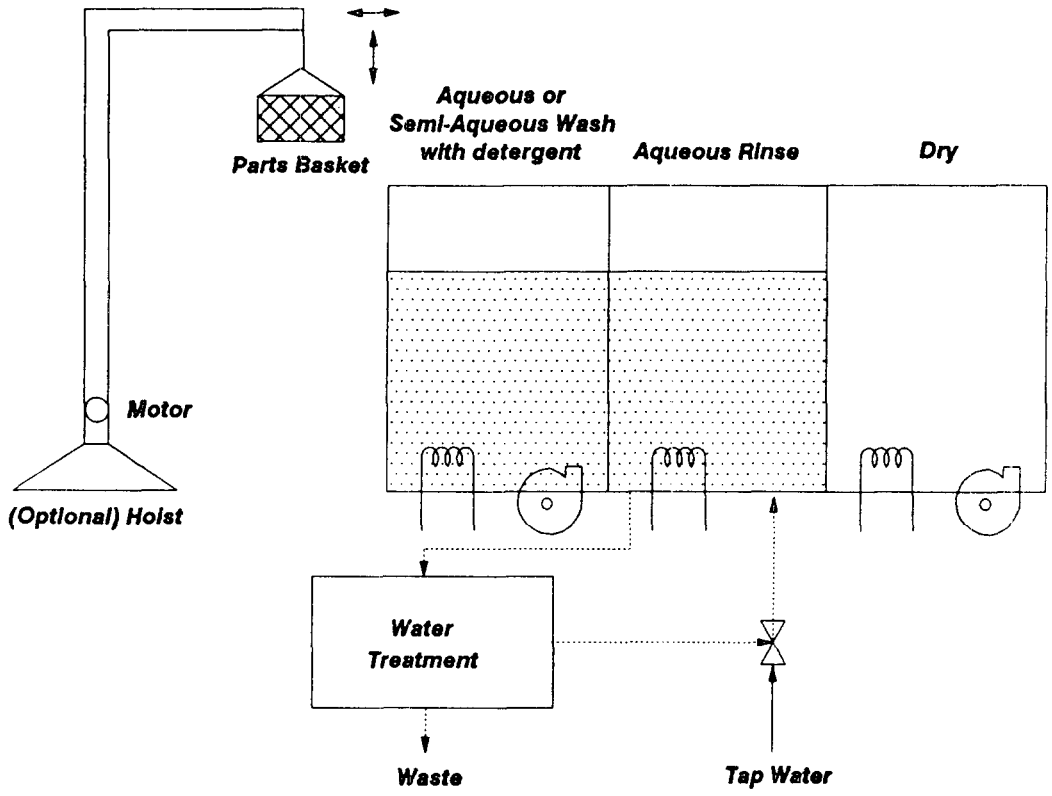


Fig. 11.5. Batch semi-aqueous or aqueous system for metal cleaning.

Calculations of the total equivalent warming impact from operation of a model batch aqueous and semi-aqueous cleaning systems have been carried out. The detailed assumptions are discussed in Appendix T. The major energy inputs and other key assumptions are:

- Electric resistance heaters are used to maintain the rinse bath temperatures. Typical temperatures are 50°C - 80°C (120°F - 175°F) for aqueous wash and rinse steps and room temperature for a semi-aqueous wash step. Heat inputs are required to heat make-up water, to make up for heat losses to the ambient environment via conduction and evaporation, and to make up for heat removed as parts are warmed up from room temperature to rinse temperature.

- Electric resistance heat is used to heat drying air.

- Electric power is required to operate pumps used for wash and rinse agitation.

- Electric power is required to operate the drying air blower.

- For comparison with solvent cleaning processes on an equivalent basis, a drying stage is included, so that dry parts exit the aqueous or semi-aqueous cleaning process.

Important variations from the baseline technology exist in practice:

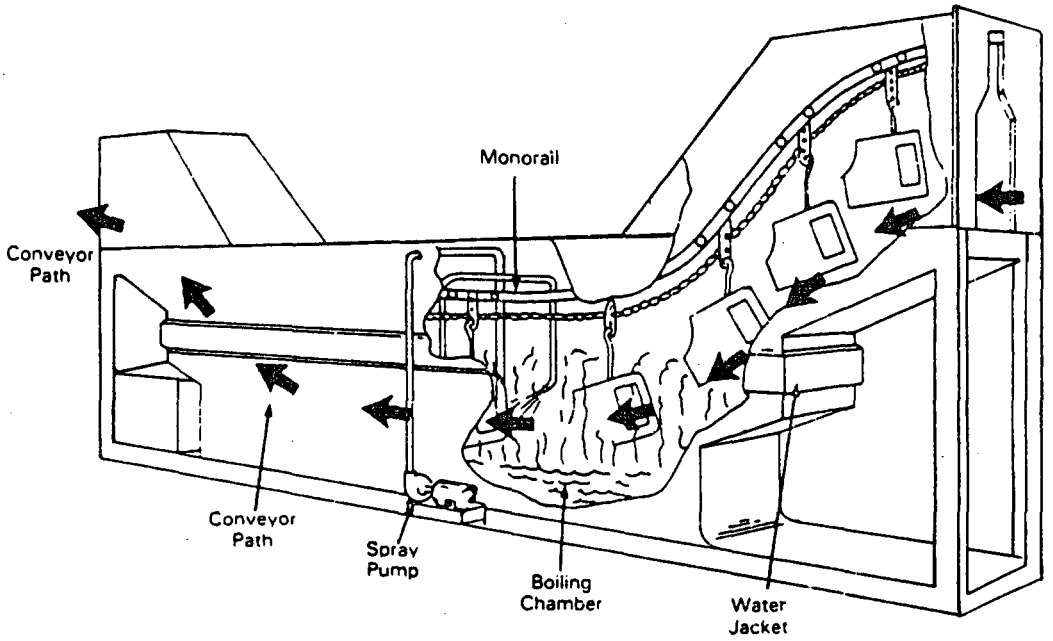
- There is a wide range of cleanliness and dryness requirements, which are met by aqueous cleaning processes having a wide range of energy intensity.

- At the low energy extreme, parts may be cleaned by immersion in a moderately agitated tank with an aqueous detergent solution or emulsion at room temperature, rinsed by low pressure sprays, and taken wet into a downstream plating or water based painting step. The energy input to such a process is almost negligible.

- At the opposite extreme, parts requiring precision cleaning may be subjected to an energy intensive series of ultrasonic cleaning, high pressure spray rinse, and heated air and vacuum drying steps.

In-Line Solvent Vapor Metal Cleaning Systems

In-line metal cleaning systems often are specially designed machines that can be broadly categorized as cross rod, monorail, and belt systems (Appendix V). Figure 11.6 shows a typical in-line monorail vapor cleaner for metal parts. Parts to be cleaned are moved through the cleaner on an overhead conveyor (larger parts, hanging from hooks as indicated in Fig. 11.6, or smaller parts in wire mesh baskets) or on a flat conveyor belt. In the basic vapor cleaning process for any of the in-line metal cleaning systems, solvent is continuously boiled from a boiling sump and condensed on a water jacket (or cooling coils) above the surface of the boiling liquid solvent. The zone below the condenser coil and above the liquid contains saturated solvent vapor at ambient pressure. As the parts to be cleaned are moved through the saturated vapor zone, the solvent vapors condense on the cooler parts, dissolving oils. The solvent and oils drain off the parts by gravity into the boiling sump. When the parts warm up, from the latent heat of the condensed vapors, solvent condensation stops. The parts continue through, and then out of, the saturated vapor zone. As the parts move up the incline on the way out of the saturated vapor zone, liquid solvent gravity drains from the parts. Solvent retained in filets, holes, at the root of screw threads, other small crevices and in a thin surface film does not begin to evaporate until the parts leave the saturated vapor zone. A portion of these solvent vapors will be condensed on the cooling coils, the remainder lost by diffusion to the surrounding atmosphere. Additional cleaning and rinsing steps can be added to the basic vapor cleaner (e.g., immersion in circulating solvent or in an ultrasonically agitated tank). The clean solvent condensed on the condenser coils may be used to provide a clean solvent rinse, as shown in Fig. 11.6, or returned directly to the boiling sump.



Source: Alternative Control Technology Document Halogenated Solvent Cleaners, 1989

Fig. 11.6. In-line solvent vapor cleaner for metal cleaning.

The space above the saturated vapor level that is enclosed by the sidewalls is called "freeboard", and is needed to minimize diffusion loss of the solvent. As with batch cleaning systems, the treatment of the condensing coils and freeboard area varies depending on the boiling point of the solvent. Equipment that is being developed for the low boiling solvents employs two basic measures to control solvent losses, higher freeboard and low temperature freeboard chillers. Increased freeboard height lengthens the diffusion path for solvent molecules. The chiller, whose cooling coil is located at the bottom of the freeboard has the primary effect of condensing a major portion of the solvent vapors that diffuse above the saturated vapor zone, reducing the solvent vapor partial pressure at this level, for a reduced diffusion driving potential. The lower condensing temperature provided by the freeboard coil can provide for increased recovery of the evaporating solvent liquid dragged out of the saturated vapor zone by the parts.

Calculations of the total equivalent warming impact from operation of a model in-line solvent vapor system have been carried out for the two high boiling and three low boiling solvents noted above. The detailed assumptions are discussed in Appendix V. The key assumptions are:

- The energy input for boiling the solvent is provided by an electric resistance immersion heater, which is the most common practice with vapor cleaners. As with batch cleaning, the volumetric "distillation" rates (gal/hr, liters/hr) were kept constant for the various solvents, at constant work throughputs.

- A solvent recovery still is installed in parallel with the boiling sump of the vapor cleaner, providing continuous removal from the cleaner of the oils removed from the parts and clean solvent for rinsing.

- The low boiling temperature solvent cases include energy inputs for both a condensing chiller and a freeboard chiller.

- A modest level of electric power input to operate spray rinse pumps was assumed.

- Solvent losses are based on state of the art practice, as shown in Appendix Y. Total losses during operation were estimated to be the same as those listed above for batch solvent systems; lesser amounts are lost during idling and downtime modes as shown in Appendix Q.

Several significant variations from this basic technology are also in practice.

- The heat input for boiling the solvent can be supplied by a heat pump that also provides the cooling required by the solvent vapor condenser, significantly reducing the total electric power input.

- Different combinations of auxiliary cleaning enhancement (ultrasonics, spray rinses, etc.) can be utilized, all of which will have a second order impact on the energy input.

- Solvent vapor recovery systems can be incorporated (Appendix AB).

In-Line Aqueous and Semi-aqueous Cleaning Systems for Metal Cleaning

The general configuration of in-line type aqueous or semi-aqueous cleaning systems for general metal parts or precision parts is similar as pictured in Fig. 11.7. The equipment consists of a series of immersion tanks and/or spray stations in which a sequence of washing, rinsing (one or multiple

rinses), and drying steps are carried out. In-line aqueous metal cleaning processes are a widely used, well established alternative to solvent vapor cleaning (not applicable to all cleaning requirements, but widely practiced nevertheless). In-line semi-aqueous systems are beginning to be applied to metal cleaning applications.

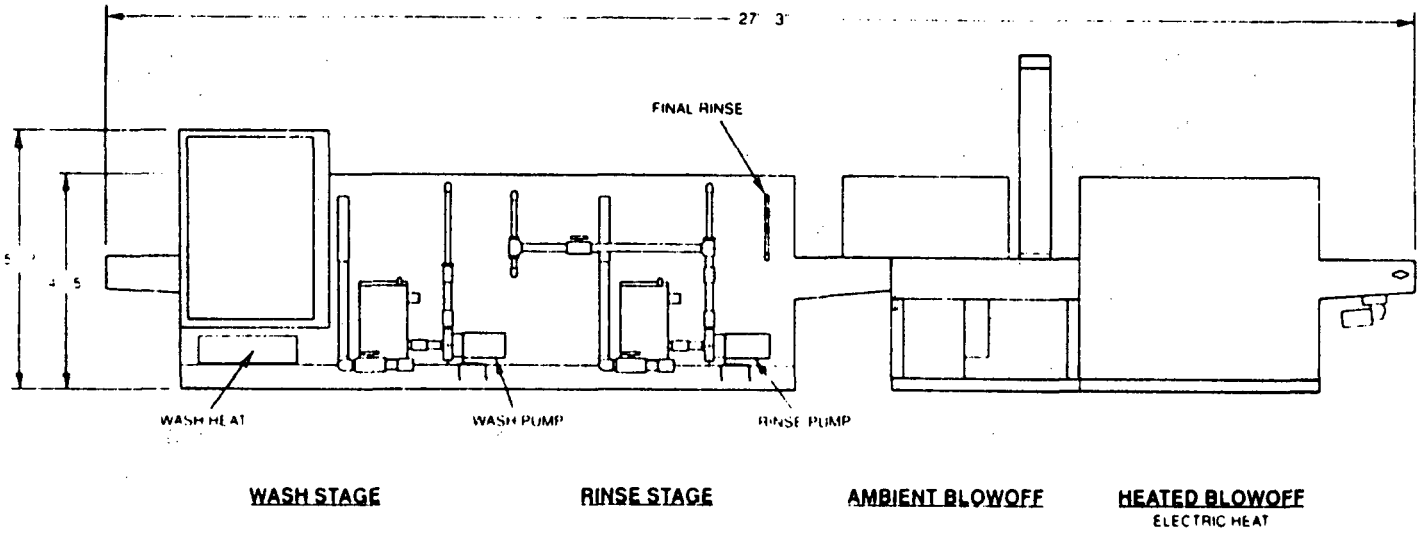


Fig. 11.7. In-line aqueous metal cleaning system.

The aqueous wash step can utilize alkaline cleaners (saponifiers), detergent based cleaning agents, or aqueous emulsions of terpene/surfactant cleaning agents. The temperature of the aqueous wash solution, the intensity of sprays or other mechanical enhancement, and the concentration and type of surfactant or cleaning agent depend on the nature of the oil, grease, metal cuttings, soil, and other contaminants to be removed, the geometry of the parts, and the degree of cleanliness required. Cleaning is effected by a combination of displacement (surfactant effect), solubilization (e.g. saponification) and fluid mechanical removal (ultrasonic, jet impingement).

The semi-aqueous wash step, using a hydrocarbon formulation or terpenes is typically carried out on an agitated immersion, rather than a spray basis, to minimize the formation of flammable vapor/air or mist/air mixtures. Cleaning is based primarily on solubilizing and flushing the contaminants from the parts. To minimize the fire risk, the bath temperature is generally well below the flash point of the solvent. Fire safety issues have been raised nevertheless, and in some instances a nitrogen (or carbon dioxide) atmosphere is maintained over the semi-aqueous wash bath.

Generally, "air knives" are used between washing and rinsing stations to minimize the carry over of wash or rinse solutions to the following stage. The first stage rinse water in semi-aqueous processes will contain the terpenes or hydrocarbons that are carried over past the air knives. These are gravity separated from the rinse water and returned to the wash tank.

Calculations of the global warming impact from operation of a model in-line aqueous and semi-aqueous cleaning systems have been carried out. The detailed assumptions are discussed in Appendix V. The major energy inputs and other key assumptions are:

- Electric resistance heaters are used to maintain the wash and rinse bath(s) temperatures. Typical temperatures are 25°C - 55°C (80°F - 130°F) for aqueous wash and rinse steps

and room temperature for a semi-aqueous wash step. Heat inputs are required to heat make-up water, to make up for heat losses to ambient via conduction and evaporation, and to make up for heat removed as parts are warmed up from room temperature to rinse temperature. Moreover, heating or cooling may be required in the semi-aqueous wash step to control system temperature.

- A detergent based aqueous wash step is assumed.

- The semi-aqueous wash step modeled is based on a hydrocarbon formulation. It is assumed that an inert atmosphere is not required over the wash tank. (It should be recognized that some hydrocarbon formulations may require an inert atmosphere and that generating the necessary inert gases would involve additional energy.)

- Electric resistance heat is used to heat drying air.

- Electric power is required to operate pumps used for wash and rinse agitation and sprays.

- Electric power is required to operate blowers for air knives.

- Electric power is required to operate the drying air blower and to heat the drying area.

- For comparison with solvent cleaning processes on an equivalent basis, a drying stage is included, so that dry parts exit the aqueous or semi-aqueous cleaning process.

Important variations from this baseline technology that exist in practice:

- There is a wide range of cleanliness and dryness requirements, which are met by aqueous cleaning processes having a wide range of energy intensity.

- Where high ambient humidity is prevalent, energy consumption can be fairly high for conditioning input air that is eventually exhausted in aqueous processes.

- At the low energy extreme, parts may be cleaned by immersion in a moderately agitated tank or by low pressure sprays with an aqueous detergent solution or emulsion at room temperature, rinsed by low pressure sprays, and taken wet into a downstream plating or water based painting step. The energy input to such a process is almost negligible.

- At the opposite extreme, parts requiring precision cleaning may be subjected to an energy intensive series of ultrasonic cleaning, high pressure spray wash and rinse steps, and heated air and vacuum drying steps.

Other Cleaning Systems

Two other types of cleaning systems have a small presence in the cleaning equipment market. Enclosed batch spray cleaners closely resemble a dishwasher in general appearance, size, and function. Centrifugal cleaners spin one, or a group of, parts in the plane of the board. Each type of system is described briefly in Appendix X. Because of the low level of current usage, detailed global warming potential analyses have not been carried out for these systems.

11.5 CLEANING SYSTEMS SELECTION AND ANALYSIS APPROACH

The overall approach for analyzing the total global warming impacts of cleaning technology involves:

- Collection of readily available data from prior work, vendors, manufacturers, users and other interested parties. Over thirty companies were contacted or visited to obtain information for inputs to this study. They were instrumental in providing much of the information shown in the Appendices.

- Selection of typical systems. This was accomplished by discussions with vendors and users. It was recognized that only a representative sample of systems could be analyzed in the scope and time of this study.

- Calculations and data analysis for estimating Total Equivalent Warming Impacts (TEWI).

Thus, the prototypical systems chosen may not be strictly mean or average values but are thought to be representative of modern machines, sizes, and solvents used. These systems were chosen in order to make engineering calculations on heat and material balances.

Figure 11.8 provides an overview of the system considered in these analyses.

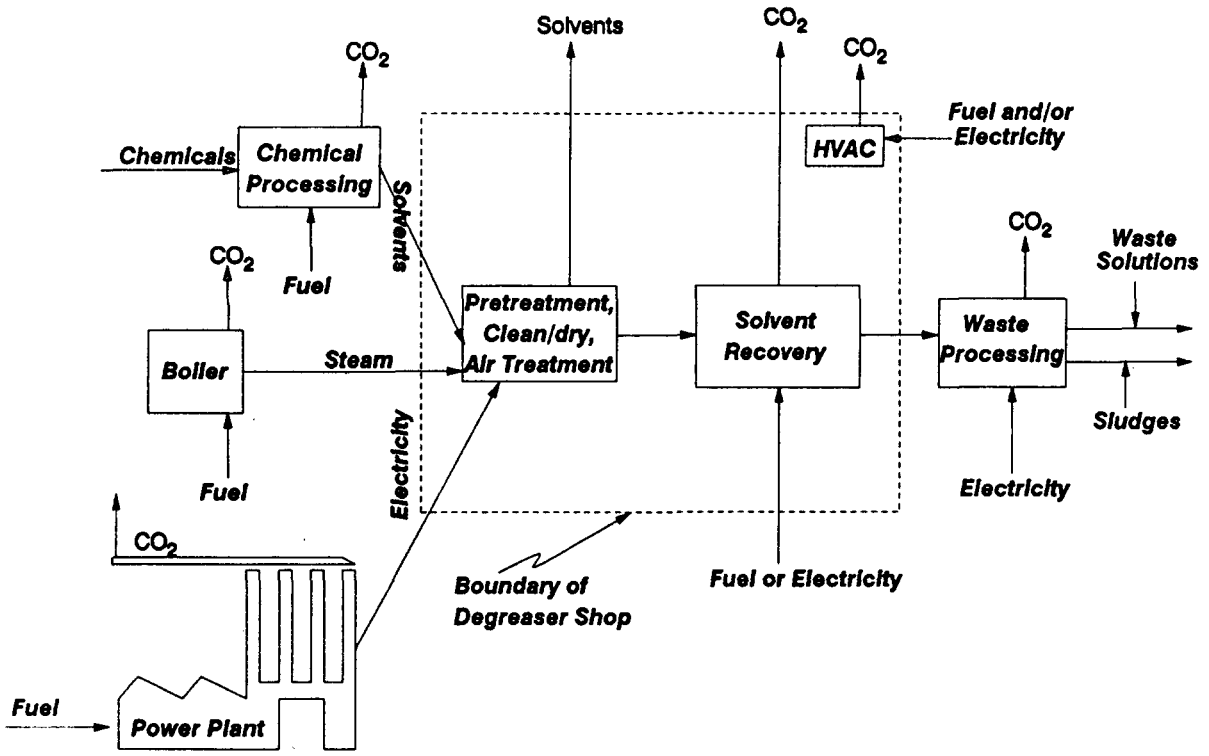


Fig. 11.8. Sources of CO_2 and greenhouse gases in the cleaning process.

- Within the dashed area is the cleaning system showing demands for electricity, steam and emissions of solvents which may contribute to the global warming impacts. The global warming potential of various chemicals is more fully discussed in Appendices R and S. The global warming potential of various chemicals is more fully discussed in Appendix R and S.

- At the power plant (or steam raising boiler) CO_2 emissions are generated when fossil fuels are used. Depending on geographical region, power may be generated from different electric energy sources (e.g. coal, oil, natural gas, nuclear, hydro-electric, etc.) and thus, CO_2 emission factors will be different from region to region as discussed in Appendix O.

- Additionally, there is energy consumed in the manufacture of solvents, in recycling in waste disposal, etc. which can contribute to the total equivalent warming impact.

Figure 11.9 provides additional detail of typical plant equipment showing:

- the cleaning/washing/drying step(s) which may be done in one machine or in sequential operations,

- ventilation, exhaust and air pollution control (if any),

- solvent clean-up and pre-treatment.

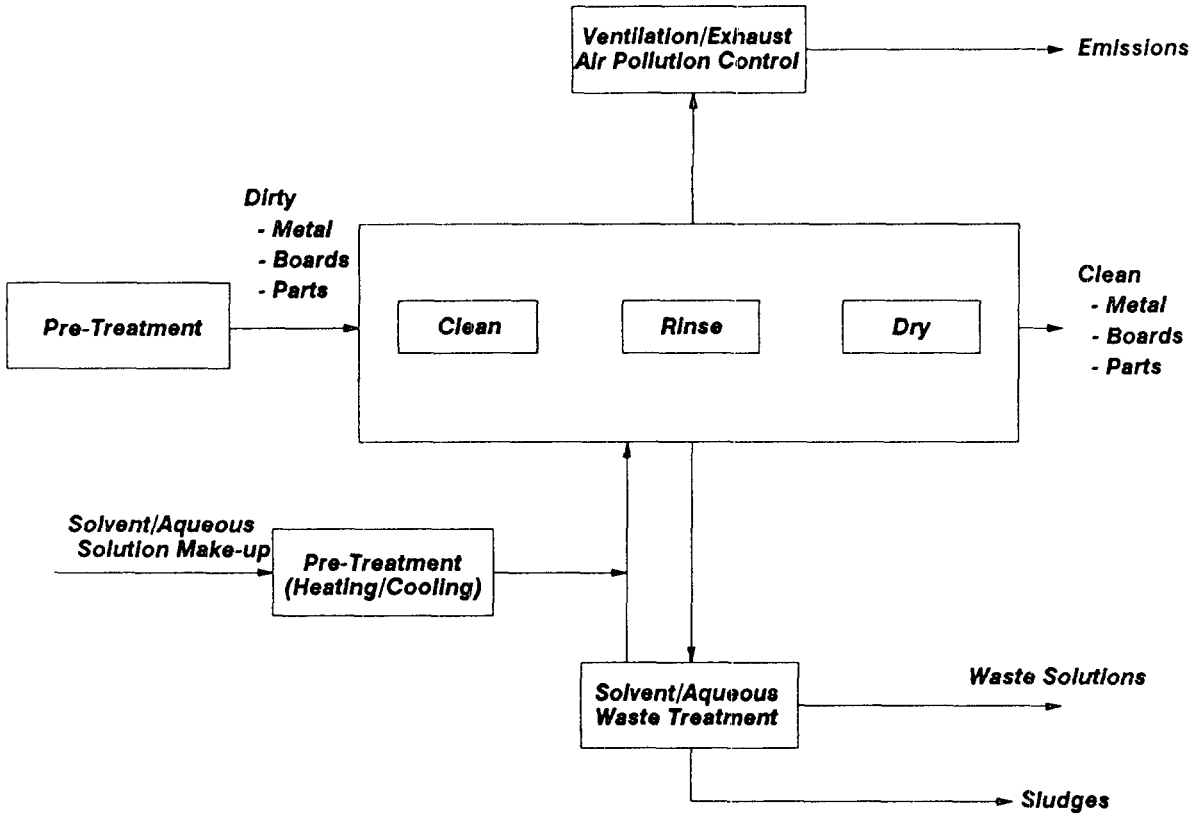


Fig. 11.9. Major material flows in cleaning process.

Depending on ambient temperatures and relative humidity, additional energy may be required for HVAC due to air intake resulting from ventilation of the exhaust gases from cleaning operations. Since such HVAC needs are highly regionally dependent, additional HVAC energy has not been taken into account.

Further details on the type of information collected for the energy analysis are shown in Table 11.4 for washing, rinsing, drying, in-line waste treatment such as for water recycling/solvent recovery, and other uses.

Table 11.4. Energy breakdown of cleaning systems by station (unit process)

Station/Component	Operating Power (kW)
Wash	
Heater	
Pump	
Total Wash	
Rinse	
Heater	
Pump	
Total Rinse	
Dry	
Heater	
Blower	
Total Dry	
Exhaust/Ventilation	
Blower	
Total Exhaust/Ventilation	
Waste Treatment	
Heater	
Pumps	
Total Waste Treatment	
Other	
Chiller	
Conveyor	
Hoist	
Total Other	
Total, System	

Energy use information from this analysis was then logged into the shaded area of forms similar to that shown in Fig. 11.10 for the prototypical machine within columns 2, 3 and 4. To translate these energy use numbers to CO_2 emissions, factors were developed (kg CO_2/kWh delivered) as shown in Appendix O to reflect the energy mix in power generation in North America (NA), Europe, and Japan.

Capacity Basis: three tonnes steel/hr	Energy Consumed			Embodied Energy in Chemicals		GWP Attributed to Solvent Emissions		North America		
1. Unit Process	2. Electric Energy (kWh/hr)	3. Steam (KJ/hr)	4. Direct Fuels (KJ/hr)	5. Name	6. Tonnes/hr	7. Short-Lived Solvents Emitted (Kg/hr)	8. Long-Lived Solvents Emitted (Kg/hr)	9. Other	10. Total for Machine	11. Total Kg CO_2/Unit Capacity
• Clean • Rinse • Dry • Air pollution • Pretreatment • Waste treatment • Other										
Total										
Efficiency factor	NA	0.80	1.0	Various	1.0					
Equivalent primary fuels (KJ/hr)	NA									
North America: CO_2 factor (b)							(a)			
Equivalent CO_2 emissions										

Japan

Europe

(a) Greenhouse Warming Potential
(b) Kg CO_2/kWh/KJ, etc.
NA not applicable: CO_2 factors are based on KWH delivered

Fig. 11.10. Methodology overview for direct and indirect impacts.

The other columns were then filled in:

- Any chemicals consumed were identified and CO_2 emission from manufacture of chemicals estimated based on Appendix P; this is labeled "embodied energy" in columns 5 and 6. Chemicals from sump replacement were allocated to the operating mode hours.

- Short lived and long lived solvents emissions were estimated and their contribution to TEWI were estimated (Appendix P and R) in terms of CO_2 equivalents shown in columns 7 and 8. The "efficiency factor" row was used to enter a GWP.

- Column 9 was used to include miscellaneous and ancillary equipment shown in Appendices Y and Z as part of the cleaning process.

- The total CO_2 equivalent emissions were then totaled for the machine in Column 10.

- Values in Column 11 were obtained by dividing the emissions per hour by the nominal machine operating rate (e.g. typical tonnes/hr or square meters of board/hr).

- Calculations were made for a 500 year GWP time horizon (sensitivity calculations for the 100 GWP time horizon are found in Appendices Y and Z).

- A similar exercise was then done to estimate total equivalent warming impacts for an idling mode (i.e. machine is operating, no parts going through, but machine is ready to accept parts for cleaning at any time) and downtime mode such as overnight or weekends.

Emissions of solvent and energy used were normalized to the nominal machine operating rate (e.g., kWh or kg CO_2 emissions per day divided by m^2 of circuit board (see Section 12) or tonne/day of parts cleaned).

- A duty cycle was estimated recognizing that operating hours range widely in the industrial sector from 2 hours/day or less operating time (as for some precision cleaning) to a 3 shift operation (approaching 24 hours/day as for a high volume PCB cleaning system). A 12-4-8 duty cycle consisting of 12 hours/day operating time, 4 hours/day idling time and 8 hours/day downtime was used for both batch and in-line systems in this study, which appears typical for medium sized operations (Radian, 1989). The information is presented so that the impact of other duty cycles can be easily calculated.

- Based on the above 12-4-8 duty cycle a "composite" global warming impact was estimated using a time weighted average of emissions over the daily operations. Effectively the results are developed on the basis of daily total equivalent warming impact (e.g., kg of CO_2) divided by the daily throughput (e.g., actual tonnes of metal/day or actual m^2 of board/day processed).

11.6 TEWI FOR METAL CLEANING

The CO_2 equivalent emissions, per unit mass of metal processed, for batch and in-line cleaning processes respectively are summarized in Figs. 11.11 and 11.12 for the 500 year GWP time horizon.

A daily duty cycle representing two shifts per day of 12 operating hours at full capacity, 4 idling hours (with the system operating, but with no throughput), and 8 hours of downtime is assumed. The figures show associated CO_2 and CO_2 equivalent emissions associated with each of the solvent or cleaning agent alternatives discussed in Section 11.5 above. Each bar is subdivided into four segments -- the lower three segments partition the CO_2 emissions associated with energy use in the cleaning process, with minor contributions from energy embodied in solvent chemicals, and auxiliary processes. The upper of the four segments gives the CO_2 equivalent of the solvent emissions to air. Energy consumption and solvent emissions during idling and downtime have been added, prorata, to the values for operation at full throughput.

Appendix Y presents the detailed calculations, and documentation of the assumptions (throughput rates, detailed breakdown of energy inputs, solvent emission rates), that provide the basis for the aggregate CO_2 equivalent emissions presented in Figs. 11.11 and 11.12.

In general, for both batch and in-line systems, energy consumption levels per throughput of solvent based systems are a fraction of the energy consumption per throughput level of the aqueous systems. In all cases, energy levels were calculated on the basis of dry parts exiting the process (i.e. electric power input associated with drying of water rinsed parts was accounted for). In general, approximate terms, solvent based vapor cleaning systems tend to have major energy inputs associated with solvent vapor generation, while aqueous systems can have major energy inputs for heating rinse water, drying air, and drying of parts. In aqueous in-line systems, power inputs to spray pumps are a significant portion of the total.

The variation in CO_2 emissions at the electric power plant between the U.S., European, and Japanese power generating mix is relatively modest (Appendices Y and Z).

The energy consumed in the production of the solvent or cleaning agent and other materials consumed by the process, and the energy consumed by auxiliary processes (solvent recycling, waste

disposal, etc.) is a minor portion of the total energy input to the cleaning process (Appendices P, Y, and Z).

The total equivalent warming impact of the CFC-113 based processes, even at the modest emission levels assumed, is dominated by the large CO_2 equivalent global warming impact of the solvent emissions, due to the very large GWP of CFC-113. All of the alternative processes have much lower total equivalent warming impacts than the CFC-113 based processes.

Batch Systems: Energy Use

Figure 11.11 compares the CO_2 equivalent emissions for the nine batch systems that were analyzed for the 500 year GWP time horizon. In the representative systems selected, the energy component of the CO_2 emissions of the solvent based systems is typically smaller than that of the aqueous or semi-aqueous systems. However, it should be noted that aqueous cleaning systems that precede another aqueous process (e.g., water based paint application, electroplating) generally do not require a drying step and thus can save considerable amounts of energy. The information on energy use has been developed to show the drying step separately. As a result, the interested reader can calculate energy savings for such situations based on the information in Appendix Y.

In-Line Systems: Energy Use

Figure 11.12 compares the CO_2 equivalent emissions associated with each of the nine representative in-line systems that were analyzed for the 500 year GWP time horizon. Typical energy consumption levels per unit of throughput of the representative solvent systems are comparable to the semi-aqueous and aqueous systems. As with batch systems, energy savings can be achieved with aqueous and semi-aqueous cleaning systems if drying is not needed.

Total Equivalent Warming Impacts

Examination of Figs. 11.11 and 11.12 shows that among solvent systems TCE offers a relatively low total equivalent warming impact in many cases due to the low GWP of solvent emissions. With some other solvent based systems, solvent emissions can contribute noticeably to the total equivalent warming impact. In the future, the adoption of best available current technologies (BACT) to limit solvent emissions has the potential to significantly reduce global warming impacts to the point that all solvent based systems will have TEWI's that are lower or comparable to aqueous systems (see Appendix AB for BACT technologies). These potential decreases in TEWI for metal cleaning equipment are shown graphically in Fig. 11.13 where the TEWI of alternative solvents and processes using BACT are shown to be only 2% to 3% of the TEWI for current industry practices using CFC-113 (BACT using CFC-113 is shown to be about 20% of current practices using CFC-113).

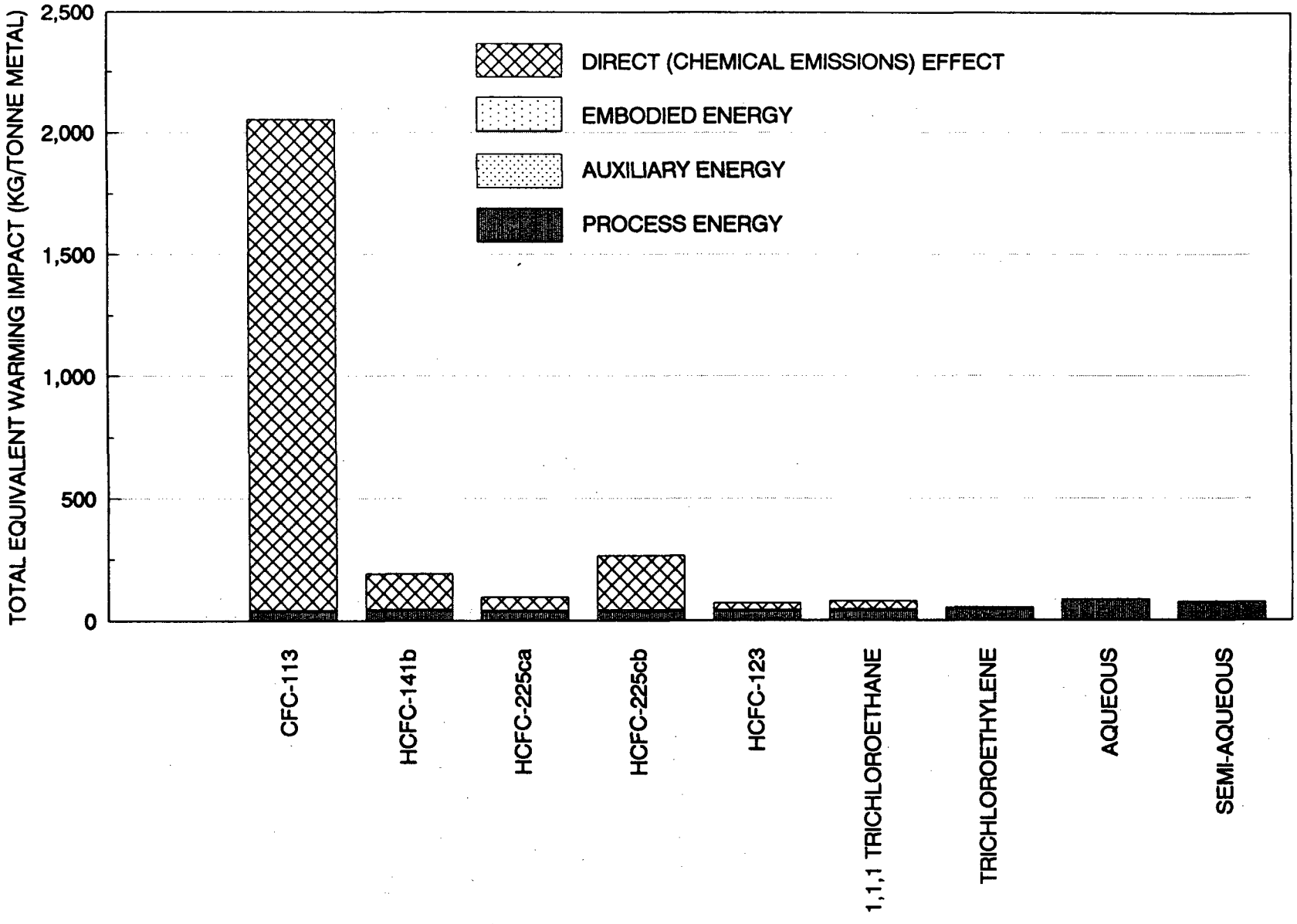


Fig. 11.11. TEWI for batch metal cleaning composite values - 500 year GWP.

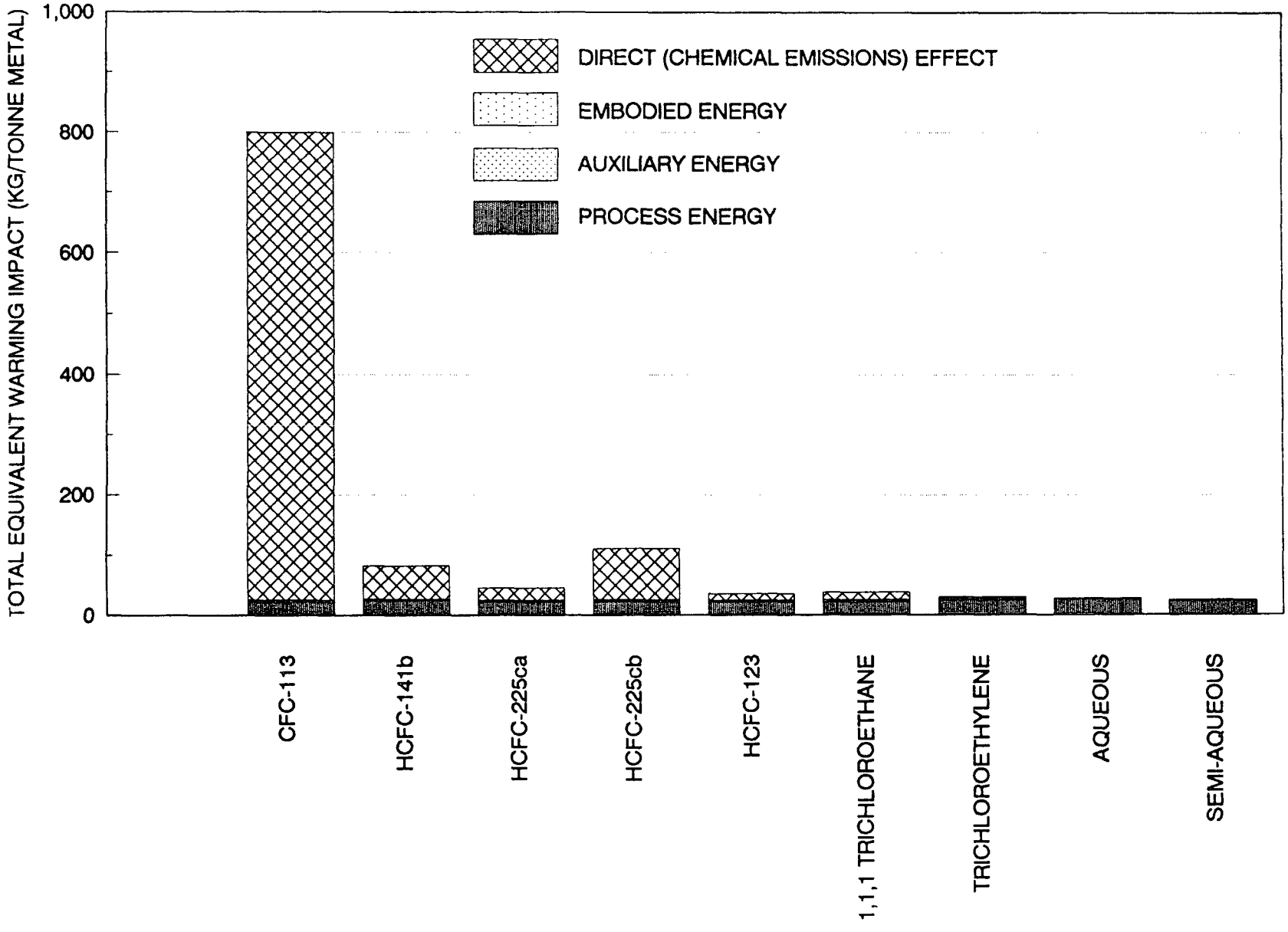


Fig. 11.12. TEWI for in-line metal cleaning composite values - 500 year GWP.

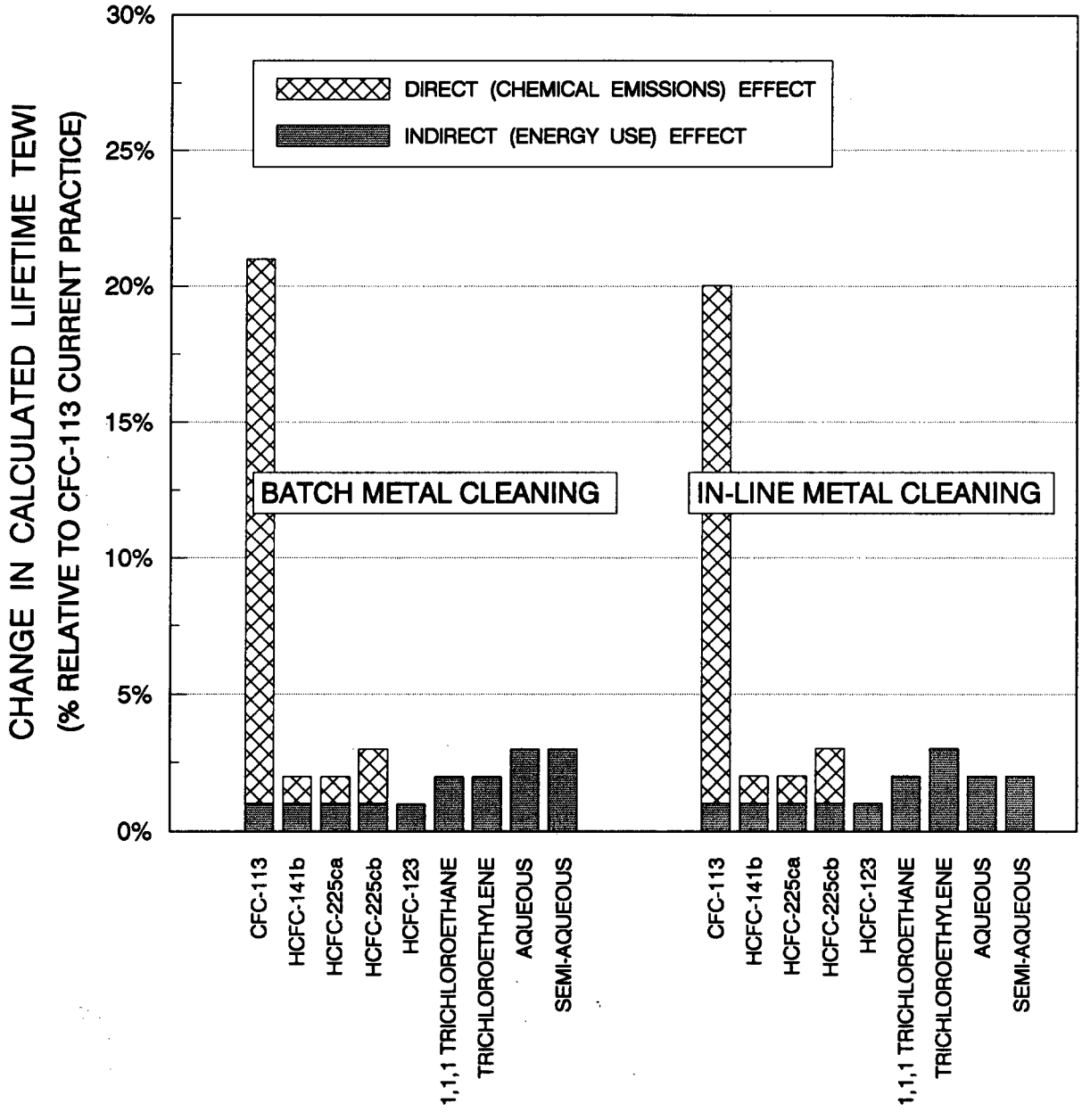


Fig. 11.13. TEWI of BACT metal cleaning equipment as a percentage of the TEWI for industry current practices using CFC-113.

12. ELECTRONIC CLEANING: SYSTEMS AND RESULTS

12.1 INTRODUCTION

The electronics industry is a major user of CFC-113 for cleaning printed circuit boards (PCBs) and circuit assemblies. In many ways the equipment and techniques used are similar to those for general and precision metal cleaning described in Sections 11.1 to 11.3.

Solvent Based Cleaning Systems

The largest single use of CFC-113 is for cleaning of electronic assemblies, the majority of this being used for defluxing printed circuit boards after soldering. PC boards are defluxed, and cleaned of other contaminants, in the interest of improving the short and long term reliability of the individual board and the complete electronic system. Contamination left on PC boards can cause current leakage and shorts between adjacent conductors on the PC board, and in the longer term, corrosion of component leads, as well as conductors on the PC board, and the soldered bond joint. Flux removal is also necessary to obtain good adhesion of conformal coating on PC boards. Advantages offered by CFC-113 as a cleaning agent are discussed later.

PC board cleaning, or provision for clean PC boards, such as the "no clean-soldering" discussed below, is widely practiced in the electronics industry, across the range of consumer electronics, computer electronics, and military electronics; and in large mass production operations and small PC board assemblers.

Aqueous Cleaning Systems

A range of solvent and aqueous, batch and in-line equipment is used to clean printed circuit boards. Cleaning to U.S. military quality standards, especially MIL-STD-2000, has been accomplished primarily in CFC-113 based processes. Although aqueous cleaning is allowed under MIL-STD-2000, many production processes using rosin flux solders were qualified with CFC-113 based cleaning, and a considerable effort will be required to qualify alternative soldering and cleaning processes (i.e., the burden of proving "efficacy" is totally left up to the manufacturer since the military specifications are silent on how to prove efficacy). In addition, "no clean" processing of completed assemblies may require that additional cleanliness requirements be imposed on the components and the PCB. Moreover, adhesion of conformal coatings may be poorer without post solder cleaning. As a result, a number of technical issues remain to be resolved before "no clean" technologies are widely accepted.

Cleaning and drying underneath surface mount components that are located with very close clearance to the printed circuit board is generally considered to be the most demanding cleaning requirement. Most state of the art cleaning systems provide high pressure sprays to attempt to penetrate and flush out this gap.

"No Cleaning" Technologies

In no cleaning technologies, a processing step is carried out so that post process cleaning is not required. The term is most commonly applied to "no clean soldering", a method of soldering that is carried out with the use of low solids fluxes, often under an inert atmosphere. Development activity in this area has been intense since the mid 1980's, when the impetus to reduce CFC-113 and other solvent usage developed and no clean technologies are being rapidly adopted where quality

requirements permit. In a number of applications, concerns have been raised about "no clean" technologies concerning reliability requirements, conformal coating adhesion, etc. (Smiley, 1991). Moreover, adoption of no clean strategies may reduce but not eliminate cleaning requirements. Additional information on this option and estimates of TEWI are presented in Appendices X and AA. A major technical issue is the extent to which no clean soldering technologies are suitable replacement processes for the type of electronic assemblies where CFC-113 and other solvent based cleaning processes have been widely used for post solder cleaning.

12.2 SPECIAL CONSIDERATIONS FOR TECHNOLOGY COMPARISONS

A suitable comparison of cleaning technologies for printed circuit boards is complicated by a number of factors, including:

- Assembly technique (through hole or surface mount, one or two sided boards, etc). Boards may enter a cleaning process more than once (e.g. sequential reflow soldering of surface mounts followed by through hole wave soldering may involve intermediate cleaning since some fluxes may "bake" in the second soldering operation; terpenes are claimed to be able to clean the residues from both soldering operations in a single pass.)

- Degree of cleanliness required, depending on user application and reliability requirements (e.g. applications in high temperature environments demanding high reliability as in military applications may require special solders/fluxes and cleaning agents). There is an increasing tendency toward choosing a cleaning process that results in a product that is fit to use rather than following blindly requirements to a specific (military) standard.

- Residence times in the cleaning solutions depending on assemblies being cleaned which are difficult to determine exactly. It is not unusual to see two companies making the same product on the same machine to run at different speeds based on operational experience and other reasons.

- Ability of cleaning agents and machines to remove solder residues.

- Use of "no-clean" technologies for soldering using low residue fluxes or inert gas soldering.

As a general observation, it is difficult to generalize on the applicability of alternative cleaning techniques; companies typically will test a number of cleaning options for their product lines before qualifying any one of them.

The most commonly used solvent for cleaning printed circuit boards (PCBs) is CFC-113 (and to some extent 1,1,1 trichloroethane). Alternatives that have been tested or implemented for PCBs include:

- Aqueous systems with saponifiers have been used for over two decades. Systems with and without saponifiers are receiving increased attention and have been introduced in a number of recent plants such as at:

  - ELTECH which has introduced a closed cycle water system using organic acid fluxes (ELTECH, 1991)

  - Toshiba which has introduced aqueous systems with saponifiers in plants located in the U.S., Germany, and Japan (Morteson, 1990).

- Electrovert which has tested aqueous cleaning with saponifiers and found they could meet the U.S. MIL-P-28809 extract test for quantitative determination of residual ionic contamination (Morteson, 1990).

- Semi-aqueous (terpene) based systems have been tested or implemented at a number of facilities:

  - Some plants producing telecommunications equipment have completely phased out CFC-113 and replaced the systems with terpene semi-aqueous systems.

  - Calcomp (a division of Lockheed) has tested terpene semi-aqueous systems and found that cleanliness results are comparable or at times superior to CFC-113 (Hamblett and Larson, 1991).

  - Electrovert has tested terpene semi-aqueous cleaning and found it met U.S. MIL-P-28809 extract test for quantitative determination of residual ionic contamination (Elliott, 1990).

  - Tests by Hitachi and Toshiba commissioned by the Japanese Ministry of Industry concluded that military approved rosin based fluxes (along with SA fluxes) can be cleaned in a semi-aqueous process. In addition, semi-aqueous cleaning gave superior results when compared to 1,1,1 trichloroethane, isopropyl alcohol, alkali solutions, and straight water (Dishhart and Wolff, 1990 Sanger and Johnson, 1983, Hitachi and Toshiba, 1989).

- HCFC test work using HCFC-123 and HCFC-141b (Bonner, 1990) which are the major HCFC candidates for replacing CFC-113. Additionally, HCFC-225ca and HCFC-225cb are considered to be candidates (DuPont, 1991c).

The above observations suggests there is considerable discussion on the viability of alternatives.

As a result, this analysis for electronics cleaning should not be interpreted as being applicable to all situations. Issues of safety (flammability of alternatives), water availability, treatment, disposal, and a number of other issues need to be addressed. Manufacturers may find that the alternatives examined may not be applicable to their products or certain products. Thus, no inference should be drawn from this analysis that the systems/solvents/cleaning agents analyzed in this study are equally well suited for cleaning all types of PCBs.

The above discussion nevertheless suggests that alternatives to CFC-113 (or 1,1,1 trichloroethane) include:

- HCFC-123, 141b, 225ca, 225cb (often these require no changes in fluxes used).

- Semi-aqueous systems such as terpenes, or hydrocarbon formulations with other organic agents. These may or may not require changes in soldering/fluxing techniques.

- Aqueous systems either with water soluble (organic acid: O-A) fluxes or saponified aqueous systems for rosin based fluxes.

Finally, there are some "no clean" technologies using low residue fluxes. It can include soldering in an inert atmosphere is discussed separately in Section 12.4 with details in Appendices X and AA.

12.3 CLEANING OF PRINTED CIRCUIT BOARDS

The systems for cleaning printed circuit boards (PCBs) are described in generic terms in Section 11, while further details of each system, and the basis for defining the system, are contained in Appendices U and W respectively. The combination of systems and solvents considered are shown in Table 12.1.

Table 12.1. Summary of electronics cleaning system types and solvent or cleaning agent combinations that were analyzed

Solvent/Cleaning Agent Classification	Open Top Batch	In-Line
High Boiling Temperature Solvent Vapor Degreaser	1,1,1 Trichloroethane	1,1,1 Trichloroethane
Low Boiling Temperature Solvent Vapor Degreaser	CFC-113 HCFC-141b HCFC-123 HCFC-225ca/cb	CFC-113 HCFC-141b HCFC-123 HCFC-225ca/cb
Semi-Aqueous	Hydrocarbon/Terpene Wash/Water Rinse	Hydrocarbon/Terpene Wash/Water Rinse
Aqueous	Saponifier/Water Rinse*	Detergent Wash/ Water Rinse

* not commonly used

As with metal cleaning the overall intent has been to define systems that are representative of modern cleaning equipment alternatives that are both environmentally sound and effective cleaning systems, concentrating on technology which is most readily applicable to cleaning requirements which have been satisfied by CFC-113 based systems. Both the open top batch and in-line systems that have been taken as representative are medium to large size systems that are in widespread use and produced as packaged equipment to a standardized design (with options available). While these example systems are representative of this class of cleaning equipment, it is recognized that there is a much wider diversity of cleaning equipment, cleaning solvents, and aqueous and semi-aqueous cleaning agents than are directly covered by the selected examples.

The aqueous system examples have assumed a detergent-based wash step (so that systems could be compared against rosin based fluxes); other cleaning agents that are used in an aqueous wash are saponifiers (strong alkalai) and terpene emulsions. For the semi-aqueous system examples, an immersion wash in a hydrocarbon formulation is assumed. Terpene immersion washing is also a viable alternative. For both types of system, the choice of cleaning agent does not significantly impact the energy inputs or emissions.

As with metal cleaning, the major energy input to solvent vapor cleaners is the continuous electric resistance heat input required to boil the solvent continuously while providing source of clean solvent for PCB cleaning. Batch and in-line vapor cleaners are available that utilize a vapor compression cycle heat pump to both boil and condense the solvent vapor (see Section 11). As in metal cleaning,

heat pump based systems are noted as an important option, and included as part of the best available current technology scenario.

For each system type that was modelled, a representative configuration and a representative set of energy inputs was defined. In practice, the exact set of design features and cleaning techniques, and the corresponding energy inputs, are tailored to the particular cleaning application. As a result, a wide range of energy consumption occurs in practice. Important issues are discussed in the material that follows in this section.

Solvent losses and dragout are discussed in Appendix Q. In general, reported solvent vapor loss rates in modern equipment have been assumed. It is recognized that CFC/HCFC solvent emissions constitute a significant portion of the total equivalent warming impact of the solvent based cleaning processes. Techniques such as carbon adsorption and superheated solvent vapor drying could be used to reduce emissions and dragout to near zero as discussed in Section 11. Such techniques are considered as part of the best available current technology (BACT) scenario.

The most common type of PCB cleaning systems found are:

- Open top batch solvent immersion systems
- Open top batch solvent immersion cleaners with two stage wash immersion rinse (with hoists);
- In-line solvent systems
- In-line aqueous systems with or without saponifiers

In-line semi-aqueous machines are available from a number of vendors (e.g. Detrex, Corpane, OSL, Vitronics, etc.) based on terpenes, or hydrocarbons.

Further details on batch machines are found in Appendix U and for in-line machines in Appendix W. In addition, "no clean" technologies with inert gas soldering are considered with descriptive text found in Section 12.4 and Appendix X. Finally, there are other machines that have been developed and are available but are less commonly found. These include batch aqueous and semi-aqueous dishwasher type machines, alcohol based machines, and others such as mentioned in Appendix X.

Table 12.1 shows the specific solvents/cleaning agent used for PCBs in this analysis for the batch and in-line machines. Many of the machines and principles of operation are similar to those found in metal cleaning (Section 13). The following subsection describes the major technologies. Readers interested only in the results of this analysis, should turn to Section 12.5.

12.4 MAJOR PCB CLEANING TECHNOLOGIES AND ENERGY USE

Batch Solvent PCB Cleaning Systems

As shown in Fig. 12.1, open top batch cleaners for electronics using CFC-113 have been simple in construction being essentially a four step process.

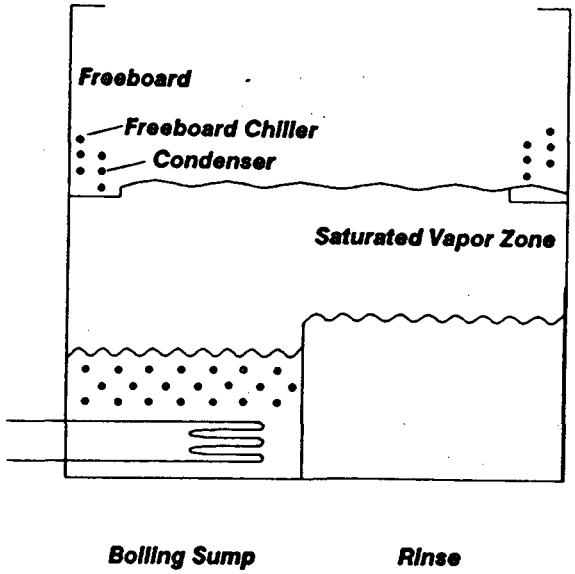


Fig. 12.1. Batch solvent cleaning system for electronics.

- *Loading Step*: The PCBs are loaded vertically into a metal basket such that upon removal drainage is assisted and dragout is minimized. An operator-controlled hoist is used to control the speed of movement of the basket into and out of the cleaning area although many units are not fitted with this option and consequently suffer from much higher solvent consumptions.

- *Cleaning Step*: The mode of operation is for the work basket to descend through the vapor at controlled speed into the boiling sump for about a 1.5 minute wash cycle.

- *Rinse Step:* The basket is then transferred to the rinse tank for approximately 0.5 minutes.

- *Draining Step:* The basket is raised again at controlled speed into the vapor zone and held for at least 0.5 minutes, enabling the majority of the solvent to drain or evaporate.

The solvent continuously boils, generating a vapor that condenses on one or more set of cooling coils. The liquid solvent is returned to the rinse tank via a water separator or desiccator constantly overflowing into the boiling sump. Thus, the rinse tank is kept clean with the flux residues concentrating in the boiling sump. Periodically the boiling tank is boiled down to recover as much solvent as possible with the remainder being sent for reclamation or disposal.

With the increasing environmental awareness and escalating cost of solvents, companies are now offering:

- *"low emission" cleaning systems:* Typical improvements that have been made include the use of 100% freeboard and a more sophisticated design of the vapor condensation configuration plus more intricate lid arrangements to reduce diffusion losses.

- *multi-tiered cooling coil systems:* For use with the new generation of HCFC solvents. Because the diffusivity of some lower molecular weight HCFC compounds is around 9%

to 16% greater than with CFCs, a three tiered cooling coil system may be needed. For example, the lowest tier (nearest the solvent) operates at around 5°C, the second tier operating at sub zero temperatures to further condense the solvent and a final dehumidification zone to prevent moisture from condensing on the lower coil. Systems and cooling coil temperatures may vary with solvent used. Automatic hoist arrangements are considered mandatory to avoid excessive mixing of the vapor and air. (Such multi-tiered systems may not be necessary for the higher molecular weight HCFC-225 which has a diffusivity roughly equal to that of CFC-113: Asahi, 1991).

Although the use of ultrasonics was forbidden under the U.S. Military standards, due to the supposed detrimental affects on IC wire bonds in cavity packages, the latest revision of MIL-STD-2000 places the onus of proof of reliability on the individual companies. In practice this is likely to lead to a significantly greater application of ultrasonic agitation, particularly in surface mount applications where flux residue removal under close fitting devices presents real problems. Where they are used, ultrasonics are applied in either a warm bath, where a separate tank is needed, or in a boiling sump where "streaming" rather than cavitation occurs.

With electronic cleaning, the overall volume of soil is generally lower than for metal cleaning leading to relatively infrequent disposals of soil laden waste and there is less need for a separate solvent regeneration unit as might be found at times on a metal cleaning unit.

Calculations of the total equivalent warming impact from operation of batch solvent vapor systems have been carried out for the one high boiling (1,1,1 trichloroethane) and five low boiling solvents noted above. The detailed assumptions are shown in Appendix Z. The key assumptions are:

- The energy input for boiling the solvent is provided by an electric resistance immersion heater, which is the most common practice. As with batch metal systems the volumetric "distillation" rate (i.e. coil condensation rate) is kept constant when comparing different solvents.

- Recognizing that each system design may differ depending on solvent used, the low boiling temperature solvent cases include average energy inputs for both a condensing chiller and a freeboard chiller.

- Ultrasonic modules and sprays are employed.

- For electronics cleaning, high boiling solvent systems are largely based on 1,1,1 Trichloroethane (methyl chloroform). From a technical standpoint, they are, in general, simpler machines with a lower degree of emphasis on solvent conservation measures because of their lower vapor pressures where chilled water is sufficient typically to control vapor losses.

- Solvent losses are based on practice using modern machines, as discussed in Appendix Q and summarized in Section 11. Total losses during operation per square meter of board processed were estimated for batch machines. Lesser amounts were assumed lost during the time that the machine was in an idling or downtime modes (see Appendix Z).

Several significant variations from this baseline arrangement are also in practice:

- The heat input for boiling the solvent can be supplied by a heat pump that also provides the cooling required by the solvent vapor condenser, significantly reducing the total electric power input. (This is considered as part of the BACT scenario.)

- Different combinations of auxiliary cleaning enhancement (ultrasonics, spray rinses, etc.) can be utilized, all of which will have a second order impact on the energy input.

- Solvent vapor recovery systems can be incorporated (Appendix AB).

Batch Aqueous and Semi-Aqueous PCB Cleaning Systems

This method of flux removal represents a small proportion of systems in use today. Those systems that are available fall into two broad categories.

- The first is a multiple tank system following the description for metal cleaning, where virtually every system is different with no obvious standard existing.

- The second is a batch cleaner constructed like, for want of a better description, a dishwasher. These systems have had relatively limited capacity by virtue of their very long cycle times (30 minutes approximately). However, advances are occurring and some machines have claimed to improve performance significantly.

For the purposes of this exercise, a multiple tank electronics cleaning system is considered which is found to be analogous to its metal cleaning equivalent. The only possible difference of significance would therefore be the fact that PC boards are required to be particularly dry, as this may affect subsequent testing, and therefore, capacity has to be carefully considered.

Another tank type operation is found with semi-aqueous systems. This method of cleaning PCBs is comparatively recent with few systems available or installed. They are in overview very similar to those supplied for metal cleaning being based on a wash tank of terpene or hydrocarbon followed by two rinse stages and a vertical dryer. Transfer is affected by a hoist arrangement to minimize dragout from the wash to rinse stages with dwell times adjustable to suit the product and cleanliness level required.

With hydrocarbon formulations, tests have shown that solvent temperature is fairly crucial to the cleaning performance with some heating being required. Other solvents, however, with a lower flash point may need specific cooling. Heat input is shown in the calculations of Appendix Z and it should be recognized that this energy may be in fact used for cooling.

Figure 12.2 shows the general configuration of these aqueous or semi-aqueous cleaning systems for PCBs consists of a series of immersion tanks in which a sequence of washing, rinsing (one or multiple rinses), and drying steps are carried out.

Calculations of the energy use, solvent emissions and global warming impact from operation of representative batch aqueous and semi-aqueous cleaning systems have been carried out with further details on energy use and assumptions presented in Appendix Z. The major energy inputs and other key assumptions are:

- Electric resistance heaters are used to maintain the wash and rinse bath temperatures. Typical temperatures are 50°C - 60°C (120°F - 140°F) for aqueous wash and rinse steps and room temperature for a semi-aqueous wash step. Heat inputs are required to heat make-up water, to make up for heat losses to ambient via conduction and evaporation, and to make up for heat removed as parts are warmed up from room temperature to rinse temperature.

- Infra-red/electric resistance heat is used to heat drying air and/or boards.

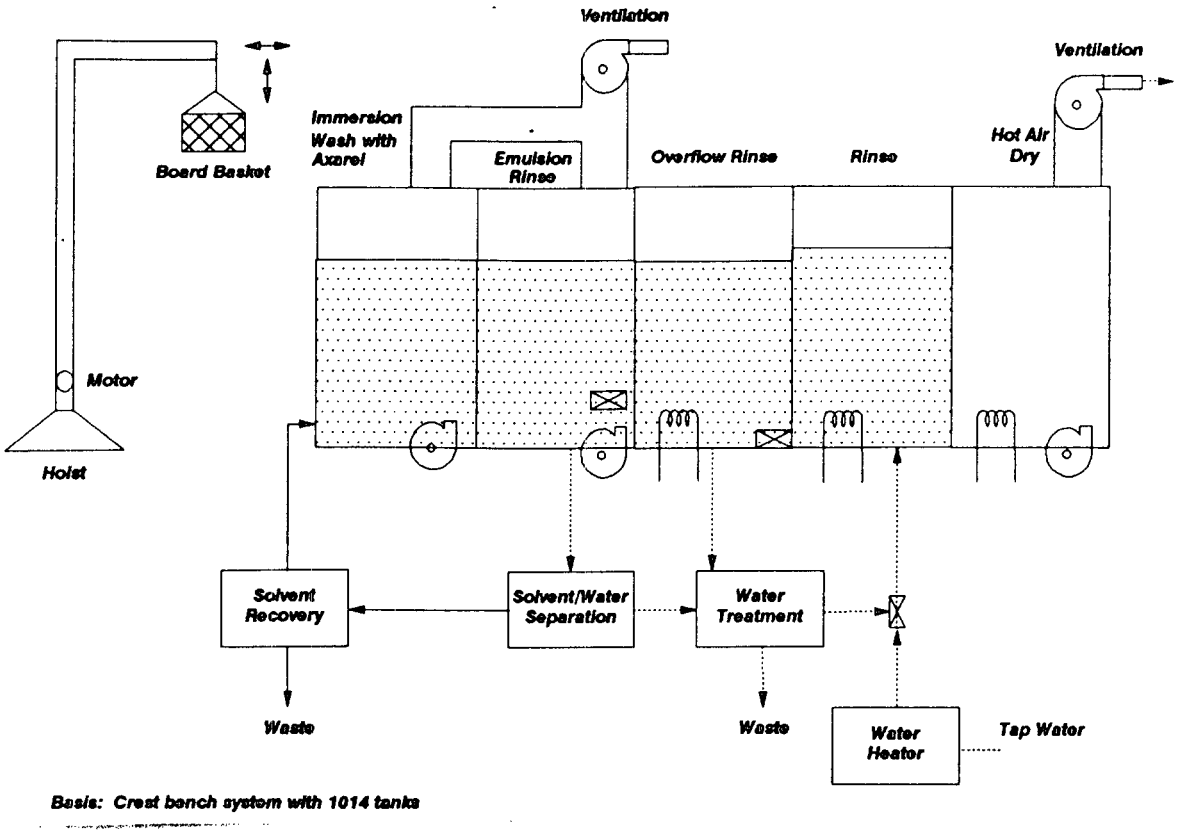


Fig. 12.2. Semi-aqueous system, batch process- electronics.

- Electric power is required to operate pumps used for wash and rinse agitation.
- Electric power is required to operate the drying air blower.

In-Line Solvent PCB Cleaning Systems

This type of PCB defluxing system (using low boiling solvents) is very common throughout the world. It has been the standard method of achieving high cleanliness levels particularly for military/aerospace products and gained wider acceptance still as the primary method of defluxing surface mount technology (SMT) panels especially when reflow soldered. The only solvents used commercially in these systems have been 1,1,1 trichloroethane and CFC-113 in the form of stabilized blends with various alcohols.

In-line high boiling point solvent systems are less commonly used at present for electronics cleaning (approximately 25% of in-line solvent systems in the U.S.). They represent a subset of in-line low boiling solvent cleaning systems described above. Their range of applicability is limited to PCB cleaning where the materials are able to withstand (mainly) 1,1,1 Trichloroethane. In practice, this means reflow soldered SMT panels, but even here blends of CFC-113 and various alcohols have been preferred or even stipulated by standards.

The typical throughput of these systems depends on the type of product being cleaned (conventional, reflowed or wave soldered SMT, or a combination of these); the cleanliness level sought and the degree of matching to the throughput of the previous process. For example cleaning of freshly wave soldered conventional boards in a state of the art system may be processed at 1.8 to 2.4 m (6 to 8 ft) per minute, whereas, a reflowed panel with tight component - substrate stand-off of less than 0.13 mm (0.005 in.) soldered in an earlier shift may require 0.9 to 1.2 (3 to 4 ft) per minute and there is

a whole range of throughputs in between. Clearly it is not possible to take account of all of these factors in a simplified analysis so a median figure has been used based on a theoretically average panel.

As depicted in Fig. 12.3, boards to be cleaned, typically, are moved through the cleaner on a flat conveyor belt. In the basic vapor cleaning process, solvent is continuously boiled from a boiling sump and condensed on a water jacket (or cooling coils) above the surface of the boiling liquid solvent.

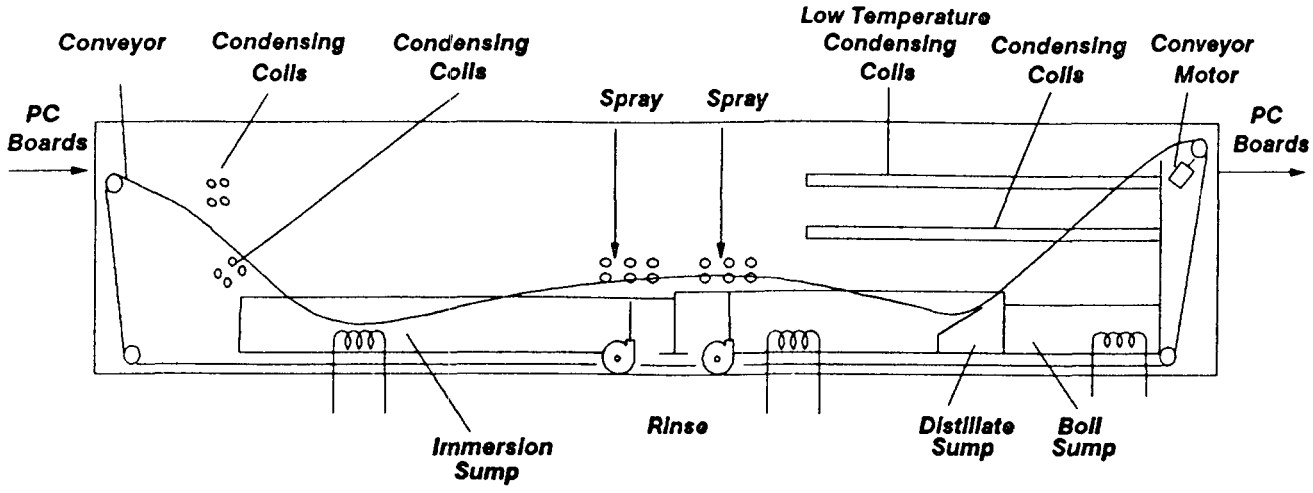


Fig. 12.3. Low boiling point solvent, in-line process - electronics.

The space above the saturated vapor level that is enclosed by the sidewalls is called "freeboard", and is needed to minimize diffusion loss of the solvent. The treatment of the condensing coils and freeboard area varies depending on whether the solvent has a high boiling point (1,1,1) or a low boiling point (CFC-113, HCFC-141b, HCFC-123, HFC-225ca/cb). For high boiling point solvents, the condensing coil is commonly water cooled, using tap water or a closed loop with a cooling tower, either being at temperatures well below the atmospheric boiling point of the solvent. A modest freeboard height, on the order of the inside width of the cleaner is used. For the new lower boiling point HCFC solvents, water at approximately 4°C (40°F), is needed to condense the solvent vapor, requiring a chiller in the system. The state of the art equipment that is being developed for the low boiling solvents employs two basic measures to control solvent losses, higher freeboard and low temperature freeboard chillers. Increased freeboard height lengthens the diffusion path for solvent molecules. The chiller, whose cooling coil is located at the bottom of the freeboard has the primary effect of condensing a major portion of the solvent vapors that diffuse above the saturated vapor zone, reducing the solvent vapor partial pressure at this level, for a reduced diffusion driving potential. The lower condensing temperature provided by the freeboard coil can provide for increased recovery of the evaporating solvent liquid dragged out of the saturated vapor zone by the parts.

Calculations of the energy use, solvent losses and global warming impact from operation of in-line solvent vapor systems have been carried out for one high boiling (1,1,1) and five low boiling solvents noted above; details are presented in Appendix Z. The key assumptions are:

- The energy input for boiling the solvent is provided by an electric resistance immersion heater, which is the most common practice with vapor cleaners. As with other systems,

the volumetric "distillation" rate is kept constant when comparing different solvents, at constant work throughput.

- The low boiling temperature solvent cases include energy inputs for both a condensing chiller and a freeboard chiller.

- Electric power input to operate spray rinse pumps was assumed.

- Solvent losses are based on modern machines, as discussed in Appendix Y. Total losses during operation were estimated as discussed in Section 11; lesser amounts lost during idling and downtime modes (Appendix Y).

Several significant variations from this basic arrangement are also in practice:

- The heat input for boiling the solvent can be supplied by a heat pump that also provides the cooling required by the solvent vapor condenser, significantly reducing the total electric power input.

- A small solvent recovery still could be operated to prolong the life of solvent. Some industry contacts indicate that this practice is becoming more widespread.

- Different combinations of auxiliary cleaning enhancement (ultrasonics, spray rinses, etc.) can be utilized, all of which will have a second order impact on the energy input.

In-Line Aqueous PCB Cleaning Systems

A standard aqueous system is difficult to define as it depends on many factors, such as type of product, cleanliness level, throughput and the type of flux used. Typically these factors will affect the following parameters:

- Water quality

- Saponifier concentration (which also varies with the type of saponifier)

- Water temperatures, pressures and flow rates

- Air temperatures, pressures and flow rates

- Line speed

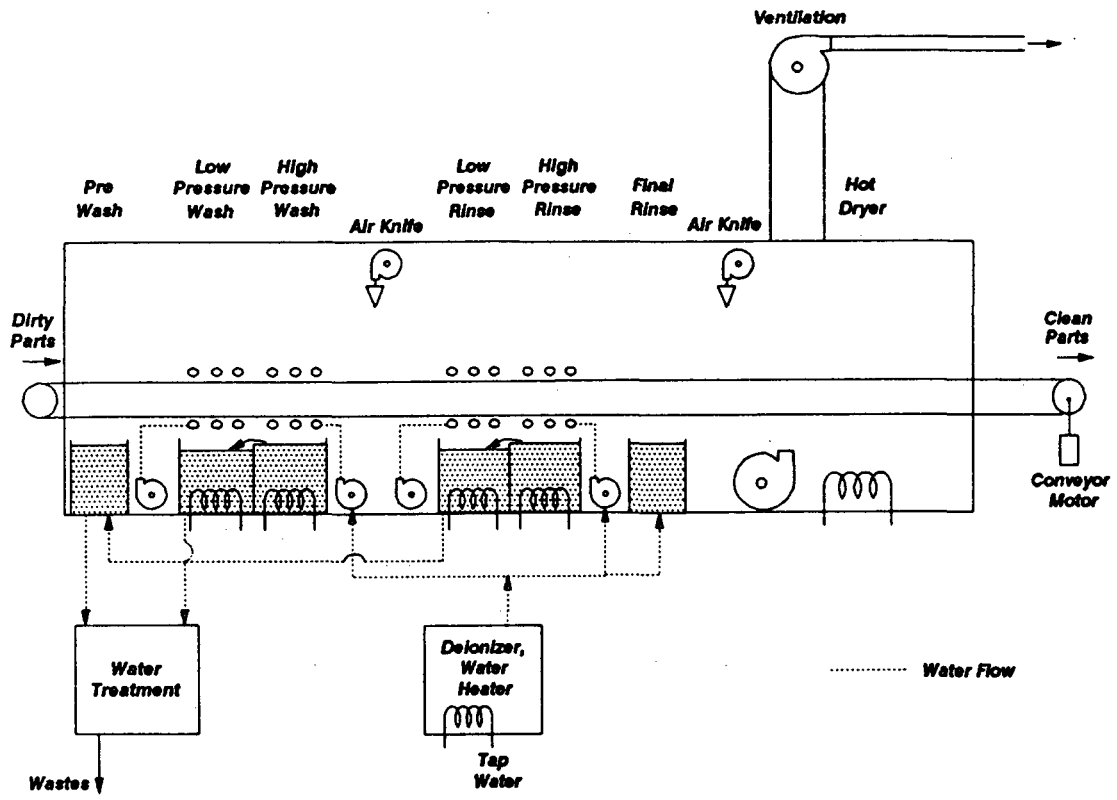
- Incoming PCB temperature

The aqueous wash step can utilize alkaline cleaners (saponifiers), detergent based cleaning agents, or aqueous emulsions of terpene/surfactant cleaning agents. The temperature of the aqueous wash solution, the intensity of sprays or other mechanical enhancement, and the concentration of cleaning agent depend on the soils (fluxes) to be removed, the geometry of the parts, and the degree of cleanliness required. Cleaning is effected by a combination of displacement (surfactant effect), solubilization (e.g. saponification) and fluid mechanical removal (ultrasonic, jet impingement).

In selecting a system for this investigation therefore, a machine is chosen that has typical features and would be appropriate for cleaning moderately dense mixed technology printed wired assemblies soldered with a rosin based flux. As a measure of cleaning difficulty it falls somewhere between

conventional and aged reflow soldered assemblies. The same assumption was made for the other electronic cleaning alternatives.

To clean such an assembly it is necessary to use mechanical agitation in an aqueous system shown in Fig. 12.4. Here it is high pressure, high flow rate sprays. For reflow soldered PCBs additional very high intensity sprays are also needed such as the Hollis' "Hurricane" wash. The flow of water around such a system is rather complex but essentially consists of three stages: pre-wash, recirculating wash and rinse (possibly deionized). In the wash tanks, the saponifier concentration (when used with rosin based fluxes, which is assumed here) is controlled to 6% to 7% by volume with a cascade system being present to ensure that the cleanest solution sprays the panels last. The rinse tank is assumed to use deionized water as is common practice and an air knife is present to minimize the carry over of saponified water. Often it is not possible to superheat the PCBs as several electronic components cannot withstand temperatures in excess of 85°C such as electrolytic capacitors.



Basis: Hollis 332 system, closed loop

Fig. 12.4. State of the art in-line aqueous cleaning process model.

Major end uses of energy include:

- Electric resistance heaters to maintain the wash and rinse baths and heat incoming water to 40-50°C (120-140°F);
- Air knives and heaters to dry boards;
- Electric power for motors to drive pumps and fans.

Calculational details are presented in Appendix Z.

In-Line Semi-Aqueous PCB Cleaning Systems

At present, the use of semi-aqueous defluxing system is rather new but likely to become of increasing importance due to excellent cleaning performance. More and more equipment suppliers are offering in-line systems including Detrex, Corpane, Vitronics, Electrovert and OSL and others having equipment under development. The solvent selected could easily have been a number of solvents (e.g. Axarel, terpenes such as EC-7, etc) with only minor modifications to the overall system.

The semi-aqueous wash step, using hydrocarbon formulations or terpenes is typically carried out on an agitated immersion (shown in Fig. 12.5), rather than a spray basis, to minimize the formation of flammable vapor/air or mist/air mixtures. Cleaning is based primarily on solubilizing and flushing the contaminants from the parts. To minimize the fire risk, the bath temperature is generally well below the flash point of the solvent. Fire safety issues have been raised nevertheless, and in some instances a nitrogen or carbon dioxide atmosphere is maintained over the semi-aqueous wash bath but this has not been assumed in the calculations in this section.

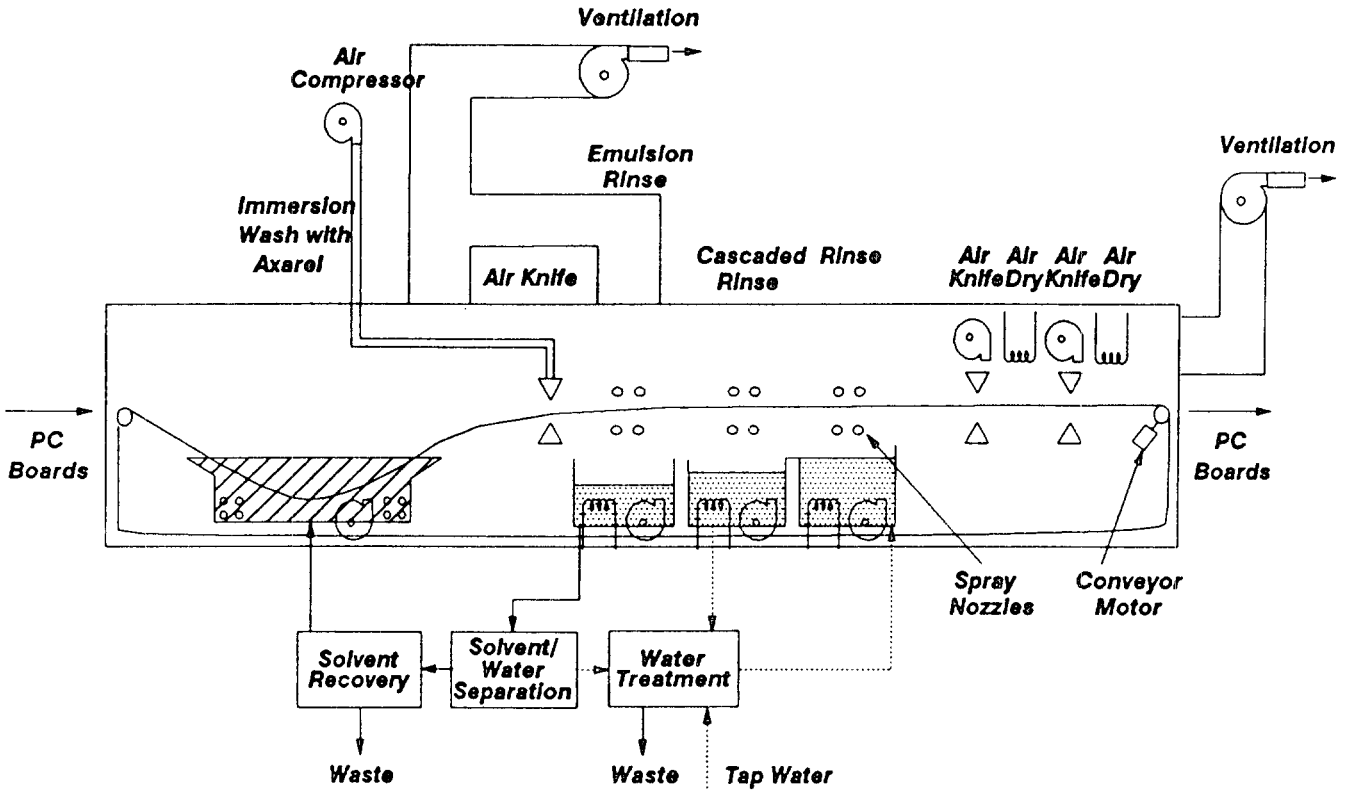


Fig. 12.5. Semi aqueous system, in-line - electronics.

Generally, "air knives" are used between washing and rinsing stations to minimize the carry over of wash or rinse solutions to the following stage. Some carryover is required from the first sump in order to maintain the dissolved flux concentration in that sump at approximately 10%. The first stage rinse water in semi-aqueous processes will contain the terpenes or hydrocarbons that are carried over past the air knives. These are gravity separated from the rinse water and returned to the wash tank.

Calculations of the energy use, chemical losses, and total equivalent warming impact from operation of representative in-line aqueous and semi-aqueous cleaning systems have been carried out. The detailed calculation assumptions are presented in Appendix Z. The major energy inputs and other key assumptions are:

- Electric resistance heaters are used to maintain the wash and rinse bath(s) temperatures.
- The semi-aqueous wash step modeled is based on a hydrocarbon or terpene formulation. It is assumed that an inert atmosphere is not required over the wash tank, but that the operation is carried out at a temperature well below the flash point. (If an inert gas is required, additional energy will be consumed in its manufacture.)
- Electric resistance heat is used to heat boards by infra-red heating or for air used in drying.
- Electric power is required to operate pumps used for wash and rinse agitation and sprays.
- Electric power is required to operate blowers for air knives.
- Electric power is required to operate the drying air blower and to heat the drying area of the machine.

"No-Clean" Soldering Technologies

Two major approaches have been utilized to eliminate the need to deflux PCBs:

- Use of low residue fluxes to eliminate the need for cleaning. They generally rely on the ability of using activators which are only active at elevated temperatures while employing solders with low residues (1-5% solids). The market penetration of such systems has been significant in those areas not bound by current military standards such as consumer telecommunications and computing. Their use for surface mount assemblies is lagging for a number of reasons (as discussed in Appendix X, Section X.1). From an energy point of view when compared to conventional soldering, the only impact is in the need to provide a small additional amount of preheating, and for pre-cleaning, if required.
- Use of inert atmosphere (nitrogen) in soldering. This is a relatively new process involving soldering in a vacuum or more commonly in an inert atmosphere. Two options are considered as described in Appendix X, Section X.2:

  - Use of a lock box which is evacuated and purged with nitrogen.
  - A continuous nitrogen purge of the soldering operation.

  Although final cleaning may be required to meet customer requirements, this has not been assumed in our TEWI calculations.

  Both systems claim oxygen levels are reduced to the ppm range.

12.5 COMPARATIVE TOTAL EQUIVALENT WARMING IMPACTS FOR PCBS

Overview

The total equivalent warming impact per square meter processed are summarized in Figs. 12.6 and 12.7 for the 500 year GWP time horizon for batch cleaning, in-line cleaning, and no clean processes respectively. For these systems, a daily duty cycle representing two shifts per day of 12 operating hours at full capacity, 4 idling hours (with the system operating, but with no throughput), and 8 hours of downtime is assumed. Information is developed in such a way that equivalent CO_2 emissions from other duty cycles can be easily calculated from Appendices Y and Z. The data in each figure show CO_2 equivalent warming impact associated with each of the solvent or cleaning agent alternatives discussed earlier in this section. Each system is subdivided into four segments -- three segments partition the CO_2 emissions associated with energy use in the cleaning process, energy embodied in solvent chemicals, and auxiliary processes; the fourth segment gives the CO_2 equivalent of the solvent emissions. Energy consumption and solvent emissions during idling and downtime are included in these estimates. It is seen that embodied energy in the solvents and auxiliary processes are negligible. Appendix Z presents the detailed calculations, and documentation of the assumptions (throughput rates, detailed breakdown of energy inputs, solvent emission rates), that provide the basis for the aggregate CO_2 equivalent emissions presented in Figs. 12.6 and 12.7.

In broad terms it is seen that:

- Solvent based vapor cleaning systems tend to have major energy inputs associated with solvent vapor generation and distillation/recovery, while aqueous systems have major energy inputs for heating rinse water, drying air, and drying PCBs by air knives or heaters. In both solvent and aqueous in-line systems, power inputs to spray pumps are a significant portion of the total;

- The variation in CO_2 emissions at the electric power plant between the U.S., European, and Japanese power generating mix is modest (see tables in Appendix Z);

- The energy consumed in the production of the solvent or cleaning agent solvent disposal/recycling and the energy consumed by auxiliary processes (ventilation, solvent recycling, etc.) are all a relatively minor portion of the total energy input to the cleaning process.

Batch Systems Energy Use

Figure 12.6 compares the CO_2 equivalent emissions for the eight batch systems that were analyzed for the 500 year GWP time horizons. For each of these alternatives, the energy component of the CO_2 emissions is significantly smaller for solvent based systems. In the representative systems selected, aqueous and semi-aqueous systems, with a post rinse heated drying process included, consume significantly more energy than the solvent based alternatives (see Figs. Z.1-4 and Z.1-5).

In-Line Systems Energy Use

Figure 12.7 compares the CO_2 equivalent emissions associated with each of the eight representative in-line systems that were analyzed for the 500 year GWP time horizons, respectively. As with batch systems energy consumption levels per unit of throughput of the representative systems are much higher with semi-aqueous and aqueous systems than with solvent systems. The energy consumption in the in-line aqueous and semi-aqueous systems is associated primarily with significant levels of

power input to rinse water heaters and to the wash and rinse sprays and air knives to minimize liquid carry over from stage to stage. Power input to the drying stage also contributes to the total electric power input.

No Clean Technologies with Inert Gas

The major energy consumers in the "no clean" systems are in the manufacture of nitrogen (smaller amounts of energy are consumed in pulling a vacuum in the lock box system). Based on calculations made in Appendix AA, "no clean" systems are found to use:

- 2 kWh/m^2 using the lock box concept or 1.3 kg CO_2 equivalent/m^2 of board
- 3 kWh/m^2 using the continuous nitrogen purge concept or 2 kg CO_2/m^2 of board.

Figure 12.6 shows the results graphically for the lock box concept and Fig. 12.7 for the continuous nitrogen purge; results are independent to the GWP time horizon chosen.

Total Equivalent Warming Impacts for PCBs

In the 500 year GWP time horizon (Figs. 12.6 and 12.7), the TEWI impacts of alternative solvent based systems are discussed below.

- For in-line PCB systems, solvent based processes are comparable to aqueous and semi-aqueous processes with results largely affected by GWP contributions of the solvent to TEWI.
- For batch PCB cleaning, the TEWI's are noticeably higher for solvent based systems. However, in the future, adoption of best available current technologies (BACT) including advanced solvent vapor recovery systems to limit solvent emissions has the potential to significantly reduce TEWI's to the point that all solvent based systems will have global warming impacts that are lower or comparable to aqueous, semi-aqueous, or "no clean" technologies (see Appendix AB for BACT technologies). Figure 12.8 shows the TEWI for the BACT electronics cleaning systems using CFC-113 and alternative solvents and technologies as a percentage of the TEWI for standard industry equipment using CFC-113. It can be clearly seen that the TEWIs for the alternative cleaning systems are only a small fraction of the TEWI of current practices.

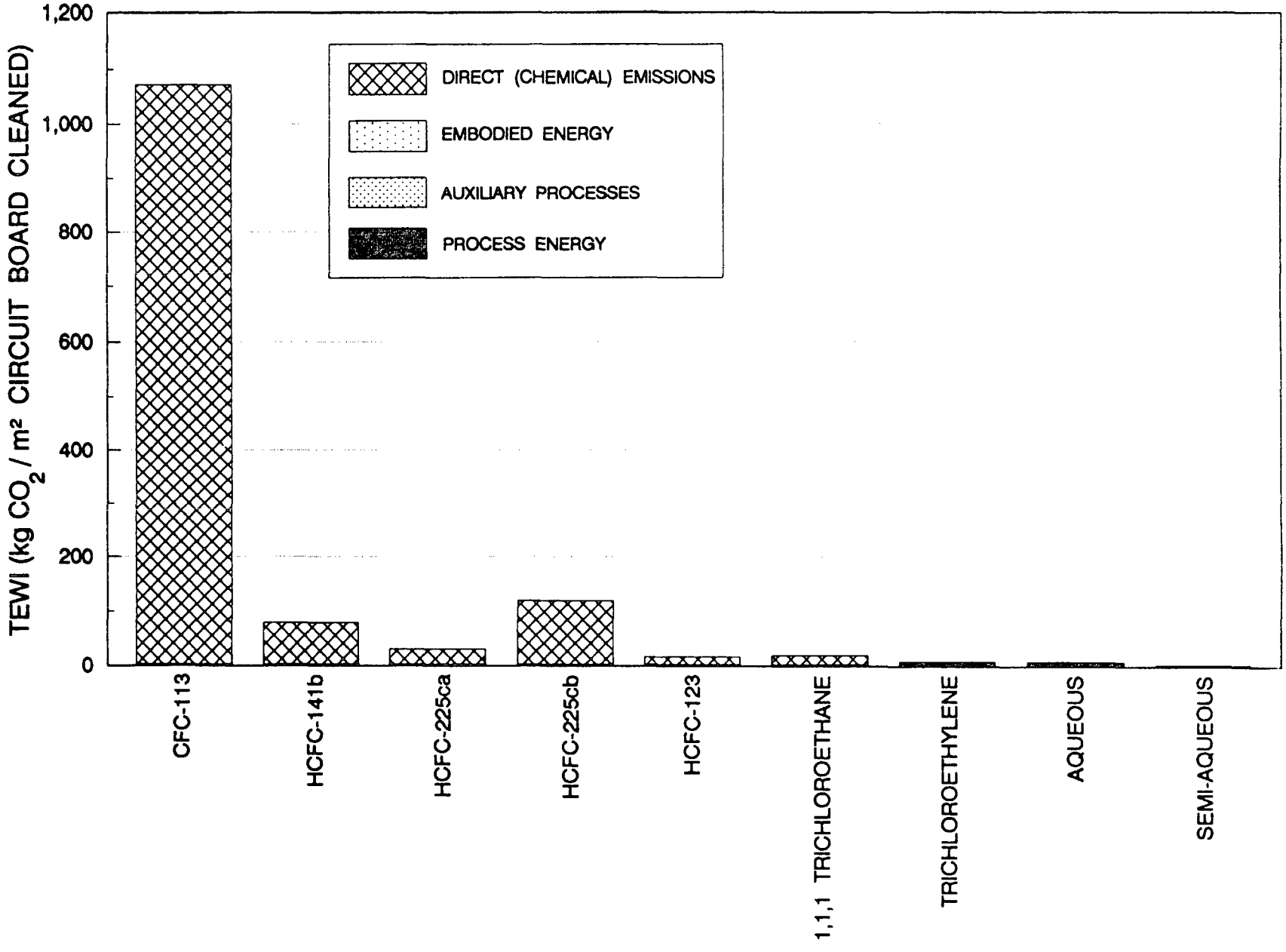


Fig. 12.6. TEWI for batch electronics cleaning: composite values - 500 year GWP.

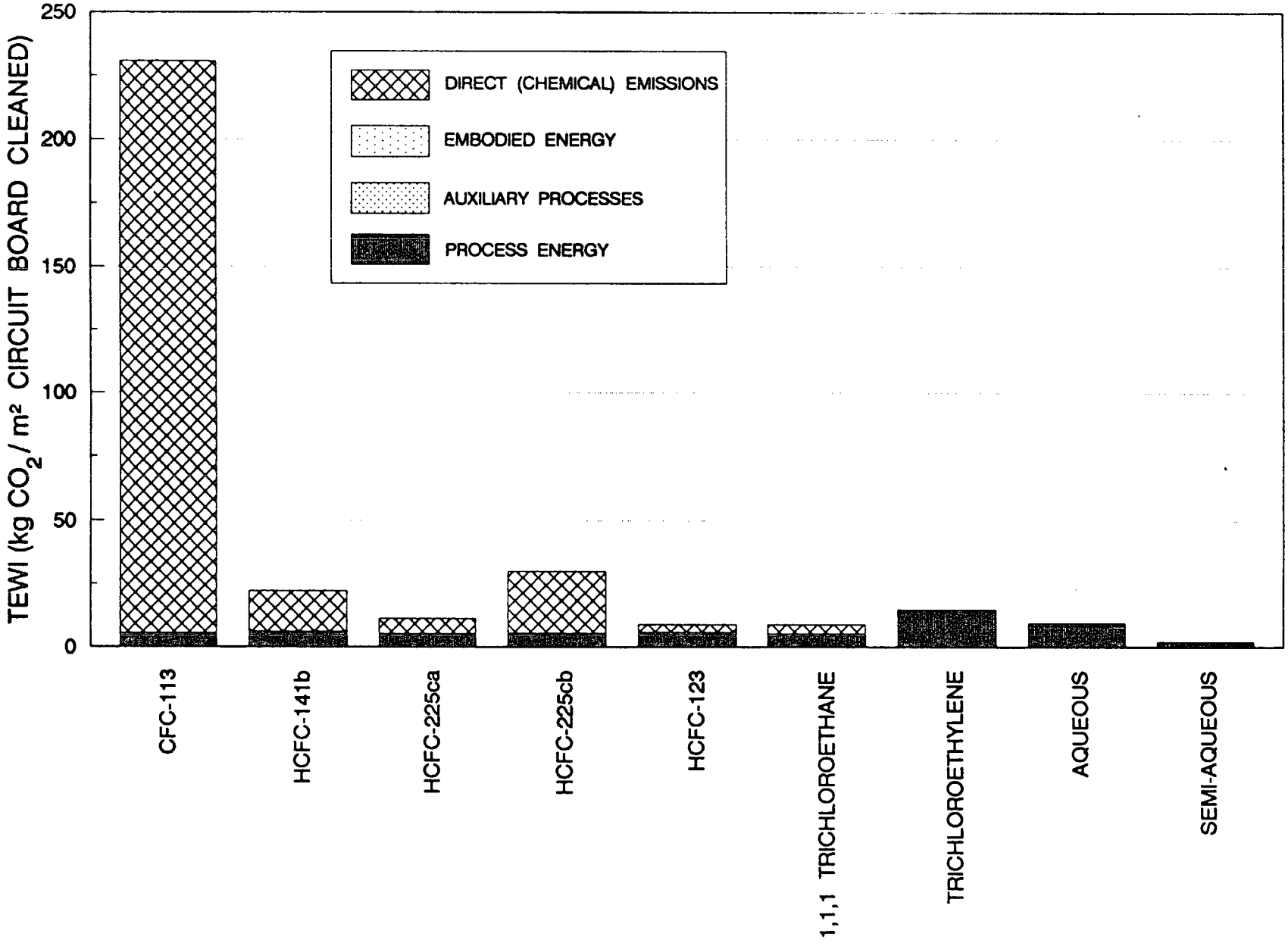


Fig. 12.7. TEWI for in-line electronics cleaning: composite values - 500 year GWP.

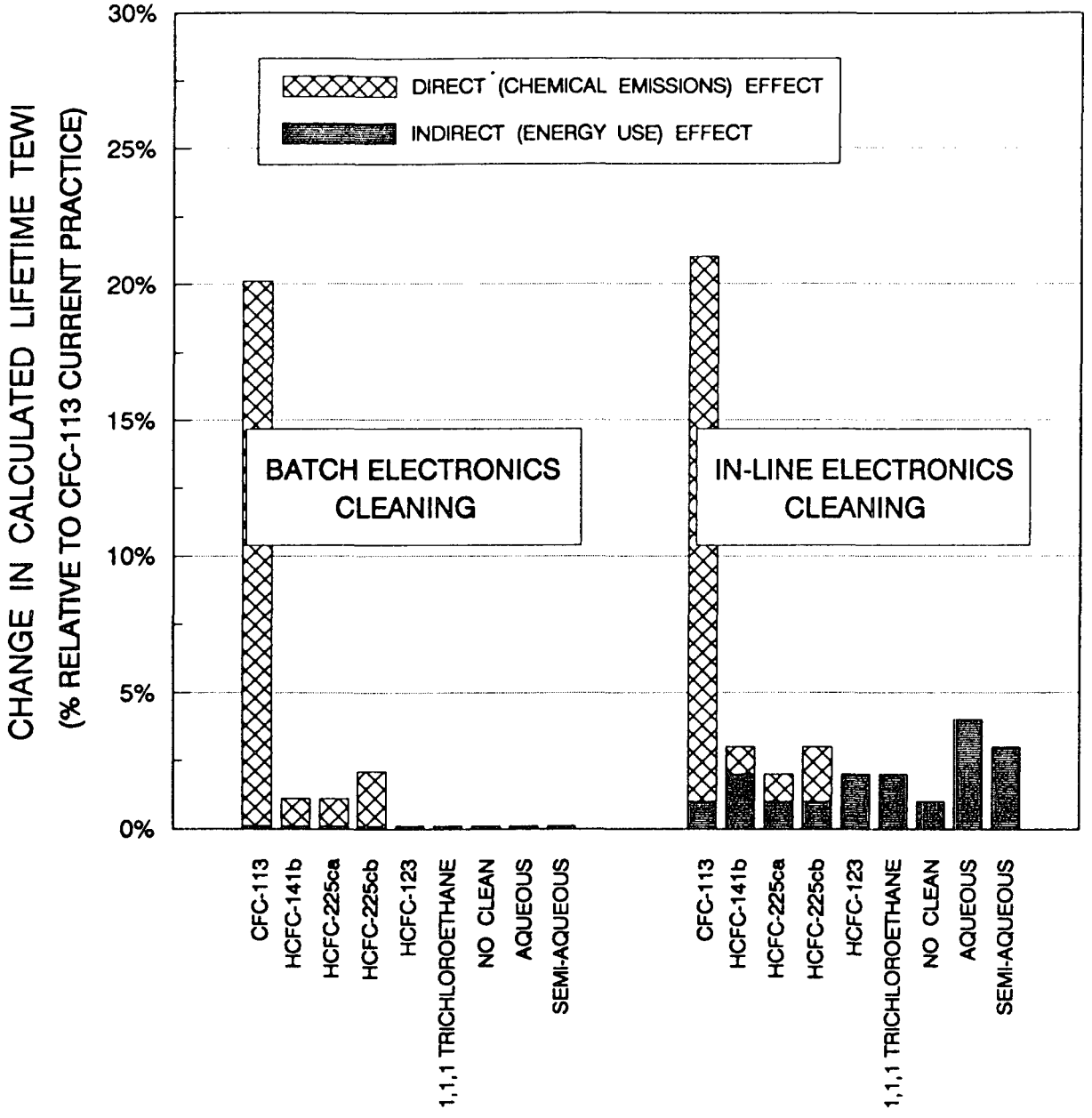


Fig. 12.8. TEWI of BACT electronics cleaning equipment as a percentage of the TEWI for industry current practices using CFC-113.

13. MAJOR FINDINGS

13.1 GENERAL FINDINGS

The results of the quantitative analyses conducted for each of the applications are illustrated in the bar graph figures in the preceding chapters. These figures show the changes in Total Equivalent Warming Impact or TEWI of the various CFC alternatives relative to the baseline CFC technology for a range of refrigerant, insulation, and cleaning applications. The relative proportions of the DIRECT and INDIRECT effects on the TEWI for each of the various alternatives or technical options are also illustrated. The major findings discussed in those application chapters are generalized, highlighted, and summarized below. The study findings are separated into major common findings and application-specific findings.

The major common findings that address all three major application areas include the following:

- Replacement of CFCs with suitable HCFCs or HFCs yields a dramatic benefit in reducing Total Equivalent Warming Impact (TEWI) for all CFC end-use applications considered; the TEWI improvements are most striking in relatively high-loss applications such as solvent cleaning, automotive air conditioning, and commercial building roof insulation.

- There is a wide variation among applications with regard to the relative importance of the INDIRECT (energy use) effect and the DIRECT (chemical emission) effect of the HCFC/HFC alternatives; the DIRECT effect can range from 2% to 98%, for instance,

  - Refrigerators/freezers show only 2-3% DIRECT impact with a variety of HFC refrigerants and HCFC foam blowing agents

  - Open top equipment for batch electronic cleaning of electronic components may have as high as a 98% DIRECT impact

- Several alternative not-in-kind (NIK) technologies were evaluated or considered in each of the three major application areas, with results for some also showing reduced TEWI benefits.

  - Aqueous and semi-aqueous cleaning technologies are examples of NIK alternatives already in widespread use which exhibit a substantial reduction in TEWI relative to the baseline CFC cleaning technology.

- Energy use for most of the available or current generation NIK options was found to be greater than for the HCFC/HFC technologies. However, some next-generation NIK options such as evacuated vacuum panel insulation for appliances and "no-clean soldering" technology in the electronics sector show promise for future energy savings. Technical issues must still be successfully resolved before these options can be widely adopted.

With regard to the fluorocarbon (HCFC and HFC) alternatives and the relative importance of their INDIRECT (efficiency-related) and DIRECT (fluorocarbon emissions-related) effects, it should be recognized that most of the "current generation" HCFC and HFC technologies are still being optimized. Thus, the currently available data are not likely to represent the lowest cost effective

energy consumption or the lowest losses/emissions achievable. Accordingly, these next findings focus on identifying opportunities for further future reductions in the TEWI.

- For applications which are dominated by the INDIRECT (energy related) impact, insulation measures and efficiency improvements that are dependent on availability of suitable HCFC and HFC substitutes, represent the most effective, and in some cases, the only practical approach for achieving further substantial reductions in greenhouse gas emissions and TEWI.

  - Use of increased thickness NIK alternative materials such as fiberboard may also be an insulation option for building. For the wall insulation case evaluated, this would require a 50% increase in thickness compared to an HCFC foam insulation to achieve equivalent thermal performance. The practicality in terms of building construction (door frames, window frames, etc.) or economics was not examined.

- For applications in which the DIRECT effect of the chemicals represents a dominant or substantial proportion of the TEWI, such as solvent cleaning, automotive air conditioning, and retail refrigeration, further reductions in TEWI will be more dependent on low-loss concepts or new technology

  - These applications represent important target opportunities for developing and demonstrating new technology options aiming at substantially no-release equipment that could work with the most efficient substitutes (in-kind or not-in-kind) available in the long term.

  - Cleaning industries have generally identified and are already adopting or evaluating improved containment measures and not-in-kind alternative options.

13.2 APPLICATION SPECIFIC FINDINGS

13.2.1. *CFC Refrigerant Alternatives*

- Energy efficiency/energy use differences are small between CFC baseline refrigerants and HCFC or HFC alternatives.

  - Early published test data indicate small penalties for substitutes, but recent industry data show near equal refrigerant performance as achievable

    -- with new lubricants
    -- with optimized engineering design

- The small differences in lifetime energy use projections and associated INDIRECT CO_2 contributions among the HCFC and HFC options do not allow a meaningful ranking of the options at this time.

13.2.1.a For household refrigerators/freezers and building air-conditioning equipment dominated by INDIRECT (energy-related) effects:

- Once HCFC/HFCs have replaced CFCs, the only way to effect further significant reductions in TEWI is through energy efficiency improvements,

- whether with conventional vapor compression cycle technology with HCFC/HFCs or other suitable working fluids,

- or with alternative cycles or processes

13.2.1.b. The DIRECT (chemical emission) effect is a substantial proportion of the TEWI for automotive air conditioning and retail refrigeration HCFC/HFC applications.

- For these applications especially, improvements and/or projected improvements in service recovery practices and reduced losses from the piping systems can have a major influence on DIRECT effects and TEWI.

- Further containment, new equipment design configurations and/or cycles/processes are longer term options for further reducing the TEWI for these applications.

13.2.2. *CFC Blowing Agents or Insulation Alternatives*

- Differences between "aged" thermal conductivity values for CFC-blown and HCFC-blown polyisocyanurate/polyurethane foam insulation materials are small;

  - therefore, energy use and INDIRECT CO_2 emission differences are minor.

- Differences in foam insulation thermal conductivity values and energy use between the leading HCFC blowing agents, 123 and 141b, are also small.

- Energy use for non-fluorocarbon foam insulation or fiber insulation is greater than for HCFC-blown foam insulation;

  - but, in some cases, the TEWI's are essentially equal, due to difference in DIRECT (chemical emission) effect of longer-lived HCFC's.

13.2.2.a. For appliance insulation and residential/commercial wall insulation dominated by INDIRECT (energy-related) effects:

- Once HCFCs are used to replace CFCs, the primary avenue for further reducing TEWI is through more or better thermal insulation via

  - improved thermal resistance foam and advanced manufacturing processes with HCFCs (or other suitable low-conductivity gases or blowing agents),

  - thermal envelopes with higher insulation levels in buildings, or

  - next-generation insulation materials such as evacuated panels for some applications.

13.2.2.b. The most significant DIRECT impact from HCFC-blown foam is associated with commercial roofing and re-roofing.

- This finding is linked to current service life of commercial building roofs, which could possibly be extended by future improvements in construction and maintenance practices.

- The significance of the DIRECT impact is critically dependent on the atmospheric lifetime, and hence, the GWP of the HCFC used in these applications.

13.2.3. *CFC Alternatives for Metal and Electronic Cleaning and Drying*

- All metal and electronic cleaning systems examined showed energy use for solvent systems are either comparable to or significantly less than for aqueous and semi-aqueous systems.

- Unless solvent losses from the cleaning equipment are carefully controlled, the DIRECT impact of solvents with the longer atmospheric lifetimes will be the predominant factor in the total equivalent warming impacts.

- A number of "no clean" technologies have been developed and are being adopted, which will also reduce TEWI levels.

- Technologies are available but not widely practiced as yet to reduce the TEWI of both solvent systems and aqueous or semi-aqueous systems. Examples include:

  - use of heat pumps in low boiling solvent based systems that can reduce energy requirements by 40 to 60%.
  - use of closed loop systems and/or heat exchangers for aqueous or semi-aqueous cleaning with potential savings of approximately 30 to 35%.
  - better control of emissions of solvents, especially in batch metal and electronic cleaning. With moderate increases in equipment costs, emissions from these systems can be reduced by 80% or more; reductions in excess of 90% are possible with more advanced systems. For example, systems are available to control solvent emissions from 0.5 kg per square meter for batch systems down to 0.02 kg/m^2 of printed circuit boards cleaned.
  - it should be noted that much of this technology can be retrofitted to existing equipment.

An estimate of the impacts of systems using the best available current technology is shown in (assuming that the energy input is reduced by 60% for low boiling solvent systems, 60% for the high boiling solvent batch metal systems, and by 8% for other high boiling solvent systems; and that solvent emissions are reduced by 80%). When widely adopted, the TEWI of solvent systems will be comparable or less than aqueous or semi-aqueous systems.

14. COMPARISON OF RESULTS AND FINDINGS FOR 100 YEAR VERSUS 500 YEAR GWP VALUES

14.1 INTRODUCTION

Inevitably questions arise about any study concerning the validity of assumptions that have been made and what differences there may be in the results and conclusions if a different set of criteria or assumptions had been used from the outset. There are questions in this study concerning what time frame is most appropriate for evaluating environmental impacts of different technological alternatives, and specifically whether the 100 year GWP values should be used or the 500 year values when calculating the direct effect of chemical emissions. Fortunately, many of the conclusions reached in this report are valid for both sets of assumptions.

This section of the report contains graphs which show comparisons of the total equivalent warming impacts for the alternatives listed in each application area (e.g., household refrigeration, residential building insulation) using both the 100 year and 500 GWP values. The conclusions based on the 500 year GWP values that are listed in the preceding sections for each application are then examined and either supported using the 100 year values or the differences are explained.

14.2 HOUSEHOLD REFRIGERATION

Figures 14.1 to 14.3 show the TEWI for European, North American, and Japanese refrigerator/ freezers using both the 100 and 500 year GWP values. The bars for the TEWI based on the 100 year values are slightly behind and to the left of the corresponding bars using the 500 year GWP values. Six conclusions for CFC alternatives in household refrigerators are listed in Section 4:

- efficiency improvements represent the most effective means of reducing TEWI in refrigerator/freezers,
- none of the alternative refrigerants considered has a decided advantage over any of the others based on total equivalent warming impact,
- the use of plastic foam insulation blown with 100% CO_2 results in a significantly higher TEWI than any of the other alternative blowing agents,
- the use of perfluoroalkanes, both as principal blowing agents and surfactants, and the use of isopropylchloride results in a TEWI that is significantly higher that for HCFC-123 or HCFC-141b at the k-factors achieved to date,
- the direct equivalent impact of the alternative refrigerants and blowing agents is only 2 to 3% of the TEWI for refrigerator/freezers, and
- small differences between TEWI of the leading alternative refrigerants are not significant.

The results in Fig. 14.1 to 14.3 show that the first four of these conclusions are also true if the TEWI is computed using the 100 year GWP values for the refrigerants and blowing agents instead of the 500 year values. The fifth conclusion would be phrased a little differently using TEWI based on the 100 year values. The direct effect is now more than 2 to 3% of the TEWI, but it is still a small

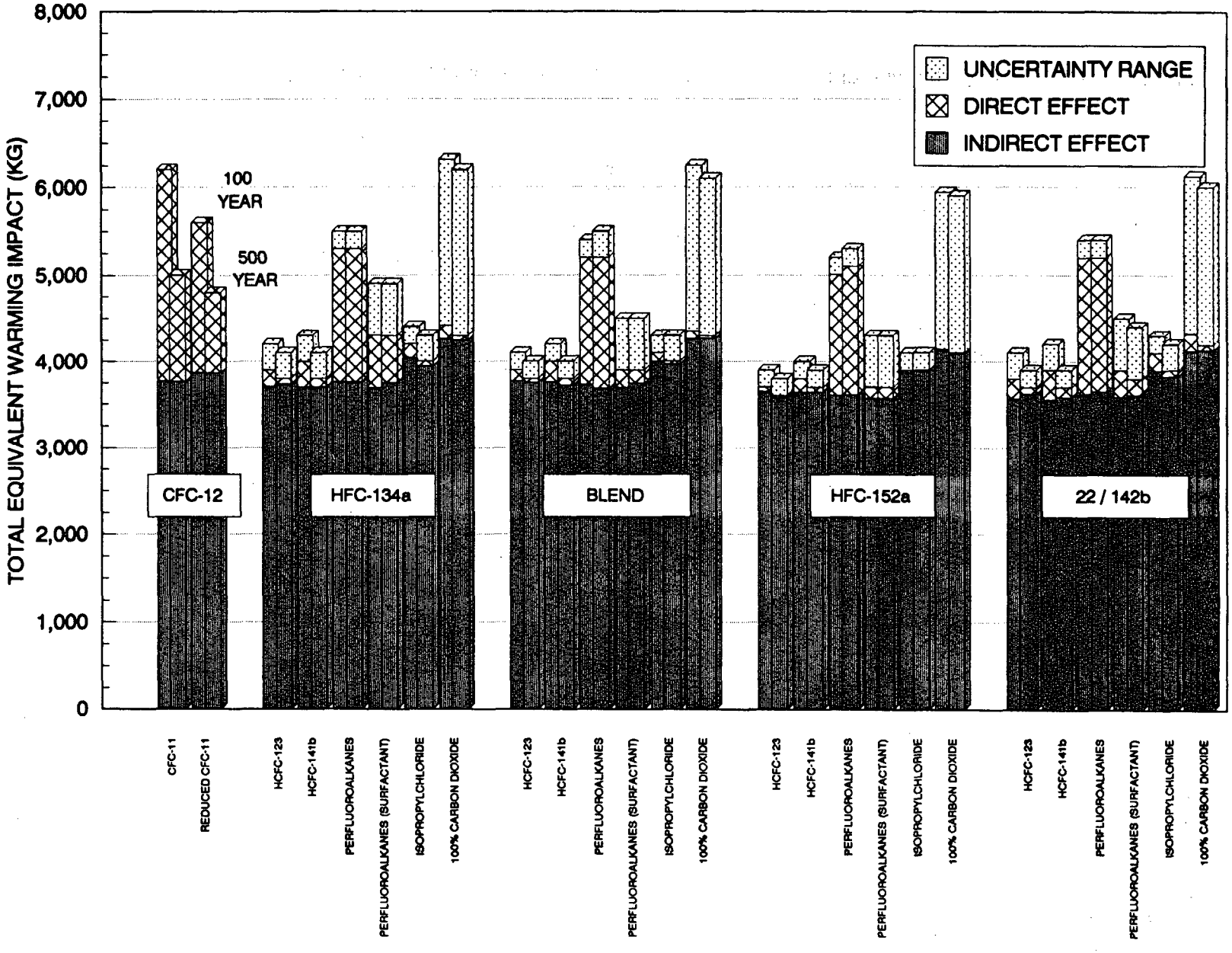


Fig. 14.1 Comparison of TEWI for refrigerator/freezers in Europe using 100 year and 500 year values for GWP.

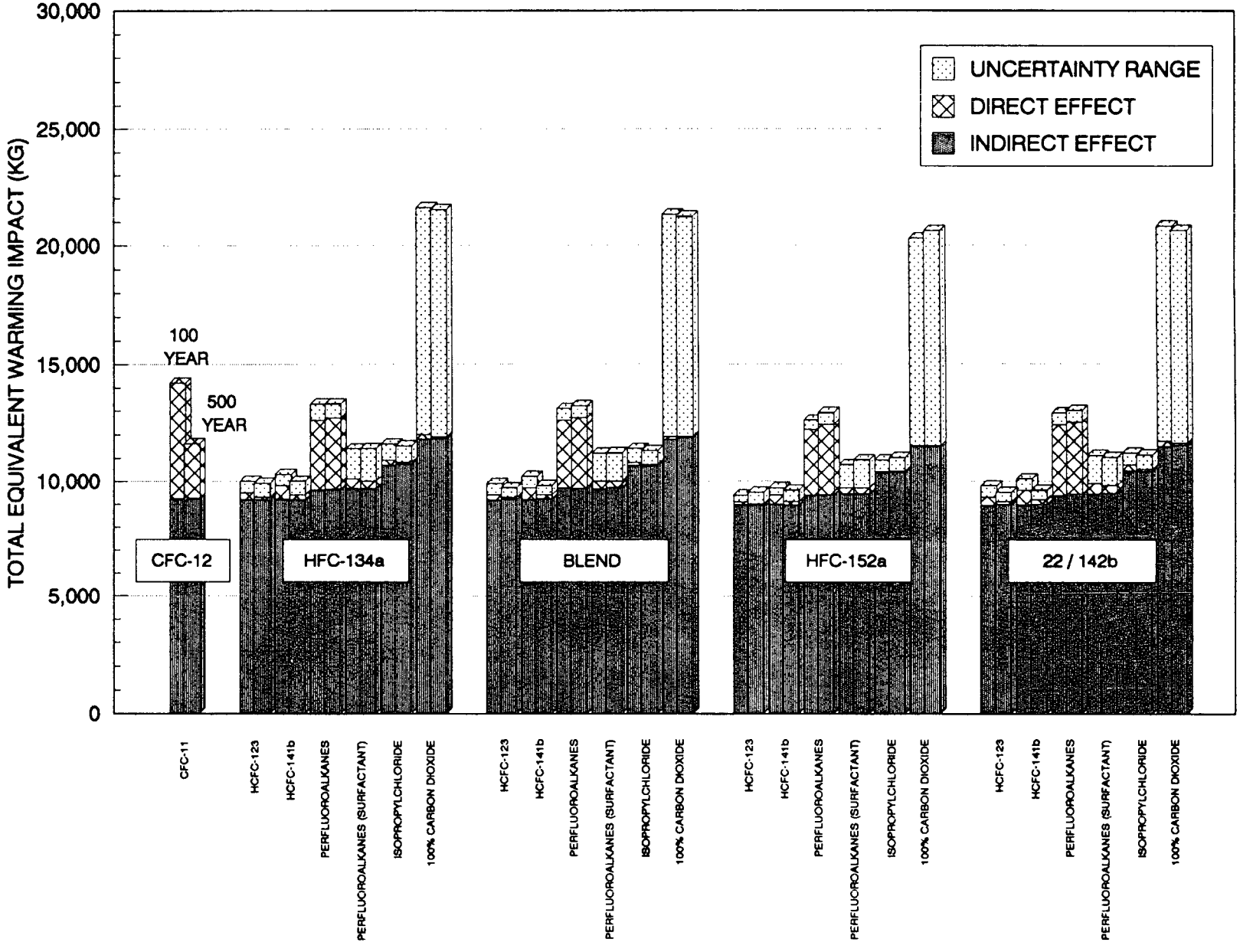


Fig. 14.2 Comparison of TEWI for refrigerator/freezers in North America using 100 year and 500 year values for GWP.

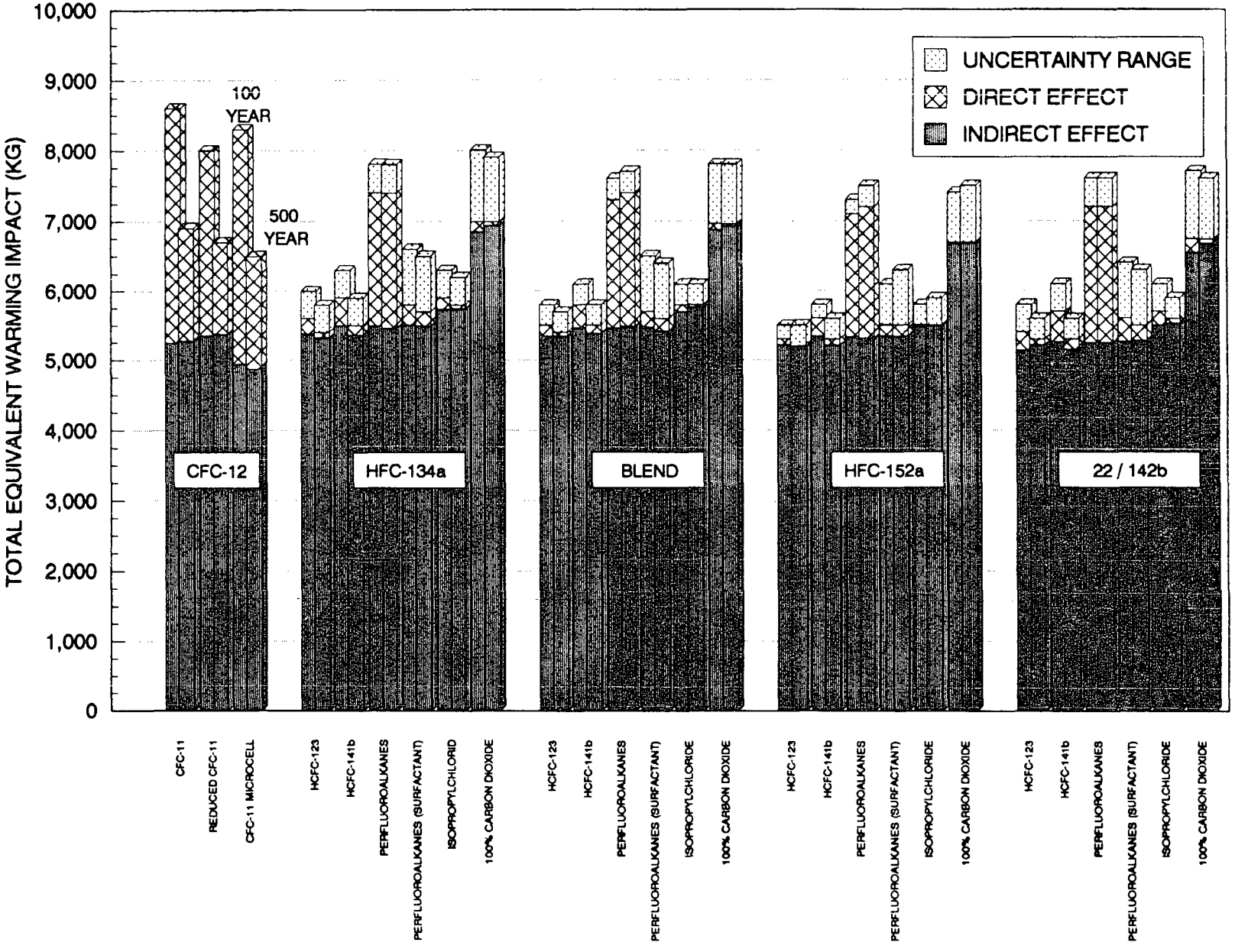


Fig. 14.3 Comparison of TEWI for refrigerator/freezers in Japan using 100 year and 500 year values for GWP.

fraction of the total. The final conclusion is not absolutely true based on the 100 year GWP values. The results in the figures for the ternary blend, HFC-152a, and the blend of HCFC-22 and HCFC-142b show a slight advantage over HFC-134a when the TEWIs are computed using the 100 year GWP values. The calculations of the TEWI, however, do not take into account the recovery of refrigerant when a refrigerator is scrapped because this is not an important factor in the calculations when the 500 year GWP values are used, and they do not include any reductions in operating efficiencies that may result from changing the refrigerator design in order to accommodate the use of a flammable refrigerant. These additional factors need to be accounted for to draw conclusions based on the TEWI using 100 year GWP values.

14.3 RETAIL REFRIGERATION

Four conclusions are listed for CFC alternatives in retail refrigeration equipment and they are all true whether the TEWI is computed using the 100 year GWP values or the 500 year values. The conclusions are:

- there are significant decreases in the TEWI as a result of switching to HFC-134a or HCFC-22 in medium or high temperature systems and to HCFC-22 in low temperature systems,
- there are no significant differences in TEWI for HFC-134a and HCFC-22 in high and medium temperature systems,
- the refrigerant losses due to leakage and service practices contribute significantly to TEWI with both HFC-134a and HCFC-22 even under the reduced loss assumptions, and
- efficiency improvements are needed in refrigeration equipment for all three temperature ranges to reduce the TEWI for a supermarket significantly.

The bars in the foreground of Fig. 14.4 illustrate these points for the 500 year GWP values and the bars for the TEWI using the 100 year GWP values in the background show the same things. The final point is not quite so clear using the 100 year values. Efficiency improvements continue to be important, but overall they will have less of an impact on the calculated TEWI using the 100 year GWP values than they will using the 500 year values because of the larger direct effect.

14.4 COMMERCIAL CHILLERS

There are five conclusions stated in Section 6 for commercial chillers. These are:

- HCFC-22 is the preferred alternative to CFC-12 in the 3000 RT category,
- HCFC-22 has a lower TEWI than HFC-134a in 100 RT air-cooled chillers,
- overall the differences in TEWI due to the alternative refrigerants are minor for the HCFCs and HFCs

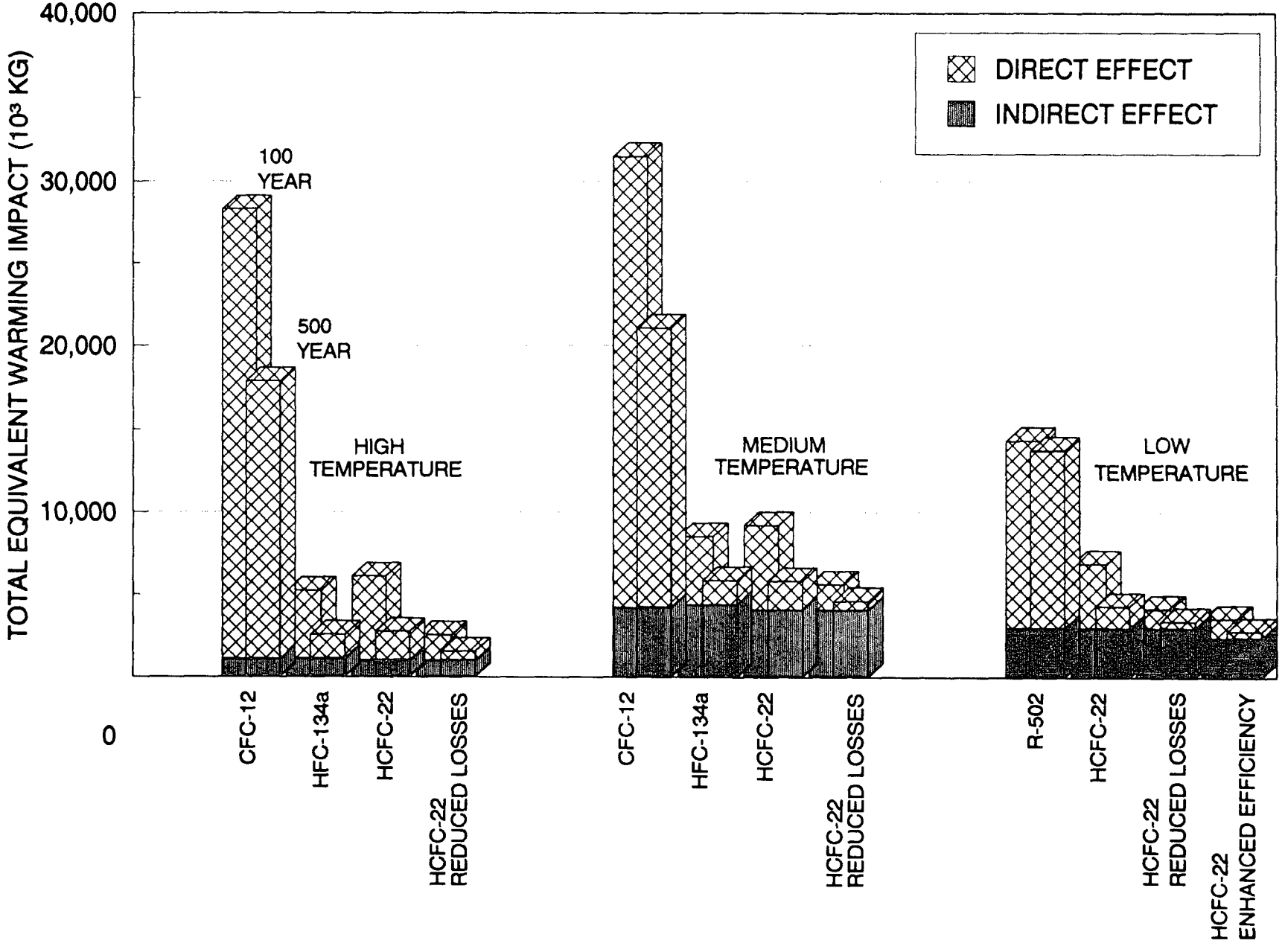


Fig. 14.4 Comparison of TEWI for supermarket display cases using 100 year and 500 year values for GWP.

- HCFC-22 has a lower TEWI for the 1000 RT category for annual refrigerant loss rates below 4%, HCFC-123 has a lower TEWI in this category at loss rates above 4%, and

- the TEWI for chillers using HFC-134a is essentially the same as that for chillers using either HCFC-22 or HCFC-123 in the 300 RT category at loss rates below about 4%.

Careful examination of Figs. 14.5, 14.6, and 14.7 shows that the first conclusion holds both for TEWI computed using the 500 year GWP values and with the 100 year values. The second conclusion is also valid in each case, although the differences in TEWI for HCFC-22 and HFC-134a is pretty small. The third conclusion is not valid if the TEWI is computed using the 100 year GWP values. Three hundred and 1000 RT chillers using HCFC-123 have noticeably lower TEWI than those with the other alternative refrigerants under the current 8% refrigerant loss assumptions, and slightly lower TEWI under the 4% annual loss rate assumption. The "breaking point" for the fifth conclusion is different if the TEWI are computed using the 100 year GWP values. HCFC-22 has a lower TEWI for 1000 RT chillers if the annual refrigerant loss rate is below about 2% of the charge, HCFC-123 has a lower TEWI if the loss rate is higher than 2%. Finally, for the last conclusion the TEWI for HFC-134a and HCFC-22 are about the same in the 300 RT category with the 100 year GWP values, but the TEWI for HCFC-123 is lower than that for either of the other two alternatives at loss rates above about 2%.

14.5 RESIDENTIAL AND COMMERCIAL UNITARY HEATING AND COOLING EQUIPMENT

The major conclusion for alternative refrigerants in unitary air-conditioning and heating systems is that the use of HCFC-134a in place of HCFC-22 in electric heat pumps would result in a significant increase in the total equivalent warming impact. The data in Figs. 14.8 and 14.9 show that this conclusion is valid no matter which GWP values are used. A second conclusion can be drawn from the 100 year TEWI in Fig. 14.9. There is a noticeable difference between the results for 2.5 RT air-conditioners in Japan with the higher refrigerant loss rates; The TEWI for HFC-134a is lower than that for HCFC-22 in this case.

14.6 AUTOMOBILE AIR-CONDITIONING

There are two major conclusions in Section 8 on automobile air-conditioning:

- the use of non-flammable fluorocarbon alternatives to CFC-12 in mobile air-conditioners will result in substantial reductions in TEWI, and

- the direct effects of HFC-134a and the ternary blend are 10 to 25% of the TEWI due to refrigerant losses.

These two statements are also true when the TEWIs are calculated using the 100 year GWP values. The results in Fig. 14.10 show that for all three geographic regions the decrease in TEWI based on the 100 year GWP values is at least as dramatic as it is for the TEWI based on the 500 year values. The results also show that the direct effect from HFC-134a and the ternary blend are significant portions of the total impact even under the low emissions scenario (refrigerant loss from leakage, accidents, and service practices reduced to less than one-third of estimated annual levels prior to 1991). The use not-in-kind technologies and very low GWP refrigerants will compare more favorably

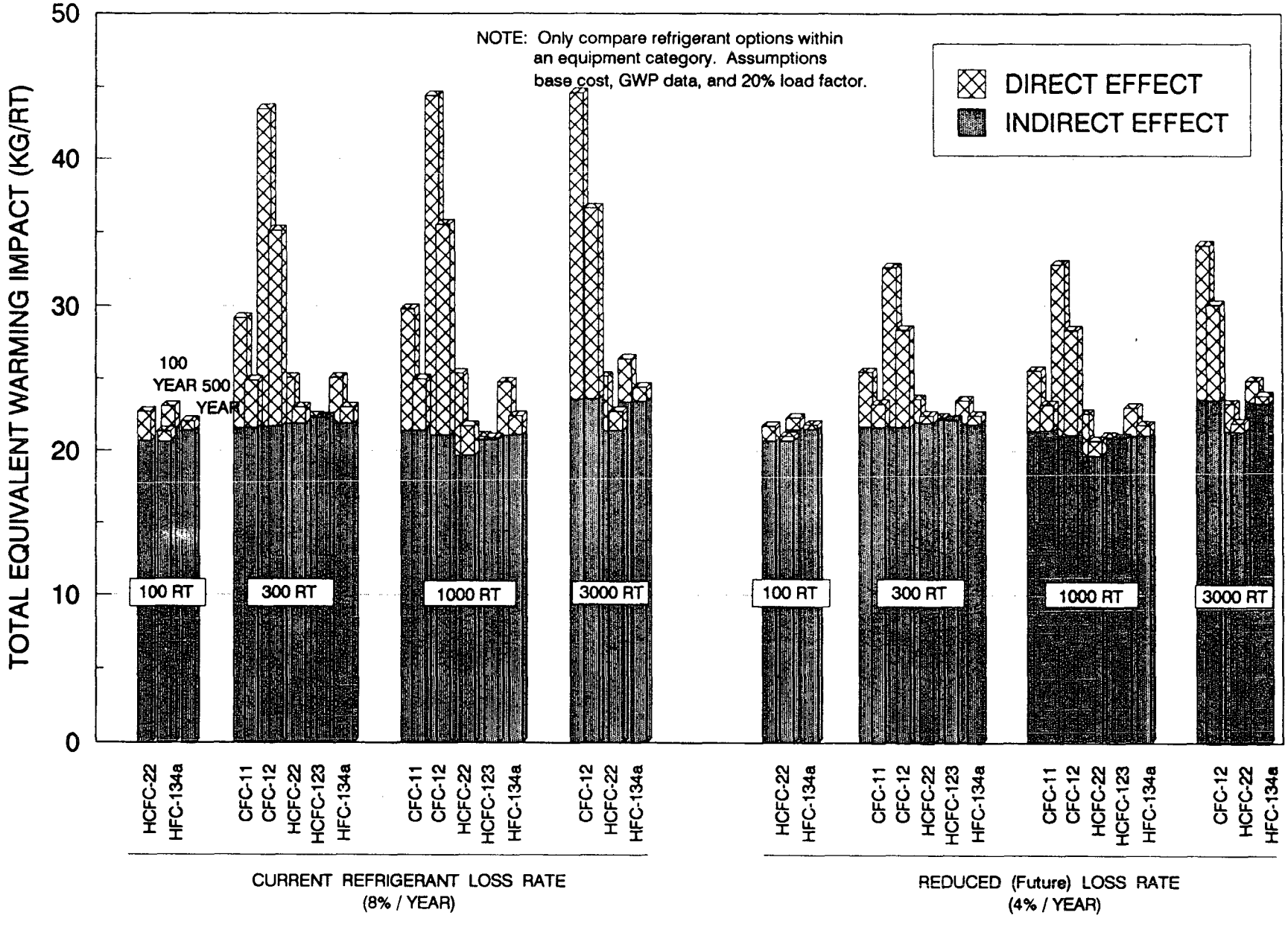


Fig. 14.5 Comparison of TEWI for commercial chillers in Europe using 100 year and 500 year values for GWP.

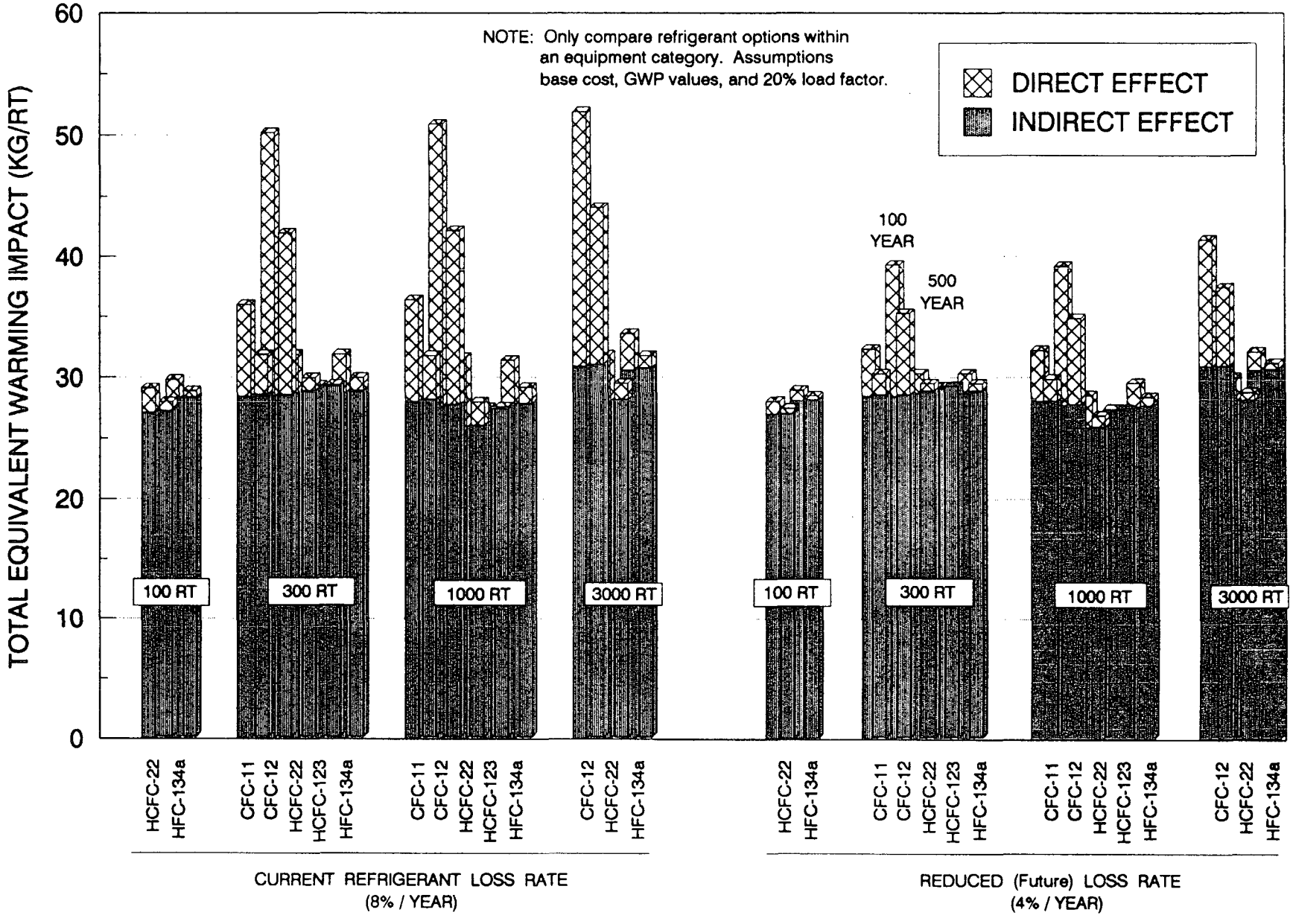


Fig. 14.6 Comparison of TEWI for commercial chillers in North America using 100 year and 500 year values for GWP.

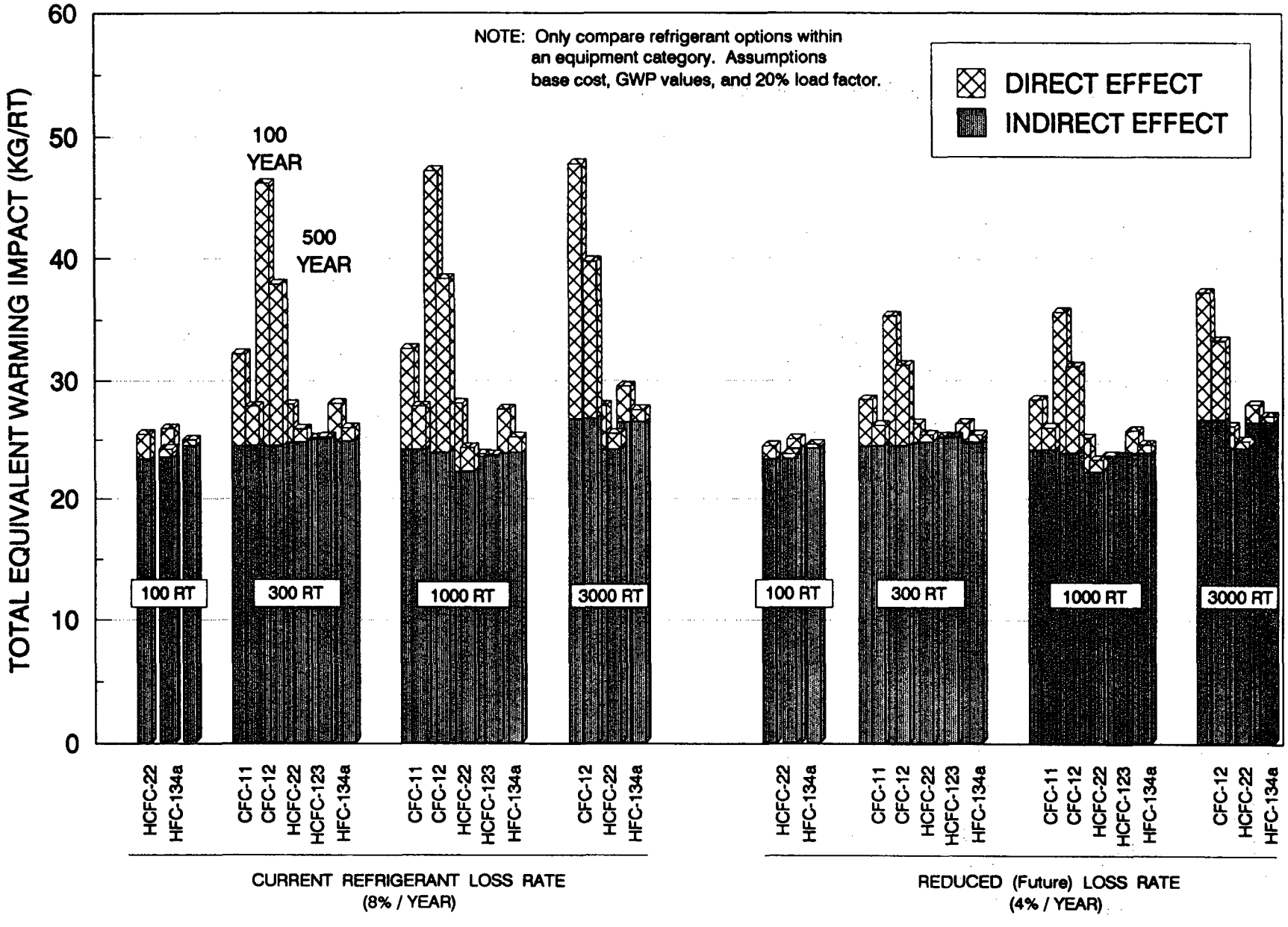


Fig. 14.7. Comparison of TEWI for commercial chillers in Japan using 100 and 500 year values for GWP.

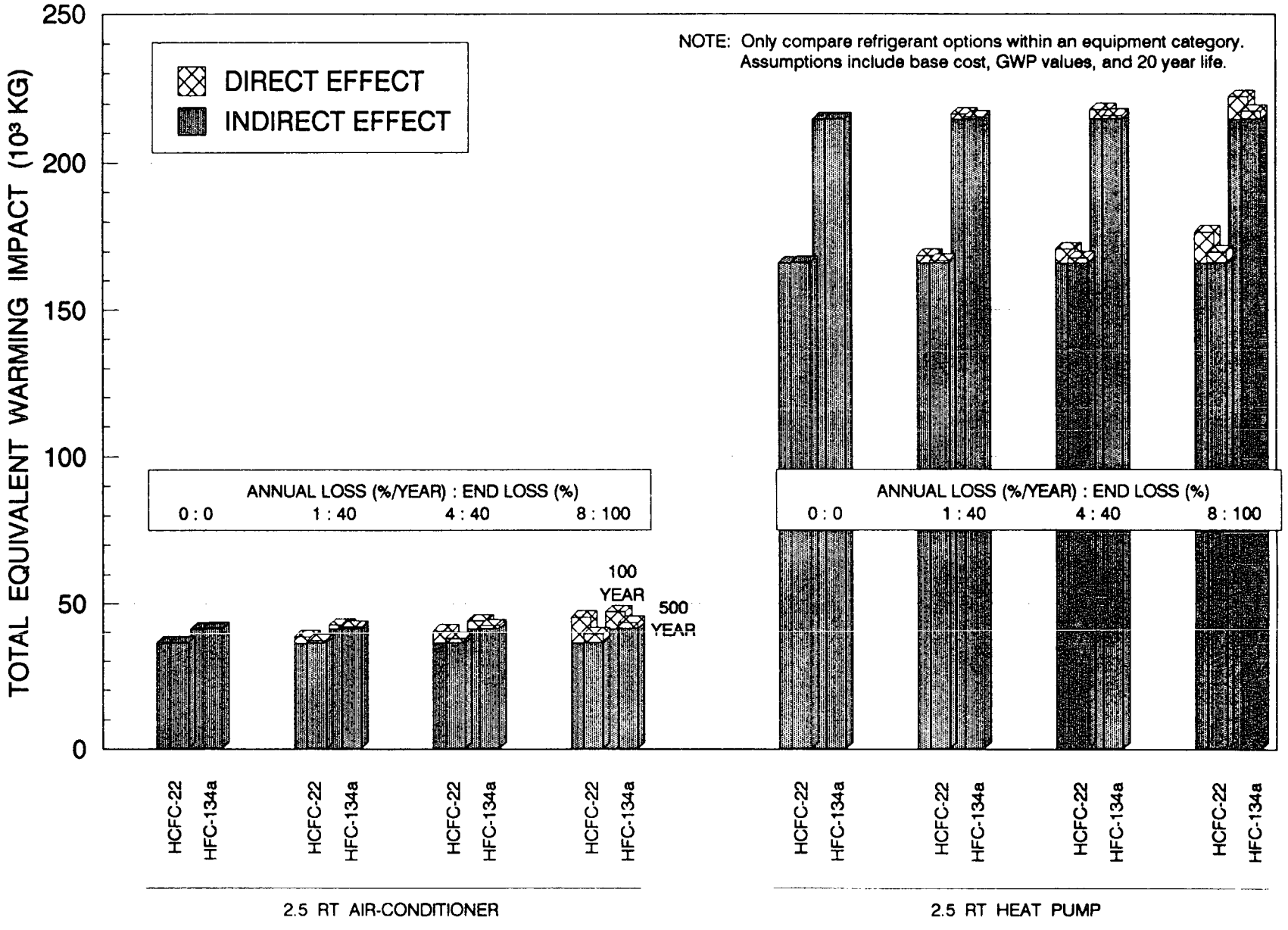


Fig. 14.8 Comparison of TEWI for unitary air-conditioning equipment in North America using 100 year and 500 year values for GWP.

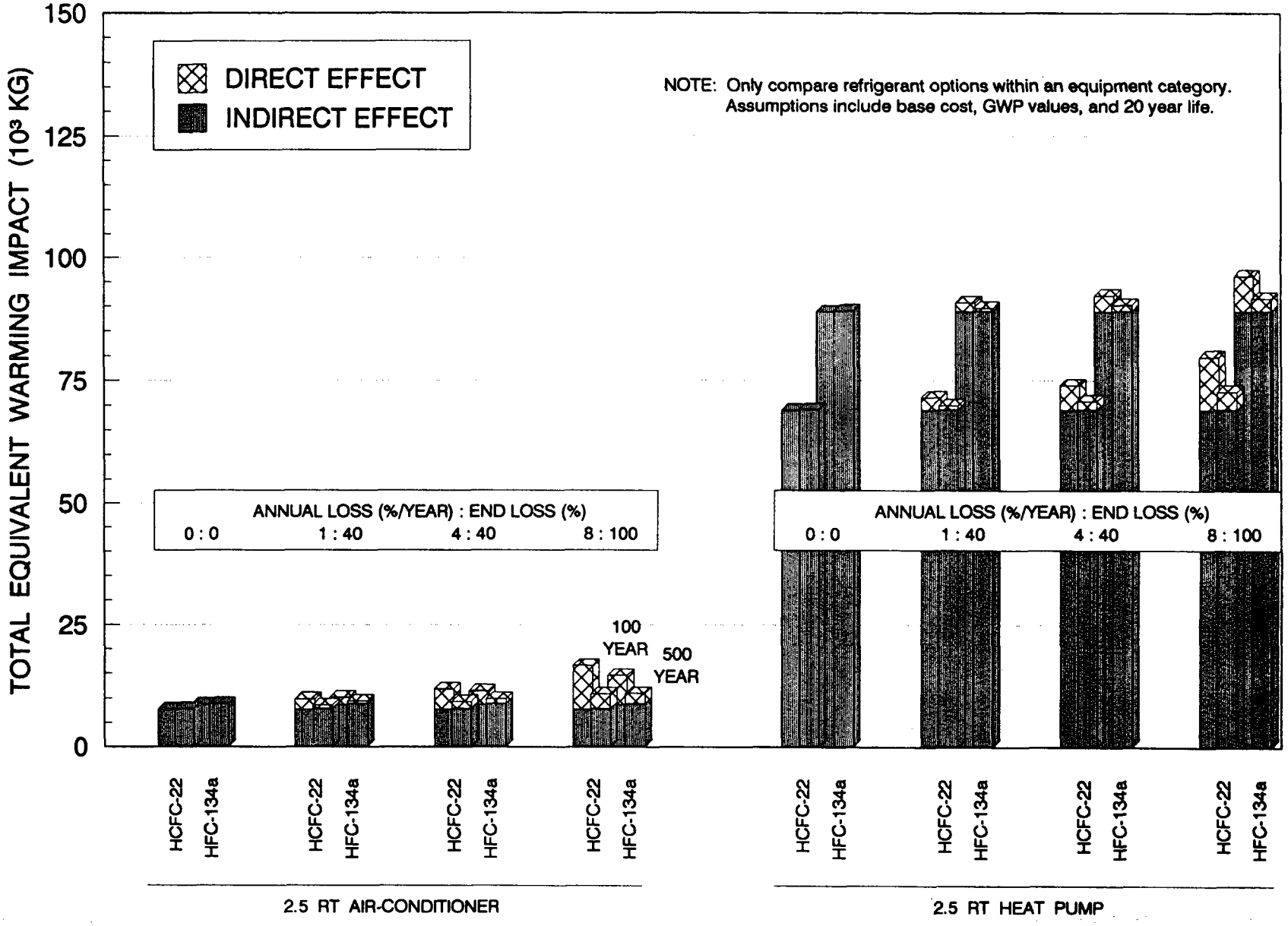


Fig. 14.9 Comparison of TEWI for unitary air-conditioning equipment in Japan using 100 year and 500 year values for GWP.

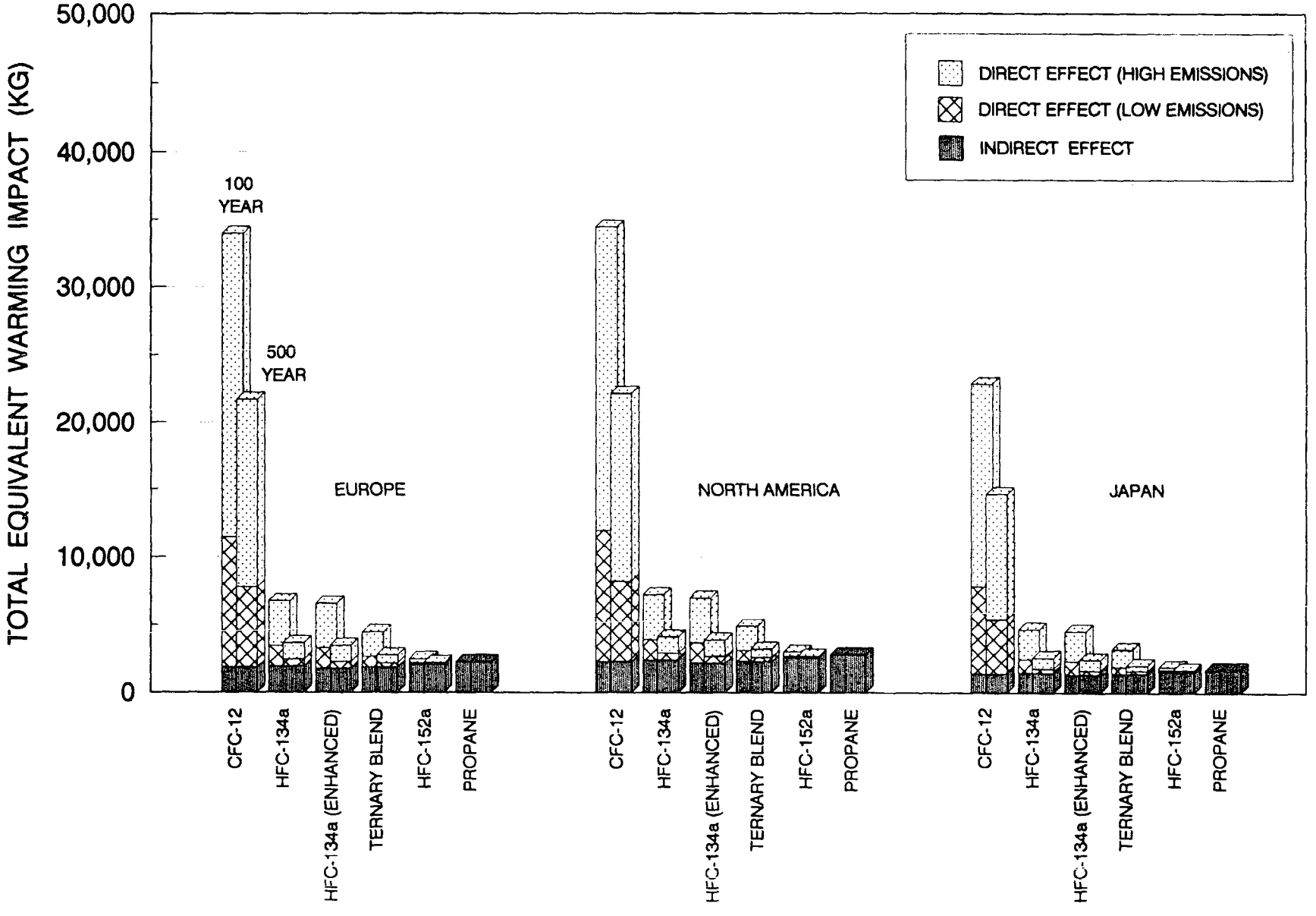


Fig. 14.10 Comparison of TEWI for automobile air-conditioners using 100 year and 500 year values for GWP.

with other alternatives when the 100 year GWP values are used. For example, the use of propane could have a noticeably lower TEWI than HFC-134a when the 100 year figures are used in the calculations.

14.7 COMMERCIAL BUILDING INSULATION

The time frame basis for the GWP used in the TEWI calculations is more significant in the conclusions for the two areas on building insulation than it is for the conclusions for refrigeration and air-conditioning. This is a consequence of the very large masses of blowing agent that are used in building foam insulation and the assumption that all of the blowing agent eventually escapes to the atmosphere (this may not occur until long after the building has been razed and the materials scrapped).

Two major conclusion are stated in Section 9 on commercial building insulation:

- the differences between the TEWI for alternative blowing agents in polyurethane/ polyisocyanurate and extruded polystyrene wall insulation are minor, and

- the differences between the TEWI for alternative blowing agents in roof insulation applications can be significantly different because of the differences in the direct effects of the blowing agents.

The first statement is not valid when the 100 year GWP values are used to compute the TEWI. It can be seen from the groups of bars for wall insulation in Fig. 14.11 and 14.12 that the TEWI for HCFC-123 using the 100 year GWP values is below the corresponding values for HCFC-141b (due to the larger direct effect) and that for isopropylchloride (due to the larger energy related indirect effect). It can be seen in Fig. 14.13 and 14.14 for alternative blowing agents for extruded polystyrene foam that there are significant differences in the direct effect when the 100 year GWP values are used in computing the TEWI. The second conclusion listed above is true independent of whether 100 or 500 year GWP values are used in computing the TEWI.

14.8 RESIDENTIAL BUILDING INSULATION

Two conclusions are stated in Section 10 for residential building insulation:

- the use of different thicknesses of foam to maintain a constant wall thermal resistance do not offset significant differences in the GWP and the relative blowing efficiencies of alternative blowing agents, and

- only a small portion of the TEWI is due to the direct effects of the blowing agent.

The first statement is true independent of whether the 100 year or 500 year GWP values are used in computing the TEWI. The fact that HCFC-141b, for example, has a much higher blowing efficiency than does HCFC-123 (less HCFC-141b is required for each unit of foam produced) does not compensate for the differences in the very large direct effect using either the 100 year or 500 year GWP values. This is evident in Figs. 14.15 and 14.16. The second statement is not valid if the 100 year GWP values are used in computing the TEWI. A significant portion of the TEWI for residential

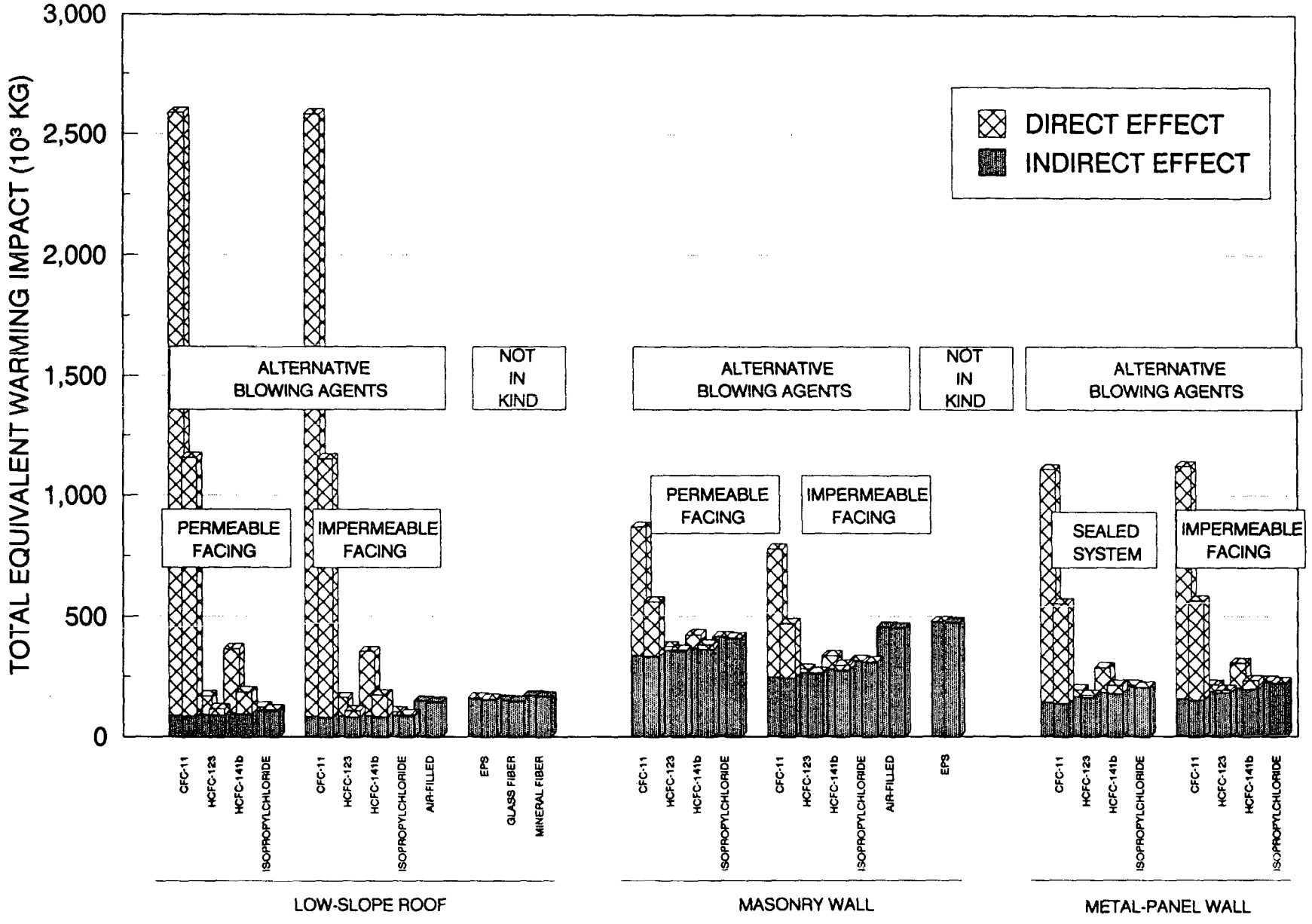


Fig. 14.11 Comparison of TEWI for polyurethane and polyisocyanurate insulation in European commercial buildings using 100 year and 500 year values for GWP.

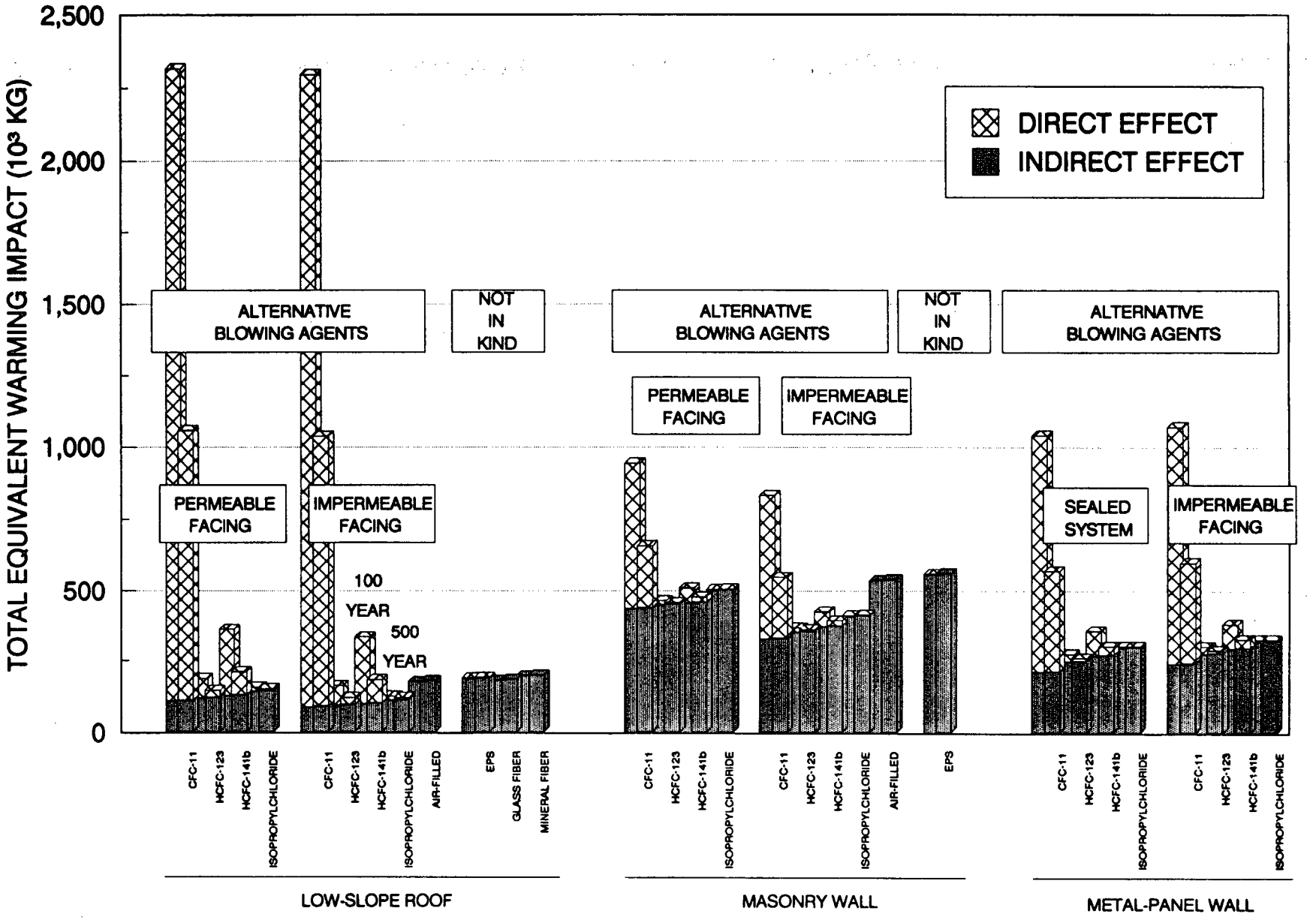


Fig. 14.12 Comparison of TEWI for polyurethane and polyisocyanurate insulation in North American commercial buildings using 100 year and 500 year values for GWP.

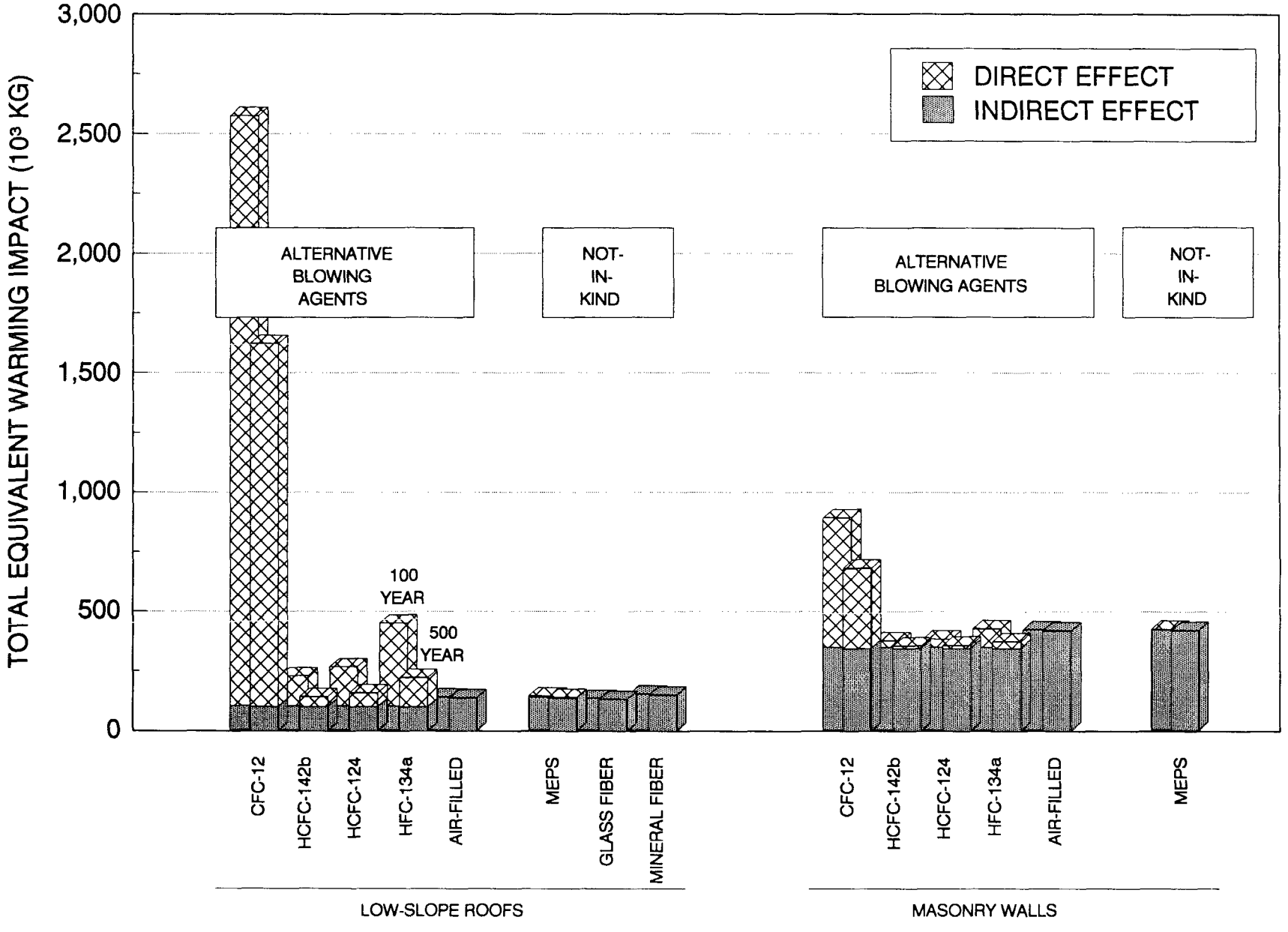


Fig. 14.13 Comparison of extruded polystyrene insulation in European commercial buildings using 100 year and 500 year values for GWP.

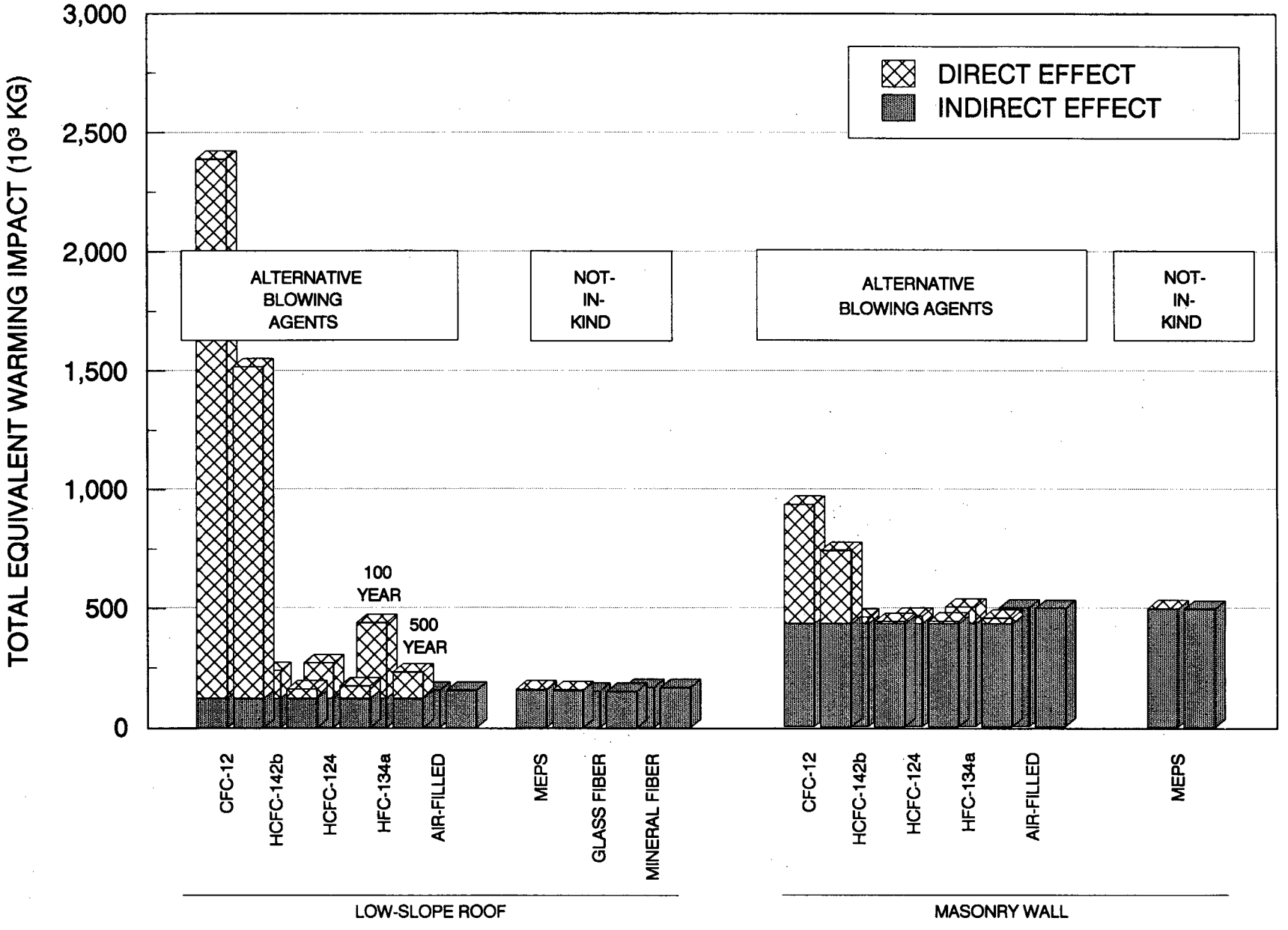


Fig. 14.14 Comparison of TEWI for extruded polystyrene insulation in North American commercial buildings using 100 year and 500 year values for GWP.

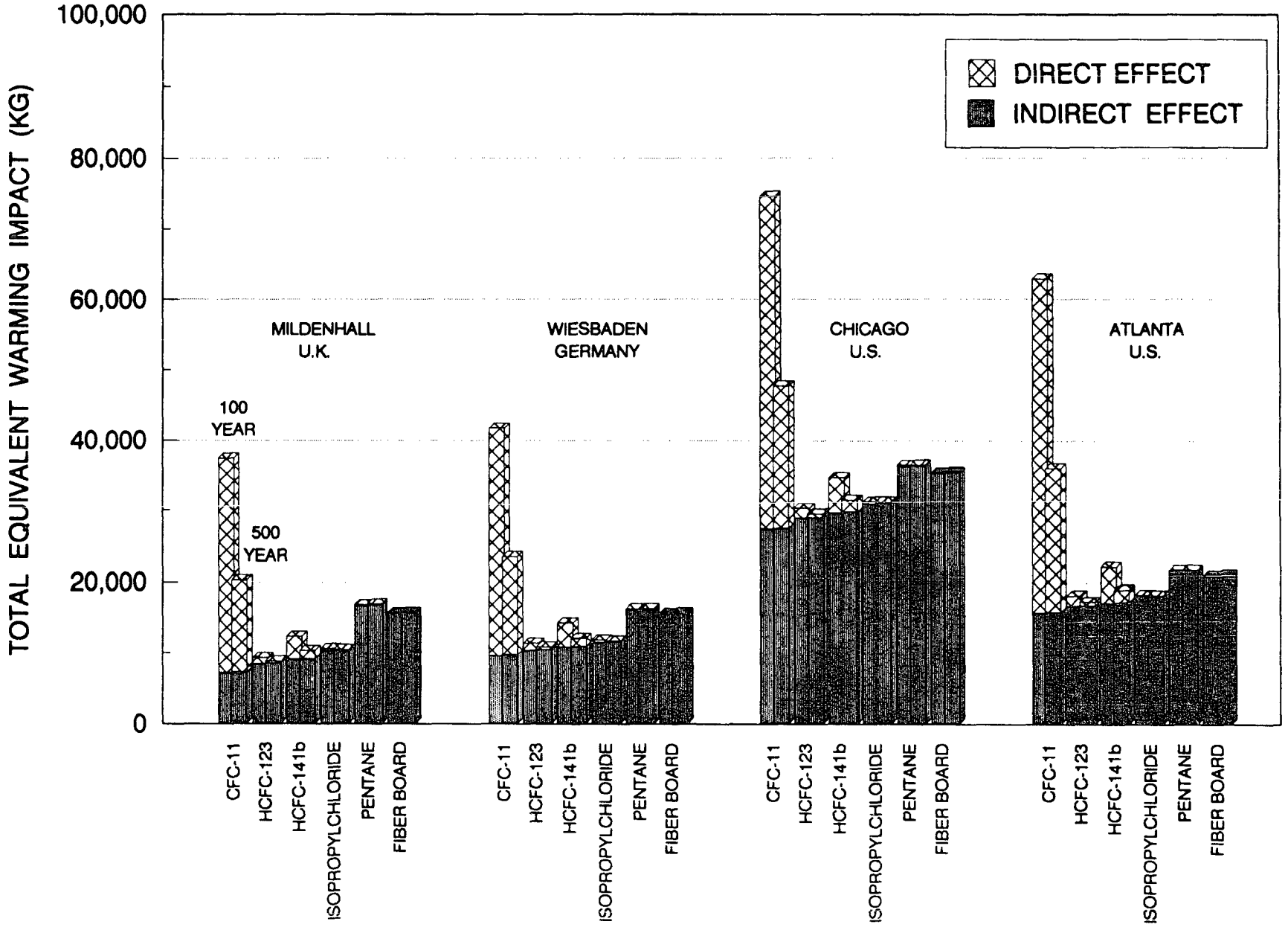


Fig. 14.15 Comparison of TEWI for polyurethane and polyisocyanurate insulation in residential buildings using 100 year and 500 year values for GWP.

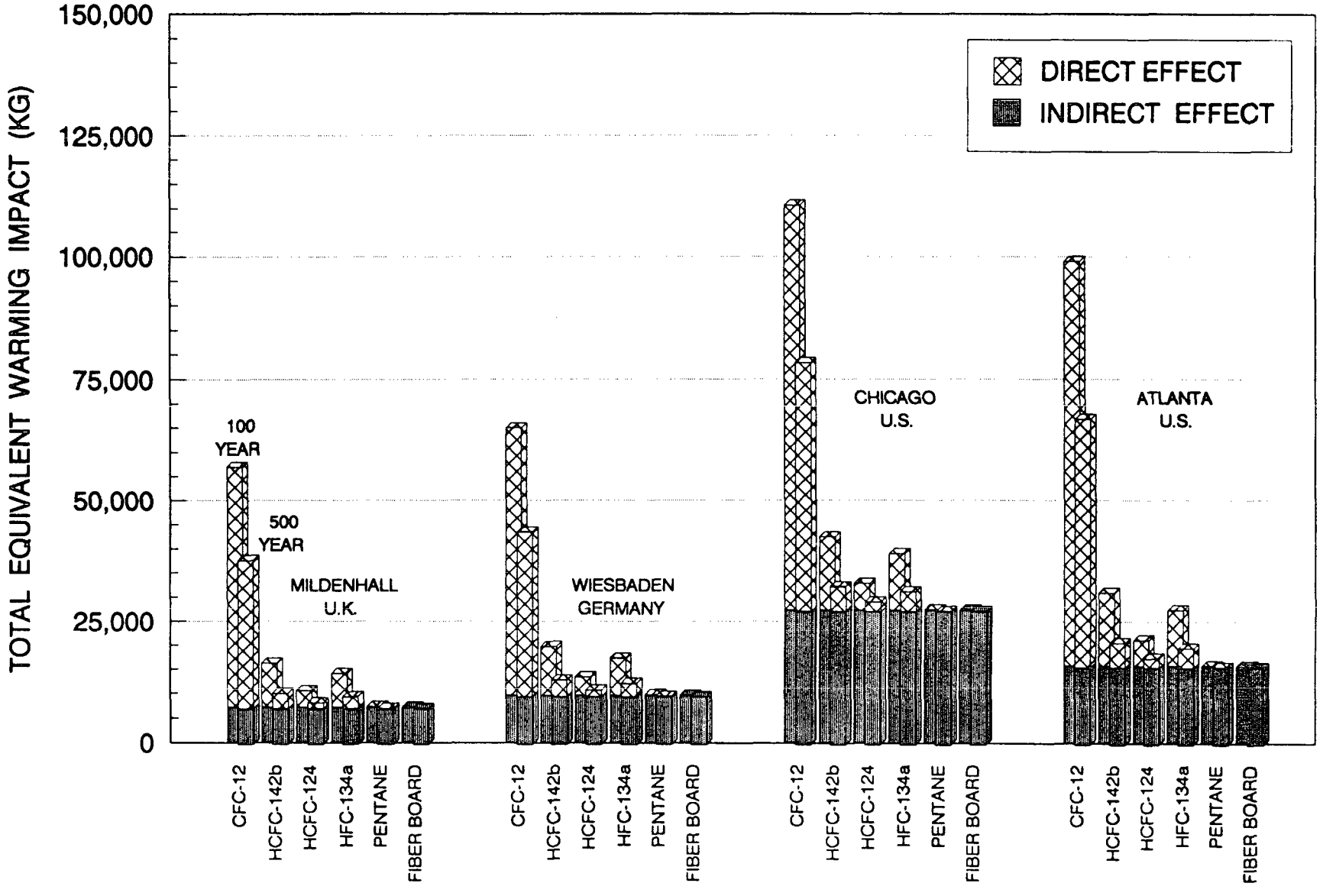


Fig. 14.16 Comparison of TEWI for extruded polystyrene insulation in residential buildings using 100 year and 500 year values for GWP.

building insulation is due to the direct effect for HCFC-141b and for some of the extruded polystyrene blowing agents when the 100 year GWP values are used to determine the direct effect.

14.9 METAL AND ELECTRONIC CLEANING/DRYING

All four of the major conclusions for Sections 12 and 13 on solvent cleaning are truly independent of whether the 100 or 500 year GWP values are used in computing the TEWI. The conclusions are:

- trichloroethylene (TCE) offers a relatively low TEWI for general metal cleaning due to the low GWP of solvent emissions,
- for in-line systems for electronics cleaning, solvent based processes are comparable to aqueous and semi-aqueous processes with the results largely affected by the GWP contributions of the solvent to the TEWI,
- for batch systems for electronics cleaning, the TEWIs of solvent based systems are noticeably higher than either aqueous or semi-aqueous cleaning systems, and
- the best available current technology for either general metal cleaning or electronics cleaning has the potential to reduce TEWIs significantly for solvent systems so that they are lower than or comparable to aqueous, semi-aqueous, or no-clean technologies.

Figs. 14.17 and 14.18 support the first conclusion using both the bars for the 100 year GWP and those for the 500 year GWP. The bars for trichloroethylene are no higher than those for aqueous and semi-aqueous cleaning for both batch and in-line systems. The results in Fig. 14.19 for in-line electronics cleaning show that solvent systems using HCFC-225ca, HCFC-123, or methyl chloroform are all comparable to aqueous and semi-aqueous processes independent of whether the direct effects are calculated using the 100 or 500 year GWP values and the direct effect is also a very large proportion of the TEWI in each case. Consequently the second conclusion in Section 10 is true using the 100 year GWP values. Figure 14.20 supports the conclusion that the TEWI for solvent based batch systems for electronics cleaning is noticeably higher than the TEWI for aqueous or semi-aqueous cleaning batch processes when the 100 year GWP data are used to compute the direct effects.

14.10 CONCLUSIONS

There are only a few instances in which the time frame used for determining the GWP makes a difference in the conclusions drawn from the TEWI of the various alternatives for each application. In general, where only small refrigerant charges and small volumes of insulation are used (e.g., household refrigeration) it does not make any difference whether the 100 year or 500 year GWP values are used to compute the TEWI. In applications where the direct effect of an alternative refrigerant is a significant fraction of the total equivalent warming impact (e.g., automobile air-conditioning, retail refrigeration), the use of the 100 year GWP values causes an even larger fraction of the TEWI to be due to the direct effect of the chemical emissions. This can affect the comparison between fluorocarbon alternatives in conventional equipment and not-in-kind technologies or refrigeration and air-conditioning using very low GWP refrigerants such as propane.

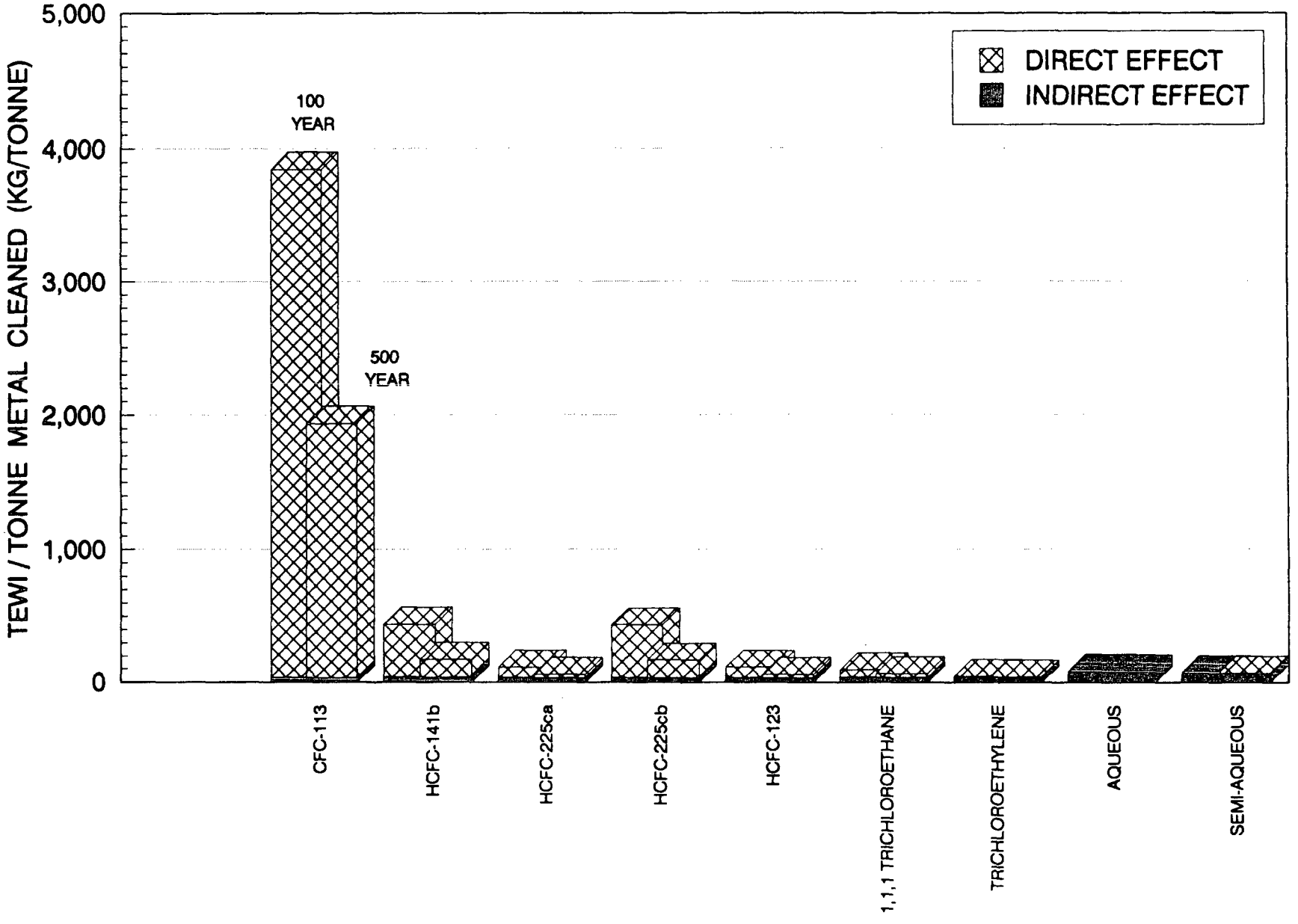


Fig. 14.17 Comparison of TEWI for batch metal cleaning processes using 100 year and 500 year values for GWP.

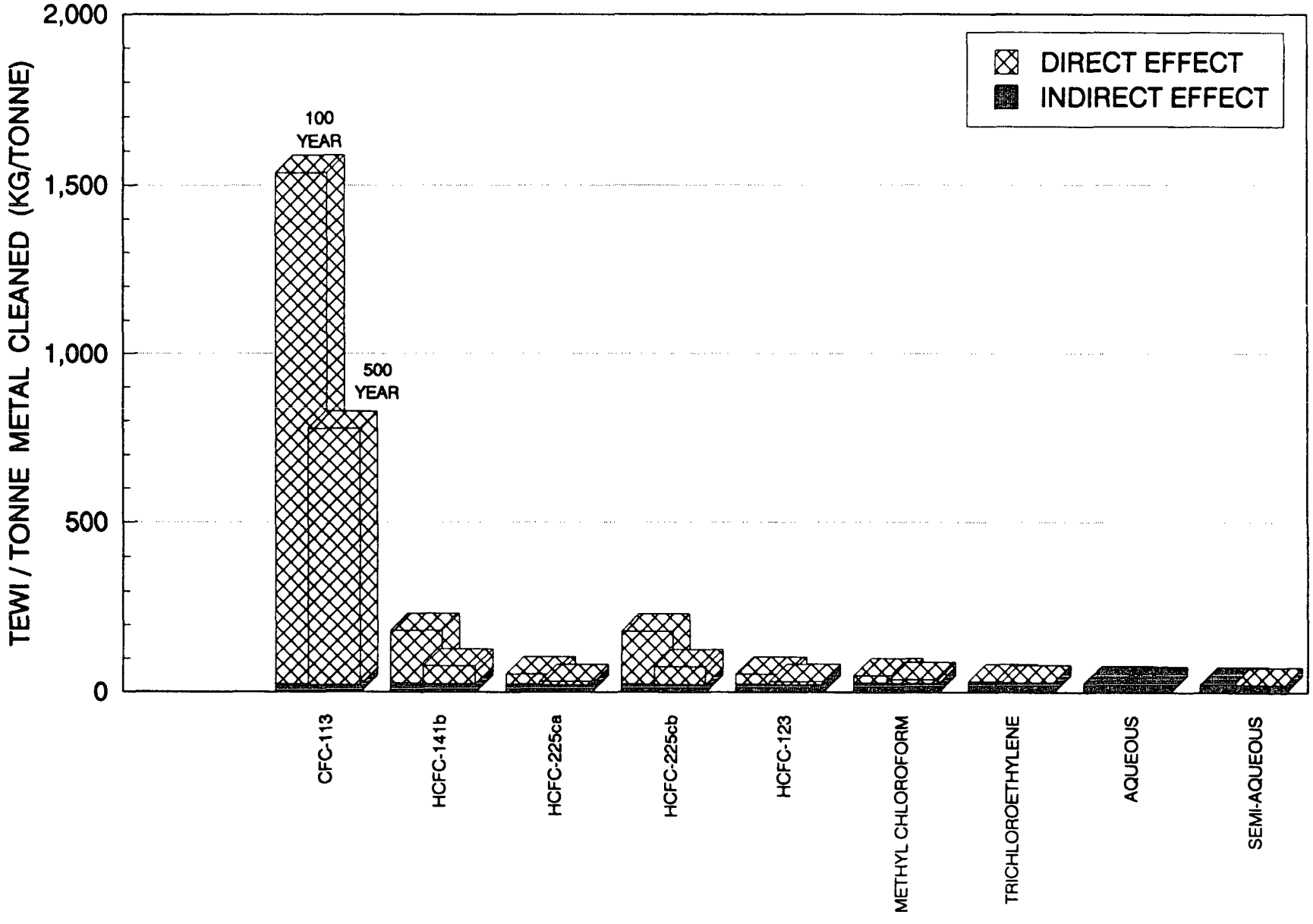


Fig. 14.18 Comparison of TEWI for in-line metal cleaning processes using 100 year and 500 year values for GWP.

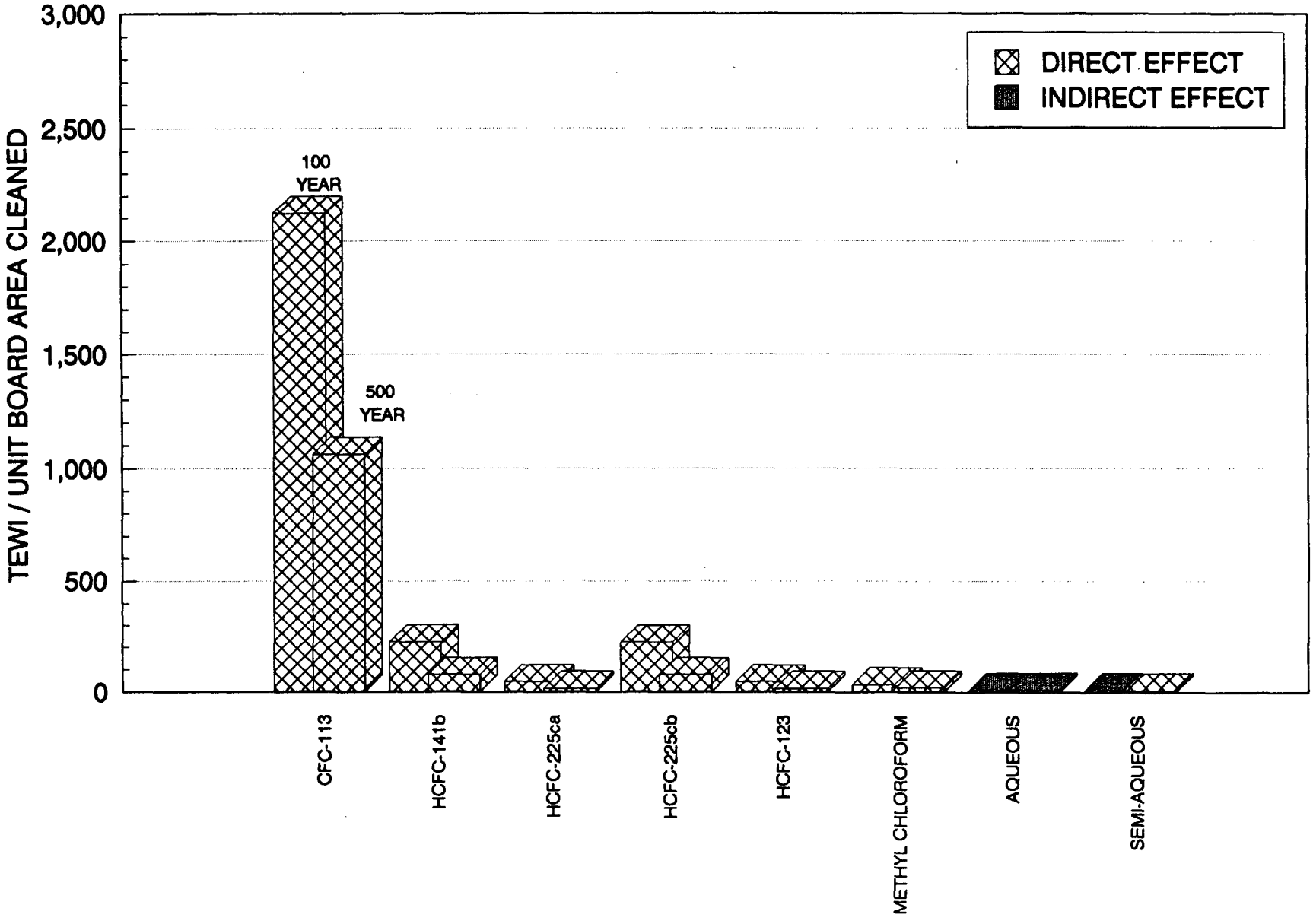


Fig. 14.19 Comparison of TEWI for batch electronics cleaning processes using 100 year and 500 year values for GWP.

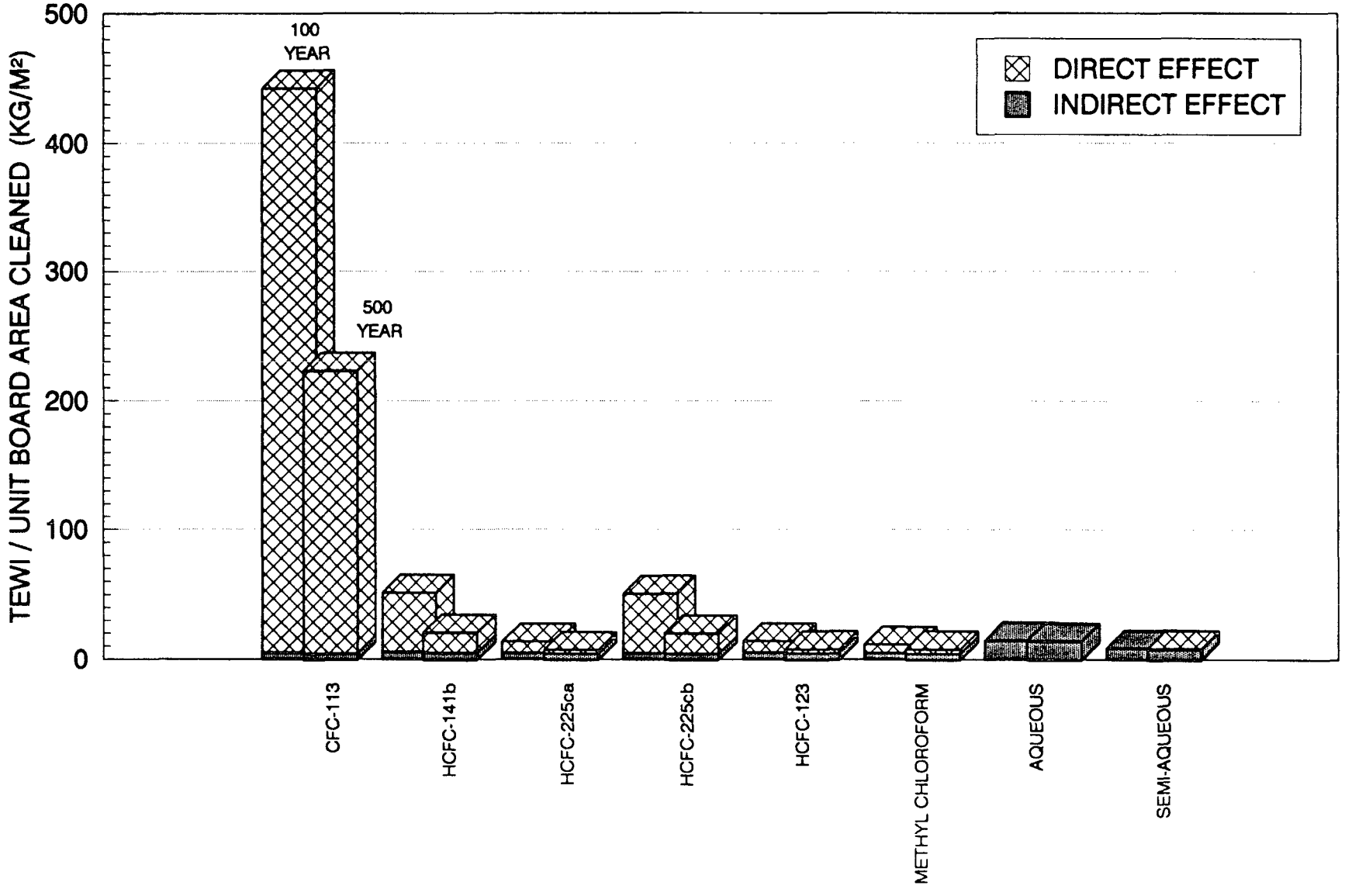


Fig. 14.20 Comparison of TEWI for in-line electronics cleaning processes using 100 year and 500 year values for GWP.

The only case where the conclusions based on the TEWI are greatly affected by the time frame for the GWP values is in building insulation where large volumes of insulation are used and there are choices of blowing agent that have large differences in GWP but create foams with very similar thermal properties. In these instances there are blowing agents that appear superior to others when the 100 year GWP values are used, but there are no significant differences in the TEWI when the 500 year GWP values are used.

15. CONCLUSIONS

The potential changes in CO_2 emissions related to energy use of CFC replacement technologies (i.e., the INDIRECT effects) were found to be relatively small due, in part, to the emphasis placed on energy efficiency by the user industries. Therefore, an estimated tenfold reduction in DIRECT effects expected from replacing CFCs should yield a substantial reduction in TEWI and, hence, in contributions to future global warming in the industrialized countries (of approximately 70%) by the end of the 1990s. This conclusion assumes that the options considered in this study are available and otherwise acceptable for the CFC transition.

Effects of not-in-kind replacement technologies and improved conservation/containment and recovery of the replacement fluorocarbons should further reduce the DIRECT effects and provide added reductions in the TEWI. The IPCC report (1990) and industry estimates (DuPont, 1991) suggest that the future demand for HCFCs and HFCs may only be 40% of that for CFCs (based on projections from demand in late 1980's), due to the effects of reduced emissions and use of non-fluorocarbon alternatives. If this occurs, a twenty-fold reduction in DIRECT effects from fluorocarbon applications could be realized.

There is ample evidence from the user industry inputs to this study that conservation efforts are receiving increased attention for controlling current CFC emissions. The improved containment and recovery practices and technological solutions generated by these efforts should be readily adopted for the alternative fluorocarbons. On the other hand, not-in-kind (NIK) alternative technologies are generally not receiving major research attention in the refrigeration, air conditioning and insulation user industries, for a variety of valid business, technical, and time-related reasons.

The potential importance of these NIK options in the longer-term is acknowledged, and the study has included some examples; though many more are under development. These options should be considered more fully, but information and verifiable data on many of these options are fragmented and difficult to interpret and compile. It is also difficult to assure comparability of available data on developmental technology with commercial or near-commercial technology. Misleading or speculative conclusions could be reached, perhaps to the detriment of the new or unconventional technology. At a later stage, when these technologies reach a more mature state of development, further analysis should be attempted.

It was judged most important in this initial assessment to focus on "current generation" technology options and to reflect the thinking and planning of the user industries "mainstream," because the impacts of their preferred options represent the most likely outcome for the immediate CFC transition in the 1990s. The analysis and findings do point out and highlight those applications in which the opportunities for NIK options may be the greatest, that is, in applications for which substantial HCFC/HFC DIRECT (emissions-related) effects remain. In the other applications in which the INDIRECT (energy-related) effects dominate, the NIK technologies would essentially have no significant TEWI advantage over fluorocarbon technologies, since the remaining DIRECT effect is so small that reducing it to zero would yield at best a 1-4% difference in TEWI benefit. To reduce TEWI in these applications, NIK technologies would have to be developed that are more energy efficient than the HCFC/HFC options.

The replacement of CFCs is probably the most important single near-term step that can be taken toward reducing the global warming impact. Reducing CO_2 and other greenhouse gases is likely to be much more difficult to achieve due to the world's dependence on fossil fuels as its primary energy

source and the difficulties in changing that significantly in the next 20-30 years (Fulkerson, et al, 1989). As demonstrated in this study, energy efficiency will be important in limiting CO_2 emissions.

The recent progress in improving energy efficiency with these HCFC and HFC alternatives represents an encouraging and important trend and suggests that further energy-related reductions are also likely. Results of previous CFC phaseout assessments (Fischer, et al., 1989) indicated the potential for more serious energy consequences. However, the energy-intensive user industries have responded strongly to this challenge in the past 2-3 years, and it now appears that the CFC transition may only cause a temporary setback in longer-term energy conservation efforts.

HCFC alternatives and HFC alternatives each have their own specific advantages in specific applications. The fluorocarbon options for refrigeration, air-conditioning, and long-life insulating foam applications offer lower or comparable TEWI over their service life than any available or near-term alternative products. Further constraints on the HCFC and HFC alternatives could be counterproductive. It is important to consider a systems approach, as was done here, to make certain that an action or policy has the intended effect.

Finally, it is well recognized that the needs of the developing countries must be considered. We in the industrialized nations must be sensitive to the applicability, adaptability, and appropriateness of our technological solutions in those regions, where, for example, refrigeration needs are increasing dramatically. These global environmental issues such as ozone depletion and global warming require near complete participation worldwide if the solutions are to be effective. The energy and CFC replacement technology choices made by the developing nations will be crucial in determining how well we do overall in minimizing contributions to these issues.

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APPENDIX A: GLOBAL WARMING POTENTIALS FOR FLUOROCARBONS AND OTHER TRACE GASES

Table A.1 GWPs for fluorocarbons and other trace gases

Trace Gas	Estimated Lifetime (years)	Global Warming Potential Integration Time Horizon (years)	
		100	500
Carbon Dioxide	*	1	1
Nitrous Oxide	150	290	190
Methane - including indirect	10	21	9
CFC-115	400	6900	7400
CFC-114	200	6900	5500
CFC-12	130	7300	4500
CFC-113	90	4200	2100
CFC-11	60	3500	1500
HFC-143a	41	2900	1000
HFC-125	28	2500	860
HCFC-142b	19	1600	540
HFC-134a	16	1200	420
HCFC-22	15	1500	510
HCFC-141b	8	440	150
HCFC-225cb	7.7	680[a]	230[a]
HCFC-124	6.6	430	150
HCFC-225ca	2.6	162[a]	55[a]
HFC-152a	1.7	140	47
HCFC-123	1.6	85	29
CF_3Br	110	5800	3200
CCl_4	50	1300	460
CH_3CCl_3	6	100	34

CFCs and other gases do not include effect through depletion of stratospheric ozone. Changes in lifetime and variations of radiative forcing with concentration are neglected.

* The persistence of carbon dioxide has been estimated by explicitly integrating the box-diffusion model of Siegenthaler (1983).

[a] The HCFC-225ca/cb GWP values used in this report have been calculated by Atmospheric and Environmental Research, Inc. (AER) and are based on rate constant measurements reported by M. J. Kurylo, et al; Geophysical Research Letter, Vol 18, No. 1, pages 5-7, January 1991, and the infrared energy absorption properties measured at ALLIED-SIGNAL Central Research Laboratory.

Source: IPCC "Climate Change," 1990, except for HCFC-225ca and HCFC-225cb (see Note a).

NOTE: The values presented in Table A.1 are under review by the Stratospheric Ozone Assessment Panel, which may lead to changes in GWP values. The revised values, where necessary, will be used to recalculate the direct energy contribution of the working fluids to the applications assessed in this report.

APPENDIX B: COMPARISON OF THEORETICAL AND ESTIMATED TOTAL EQUIVALENT WARMING

INTRODUCTION

According to the definitions of GWP(ITH), TEWI, and the normalized integrated forcing (NIRF) in Section 3, TEWI and NIRF should be identical if all the gases were emitted in the first year. Several examples are considered to illustrate how well TEWI approximates the integrated radiative forcing when gases are emitted from an application over a period of several years to several decades. The applications considered are batch metal and batch electronic cleaning, automobile air-conditioning, refrigerator/freezers, and residential building insulation. For each application, the TEWI is computed as defined in Equ. 3.9 for two choices of integration time horizon (ITH), namely 100 and 500 years. The results are compared with the normalized integrated radiative forcings over the same time horizon as computed using the emission history associated with each application. If all the material were emitted in the first year of the application, the normalized integrated radiative forcing should be identical to TEWI. TEWI should be larger than the normalized integrated radiative forcing for applications in which the emissions occur over several years. This holds true for the cases considered up to the round-off error introduced in Table B.6.

BATCH CLEANING

The integrated radiative forcing per tonne of metal and per square meter of electronic board cleaned are calculated based on data from Arthur D. Little (ADL, 1991). The values used in this report are those given by ADL for the case corresponding to current practice, not the best available current technology. The emission estimates for each process are discussed in Section 12 of this report. The case for best available current technology could be calculated in a similar fashion.

The CO_2 and CFC-113 emission for the baseline batch electronic cleaning that uses CFC-113 as the solvent are 1.69 kg and 0.505 kg / m^2 of electronic circuit board cleaned. The corresponding values for CO_2 is 1.71 kg/m^2 and the solvent emission (HCFC-123) is still 0.505 kg/m^2 for the substitution electronic case. The corresponding values for batch metal cleaning are 36 kg CO_2 and 0.91 kg CFC-113 per tonne of metal cleaned and 36.8 kg CO_2 and 0.91 kg HCFC-123 per tonne of metal for the substitution metal cleaning case. The time evolution of the radiative forcing is shown in Figs. B.1 and B.2. The radiative forcing due to CO_2 emissions from energy use is less than two units in both the baseline and substitution cases for electronics cleaning in Fig. B.1 and less than 36 units for batch metal cleaning in Fig. B.2 and does not show up in the figures.

In both applications, CFC-113 is replaced with the same amount of HCFC-123. Since $R_{HCFC\text{-}123}$ is small than $R_{CFC\text{-}113}$ and the lifetime of HCFC-123 is also shorter, the direct radiative forcing from HCFC-123 is uniformly smaller than that of CFC-113.

The calculated integrated radiative forcing results are given below in Tables B.1 and B.2. Because the total radiative forcing is dominated by the time of fluorocarbon used, it is clear that for both applications, the substitution case that employs HCFC-123, which has a shorter lifetime and lower relative forcing factor than CFC-113, produces less radiative forcing than the baseline case. In fact, for batch electronic cleaing the substitution case should produce about 2% of the radiative forcing produced by the baseline case and for batch metal the value is about 3%.

For these applications, gases are emitted at the start of the integration. Thus, there should be no differences between normalized integrated forcing and TEWI. The differences shown in Tables B.1 and B.2 are due to round-off in the GWP values given in Table A.1 in Appendix A.

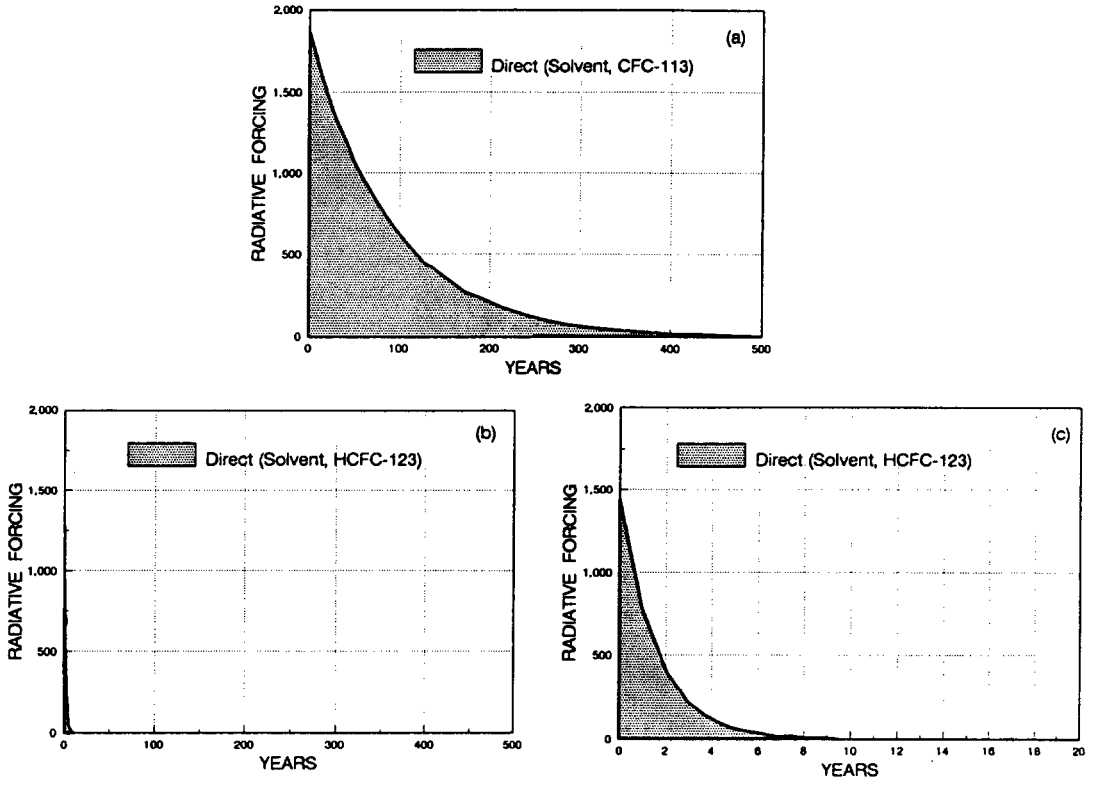

Fig. B.1. Potential radiative forcing from gases associated with batch electronic cleaning: (a) baseline case using CFC-113, (b) substitution case using HCFC-123 (same scale), and (c) substitution case using HCFC-123 (expanded scale).

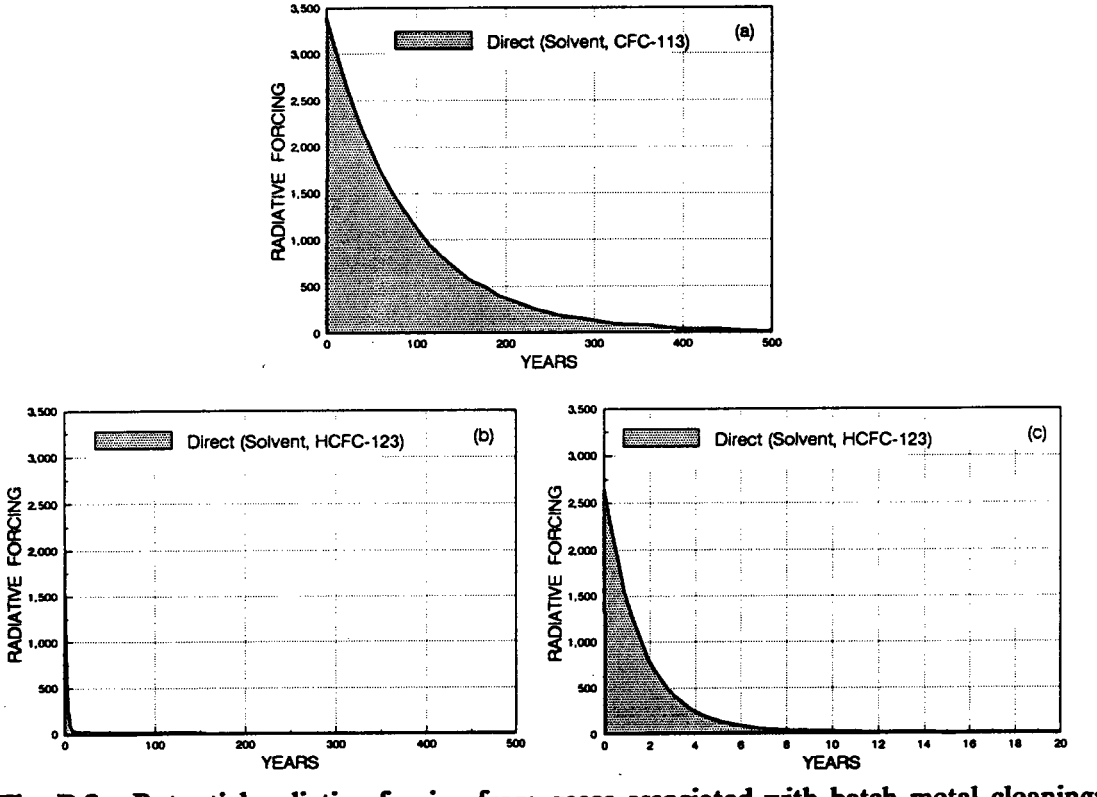

Fig. B.2. Potential radiative forcing from gases associated with batch metal cleaning: (a) baseline case using CFC-113, (b) substitution case using HCFC-123 (same scale), and (c) substitution case using HCFC-123 (magnified scale).

Table B.1. Comparison of normalized integrated radiative forcing and TEWI for batch electronics cleaning in North America

Algorithm for Computing Potential Warming Impact	Baseline					
	ITH=100 years			ITH=500 years		
	Direct CFC-113	Indirect CO_2	Total	Direct CFC-113	Indirect CO_2	Total
Normalized Integrated Forcing	2095	1.69	2097	1050	1.69	1052
TEWI	2121	1.69	2123	1061	1.69	1063
% Difference	1.2	0	1.2	1.0	0	1.0
Algorithm for Computing Potential Warming Impact	Substitution					
	ITH=100 years			ITH=500 years		
	Direct HCFC-123	Indirect CO_2	Total	Direct HCFC-123	Indirect CO_2	Total
Normalized Integrated Forcing	43	1.71	45	15	1.71	17
TEWI	43	1.71	45	15	1.71	17
% Difference	~0	0	~0	~0	0	~0

Table B.2. Comparison of normalized integrated radiative forcing and TEWI for batch metal cleaning in North America

Algorithm for Computing Potential Warming Impact	Baseline					
	ITH=100 years			ITH=500 years		
	Direct CFC-113	Indirect CO_2	Total	Direct CFC-113	Indirect CO_2	Total
Normalized Integrated Forcing	3775	36	3811	1892	36	1928
TEWI	3822	36	3858	1911	36	1947
% Difference	1.2	0	1.2	1.0	0	1.0
Algorithm for Computing Potential Warming Impact	Substitution					
	ITH=100 years			ITH=500 years		
	Direct HCFC-123	Indirect CO_2	Total	Direct HCFC-123	Indirect CO_2	Total
Normalized Integrated Forcing	77	36.8	114	26	36.8	63
TEWI	77	36.8	114	26	36.8	63
% Difference	~0	0	~0	~0	0	~0

AUTOMOBILE AIR-CONDITIONING

It is assumed that an automobile lasts for eleven years during which time the air-conditioner leaks a certain amount of refrigerant each year. In the twelfth year, the refrigerant charge is recovered before the car is destroyed. The refrigerant in the baseline case is CFC-12 and in the substitution case it is HFC-134a. The annual emission of CO_2 from the energy used to power the air-conditioner is based on the assumption that there are 2.32 kg CO_2/liter of gasoline and the number of liters used to power the air-conditioner depends on the refrigerant. The emissions for the baseline case refrigerant (CFC-12) are: 0.120 kg/year for eleven years and the energy use in this case is 212 kg CO_2/year for eleven years. The emissions for the substitution case refrigerant (HFC-134a) are 0.110 kg/year for eleven years and CO_2 emitted from energy use in this case is 200 kg CO_2/year. See Section 8 in this report for a full description of the derivation of these values. Figure B.3 shows the time evolution of the radiative forcing. Again, the direct effect from the substitution case is uniformly smaller than that from the baseline case.

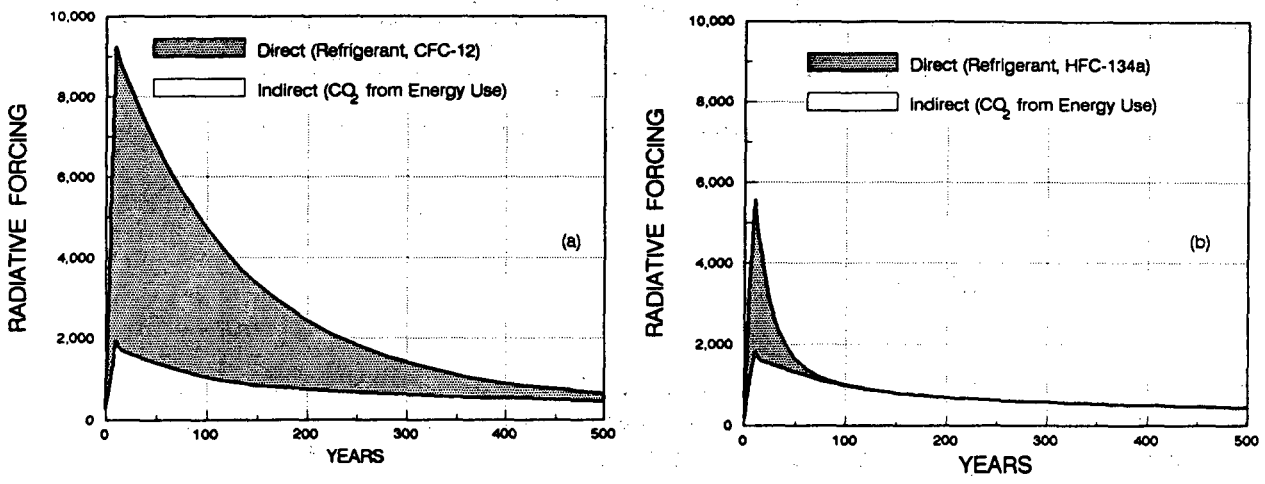

Fig. B.3. Potential radiative forcing from gases associated with automobile air-conditioners: (a) baseline case using CFC-12 and (b) substitution case using HFC-134a.

The normalized integrated forcing and TEWI for each case are computed and shown in Table B.3. With the emission of the refrigerant and CO_2 emissions spread over an eleven year period, the difference between the normalized integrated forcing and TEWI is still within the round-off error for either ITH.

Table B.3. Comparison of normalized integrated radiative forcing and TEWI for North American automobile air-conditioners

Algorithm for Computing Potential Warming Impact	Baseline					
	ITH=100 years			ITH=500 years		
	Direct CFC-12	Indirect CO_2	Total	Direct CFC-12	Indirect CO_2	Total
Normalized Integrated Forcing	9470	2249	11719	6030	2326	8356
TEWI	9636	2321	11957	5940	2321	8261
% Difference	1.7	3.1	2.0	-1.5	-0.2	-1.1
Algorithm for Computing Potential Warming Impact	**Substitution**					
	ITH=100 years			ITH=500 years		
	Direct HFC-134a	Indirect CO_2	Total	Direct HFC-134a	Indirect CO_2	Total
Normalized Integrated Forcing	1477	2131	3609	500	2205	2705
TEWI	1452	2200	3652	508	2200	2708
% Difference	-1.7	3.1	1.2	1.7	-0.2	0.1

REFRIGERATOR/FREEZERS

North American refrigerator/freezers last approximately fifteen years and the assumption made in these calculations is that blowing agent is released when the appliance is destroyed in the sixteenth year. The amount of energy consumed depends on the fluorocarbons used and 0.67 kg of CO_2 are emitted in power generation for each kilowatt-hour of electricity consumed by the appliance. The emissions for the baseline foam blowing agent (CFC-11) are 1.06 kg in the 16th year. The emission of the baseline refrigerant (CFC-12) is 0.17 kg in the sixteenth year. The CO_2 emitted from the energy use in this case is 617 kg/year for fifteen years. The emissions for the substitution blowing agent (HCFC-123) are 1.33 kg in the sixteenth year. The refrigerant (HFC-134a) emission is 0.155 kg in the sixteenth year. The CO_2 emitted from energy use in this case is 614 kg/year for fifteen years.

Figure B.4 illustrates the time evolution of the radiative forcing.

Table B.4 shows the comparison between the calculated integrated radiative forcing and TEWI. Again, the answers obtained using either method of computation agree to within the round-off error except for CFC-12. With a lifetime of 130 years, there is a significant difference between the two methods when ITH=100 years is assumed.

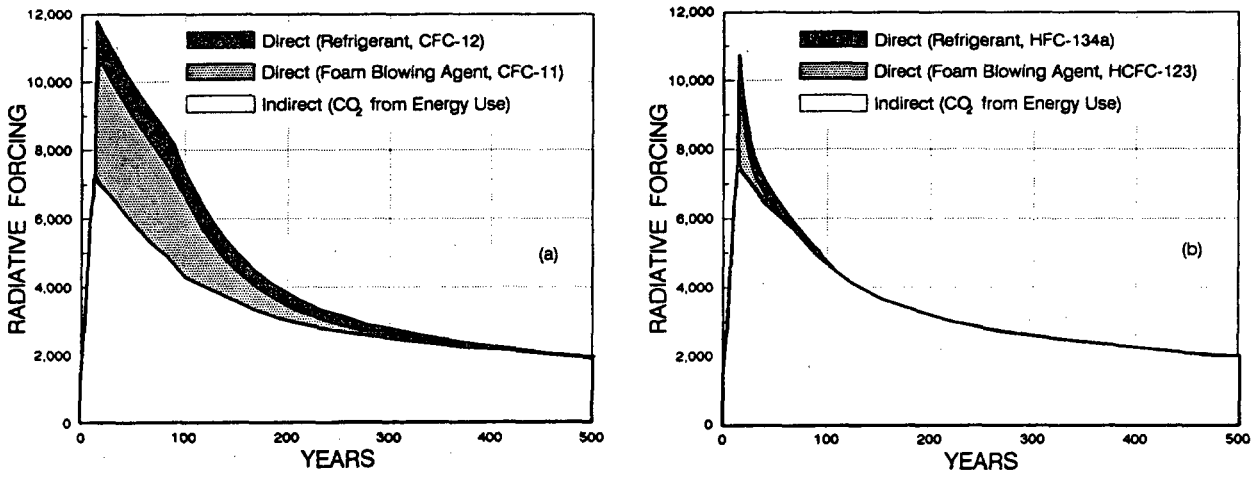

Fig. B.4. Potential radiative forcing from gases associated with refrigerator/freezers: (a) baseline case using CFC-11 blown foam insulation and CFC-12 refrigerant and (b) substitution case using HCFC-123 blown foam and HFC-134a refrigerant.

Table B.4. Comparison of normalized integrated radiative forcing and TEWI for North American refrigerator/freezers

Algorithm for Computing Potential Warming Impact	Baseline							
	ITH=100 years				ITH=500 years			
	Direct CFC-11	Direct CFC-12	Indirect CO_2	Total	Direct CFC-11	Direct CFC-12	Indirect CO_2	Total
Normalized Integrated Forcing	3542	1129	8780	13451	1578	775	9166	11519
TEWI	3710	1241	9254	14205	1590	765	9254	11609
% Difference	4.7	9.0	5.4	5.6	0.8	-1.3	1.0	1.0
Algorithm for Computing Potential Warming Impact	Substitution							
	ITH=100 years				ITH=500 years			
	Direct HCFC-123	Direct HFC-134a	Indirect CO_2	Total	Direct HCFC-123	Direct HFC-134a	Indirect CO_2	Total
Normalized Integrated Forcing	113	188	9194	94995	38	64	9598	9700
TEWI	113	185	9690	9988	39	65	9690	9794
% Difference	0	-1.6	5.4	5.2	1.4	1.6	1.0	1.0

RESIDENTIAL BUILDING INSULATION

The representative house considered is a single-family, detached home in Chicago. There are two different baseline cases that must be addressed: one uses CFC-11 blown polyisocyanurate as the insulation (assumed to be 21 mm thick) and the other uses CFC-12 blown extruded polystyrene (assumed thickness of 37 mm). In either case, it is assumed that the buildings will last fifty years. The total mass of CFC-11 used in the foam is 13.5 kg, all of which is emitted in the manufacturing process. The annual CO_2 from the energy used for heating (supplied by natural gas) is 548 kg for the CFC-11 case and 547 kg for the CFC-12 case. There are two ways to replace the insulation in the baseline cases. One way is to keep the thickness of the insulation the same as the baseline case. When this occurs, the heating load usually increases as the foams blown with alternative fluorocarbons have higher thermal conductivities. The other way is to increase the thickness of the insulation so the heating load is the same as the baseline case. In this report, the first method is employed and, as with the previous applications, there is a tradeoff between energy efficiency and fluorocarbon use. The substitute for CFC-11 is taken to be HCFC-123 which has a total mass of 16.8 kg (0.336 kg/year are emitted). The associated CO_2 emissions from the new energy use are 578 kg/year. The blowing agent to replace CFC-12 is HFC-134a, which would have a total mass of 11.2 kg and assumed to be released in the first year. The annual CO_2 emitted would remain at 547 kg/year (no change in energy efficiency). See Section 10 of the report for a complete description of the analysis used to derive these values.

The graphs in Figs. B.5 and B.6 indicate the time evolution of the radiative forcing from the emitted gases.

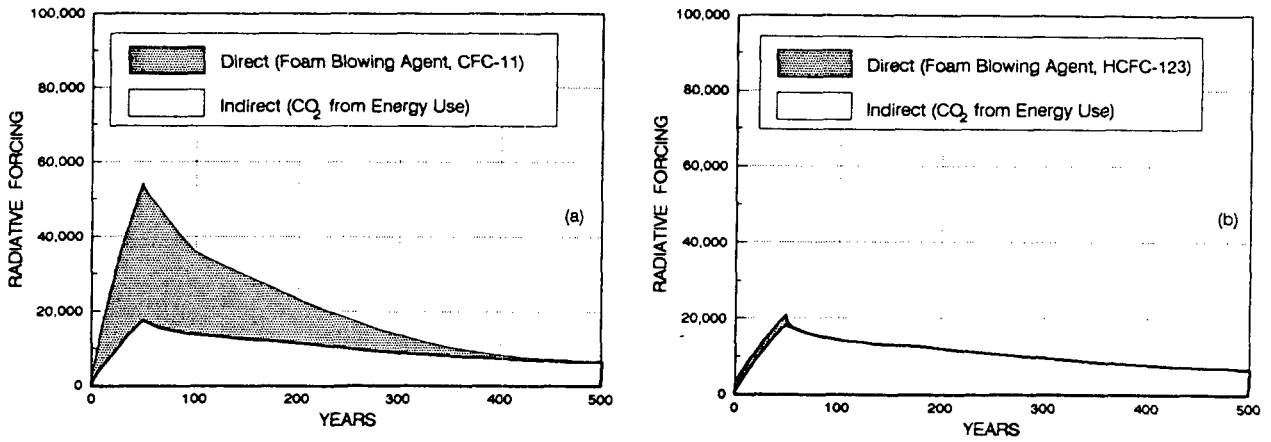

Fig. B.5. Potential radiative forcing from gases associated with polyisocyanurate, polyurethane, and alternative materials in residential building insulation: (a) baseline case using CFC-11 and (b) substitution case using HCFC-123.

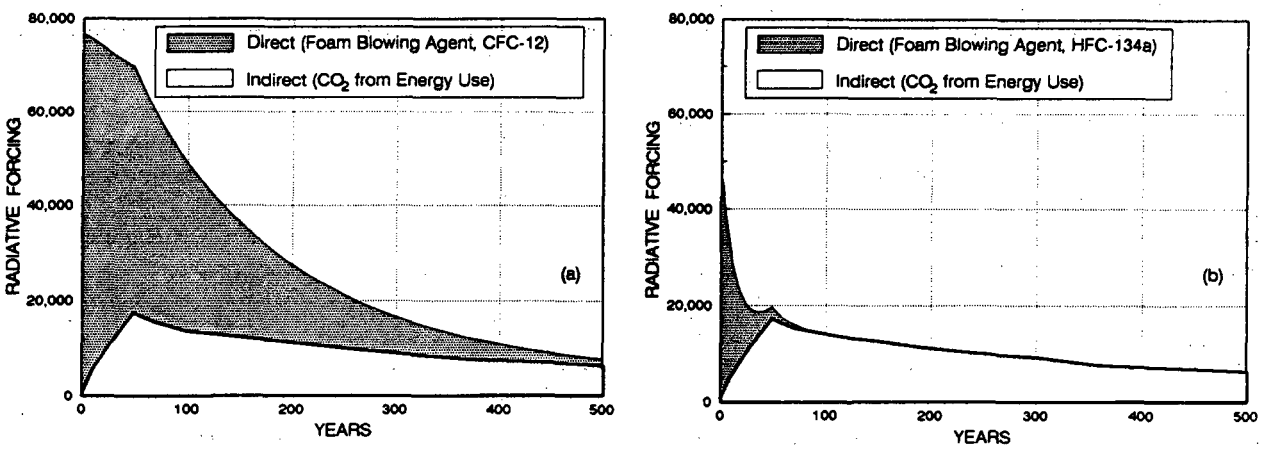

Fig. B.6. Potential radiative forcing from gases associated with extruded polystyrene insulation and alternative materials in residential building insulation: (a) baseline case using CFC-12 and (b) substitution case using HFC-134a.

Tables B.5 and B.6 show the results of the building insulation applications using the two methods. In these examples where the emissions last fifty years, the difference between TEWI and the normalized integrated forcing method is 15% to 23% for ITH=100 years. The difference between the two methods is within the expected round-off error for ITH=500 years.

Table B.5. Comparison of normalized integrated radiative forcing and TEWI for a representative house in Chicago with polyisocyanurate insulation in North America

Algorithm for Computing Potential Warming Impact	Baseline					
	ITH=100 years			ITH=500 years		
	Direct CFC-11	Indirect CO_2	Total	Direct CFC-11	Indirect CO_2	Total
Normalized Integrated Forcing	42137	22103	64240	20091	26545	46636
TEWI	47250	27400	74650	20250	27400	47650
% Difference	12.1	24.0	16.2	0.8	3.2	2.2
Algorithm for Computing Potential Warming Impact	Substitution					
	ITH=100 years			ITH=500 years		
	Direct HCFC-123	Indirect CO_2	Total	Direct HCFC-123	Indirect CO_2	Total
Normalized Integrated Forcing	1424	23314	24738	480	27988	28478
TEWI	1428	28900	30328	487	28900	29387
% Difference	0.2	24.0	22.6	1.5	3.2	3.2

Table B.6. Comparison of normalized integrated radiative forcing and TEWI for a representative house in Chicago with extruded polystyrene insulation

Algorithm for Computing Potential Warming Impact	Baseline					
	ITH=100 years			ITH=500 years		
	Direct CFC-12	Indirect CO_2	Total	Direct CFC-12	Indirect CO_2	Total
Normalized Integrated Forcing	98054	22064	120118	60351	26496	86847
TEWI	96360	27350	123710	59400	27350	86750
% Difference	-1.7	24.0	3.0	-1.6	3.2	-0.1
Algorithm for Computing Potential Warming Impact	**Substitution**					
	ITH=100 years			ITH=500 years		
	Direct HFC-134a	Indirect CO_2	Total	Direct HFC-134a	Indirect CO_2	Total
Normalized Integrated Forcing	13679	22064	35743	4626	26496	31122
TEWI	13440	27350	40790	4704	27350	32054
% Difference	-1.7	24.0	14.1	1.7	3.2	3.0

USE OF TEWI IN DETERMINING REDUCTION IN RADIATIVE FORCING

Part of the purpose of this study is to determine the relative merits of alternative systems that employ CFC substitutes using the criteria of reduction in total greenhouse warming. The methodology developed suggests that the quantity TEWI is closely related to the integrated radiative forcing and can be used as an indicator for the expected warming. However, the derived values of TEWI depend on the integration time horizon used in evaluting the GWPs.

Two quantitutes are discussed in the executive summary of this report. The first of these is the TEWI of the alternative system expressed as a percentage of the TEWI of the bsaeline system (see Figs. 1.7 in the Executive Summary). The TEWI values computed using GWP(100) and GWP(500) are summarized in Table B.8.

While the overall conclusion that employing a substitute will lead to a reduction in warming is not changed, the percent reductions in TEWI calculated using different integration time horizons could be different for applications where the indirect effect from CO_2 is large. In the example for refrigerator/freezers, the TEWI for the system using substitutes are 72% of the baseline system if the 100 year integration time horizon is used and 86% if 500 years is used.

Table B.8. Comparison of reduction in total greenhouse forcing using TEWI with ITH=100 years versus TEWI with ITH=500 years

Application	ITH=100 years			ITH=500 years		
	Baseline CFC	HFC/HCFC alternative	TEWI relative to baseline	Baseline CFC	HFC/HCFC alternative	TEWI relative to baseline
Electronic Cleaning	2123	45	2.1%	1063	17	1.6%
Metal Cleaning	3858	114	3.0%	1947	63	3.2%
Automobile Air-Conditioning	27,020	6259	23%	17,500	3685	21%
Refrigerator/Freezer	13,820	9965	72%	11,444	9786	86%
Domestic Insulation (polyisocyanurate)	74,650	30,328	41%	47,650	29,387	62%
Domestic Insulation (extruded polystyrene)	123,710	40,790	33%	86,750	32,054	37%

The second quantity discussed is the break down between the direct and indirect effects in each system (see Fig. 1.9 in the Executive Summary). In Table B.9, the contribution from the direct effect expressed as a percentage of TEWI are given for GWP(100) and GWP(500). Note that there are significant differences between the values obtained for ITH=100 years and ITH=500 years. This is a reflection of the fact that with ITH=100 years, the warming effects from the long-lived CFCs and CO_2 are not captured.

Table B.9. The direct effect expressed as a percentage of TEWI for different applications

Application	ITH=100 years		ITH=500 years	
	Direct Effect Expressed as a Percentage of Total GWP(100)		Direct Effect Expressed as a Percentage of Total GWP(500)	
	Baseline CFC	HFC/HCFC Alternative	Baseline CFC	HFC/HCFC Alternative
Electronic Cleaning	> 99%	> 99%	96%	90%
Metal Cleaning	99%	68%	98%	42%
Automobile Air-Conditioning	92%	63%	87%	38%
Refrigerator/Freezers	33%	3%	19%	1%
Domestic Insulation (polyisocyanurate)	63%	5%	42%	2%
Domestic Insulation (extruded polystyrene)	78%	33%	68%	15%

DISCUSSION

The purpose of the system study is to judge the relative merits of the total effects (both direct and indirect) from applications that employ CFCs or their substitutes. In replacing the CFC by a substitute that has a shorter lifetime and comparable radiative forcing, the direct effect is always smaller independent of the choice of the integration time horizon. However, to capture the impact of the indirect effect appropriately, it is necessary to use the 500 year integration time horizon. Specific examples are used to demonstrate that the TEWI provides a good representation of the warming commitment in most applications. Differences between the normalized integrated forcing and TEWI are due to the fact that the gases are not all emitted in the first year, but are emitted over an extended period of time. This difference is small if the emissions of the gases occur in a period that is short compared to the integration time horizon. For the applications considered here, there is no significant difference if an integration time horizon if 500 years is adopted.

REFERENCES

ADL, 1991. *Comparison of Global Warming Implications of Cleaning Technologies Using a Systems Approach.*

APPENDIX C: REFRIGERATOR / FREEZER SUPPORTING DATA

Table C.1. Assumptions for alternative appliance insulating materials

Foam Blowing Agent	K-Factor (W/m·K)			Weight % Blowing Agent			Mass of Foam Insulation (kg)		
	North America	Europe	Japan	North America	Europe	Japan	North America	Europe	Japan
CFC-11									
Sole Blowing Agent	0.017	0.018	0.016	15.8%	12%	15.8%	6.75	3.36	4.26
Reduced CFC-11	N/A	0.020	0.017	N/A	6%	11%	N/A	3.36	4.26
Microcell CFC-11	N/A	N/A	0.016	N/A	N/A	15.8%	N/A	N/A	4.26
HCFC-123	0.017	0.018	0.017	19.8%	15%	19.8%	6.75	3.36	4.26
HCFC-141b	0.017	0.018	0.017	11.8%	9.6%	11.8%	6.75	3.36	4.26
Perfluoroalkanes									
Sole	0.018	0.018	0.018	6%	6%	6%	6.75	3.36	4.26
Surfactant	0.018	0.018	0.018	½ to 2%	½ to 2%	½ to 2%	6.75	3.36	4.26
Isoprolylchloride	0.020	0.020	0.020	8%	8%	8%	6.75	3.36	4.26
100% CO_2									
Fresh	0.022	0.022	0.022	15.8%	12%	5.8%	6.75	3.36	4.26
Fully Aged	0.033	0.033	0.033	15.8%	12%	15.8%	6.75	3.36	4.26

Table C.2. Direct equivalent warming potentials of alternative insulating materials

Foam Blowing Agent	Global Warming Potential (kg CO_2/kg)	Mass of Blowing Agent (kg)			Direct Equivalent Warming Potential (kg CO_2)		
		North America	Europe	Japan	North America	Europe	Japan
500 Year GWP Data							
CFC-11	1500	1.06	0.403	0.673	1590	605	1010
Sole Blowing Agent	1500	N/A	0.202	0.471	N/A	302	707
Reduced CFC-11	1500	N/A	N/A	0.673	N/A	N/A	1010
Microcell CFC-11	29	1.33	0.503	0.841	39	15	24
HCFC-123	150	0.905	0.342	0.572	136	51	86
HCFC-141b							
Perfluoroalkanes	7400[1]	0.404	0.201	0.256	2990	1487	1894
Sole Blowing Agent	7400[1]	0.034 - 0.135	0.017 - 0.067	0.021 - 0.085	252 - 999	126 - 496	155 - 629
Surfactant	15[2]		0.269	0.341	8	4	5
Isopropylchloride		0.539					
CO_2	1		0.403	0.673	1	0	1
Fresh	1	1.06	0.403	0.673	1	0	1
Fully Aged		1.06					

[1] estimated to be comparable to CFC-115 (Kuijpers, 1990)
[2] estimated at 1% of CFC-11 (Creyf, 1991)

Table C.3. Assumptions for alternative refrigerants

Refrigerant	Global Warming Potential (kg CO_2/kg)	Mass of Refrigerant (kg)			Direct Equivalent Warming Potential (kg CO_2)		
		North America	Europe	Japan	North America	Europe	Japan
500 Year GWP Data							
CFC-12	4500	0.170	0.140	0.137	765	630	617
HFC-134a	420	0.155	0.127	0.125	65	53	53
HCFC-22/HFC-152a/HCFC-124[1]	255	0.146	0.120	0.118	37	30	30
HFC-152a	47	0.114	0.094	0.092	5	4	4
HCFC-22/HCFC-142b[2]	527	0.155	0.127	0.125	82	66	66
Stirling Cycle[3]	0	N/A	N/A	N/A	0	0	0
Absorption Cycle[4]	0	N/A	N/A	N/A	0	0	0

[1] 36% HCFC-22, 24% HFC-152a, 40% HCFC-124 (AHAM, 1991)
[2] 45% HCFC-22, 55% HCFC-142b
[3] uses helium as the working fluid
[4] uses ammonia-water as the working fluid

Table C.4. Basis for relative refrigerating efficiency and calculated annual energy use

Refrigerant	Relative Energy Use	Annual Energy Use* (kWh/year)		
		North America	Europe	Japan
CFC-12	1.0	918	503	601
HFC-134a	-½% to +6.9%	914 - 968	500 - 537	599 - 641
HCFC-22/HFC-152a/HCFC-124	-½% to +5.8%	914 - 960	500 - 531	599 - 635
HFC-152a	-4% to +2.7%	889 - 939	485 - 515	580 - 616
HCFC-22/HCFC-142b	-4% to 2½%	889 - 936	485 - 515	580 - 615
Stirling Cycle Cycle	0.85 to 1.33	812 - 1153	536 - 767	476 - 707
	2.5 to 3.0	2295 - 2754**	1258 - 1509**	1502 - 1803**

* data derived from laboratory measurements and differences of less than 10 kwh/year are within the range of experimental error and are not significant

** energy-use data for absorption systems are in kWh of natural gas instead of kWh of electricity

Table C.5. Data for European refrigerator/freezers

Insulation Blowing Agent	Direct Equivalent CO_2 (kg)	Refrigerant	Direct Equivalent CO_2 (kg)	Direct Equivalent Warming Potential		Indirect Warming Potential		Total Equivalent Warming Potential	
				(kg)	(%)	(kg)	(%)	(kg)	Uncertainty (kg)
CFC-11 (sole blowing agent)	605	CFC-12	630	1235	25%	3732	75%	4967	0
		HFC-134a	53	658	15%	3717	85%	4374	269
		Ternary Blend	30	635	15%	3717	85%	4351	223
		HFC-152a	4	609	14%	3601	86%	4210	223
		HCFC-22/HCFC-142b	66	671	16%	3601	84%	4272	223
CFC-11 (partially water blown foam)	302	CFC-12	630	932	19%	3871	81%	4803	0
		HFC-134a	53	355	8%	3848	92%	4203	285
		Ternary Blend	30	332	8%	3848	92%	4180	239
		HFC-152a	4	306	8%	3732	92%	4038	231
		HCFC-22/HCFC-142b	66	368	9%	3732	91%	4100	231
HCFC-123	15	CFC-12	630	645	15%	3732	85%	4377	0
		HFC-134a	53	68	2%	3717	98%	3785	269
		Ternary Blend	30	45	1%	3717	99%	3762	223
		HFC-152a	4	19	1%	3601	99%	3620	223
		HCFC-22/HCFC-142b	66	81	2%	3601	98%	3682	223
HCFC-141b	51	CFC-12	630	681	15%	3732	85%	4413	0
		HFC-134a	53	104	3%	3717	97%	3821	269
		Ternary Blend	30	81	2%	3717	98%	3798	223
		HFC-152a	4	55	2%	3601	98%	3656	223
		HCFC-22/HCFC-142b	66	117	3%	3601	97%	3718	223
Perfluoroalkanes (sole blowing agent)	1487	CFC-12	630	2117	36%	3732	64%	5849	0
		HFC-134a	53	1540	29%	3717	71%	5257	269
		Ternary Blend	30	1517	29%	3717	71%	5234	223
		HFC-152a	4	1491	29%	3601	71%	5093	223
		HCFC-22/HCFC-142b	66	1553	30%	3601	70%	5155	223
Perfluoroalkanes (surfactants)	126 to 496	CFC-12	630	756	17%	3732	83%	4488	370
		HFC-134a	53	179	5%	3717	95%	3895	639
		Ternary Blend	30	156	4%	3717	96%	3872	593
		HFC-152a	4	130	3%	3601	97%	3731	593
		HCFC-22/HCFC-142b	66	192	5%	3601	95%	3793	593
Isopropylchloride	4	CFC-12	630	634	14%	4001	86%	4635	0
		HFC-134a	53	57	1%	3986	99%	4043	292
		Ternary Blend	30	34	1%	3986	99%	4020	246
		HFC-152a	4	8	0%	3863	100%	3871	246
		HCFC-22/HCFC-142b	66	70	2%	3863	98%	3933	239
100% Carbon Dioxide	0	CFC-12	630	630	29%	4270	71%	4900	1494
		HFC-134a	53	53	1%	4255	99%	4309	1908
		Ternary Blend	30	30	1%	4255	99%	4286	1839
		HFC-152a	4	4	0%	4125	100%	4129	1839
		HCFC-22/HCFC-142b	66	66	2%	4125	98%	4191	1778

Table C.6. Data for North American refrigerator/freezers

Insulation Blowing Agent	Direct Equivalent CO_2 (kg)	Refrigerant	Direct Equivalent CO_2 (kg)	Direct Equivalent Warming Potentia		Indirect Warming Potential		Total Equivalent Warming Potential	
				(kg)	(%)	(kg)	(%)	(kg)	Uncertainty (kg)
CFC-11 (sole blowing agent)	1590	CFC-12	765	2,355	20%	9,240	80%	11,595	0
		HFC-134a	65	1,655	15%	9,199	85%	10,855	544
		Ternary Blend	37	1,627	15%	9,199	85%	10,827	463
		HFC-152a	5	1,595	15%	8,948	85%	10,543	503
		HCFC-22/HCFC-142b	82	1,672	16%	8,948	84%	10,619	473
HCFC-123	39	CFC-12	765	804	8%	9,240	92%	10,043	0
		HFC-134a	65	104	1%	9,199	99%	9,303	544
		Ternary Blend	37	76	1%	9,199	99%	9,275	463
		HFC-152a	5	44	0%	8,948	100%	8,992	503
		HCFC-22/HCFC-142b	82	120	1%	8,948	99%	9,068	473
HCFC-141b	136	CFC-12	765	901	9%	9,240	91%	10,140	0
		HFC-134a	65	201	2%	9,199	98%	9,400	544
		Ternary Blend	37	173	2%	9,199	98%	9,372	463
		HFC-152a	5	141	2%	8,948	98%	9,089	503
		HCFC-22/HCFC-142b	82	217	2%	8,948	98%	9,165	473
Perfluoroalkanes (sole blowing agent)	2990	CFC-12	765	3,755	28%	9,713	72%	13,467	0
		HFC-134a	65	3,055	24%	9,672	76%	12,727	614
		Ternary Blend	37	3,027	24%	9,672	76%	12,699	513
		HFC-152a	5	2,995	24%	9,421	76%	12,416	513
		HCFC-22/HCFC-142b	82	3,071	25%	9,421	75%	12,492	493
Perfluoroalkanes (surfactants)	252 to 999	CFC-12	765	1,017	9%	9,713	91%	10,729	748
		HFC-134a	65	317	3%	9,672	97%	9,989	1,362
		Ternary Blend	37	289	3%	9,672	97%	9,961	1,261
		HFC-152a	5	257	3%	9,421	97%	9,678	1,261
		HCFC-22/HCFC-142b	82	333	3%	9,421	97%	9,754	1,241
Isopropylchloride	539	CFC-12	765	773	7%	10,739	93%	11,512	0
		HFC-134a	65	73	1%	10,699	99%	10,772	694
		Ternary Blend	37	45	0%	10,699	100%	10,744	584
		HFC-152a	5	13	0%	10,407	100%	10,421	594
		HCFC-22/HCFC-142b	82	90	1%	10,407	99%	10,497	564
100% Carbon Dioxide	1	CFC-12	765	766	6%	11,877	94%	12,643	8,203
		HFC-134a	65	66	1%	11,836	99%	11,903	9,582
		Ternary Blend	37	38	0%	11,836	100%	11,875	9,350
		HFC-152a	5	6	0%	11,504	100%	11,511	9,099
		HCFC-22/HCFC-142b	82	83	1%	11,504	99%	11,587	9,038

Table C.7 Data for Japanese refrigerator/freezers

Insulation Blowing Agent	Direct Equivalent CO_2 (kg)	Refrigerant	Direct Equivalent CO_2 (kg)	Direct Equivalent Warming Potential		Indirect Warming Potential		Total Equivalent Warming Potential	
				(kg)	(%)	(kg)	(%)	(kg)	Uncertainty (kg)
CFC-11 (sole blowing agent)	1010	CFC-12	617	1626	24%	5238	76%	6864	0
		HFC-134a	53	1062	17%	5220	83%	6282	366
		Ternary Blend	30	1040	17%	5220	83%	6260	314
		HFC-152a	4	1014	17%	5055	83%	6069	314
		HCFC-22/HCFC-142b	66	1075	18%	5055	82%	6130	305
CFC-11 (partially water blown foam)	707	CFC-12	617	1323	20%	5360	80%	6683	0
		HFC-134a	53	759	12%	5342	88%	6101	383
		Ternary Blend	30	737	12%	5342	88%	6079	322
		HFC-152a	4	711	12%	5177	88%	5888	322
		HCFC-22/HCFC-142b	66	772	13%	5177	87%	5949	314
HCFC-123	24	CFC-12	617	641	11%	5360	89%	6001	0
		HFC-134a	53	77	1%	5342	99%	5419	383
		Ternary Blend	30	54	1%	5342	99%	5397	322
		HFC-152a	4	29	1%	5177	99%	5205	322
		HCFC-22/HCFC-142b	66	90	2%	5177	98%	5267	314
HCFC-141b	86	CFC-12	617	702	11%	5482	89%	6184	0
		HFC-134a	53	138	2%	5464	98%	5603	392
		Ternary Blend	30	116	2%	5464	98%	5580	322
		HFC-152a	4	90	2%	5290	98%	5380	331
		HCFC-22/HCFC-142b	66	152	3%	5290	97%	5442	322
Perfluoroalkanes (sole blowing agent)	1887	CFC-12	617	2504	31%	5482	69%	7985	0
		HFC-134a	53	1940	26%	5464	74%	7404	392
		Ternary Blend	30	1917	26%	5464	74%	7381	322
		HFC-152a	4	1891	26%	5290	74%	7181	331
		HCFC-22/HCFC-142b	66	1953	27%	5290	73%	7243	322
Perfluoroalkanes (surfactants)	155 to 629	CFC-12	617	772	12%	5482	88%	6254	474
		HFC-134a	53	208	4%	5464	96%	5672	866
		Ternary Blend	30	185	3%	5464	97%	5650	796
		HFC-152a	4	160	3%	5290	97%	5450	805
		HCFC-22/HCFC-142b	66	221	4%	5290	96%	5511	796
Isopropylchloride	5	CFC-12	617	622	10%	5726	90%	6347	0
		HFC-134a	53	58	1%	5708	99%	5766	410
		Ternary Blend	30	35	1%	5708	99%	5744	340
		HFC-152a	4	9	0%	5525	100%	5535	349
		HCFC-22/HCFC-142b	66	71	1%	5525	99%	5596	340
100% Carbon Dioxide	1	CFC-12	617	618	9%	5978	91%	6597	1351
		HFC-134a	53	54	1%	5944	99%	5998	1891
		Ternary Blend	30	31	1%	5944	99%	5974	1804
		HFC-152a	4	5	0%	5769	100%	5774	1752
		HCFC-22/HCFC-142b	66	66	1%	5769	99%	5837	1734

APPENDIX D: COMMERCIAL REFRIGERATION

Table D.1. Lifetime equivalent CO_2 emissions for North American supermarket refrigeration system

Supermarket Refrigeration System	Refrigerant Data		Direct CO_2 Emissions	Energy Use		Indirect CO_2 Emissions		TEWI
	Initial Charge (kg)	Usage Rate (kg/yr)	(10^3 kg)	Annual (10^3 kWh/yr)	Lifetime (10^3 kWh)	Annual (10^3 kg/yr)	Lifetime (10^3 kg)	(10^3 kg)
Baseline CFC-12 & R-502 Systems								
R-502 Freezers	398	133	10,700	223	4,500	150	3000	13,700
CFC-12 Meats & Dairy	560	187	16,800	316	6,300	212	4200	21,000
CFC-12 Produce & Prep Rooms	560	187	16,800	80	1,600	54	1100	17,900
Total	1518	507	44,300	619	12,400	416	8300	52,600
Conversion of High & Meats & Dairy Systems to HCFC-22								
R-502 Freezers	398	133	10,700	223	4,500	150	3000	13,700
HFC-134a Meats & Dairy	517	172	1,450	328	6,600	220	4400	5,850
HFC-134a Produce & Prep Rooms	516	172	1,450	83	1,700	56	1100	2,550
Total	1431	477	13,600	618	12,800	415	8500	22,100
Baseline R-502 System								
R-502 Freezers	398	133	10,700	223	4,500	150	3000	13,700
HCFC-22 Meats & Dairy	511	170	1,750	304	6,100	205	4100	5,850
HCFC-22 Produce & Prep Rooms	511	170	1,750	75	1,500	50	1000	2,750
Total	1420	473	14,200	602	12,100	405	8100	22,300
Conversion to HCFC-22								
HCFC-22 Freezers	390	130	1300	223	4,500	150	3000	4,300
HCFC-22 Meats & Dairy	511	170	1750	304	6,100	205	4100	5,850
HCFC-22 Produce & Prep Rooms	511	170	1750	75	1,500	50	1000	2,750
Total	1412	470	4800	602	12,100	405	8100	12,900
10% Leakage Rate								
HCFC-22 Freezers	390	39	400	223	4,500	150	3000	3400
HCFC-22 Meats & Dairy	511	51	520	304	6,100	205	4100	4620
HCFC-22 Produce & Prep Rooms	511	51	520	75	1,500	50	1000	1520
Total	1412	141	1440	602	12,100	405	8100	9540
20% Low Temp. Efficiency Improvement								
HCFC-22 Freezers	390	39	400	178	3,600	120	2400	2800
HCFC-22 Meats & Dairy	511	51	520	304	6,100	205	4100	4620
HCFC-22 Produce & Prep Rooms	511	51	520	75	1,500	50	1000	1520
Total	1412	141	1440	557	11,200	375	7500	8940

APPENDIX E: COMMERCIAL CHILLERS

TABULATED DATA AND SOURCES OF INFORMATION

Table E.1. Refrigerant charge by chiller category, chiller type, and refrigerant (kg/RT)

Chiller Category	Chiller	Refrigerant	Table Reference	Reference Inventory (kg/RT)
100-RT air-cooled	80 RT screw	HCFC-22	1.	1.55
	5-400 RT recip	HCFC-22	2.	0.7
	20-200 RT screw	HCFC-22	2.	0.7
	20 RT average recip/screw/scroll	HCFC-22	4.	1.3
300-RT water-cooled	300 RT centrifugal	CFC-11	1.	1.0
	300 RT centrifugal	HCFC-123	1.	1.0
	300 RT screw	HCFC-22	1.	1.5
	5-250 RT reciprocating	HCFC-22	2.	0.9
	40-600 RT screw	HCFC-22	2.	0.9-1.4
	150-500 RT centrif	CFC-11	2.	0.7
	150-500 RT centrifugal	HCFC-123	2.	0.7
	100-200 RT centrifugal	CFC-11	3.	1.7 average
	201-300 RT centrifugal	CFC-11	3.	1.2 average
	301-400 RT centrifugal	CFC-11	3.	1.3 average
	401-500 RT centrifugal	CFC-11	3.	1.0 average
	100-200 RT centrifugal	CFC-113	3.	1.4 average
	300 RT centrifugal	CFC-11	4.	1.0 average
1000 & 3000-RT water-cooled	1000 RT centrifugal	CFC-11	1.	1.0
	1000 RT centrifugal	HCFC-123	1.	1.0
	500-1200 RT centrifugal	CFC-11	2.	0.7
	500-1000 RT centrifugal	HCFC-123	2.	0.7
	501-750 RT centrifugal	CFC-11	3.	0.8 average
	1000 RT centrifugal	CFC-12	3.	2.1

Table references:

1. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 8, 1991.

2. Letter from William Kopko of the U.S. Environmental Protection Agency to P.D. Fairchild of Oak Ridge National Laboratory, March 1, 1991.

3. Radian Corporation, "Final Report--Survey of the Use and Emission of Chlorofluorocarbons From Large Chillers", for ASHRAE Halocarbon Emission Task Group, DCN#89-259-064-02, February 1990.

4. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 25, 1991.

Table E.2. Common-basis refrigerant charge by chiller category, refrigerant, and relative cost (kg/RT)

Chiller Category	Refrigerant	Refrigerant charge at relative cost*		
		Base = 1.0	Level A	Level B
100 RT air-cooled	HCFC-22	0.74	0.85	1.04
	HFC-134a	0.72	0.91	1.10
300 RT water-cooled	CFC-11	0.91	1.02	1.48
	CFC-12	1.24	1.31	1.57
	HCFC-22	0.6-1.2	0.7-1.3	1.4-2.0
	HCFC-123	0.5-1.1	0.6-1.2	0.9-1.5
	HFC-134a	1.0-1.2	1.1-1.3	1.3-1.6
1000 RT water-cooled	CFC-11	0.6-1.4	0.6-1.5	0.7-1.7
	CFC-12	1.33	1.39	1.49
	HCFC-22	1.4-1.8	1.5-1.9	---
	HCFC-123	1.05	1.10	1.19
	HFC-134a	1.1-1.5	1.2-1.5	1.3-1.6
3000 RT water-cooled	CFC-12	1.0-1.4	1.1-1.5	---
	HCFC-22	0.6-1.5	0.9-1.6	---
	HFC-134a	0.7-1.4	0.8-1.5	---

* Relative cost refers to cost of chiller fabrication (including the initial refrigerant charge) normalized to those of a selected (representative) reference system in each chiller category. The relative cost levels and refrigerant charges indicated are consistent with Tables F.1 and F.2 of Appendix F. Therefore, the charge data are more representative of current and near-term practice than past practice.

Source: Calm, J.M., "Refrigerant Charge in Air-Conditioning Equipment for Selected Refrigerant Alternatives," June 1991, Report JMC/AFEAS-91060.

Table E.3. Refrigerant loss rates by refrigerant type for centrifugal chillers (% of charge lost per year)

Chiller	Table Reference	CFC-11	CFC-12	CFC-113	All
Centrifugal	1.	10.2	7.4	10.8	
	2.	14	2.2	18	13.3
	3.				26.
	4.				37
	5.				12
	6.				17.4
	7.				13.0
	8.				16.7

Table References:

1. Radian Corporation, "Final Report--Survey of the Use and Emission of Chlorofluorocarbons From Large Chillers", for ASHRAE Halocarbon Emission Task Group, DCN#89-259-064-02, February 1990.

2. Miyasaka, A., "Survey on the Use and Emission of Chlorofluorocarbons in Centrifugal Chillers", Prepared for the Japanese Association of Refrigeration and Air-Conditioning Contractors, March 1989.

3. Reference 1 lists this source as Air-Conditioning & Refrigeration Institute, R.J. Denny, 1989.

4. Reference 1 lists this as the most recent estimate of the U.S. Environmental Protection Agency.

5. Hoffman, D.C., "Chiller Refrigerant Emissions", Heating/Piping/Air Conditioning, July 1978.

6. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989.

7. Andrews, C.J., "Designing Strategically For The Possibility Of A Future Without R-22 and R-134a", ASHRAE Technical Data Bulletin: CFC Alternatives, V6, No.1, 1990.

8. Carrier Corp. announcement, Air-Conditioning, Heating & Refrigeration News, January 15, 1990, page 5.

Table E.4. Chiller service life

Table Reference	Life (years)	Comments
1.	27	ARI–centrifugal
1.,2.,3.,4.,5.	34	Trane–derived, centrifugal
6.	18-23	reciprocating
6.	20-25	centrifugal
7.	20	ASHRAE–reciprocating
7.	23	ASHRAE–centrifugal
8.	30	centrifugal

Table References:

1. Radian Corporation, "Final Report--Survey of the Use and Emission of Chlorofluorocarbons From Large Chillers", for ASHRAE Halocarbon Emission Task Group, DCN#89-259-064-02, February 1990.

2. Pietsch, J.A., "Commercial Unitary Heat Pumps: An Assessment Study", Electric Power Research Institute, EPRI CU-6371, May 1989.

3. MacDonald, M. et.al., "RD&D Opportunities for Large Air-Conditioning and Heat Pump Systems", ORNL/Sub/80-13817/1&20, June 1982.

4. "Nonresidential Buildings Energy Consumption Survey: Characteristics of Commercial Buildings 1986", September 13, 1988, U.S. Department of Energy--Energy Information Administration, DOE/EIA-0246(86).

5. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989.

- Methodology: References 1-4 were used to estimate the 34 year life as follows. According to Reference 4, significant commercial use of centrifugal water chillers began in the mid-1930's. According to Reference 1, Trane started shipping Centra-Vac centrifugal chillers in 1938 and 87-88% of chillers placed in service in the U.S. were still in service in 1988. In order to estimate typical chiller life, References 2, 3, and 4 were used to estimate the year after which 88% of the 1988 centrifugal chiller stock was shipped. This approach assumes that Trane chillers and all other centrifugal chillers have similar lives.

  Reference 2 provided U.S. centrifugal chiller shipments in tons for the years 1978-1987. Reference 3 extended the shipments history back to 1970, although the modifiers derived in Reference 2 had to be applied for consistency. By comparing the annual tonnage shipments history to average annual floorspace additions for the periods 1921-45, 1946-60, 1961-70, 1971-73, 1974-79, 1980-83, and 1984-86 derived from Reference 4 the following observations were made. In 1970 chiller shipments exceeded by about 5% the tonnage expected based on additions of cooled floorspace in buildings with 50,000 ft^2 or more, and three floors or more. It was assumed that this floorspace definition was a valid proxy for "potential" new construction centrifugal chiller additions since by 1970 some replacement should have been occurring which could account for the 5%. With the proxy assumption, Reference 4. provided the basis to

estimate chiller shipments up to about 1960, a period when most chillers would go to new construction and chillers would retain most of the estimated market. The period from 1960 to 1970 trended nicely from the 1960-and-prior estimates and the post-1970 data, resulting in a complete estimated shipment history. Based on this shipment history, 88% of centrifugal tonnage was shipped after 1954. The interval from 1954 to 1988 is the basis for the estimated life of 34 years.

As a cross-check the shipment history and 34 year life was used to estimate the fraction of shipments that would be replacements in 1987. The resulting replacement fraction compared well with the 45% of Reference 2 for 1987 and the 42% of Reference 6 during the 1985-88 period. Reference 4 and the proxy for "potential" chiller capacity going to new construction were used to estimate the average annual "potential" for new shipments for the intervals listed previously. Extrapolating the 1984-86 interval to 1987 indicated new construction shipments were only 60% of the potential, down from 100% in 1960. This agrees with a trend identified in References 2 and 6 (i.e., that commercial unitary equipment has significantly eroded traditional packaged chiller markets since 1960).

6. Easton Consultants, Inc., "Replacement Market For Selected Commercial Energy Service Equipment", Gas Research Institute, GRI-89/0204.02, June 1990.

7. The 1987 ASHRAE Handbook of HVAC Systems and Applications, page 49.7.

8. Clark, E.M, et.al., "Retrofitting Existing Chillers With Alternative Refrigerants", ASHRAE Journal, April 1991, page 38.

Table E.5. Impacts of conversion of CFC-11 centrifugal chillers to HCFC-123

Table Reference	kW_e/RT:		Capacity:		Other Comments
	Reported Impact (% change)	Comments	Reported Impact (% change)	Comments	
1.	up 5%	can use same motor	down 10-15%	impeller change may improve	material compatibility problems in hermetic configurations
2.	---	--	up to 18% drop	impeller change may improve	open-drive conversion easiest
3.	---	--	---	---	believes acceptable materials found, can also field-convert hermetic to open. R-123 commercially available in 1992.
4.	up to 5% increase	--	up to 10% drop	---	---
5.	up 8.2% up 9.6%	new chiller new chiller	same same	new chiller new chiller	300 RT, cost up 10% 1000 RT, cost up 10%
6.	up 6-8 %	---	down 0-15%	---	gear and/or motor changes are needed
7.	up 2%	---	---	---	---
8.	up 1.8%	based on cycle thermodynamics, heat transfer not included	about 10% down	based on cycle thermodynamics, heat transfer not included	---
9.	up 2.4%	based on cycle thermo-dynamics, heat transfer not included	down 12.2%	based on cycle thermodynamics, heat transfer not included	---
10.	up to 5% increase	---	up to 18% drop	---	---
11.	up 7-15%	---	down 5-10%	---	---
12.	same	---	same	---	new impeller, 10% cost increase
13.	up 3.9% up 4.9% up 8.6% down 2.9% up 2.0% up 9.0%	new chiller new chiller new chiller new chiller new chiller new chiller	same same same same same same	new chiller new chiller new chiller new chiller new chiller new chiller	300 RT, same cost 300 RT, same cost but higher 300 RT, same cost but higher yet 1000 RT, same cost 1000 RT, same cost but higher 1000 RT, same cost but higher yet
14.	up 0-15%	retrofit	down 0-18%	retrofit	6 chiller retrofits
15.	up 3-5%	retrofit	down 3-20%	retrofit	---

Table References:

1. Radian Corporation, "Final Report--Survey of the Use and Emission of Chlorofluorocarbons From Large Chillers", for ASHRAE Halocarbon Emission Task Group, DCN#89-259-064-02, February 1990. Page E.2 report on teleconference with Michael Hughes of Allied-Signal Corporation.

2. Reference 1, page E.3 report on teleconference with Earl Clarke of DuPont Corporation.

3. Reference 1, page E.6 report on teleconference with Joseph Lechtanski of Carrier Corporation.

4. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989, page 84.

5. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 8, 1991.

6. Industry News Column, ASHRAE Journal, March 1991, page 9.

7. Fischer, S.K. et.al., "Energy-Use Impact of Chlorofluorocarbon Alternatives", Oak Ridge National Laboratory, ORNL/CON-273, February 1989.

8. Hayes, F.C., "Centrifugal Water Chillers", CFCs: Today's Options-Tomorrow's Solutions, Proceedings of ASHRAE's 1989 CFC Technology Conference at NIST in Gaithersburg, MA, September 27-28, 1989. (Mr. Hayes is with Trane Corporation).

9. Sand, J.R., Oak Ridge National Laboratory, preliminary results from EPRI Project RP-2891-14, March 1991.

10. Reitz, K., "CFCs for Water Chillers", Heating/Piping/Air Conditioning Magazine, April 1990.

11. Lorenz, M.R., "CFCs: The Designer's Dilemma", Heating/Piping/Air Conditioning Magazine, April 1990.

12. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 25, 1991.

13. Calm, J. M., "Characteristic Efficiencies and Costs for Air-Conditioning Equipment with Selected Refrigerant Alternatives: ARI Inputs to the AFEAS/ORNL Study of Global Warming Impacts of Refrigerants," April 1991 (rev. 5/28/91), Report JMC/ARI-9104A.

    - Note: percentage changes in kW_e/RT are expressed relative to CFC-11 machines at each cost level. CFC-11 machine kW_e/RT decreases with increased cost so the base performance is not constant. This reference is presented as Appendix F.

14. Clark, E.M, et.al., "Retrofitting Existing Chillers With Alternative Refrigerants", ASHRAE Journal, April 1991, page 38.

    - Note: based on field retrofits of 6 chillers including open and hermetic, single and multi-stage, and old and new designs.

Table E.6. Impacts of conversion of CFC-12 centrifugal chillers to HFC-134a

Table Reference	kW_e/RT:		Capacity:		Other Comments
	Reported Impact (% change)	Comments	Reported Impact (% change)	Comments	
1.	up 5%	---	---	---	requires impeller and/or gear change
2.	"down"	--	"same"	---	actual R-12 chiller retrofit, new gearset
3.	down 4.1%	--	up 0.8%	---	new gearset, lab test as per ARI Std 550 on 100 RT machine
4.	up 1-2%	--	same	---	new gearset
5.	up 2.1%	based on cycle thermodynamics, ht. trans. not incl.	up 20%	based on cycle thermodynamics, heat transfer not included	---
6.	up 1-8 %	based on cycle thermodynamics, ht. trans. not incl.	---	---	field-change not recommended
7.	up 8-10%	---	---	---	---
8.	up 2%	---	---	---	---
9.	up 0.4% same down 2.4% down 0.3% down 1.0% down 1.8%	new chiller new chiller new chiller new chiller new chiller new chiller	same same same same same same	new chiller new chiller new chiller new chiller new chiller new chiller	300 RT, same cost 300 RT, same cost but higher 300 RT, same cost but higher yet 1000 RT, same cost 1000 RT, same cost but higher 1000 RT, same cost but higher yet
10.	same	retrofit	same	retrofit	2 chiller retrofits

Table References:

1. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989, pp. 82 and 84.

2. SnyderGeneral Corp. announcement, Air-Conditioning, Heating & Refrigeration News, p. 6, February 25, 1991.

3. SnyderGeneral Corp. announcement, ASHRAE Journal, p. 6, November 1990.

4. Industry News Column, ASHRAE Journal, p. 9, March 1991.

5. Sand, J.R., Oak Ridge National Laboratory, preliminary results from EPRI Project RP-2891-14, March 1991.

6. Hayes, F.C., "Centrifugal Water Chillers", CFCs: Today's Options-Tomorrow's Solutions, Proceedings of ASHRAE's 1989 CFC Technology Conference at NIST in Gaithersburg, MA, September 27-28, 1989. (Mr. Hayes is with Trane Corporation).

7. Braswell, A., "CFCs: The Industry's Stand", Heating/Piping/Air Conditioning Magazine, April 1989.

8. Fischer, S.K. et.al., "Energy-Use Impact of Chlorofluorocarbon Alternatives", Oak Ridge National Laboratory, ORNL/CON-273, February 1989.

9. Calm, J. M., "Characteristic Efficiencies and Costs for Air-Conditioning Equipment with Selected Refrigerant Alternatives: ARI Inputs to the AFEAS/ORNL Study of Global Warming Impacts of Refrigerants," April 1991 (rev. 5/28/91), Report JMC/ARI-9104A.

   - Note: percentage changes in kW_e/RT are expressed relative to CFC-12 machines at each cost level. CFC-12 machine kW_e/RT decreases with increased cost so the base performance is not constant. This reference is presented as Appendix F.

10. Clark, E.M, et.al., "Retrofitting Existing Chillers With Alternative Refrigerants", ASHRAE Journal, April 1991, p. 38.

   - Note: based on field retrofits of 2 open drive chillers, one single and one multi-stage.

Table E.7. Chiller annual load factors in applications

Table Reference	Load Factor	Comments
1.	0.30	---
2., 3.	0.20–0.25	average of 35 chiller applications, correction factor based on four monitored buildings in Chicago
4., 5.	0.17	based on DOE-2.1 simulations and DOE/EIA-NBECS

Table References:

1. Fischer, S.K. et.al., "Energy-Use Impact of Chlorofluorocarbon Alternatives", Oak Ridge National Laboratory, ORNL/CON-273, February 1989.

2. Radian Corporation, "Final Report--Survey of the Use and Emission of Chlorofluorocarbons From Large Chillers", for ASHRAE Halocarbon Emission Task Group, DCN#89-259-064-02, February 1990.

3. Technical Marketing Associates, Inc., "Applications Assessment for Gas Engine-Driven Chillers", Gas Research Institute, GRI-86/0246, November 1986.

   - In Reference 2, operating hours were reported with no information on load duration at various capacity throttling ranges. A load factor of 0.38 is calculated if one assumes that all hours were with the chiller at full capacity. This represents a very unlikely upper limit for the desired value defined as the refrigeration ton-hours of cooling delivered annually divided by the installed chiller capacity times 8760. Reference 3 provided information derived from four instrumented buildings in Chicago (hospital, office, department store, library) that indicated that the desired load factor is 52-65% of the value estimated by assuming that all operating hours are at full capacity. The range stated is derived by applying these percentages to 0.38.

4. Patel, R.F., "Assessment of Large Tonnage, Gas-Fired Cooling Technologies For The Commercial Sector", Gas Research Institute, GRI-88/0162, June 1989.

5. "Nonresidential Buildings Energy Consumption Survey: Characteristics of Commercial Buildings 1986", September 13, 1988, U.S. Department of Energy--Energy Information Administration, DOE/EIA-0246(86).

   - Methodology: Reference 4 provided chiller load factors for nine applications (school, medium office, large office, restaurant, retail store, apartment, large hotel, medium hotel, hospital, and assembly) and five locations (Detroit, New York, Atlanta, Los Angeles, and Houston). The load factors ranged from .024 to .474. Reference five provided the basis to estimate weighting factors for the Reference 4 load factors. The weighting factors were used to estimate an average chiller load factor for the 1986 building stock of 0.17.

Table E.8. Use of refrigerants in chillers: annual usage for new chillers, annual usage for servicing existing chillers, and inventory in chillers (10^6 kg)

Table Reference	New Chiller Annual Usage	Service Annual Usage	Inventory	Comments
1.	---	6.8	40.8	CFC-11 centrifugal in U.S.
2.	0.39	---	6.5	HCFC-22 in reciprocating/screw/ scroll compressors in Japan
	0.14	---	3.73	CFC-11 centrifugal in Japan
	---	---	0.18	CFC-12 centrifugal in Japan
	---	---	0.52	CFC-113 centrifugal in Japan
	---	---	0.08	CFC-114 centrifugal in Japan
3.	---	7.8	39.5	CFC-11 centrifugal in U.S.
	2.5	---	---	All CFCs worldwide
4.	---	---	29.6	CFC-11 centrifugal in U.S.
	---	---	5.4	CFC-12 centrifugal in U.S.
	---	---	0.4	CFC-114 centrifugal in U.S.
	---	---	5.4	HCFC-22 centrifugal in U.S.
	---	---	4.4	R-500 centrifugal in U.S.
	---	---	45.2	All centrifugal in U.S.
	2.5	7.9	67.2	All centrifugal in World
5.	---	---	0.85	CFC-11 centrifugal in Europe
	---	---	0.78	CFC-12 water-cooled centrifugal in Europe
	---	---	0.20	CFC-12 air-cooled centrifugal in Europe
	---	---	5.00	HCFC-22 reciprocating in Europe
6.,7.	1.59	---	31.7	Centrifugal–all refrigerants in U.S.
	0.25	---	5.5	Reciprocating–all refrigerants in U.S.
2.,8.	0.18	---	4.73	CFC-11 centrifugal in Japan
	---	---	0.23	CFC-12 centrifugal in Japan
	---	---	0.66	CFC-113 centrifugal in Japan
	---	---	0.10	CFC-114 centrifugal in Japan

Table References:

1. Carrier Corp. announcement, Air-Conditioning, Heating & Refrigeration News, January 15, 1990, p. 5.

2. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 25, 1991.

3. Reitz, K., "CFCs for Water Chillers", Heating/Piping/Air Conditioning Magazine, April 1990.

4. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989.

5. Letter from Laurent Legin of Societe Trane to P.D. Fairchild of Oak Ridge National Laboratory, March 29, 1991. Assumed 1.0 kg/RT for CFC-11 centrifugal chillers, 1.3 kg/RT for CFC-12 centrifugal chillers, and 1.0 kg/RT for HCFC-22 reciprocating chillers as per Table E.2.

6. Easton Consultants, Inc., "Replacement Market For Selected Commercial Energy Service Equipment", Gas Research Institute, GRI-89/0204.02, June 1990.

7. Pietsch, J.A., "Commercial Unitary Heat Pumps: An Assessment Study", Electric Power Research Institute, EPRI CU-6371, May 1989.

   - Methodology: Reference 7 provides annual U.S. reciprocating and centrifugal chiller shipments for the period 1978-87. The period 1981-85 was used, along with U.S. tonnage shipped for the same period from Reference 6, to determine that the average reciprocating chiller capacity is about 60 RT and the average centrifugal capacity is about 570 RT. From Table A2, reciprocating chillers in this size have about 0.74 kg/RT of refrigerant (primarily HCFC-22), and centrifugals in this size have about 1.0 kg/RT of refrigerant (primarily CFC-11). These values were multiplied by the average annual U.S. tonnage shipments for the period 1986-88 from Reference 6 to estimate annual refrigerant shipments to charge new chillers.

     Table E.4 indicates that industry sources estimate centrifugal chiller life at 27-34 years so 30 yr is a reasonable assumption. The U.S. centrifugal chiller inventory in tons was estimated as the tons shipped from 1959-88 from Reference 6. It is widely known that reciprocating chillers have shorter lives, for example Reference 6 estimated 18-23 years. Since Reference 6 appeared to underestimate centrifugal chiller life at 20-25 years, the high end of the Reference 6 range was selected for reciprocating chiller life. The U.S. reciprocating chiller inventory in tons was estimated as the tons shipped from 1966-88 from Reference 6. Refrigerant inventories were estimated assuming 0.74 kg/RT for reciprocating machines and 1.0 kg/RT for centrifugal machines.

8. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 8, 1991. Information here implies an average centrifugal chiller size of 380 RT rather than the 300 RT assumed in Reference 2.

Table E.9. Region and world inventory of major refrigerants in chillers by equipment category (10^6 kg)

Equipment Category	Most Common Refrigerants		North America	Europe	Japan	Rest of World
100 RT air-cooled (primarily reciprocating, some screw and scroll)	sub-atm:	R-11 Other				n/a
	above atm:	R-12 R-22 Other	0.4 7.5	0.2 5.0	6.5	n/a
300 RT water-cooled (primarily centrifugal, some screw)	sub-atm:	R-11 Other	23.8	0.9	4.7 0.8	n/a
	above atm:	R-12 R-22 Other	1.8 0.8 1.5	0.8	0.2	n/a
1000 & 3000 RT water-cooled (primarily centrifugal, some screw)	sub-atm:	R-11 Other	5.8 0.4	---	---	n/a
	above atm:	R-12 R-22 Other	3.6 4.6 2.9	---	---	n/a
All	All		53	7	12	7
Column References			1.,2.,3.	4.	5.,6.	7.

Table References:

1. United Nations Environment Program (UNEP), "Technical Progress On Protecting The Ozone Layer--Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Report", Prepared for the Reassessment of the Montreal Protocol in March 1990, June 1989.

2. Technical Marketing Associates, Inc., "Applications Assessment for Gas Engine-Driven Chillers", Gas Research Institute, GRI-86/0246, November 1986.

3. Fischer, S.K. et.al., "Energy-Use Impact of Chlorofluorocarbon Alternatives", Oak Ridge National Laboratory, ORNL/CON-273, February 1989.

- Methodology: Reference 1 provided a centrifugal chiller refrigerant breakout for the U.S. Table E.8 indicates that the Reference 1 refrigerant inventory of 45.2×10^3 kg is higher than the only other independent estimate of 31.7×10^3 kg (Table E.8, References 6 and 7). Different assumptions about tonnage inventory and kg/RT refrigerant charge are possible reasons. The apparent uncertainty is large, therefore the Reference 1 total and breakout for the U.S. were used for North America as the estimate appears high enough to include Canada

and Mexico. It was assumed that this estimate applied to the fluid inventories of the 300 RT, 1000 RT, and 3000 RT categories that are primarily centrifugal, but also include some water-cooled screw-type chillers.

The sources leading to the independent estimate of 31.7×10^3 kg in Table E.8 also provided a common-basis estimate for reciprocating chillers of 5.5, or 17.4% of the centrifugal value. This percentage was applied to the larger Reference 1 centrifugal total of 45.2, resulting in an estimate of 7.9×10^3 kg for reciprocating chillers, and a total for all chillers of about 53×10^3 kg in North America.

Allocations of refrigerant inventories in North America were estimated as follows. It is widely known that reciprocating chillers in the U.S. are primarily HCFC-22 machines with a small CFC-12 population, hence the 7.5 and 0.4 split. Reference 1 provided refrigerant breakouts for all centrifugals (we include screw-types). These percentages were maintained while estimating a breakout between the 300 RT and 1000/3000 RT categories. Reference 2 provided a basis to estimate the U.S. installed tonnage of water-cooled screw-type chillers. These are HCFC-22 machines with a typical size of about 200 RT. The 0.8×10^3 kg estimate is based on 0.9 kg/RT (see Table E.2) and is assigned to the 300 RT category. The rest of the HCFC-22 was assigned to the 1000/3000 RT category since it is used primarily in very large centrifugals (2000 RT and over). All CFC-114 is used in large centrifugals and was assigned to the 1000/3000 RT category.

600 RT was arbitrarily chosen as the dividing line between the 300 RT and 1000/3000 RT categories. CFC-11, CFC-12, and R-500 machines cross this boundary. Reference 2 indicates that about 60% of 1984 centrifugal tonnage shipped was below 600 RT. This breakout was assumed typical for the total inventory of CFC-11, CFC-12, and R-500 machines. Reference 3 indicated that CFC-12 and R-500 machines were on the average larger than 600 RT, so 67% of these refrigerants were assigned to the 1000/3000 RT category. The allocation of CFC-11 is based on the material balance.

4. Letter from Laurent Legin of Societe Trane to P.D. Fairchild of Oak Ridge National Laboratory, March 29, 1991. Assumed 1.0 kg/RT for CFC-11 centrifugal chillers, 1.3 kg/RT for CFC-12 centrifugal chillers, and 1.0 kg/RT for HCFC-22 reciprocating chillers as per Table E.2.

5. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 8, 1991.

6. Letter from Kenichi Taguchi of Daikin Industries, Inc. to P.D. Fairchild of Oak Ridge National Laboratory, March 25, 1991.

7. The Reference 1 assumption that the U.S. has about 67% of the world installed chiller tonnage and refrigerant inventory was used. Refrigerant in the "rest of the world" category was obtained by subtraction.

APPENDIX F: COMMERCIAL CHILLERS - OPERATING DATA FROM ARI

report JMC/ARI-9104A

CHARACTERISTIC EFFICIENCIES AND COSTS FOR AIR-CONDITIONING EQUIPMENT WITH SELECTED REFRIGERANT ALTERNATIVES

ARI Inputs to the AFEAS/ORNL Study of Global Warming Impacts of Refrigerants

April 1991
(including 28 May 1991 revision)

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The performance data for the 2½ ton air conditioner in tables 1 (COPs) and 2 (SEERs) were revised after release of this report. The modifications reflect corrections to the consolidated information on which the tables were based. Amended inputs were provided by one or more manufacturers, based on error(s) discovered in the original analyses used to estimate performance and fabrication costs. The selected values for relative cost levels A and B also were changed, accordingly, for this equipment option. The net effect is that the efficiency indicated for the 2½ ton air conditioner using R-134a was reduced by approximately 2% at the corresponding costs. Revised data are flagged by a bar in the left margin.

revised 28 May 1991

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CHARACTERISTIC EFFICIENCIES AND COSTS FOR AIR-CONDITIONING EQUIPMENT WITH SELECTED REFRIGERANT ALTERNATIVES

ARI Inputs to the AFEAS/ORNL Study of Global Warming Impacts of Refrigerants

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Abstract

This document summarizes analyses of the comparative efficiencies of selected refrigerant alternatives in representative air-conditioning equipment. The data were prepared and consolidated as inputs to a study of global warming. The objective was to facilitate assessment of impacts from use of refrigerants. The performance data provided enable evaluation of indirect effects for conventionally applied and near-term alternatives. Efficiency data are presented for several equipment cost levels to permit trade-off comparisons between fluid substitutions and performance enhancements. The background, approach, and analyses are summarized in this report. Resulting data are tabulated for representative air conditioner, heat pump, and chiller capacities. Vapor-compression-cycle equipment using CFC-11, CFC-12, HCFC-22, HCFC-123, and HFC-134a are addressed. Direct-fired, absorption-cycle chillers, both single-effect using ammonia/water and double-effect using water/lithium bromide, also are included. Limitations to the study resulting from both competitive and antitrust considerations are outlined.

Background

The Alternative Fluorocarbon Environmental Acceptability Study (AFEAS), an international consortium of twelve chemical producers, has undertaken an evaluation of global warming. The objective is to examine the direct and indirect warming effects resulting from use of refrigerants. The direct component reflects the greenhouse-gas impact of the refrigerant, or refrigerant and insulation blowing agent, used in a system. The indirect effect results from combustion emissions produced in powering the system. Examples include the carbon dioxide and nitrous oxides, both greenhouses gases, from generation of electricity or combustion used for operation. This study was initiated to demonstrate the importance of considering both components in future regulatory actions. Unless adequately documented, there is a risk that only the direct effect (i.e., the heat trapping by refrigerant emissions) will be considered. The consequence could be restrictions on future use of HCFC-22, HFC-134a, or other refrigerants by upcoming global-warming control protocols, legislation, or regulations.

The primary analyses to quantify and assess tradeoffs between direct and indirect global warming are being performed by staff of the Building Equipment Research Program of Oak Ridge National Laboratory (ORNL). The Research and Technology (R&T) and Executive Com-

mittees of the Air-Conditioning and Refrigeration Institute (ARI) unanimously agreed to cooperate with AFEAS by providing necessary data to compare efficiencies using selected alternative refrigerants.

Refrigerant Efficiency

It is feasible to calculate a theoretical efficiency for a refrigerant based on thermodynamic properties. As conceptually shown in figure 1, however, equipment efficiency is not solely a function of the refrigerant used. Rather, it is related to cost, with a different relationship (curve) for each refrigerant. Equipment may be optimized for any refrigerant considered by increasing or decreasing heat exchanger area or refrigerant charge, by changing exchanger surface enhancement or compressor volumetric displacement, or by varying other design parameters; each of these modifications translates to a cost impact. The same efficiency can be achieved with either a conventional refrigerant or alternatives. Uniform efficiency may be viewed in figure 1 by drawing a horizontal line through the three curves at the desired efficiency level. The cost to maintain efficiency with refrigerants X and Y might be higher, or significantly higher, than for the conventional fluid, independent of the asymptotic limits to practical efficiency for the refrigerants involved. Alternatively stated, the efficiency of refrigerants X or Y, for the same equipment cost, might be significantly lower than for the refrigerant replaced. This comparison may be made by drawing a vertical line through the three curves at a selected cost.

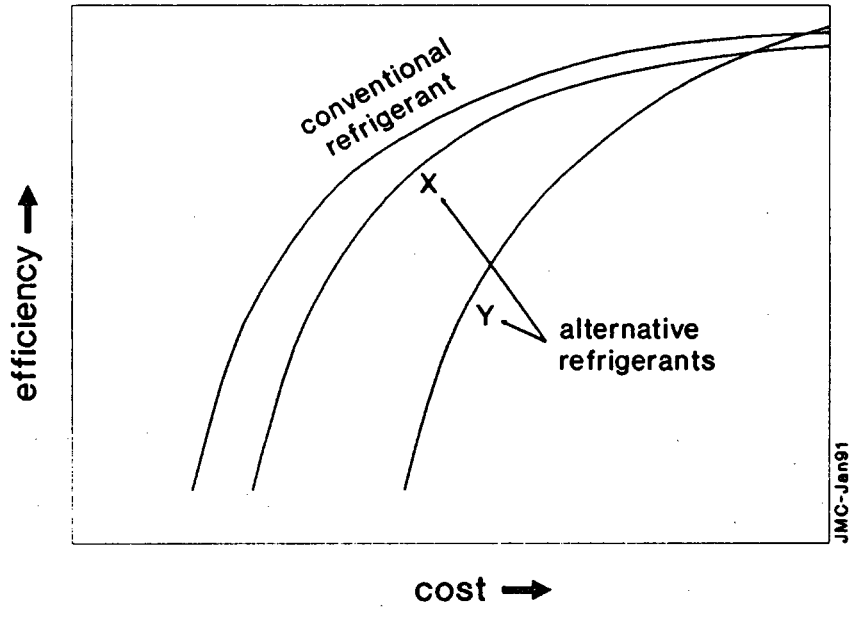

FIGURE 1 – EFFICIENCY AND COST RELATION

A corollary view results from treating efficiency as the independent variable, and calculating the dependent cost to achieve it. The former perspective was chosen on the belief that it would be both easier and more reliable for manufacturers to calculate performance in equipment modified – with known cost consequences – for various efficiency levels. The intent was to allow use of existing engineering design models and, as available, accumulated test data.

The ARI unitary equipment directory[1] lists split-system air conditioners using HCFC-22 having Seasonal Energy Efficiency Ratios (SEERs) approaching 17, even though the average SEER sold is closer to 9 (cooling seasonal COPs of 5.0 and 2.6, respectively). The cost of the former relative to the latter can be quantified. This example suggests that global warming can be reduced significantly by shifting to higher-performance equipment, using the original refrigerant, for the same cost as changing refrigerants. Figure 2 illustrates this case.

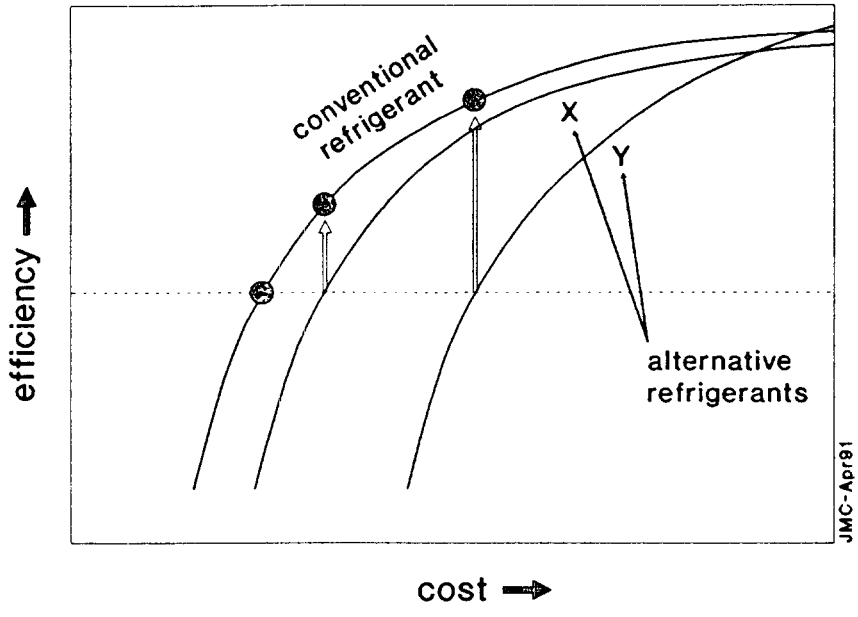

FIGURE 2 – TRADEOFFS BETWEEN EFFICIENCY AND SUBSTITUTION

The performance-cost relationships are needed to assess whether greater environmental benefit, for the same investment, derives from performance improvement (i.e, reduction of indirect effect) or refrigerant substitution (i.e., addressing direct effect).

There is no doubt that the relationship between efficiency and cost will change as the technologies utilized are further refined. Efficiency, therefore, also may be viewed as a function of time. Existing equipment, for example, has improved over the years, and higher-performance equipment is available today for the same price – with adjustments for inflation – as a decade ago. This evolution in technology will continue for both commonly used and new, alternative refrigerants. While the real (i.e., with adjustment for inflation) cost of increasing efficiency may decline with time, the changes in relative costs among equipment with different refrigerants should be much smaller.

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1 *Directory of Certified Unitary Air Conditioners, Unitary Air-Source Heat Pumps, and Sound-Rated Outdoor Unitary Equipment (February 1, 1991 - July 31, 1991)*, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, 1990 (updated every six months)

Data Source

The data reported in this document resulted from consolidation and analyses, described below, of information voluntarily provided by manufacturers. A request was sent to companies that produce the targeted equipment options.[2] This letter outlined the objectives, safeguards for legal and proprietary concerns, and instructions for data submission. It is reproduced in the appendix to this report.

Data provided by the manufacturers were analytically determined, using product design and other engineering models. Each manufacturer optimized the specific equipment addressed for the individual refrigerants under consideration. The degree of optimization varied to the extents feasible within the response time allowed, modeling abilities, and existing information on the alternative refrigerants. The engineering models, in some cases, were calibrated and resulting data verified against available experimental data.

Limitations

The collection, analyses, and publication of the data were limited to avoid dissemination of competitively-sensitive and/or proprietary information. Several measures were taken in this regard. First, there was no exchange of information regarding current or projected prices among the manufacturers involved, except for normal (and confidential) communications between individual equipment manufacturers and their refrigerant suppliers. Similarly, there was no sharing of design and product strategies, engineering models, or performance data.

Second, the costs considered were solely for fabrication, not sales prices or consumer costs for installed systems. The goal was to enable comparison of consistent efficiencies among various refrigerants, not to address market projections or similar competitive issues.

Third, the manufacturers independently converted the costs of fabrication to *relative costs* before submission to the author. This normalization was done by dividing the calculated costs of fabrication by those for the corresponding reference systems (i.e., by treating the cost for reference systems including their refrigerant as 1.0). Use of relative costs avoided disclosure of proprietary information and subsequent sales mark-ups.

Fourth, confidential treatment of individual company data was assured to the extent that neither the companies responding, the number of companies doing so, or the data received will be disclosed – even to members of the ARI R&T Committee or its Refrigerants Subcommittee. Only consolidated data will be released, and even those will be limited.

And fifth, neither the resulting relationships between efficiency and relative costs, nor sufficient data points to recalculate them, will be published without prior review by government antitrust authorities.

Equipment and Refrigerant Options

The equipment and refrigerant options chosen for analyses were jointly selected by representatives of AFEAS, ARI, and ORNL. These selections considered both the volume of refrigerant

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2 The submission request was sent to all companies participating in the following ARI Product Sections: Liquid Chiller, Unitary Large Equipment, and Unitary Small Equipment Sections. It also was sent to members of the Executive Committee, Research and Technology Committee, and Refrigerants Subcommittee.

used and the ability of manufacturers to provide the data needed. Data were requested for the following options:

unitary air conditioners / chillers (SEERs and relative costs)

- 2½ ton, split-system, air conditioner using HCFC-22 and HFC-134a as well as a chiller using ammonia (R-717) – the ammonia option was to include an intermediate water delivery system to keep the ammonia outdoors (reference system: HCFC-22, SEER = 10 Btu/Wh)
- 7½ ton, packaged (rooftop), gas-electric system using HCFC-22, HFC-134a, and ammonia (R-717) – the ammonia option was to include either an intermediate water loop, to avoid ammonia in the air-cooling coil, or use of a double-wall, externally-vented, heat exchanger (reference system: HCFC-22, EER = 8.9 Btu/Wh)

unitary heat pumps (SEERs, HSPFs, and relative costs)

- 2½ ton, split-system using HCFC-22, HFC-134a, and ammonia (R-717) – the ammonia option was to include an intermediate water delivery system to keep the ammonia outdoors (reference system: HCFC-22, SEER = 10 Btu/Wh, HSPF = 6.8 Btu/Wh)

air-cooled chillers (IPLV and relative costs)

- 100 ton chiller using consistent manufacturer's choice of reciprocating-piston, screw, or scroll compressor(s) with HCFC-22 and HFC-134a (reference system: HCFC-22, IPLV = 1.00 kW/ton)

water-cooled chillers (IPLV and relative costs)

- 300 ton chiller using consistent manufacturer's choice of centrifugal (turbo) or screw compressor with CFC-11 and HCFC-123, and/or CFC-12 and HFC-134a, and HCFC-22 (reference system: centrifugal compressor, CFC-11, IPLV = 0.66 kW/ton)
- 1000 ton chiller using consistent manufacturer's choice of centrifugal or screw compressor(s) with CFC-11, CFC-12, HCFC-22, HCFC-123, HFC-134a, and R-500 (reference system: centrifugal compressor(s), CFC-11, IPLV = 0.66 kW/ton)
- 3000 ton chiller with centrifugal compressor(s) with CFC-12, HCFC-22, and HFC-134a (reference system: HCFC-22, IPLV = 0.66 kW/ton)

direct-fired (gas) chillers [IPLV-equivalent values – gas in Mbh/ton and parasitic electricity in kW/ton – for a single-effect, double-effect, and advanced (e.g., dual-cycle or triple-effect) system(s) as well as relative costs]

- 2½ ton chiller and indoor water (brine) coil (reference system: single-effect ammonia/water)
- 300 ton chiller (reference system: double-effect water/lithium-bromide)
- 1000 ton chiller (reference system: double-effect water/lithium-bromide)

Data for HFC-32, HFC-152a, blends of these fluids, or additional refrigerants were not requested for three reasons. First, significant effort – of the order of person-years rather than hours, days, or weeks – was envisioned to prepare the information for the options selected. Both the necessary response period and conflicting demands on the personnel involved limited the number of options that might have been assessed in a timely manner. Second, concern was expressed whether equipment using such fluids would be viable in light of consequential liability exposure due to flammability. While zeotropic blends might reduce this hazard, the

potential for fractionation to flammable levels mitigates their prospects. Efforts are underway to further examine the flammability and related liability issues. Third, the engineering models used require calibration and validation with actual data, not yet sufficient for more exotic alternatives. Exploratory attempts to collect data for unitary air conditioners using HFC-32 or HFC-32 blends were rejected, consistently, by the individual manufacturers contacted based on the inadequacy of available information.

Retrospectively, data dispersion was greater for newer refrigerants (e.g., HCFC-123 and HFC-134a) than for those more widely used. While all results reported herein were statistically significant, the confidence levels were highest for the conventional fluids.

Performance Measures

The dimensionless Coefficient of Performance (COP) values presented in the tables that follow approximate seasonal performance, to facilitate subsequent determination of annualized energy use. They are based on converted Heating Seasonal Performance Factors (HSPFs),[3] Seasonal Energy Efficiency Ratios (SEERs),[4] Energy Efficiency Ratios (EERs) calculated on an the basis of Integrated Part Load Value (IPLV),[5] chiller IPLVs,[6,7] or - for direct-fired absorption chillers – COPs calculated on IPLV bases for both natural gas and electricity. Actual performance will vary with local conditions and load profiles. IPLV efficiency, for example, may not be representative of seasonal performance in some installations. As an example, multiple chillers are commonly used in plants with high capacities to mitigate the impacts of a failure, enable operation during service, and improve part-load operation. A large chiller, therefore, might run only seldomly at less than 50% load.

The chiller COPs did not include energy for condensing-water pumps and cooling-towers fans. These COPs also excluded energy for chilled-water pumps, with the exception of the COPs for the 2½ ton ammonia/water absorption chiller, where parity with the corresponding vapor-compression air conditioners was sought. Some of the secondary energy uses, specifically those for condensing-water pumps and cooling-tower fans, will be lower for chillers with higher efficiency. Subsequent analyses using the data provided should address these differences, particularly as they impact indirect global warming.

Costs

The relative costs addressed refer to costs of fabrication normalized to those of a selected (representative) reference system, as outlined above. Several considerations follow for use of the relative-cost data in further analyses.

Costs of Fabrication

The calculated fabrication costs comprised materials, labor, allocated tooling, integral components, refrigerant charge, and similar cost elements normally associated with the equipment option addressed. The costs were estimated and normalized by the individual manufacturers based on the designs for which the corresponding efficiency data were provided. The capaci-

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3 *Unitary Air-Conditioning and Air-Source Heat Pump Equipment*, standard 210/240, ARI, 1989

4 *Ibid*

5 *Ibid*, appendix C

6 *Reciprocating Water-Chilling Packages*, standard 590-86, ARI, 1986

7 *Centrifugal or Rotary Screw Water-Chilling Packages*, standard 550-90, ARI, 1990

ties were maintained at the specified levels to enable subsequent comparisons. Sales mark-ups, typically higher for premium performance products, and other cost margins were excluded to minimize the influence of competitive issues and to avoid antitrust concerns.

Costs associated with aesthetics, serviceability, and other features that do not impact efficiency were excluded. Similarly, the cost of ancillary components and equipment (e.g., cooling towers or similar devices, condensing and chilled water pumps, mechanical areas, and installation provisions unique to specific refrigerants) were not included. The goal was to provide relative costs consistent with the equipment involved rather than their installed costs.

Relative costs of fabrication do not address differences in pricing strategies among manufacturers or, even for a single manufacturer, between separate (e.g., low- and high-volume) products. More importantly, they do not reflect either the final cost to consumers or life-cycle costs (e.g., including components for installation, operation, maintenance, and financing). They were used in this study to attain consistency for efficiency comparisons. They are not intended to suggest the comparative economic merits to the ultimate users.

Refrigerant Costs

The relative costs for the equipment include the factory-charged refrigerant. The charge quantities depend on the equipment, specific refrigerant, and efficiency. The refrigerant may represent of the order of 10% of the cost for some chillers. Each manufacturer used its own projections of 1995 refrigerant prices. Variations in predicted refrigerant prices, therefore, introduced small differences between individual manufacturer analyses. Since the refrigerant charge size is unique to individual designs, and is part of the equipment cost optimization for each refrigerant, exclusion and subsequent addition of consistent refrigerant costs was not feasible.

Both actual and relative prices for refrigerants will change, during the next several years, for a number of reasons. First, excise taxes will escalate for CFC-11 and CFC-12. Second, the prices for refrigerants being phased out under the Montreal Protocol may increase as the supply falls and the primary source becomes reclamation. This prospect is particularly true for R-12, for which a shortage may materialize, depending on the level of recycling for automotive air conditioning. Third, the prices for alternative refrigerants may drop as additional commercial scale plants are completed.

The participating manufacturers were asked to project 1995 refrigerant prices, expressed in 1991 dollars for consistency in the present study. Allowing for full design, materials qualification, prototype testing, production design, tooling, manufacturing lead time, service personnel training, and similar requirements, products require several years to make it into the market place. Projected 1995 refrigerant price levels, therefore, are consistent with hardware costs based on optimization with current technologies.

Implied Costs

Depending on local construction codes and safety requirements, use of selected equipment and/or refrigerants may dictate additional installation provisions and costs. Proposed safety classifications[8] and anticipated code requirements[9] may result, for example, in the need for a special purge vent, sensors, mechanical room isolation, or similar equipment-area features for

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8 *Number Designation and Safety Classification of Refrigerants, First Public Review Draft*, standard BSR/ASHRAE 34-1989R, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, March 1991

9 *Safety Code for Mechanical Refrigeration, First Public Review Draft*, standard BSR/ASHRAE 15-1989R, ASHRAE, March 1991

some alternative refrigerants. Such features were omitted from the relative equipment costs provided. They should, however, be considered in subsequent economic analyses using these data. As an example, the cost of purge vents and sensors for chillers using HCFC-123 could increase installation costs by the equivalent of 1-4% of the chiller cost, exclusive of ventilation provisions, depending on the capacity and quantity. Installations using ammonia would incur similar costs for tanks, stacks, or similar devices for safe release.

Further analyses also should address differential pumping requirements for chillers of dissimilar efficiencies. The heat of rejection – and therefore the power for cooling towers, or similar devices, and condensing water pumps – will increase with decreasing efficiency. The incremental power also will impact energy requirements and indirect global warming.

Data Consolidation

Insufficient and Inconsistent Data

Insufficient data for inclusion were received for some equipment and refrigerant options, namely:

- Equipment using ammonia: No data were received for the vapor-compression equipment options. The responding manufacturers independently, but consistently, reported that their design models were not suited to address ammonia. Necessary differences in materials and design for use of ammonia precluded the accuracy sought in this study. Limited data were received for single-effect, ammonia/water, absorption-cycle chillers.
- 7½ ton, gas-electric, packaged air conditioners (typical of those used in light-commercial, rooftop applications): Only limited data were received, and the data dispersion yielded inconclusive results. Significant variances resulted from disparate abilities to optimize this product class for alternative refrigerants, specifically for HFC-134a. Further data may become available in the near future, but the present data are not statistically meaningful.
- Chiller data using R-500: Insufficient data were received for analysis of this option.

The data obtained were limited for several options. There are, for example, only two domestic manufacturers of very large chillers, in the several-thousand-ton class; the number of prospective respondents was, therefore, constrained.

Reporting a single manufacturer's data for an option – if noted as from a single respondent – would compromise proprietary data. Similarly, flagging data consolidated from two companies would enable each respondent to back out proprietary data from the other. Flagging applicable data as from three or more firms would, by omission, signal the same information for other cases. As a safeguard, neither the identities nor quantities of firms responding to each option will be disclosed.

Data ranges were introduced in the subsequent tabulations, to signify uncertainty, when the number of respondents was small or in cases for which reasonable dispersion was noted. Where single efficiency values are provided instead of ranges, they imply sufficient responses with high consistency.

Screening, Consolidation, and Analyses

The data received were entered into a single, carefully-verified database to minimize incorrect reentry in analyses. Efforts were made to identify options for which insufficient replies were received. Additional manufacturers were recontacted, and encouraged to respond, to fill these voids.

The first analyses were to calculate efficiency-cost[10] relations for the data for each option from individual manufacturers. The curve fits used included a suite of linear and nonlinear equations. While no single equation form was universally acceptable, most of the resulting fits were among several hyperbolic relations. The resulting regression equations were plotted together with the raw data. These plots were examined to identify suspicious data and verify the fits. Data pointing to decreasing efficiency with cost, low correlations, and relations that did not follow anticipated patterns prompted further examination and confidential manufacturer contacts. Some anomalies were explained and accepted; others were corrected.

The individual fits were then compared with those from other manufacturers for each equipment, capacity, and refrigerant option. Aberrations were again pursued. One problem that was encountered at this stage was use of dissimilar refrigerant price projections. Some identified discrepancies, such as omission of escalating excise taxes for chlorofluorocarbon (CFC) refrigerants, led to data replacement. Where disagreement was evident among independent manufacturer estimates, the bases for the inputs were individually discussed to seek uniform assumptions. One manufacturer, for example, originally included installation provisions in equipment costs.

The data then were consolidated, by equipment and refrigerant options, and regression equations were fit to and plotted against the composite raw data. The resulting correlation coefficients were assessed for statistical confidence.

Finally, the regression equations for the consolidated data were used to extrapolate consistent efficiency estimates at selected relative costs. Plots of the comparative efficiency-cost curves for each refrigerant, within separate equipment and capacity options, were used to locate changes in the relative merits of refrigerant options. Where crossovers were found, either the relative cost corresponding to the intersection or representative cost ranges between intersections were picked. The final selections within ranges of relative costs were made with a view toward facilitating subsequent comparisons of indirect global warming. This was done by finding the relative cost – within the applicable range – for which the efficiency of a primary alternative refrigerant matched that of the reference system refrigerant at the reference system cost. Figure 3 illustrates a selection of this type.

Resulting efficiency data were tabulated for the reference systems costs (relative cost equal to 1.0) and either one or two higher relative costs, identified herein as *A* and *B*. These two relative-cost levels (vertical lines in figure 3) were different for each equipment and capacity option, but the same for each refrigerant within an equipment size. As a guide, level *B* is greater than *A* which is greater than 1.0, but the increment between *A* and 1.0 does not necessarily equal that between *A* and *B*.

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10 As used in this discussion, *costs* refer to relative rather than absolute costs unless otherwise indicated.

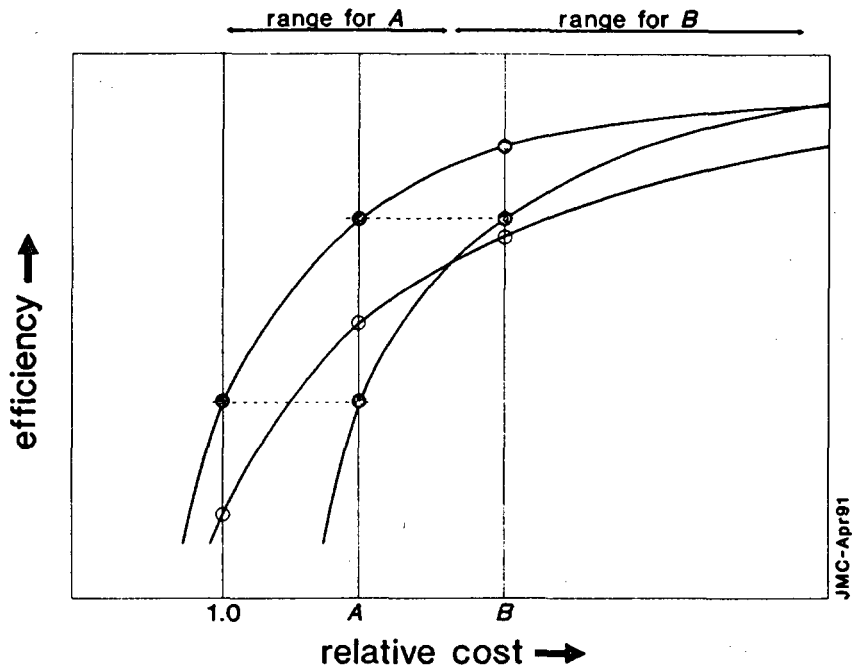

FIGURE 3 – RELATIVE COST SELECTIONS

Two observations follow to provide some perspective on the data received:

- The consistency was generally high, particularly for the consolidated data for some equipment options for the conventional refrigerants;[11] many of the regression coefficients exceeded 0.9. There was a procedural question with comparing efficiencies at equivalent relative costs, since the corresponding costs without normalization might differ between manufacturers. The results suggest that competitive market forces have provided reasonable consistency, even where dissimilar technologies were included in an equipment group.
- There was no evidence of intentional skewing of the data to favor competitive interests. Several instances were found where companies marketing equipment using one alternative refrigerant provided data showing superiority of a competing fluid. In one particular case, two direct competitors each provided data more favorable for the equipment of the other.

Results

Options Employing Vapor-Compression Cycles

The resulting data for the vapor-compression systems are summarized in tables 1 and 2; these tables provide the same information, the latter as conventional efficiency measures (HSPFs, IPLVs, and SEERs) and the former coefficients of performance (COPs).

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[11] Identifying the options with very-high correlations would facilitate backing out the efficiency-cost relations.

TABLE 1 – ARI INPUTS FOR AFEAS/ORNL GLOBAL-WARMING STUDY FOR VAPOR-COMPRESSION-CYCLE OPTIONS (EXPRESSED AS COPS)

option	refrigerant	COP at relative cost[a] 1.0	*A*	*B*
unitary air conditioners				
• 2½ ton, split system	**22**	2.93	3.25	3.53
	134a	2.58	2.93	3.25
unitary heat pumps				
• 2½ ton, split system: cooling mode	**22**	2.93	3.5 - 3.9	·
	134a	2.0 - 2.4	2.93	·
• 2½ ton, split system: heating mode	**22**	1.99	2.4 - 2.8	·
	134a	1.3 - 1.8	1.99	·
air-cooled chillers				
• 100 ton	**22**	3.51	3.78	4.25
	134a	3.37	3.51	3.78
water-cooled chillers				
• 300 ton	**11**	5.27	5.53	6.58
	12	5.22	5.36	5.92
	22	5.14	5.40	6.48
	123	5.07	5.27	6.06
	134a	5.19	5.36	6.06
• 1000 ton	**11**	5.31	5.91	6.86
	12	5.40	5.70	6.18
	22	5.6 - 6.2	6.1 - 6.7	·
	123	5.47	5.79	6.29
	134a	5.42	5.75	6.29
• 3000 ton	12	4.4 - 5.1	5.0 - 5.6	·
	22	5.30	5.8 - 5.9	·
	134a	4.5 - 5.1	5.0 - 5.6	·

[a] The dimensionless Coefficient of Performance (COP) values approximate seasonal performance based on converted Heating Seasonal Performance Factor (HSPF), Seasonal Energy Efficiency Ratio (SEER), an Energy Efficiency Ratio (EER) calculated on an Integrated Part Load Value (IPLV) basis, or chiller IPLV. Relative costs refer to costs of fabrication normalized to those of a selected (representative) reference system. *A* and *B* are different for each equipment option, but are the same for each refrigerant within an equipment size. As a guide, $1.0 < A < B$, but B-A does not necessarily equal A-1.0.

TABLE 2 – ARI INPUTS FOR AFEAS/ORNL GLOBAL-WARMING STUDY FOR VAPOR-COMPRESSION-CYCLE OPTIONS (IN DIMENSIONAL EFFICIENCIES)

option	refrigerant	efficiency at relative cost [a] 1.0	*A*	*B*
unitary air conditioners (SEER)				
• 2½ ton, split system	22	10.0	11.1	12.0
	134a	8.8	10.0	11.1
unitary heat pumps (SEER, HSPF)				
• 2½ ton, split system: cooling mode	22	10.0	12.0 - 13.3	·
	134a	6.8 - 8.2	10.0	·
• 2½ ton, split system: heating mode	22	6.8	8.2 - 9.6	·
	134a	4.4 - 6.1	6.8	·
air-cooled chillers (IPLV)				
• 100 ton	22	1.00	0.93	0.83
	134a	1.04	1.00	0.93
water-cooled chillers (IPLV)				
• 300 ton	11	0.67	0.64	0.53
	12	0.67	0.66	0.59
	22	0.68	0.65	0.54
	123	0.69	0.67	0.58
	134a	0.68	0.66	0.58
• 1000 ton	11	0.66	0.59	0.51
	12	0.65	0.62	0.57
	22	0.57 - 0.63	0.52 - 0.58	·
	123	0.64	0.61	0.56
	134a	0.65	0.61	0.56
• 3000 ton	12	0.69 - 0.80	0.63 - 0.70	·
	22	0.66	0.60 - 0.61	·
	134a	0.69 - 0.78	0.63 - 0.70	·

[a] Efficiency is expressed in conventional (dimensional) measures: HSPF (Heating Seasonal Performance Factor) and SEER (Seasonal Energy Efficiency Ratio) are in Btu/Wh; IPLV (Integrated Part Load Value) is in kW/ton. Relative costs refer to costs of fabrication normalized to those of a selected (representative) reference system. *A* and *B* are different for each equipment option, but are the same for each refrigerant within an equipment size. As a guide, $1.0 < A < B$, but B-A does not necessarily equal A-1.0.

Five explanatory notes may help in interpreting the data in tables 1 and 2:

- First, no performance comparisons should be made between equipment options or capacities with data for relative costs *A* and *B*. The corresponding values for either *A* or *B* are not necessarily the same except for the several refrigerants within each equipment and capacity group.
- Second, some inconsistencies were noted in the efficiency data between equipment options even for relative cost equal to 1.0. Discrepancies resulted from differences in the specific companies that provided the data for each option. As an example, the cooling efficiencies for HFC-134a at relative cost equal to 1.0 should not be compared between the 2½ ton air conditioner and the heat pump. The companies providing data for these two options were different, the absolute costs were dissimilar even though the relative costs are the same due to normalization, and the heat pump designs required optimization tradeoffs between the separate heating and cooling modes. The consequence for HFC-134a is noticeable due to higher refrigerant circulation requirement compared to HCFC-22 used in the reference system.
- Third, the performance of CFC-11 leads those of the other refrigerants for the 300 ton chiller at the reference system cost (relative cost of 1.0). By contrast, the efficiency of CFC-11 appears lower than for other refrigerants for 1000 ton chillers at the reference cost. This anomaly is partially consistent with market observations that CFC-11 dominates for 300 ton centrifugal chillers, but falls off as capacity increases; CFC-11 is not competitive in very large capacities. There is some concern with the comparative CFC-11 performance found at 1000 tons, however, since it parts with market indications for this capacity. The asymptote to the efficiency-cost relation for CFC-11 exceeded those for other refrigerants examined, including that for the limited R-500 data (see page 8). This observation is consistent with expectations based on ideal-cycle analyses.
- Fourth, whereas little variation is evident in the efficiencies indicated for the several refrigerants for the 300 ton chiller at relative cost of 1.0, this similarity probably would not occur if consistent compressor-types were specified. The low-pressure options (i.e., CFC-11 and HCFC-123) reflect centrifugal (turbo) machines, while the high-pressure options (i.e., HCFC-22) are screws; the compressors for medium-pressure refrigerants (e.g., CFC-12 and HFC-134a) varied by manufacturer.
- Fifth, the asymptotic limits to the efficiency-cost regression equations were consistently highest for the reference-system (i.e., most common) refrigerants, which are highlighted in boldface in tables 1 and 2. This observation is consistent with expectations for a highly competitive market.

Comparisons with the data presented should be limited to refrigerant options within each equipment and capacity group; this study was not intended to enable broader comparisons.

Options Employing Absorption Cycles

Table 3 summarizes data for the direct-fired, absorption-cycle options. Additional performance data are provided for the reference systems and HCFC-22 options, at relative costs *C* and *D*, to enable comparison of absorption to vapor-compression options.

Caution is advised in use of the vapor-compression-equipment data at the high relative costs of table 3. Performance at relative costs *C* and *D* reflects extrapolations well beyond both the source data and conventional designs. Moreover, the extrapolated values were deliberately

understated, in those cases where the asymptotes were closely approached, to avoid disclosure of the asymptotic limits. The intent was to provide data of the right order of magnitude for comparisons, but to avoid disclosure of data that would enable recalculation of the regression equations (refer to discussion of limitations beginning on page 4). To avoid misunderstanding, the asymptotic limits may be achieved by combining exotic technologies. Examples include compression staging with intercooling, very-tight and unforgiving compressor clearances, extremely-large heat exchangers employing maximum surface enhancement, tube-cleaning devices to minimize fouling, and top-efficiency motors with inverter drives. Such designs, however, would be impractical and – for some of the technologies cited – less durable and reliable. The known absorption alternatives cannot be produced with costs comparable to those of the options in tables 1 and 2. Research of more advanced absorption cycles, as well as of improved vapor-compression equipment, is underway.

TABLE 3 – ARI INPUTS FOR AFEAS/ORNL GLOBAL-WARMING STUDY FOR DIRECT-FIRED, ABSORPTION-CYCLE ALTERNATIVES

option	refrigerant / absorbent	fuel	COP at relative cost [a] 1.0	*C*	*D*
2½ ton, air-cooled, unitary split system					
• vapor-compression air conditioner	22	electricity	2.9	>4.5	·
• direct-fired, single-effect chiller	A/W [b]	gas	·	0.4-0.5	·
		electricity	·	7-8 [c]	·
300 ton, water-cooled chillers					
• vapor-compression	11	electricity	5.3	·	>7
	22	electricity	5.1	·	>7
• direct-fired, double-effect	W/LB [b]	gas	·	·	0.9-1.0
		electricity	·	·	~100
1000 ton, water-cooled chillers					
• vapor-compression	11	electricity	5.3	>7	~8
	22	electricity	5.8-6.0	~8	~8
• direct-fired, double-effect	W/LB [b]	gas	·	0.8-1.2	1.1-1.4
		electricity	·	~150	~150

[a] The dimensionless Coefficient of Performance (COP) values approximate seasonal performance based on converted Seasonal Energy Efficiency Ratio (SEER) for air conditioners, Integrated Part Load Value (IPLV) for vapor-compression chillers, and IPLV COP for absorption-cycle equipment. Two COP values are indicated for absorption equipment. The one for gas represents the primary fuel. The COP for electricity includes energy for the solution pump and similar parasitics. It also includes the chilled-water pump, outdoor fan, and indoor blower energy for the 2½ ton chiller, to achieve consistency with the corresponding air conditioner COP values. No energy is included in chiller COPs for condensing-water pumps. Relative costs refer to costs of fabrication normalized to those of a selected (representative) reference system. *C* and *D* are the same for all options in this table. As a guide, $1.0 < C < D$, but *D*-*C* does not necessarily equal *C*-1.0; *C* also is greater than *B* in Tables 1 and 2.

[b] A/W = ammonia / water; W/LB = water / lithium bromide

[c] Estimate based on commercially-available equipment.

Conclusions

The resulting data provide a basis for evaluation of indirect global warming effects, for conventionally applied and near-term alternative refrigerants. Efficiency data are presented for representative air-conditioning equipment at several cost levels. Mitigation of indirect effect (i.e., increasing efficiency) may be more beneficial environmentally, and more cost effective, than reducing direct effect warming by changing refrigerants. While the two options, efficiency improvement and fluid substitution, are not mutually exclusive, the data generally indicate that lower efficiency, and therefore increased warming, results from fluid substitution. Subsequent analyses will assess the implied tradeoffs to indicate which approach is preferred. A third measure, namely reduction of emissions by reducing service losses, leakage, and disposal venting, should be emphasized. As refrigerant emissions are reduced, the relative importance of reducing indirect warming will increase.

Acknowledgements

This document provides information based on independent evaluations by equipment manufacturers of a number of refrigerant and equipment options. Because the underlying information is highly proprietary, neither the companies nor individuals involved may be identified. Accelerated efforts to develop and introduce equipment with environmentally-safer refrigerants has placed high demands on the firms and people so engaged. The additional effort to prepare the information for this study – exacerbated by the tight schedule – further strained the key participants. Their contributions are gratefully, even though anonymously, acknowledged.

This study was undertaken on behalf of ARI, a not-for-profit, voluntary trade association representing manufacturers of air-conditioning, heating, and refrigeration equipment and components. Oversight was provided by the Research and Technology Committee, chaired by Dr. Kenneth E. Hickman, and its Refrigerants Subcommittee, chaired by Mr. Howard W. Sibley.

The author began this work while employed as Vice President, Research and Technology, at ARI. He consolidated, analyzed, and documented the data as an independent consultant to ARI following his resignation.

AIR-CONDITIONING
& REFRIGERATION
INSTITUTE

Representing Manufacturers
of Heating, Ventilating,
Air-Conditioning and
Refrigeration Products

8 February 1991

MEMBERS: UNITARY SMALL EQUIPMENT SECTION
UNITARY LARGE EQUIPMENT SECTION
LIQUID CHILLER SECTION

Ladies and Gentlemen:

The Alternative Fluorocarbon Environmental Acceptability Study (AFEAS), an international consortium of twelve chemical producers, has undertaken a study of global warming. The objective is to evaluate the potential contributions of both direct and indirect warming effects. The direct contribution reflects the greenhouse-gas impact of the refrigerant, or refrigerant and insulation blowing agent, used in a system. The indirect effect results from combustion emissions produced in powering the system. Examples include the carbon dioxide and nitrous oxides, both greenhouses gases, from generation of electricity used for operation. This study is needed to demonstrate the importance of considering both components in future regulatory actions. Unless adequately documented, there is a risk that only the direct effect (i.e., the heat trapping of refrigerant emissions) will be considered. HCFC-22 or HFC-134a, as two examples, may be eliminated from future use by upcoming global-warming control protocols, legislation, or regulations. The ARI Research and Technology (R&T) Committee unanimously agreed to cooperate in this study by providing data from equipment manufacturers where feasible.

Data are being sought from your company, on a confidential basis, on the relative costs of representative efficiency levels for equipment using alternative refrigerants. A critical premise for the data being requested is illustrated by figure 1:

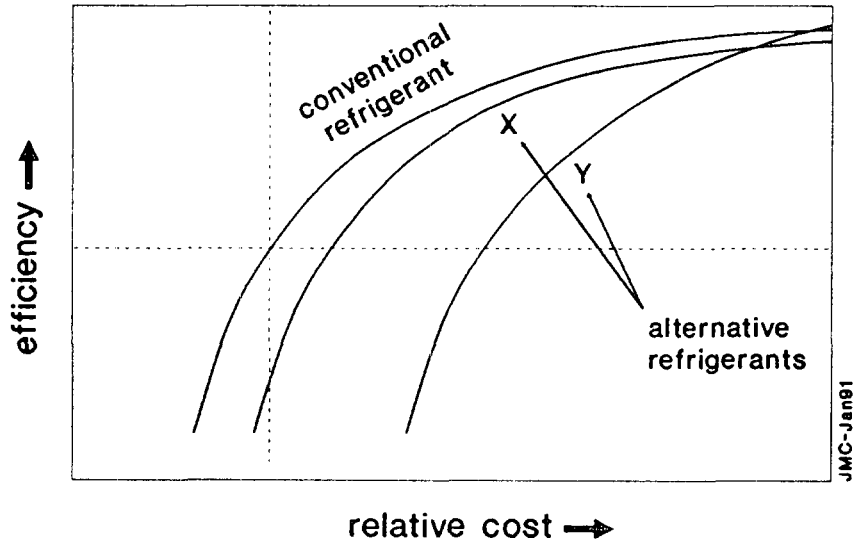

Figure 1 – Equipment Efficiency Compared to Cost

1501 Wilson Boulevard, 6th Floor, Arlington, Virginia, 22209-2403
(703) 524-8800, Telex 892351, Telecopier (703) 528-3816

APPENDIX – ARI Data Request

As conceptually shown, equipment efficiency is not solely a function of the refrigerant used. Rather, it is a function of cost, with a different curve for each refrigerant. Equipment may be optimized for any refrigerant considered by increasing or decreasing heat exchanger area or refrigerant charge, changing exchanger surface enhancement or compressor volumetric displacement, or varying other design parameters; each of these modifications translates to a cost impact. Following the dashed horizontal line, we see that the same efficiency might be achieved either for a conventional refrigerant or an alternative. The cost to do so for refrigerants X and Y, relative to that for the conventional fluid, might be higher or significantly higher, independent of the asymptotic limits to practical efficiency for the refrigerants involved. Alternatively stated, the efficiency of refrigerant X, for the same equipment cost, might be significantly lower than for the refrigerant it replaces, as shown by intercepts with the dashed vertical line.

A corollary view results from treating efficiency as the independent variable, and calculating the dependent cost to achieve it. We have chosen the former perspective, since it may be easier and more reliable to calculate performance for new refrigerants in equipment modified – with known cost consequences – for various efficiency levels by using existing engineering design models. For present purposes, relative equipment fabrication costs are being discussed, not those of installed systems.

The term *relative costs* implies conversion of estimated fabrication costs to ratios (multipliers) relative to (divided by) a reference cost (e.g., by treating the cost for a reference system and refrigerant as 1.0). By using relative costs, disclosure of proprietary information and subsequent sales mark-ups will be avoided.

The importance of the performance-cost relationships becomes apparent as soon as the dominance of indirect global warming over direct effect is considered. Mitigation of indirect effect (i.e., increasing efficiency) entails a cost that might, alternatively, be spent on increasing building or cabinet insulation or constructing more-efficient power plants. These options are alternatives to manufacturing more-expensive equipment, to achieve equivalent or lower efficiency, with substitute refrigerants. The ARI unitary equipment directory, for example, lists split-system air-conditioners using HCFC-22 with Seasonal Energy Efficiency Ratios (SEERs) exceeding 16, even though the average SEER sold is closer to 9. The cost of the former relative to the latter can be quantified. This example suggests that the net global warming effect can be reduced significantly by shifting to higher-performance equipment using the same refrigerant – a greenhouse gas – even with an increased charge of refrigerant.

There is no doubt that the relationship between efficiency and cost will change as the technologies utilized are further developed. Efficiency, therefore, also may be viewed as a function of time. Existing equipment, for example, has improved over the years, and higher-performance equipment is available today for the same price – with adjustments for inflation – as a decade ago. This evolution in technology will continue for both commonly used and new, alternative refrigerants. While the real (i.e., with adjustment for inflation) cost of increasing efficiency may decline with time, the changes in relative costs among equipment with different refrigerants should be much smaller.

Efficiency data are being sought for several relative cost levels for specific equipment categories and nominal capacities, jointly selected by representatives of AFEAS and ARI. These data should be based on equipment designed for the individual refrigerants. The intent is to examine options optimized for the specific refrigerants, rather than *drop-in* substitutions in equipment tailored for another fluid. Please **provide data for four or more pairs of efficiency and corresponding relative costs, with each indicated refrigerant, for any of the following equipment that you manufacture or are able to**

APPENDIX - ARI Data Request

reliably estimate (e.g., within 5% on efficiencies and costs). A reference system is suggested for each equipment category to increase the uniformity in calculating relative costs.*

unitary air conditioners/chillers: **provide SEERs and relative costs**

2½-ton split-system air conditioner using HCFC-22, HFC-134a, and ammonia (R-717) coupled with an intermediate water delivery system to keep the ammonia outdoors (reference system: HCFC-22, SEER = 10 Btu/Wh)

7½-ton packaged gas-electric system using HCFC-22, HFC-134a, and ammonia (R-717) – the ammonia option should include either an intermediate water loop, to avoid ammonia in the air-cooling coil, or use of a double-wall, externally-vented heat exchanger (reference system: HCFC-22, EER = 8.9 Btu/Wh)

unitary heat pumps: **provide SEERs, HSPFs, and relative costs**

2½-ton split-system using HCFC-22, HFC-134a, and ammonia (R-717) coupled with an intermediate water delivery system to keep the ammonia outdoors (reference system: HCFC-22, SEER = 10 Btu/Wh, HSPF = 6.8 Btu/Wh)

air-cooled chillers: **provide IPLV and relative costs**

100-ton chiller using consistent manufacturer's choice of reciprocating-piston, screw, or scroll compressor(s) with HCFC-22 and HCFC-134a (reference system: HCFC-22, IPLV = 1.00 kW/ton)

water-cooled chillers: **provide IPLV and relative costs**

300-ton chiller using consistent manufacturer's choice of centrifugal or screw compressor with CFC-11 and HCFC-123, and/or CFC-12 and HFC-134a, and HCFC-22 (reference system: centrifugal compressor, CFC-11, IPLV = 0.66 kW/ton)

1000-ton chiller using consistent manufacturer's choice of centrifugal or screw compressor(s) with CFC-11, CFC-12, HCFC-22, HCFC-123, HFC-134a, and R-500 (reference system: centrifugal compressor(s), CFC-11, IPLV = 0.66 kW/ton)

3000-ton chiller with centrifugal compressor(s) with CFC-12, HCFC-22, and HFC-134a (reference system: HCFC-22, IPLV = 0.66 kW/ton)

direct-fired (gas) chillers: **provide IPLV-equivalent values (gas in Mbh/ton and parasitic electricity in kW/ton) as well as relative costs** for a single-effect, double-effect, and advanced (e.g., dual-cycle or triple-effect) system(s)

2½-ton chiller and indoor water (brine) coil (reference system: single-effect ammonia/water)

300-ton chiller (reference system: double-effect water/lithium-bromide)

1000-ton chiller (reference system: double-effect water/lithium-bromide)

---

* The reference performance levels are based on minimum 1992 efficiencies, under ASHRAE/IES standard 90.1-1989, for applicable products. The 2½-ton air conditioner performance is consistent with the requirements under the National Appliance Energy Conservation Act (NAECA) for 1992.

Costs for the refrigerants to charge the equipment should be based on your company's estimates of 1995 refrigerant prices, including applicable excise taxes for CFC-11 and CFC-12. Performance should be calculated for standard rating conditions in accordance with the applicable ARI standards (210/240, 550, 560, and 590) for uniformity. Please do not substitute efficiency-to-cost or efficiency-to-relative-cost regressions, but provide the requested data as calculated. Your doing so will enable calculation of industry regressions with primary data, rather than basing compilations on secondary data derived from individual correlations.

Now the hard part. **These data are needed <u>by 28 February 1991</u>.** Please send or fax the requested data, for the equipment and refrigerant options that you are able to calculate, to:

James M. Calm
Vice President, Research and Technology
Air-Conditioning and Refrigeration Institute
1501 Wilson Boulevard, Sixth Floor
Arlington, VA 22209-2403
703/524-8800 (fax 703/528-3816)

So you know what will follow, the data will be merged by ARI staff, and regression relations will be computed based on the consolidated data. ARI staff will calculate efficiencies at comparable costs for alternative refrigerants, as depicted in figure 2 by the intercepts of the regression curves with a vertical line, for each system option.

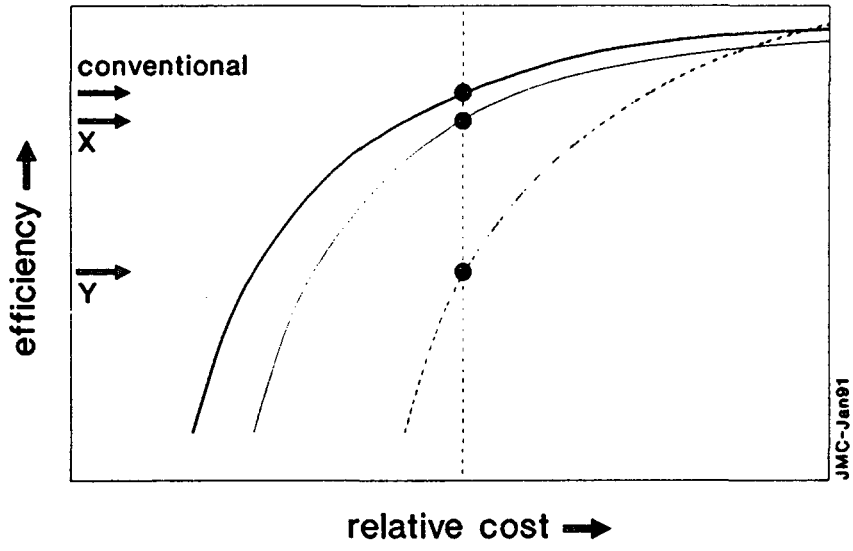

Figure 2 – Efficiencies for Comparable Costs

Two or more sets of calculated efficiencies (intercepts) will be provided by ARI to staff of the Oak Ridge National Laboratory (ORNL), with whom AFEAS has contracted for further analyses. The first sets of efficiency intercepts will enable comparisons of global warming among alternative refrigerants for the reference systems. These analyses will be based on integrated emissions over estimated equipment lifetimes considering both direct and indirect effects. The second set will be used to analyze whether global warm-

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ing can be reduced more, for a given cost increase, by changing refrigerants or by increasing efficiency with the reference fluid. The second set also will enable a comparison of alternative refrigerants for equipment with improved efficiencies. A third set of intercepts may be provided, if there are significant changes in efficiency rankings among alternative refrigerants with increasing costs (i.e., if the efficiency to relative-cost relationships cross for practical options). The resulting study is expected to identify the options to reduce net global warming requiring the lowest investments.

Several specific steps are being taken both to protect proprietary information and to eliminate any potential antitrust concerns. First, neither the individual company data submitted nor the resulting industry regressions will be made available to anyone except involved ARI staff; the data and regressions will not be provided to member companies, the ARI R&T Committee, AFEAS, or ORNL. Both the original company data and the calculated regressions will be carefully destroyed as soon as they are no longer needed for this study. ORNL will be restricted in the ARI data it may release (including to AFEAS) or retain. ORNL will be allowed to publish the efficiency intercepts, but not to identify the relative costs for these efficiencies except to indicate which correspond to the reference systems. Similarly, ORNL will not be allowed to publish any information from which the restricted information could be backed out; only ARI staff will review ORNL computations from which the restricted ARI information could be determined. ORNL will return the data received from ARI and agree not to retain any copies; ARI, in turn, will destroy this material. ORNL has agreed to these terms, and a binding written agreement will be executed before the data are provided by ARI.

To assure the reliability of the study, the R&T Committee will review the analytical procedures (but not the actual data or calculations). The Committee also will review the resulting ORNL interpretations. The AFEAS and ORNL publications may summarize the approach used and explain the need to withhold the cited cost data.

The AFEAS/ORNL study also will address several scenario's of emission mitigation. The Clean Air Act Amendments of 1990 will prohibit deliberate venting of refrigerants during service. Similarly, broader conformance to the ASHRAE Guideline on emission reductions and, for low-pressure systems, improved purge systems will curtail avoidable refrigerant emissions. Since the net impact cannot be determined at this time, this effect will be treated parametrically.

The stringent time frame for this study is driven by scheduled actions of the United Nations Environment Programme (UNEP). A timely submission by ARI is needed to enable completion of the larger study by June 1991. The resultant data then will be used in the science and technology assessments required before the 1992 review of the control provisions of the Montreal Protocol. Under UNEP procedures, changes to the Protocol must be proposed at least six months in advance, so the assessments must be completed in 1991. The study also will provide important information to governments, for a scheduled meeting in June 1992 in Brazil to address development of an international climate convention and for other legislative and regulatory actions.

This letter is somewhat technical in nature and may not be clear to all of you, particularly those unacquainted with the background. The information sought should be more familiar to your engineering staff, who will necessarily be involved in the replies. The underlying issue is assurance that HCFC-22 and some of the new alternative refrigerants, including HCFC-123 and HFC-134a, receive fair assessments in current environmental policy making.

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Some companies may not be able to provide the data requested, and only a few will be able to supply data for all the equipment and refrigerant options identified. I will gladly provide any clarification or further guidance needed, but will necessarily rely on your decisions regarding which options you can or are willing to respond to.

Thank you for your assistance in this critical study.

Sincerely,

James M. Calm
Vice President
Research and Technology

cc: AFEAS Science Committee
ARI Executive Committee
ARI R&T Committee
ARI R&T Refrigerants Subcommittee
ARI R&T Energy Conservation Subcommittee

APPENDIX - ARI Data Request

APPENDIX G: COMMERCIAL CHILLERS - TABULATED RESULTS

Table G.1. European electric-driven chillers at base cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	20.7	21.0	1.6	21.4	3.2	21.7	4.8	22.1	6.3
	R-134a	21.5	21.8	1.3	22.1	2.5	22.3	3.7	22.6	4.9
300 RT water-cooled	R-11	21.7	23.3	7.0	24.9	13.1	26.6	18.5	28.2	23.2
	R-12	21.7	28.4	23.6	35.1	38.2	41.7	48.1	48.4	55.3
	R-22	21.9	22.5	2.4	23.0	4.8	23.6	7.0	24.1	9.1
	R-123	22.2	22.2	0.1	22.3	0.2	22.3	0.4	22.3	0.5
	R-134a	21.9	22.5	2.5	23.0	4.8	23.6	7.0	24.2	9.2
1000 RT water-cooled	R-11	21.4	23.2	7.8	25.0	14.4	26.8	20.2	28.6	25.2
	R-12	21.1	28.3	25.4	35.5	40.5	42.7	50.5	49.8	57.6
	R-22	19.7	20.7	4.7	21.7	9.0	22.7	13.0	23.6	16.6
	R-123	20.8	20.9	0.2	20.9	0.3	20.9	0.5	21.0	0.7
	R-134a	21.1	21.8	3.0	22.4	5.8	23.1	8.5	23.7	11.0
3000 RT water-cooled	R-12	23.6	30.1	21.5	36.6	35.4	43.0	45.1	49.5	52.3
	R-22	21.4	22.0	2.9	22.7	5.7	23.3	8.3	24.0	10.7
	R-134a	23.3	23.9	2.2	24.4	4.3	24.9	6.4	25.4	8.3

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.2. European electric-driven chillers at level A cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	19.2	19.6	1.8	19.9	3.5	20.3	5.1	20.6	6.7
	R-134a	20.7	20.9	1.3	21.2	2.6	21.5	3.9	21.8	5.1
300 RT water-cooled	R-11	20.8	22.5	7.3	24.1	13.6	25.7	19.1	27.4	23.9
	R-12	21.4	28.1	23.8	34.8	38.5	41.5	48.4	48.2	55.6
	R-22	21.1	21.7	2.5	22.2	5.0	22.8	7.3	23.3	9.4
	R-123	21.7	21.7	0.1	21.7	0.3	21.7	0.4	21.8	0.5
	R-134a	21.4	21.9	2.5	22.5	4.9	23.0	7.2	23.6	9.4
1000 RT water-cooled	R-11	19.4	21.2	8.5	23.0	15.6	24.8	21.7	26.6	27.0
	R-12	20.3	27.5	26.2	34.6	41.5	41.8	51.5	49.0	58.6
	R-22	18.3	19.3	5.1	20.3	9.6	21.3	13.8	22.2	17.6
	R-123	20.0	20.0	0.2	20.1	0.4	20.1	0.5	20.1	0.7
	R-134a	20.0	20.6	3.2	21.3	6.1	22.0	8.9	22.6	11.6
3000 RT water-cooled	R-12	21.4	27.9	23.2	34.3	37.7	40.8	47.6	47.3	54.8
	R-22	19.7	20.4	3.2	21.0	6.1	21.6	8.9	22.3	11.5
	R-134a	21.4	21.9	2.4	22.4	4.7	23.0	6.9	23.5	9.0

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.3. European electric-driven chillers at level B cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	17.2	17.5	2.0	17.8	3.9	18.2	5.7	18.5	7.5
	R-134a	19.2	19.5	1.4	19.8	2.8	20.1	4.2	20.3	5.5
300 RT water-cooled	R-11	17.8	19.4	8.4	21.0	15.6	22.7	21.7	24.3	26.9
	R-12	19.4	26.1	25.6	32.8	40.8	39.5	50.8	46.2	57.9
	R-22	18.0	18.6	3.0	19.1	5.7	19.7	8.4	20.2	10.9
	R-123	19.2	19.2	0.1	19.2	0.3	19.2	0.4	19.3	0.6
	R-134a	19.2	19.7	2.8	20.3	5.5	20.8	8.0	21.4	10.4
1000 RT water-cooled	R-11	17.2	19.0	9.5	20.8	17.3	22.6	23.9	24.4	29.5
	R-12	18.9	26.1	27.6	33.2	43.2	40.4	53.3	47.6	60.3
	R-22	---	---	---	---	---	---	---	---	---
	R-123	18.6	18.6	0.2	18.7	0.4	18.7	0.6	18.7	0.8
	R-134a	18.6	19.3	3.4	19.9	6.6	20.6	9.6	21.2	12.3
3000 RT water-cooled	R-12	---	---	---	---	---	---	---	---	---
	R-22	---	---	---	---	---	---	---	---	---
	R-134a	---	---	---	---	---	---	---	---	---

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.4. North American electric-driven chillers at base cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	27.1	27.4	1.3	27.8	2.5	28.1	3.7	28.5	4.9
	R-134a	28.2	28.4	1.0	28.7	1.9	29.0	2.9	29.3	3.8
300 RT water-cooled	R-11	28.4	30.0	5.5	31.7	10.3	33.3	14.8	34.9	18.8
	R-12	28.4	35.1	19.1	41.8	32.1	48.5	41.4	55.2	48.6
	R-22	28.7	29.3	1.9	29.8	3.7	30.4	5.4	30.9	7.1
	R-123	29.1	29.1	0.1	29.2	0.2	29.2	0.3	29.2	0.4
	R-134a	28.7	29.3	1.9	29.8	3.7	30.4	5.5	31.0	7.2
1000 RT water-cooled	R-11	28.0	29.8	6.0	31.6	11.4	33.4	16.2	35.2	20.4
	R-12	27.6	34.8	20.6	42.0	34.2	49.2	43.8	56.4	50.9
	R-22	25.8	26.8	3.6	27.8	7.0	28.8	10.2	29.7	13.2
	R-123	27.3	27.3	0.1	27.4	0.3	27.4	0.4	27.4	0.5
	R-134a	27.6	28.3	2.3	29.0	4.5	29.6	6.6	30.3	8.7
3000 RT water-cooled	R-12	30.9	37.4	17.3	43.9	29.5	50.4	38.6	56.8	45.6
	R-22	28.0	28.7	2.2	29.3	4.4	29.9	6.4	30.6	8.4
	R-134a	30.6	31.1	1.7	31.6	3.3	32.2	4.9	32.7	6.5

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.5. North American electric-driven chillers at level A cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	25.2	25.5	1.4	25.9	2.7	26.2	4.0	26.6	5.2
	R-134a	27.1	27.4	1.0	27.6	2.0	27.9	3.0	28.2	3.9
300 RT water-cooled	R-11	27.3	28.9	5.7	30.6	10.7	32.2	15.3	33.8	19.4
	R-12	28.0	34.7	19.3	41.4	32.3	48.1	41.8	54.8	48.9
	R-22	27.6	28.2	1.9	28.7	3.8	29.3	5.6	29.9	7.4
	R-123	28.4	28.4	0.1	28.4	0.2	28.5	0.3	28.5	0.4
	R-134a	28.0	28.6	1.9	29.1	3.8	29.7	5.6	30.2	7.3
1000 RT water-cooled	R-11	25.5	27.3	6.6	29.1	12.4	30.9	17.5	32.7	22.0
	R-12	26.6	33.7	21.3	40.9	35.1	48.1	44.8	55.3	52.0
	R-22	24.0	25.0	3.9	26.0	7.5	26.9	10.9	27.9	14.0
	R-123	26.2	26.2	0.1	26.3	0.3	26.3	0.4	26.3	0.5
	R-134a	26.2	26.8	2.4	27.5	4.8	28.2	7.0	28.8	9.1
3000 RT water-cooled	R-12	28.0	34.5	18.8	41.0	31.6	47.5	41.0	53.9	48.1
	R-22	25.8	26.5	2.4	27.1	4.7	27.8	6.9	28.4	9.0
	R-134a	28.0	28.5	1.8	29.1	3.6	29.6	5.4	30.1	7.0

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.6. North American electric-driven chillers at level B cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	22.5	22.8	1.5	23.2	3.0	23.5	4.4	23.9	5.8
	R-134a	25.2	25.5	1.1	25.7	2.2	26.0	3.2	26.3	4.2
300 RT water-cooled	R-11	23.3	24.9	6.6	26.5	12.3	28.2	17.4	29.8	22.0
	R-12	25.5	32.2	20.8	38.9	34.5	45.5	44.1	55.2	51.3
	R-22	23.6	24.2	2.3	24.7	4.4	25.3	6.5	25.8	8.5
	R-123	25.1	25.1	0.1	25.2	0.2	25.2	0.3	25.2	0.4
	R-134a	25.1	25.7	2.2	26.2	4.2	26.8	6.2	27.3	8.1
1000 RT water-cooled	R-11	22.5	24.3	7.4	26.1	13.8	27.9	19.3	29.7	24.2
	R-12	24.7	31.9	22.5	39.1	36.7	46.3	46.5	53.5	53.7
	R-22	---	---	---	---	---	---	---	---	---
	R-123	24.4	24.4	0.1	24.4	0.3	24.5	0.4	24.5	0.6
	R-134a	24.4	25.0	2.6	25.7	5.1	26.3	7.5	27.0	9.7
3000 RT water-cooled	R-12	---	---	---	---	---	---	---	---	---
	R-22	---	---	---	---	---	---	---	---	---
	R-134a	---	---	---	---	---	---	---	---	---

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.7. Japanese electric-driven chillers at base cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	23.4	23.8	1.5	24.1	2.9	24.4	4.3	24.8	5.6
	R-134a	24.3	24.6	1.1	24.9	2.2	25.2	3.3	25.5	4.4
300 RT water-cooled	R-11	24.5	26.2	6.3	27.8	11.8	29.4	16.7	31.1	21.1
	R-12	24.5	31.2	21.4	37.9	35.3	44.6	45.0	51.3	52.2
	R-22	24.8	25.4	2.2	25.9	4.2	26.5	6.2	27.1	8.1
	R-123	25.2	25.2	0.1	25.2	0.2	25.2	0.3	25.3	0.4
	R-134a	24.8	25.4	2.2	26.0	4.3	26.5	6.3	27.1	8.2
1000 RT water-cooled	R-11	24.2	26.0	6.9	27.8	12.9	29.6	18.2	31.4	22.9
	R-12	23.9	31.1	23.1	38.3	37.5	45.4	47.4	52.6	54.6
	R-22	22.3	23.3	4.2	24.3	8.1	25.3	11.6	26.2	14.9
	R-123	23.6	23.6	0.1	23.7	0.3	23.7	0.5	23.7	0.6
	R-134a	23.9	24.6	2.7	25.2	5.2	25.9	7.6	26.5	9.9
3000 RT water-cooled	R-12	26.7	33.2	19.5	39.7	32.6	46.2	42.1	52.7	49.2
	R-22	24.2	24.9	2.6	25.5	5.0	26.1	7.4	26.8	9.6
	R-134a	26.4	27.0	2.0	27.5	3.8	28.0	5.7	28.5	7.4

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.8. Japanese electric-driven chillers at level A cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	21.8	22.1	1.6	22.5	3.1	22.8	4.6	23.2	6.0
	R-134a	23.4	23.7	1.2	24.0	2.3	24.2	3.4	24.5	4.5
300 RT water-cooled	R-11	23.6	25.2	6.5	26.9	12.2	28.5	17.2	30.1	21.7
	R-12	24.2	30.9	21.7	37.6	35.6	44.3	45.3	51.0	52.5
	R-22	23.9	24.5	2.2	25.0	4.4	25.6	6.5	26.1	8.4
	R-123	24.5	24.6	0.1	24.6	0.2	24.6	0.3	24.6	0.4
	R-134a	24.2	24.8	2.2	25.3	4.4	25.9	6.4	26.4	8.4
1000 RT water-cooled	R-11	22.0	23.8	7.6	25.6	14.0	27.4	19.7	29.2	24.6
	R-12	23.0	30.1	23.8	37.3	38.5	44.5	48.4	51.7	55.6
	R-22	20.8	21.7	4.5	22.7	8.6	23.7	12.4	24.7	15.9
	R-123	22.6	22.7	0.2	22.7	0.3	22.8	0.5	22.8	0.6
	R-134a	22.6	23.3	2.8	24.0	5.5	24.6	8.0	25.3	10.4
3000 RT water-cooled	R-12	24.2	30.7	21.2	37.2	34.8	43.7	44.5	50.1	51.7
	R-22	22.3	23.0	2.8	23.6	5.4	24.3	7.9	24.9	10.3
	R-134a	24.2	24.7	2.1	25.3	4.2	25.8	6.1	26.3	8.0

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

Table G.9. Japanese electric-driven chillers at level B cost, 500 year GWP, and 20% load factor: summary of total equivalent warming impact (TEWI)

Equipment Category	Refrigerant	Refrigerant Loss (%/yr)								
		0%	4%		8%		12%		16%	
		INDIRECT Contribution (10^3 kg CO_2 per RT)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)	TEWI (10^3 kg CO_2 per RT)	DIRECT Contribution (%)
100 RT air-cooled	R-22	19.4	19.8	1.8	20.1	3.4	22.5	5.1	20.8	6.7
	R-134a	21.8	22.0	1.3	22.3	2.5	22.6	3.7	22.9	4.9
300 RT water-cooled	R-11	20.1	21.8	7.5	23.4	14.0	25.0	19.6	26.7	24.6
	R-12	22.0	28.7	23.3	35.4	37.8	42.1	47.7	48.8	54.9
	R-22	20.4	21.0	2.6	21.5	5.1	22.1	7.5	22.6	9.7
	R-123	21.7	21.7	0.1	21.8	0.3	21.8	0.4	21.8	0.5
	R-134a	21.7	22.3	2.5	22.8	4.9	23.4	7.1	23.9	9.3
1000 RT water-cooled	R-11	19.5	21.3	8.4	23.1	15.6	24.9	21.7	26.7	27.0
	R-12	21.4	28.6	25.1	35.7	40.2	42.9	50.2	50.1	57.3
	R-22	---	---	---	---	---	---	---	---	---
	R-123	21.1	21.1	0.2	21.1	0.3	21.2	0.5	21.2	0.7
	R-134a	21.1	21.7	3.0	22.4	5.8	23.0	8.5	23.7	11.1
3000 RT water-cooled	R-12	---	---	---	---	---	---	---	---	---
	R-22	---	---	---	---	---	---	---	---	---
	R-134a	---	---	---	---	---	---	---	---	---

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

APPENDIX H: RESIDENTIAL AND COMMERCIAL UNITARY HEATING AND COOLING EQUIPMENT

Table H.1. North American unitary equipment at 500 year GWP and 20 year life: summary of Total Equivalent Warming Impact (TEWI) ($x10^3$ CO_2/unit)

Equipment Category	Refrigerant	Refrigerant Loss Rate (%/yr): End of Life Loss (%)						
		0%/yr:0%	1%/yr:40%		4%/yr:40%		8%/yr:100%	
		INDIRECT (Energy Use) Contribution Equals TEWI (10^3 kg)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)
Base Cost								
2.5 RT Split System AC	R-22	36.3	37.0	1.9	37.7	3.7	39.3	7.7
	R-134a	41.2	41.7	1.1	42.2	2.3	43.3	4.8
2.5 RT Split System HP	R-22	166.0	166.8	0.5	167.6	1.0	169.6	2.1
	R-134a	214.7	215.3	0.3	215.9	0.5	217.3	1.2
Level A Cost								
2.5 RT Split System AC	R-22	32.7	33.3	2.1	34.0	4.1	35.7	8.4
	R-134a	36.3	36.8	1.3	37.2	2.6	38.4	5.4
2.5 RT Split System HP	R-22	128.9	128.9	0.6	129.7	1.3	131.7	2.8
	R-134a	166.0	166.6	0.4	167.1	0.7	168.5	1.5
Level B Cost								
2.5 RT Split System AC	R-22	30.1	30.8	2.2	31.5	4.4	33.1	9.1
	R-134a	32.7	33.1	1.4	33.6	2.8	34.7	6.0
2.5 RT Split System HP	R-22	---	---	---	---	---	---	---
	R-134a	---	---	---	---	---	---	---

Note: Refrigerant options within an equipment category are on a consistent basis and can by compared directly. Comparisons across equipment categories should be avoided.

Table H.2. Japanese unitary equipment at 500 year GWP and 20 year life: summary of Total Equivalent Warming Impact (TEWI) (x103 CO_2/unit)

Equipment Category	Refrigerant	Refrigerant Loss Rate (%/yr): End of Life Loss (%)						
		0%/yr:0%	1%/yr:40%		4%/yr:40%		8%/yr:100%	
		INDIRECT (Energy Use) Contribution Equals TEWI (10^3 kg)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)	TEWI (10^3 kg)	DIRECT (Refrigerant Loss) Contribution (%)
Base Cost								
2.5 RT Split System AC	R-22	7.7	8.4	8.3	9.1	15.3	10.7	28.2
	R-134a	8.7	9.2	5.2	9.7	9.9	10.8	19.2
2.5 RT Split System HP	R-22	69.0	69.8	1.2	70.7	2.4	72.6	5.0
	R-134a	88.9	89.5	0.7	90.1	1.3	91.5	2.8
Level A Cost								
2.5 RT Split System AC	R-22	6.9	7.6	9.1	8.3	16.7	9.9	30.4
	R-134a	7.7	8.1	5.9	8.6	11.1	9.7	21.3
2.5 RT Split System HP	R-22	53.0	53.8	1.6	54.7	3.1	56.7	6.4
	R-134a	69.0	69.6	0.9	70.2	1.7	71.6	3.6
Level B Cost								
2.5 RT Split System AC	R-22	6.4	7.1	9.8	7.7	17.9	9.4	32.1
	R-134a	6.9	7.4	6.5	7.9	12.2	9.0	23.1
2.5 RT Split System HP	R-22	---	---	---	---	---	---	---
	R-134a	---	---	---	---	---	---	---

Note: Refrigerant options within an equipment category are on a consistent basis and can be compared directly. Comparisons across equipment categories should be avoided.

APPENDIX I: AUTOMOBILE AIR-CONDITIONING

Table I.1. Lifetime equivalent CO_2 emissions for mobile air-conditioning
500 year GWP data

Refrigerant	Charge (g)	Loss Rate (g/yr)* low - high loss	GWP (kg CO_2/kg)	Direct** (kg) low - high loss	Direct** (%) low - high loss	Indirect (kg)	Indirect (%) high - low loss	Total (kg) low - high loss
Europe								
CFC-12	1200	120 - 400	4,500	5900 - 19,800	76 - 91%	1873	9 - 24%	7770 - 21,670
HFC-134a	1100	110 - 367	420	500 - 1,700	20 - 46%	1961	54 - 80%	2460 - 3660
HFC-134a (enhanced)	1100	110 - 367	420	500 - 1,700	22 - 49%	1769	51 - 78%	2270 - 3470
Ternary Blend	1040	104 - 347	234	300 - 900	14 - 32%	1873	68 - 86%	2170 - 2770
HFC-152a	750	75 - 250	47	0 - 100	0 - 5%	2109	95 - 100%	2110 - 2210
Propane	450	45 - 150	6	0	0%	2287	100%	2290
Brayton Cycle	-	-	0	0	0%	2021 - 4244	100%	2020 - 4240
Stirling Cycle	-	-	0	0	0%	2368 - 2975	100%	2370 - 2970
North America								
CFC-12	1200	120 - 400	4,500	5900 - 19,800	72 - 89%	2327	11 - 28%	8230 - 22,130
HFC-134a	1100	110 - 367	420	500 - 1,700	17 - 41%	2436	59 - 83%	2940 - 4140
HFC-134a (enhanced)	1100	110 - 367	420	500 - 1,700	19 - 44%	2197	56 - 81%	2700 - 3900
Ternary Blend	1040	104 - 347	234	300 - 900	11 - 28%	2327	72 - 89%	2630 - 3230
HFC-152a	750	75 - 250	47	0 - 100	0 - 4%	2620	96 - 100%	2620 - 2720
Propane	450	45 - 150	6	0	0%	2842	100%	2840
Brayton Cycle	-	-	0	0	0%	2511 - 5273	100%	2510 - 5270
Stirling Cycle	-	-	0	0	0%	2942 - 3696	100%	2940 - 3700
Japan								
CFC-12	800	80 - 267	4,500	4000 - 13,200	74 - 90%	1430	10 - 26%	5430 - 14,330
HFC-134a	725	73 - 242	420	300 - 1,100	17 - 42%	1500	58 - 83%	1800 - 2600
HFC-134a (enhanced)	725	73 - 242	420	300 - 1,100	18 - 45%	1350	55 - 82%	1650 - 2450
Ternary Blend	700	70 - 233	234	200 - 600	12 - 30%	1430	70 - 88%	1630 - 2030
HFC-152a	500	50 - 167	47	0 - 100	0 - 6%	1610	96 - 100%	1610 - 1710
Propane	380	38 - 127	6	0	0%	1750	100%	1750 - 1750
Brayton Cycle	-	0	0	0	0%	1550 - 3250	100%	1550 - 3250
Stirling Cycle	-	0	0	0	0%	1810 - 2280	100%	1810 - 2280

* estimated based on current leakage rates of 340 g (0.75 lb) for North America (Halberstadt, 1991) and Europe and 265 g (0.58 lb) for Japan (JAMA, 1990) and target rates of 113 g (0.25 lb) and 80 g (0.18 lb) in Japan.

** assumes 100% recovery of remaining charge when vehicle is scrapped.

APPENDIX J: COMMERCIAL BUILDING INSULATION

TABLES OF MARKET DATA AND REFERENCES

Table J.1. Estimated 1989 usage of PUR/PIR boardstock and laminate in building insulation in the United States

	Board/Laminate (10^6 kg)	Percent	Table References
Residential			
wall sheathing	39.5	21.5	11.
Non-residential			
roof: low-slope	110.2	60.0	1., 2., 12., 13
walls: masonry	22.7	12.3	2. 3.,4.,5.,6.,7.,8.,9.
walls: metal panels	11.3	6.2	2.,3.,4.,5.,6.,7.,8.,9.,10.
Total	183.7	100.0	1.

Table J.1 References:

1. "End-Use Market Survey Of The Polyurethane Industry In The United States And Canada", 1990, The Society of the Plastics Industry, Inc.--Polyurethane Division, 355 Lexington Avenue, New York, NY 10017.

2. "Nonresidential Buildings Energy Consumption Survey: Characteristics of Commercial Buildings 1986", September 13, 1988, U.S. Department of Energy--Energy Information Administration, DOE/EIA-0246(86).

12. August 7, 1989 issue of Rubber & Plastics News.

13. Data from the Polyisocyanurate Insulation Manufacturers Association (PIMA) received from Jean Lupinacci, of the U.S. Environmental Protection Agency, on February 6, 1991.

- Total in 1989-- Exhibit 10 of Reference 1.

- %roofing in 1989-- Page 21 of Reference 1. 60% roofing. Residential use of foam board in roofing is not common so all was assumed to be used in non-residential low-slope roofs. References 2, 12 and 13 were used as an independent check. Reference 12 estimates the total U.S. non-residential roofing market at 287×10^6 m^2 (3088×10^6 ft^2). Reference 2 indicates that 72.2% of the 1986 non-residential roof stock is insulated low-slope roofing. Reference 13 was used to estimate PUR/PIR market share for 1984-86 and extrapolation to 1989 resulted in 35%. Assuming a 5.08 cm (2 in.) typical thickness and 32.04 kg/m^3 (2 lb/ft^3) resulted in 111.1×10^6 kg (245×10^6 lb) versus 110.2×10^6 kg (243×10^6 lb) from Reference 1

2. "Nonresidential Buildings Energy Consumption Survey: Characteristics of Commercial Buildings 1986", September 13, 1988, U.S. Department of Energy--Energy Information Administration, DOE/EIA-0246(86).

3. "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings, Volume III: Description of the Testing Process", October 1983, U.S. Department of Energy, DOE/NBB-0051/6.

4. "Commercial Buildings Energy Performance Standards Technical Support Document No. 1.b.9: Reference Building Descriptions", May 29, 1980, The Ehrenkrantz Group, Inc. for the U.S. Department of Energy, DOE/BEPS-TSD1.b.9.

5. "Economic Screening Guidebook for Cogeneration in Buildings", November 1985, ARS Group, Inc. for the Gas Research Institute, GRI 85/0223.

6. "The Project on Restaurant Energy Performance-- End-Use Monitoring and Analysis", May 1985, Pacific Northwest Laboratory for the U.S. Department of Energy, PNL-5462.

7. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Grocery #2", October 1988, United Industries Corp. for Seattle City Light.

8. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Restaurant #1", November 1988, United Industries Corp. for Seattle City Light.

9. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Restaurant #2", November 1988, United Industries Corp. for Seattle City Light.

10. February 5, 1991 letter from Dr. G.M.F. Jeffs of ICI Polyurethanes of Belgium to P.D. Fairchild of Oak Ridge National Laboratory.

- General procedure-- Reference 2 does not provide opaque wall areas directly. References 3 to 9 provide definitions of 53 actual non-residential buildings built in the U.S. The 53 buildings were used as the basis to construct plots of opaque wall area versus floor space for each Reference 2 non-residential building type. For building types not well represented throughout the range of possible floor space, reasonable design variations were made off of the available buildings to obtain smaller and larger buildings. After opaque wall area by building type was derived, Reference 2 did provide the basis to estimate insulated metal panel wall areas and other wall areas likely to be insulated with foam board/laminate type products.

- Walls: metal panels in 1989--Reference 2 was used to estimate the area of insulated metal wall panels added during 1984-86. This value was divided by three to estimate the 1985 shipments. 10% per year growth was assumed from 1985 to 1989. To calculate PUR/PIR weight it was assumed that PUR/PIR has 100% of this market, a typical thickness of 5.08 cm (2 in.), and a typical density of 32.04 kg/m^3 (2 lb/ft^3). Reference 10 provided an estimate of Western European insulated metal panels and stated that North American usage is an order of magnitude less. This statement is roughly consistent with the estimate.

- Walls: masonry in 1989--Reference 2 was used to estimate the area of site-applied PUR/PIR wall insulation added during 1984-86. This value was divided by three to estimate the 1985 shipments. A 5% per year growth was assumed from 1985 to 1989. Wood frame and steel frame walls were excluded because fiberglass batts in the stud spaces would meet ASHRAE/IES Std. 90.1-1989 requirements except for some building types in the northern part of the U.S. It was reasoned that the frame wall sheathing not counted roughly offset the use of XEPS and MEPS so that a 100% PUR/PIR market share could be assumed for the estimated area. Other assumptions were a typical thickness of 2.54 cm (1 in.) and a typical density of 32.04 kg/m^3 (2 lb/ft^3).

11. February 1991 personal communication from Joe Hagan of Jim Walter Corporation.

- Residential wall sheathing in 1989--An estimate was provided of 55.3×10^6 m^2 (595×10^6 ft^2) per year, with thicknesses ranging from 1.59 to 2.54 cm (5/8 to 1 in.). At 32.04 kg/m^3 (2 lb/ft^3), that corresponds to a range of 28.1 to 45.4×10^6 kg (62 to 100×10^6 lb). The selected value of 38.5×10^6 kg (85×10^6 lb) provides a material balance and is near the midpoint of this range.

Table J.2. Estimated 1989 usage of PUR/PIR boardstock and laminate in building insulation in North America

	Board/Laminate (10^6 kg)	Percent	Table References
Residential			
wall sheathing	44.0	21.6	2.
Non-residential			
roof: low-slope	122.5	60.0	2.
walls: masonry	24.9	12.2	2.
walls: metal panels	12.7	6.2	2.
Total	204.1	100.0	1.

Table A2 References:

1. "End-Use Market Survey Of The Polyurethane Industry In The United States And Canada", 1990, The Society of the Plastics Industry, Inc.--Polyurethane Division, 355 Lexington Avenue, New York, NY 10017.

   - Total in 1989-- Exhibit 29 value plus U.S. total. North America is approximated as U.S. plus Canada.

2. Same percentages as in the U.S.

Table J.3. Estimated 1989 usage of PUR/PIR boardstock and laminate in building insulation in Western Europe

	Board/Laminate (10^6 kg)	Percent	Table References
Residential			
wall: frame sheathing	3.6	1.5	1.,3.
wall: masonry cavity	4.6	1.9	1.,3.
wall: masonry inside (dry-lined)	4.5	1.9	1.,3.
wall: masonry outside (EIFS)	1.9	0.8	1.,3.
roof: low-slope	14.0	5.8	1.,3.
roof: pitched	14.6	6.1	1.,3.
Non-residential			
roof: low-slope	50.9	21.2	1.,3.
roof: pitched	3.8	1.6	1.,3.
walls: masonry (all types)	10.0	4.2	1.,3.
walls/roof: metal panels	132.0	55.0	1.
Total	239.9	100.0	1.,2.

Table A3 References:

1. February 5, 1991 letter from Dr. G.M.F. Jeffs of ICI Polyurethanes of Belgium to P.D. Fairchild of Oak Ridge National Laboratory.

2. March 1, 1991 telefax from M.J. Cartmell of European Isocyanurate Producers Association (ISOPA) to Jean Lupinacci of the U.S. Environmental Protection Agency.

   - Non-residential wall/roof metal sandwich panels in 1989--Reference 1 annual shipments of $55x10^6$ m^2 ($592x10^6$ ft^2) with a typical density of 40 kg/m^3 (2.5 lbs/ft^3) and thickness of 60 mm (2.36 in.).

   - Residential and non-residential flexible-faced laminate boardstock in 1989--Reference 1 annual shipments of $75x10^6$ m^2 ($807x10^6$ ft^2) with a typical density of 32 kg/m^3 (2 lbs/ft^3) and thickness of 45 mm (1.77 in.).

   - Total in 1989-- The total of $239.9x10^6$ kg ($529x10^6$ lbs) was derived from adding the Reference 1 components. Reference 2 was used as an independent check. In 1986, 32,040 metric tons of CFC in the Rigid Building/Industrial category was stated for Western Europe. At a 15% CFC by weight that corresponds to $213.6x10^6$ kg ($471x10^6$ lbs). Assuming 4% per year growth from 1986 to 1989 results in $240.4x10^6$ kg ($530x10^6$ lbs).

3. Galloway, P., "A Survey of the European Uses of Laminates Based on Rigid Polyurethane Foam," performed for ICI Polyurethanes, April 21, 1991. Transmitted with cover letter dated April 29, 1991, from G. M. F. Jeffs of ICI Polyurethanes of Belgium to P. D. Fairchild of Oak Ridge National Laboratory.

- Distribution of flexible-faced laminate boardstock to end-uses in 1989--Reference 1 and Reference 2 provide the total PUR/PIR and Reference 1 provides the breakout between sandwich panels and flexible-faced materials. On a weight basis, Reference 1 indicates that 55% of PUR/PIR goes to metal sandwich panels. Reference 3 is in rough agreement, indicating 43% if it is assumed that all cold stores and agricultural boardstock are of this type. Assuming Reference 1 is correct, a 20/80% split between residential and non-residential is indicated for the flexible-faced materials. Reference 3 indicates a 55/45% split. An intermediate 40/60% split was assumed here. The Reference 3 residential pitched roof usage for Germany seemed too high, so a material transfer to commercial low-slope roof usage was made to force the 40/60% split. After Reference 3 was adjusted in this way, Reference 3 percentages were used to allocate flexible-faced materials to the end-uses in residential and non-residential applications.

Table J.4. Estimated 1989 usage of PUR/PIR boardstock and laminate in building insulation in Japan

	Board/Laminate (10^6 kg)	Percent	Table References
Residential			
wall sheathing	20.4	59.1	2.
Non-residential			
roof: low-slope	11.8	34.2	2.
walls: masonry	2.3	6.7	2.
walls: metal panels	---	---	---
Total	34.5	100.0	1.,2.

Table A4 References:

1. March 1, 1991 telefax from M.J. Cartmell of European Isocyanurate Producers Association (ISOPA) to Jean Lupinacci of the U.S. Environmental Protection Agency.

2. March 4, 1991 letter from J. H. Minsker of Dow Chemical U.S.A. to P.D. Fairchild of Oak Ridge National Laboratory.

   - Total in 1989-- Reference 1 stated 5200 metric tons of CFC in the Rigid Building/Industrial category for Japan in 1986. At 15% CFC by weight that corresponds to 34.5×10^6 kg (76.4×10^6 lbs). Reference 2 stated 30700 metric tons of PUR/PIR for Japan in 1990, which corresponds to 30.7×10^6 kg (67.7×10^6 lbs). The 1990 estimate is lower than the 1986 estimate. The Reference 1 value is used for 1989.

   - Commercial wall sheathing in 1989-- Reference 2 provided the basis for the split between residential and commercial.

   - Non-residential materials in 1989-- It was assumed that curtain wall metal panels were not common in Japan. The same end-use split as in North America was assumed for the remaining categories.

Table J.5. Estimated 1989 usage of PUR/PIR boardstock and laminate in building insulation in the world

	Boardstock/Laminate (10^6 kg)				
	North America	Europe	Japan	Rest Of The World	World Total
Residential -walls: all types -roofs: all types	 44.0 --	 17.2 33.7	 20.4 --		
Non-residential -roofs: low-slope -walls: masonry -walls/roof: metal panels	 122.5 24.9 12.7	 64.4 11.8 155.4	 11.8 2.3 ---		
Total	204.1 36%	282.5 50%	34.5 6%	46.2 8%	567.3 100%
Column references:	1.	2.,3.	4.	5.	6.

Table J.5 References::

1. Table J.2.

2. Table J.3.

3. March 1, 1991 telefax from M.J. Cartmell of European Isocyanurate Producers Association (ISOPA) to Jean Lupinacci of the U.S. Environmental Protection Agency.

   - Combination of Western and Eastern Europe-- Western Europe is from Reference 2. Eastern Europe is from Reference 3 assuming 4% per year growth from 1986 to 1989. The end-use breakouts were assumed to be the same throughout Europe.

4. Table J.4.

5. March 1, 1991 telefax from M.J. Cartmell of European Isocyanurate Producers Association (ISOPA) to Jean Lupinacci of the U.S. Environmental Protection Agency.

   - Rest of the world-- Obtained from Reference 5 assuming 4% per year growth from 1986 to 1989.

6. Sum of column totals.

Table J.6. Estimated 1989 distribution of usage of PUR/PIR boardstock and laminate among non-residential building types in the United States

	Board/Laminate (10^6 kg)				
	Low-Slope Roof	Walls: Masonry	Walls: Metal Panels	Total	
assembly	8.7	4.0	1.3	14.0	9.7%
education	17.0	2.6	--.-	19.6	13.6%
food sales	1.3	0.4	--.-	1.7	1.2%
food service	1.8	0.6	0.3	2.7	1.9%
health care	5.5	0.6	0.2	6.3	4.4%
lodging	4.6	1.2	0.2	6.0	4.2%
mercantile+service	26.6	5.9	3.9	36.4	25.2%
office	21.3	3.4	1.2	25.9	17.9%
public order+safety	1.3	0.6	--.-	1.9	1.3%
warehouse	22.1	3.4	4.2	29.7	20.6%
total	110.2	22.7	11.3	144.2	100%
	76.4%	15.7%	7.9%	100%	

1. "Nonresidential Buildings Energy Consumption Survey: Characteristics of Commercial Buildings 1986", September 13, 1988, U.S. Department of Energy--Energy Information Administration, DOE/EIA-0246(86).

2. "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings, Volume III: Description of the Testing Process", October 1983, U.S. Department of Energy, DOE/NBB-0051/6.

3. "Commercial Buildings Energy Performance Standards Technical Support Document No. 1.b.9: Reference Building Descriptions", May 29, 1980, The Ehrenkrantz Group, Inc. for the U.S. Department of Energy, DOE/BEPS-TSD1.b.9.

4. "Economic Screening Guidebook for Cogeneration in Buildings", November 1985, ARS Group, Inc. for the Gas Research Institute, GRI 85/0223.

5. "The Project on Restaurant Energy Performance-- End-Use Monitoring and Analysis", May 1985, Pacific Northwest Laboratory for the U.S. Department of Energy, PNL-5462.

6. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Grocery #2", October 1988, United Industries Corp. for Seattle City Light.

7. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Restaurant #1", November 1988, United Industries Corp. for Seattle City Light.

8. "Commercial Hourly End-Use Study: Energy Conservation Analysis of Restaurant #2", November 1988, United Industries Corp. for Seattle City Light.

- Low-slope roof insulation allocation--Reference 1 does provide the basis for estimating low-slope roof insulation allocations. Floor space is provided by building type and size. The fraction of floor space with low-slope roofs could be estimated by building type. The ratio of insulated low-slope roof area to floor space with low-slope roof could be estimated by building size. From this information insulated low-slope roof area could be estimated by building type and size. Insulated low-slope roof area by building type was obtained by summing across all building sizes. By assuming average insulation thickness is independent of building type, this provides an allocation of roof insulation to building types based on the 1986 non-residential building stock. It was assumed that 1989 shipments allocate as per the historical experience.

- Masonry and metal panel wall insulation allocation--Reference 1 does not provide opaque wall areas or other means to allocate wall insulation directly. References 2 to 8 provide definitions of 53 actual non-residential buildings built in the U.S. The 53 buildings were used as the basis to construct plots of opaque wall area versus floor space for each Reference 1 non-residential building type. For building types not well represented throughout the range of possible floor space, reasonable design variations were made off of the available buildings to obtain smaller and larger buildings. After opaque wall area by building type was derived, Reference 1 did provide the basis to estimate site-applied and metal panel wall insulation allocations by building type.

APPENDIX K: COMMERCIAL BUILDING INSULATION

ESTIMATION OF THERMAL PROPERTIES FOR AGED

AGED FOAM WALL INSULATION

INDIRECT CO_2 EMISSIONS ANALYSIS METHODOLOGY

The INDIRECT CO_2 emission calculations are necessarily quite involved. The method relies on the DOE-2.1D building energy analysis computer program (LBL, 1990) to estimate annual energy consumption for a number of variations of wall and roof R-values in retail malls and warehouses in two North American and two European cities. An overview of the methodology is provided, followed by detailed descriptions of foam boardstock thermal property estimation, building energy analysis, and lifetime INDIRECT CO_2 emissions estimation.

OVERVIEW

Typical foam insulating boardstock applications in commercial buildings include low-slope roofs, masonry walls, and metal panel walls in low-rise retail malls and warehouses. The typical service life of foam board in low-slope roofs is approximately fifteen years and in walls is approximately 50 years. The objective of the analysis is to estimate typical insulation-related space conditioning energy consumptions over the insulation service lives appropriate for walls and roofs. The lifetime energies are then used to estimate insulation-related lifetime INDIRECT CO_2 emissions.

Annual insulation-related space conditioning energies are estimated for prototypical buildings in specific locations using DOE-2.1D. It is widely known that the thermal properties of foam boardstock vary with time and thickness. Therefore the analysis is based on reasonable insulation thicknesses and time averaged R-values that correspond to the insulation service life and thickness. Reasonable board thicknesses are selected for each building application by following the prescriptive guidelines of a widely recognized model building standard. Lifetime energies are estimated by multiplying annual values by service life.

The insulation-related annual heating energies and cooling electric consumptions are accounted for separately. This enables regional heating energy and power generation fuel mixes to be considered in the INDIRECT CO_2 emissions calculations.

Many commercial building types in addition to retail malls and warehouses use foam board. Also many wall and roof cross-sectional designs in addition to the ones selected use foam board. This analysis was not intended to be all inclusive but rather was intended to yield typical insulation-related energies for use in the INDIRECT CO_2 emissions calculations.

ESTIMATION OF THERMAL PROPERTIES OF FOAM INSULATING BOARDSTOCK

Foam insulating boardstock has superior thermal performance due to the low thermal conductivity of blowing agent gases in the foam cells. However it is widely known that the thermal conductivity (k) of foam boardstock varies with time and thickness. Heat is transferred through foam by conduction and radiation in parallel mechanisms, with conduction occurring through both solid and gaseous phases. When exposed to air the composition of the foam cell gas changes with time due to inward diffusion of air components and outward diffusion of blowing agent. As the thermal conductivity of the cell gas increases with the change in composition, k of the foam board increases or "ages". Thickness is important because it influences diffusion time to the interior of the board.

The typical aging pattern of closed-cell foams is illustrated in Figure K.1 (Booth, 1991). The value of k is imbedded in a "k-factor" (i.e., ln[100 k]) expressed as a function of "scaled age" (i.e., $\sqrt{\text{time/thickness}}$). Three regions are identified on the aging curve. Initially the foam k-factor equals the fresh-foam value. Region 1 (thermal drift) represents a period of relatively rapid increase in k-factor due to inward diffusion of air components in PUR/PIR foams (McElroy, March 1991) and the combination of inward air diffusion and outward diffusion of fugitive (i.e., auxiliary) blowing agents in XEPS (Booth, 1991). Region 2 (plateau) represents a subsequent period of relatively modest increase in PUR/PIR or XEPS k-factor due to the slow outward diffusion of the insulating blowing agent from air-saturated foam (Booth, 1991; McElroy, March 1991). Region 3 represents the period when the insulating blowing agent has been depleted and the foam k-factor remains constant at its air-filled value.

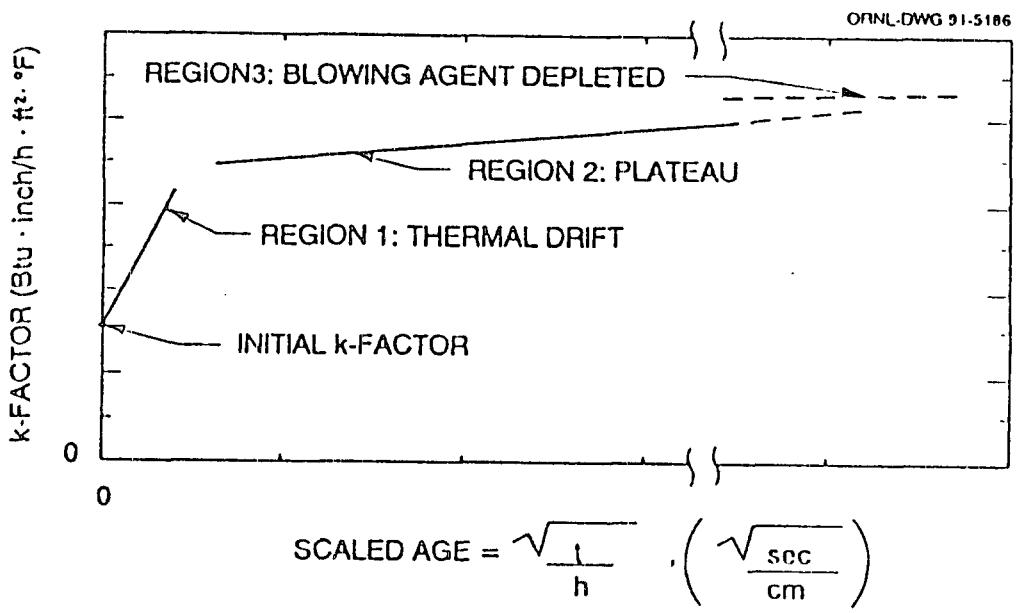

Fig. K.1. Characteristic closed-cell foam thermal conductivity aging curve.

Equations describing closed-cell foam aging curves within Regions 1 and 2 assume that k has an exponential dependence on diffusion coefficient (D), time (t), and thickness (h) within the region of interest,

$$k(t) = k(0) \times e^{\frac{\sqrt{Dt}}{h}} \tag{K.1}$$

or

$$\ln[100 \times k] = \ln[100 \times k(0)] + \frac{\sqrt{Dt}}{h} \tag{K.2}$$

or

$$\ln[100 \times k] = A + B \times \frac{\sqrt{t}}{h} \tag{K.3}$$

For specific foams the A and B coefficients for Regions 1 and 2 were empirically derived from experimental data. The Region 1 and 2 equations and the Region 3 constant were used to calculate the intersect times between regions for several specific board thicknesses. The intersects were used to declare the appropriate times for Regions 1, 2, and 3. Then k was calculated as a function of time for each region encountered (1; or 1 and 2; or 1, 2, and 3) and average k was estimated as the integral of k over the service life divided by the service life. Then for each service life of interest,

the average R-values (reciprocals of k) were plotted versus thickness and curves drawn to enable estimates of average R-value at any thickness.

For specific foams the fresh foam k was empirically derived from experimental data. Describing k(foam) as the sum of parallel mechanisms for gas conduction, solid conduction, and radiation (Booth, 1991),

$$k(foam) = k(gas) + k(solid) + k(radiation) \quad \text{(K.4)}$$

For fresh foam k(gas) equals k(blowing agent) and k(solid) + k(radiation) can be calculated from Equ. K.4. For specific types of foams k(solid) + k(radiation) is a constant independent of blowing agent and age. The value of k(solid) + k(radiation) for PUR/PIR foams equals 0.0094 W/m-°K (0.065 Btu-in/h-ft^2-°F) at 24°C (75°F), and for XEPS foams equals 0.0124 W/m-°K (0.083 Btu-in/h-ft^2-°F) at 24°C (75°F). For Region 3 foam, k(gas) equals k(air) equals 0.0259 W/m-°K (0.18 Btu-in/h-ft^2-°F) and k(foam) can be calculated from Equ. K.4.

Test Data

As part of a U.S. Cooperative Industry/Government project, k as a function of aging time at 24°C (75°F) has been measured at Oak Ridge National Laboratory (ORNL) for permeably-faced PUR/PIR boards blown with CFC-11, HCFC-123, and HCFC-141b (McElroy, 1990; McElroy, March 1991). A slicing technique was used whereby full-thickness, half-thickness, and quarter-thickness specimens were tested to accelerate the change in k with time by shortening the distance for diffusion of gases to the board centerline. ORNL also performed limited testing on 5.08 cm (2.0 in) thick XEPS insulating board blown with HCFC-142b for aging times up to 1.45 years (McElroy, March 1991).

Table K.1 summarizes the fresh-foam values of k(gas) (McElroy, March 1990) and k(foam), the Equ. K.3 values of A and B for Region 1 and Region 2, and the Region 3 air-filled values of k(foam) found for these specimens. Also summarized are the intersect times between regions at board thicknesses of 2.54 cm (1.0 in), 5.08 cm (2.0 in), and 7.62 cm (3.0 in).

Extensions of Test Data

Several approximations were made in order to include in the analysis a new PUR/PIR foam blown with isopropylchloride (IPC) (McElroy, May 1991). As previously explained for PUR/PIR foams k(solid) + k(radiation) is a constant equal to 0.0094 W/m-°K (0.065 Btu-in/h-ft^2-°F) at 24°C (75°F). For PUR/PIR blown with IPC, k(fresh foam) equals 0.020 W/m-°K (0.139 Btu-in/h-ft^2-°F) at 10°C (50°F) and k(IPC) equals 0.012 (0.083 Btu-in/h-ft^2-°F) (Creyf, 1991). The k(fresh foam) value was adjusted from 10°C (50°F) to 24°C (75°F) using a coefficient of 1.3×10^{-4}/°C to obtain 0.0218 W/m-°K (0.151 Btu-in/h-ft^2-°F). Using the adjusted k(fresh foam) and k(IPC) in Equ. K.4 estimated k(solid) + k(radiation) within 4% of the U.S. Cooperative Industry/Government project value, indicating that the adjusted value of k(fresh foam) is valid.

Since no data were available to generate A and B coefficients for IPC blown foam in Region 1 and Region 2, it was assumed that Region 1 and 2 intersect at a scaled age of 1900 $\sqrt{s}$/cm (the other PUR/PIR blowing agents ranged from 1850 to 1948). Coefficient A for Region 1 was calculated from Equ. K.3 using k(fresh foam) at time zero. Region 1 and 2 B coefficients were assumed equal to those for HCFC-123 because they were intermediate between those for CFC-11 and HCFC-141b.

Table K.1. Summary of test data for various foam insulating boards

Foam	k(gas)	Fresh Foam k	Air filled k	Region	A	Bx10^4	Thick-ness	Intersect times	
								R1-2	R2-3
Inch-Lb Units	Btu-in / h-ft^2-°F	Btu-in / h-ft^2-°F	Btu-in / h-ft^2-°F	--	--	cm^2 / s	cm	yr	yr
PUR/PIR -CFC-11	.057	.122	.245	1	2.4897	1.2300	2.54	0.78	125.
				2	2.6892	0.2063	5.08	3.10	499.
							7.62	6.99	1123.
-HCFC-123	.072	.137	.245	1	2.5808	1.2180	2.54	0.75	132.
				2	2.7820	0.1643	5.08	2.98	526.
							7.62	6.71	1184.
-HCFC-141B	.070	.135	.245	1	2.6386	1.1437	2.54	0.71	160.
				2	2.8266	0.1329	5.08	2.83	641.
							7.62	6.37	1443.
XEPS -HCFC-142B	.077	.160	.263	1	2.7896	3.2879	2.54	0.08	14.3
				2	2.9659	0.3758	5.08	0.30	57.1
							7.62	0.67	128.
							10.16	1.20	228.
S-I Units	W / m-°K	W / m-°K	W / m-°K	--	--	cm^2 / s	cm	yr	yr
PUR/PIR -CFC-11	.0082	.0176	.0353	1	0.5530	1.2300	2.54	0.78	125.
				2	0.7528	0.2063	5.08	3.10	499.
							7.62	6.99	1123.
-HCFC-123	.0104	.0198	.0353	1	0.6445	1.2180	2.54	0.75	132.
				2	0.8454	0.1643	5.08	2.98	526.
							7.62	6.71	1184.
-HCFC-141B	.0101	.0195	.0353	1	0.7021	1.1437	2.54	0.71	160.
				2	0.8904	0.1329	5.08	2.83	641.
							7.62	6.37	1443.
XEPS -HCFC-142B	.0111	.0231	.0379	1	0.8533	3.2879	2.54	0.08	14.3
				2	1.0296	0.3758	5.08	0.30	57.1
							7.62	0.67	128.0
							10.16	1.20	228.0

The remaining A coefficient was calculated by setting the Region 1 and 2 equations equal to each other at the intersect. The resulting properties of PUR/PIR blown with IPC are summarized in Table K.2.

All of the PUR/PIR data and analysis described above is for permeably-faced or unfaced foam board. No data were available for impermeably-faced material. In order to include this important product option in the analysis, characteristics of impermeably-faced PUR/PIR were approximated based on engineering judgment by dividing the Region 1 and 2 B coefficients by 10 (McElroy, May 1991). To be considered impermeable an aluminum foil facing must be at least 40 to 50 μ thick.

Table K.2. Summary of test data for various foam insulating boards

Foam	k(gas)	Fresh Foam k	Air filled k	Region	A	Bx10^4	Thickness	Intersect times	
								R1-2	R2-3
Inch-Lb Units	$\frac{Btu\text{-}in}{h\text{-}ft^2\text{-}°F}$	$\frac{Btu\text{-}in}{h\text{-}ft^2\text{-}°F}$	$\frac{Btu\text{-}in}{h\text{-}ft^2\text{-}°F}$	--	--	$\frac{cm^2}{s}$	cm	yr	yr
PUR/PIR -IPC	.083	.151	.245	1 2	2.717 2.917	1.2180 0.1643	2.54 5.08 7.62	0.74 2.95 6.65	60.2 241. 542.
S-I Units	$\frac{W}{m\text{-}°K}$	$\frac{W}{m\text{-}°K}$	$\frac{W}{m\text{-}°K}$	--	--	$\frac{cm^2}{s}$	cm	yr	yr
PUR/PIR -IPC	.012	.0218	.0353	1 2	0.7806 0.9806	1.2180 0.1643	2.54 5.08 7.62	0.74 2.95 6.65	60.2 241. 542.

Data were only available for XEPS blown with HCFC-142b leaving no basis to estimate A and B coefficients for Regions 1 and 2 for other blowing agents. Based on engineering judgment it was assumed that XEPS blown with CFC-12, HCFC-124, and HFC-134a would have similar thermal behavior to XEPS blown with HCFC-142b. (McElroy, May 1991).

Average Thermal Behavior Over The Service Life of Foam Insulating Board

Expressions for k versus time over Regions 1, 2, and 3 for specific foams and thicknesses were described previously for each blowing agent. The typical service life of foam board in commercial roofs is fifteen years and in residential and commercial walls is fifty years. Average values of k over these service lives were estimated as the integral of k over the service life divided by the service life. Then for each service life of interest, the average R-values per unit thickness (reciprocals of k) were plotted versus thickness and curves drawn to enable estimates of average R-values per unit thickness at any thickness.

Figures K.2 and K.3 present average R-values for PUR/PIR foam boards over fifteen and fifty year service lives as a function of thickness. Separate curves are provided for all combinations of blowing agent (CFC-11, HCFC-123, HCFC-141b, or IPC) and type of facing (permeable = unfaced, or impermeable). All curves approach the Region 3 air-filled foam R-value at thickness equal zero. All curves approach the fresh foam R-value at large thicknesses.

Figure K.4 presents average R-values for XEPS foam boards over ten, fifteen, and fifty year service lives as a function of thickness. Separate curves are provided for each service life. The average R-value curves show progressively increasing inflection at small thicknesses as service life increases. This is caused by the foam board reaching the air-filled Region 3 state. At thicknesses near zero average R-value curves for all foams should show some inflection.

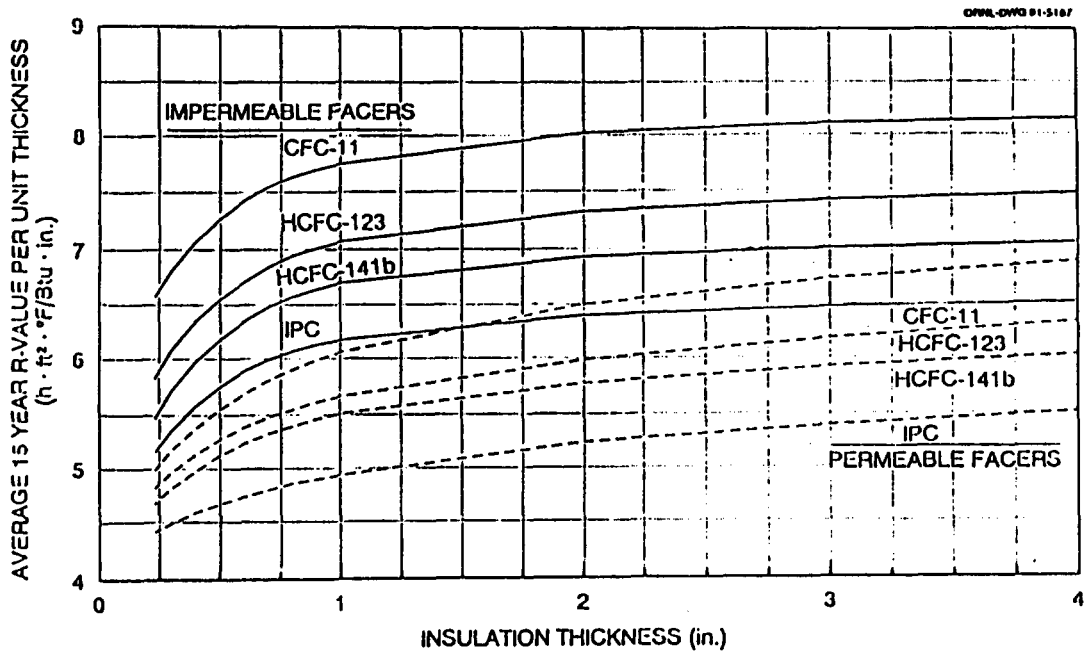

Fig. K.2. PUR/PIR average aged R-values over a fifteen year service life.

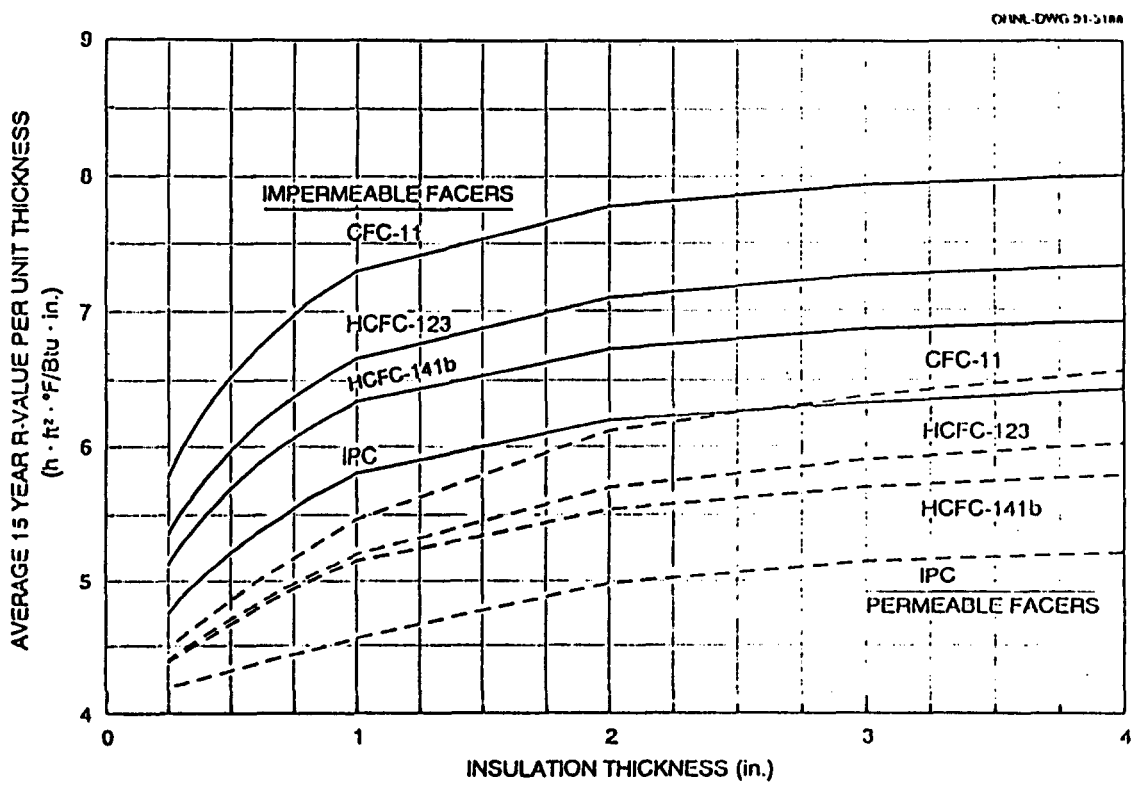

Fig. K.3. PUR/PIR average aged R-values over a fifty year service life.

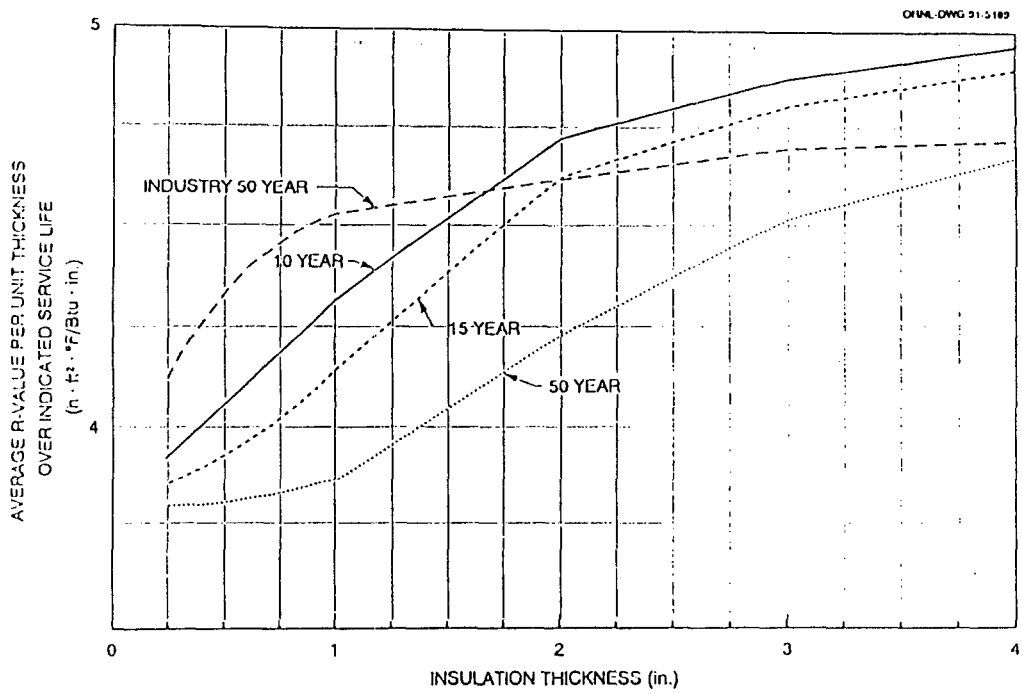

Fig. K.4. XEPS average aged R-values over various service lives.

Also shown on Figure K.4 is a fifty year service life average R-value curve for XEPS provided by industry (Minsker, 1991). This curve is based on XEPS blown with CFC-12 rather than HCFC-142b. At large thicknesses the blowing agent could account for the differences relative to the fifty year HCFC-142b curve described here. However at low thicknesses the curves are quite different and cannot be reconciled. Consequently both curves have been used for fifty year service life applications to determine whether global warming results are sensitive to the difference. Only the results based on the industry values are presented in Section 9, although the conclusions of the report are supported by both sets of data.

BUILDING ENERGY ANALYSIS

Three foam board end-uses have been previously described (i.e., low-slope roof, masonry wall, and metal panel wall). The objective of the building energy analysis is to estimate lifetime insulation-related energy consumptions for foam insulations with alternate blowing agents and for not-in-kind alternative types of insulation. Typical energies are needed for the three insulation end-uses in North America and Europe. The approach is to select two cities in each region that roughly bound the expected energy impacts of the insulation and that can be assumed to represent roughly half of the total application floorspace. Two building types are modeled in each location that also roughly bound the expected energy impacts of the insulation in the three end-uses. The results are used to estimate composite insulation-related energy values for the three insulation end-uses in the two regions.

Chicago and Atlanta were selected for North America. Selections for Europe were constrained by the availability of hourly weather data in a form compatible with DOE-2.1D. Paris and Frankfurt were used for this analysis.

Ideally complete building code information would have been available for the European cities so that insulation meeting the minimum European standards could have been selected for Paris and Frankfurt. This was not the case, so ASHRAE/IES 90.1-1989 was used to establish minimum insulation values in all cities. This model standard is weather sensitive and prescribes reasonable insulation requirements for specific locations when entered with weather indices appropriate for the locations.

The retail mall and warehouse reference buildings, described previously, each have one possible roof and two possible walls for a total of six foam board insulation applications. For each application, the prescriptive path of ASHRAE/IES 90.1-1989 was used to establish the required minimum total R-values for the insulation. The standard sets forth the required R-values for walls and roofs and insulation R-values were derived by subtracting the thermal contributions of the other wall or roof materials. The resulting minimum insulation R-values are summarized in Table K.3.

Table K.3. ASHRAE/IES Standard 90.1-1989 Minimum total R-values for wall and roof insulation in the reference buildings for each analysis location

Units: $\frac{m^2K}{W}$ *and* $\left(\frac{ft^2\text{-}h\text{-}°F}{Btu}\right)$

	Chicago	Atlanta	Paris	Frankfurt
roof type: low slope				
retail mall	2.62 (14.90)	1.74 (9.91)	2.56 (14.55)	2.56 (14.55)
warehouse	3.12 (17.71)	2.24 (12.72)	3.06 (17.36)	3.06 (17.36)
wall type: masonry				
retail mall	1.12 (6.39)	0.23 (1.29)	1.01 (5.75)	1.01 (5.75)
warehouse	1.42 (8.06)	0.34 (1.91)	1.12 (6.39)	1.12 (6.39)
wall type: metal panels				
retail mall	2.00 (11.35)	1.20 (6.84)	2.05 (11.65)	2.05 (11.65)
warehouse	2.00 (11.35)	1.20 (6.84)	2.05 (11.65)	2.05 (11.65)

The base insulations for the analysis were permeably-faced CFC-11 blown PUR/PIR and CFC-12 blown XEPS. ASHRAE/IES 90.1-1989 references handbooks for insulation thermal property design values. The handbook lists a range of design values for the PUR/PIR base material (ASHRAE, 1989). The highest value, 0.545 m^2-K/cm (7.86 ft^2-hr-°F/Btu-in), was selected. For the XEPS base material the handbook lists a design value of 0.364 m^2-K/W-cm (5.0 h-ft^2-F/Btu-in). Using these design values and assuming that the PUR/PIR and XEPS base insulations are available in 0.63 cm (.25 in) increments, the minimum required insulation thicknesses of Table K.4 were established.

Table K.4. Required thicknesses of foam boardstock for wall and roof insulation in the reference buildings for each analysis location

Unit: mm or (in.)

	Chicago	Atlanta	Paris	Frankfurt
Base: CFC-11 Blown Permeably-Faced PUR/PIR--0.433 m^2K/cm(6.25 h-ft^2-F/Btu-in)				
roof type: low slope				
retail mall	63.5 (2.5)	44.4 (1.75)	63.5 (2.5)	63.5 (2.5)
warehouse	76.2 (3.0)	57.1 (2.25)	76.2 (3.0)	76.2 (3.0)
wall type: masonry				
retail mall	31.7 (1.25)	6.3 (0.25)	25.4 (1.0)	25.4 (1.0)
warehouse	31.7 (1.25)	12.7 (0.50)	31.7 (1.25)	31.7 (1.25)
wall type: metal panels				
retail mall	50.8 (2.0)	31.7 (1.25)	50.8 (2.0)	50.8 (2.0)
warehouse	50.8 (2.0)	31.7 (1.25)	50.8 (2.0)	50.8 (2.0)
Base: CFC-12 Blown XEPS--0.364 m^2K/cm(5.0 h-ft^2-F/Btu-in)				
roof type: low slope				
retail mall	76.2 (3.0)	50.8 (2.0)	76.2 (3.0)	76.2 (3.0)
warehouse	95.3 (3.75)	69.9 (2.75)	88.9 (3.5)	88.9 (3.5)
wall type: masonry				
retail mall	38.1 (1.5)	12.7 (0.5)	31.8 (1.25)	31.8 (1.25)
warehouse	38.1 (1.5)	12.7 (0.5)	38.1 (1.5)	38.1 (1.5)

All of the analysis of base foam insulations, base foams with alternate blowing agents, and alternate types of insulation is performed assuming the insulation thicknesses of Table K.4. To minimize the number of DOE-2.1D simulations required to perform the analysis, R-values per unit thickness were parametrically varied in groups of three (low, medium, high) so that energies could be plotted and obtained for other R-values graphically. The low, medium, and high values were selected so that all blowing agent and insulation alternatives to be evaluated later would have average service life R-values per unit thickness within the range. The low, medium, and high values used in this study were 0.242, 0.433, and 0.623 m^2-K/W-cm (3.5, 6.25, and 9.0 ft^2-hr-F/Btu-in).

Table K.5 defines the 36 DOE-2-1D simulations performed in each location. Each simulation utilized a unique pair of R-values per unit thickness for the roof and wall; one R-value is set to the parametric low-medium-high value and the other is held constant at the base PUR/PIR insulation average service life R-value per unit thickness that is appropriate for the insulation thickness (Table K.4) and service life (15 years in roof, 50 years in wall) of the particular case. The constant R-values per unit thickness for the base PUR/PIR insulation are documented in Table K.6.

Table K.5. Summary of DOE-2.1D simulations performed in each location

Parametric variations of roof R-values per unit thickness...						
Run #	1	2	3	4	5	6
retail mall						
roof: low slope	R(1)	R(m)	R(h)	R(1)	R(m)	R(h)
wall: masonry	R(*)	R(*)	R(*)			
wall: metal				R(*)	R(*)	R(*)
Run #	7	8	9	10	11	12
warehouse--heated/cooled						
roof: low slope	R(1)	R(m)	R(h)	R(1)	R(m)	R(h)
wall: masonry	R(*)	R(*)	R(*)			
wall: metal				R(*)	R(*)	R(*)
Run #	13	14	15	16	17	18
warehouse--heated/ventilated						
roof: low slope	R(1)	R(m)	R(h)	R(1)	R(m)	R(h)
wall: masonry	R(*)	R(*)	R(*)			
wall: metal				R(*)	R(*)	R(*)
Parametric variations of wall R-values per unit thickness...						
Run #	19	20	21	22	23	24
retail mall						
roof: low slope	R(**)	R(**)	R(**)	R(**)	R(**)	R(**)
wall: masonry	R(1)	R(m)	R(h)			
wall: metal				R(1)	R(m)	R(h)
Run #	25	26	27	28	29	30
warehouse--heated/cooled						
roof: low slope	R(**)	R(**)	R(**)	R(**)	R(**)	R(**)
wall: masonry	R(1)	R(m)	R(h)			
wall: metal				R(1)	R(m)	R(h)
Run #	31	32	33	34	35	36
warehouse--heated/ventilated						
roof: low slope	R(**)	R(**)	R(**)	R(**)	R(**)	R(**)
wall: masonry	R(1)	R(m)	R(h)			
wall: metal				R(1)	R(m)	R(h)

Definitions: -Parametric values "l,m,h" refer to low, medium, and high values.
-"*" refers to the 50 yr aged R-value for CFC-11 blown permeably-faced PUR/PIR.
-"**" refers to the 15 yr aged R-value for CFC-11 blown permeably-faced PUR/PIR.

The results of the building energy analysis are summarized in Tables K.7, K.8, and K.9. Tables K.7 and K.8 document the total building annual heating energies and annual electric consumptions for PUR/PIR and XEPS insulation cases respectively. Table K.9 documents the percentages of total building space conditioning energies that are insulation-related for the permeably-faced CFC-11 blown PUR/PIR insulation case. The percentages are multiplied by the total building values to obtain insulation-related energies. Insulation-related energies for the other PUR/PIR and XEPS cases are derived using total building increments applied to the insulation-related values for permeably-faced CFC-11 blown PUR/PIR.

Table K.6. Summary of constant R-values per unit thickness used in DOE-2.1D simulations performed in each location

Units: $\frac{m^2K}{W\text{-}cm}$ $\left(\frac{ft^2\text{-}h\text{-}°F}{Btu\text{-}in}\right)$

Constant R-values per unit thickness for retail malls...			
	Masonry Wall R(*)	Metal Panel Wall R(*)	Low-Slope Roof R(**)
Chicago	0.396 (5.72)	0.426 (6.15)	0.471 (6.80)
Atlanta	0.308 (4.44)	0.396 (5.72)	0.453 (6.54)
Paris	0.354 (5.11)	0.426 (6.15)	0.471 (6.80)
Frankfurt	0.354 (5.11)	0.426 (6.15)	0.471 (6.80)
Constant R-values per unit thickness for warehouses...			
	Masonry Wall R(*)	Metal Panel Wall R(*)	Low-Slope Roof R(**)
Chicago	0.396 (5.72)	0.426 (6.15)	0.480 (6.93)
Atlanta	0.335 (4.84)	0.396 (5.72)	0.466 (6.72)
Paris	0.396 (5.72)	0.426 (6.15)	0.480 (6.93)
Frankfurt	0.396 (5.72)	0.426 (6.15)	0.480 (6.93)

Definitions: "*" refers to the 50 yr. aged R-value for CFC-11 blown permeably-faced PUR/PIR.
"**" refers to the 15 yr. aged R-value for CFC-11 blown permeably-faced PUR/PIR.

Table K.7. Energy use values for buildings having PUR/PIR made with alternate blowing agents or having alternate types of insulation

		Low-Slope Roof											
		PUR/PIR									Not-in-Kind Alternatives		
		Permeable Facings				Impermeable Facings							
Building	Cooling	11	123	141b	IPC	11	123	141b	IPC	Air	MEPS: Pentane	Glass Fiber	Mineral Fiber
Chicago - heat energy delivered - total building (10^6 Btu/yr)													
Rtail-Mas	A/C	431.4	436.1	438.3	444.1	421.2	425.6	428.5	431.4	461.0	465.7	463.2	471.6
Rtail-Met	A/C	407.8	412.5	414.8	422.1	397.8	402.2	405.1	409.5	437.4	441.9	439.6	447.7
Wrhse-Mas	A/C	1078.9	1093.4	1101.7	1118.3	1053.1	1064.5	1072.8	1085.9	1171.7	1185.7	1178.2	1205.4
Wrhse-Met	A/C	1006.3	1019.4	1026.0	1041.7	982.2	993.6	1001.0	1012.4	1092.9	1107.8	1099.9	1127.1
Wrhse-Mas	Vent	1003.2	1015.5	1022.0	1036.5	980.5	991.4	998.4	1008.9	1085.9	1100.8	1092.9	1120.9
Wrhse-Met	Vent	916.2	928.0	934.5	949.0	894.3	904.4	911.8	921.9	998.0	1012.9	1005.4	1034.3
Chicago - cooling electricity - total building (kWh/yr)													
Rtail-Mas	A/C	27884.	27884.	27884.	27882.	27878.	27882.	27883.	27884.	27873.	27868.	27871.	27860.
Rtail-Met	A/C	29683.	29696.	29703.	29720.	29661.	29670.	29676.	29687.	29776.	29791.	29783.	29810.
Wrhse-Mas	A/C	10082.	10192.	10250.	10381.	9870.	9968.	10035.	10135.	10845.	10980.	10910.	11170.
Wrhse-Met	A/C	11300.	11425.	11492.	11650.	11053.	11170.	11245.	11358.	12175.	12360.	12250.	12530.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Atlanta - heat energy delivered - total building (10^6 Btu/yr)													
Rtail-Mas	A/C	237.8	240.4	241.6	244.8	231.2	233.9	235.6	238.1	253.0	255.4	254.1	258.7
Rtail-Met	A/C	189.5	191.9	193.1	196.3	182.9	185.6	187.3	189.8	204.2	206.5	205.3	210.9
Wrhse-Mas	A/C	566.6	575.8	578.8	588.0	553.5	560.0	564.0	570.5	613.4	621.3	617.3	631.8
Wrhse-Met	A/C	478.6	487.0	490.0	501.4	462.9	469.0	473.8	481.3	529.8	537.3	533.8	546.9
Wrhse-Mas	Vent	545.1	552.2	555.7	564.4	531.6	536.8	540.8	546.9	589.3	595.9	592.5	604.7
Wrhse-Met	Vent	454.6	462.0	465.5	475.1	440.1	445.8	450.2	456.8	500.5	506.6	503.6	515.4
Atlanta - cooling electricity - total building (kWh/hr)													
Rtail-Mas	A/C	43800.	43900.	43945.	44075.	43548.	43650.	43718.	43815.	44390.	44485.	44435.	44615.
Rtail-Met	A/C	48280.	48365.	48405.	48522.	48080.	48160.	48210.	48290.	48870.	48935.	48885.	49080.
Wrhse-Mas	A/C	15850.	16140.	16260.	16620.	15225.	15490.	15665.	15940.	17670.	17980.	17820.	18400.
Wrhse-Met	A/C	18270.	18630.	18790.	19230.	17490.	17830.	18040.	18370.	20500.	20860.	20680.	21320.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0	0	0	0

Table K.7. (Continued). Energy use values for buildings having PUR/PIR made with alternate blowing agents or having alternate types of insulation

Building	Cooling	Low-Slope Roof											
		PUR/PIR									Not-in-Kind Alternatives		
		Permeable Facings				Impermeable Facings				Air	MEPS: Pentane	Glass Fiber	Mineral Fiber
		11	123	141b	IPC	11	123	141b	IPC				
Paris - heat energy delivered - total building (10^6 Btu/yr)													
Rtail-Mas	A/C	306.9	311.6	314.0	320.3	298.4	301.3	304.3	308.5	339.6	344.8	342.2	351.6
Rtail-Met	A/C	280.5	285.2	287.5	293.4	270.2	274.8	277.8	282.2	310.5	314.9	312.6	321.0
Wrhse-Mas	A/C	476.9	487.8	494.8	507.5	455.5	465.5	472.1	482.1	553.0	566.6	559.6	585.4
Wrhse-Met	A/C	408.6	420.0	426.6	440.1	386.8	396.8	403.8	413.9	488.3	502.7	495.3	522.4
Wrhse-Mas	Vent	474.7	485.6	491.8	504.9	453.7	463.8	470.3	480.0	548.7	561.3	554.8	578.8
Wrhse-Met	Vent	406.0	417.0	423.1	436.6	384.6	394.6	401.2	411.3	482.6	495.7	489.1	514.5
Paris - cooling electricity - total building (kWh/yr)													
Rtail-Mas	A/C	12966.	12967.	12968.	12973.	12983.	12971.	12968.	12966.	12998.	13008.	13003.	13025.
Rtail-Met	A/C	15059.	15062.	15064.	15071.	15059.	15058.	15058.	15060.	15101.	15112.	15106.	15131.
Wrhse-Mas	A/C	6142.	6193.	6223.	6292.	6061.	6097.	6123.	6168.	6540.	6610.	6575.	6703.
Wrhse-Met	A/C	7368.	7460.	7513.	7638.	7210.	7280.	7330.	7410.	8050.	8155.	8100.	8290.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Frankfurt - heat energy delivered - total building (10^6 Btu/yr)													
Rtail-Mas	A/C	380.8	385.7	388.1	394.2	370.2	374.8	377.8	382.6	411.8	416.7	414.2	423.1
Rtail-Met	A/C	343.7	348.7	351.0	356.9	333.4	337.9	340.8	345.5	374.6	379.5	377.1	386.1
Wrhse-Mas	A/C	779.7	792.8	799.8	815.5	755.2	766.5	774.4	785.8	868.5	883.8	875.9	904.8
Wrhse-Met	A/C	700.9	714.0	721.5	737.7	674.2	686.5	695.2	707.0	791.5	806.3	798.9	826.0
Wrhse-Mas	Vent	755.6	767.8	774.4	789.7	732.4	743.3	750.3	761.3	840.0	855.4	847.0	875.0
Wrhse-Met	Vent	686.9	702.2	710.1	725.8	654.1	669.8	680.3	694.3	768.3	777.9	773.1	789.3
Frankfurt - cooling electricity - total building (kWh/hr)													
Rtail-Mas	A/C	13627.	13598.	13585.	13553.	13692.	13662.	13644.	13617.	13472.	13452.	13462.	13428.
Rtail-Met	A/C	15647.	15619.	15607.	15578.	15715.	15683.	15664.	15637.	15508.	15492.	15500.	15472.
Wrhse-Mas	A/C	5573.	5578.	5581.	5591.	5573.	5572.	5572.	5575.	5632.	5646.	5638.	5670.
Wrhse-Met	A/C	6467.	6483.	6493.	6516.	6443.	6454.	6461.	6474.	6614.	6648.	6630.	6698.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0	0	0
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0	0	0	0

Table K.7. (Continued). Energy use values for buildings having PUR/PIR made with alternate blowing agents or having alternate types of insulation

Building	Cooling	Masonry Wall									
		PUR/PIR									Not-in-Kind Alternatives
		Permeable Facings				Impermeable Facings				Air	MEPS: Pentane
		11	123	141b	IPC	11	123	141b	IPC		
Chicago - heat energy delivered - total building (10^6 Btu/yr)											
Rtail-Mas	A/C	430.5	433.4	434.3	441.4	416.5	421.0	423.6	428.2	450.2	453.0
Wrhse-Mas	A/C	1076.7	1084.2	1086.8	1105.2	1040.0	1051.8	1058.4	1070.6	1125.7	1137.6
Wrhse-Mas	Vent	999.3	1006.3	1008.9	1026.4	965.6	976.1	982.2	993.2	1046.5	1057.5
Chicago - cooling electricity - total building (kWh/yr)											
Rtail-Mas	A/C	27878.	27830.	27815.	27703.	28108.	28033.	27991.	27918.	27580.	27518.
Wrhse-Mas	A/C	10051.	10045.	10044.	10033.	10078.	10069.	10063.	10055.	10022.	10017.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0
Atlanta - heat energy delivered - total building (10^6 Btu/yr)											
Rtail-Mas	A/C	237.2	237.6	237.7	238.8	229.6	231.9	233.3	235.4	239.6	241.4
Wrhse-Mas	A/C	560.5	562.7	563.1	569.7	536.0	543.4	547.3	554.3	574.0	579.7
Wrhse-Mas	Vent	539.9	541.6	542.1	548.2	516.7	523.3	527.2	533.8	552.2	557.4
Atlanta - cooling electricity - total building (kWh/yr)											
Rtail-Mas	A/C	43770.	43760.	43758.	43718.	44010.	43938.	43890.	43835.	43695.	43636.
Wrhse-Mas	A/C	15790.	15783.	15782.	15760.	15876.	15849.	15835.	15810.	15747.	15730.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0
Paris - heat energy delivered - total building (10^6 Btu/yr)											
Rtail-Mas	A/C	310.5	313.3	313.9	321.4	294.7	299.3	302.0	306.9	327.6	331.6
Wrhse-Mas	A/C	474.3	481.3	483.9	500.5	440.1	451.1	457.2	468.6	519.3	529.4
Wrhse-Mas	Vent	472.1	479.5	481.7	497.9	439.3	449.8	455.9	466.8	516.3	525.9
Paris - cooling electricity - total building (kWh/yr)											
Rtail-Mas	A/C	12935.	12870.	12860.	12716.	13300.	13180.	13120.	13010.	12595.	12520.
Wrhse-Mas	A/C	6142.	6121.	6115.	6065.	6260.	6222.	6200.	6162.	6013.	5985.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0
Frankfurt - heat energy delivered - total building (10^6 Btu/yr)											
Rtail-Mas	A/C	380.8	383.8	384.4	392.0	364.2	369.0	371.9	377.3	398.7	402.8
Wrhse-Mas	A/C	777.0	784.5	787.5	805.5	739.8	751.7	758.7	770.5	826.5	837.4
Wrhse-Mas	Vent	753.0	760.4	762.6	780.5	717.1	728.5	735.0	746.8	800.7	811.6
Frankfurt - cooling electricity - total building (kWh/yr)											
Rtail-Mas	A/C	13640.	13580.	13568.	13432.	13934.	13840.	13790.	13695.	13330.	13240.
Wrhse-Mas	A/C	5580.	5567.	5562.	5532.	5650.	5626.	5613.	5592.	5499.	5484
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0	0

Table K.7. (Continued). Energy use values for buildings having PUR/PIR made with alternate blowing agents or having alternate types of insulation

Building	Cooling	Metal Panel Wall								
		PUR/PIR								
		Sealed System				Impermeable Facings				Air
		11	123	141b	IPC	11	123	141b	IPC	
Chicago - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Met	A/C	393.0	396.3	398.8	402.7	395.1	399.1	401.6	406.1	431.4
Wrhse-Met	A/C	969.5	978.7	984.9	994.0	975.7	985.7	991.9	1001.9	1063.6
Wrhse-Met	Vent	881.6	889.9	895.6	904.4	887.3	896.5	902.2	911.8	971.3
Chicago - cooling electricity - total building (kWh/yr)										
Rtail-Met	A/C	29847.	29798.	29767.	29721.	29814.	29762.	29733.	29682.	29390.
Wrhse-Met	A/C	11218.	11227.	11234.	11244.	11224.	11235.	11241.	11254.	11324.
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0
Atlanta - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Met	A/C	177.3	179.7	181.5	183.9	180.0	182.9	184.6	187.7	205.6
Wrhse-Met	A/C	443.2	450.2	455.5	463.8	451.1	460.3	466.0	476.5	529.0
Wrhse-Met	Vent	424.4	430.1	434.5	441.5	431.0	438.4	443.2	452.4	498.8
Atlanta - cooling electricity - total building (kWh/yr)										
Rtail-Met	A/C	48640.	48555.	48495.	48415.	48545.	48450.	48400.	48300.	47845.
Wrhse-Met	A/C	18022.	18047.	18068.	18108.	18050.	18090.	18118.	18172.	18588.
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0
Paris - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Met	A/C	265.8	269.1	271.1	275.5	267.9	271.9	274.6	279.1	304.2
Wrhse-Met	A/C	375.0	383.3	389.4	397.7	380.6	390.3	396.0	405.1	462.0
Wrhse-Met	Vent	372.3	380.6	386.8	395.1	378.0	387.4	372.9	402.1	457.6
Paris - cooling electricity - total building (kWh/yr)										
Rtail-Met	A/C	15292.	15225.	15180.	15112.	15247.	15172.	15128.	15057.	14654.
Wrhse-Met	A/C	7463.	7433.	7415.	7385.	7442.	7413.	7393.	7362.	7217.
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0
Frankfurt - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Met	A/C	329.5	332.6	335.2	338.9	331.6	335.4	338.0	342.2	367.9
Wrhse-Met	A/C	664.2	673.3	679.5	688.7	670.3	680.3	686.5	696.5	760.0
Wrhse-Met	Vent	635.3	644.9	651.0	660.2	641.8	651.9	658.0	667.7	727.6
Frankfurt - cooling electricity - total building (kWh/yr)										
Rtail-Met	A/C	15872.	15810.	15770.	15710.	15830.	15765.	15723.	15658.	15285.
Wrhse-Met	A/C	6513.	6497.	6487.	6473.	6502.	6486.	6476.	6460.	6372.
Wrhse-Met	Vent	0	0	0	0	0	0	0	0	0

Table K.8. Energy use values for buildings having XEPS made with alternate blowing agents or having alternate insulation

Building	Cooling	Roof					Masonry Wall			
		XEPS:		Not-In-Kind Alternatives:			XEPS:			Not-In-Kind Alternatives
		ORNL: CFCs HCFCs HFCs	Air	MEPS: Pentane	Glass Fiber	Mineral Fiber	ORNL: CFCs HCFCs HFCs	Industry: CFCs HCFCs HFCs	Air	MEPS: Pentane
Chicago - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Mas	A/C	439.2	453.9	453.9	451.5	460.1	439.8	432.3	442.9	442.9
Wrhse-Mas	A/C	1098.2	1142.4	1142.4	1134.9	1161.2	1101.2	1081.5	1109.1	1109.1
Wrhse-Mas	Vent	1017.2	1057.9	1057.9	1050.9	1075.4	1022.5	1003.7	1029.9	1029.9
Chicago - cooling electricity - total building (kWh/yr)										
Rtail-Mas	A/C	27883.5	27878.0	27878.0	27879.3	27873.9	27727.0	27850.0	27677.0	27677.0
Wrhse-Mas	A/C	10210.	10585.	10585.	10520.	10750.	10035.2	10047.6	10030.6	10030.6
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0
Atlanta - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Mas	A/C	244.1	250.8	250.8	249.7	254.1	221.0	216.9	221.0	221.0
Wrhse-Mas	A/C	578.8	600.7	600.7	596.8	610.3	579.7	569.7	579.7	579.7
Wrhse-Mas	Vent	555.2	577.1	577.1	573.6	586.3	557.4	147.4	557.4	557.4
Atlanta - cooling electricity - total building (kWh/yr)										
Rtail-Mas	A/C	44048.	44310.	44310.	44262.	44435.	44305.	44470.	44305.	44305.
Wrhse-Mas	A/C	16250.	17130.	17130.	16980.	17530.	15730.	15761.	15730.	15730.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0
Paris - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Mas	A/C	314.9	331.5	331.5	328.7	338.7	316.9	308.1	318.9	318.9
Wrhse-Mas	A/C	500.1	538.6	538.6	532.5	555.7	497.0	478.6	504.0	504.0
Wrhse-Mas	Vent	497.5	535.1	535.1	529.0	551.3	494.4	476.5	501.4	501.4
Paris - cooling electricity - total building (kWh/yr)										
Rtail-Mas	A/C	12968.5	12985.7	12985.7	12982.	12996.8	12800.	12985.	12763.	12763.
Wrhse-Mas	A/C	6255.	6465.	6465.	6430.	6552.	6075.	6131.	6055.	6055.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0
Frankfurt - heat energy delivered - total building (10^6 Btu/yr)										
Rtail-Mas	A/C	389.0	404.3	404.3	401.8	410.7	387.6	378.4	389.6	389.6
Wrhse-Mas	A/C	806.8	851.4	851.4	844.4	871.1	801.5	781.4	809.4	809.4
Wrhse-Mas	Vent	781.4	824.3	824.3	816.8	842.7	776.6	757.3	784.5	784.5
Frankfurt - cooling electricity - total building (kWh/yr)										
Rtail-Mas	A/C	13581.	13505.	13505.	13516.	13476.	13512.	13675.	13477.	13477.
Wrhse-Mas	A/C	5585.5	5617.	5617.	5611.	5634.	5538.	5572.	5525.	5525.
Wrhse-Mas	Vent	0	0	0	0	0	0	0	0	0

Table K.9. Percentages of total building heating and cooling energies that are insulation-related for permeably-faced CFC-11 blown PUR/PIR (% of annual heating or cooling energy)

	Heating		Cooling	
	Opaque Wall	Roof	Opaque Wall	Roof
I. RETAIL MALL				
Chicago				
Masonry	12.2	11.0	0.5	4.3
Metal Panel	9.4	12.0	1.5	4.4
Atlanta				
Masonry	28.6	13.0	1.3	6.2
Metal Panel	14.7	15.9	2.3	6.1
Paris				
Masonry	17.4	13.2	0.1	9.2
Metal Panel	10.9	14.3	1.6	8.7
Frankfurt				
Masonry	16.0	12.2	0.1	5.0
Metal Panel	10.2	13.4	1.2	4.9
II. WAREHOUSE				
Chicago				
Ventilated	14.7	10.9	--	--
Masonry	11.5	12.3	--	--
Metal Panel				
Air-conditioned	14.6	11.1	0.7	20.4
Masonry	11.4	12.2	6.4	21.5
Metal Panel				
Atlanta				
Ventilated	21.0	11.6	--	--
Masonry	17.3	14.6	--	--
Metal Panel				
Air-conditioned	20.8	12.2	0.07	30.7
Masonry	18.2	15.4	10.1	29.8
Metal Panel				
Paris				
Ventilated	20.5	14.4	--	--
Masonry	16.2	18.1	--	--
Metal Panel				
Air-conditioned	21.3	15.4	0.0	7.7
Masonry	17.7	19.7	2.7	11.0
Metal Panel				
Frankfurt				
Ventilated	16.4	13.0	--	--
Masonry	13.9	15.4	--	--
Metal Panel				
Air-conditioned	16.7	13.6	0.0	0.6
Masonry	14.5	16.1	1.0	3.0
Metal Panel				

ESTIMATION OF LIFETIME INDIRECT CO_2 EMISSIONS

The procedure used to estimate lifetime INDIRECT CO_2 emissions is summarized in Table K.10. The previously described building energy analysis steps are also included in Table K.10 for completeness. Table K.11 provides a summary of the assumptions and conversion factors used to implement the lifetime INDIRECT CO_2 emissions calculations.

The first step identified in Table K.10 was to implement the DOE-2.1D simulations. Step 2 was to plot the results. Step 3 was to use the plots to construct Tables K.7 and K.8 that document total building heating and cooling energies. Total building energies are converted to insulation-related energies in Step 4. The insulation-related energies are converted to lifetime CO_2 emissions in Step 5. In Step 6 weighting factors are used to condense the cases into a typical composite low-slope roof, masonry wall, and metal panel wall for North America and Europe.

The warehouse HVAC system weighting factors for North America are based on the 1986 U.S. commercial building stock (EIA, 1988). The building stock indicates that nearly two-thirds of the warehouse floorspace is cooled. The factors are reversed for Europe to recognize that most warehouses are not cooled.

The heating fuel weighting factors for North America are also based on the U.S. building stock (EIA, 1988). The European values are based on EEC aggregates and an arbitrary assumption that electricity heats 6% of the floorspace (IEA, 1984). No information was available to justify different weights for retail malls and warehouses in Europe.

Wall type weighting factors for North America are based on the U.S. building stock (EIA, 1988). The European values are based on typical thicknesses for foam core panels and masonry walls, and the Table J.5 European allocation of PUR/PIR between the two wall types.

The building type weighting factors for North America are based on the U.S. building stock (EIA, 1988). These values were also used for Europe as no better information was available. It appears reasonable that similar industrialized regions would maintain similar ratios of retail and warehouse floorspace in aggregate.

The location weighting factors are used to account for the greater need for insulation in one city in a region versus the other if floorspace is equally split. The insulation volume or mass differences between cities in a region result from the different insulation thickness requirements. Insulation mass was calculated for each building type and then weighted with the building type weighting factors to obtain the location weighting factors. The Paris and Frankfurt weighting factors are always 0.5 each because the insulation thicknesses are the same in both locations.

Table K.10. Summary of procedure to estimate INDIRECT CO_2 emissions

Step 1:	DOE-2.1D SIMULATIONS 36 simulations (see Table J.11) X 4 locations = 144. If roof parametric - R(l,m,h) and R(*) per unit thickness. If wall parametric - R(l,m,h) and R(**) per unit thickness. Results: - heating energy delivered (10^6 Btu/yr). - cooling electricity (kWh/yr).
Step 2:	PLOT RESULTS 144 ÷ 3 = 48 plots, 3 points per plot for heating and cooling energies. Plot contents... - annual heating energy delivered vs. R(l,m,h), - annual cooling electricity vs. R(l,m,h).
Step 3:	CONSTRUCT TABLES OF RESULTS FOR BASE AND ALTERNATIVE INSULATIONS Enter plots with average service life R-values per unit thickness... - 50 year insulation service life for walls - 15 year insulation service life for roofs Construct tables of annual energy values for insulation cases (Tables J.13 and J.14)... - annual heating energy delivered (10^6 Btu/yr), - annual cooling electricity (kWh/yr).
Step 4:	CONVERT TOTAL BUILDING HEATING AND COOLING ENERGIES TO INSULATION-RELATED ENERGIES For permeably-faced CFC-11 blown PUR/PIR, multiply Table J.13 energies by Table J.15 percentages to obtain insulation-related energies. For the other PUR/PIR and XEPS cases, calculate total-building energy increments relative to permeably-faced CFC-11 blown PUR/PIR. Derive insulation-related energies for the other PUR/PIR and XEPS cases using the increments and the insulation-related energies for permeably-faced CFC-11 blown PUR/PIR.
Step 5:	CONVERT INSULATION-RELATED ENERGIES TO LIFETIME CO_2 EMISSIONS FOR EACH CASE Heating energy conversion... multiply annual values by service life convert to CO_2 using the average regional heating fuel mix Cooling electricity conversion... multiply annual values by service life convert to CO_2 using the average regional power generation fuel mix Add heating and cooling values Repeat for each case.
Step 6:	APPLY WEIGHTING FACTORS TO COMBINE MULTIPLE CASES INTO COMPOSITE RESULTS FOR ROOF, MASONRY WALL, AND METAL PANEL WALL IN NORTH AMERICA AND EUROPE Roof: 2 locations x 6 physical options (3 buildings: retail, wrhse-ht/cl, wrhse-ht/vt, by 2 wall types) = 12 cases for each region. After warehouse HVAC weighting factors: 2 x 4 = 8 cases. After wall type weighting factors: 2 x 2 = 4 cases. After building type weighting factors: 2 x 1 = 2 cases. After location weighting factors: 1 composite case for each region. The two locations per region are assumed to represent equal floorspace. The location weighting factors are intended to represent the relative mass of base insulation in the two locations due to insulation thickness differences. Walls: 2 locations x 3 physical options = 6 cases for each wall type in each region. After warehouse HVAC weighting factors: 2 x 2 = 4 cases. After building type weighting factors: 2 x 1 = 2 cases. After location weighting factors: 1 composite case for each wall type in each region.

Table K.11: Summary of assumptions and conversion factors used to derive results from DOE-2.1D outputs

	North America		Europe	
Conversions to CO_2 emissions:				
CO_2 emissions kg CO_2/kWh_e:	.672		.513	
CO_2 emissions kg CO_2/kWh_{th} (kg CO2/mill btu):				
gas	.184 (53.9)		.184 (53.9)	
oil	.257 (75.4)		.257 (75.4)	
Weighting factors:				
heating fuel: retail mall: gas	.68		.47	
(1 system) oil	.15		.47	
elec	.17		.06	
	1.00		1.00	
warehouse: gas	.68		.47	
(2 systems) oil	.17		.47	
elec	.15		.06	
	1.00		1.00	
warehouse HVAC system: heat/cool	.64		.36	
heat/vent	.36		.64	
	1.00		1.00	
	PUR/PIR	XEPS	PUR/PIR	XEPS
wall type: retail mall: masonry	.81	1.0	.30	1.0
metal panel	.19	0.0	.70	0.0
	1.00	1.0	1.00	1.0
warehouse: masonry	.69	1.0	.20	1.0
metal panel	.31	0.0	.80	0.0
(Note: wall type weighting factors are only needed for roof insulation)	1.00	1.0	1.00	1.0
building type: retail mall	0.6	0.6	0.6	0.6
warehouse	0.4	0.4	0.4	0.4
	1.0	1.0	1.0	1.0

	ROOF		MASONRY WALLS		METAL PANEL WALLS
Location:	PUR/PIR	XEPS	PUR/PIR	XEPS	PUR/PIR ONLY
Chicago	.58	.63	.78	.74	.62
Atlanta	.42	.37	.22	.26	.38
	1.0	1.0	1.0	1.0	1.0
Paris	0.5	0.5	0.5	0.5	0.5
Frankfurt	0.5	0.5	0.5	0.5	0.5
	1.0	1.0	1.0	1.0	1.0

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APPENDIX L: COMMERCIAL BUILDING INSULATION -TABULATED RESULTS

TABLE L.1. European commercial building insulation summary of total equivalent warming impact (TEWI)

Building Envelope Component	Alternative Foam Blowing Agent or NIK Alternative	TEWI (Total Equivalent Warming Impact	INDIRECT (Energy Use) Contribution		DIRECT (Blowing Agent Loss) Contribution	
		(10^3 kg CO_2)	(10^3 kg CO_2)	(%)	(10^3 kg CO_2)	(%)
PUR/PIR Insulations and Alternatives						
Low-Slope Roof	PUR/PIR:					
	Permeable Facings					
	CFC-11	1160	89	7.3	1071	92.7
	HCFC-123	119	93	78.2	26	21.8
	HCFC-141b	189	98	51.9	91	48.1
	IPC	115	109	94.8	6	5.2
	Impermeable Facings					
	CFC-11	1155	84	7.3	1071	92.7
	HCFC-123	112	86	76.8	26	23.2
	HCFC-141b	178	87	48.9	91	51.1
	IPC	95	89	93.7	6	6.3
	Air-filled	148	148	100.0	0	0.0
	Not-in-Kind Alternatives:					
	MEPS	159	157	98.7	2	1.3
	Glass Fiber	151	151	100.0	0	0
	Mineral Fiber	170	170	100.0	0	0
Masonry Wall	PUR/PIR:					
	Permeable Facings					
	CFC-11	565	338	59.8	227	40.2
	HCFC-123	364	359	98.6	5	1.4
	HCFC-141b	386	367	95.1	19	4.9
	IPC	415	414	99.8	1	0.2
	Impermeable Facings					
	CFC-11	475	248	52.2	227	47.8
	HCFC-123	271	266	98.2	5	1.8
	HCFC-141b	300	281	93.7	19	6.3
	IPC	315	314	99.7	1	0.3
	Air-filled	456	456	100.0	0	0
	Not-in-Kind Alternatives:					
	MEPS	478	478	99.9	0.4	0.1
Metal Panel Wall	PUR/PIR:					
	Sealed Systems					
	CFC-11	556	142	25.5	414	74.5
	HCFC-123	175	165	94.3	10	5.7
	HCFC-141b	218	183	83.9	35	16.1
	IPC	210	208	99.0	2	1.0
	Impermeable Facings					
	CFC-11	570	156	27.4	414	72.6
	HCFC-123	196	186	94.9	10	5.1
	HCFC-141b	237	202	85.2	35	14.8
	IPC	228	226	99.1	2	0.9

TABLE L.1. (Continued) European commercial building insulation summary of total equivalent warming impact (TEWI)

Building Envelope Component	Alternative Foam Blowing Agent or NIK Alternative	TEWI (Total Equivalent Warming Impact	INDIRECT (Energy Use) Contribution		DIRECT (Blowing Agent Loss) Contribution	
		(10^3 kg CO_2)	(10^3 kg CO_2)	(%)	(10^3 kg CO_2)	(%)
XEPS Insulations and Alternatives						
Low-Slope Roof	XEPS-ORNL:					
	CFC-12	1626	102	6.3	1524	93.7
	HCFC-142b	144	102	70.8	42	29.2
	HCFC-124	159	102	64.2	57	35.8
	HFC-134a	223	102	45.7	121	54.3
	Air-filled	139	139	100.	0	0
	Not-in-Kind Alternatives:					
	MEPS	141	139	98.6	2	1.4
	Glass Fiber	134	134	100.	0	0
	Mineral Fiber	151	151	100.	0	0
Masonry Wall	XEPS-ORNL:					
	CFC-12	742	407	54.9	335	45.1
	HCFC-142b	416	407	97.8	9	2.2
	HCFC-124	419	407	97.1	12	2.9
	HFC-134a	434	407	93.8	27	6.2
	XEPS-Industry					
	CFC-12	682	347	50.9	335	49.1
	HCFC-142b	356	347	97.5	9	2.5
	HCFC-124	359	347	96.7	12	3.3
	HFC-134a	374	347	92.8	27	7.2
	Air-filled	420	420	100.	0	0
	Not-in-Kind Alternatives:					
	MEPS	420	420	99.9	0.4	0.1

TABLE L.2. North American commercial building insulation summary of total equivalent warming impact (TEWI)

Building Envelope Component	Alternative Foam Blowing Agent or NIK Alternative	TEWI (Total Equivalent Warming Impact)	INDIRECT (Energy Use) Contribution		DIRECT (Blowing Agent Loss) Contribution	
		(10^3 kg CO_2)	(10^3 kg CO_2)	(%)	(10^3 kg CO_2)	(%)
PUR/PIR Insulations and Alternatives						
Low-Slope Roof	PUR/PIR:					
	Permeable Facings					
	CFC-11	1054	108	10.2	946	89.8
	HCFC-123	142	119	83.8	23	16.2
	HCFC-141b	207	127	61.4	80	38.6
	IPC	148	142	95.9	6	4.1
	Impermeable Facings					
	CFC-11	1034	88	8.5	946	91.5
	HCFC-123	118	95	80.5	23	19.5
	HCFC-141b	180	100	55.6	80	44.4
	IPC	118	112	94.9	6	5.1
	Air-filled	177	177	100.0	0	0.0
	Not-in-Kind Alternatives:					
	MEPS	188	186	98.9	2	1.1
	Glass Fiber	182	182	100.0	0	0
	Mineral Fiber	197	197	100.0	0	0
Masonry Wall	PUR/PIR:					
	Permeable Facings					
	CFC-11	655	438	66.9	217	33.1
	HCFC-123	456	451	98.9	5	1.1
	HCFC-141b	476	458	96.2	18	3.8
	IPC	504	503	99.8	1	0.2
	Impermeable Facings					
	CFC-11	545	328	60.2	217	39.8
	HCFC-123	359	354	98.6	5	1.4
	HCFC-141b	392	374	95.4	18	4.6
	IPC	412	411	99.8	1	0.2
	Air-filled	538	538	100.0	0	0
	Not-in-Kind Alternatives:					
	MEPS	559	559	99.9	0.3	0.1
Metal Panel Wall	PUR/PIR:					
	Sealed Systems					
	CFC-11	567	212	37.4	355	62.6
	HCFC-123	258	249	96.5	9	3.5
	HCFC-141b	300	270	90.0	30	10.0
	IPC	300	298	99.3	2	0.7
	Impermeable Facings					
	CFC-11	597	242	40.5	355	59.5
	HCFC-123	286	277	96.9	9	3.1
	HCFC-141b	325	295	90.8	30	9.2
	IPC	324	322	99.4	2	0.6

TABLE L.2. (Continued) North American commercial building insulation summary of total equivalent warming impact (TEWI)

Building Envelope Component	Alternative Foam Blowing Agent or NIK Alternative	TEWI (Total Equivalent Warming Impact)	INDIRECT (Energy Use) Contribution		DIRECT (Blowing Agent Loss) Contribution	
		(10^3 kg CO_2)	(10^3 kg CO_2)	(%)	(10^3 kg CO_2)	(%)
XEPS Insulation and Alternatives						
Low-Slope Roof	XEPS-ORNL:					
	CFC-12	1520	124	8.2	1396	91.8
	HCFC-142b	163	124	76.1	39	23.9
	HCFC-124	176	124	70.5	52	29.5
	HFC-134a	235	124	52.8	111	47.2
	Air-filled	158	158	100.	0	0
	Not-in-Kind Alternatives:					
	MEPS	160	158	98.8	2	1.2
	Glass Fiber	153	153	100.	0	0
	Mineral Fiber	170	170	100.	0	0
Masonry Wall	XEPS-ORNL:					
	CFC-12	795	487	61.3	308	38.7
	HCFC-142b	495	487	98.4	9	1.6
	HCFC-124	498	487	97.8	11	2.2
	HFC-134a	511	487	95.3	24	4.7
	XEPS-Industry					
	CFC-12	740	432	58.4	308	41.6
	HCFC-142b	441	432	98.0	9	2.0
	HCFC-124	443	432	97.5	11	2.5
	HFC-134a	456	432	94.7	24	5.3
	Air-filled	497	497	100.	0	0
	Not-in-Kind Alternatives:					
	MEPS	497	497	99.9	0.4	0.1

APPENDIX M: RESIDENTIAL BUILDING INSULATION

SUPPORTING DATA

Table M.1a. Annual heating load, fuel use, and CO_2 emissions resulting from heat loss through insulated portions of building walls for polyisocyanurate, polyurethane, and alternatives (wall sized to meet building codes with impermeably faced CFC-11 polyurethane)

Calculated Value blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago, US		Atlanta, US	
Annual Heating Load:	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)
CFC-11	6,112	5,799	6,014	5,706	29,644	28,125	11,151	10,580
HCFC-123	6,426	6,097	6,155	5,840	30,125	28,582	11,349	10,768
HCFC-141b	6,598	6,260	6,233	5,914	30,367	28,811	11,449	10,862
Isopropylchloride	8,532	6,543	6,366	6,040	30,796	29,218	11,624	11,028
Pentane (Bead Board)	6,896	8,095	7,223	6,853	32,544	30,877	12,389	11,754
Fiber Board	8,257	7,834	7,135	6,769	32,248	30,596	12,265	11,637
Losses Through Opaque Walls*:								
CFC-11	1,834	1,740	1,804	1,712	8,893	8,438	3,345	3,174
HCFC-123	2,147	2,038	1,945	1,846	9,375	8,895	3,544	3,362
HCFC-141b	2,319	2,201	2,023	1,920	9,616	9,124	3,643	3,456
Isopropylchloride	4,254	2,484	2,156	2,046	10,045	9,531	3,818	3,622
Pentane (Bead Board)	2,617	4,036	3,013	2,859	11,794	11,190	4,583	4,348
Fiber Board	3,978	3,775	2,925	2,775	11,498	10,909	4,459	4,231
Annual Fuel Use:	Natural Gas		No. 2 Fuel Oil		Natural Gas		Electricity	
	(m^3)	(ft^3)	(liter)	(gal.)	(m^3)	(ft^3)	(kWh)	
CFC-11	73.9	2,611	71.6	18.9	280.8	9,918	469	
HCFC-123	86.6	3,058	77.2	20.4	296.1	10,455	497	
HCFC-141b	93.5	3,303	80.3	21.2	303.7	10,724	511	
Isopropylchloride	105.6	3,728	85.6	22.6	317.2	11,202	535	
Pentane (Bead Board)	171.5	6,057	119.6	31.6	372.4	13,153	642	
Fiber Board	160.4	5,666	116.1	30.7	363.1	12,822	625	
Annual CO_2 Emissions:	(kg)		(kg)		(kg)		(kg)	
CFC-11	144		193		548		315	
HCFC-123	169		208		578		334	
HCFC-141b	182		217		592		343	
Isopropylchloride	206		231		619		360	
Pentane (Bead Board)	335		323		727		432	
Fiber Board	313		313		708		420	

* losses through opaque section of walls for the CFC baseline are computed as 30% of the heating load, losses through the opaque wall section for the alternative materials is calculated as 30% of the building losses for the CFC baseline plus the difference in heating loads between the alternative material and the baseline

Table M.1b. **Annual heating load, fuel use, and CO_2 emissions resulting from heat loss through insulated portions of building walls for polyisocyanurate, polyurethane, and alternatives (wall sized to meet building codes with fiber board insulation)**

Calculated Value blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago, US		Atlanta, US	
Annual Heating Load:	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)
CFC-11	4,364	4,140	5,037	4,779	26,206	24,863	9,754	9,254
HCFC-123	4,564	4,331	5,176	4,911	26,736	25,366	9,972	9,461
HCFC-141b	4,687	4,447	5,258	4,989	27,028	25,643	10,092	9,575
Isopropylchloride	4,893	4,643	5,390	5,114	27,506	26,096	10,289	9,762
Pentane (Bead Board)	6,386	6,059	6,132	5,818	29,992	28,456	11,295	10,717
Fiber Board	6,145	5,830	6,022	5,714	29,616	28,099	11,140	10,569
Losses Through Opaque Walls*:								
CFC-11	62	59	822	780	5,475	5,194	1,956	1,855
HCFC-123	263	249	960	911	6,004	5,697	2,174	2,062
HCFC-141b	85	366	1,043	989	6,296	5,974	2,294	2,176
Isopropylchloride	592	561	1,174	1,114	6,774	6,427	2,491	2,363
Pentane (Bead Board)	2,085	1,978	1,916	1,818	9,261	8,786	3,497	3,318
Fiber Board	1,844	1,749	1,807	1,714	8,885	8,430	3,342	3,171
Annual Fuel Use:	Natural Gas		No. 2 Fuel Oil		Natural Gas		Electricity	
	(m^3)	(ft^3)	(liter)	(gal.)	(m^3)	(ft^3)	(kWh)	
CFC-11	2.5	89	32.6	8.6	172.9	6,105	274	
HCFC-123	10.6	374	38.1	10.1	189.6	6,696	305	
HCFC-141b	15.5	549	41.4	10.9	198.8	7,021	322	
Isopropylchloride	23.9	843	46.6	12.3	213.9	7,554	349	
Pentane (Bead Board)	84.1	2,968	76.0	20.1	292.4	10,328	490	
Fiber Board	74.3	2,625	71.7	18.9	280.6	9,909	469	
Annual CO_2 Emissions:	(kg)		(kg)		(kg)		(kg)	
CFC-11	5		88		337		184	
HCFC-123	21		103		370		205	
HCFC-141b	30		112		388		216	
Isopropylchloride	47		126		417		235	
Pentane (Bead Board)	164		205		571		329	
Fiber Board	145		193		547		315	

* losses through opaque section of walls for the fiber board baseline are computed as 30% of the heating load, losses through the opaque wall section for the alternative materials is calculated as 30% of the building losses for the fiber board baseline plus the difference in heating loads between the alternative material and the baseline

Table M.2a. Annual heating load, fuel use, and CO_2 emissions resulting from heat loss through insulated portions of building walls for extruded polystyrene and alternative insulating materials (wall sized to meet building codes with CFC-12 extruded polystyrene)

Calculated Value blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago, US		Atlanta, US	
Annual Heating Load:	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)
CFC-12	6,112	5,799	6,023	5,714	29,616	28,099	11,140	10,569
HCFC-142b	6,112	5,799	6,023	5,714	29,616	28,099	11,140	10,569
HCFC-124	6,112	5,799	6,023	5,714	29,616	28,099	11,140	10,569
HFC-134a	6,112	5,799	6,023	5,714	29,616	28,099	11,140	10,569
Pentane (Bead Board)	6,638	6,298	6,202	5,884	29,885	28,351	11,251	10,675
Fiber Board	6,393	6,065	6,093	5,781	29,510	27,998	11,097	10,528
Losses Through Opaque Walls*:	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)
CFC-12	1,834	1,740	1,807	1,714	8,885	8,430	3,342	3,171
HCFC-142b	1,834	1,740	1,807	1,714	8,885	8,430	3,342	3,171
HCFC-124	1,834	1,740	1,807	1,714	8,885	8,430	3,342	3,171
HFC-134a	1,834	1,740	1,807	1,714	8,885	8,430	3,342	3,171
Pentane (Bead Board)	2,360	2,239	1,986	1,884	9,154	8,685	3,454	3,277
Fiber Board	2,114	2,006	1,877	1,781	8,778	8,329	3,299	3,130
Annual Fuel Use:	Natural Gas		No. 2 Fuel Oil		Natural Gas		Electricity	
	(m^3)	(ft^3)	(liter)	(gal.)	(m^3)	(ft^3)	(kWh)	
CFC-12	73.9	2,611	71.6	18.9	280.6	9,909	468	
HCFC-142b	73.9	2,611	77.2	18.9	280.6	9,909	468	
HCFC-124	73.9	2,611	80.3	18.9	280.6	9,909	468	
HFC-134a	73.9	2,611	85.6	18.9	280.6	9,909	468	
Pentane (Bead Board)	95.1	3,360	119.6	20.8	289.1	10,208	484	
Fiber Board	85.2	3,010	116.1	19.7	277.2	9,790	462	
Annual CO_2 Emissions:	(kg)		(kg)		(kg)		(kg)	
CFC-12	144		193		547		315	
HCFC-142b	144		193		547		315	
HCFC-124	144		193		547		315	
HFC-134a	144		193		547		315	
Pentane (Bead Board)	186		213		564		325	
Fiber Board	166		201		641		311	

* losses through opaque section of walls for the CFC baseline are computed as 30% of the heating load, losses through the opaque wall section for the alternative materials is calculated as 30% of the building losses for the CFC baseline plus the difference in heating loads between the alternative material and the baseline

Table M.2b. Annual heating load, fuel use, and CO_2 emissions resulting from heat loss through insulated portions of building walls for extruded polystyrene and alternative insulating materials (wall sized to meet building codes with fiber board)

Calculated Value blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago, US		Atlanta, US	
Annual Heating Load:	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)	(MJ)	(KBtu)
CFC-12	5,759	5,464	5,936	5,632	29,723	28,201	11,186	10,613
HCFC-142b	5,759	6,454	5,936	5,632	29,723	28,201	11,186	10,613
HCFC-124	5,759	5,464	5,936	5,632	29,723	28,201	11,186	10,613
HFC-134a	5,759	5,464	5,936	5,632	29,723	28,201	11,186	10,613
Pentane (Bead Board)	6,386	6,059	6,132	5,818	29,993	28,456	11,296	10,717
Fiber Board	6,145	5,830	6,023	5,714	29,616	28,099	11,140	10,569
Annual Fuel Use:	Natural Gas		No. 2 Fuel Oil		Natural Gas		Electricity	
	(m^3)	(ft^3)	(liter)	(gal.)	(m^3)	(ft^3)	(kWh)	
CFC-12	58.8	2,076	68.3	18.0	284.0	10,028	475	
HCFC-142b	58.8	2,076	68.3	18.0	284.0	10,028	475	
HCFC-124	58.8	2,076	68.3	18.0	284.0	10,028	475	
HFC-134a	58.8	2,076	68.3	18.0	284.0	10,028	475	
Pentane (Bead Board)	84.1	2,968	76.1	20.1	292.5	10,328	490	
Fiber Board	74.3	2,625	71.7	18.9	280.6	9,909	468	
Annual CO_2 Emissions:	(kg)		(kg)		(kg)		(kg)	
CFC-12	115		184		554		319	
HCFC-142b	115		184		554		319	
HCFC-124	115		184		554		319	
HFC-134a	115		184		554		319	
Pentane (Bead Board)	164		205		571		329	
Fiber Board	145		193		547		315	

* losses through opaque section of walls for the fiber board baseline are computed as 30% of the heating load, losses through the opaque wall section for the alternative materials is calculated as 30% of the building losses for the fiber board baseline plus the difference in heating loads between the alternative material and the baseline

Table M.3. Physical properties of foam insulations in baseline residences for polyisocyanurate, polyurethane, and alternative materials

Value Calculated blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago and Atlanta, US	
	constant thickness	constant resistance	constant thickness	constant resistance	constant thickness	constant resistance
Volume of Foam (m^3):						
CFC-11	2.16	2.16	2.29	2.29	3.37	3.37
HCFC-123	2.16	2.39	2.29	2.48	3.37	3.69
HCFC-141b	2.16	2.47	2.29	2.57	3.37	3.85
Isopropylchloride	2.16	2.62	2.29	2.75	3.37	4.17
Pentane (Bead Board)	2.16	4.09	2.29	4.31	3.37	6.26
Mass of Foam (kg):						
CFC-11	69.1	69.1	73.4	73.4	107.8	107.8
HCFC-123	69.1	76.5	73.4	79.3	107.8	118.1
HCFC-141b	69.1	79.0	73.4	82.2	107.8	123.2
Isopropylchloride	69.1	83.9	73.4	88.1	107.8	133.5
Pentane (Bead Board)	69.1	130.8	73.4	138.0	107.8	200.3
Mass of Blowing Agent (kg):						
CFC-11	8.6	8.6	9.2	9.2	13.5	13.5
HCFC-123	10.8	12.0	11.5	12.4	16.8	18.5
HCFC-141b	7.3	8.4	7.8	8.7	11.5	13.1
Isopropylchloride	5.5	6.7	5.9	7.0	13.5	10.7
Pentane (Bead Board)	8.6	16.3	9.2	17.3	8.6	25.0
Equivalent CO_2 Emissions (kg):						
CFC-11	12,950	12,950	13,750	13,750	20,200	20,200
HCFC-123	300	350	350	350	500	550
HCFC-141b	1,100	1,250	1,150	1,300	1,700	1,950
Isopropylchloride	61	74	88	106	81	150
Pentane (Bead Board)	50	100	50	100	129	160
Fiber Board	0	0	0	0	0	0

Table M.4. Physical properties of foam insulations in baseline residences for extruded polystyrene and alternative materials

Value Calculated blowing agent/material	Mildenhall, UK		Wiesbaden, Germany		Chicago and Atlanta, US	
	constant thickness	constant resistance	constant thickness	constant resistance	constant thickness	constant resistance
Volume of Foam (m^3):						
CFC-12	3.55	3.55	3.95	3.95	6.90	5.94
HCFC-142b	3.55	3.55	3.95	3.95	6.90	5.94
HCFC-124	3.55	3.55	3.95	3.95	6.90	5.94
HFC-134a	3.55	3.55	3.95	3.95	6.90	5.94
Pentane (Bead Board)	3.55	4.16	3.95	4.31	6.90	6.26
Mass of Foam (kg):						
CFC-12	113.5	113.5	126.3	126.3	220.8	190.0
HCFC-142b	113.5	113.5	126.3	126.3	220.8	190.0
HCFC-124	113.5	113.5	126.3	126.3	220.8	190.0
HFC-134a	113.5	113.5	126.3	126.3	220.8	190.0
Pentane (Bead Board)	113.5	133.2	126.3	138.0	220.8	200.3
Mass of Blowing Agent (kg):						
CFC-12	6.8	6.8	7.6	7.6	13.2	11.4
HCFC-142b	5.6	5.6	6.3	6.3	11.0	9.4
HCFC-124	7.7	7.7	8.5	8.5	14.9	12.8
HFC-134a	5.8	5.8	6.4	6.4	11.2	9.6
Pentane (Bead Board)	6.8	8.0	7.6	8.3	13.2	12.0
Equivalent CO_2 Emissions (kg):						
CFC-12	30,650	30,650	34,100	34,100	59,600	51,300
HCFC-142b	3,050	3,050	3,400	3,400	5,900	5,100
HCFC-124	1,150	1,150	1,300	1,300	2,250	1,900
HFC-134a	2,400	2,400	2,700	2,700	4,700	4,050
Pentane (Bead Board)	50	50	50	50	100	50
Fiber Board	0	0	0	0	0	0

Table M.5a Lifetime CO_2 emissions for polyisocyanurate, polyurethane, and alternatives for residential buildings with constant wall thickness (wall sized to meet building codes with impermeably faced CFC-11 polyurethane)

Location	Polyisocyanurate or Polyurethane Blowing Agent or Insulating Material					
	CFC-11	HCFC-123	HCFC-141b	Isopropylchloride	Pentane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	13,000	300	1,100	100	0	0
Indirect	7,200	8,500	9,100	10,300	16,800	15,700
Total	20,200	8,800	10,200	10,400	16,800	15,700
Wiesbaden, Germany						
Direct	13,800	400	1,200	100	100	0
Indirect	9,700	10,400	10,900	11,600	16,200	15,700
Total	23,500	10,800	12,100	11,700	16,300	15,700
Chicago, US						
Direct	20,200	500	1,700	100	100	0
Indirect	27,400	28,900	29,700	31,000	36,400	35,400
Total	47,600	29,400	31,400	31,100	36,500	35,400
Atlanta, US						
Direct	20,200	500	1,700	100	100	0
Indirect	15,800	16,700	17,200	18,000	21,600	21,000
Total	36,000	17,200	18,900	18,100	21,700	21,000

Table M.5b. Lifetime CO_2 emissions for extruded polystyrene and alternatives for residential buildings with constant wall thickness: (wall sized to meet building codes with CFC-12 extruded polystyrene)

Location	Extruded Polystyrene Alternative Blowing Agents					
	CFC-12	HCFC-142b	HCFC-124	HFC-134a	Pentane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	30,700	3,100	1,200	2,400	100	0
Indirect	7,200	7,200	7,200	7,200	9,300	8,300
Total	37,900	10,300	8,400	9,600	9,400	8,300
Wiesbaden, Germany						
Direct	34,100	3,400	1,300	2,700	100	0
Indirect	9,700	9,700	9,700	9,700	10,700	10,100
Total	43,800	13,100	11,000	12,400	10,800	10,100
Chicago, US						
Direct	59,600	5,900	2,300	4,700	100	0
Indirect	27,400	27,400	27,400	27,400	28,200	27,100
Total	87,000	33,300	29,700	32,100	28,300	27,100
Atlanta, US						
Direct	59,600	5,900	2,300	4,700	100	0
Indirect	15,800	15,800	15,800	15,800	16,300	15,600
Total	75,400	21,700	18,100	20,500	16,400	15,600

Table M.6a. Lifetime CO_2 emissions for polyisocyanurate, polyurethane, and alternatives for residential buildings with constant wall thickness (wall sized to meet building codes with fiber board)

Location	Polyisocyanurate or Polyurethane Blowing Agent					
	CFC-11	HCFC-123	HCFC-141b	Isopropylchloride	Propane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	23,150	600	2,000	200	100	0
Indirect	250	1,100	1,500	2,400	8,200	7,300
Total	23,400	1,700	3,500	2,600	8,300	7,300
Wiesbaden, Germany						
Direct	23,700	600	2,000	200	100	0
Indirect	4,400	5,200	5,600	6,300	10,300	9,700
Total	28,100	5,800	7,600	6,500	10,400	9,700
Chicago, US						
Direct	35,600	900	3,100	100	200	0
Indirect	16,900	18,500	19,400	20,900	28,600	27,400
Total	52,500	19,400	22,500	21,000	28,800	27,400
Atlanta, US						
Direct	35,600	900	3,100	100	200	0
Indirect	9,200	10,300	10,800	11,800	16,500	15,800
Total	44,800	11,200	13,900	11,900	16,700	15,800

Table M.6b. Lifetime CO_2 emissions for extruded polystyrene and alternatives for residential buildings with constant wall thickness (wall sized to meet building codes with expanded polystyrene bead board)

Location	Extruded Polystyrene Alternative Blowing Agents					
	CFC-12	HCFC-142b	HCFC-124	HFC-134a	Pentane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	33,300	3,300	1,300	2,700	100	0
Indirect	5,800	5,800	5,800	5,800	8,200	7,300
Total	39,100	9,100	7,100	8,500	8,300	7,300
Wiesbaden, Germany						
Direct	34,100	3,400	1,300	2,700	100	0
Indirect	9,200	9,200	9,200	9,200	10,300	9,700
Total	43,300	12,600	10,500	11,900	10,400	9,700
Chicago, US						
Direct	51,300	5,100	1,900	4,100	100	0
Indirect	27,700	27,700	27,700	27,700	28,600	27,400
Total	79,000	32,800	29,600	31,800	28,700	27,400
Atlanta, US						
Direct	51,300	5,100	1,900	4,100	100	0
Indirect	16,000	16,000	16,000	16,000	16,500	15,800
Total	67,300	21,100	17,900	20,100	16,600	15,800

Table M.7a. Lifetime CO_2 emissions for polyisocyanurate, polyurethane, and alternatives in residential buildings for constant resistance walls

Location	Polyisocyanurate or Polyurethane Blowing Agent					
	CFC-11	HCFC-123	HCFC-141b	Isopropylchloride	Propane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	12,950	350	1,250	74	100	0
Indirect	7,200	7,200	7,200	7,200	7,200	7,200
Total	20,150	7,550	8,450	7,274	7,300	7,200
Wiesbaden, Germany						
Direct	13,750	350	1,300	106	100	0
Indirect	9,700	9,700	9,700	9,700	9,700	9,700
Total	23,450	10,050	11,000	9,806	9,800	9,700
Chicago, US						
Direct	20,200	550	1,950	150	160	0
Indirect	27,400	27,400	27,400	27,400	27,400	27,400
Total	47,600	27,950	29,350	27,550	27,560	27,400
Atlanta, US						
Direct	20,200	550	1,950	150	160	0
Indirect	15,800	15,800	15,800	15,800	15,800	15,800
Total	36,000	16,350	17,750	15,950	15,960	15,800

Table M.7b. Lifetime CO_2 emissions for extruded polystyrene and alternatives for residential buildings with constant wall thickness

Location	Extruded Polystyrene Alternative Blowing Agents					
	CFC-12	HCFC-142b	HCFC-124	HFC-134a	Pentane (Bead Board)	Fiber Board
Mildenhall, UK						
Direct	30,650	3,050	1,150	2,400	50	0
Indirect	7,200	7,200	7,200	7,200	7,200	7,200
Total	37,850	10,250	8,350	9,600	7,250	7,200
Wiesbaden, Germany						
Direct	34,900	3,450	1,300	2,750	50	0
Indirect	9,700	9,700	9,700	9,700	9,700	9,700
Total	44,600	13,150	11,000	12,450	9,750	9,700
Chicago, US						
Direct	51,300	5,100	1,900	4,500	50	0
Indirect	27,400	27,400	27,400	27,400	27,400	27,400
Total	78,700	32,600	29,300	31,900	27,450	27,400
Atlanta, US						
Direct	51,300	5,100	1,900	4,050	50	0
Indirect	15,800	15,800	15,800	15,800	15,800	15,800
Total	67,100	20,900	17,700	19,850	15,850	15,800

APPENDIX N: CONVERSION FACTORS

Table N.1. English-Metric (SI) Conversion Factors

To Convert From	To	Multiply By
Atmosphere (normal)	Pascal	101,325
Barrel (42 gal)	Metre^3	0.1589
British Thermal Unit	Joule	1,055
Centipoise	Pascal-second	0.001
Degree Fahrenheit	Degree Celsius	$t_C^0 = [t_F^0 - 32]/1.8$
Degree Rankine	Degree Kelvin	$t_K^0 = t_R^0/1.8$
Foot	Metre	0.3048
Foot^3/minute	Metre^3/sec	0.0004719
Foot^3	Metre^3	0.02831
Foot^2	Metre^2	0.09290
Foot/sec	Metre/sec	0.3048
Foot^2/hr	Metre^2/sec	0.00002580
Gallon (U.S. liquid)	Metre^3	0.003785
Horsepower (550 ft-lbf/sec)	Watt	745.7
Horsepower (electric)	Watt	746.0
Horsepower (metric)	Watt	735.5
Inch	Metre	0.02540
Kilowatt-hour	Joule	3.60×10^6
Litre	Metre^3	1.000×10^{-3}
Micron	Metre	1.000×10^{-6}
Mil	Metre	0.00002540
Poise	Pascal-second	0.1000
Pound force (avdp)	Newton	4.448
Pound mass (avdp)	Kilogram	0.4536
Ton (assay)	Kilogram	0.02916
Ton (long)	Kilogram	1,016
Ton (metric)	Kilogram	1,000
Ton (short)	Kilogram	907.1
Tonne	Kilogram	1,000

Source: American National Standards Institute, "Standard Metric Practice Guide," March 15, 1973. (ANS72101-1973) ASTM Designation E380-72).

APPENDIX O. CARBON DIOXIDE GENERATION FROM POWER GENERATION

The total carbon dioxide emissions (lbs CO_2/kWh delivered) generation varies by region due to fuel mix variations by region. This can be seen in Table).1 for three regions: Europe, North America and Japan.

The carbon dioxide emissions (lb CO_2/kWh delivered) for each fuel in Table O.1 are shown in Table O.2. As can be seen from Table O.2, coal represents the primary source of CO_2 per kWh of electricity. Therefore, regions in which coal is a high percentage of their power generation fuel mix will have a higher total carbon dioxide emission level. The range in average values for the regions of primary interest range from 0.51 to 0.68 Kg/kWh delivered. Thus, variations around an average value of 0.59 Kg/kWh are about 15%. These data were supplied by Oak Ridge National Laboratories.

Table O.1. Carbon dioxide emissions from power generation (lbs. CO_2/kWh delivered)

Region	Nuclear	Hydro-electric	Natural Gas	Fuel Oil	Coal	Total lbs/kWh	Total kg/kWh
Europe	0	0	0.09	0.46	0.58	1.13	0.51
North America	0	0	0.15	0.40	0.93	1.48	0.67
Japan	0	0	0.15	0.93	0.20	1.28	0.58

Table O.2. Electrical power generating capacity by fuel source

Region	Nuclear	Hydro-electric	Natural Gas	Fuel Oil	Coal	CO_2 Emissions lbs/kWh	CO_2 Emissions kg/kWh
Europe	21%	27%	7%	22%	23%	1.13	0.51
North America	13%	19%	12%	19%	37%	1.48	0.67
Japan	15%	21%	12%	44%	8%	1.28	0.58

APPENDIX P: INDIRECT IMPACTS

P.1 ENERGY USE IN MANUFACTURE OF SOLVENTS

Background

There are a large number of factors influencing energy used in the production of solvents and chemicals ranging from:

- Feedstocks used (e.g. ethylene derived from ethane - propane derived from the natural gas industry, naphtha cracking of fractions from petroleum refinery).
- Energy accounting methodologies for by-product and co-product relationships.
- Process routes for chemicals manufactured (e.g. alkaline/caustic values produced via chloralkali cells, mercury cells, Solvay process, trona, etc.).

As a result the energy used in manufacture of chemicals can vary widely even for the same chemical end product and typically, information on energy use is not readily available. However, an analysis shows that the amount of chemicals consumed in cleaning processes is rather modest and that these contributions to GWP are relatively small. As a result, the energy used in manufacture of chemicals is presented here as estimates or ranges of values (these values can be updated at a later time if deemed to be of significant importance and warranting such effort).

To obtain a perspective on the energy used in chemical/solvent manufacture, several examples are provided.

Halogenated Hydrocarbons

There are two major bulk chemicals, accounting for the majority of energy used in the production of bulk chemicals used in cleaning:

- production of halogens such as chlorine, fluorine, bromine
- production of hydrocarbon feedstock such as ethylene, propylene etc.

Halogens

The production of chlorine and sodium hydroxide has been reported to involve energy use from 2300 to 3000 kWh of electric energy per metric ton of sodium hydroxide (C&EN, 81). After adding energy for concentration of sodium hydroxide and allocating energy consumed between chlorine and sodium hydroxide the following values have been reported (Hey, 1990).

- 1,650 kWh/te of chlorine
- 1,850 kWh/te of caustic

Ethylene (from Naphtha)

In a similar fashion,

- Manufacture of one tonne of ethylene requires 8,000 kWh of electric energy equivalent.

- Production of one tonne trichloroethylene requires about 0.19 tonnes of ethylene and 0.81 tonnes of chlorine.

- Assuming the reaction of ethylene and chlorine to solvent is energy neutral (Hey, 1990), the energy consumed in manufacture of one tonne of trichloroethylene is then 2,860 kWh/tonne (0.81 x 1,640 + 8,000 x 0.19).

Hydrocarbons from Crude Oil

Energy consumption to produce refined oil products from crude oil will vary widely depending on composition of crude, products produced and refinery configuration. An idea of the average energy use in producing refined products like No. 2 fuel oil, kerosene, gasoline, etc. can be obtained from the Energy Information Administration (USDOE) indicating that energy use in the petroleum refinery industry amounted to about 8% of the product heating value (assumed to be about 20,000 Btu/lb). This amounts to 1,600 Btu/lb or a value (rounded) of 1000 kWh/tonne of hydrocarbon (1600 x 2205 lb/tonne/3413).

Inorganic

In a number of applications for aqueous cleaning, a variety of chemicals are used and their energy content have been estimated to be (Hey, 1990):

- caustic soda (see section on halogens): 1,850 kWh/tonne

- sodium carbonate: 500 kWh/tonne

- sodium silicate: 130 kWh/tonne

- sodium phosphate: 100 kWh/tonne

- surfactant: 1,000 kWh/tonne (roughly estimated)

Summary

For a typical aqueous formulation it was found (Hey, 1990) that the energy consumed was about 48 kWh/tonne of formulation (see Table P.1). For aqueous systems the embodied energy in chemicals is extremely small and can be neglected (Hey, 1990).

For hydrocarbon organic based solvents, the embodied energy in material consumed can typically range from 1000 to 3000 kWh_T/tonne. An average value of 2,860 kWh_T[1]/tonne of chemical (solvent) (e.g. the same value as for trichloroethylene) is used recognizing that the energy in solvent manufacturing provides only a small contribution to TEWI and thus errors in estimation will only have a small impact on the systems analysis.

[1] kWh_T means kWh of thermal energy.

Table P.1. Estimated energy content of aqueous formulation

Typical Formulation		Content	Energy of Production kWh/te of Chemical	Energy Content of Formulation kWh/te
New	Old			
20% complexes, e.g. EDTA, NTA	Caustic soda	15 g/l	1.85×10^3	28
Naglucomate	Sodium carbonate	20 g/l	0.5×10^3	10
5% Corrosion inhibitor	Sodium silicate	20 g/l	0.13×10^3	3
5% saa	Sodium phospate surfactant	20 g/l 5 g/l	0.1×10^3 1×10^3	2 5
Total				48

P.2 SOLVENT RECOVERY

Overview

Used solvent may be recovered in small in-house units or collected for solvent recovery in a large centralized facility. Energy use in solvent recovery will vary by the type of solvent, degree of contamination, etc. Calculations shown below indicate that energy use in solvent recovery is relatively small.

Energy Use

Energy use in solvent recovery (e.g., hydrocarbons, chlorinated hydrocarbons, CFCs etc.) is estimated using three different approaches to develop a likely range of values.

- Average energy use in a small solvent recovery still (e.g., Baron Blakeslee's model MRR-60) is on the order of 100 kWh/tonne of CHC or CFC.

- Estimated energy required for used hydrocarbon solvent recovery is on the order of seven times the heat of vaporization (Miasek, 1991). Using a value of 240 kJ/kg for the heat of vaporization of a hydrocarbon, the estimated energy for solvent recovery is 470 kWh_t/tonne (= 7 x 240,000 kJ/tonne/3600kJ/kWh_t).

- For a solvent recovery process on vacuum bottoms which would represent a fairly complex separation using isobutane, the following values were reported (for treating about 30 tonnes/hr) (Newcomer, 1982):

Steam 2500 lbs/hr	=	880 kWh_t/hr
Electricity 635 kWh/hr	=	635
Fuel 24.4 MMBtu/hr	=	7149
Total		8664

This amounts to 289 kWh_t/tonne (=8664/30) which is rounded to 300 kWh/tonne.

As a result of the above consideration, the energy for used solvent recovery is expected to be well under 1000 kWh_T/tonne. For calculational purposes here we use a maximum value (erring on the conservative side) of 1000 kWh_t/tonne. (This will give the largest contribution to TEWI, is found to be small and is neglected in further considerations.)

P.3 SOLVENT/CLEANING AGENT DISPOSAL

During its life, a solvent becomes contaminated as it picks up soils in the cleaning process. At the end of its useful cleaning life the solvent may be disposed of in a number of ways, each with different but relatively small affects on GWP.

- The used solvent (e.g. hydrocarbon, CFC, CHC, etc.) can be recovered for re-use. This would require energy for separation/distillation in the same order of magnitude as in Section P.2 on energy use for CHC, CFCs of 360 kJ/kg (i.e. 100 kWh/tonne). Based on an emission factor of 0.00005 kg CO_2/kJ, the TEWI impacts due to CO_2 emissions are only 0.02 kg CO_2 per kg of solvent recovered (= 360 x 0.00005).

- A hydrocarbon waste solvent can be used as a fuel in which case it would substitute for other fuels and the net impact is a fuel-fuel substitution with little net impact on CO_2 emissions.

- The solvent can be incinerated with other wastes; because many solvents have a net heat of combustion, they add to the heating value and reduce fuel requirements. The reduction in fuel use (and CO_2 emissions) from the fuels will balance to some extent the CO_2 emissions from combustion of the solvent.

It should be noted that the above calculations do not include the heating value of the solid (oils) removed since these are assumed to be constant from process to process.

The most likely route is probably solvent recovery involving emissions of 0.02 kg CO_2 per kg of solvent recovered which are used in the calculations presented below. In order to estimate how much solvent is used in metal cleaning it is noted that:

- Impurities and soils (oils) build up in the boil sump until one sees a boiling point temperature rise of a few degrees which is assumed to occur as the soil (oil) concentration approaches about one-third the weight of the solvent. As a result, 2 kg of solvent remove about 1 kg of soil (oils).

- A rough estimate of the soils (oils) contained on 1 tonne of metal is in the order of 0.5 kg of soils/oils/tonne. This solvent required to dissolve this soil (oil) is about 1 kg/tonne of metal.

- If it is assumed 75% of the solvent is recovered with the difference remaining with the oil sludge, the CO_2 emissions in solvent recovery are 0.03 kg CO_2/tonne of metal (0.02/(1 kg x 0.75). The oily sludge with the remainder of solvent can be used as a fuel with little net affect on GWP as discussed above. These emissions of CO_2 are negligible compared to typical values of 20 to 30 (or more) kg CO_2 per tonne of metal cleaned (see Appendix Y). Even if the solid (oil) to be removed required ten times as much solvent, the effect on TEWI and CO_2 emissions is small. With PCB cleaning the soils to be removed are much smaller in quantity and the relative effect of solvent recovery/disposal on TEWI is expected to be even smaller.

As a result, energy used (and TEWI affects) in solvent disposal are second order effects and are neglected in this analysis.

P.4 WASTE WATER TREATMENT

Ultrafiltration Before Disposal/Recycling

The oily wastewaters can be grouped into three broad categories: waste containing free floating oil, unstable oil/water emulsion and highly stable oil/water emulsions. The stable emulsions usually require more sophisticated treatment techniques and ultrafiltration (UF) in conjunction with gravity separation devices have been found to be an adequate solution.

In typical UF systems, oily wastewater is pumped through the membrane modules at about 10 to 100 psig (EPRI, 1988) or an average of 50 psig. The modules types (flat element, spiral wound, tubular and the hollow fiber) have their own advantages and disadvantages and for oily wastewaters tubular design seems to dominate the market place. Other than the membrane modules, the UF system comprises of housing, pumps, tanks, controls and membrane cleaning solutions. The factors in overall treatment system design that have significant impact on UF performance are equalization tank capacity for free oil removal, free oil removal efficiency and process tank capacity. Major energy use is in the pumping system. Typical design fluxes are about 300 U.S. gallon per square meter per day. The energy to overcome a 50 psi pressure drop is about 0.7 kWh/m^3 of water (for comparison, a 500 psi reverse osmosis plant operates at about one tenth (EPRI, 1988) the energy of a conventional five to seven step evaporator. Adjusting for a 50 psig pressure drop for ultrafiltration one calculates a value of 1.1 kWh/m^3 (of water treated, compared to a value of 0.7 calculated above). In further discussions, a rounded value of 1 kWh/m^3 of water treated is used.

Deionization Closed Loop Water Treatment and Recycling Systems

An alternative to discharging large quantities of spent rinse water from aqueous and semi-aqueous processes is to treat and recycle the rinse water. A typical system that provides deionized (DI) water is illustrated schematically in Fig. P.1. At the inlet to the system, a pump provides enough pressure to make up for the approximately 20 psi pressure drop through the system and to supply the processed water at 40 to 50 psig. The clean up process is a series of steps consisting of particulate filtration, carbon adsorption to remove organics, and anion and cation exchange to remove dissolved, ionic solids. The water supply is essentially free of dissolved solids (typically <1 PPM). The ion exchange resins are used and replaced on a batch basis, with a typical working inventory of 300 lb (136 kg). The ion exchange resins are long chain polymers with active side groups to attract positive or negatively charged ions. In their regenerated state, the cation exchange resins active sites are occupied by H^+ ions; the active sites of the anion exchange resins are occupied by OH^- ions. In operation, the dissolved ions in the process water exchange with the H^+ and OH^-, which combine to

form additional water molecules, leaving the dissolved solids attached to the ion exchange resins. The amount of water that can be processed with a given amount of ion exchange resins depends primarily on the dissolved solids content on the incoming or recycled water. Closed loop recycling to DI water purity levels is most attractive economically with non-saponifier operations where DI rinse water is needed to meet the quality specifications. This type of system can be used with aqueous cleaning systems using DI water in both the wash and rinse stages, cleaning water soluble flux residues, and for recycling the rinse water in terpene based semi-aqueous systems following gravity separation of the rinse water from terpenes carried over from the wash stage.

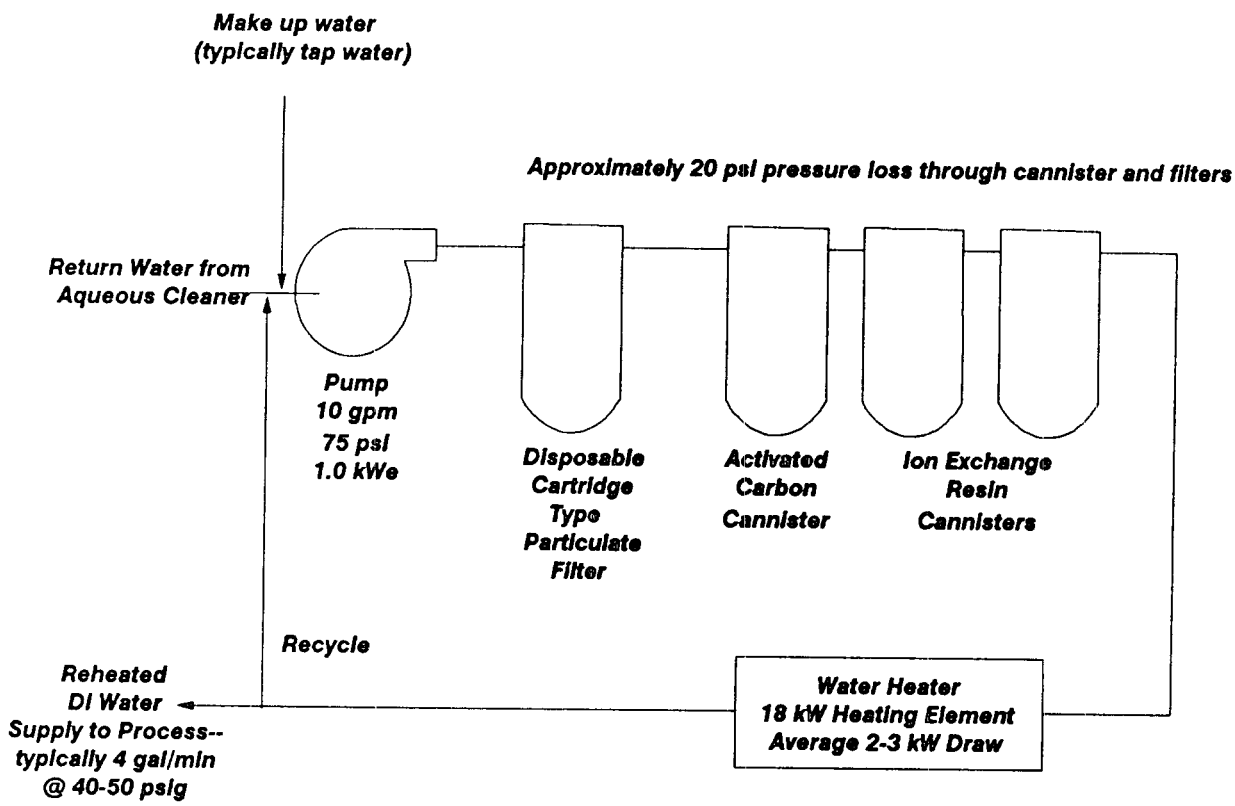

Fig. P.1. Closed loop water treatment.

The energy requirements are estimated as follows:

- Average cartridge life is expected to be about two months or more based on discussions with vendors and users of aqueous equipment. Assuming 60 hours per week for 8 weeks (480 hours) on a system treating 10 to 20 m^2 board/hr the average bead use is about 0.28 kg beads/hr (136 kg beads/(480 hours)).

- Energy to manufacture the beads is roughly estimated to be 2860 kWh/tonne (see the summary of Section P.1) or 2.86 kWh/kg.

Finally, it should be noted that many aqueous cleaning systems use untreated tap water for the fresh rinse water supply in which case the energy requirements are nil.

CITATIONS

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APPENDIX Q: SOLVENT LOSSES/DRAGOUT

In solvent based systems, solvent lost to air can have a significant CO_2 equivalent global warming impact, in comparison with the energy consumption related impact. Solvent losses can be categorized as:

- *Diffusion Loss* - Solvent vapors that diffuse from the vapor zone through openings to the surrounding air, and ultimately are vented to the atmosphere. This loss occurs continuously, whether or not the unit is operating, unless the openings are tightly closed.

- *Dragout* - Liquid solvent held in gaps and crevices of the metal parts or printed circuit board assemblies tends not to evaporate within the saturated vapor zone of a vapor cleaner, and is carried out of the cleaner into the surrounding plant atmosphere, where it quickly evaporates. Ultimately these vapors are lost to the atmosphere.

- *Leakage* - Leaks through shaft seals, valve stems, etc., and at joints in the piping result in unrecovered solvent losses, which field surveys have shown to be significant in practice. In the context of this study, the use of state of the art equipment is assumed; this equipment is assumed to be leak tight.

- *Spent Solvent and Residues* - This is potentially a source of additional loss to atmosphere but when handled carefully and reprocessed, by solvent recovery and incineration of the residues, the resulting airborne solvent emissions are negligible.

Table Q.1 lists published solvent loss rates, expressed in terms of solvent mass loss rate per mass of metal processed or per plan area of PC board (kg solvent/kg of metal, or kg solvent/square meter of PC board, respectively). These values apply to cleaning systems in operation and are a composite of diffusion and dragout losses. Diffusion and dragout losses are discussed separately in Sections Q.1 and Q.2 below.

Given the presumption of state of the art equipment usage, the values at the low end of the range have been adopted in this study, as summarized in Table Q.1.

Q.1 DIFFUSION LOSSES

Figure Q.1 illustrates the diffusion loss mechanism for an open top vapor degreaser. Under ideal circumstances, the freeboard area above the saturated vapor zone is relatively undisturbed by convection currents. The air and solvent will tend to remain stratified due to the much higher molecular weight and density of the solvent molecules relative to air, and the concentration and partial pressure of the solvent vapor continually decrease, approaching zero at the top of the freeboard area. The concentration gradient drives the diffusion of solvent vapor from the vapor zone to the ambient air at the open top of the tank, from where it is ultimately dissipated to the atmosphere. For enclosed, in-line systems the same mechanism drives the diffusion loss, but the size of the openings is smaller than the open area of a typical open top batch vapor degreaser.

The basic factors controlling the magnitude of the diffusion loss are freeboard height, interior open area of the freeboard, the diffusivity of the solvent vapors in air, and condensing temperature. Measures to control solvent losses include tank covers and freeboard chillers. Table Q.2 summarizes measured diffusion losses in open top vapor cleaners.

Table Q.1. Examples of reported solvent losses

Solvent	Loss	Source
Metal Cleaning	kg/tonne steel	
- various solvents (av)	2 to 3	ASTM, 1989
- trichloroethylene (av)	4	Askengren, 1989
- trichloroethylene (best)	0.5	Askengren, 1989
- hydrocarbon	2 to 6[1]	Miasek, 1991
- HCFC (batch)	0.75	Osterman, 1991
- HCFC (in-line)	0.35	Osterman, 1991
Electronic Circuit Board	kg/m^2	
- CFC (av)	2.0	Fitzgerald, 1990 (EPA)
- CFC (ave)	1.8	Brox, 1989
- CFC (best)	0.5	Fitzgerald, 1990 (EPA)
- CFC (best in-line)	0.5	Hamblett, 1990
- HCFC (current SOA in-line)	0.103	Osterman, 1991
- Terpene (system tests)	0.15	Hamblett, 1990

Table Q.2. Measured solvent diffusion losses

Vapor Cleaner Configuration	Solvent	Diffusion Loss $kg/h\text{-}m^2$[2]	Reference
Open top 100% freeboard	Vertrel 434[3]	0.77	Hoppestad, 1991
Open top 100% freeboard, covered	Vertrel 434	0.46	Hoppestad, 1991
Open top 200% freeboard	Vertrel 434	0.39	Hoppestad, 1991
Open top 200% freeboard, with freeboard chiller	Vertrel 434	0.20	Hoppestad, 1991
Open top, 200% freeboard	94.3% CFC-113, 5.7% methanol	0.29	Hoppestad, 1991
Open top, 100% freeboard	Genesolv 2010[4]	0.30	Osterman, 1991
In-line, with freeboard chiller (Baron Blakeslee CFC-18LE)	Genesolv 2010	0.046 kg/hr	Osterman, 1991

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1 Dragout with low vapor pressure hydrocarbon for spherical objects of 0.5 to 1 cm in diameter based on 4 to 6 mg/cm^2.

2 per square meter of open area

3 Vertrel 434 is the du Pont trade name for a blend of 62.2% HCFC-141b, 35% HCFC-123, 2.5% methanol.

4 Genesolv 2010 is the Allied-Signal trade name for a blend of 86.1% HCFC-141b and 10% HCFC-123, 3.6% methanol, 0.3% nitromethane.

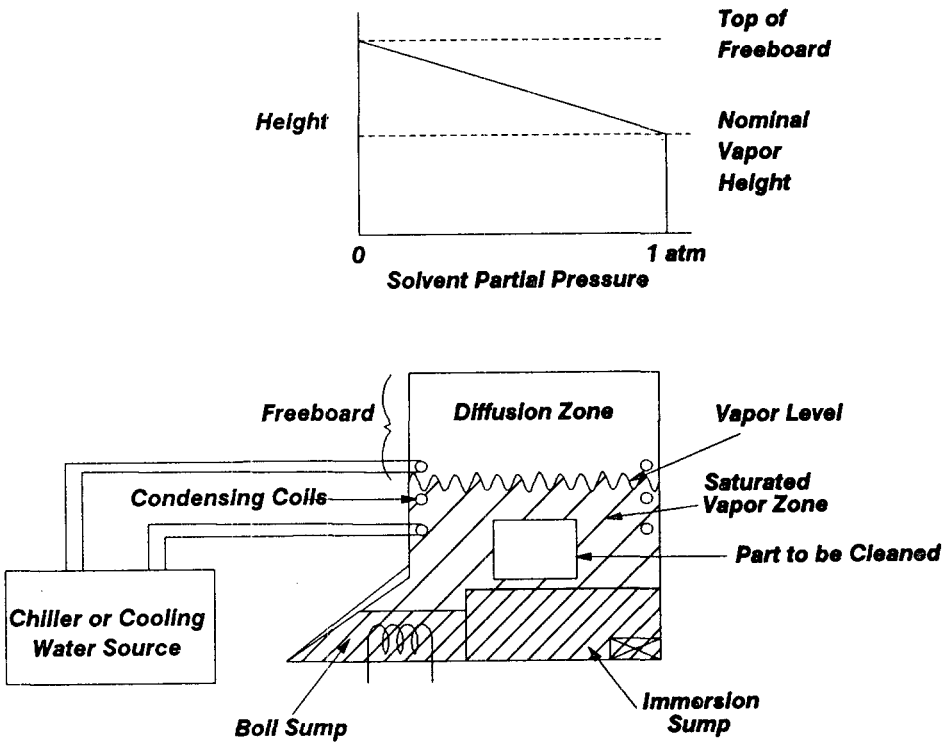


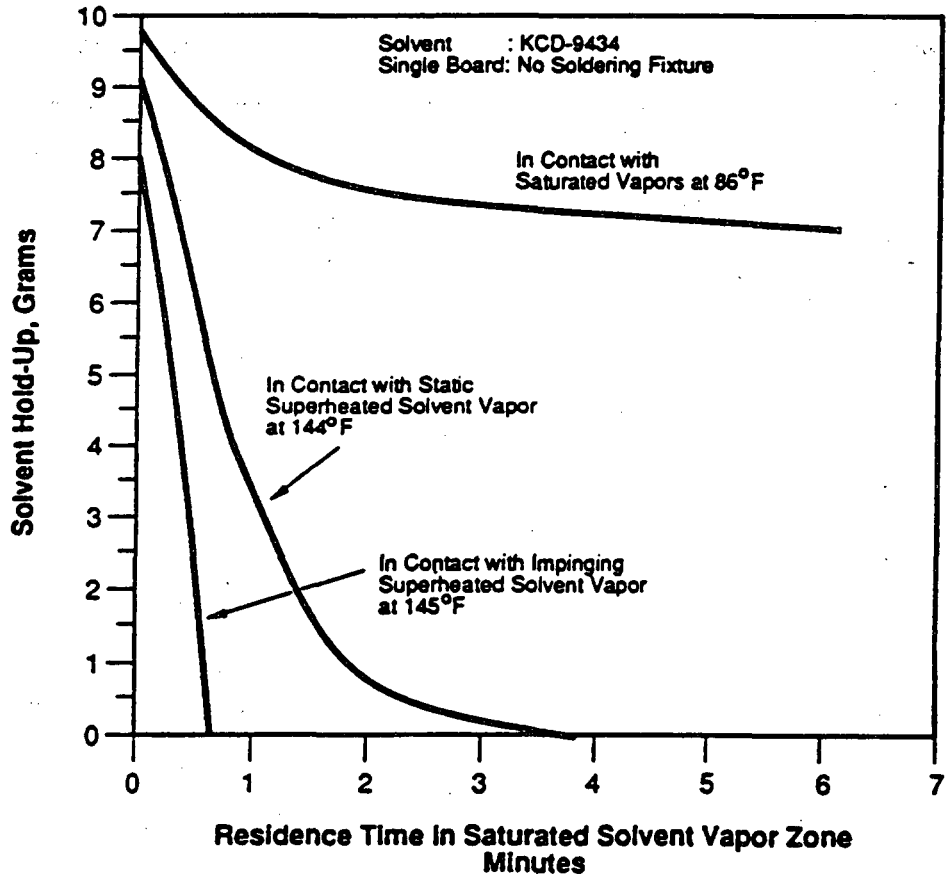
Fig. Q.1. Diffusion loss mechanism.

Q.2 DRAGOUT

Dragout plus diffusion losses account for virtually all solvent losses in a state of the art vapor cleaner. "Dragout" refers to solvent carried out of the cleaning process on the work (i.e., the metal parts or printed circuit boards). The majority of the solvent dragged out is trapped in crevices and other close clearance areas of the work, with a lesser amount coating open areas of the work in a thin film. The areas holding up solvent on assembled printed circuit boards include female connector sockets and spaces between the board and chips mounted with close clearances. Solvent is retained on metal parts and assemblies in screw holes and clearances between close fitting parts. The density of these features varies widely.

Recent investigations of dragout on printed circuit boards in a vapor cleaner (Ramsey, 1990) show that an equilibrium level of retained liquid is reached after a board is held in the saturated vapor zone for a brief period of time, as shown in Fig. Q.2. For the several samples tested, (all 5 1/2 inches by 8 inches) the dragout would range from .25 to .75 kg/m^2 of board area; when handled in soldering fixtures this range can double. The surface film on parts or PC boards typically ranges between 2 and 3 mg/cm^2 (.02 to .03 kg/m^2) (Grace, 1989).

In Ramsey's study, superheated vapor drying was investigated as a means of reducing the amount of solvent held up on PC board assemblies. As shown in Fig. Q.2, rapid evaporation of solvent occurred through either natural or forced convection exposure to solvent vapors superheated by approximately 30° C over saturation temperature. Based on this result, dragout can be reduced to near zero. The equipment design must provide for complete containment of the superheated vapor.



Source: Ramsey, 1990

Fig. Q.2. Solvent hold-up on printed-wiring board "D" under various processing conditions.

Q.3 RATES OF SOLVENT LOSS USED IN THE TOTAL EQUIVALENT WARMING IMPACT ANALYSES

It is recognized that solvent losses will depend on a wide range of parameters (e.g. boiling point, heats of vaporization, liquid density, surface tension, etc.). Reliable correlations of loss rate have yet to be developed. For purposes of the analyses Tables Q.3 and Q.4 list the average solvent loss rates that were used in the analyses of the global warming impact of the different types of cleaning systems. Table Q.3 summarizes operating mode solvent loss rates; Table Q.4 applies to idling mode and downtime.

As discussed elsewhere in the report, operating mode is treated on the basis of operation at the maximum practical throughput. The loss rates shown in Table Q.3 are based on the lowest measured values for solvents that were identified, from either published sources or information collected during the study.

Idling and downtime losses were based on information collected during the study, for state of the art vapor cleaning equipment. The values were measured, with an HCFC-141b/HCFC-123 blend.

Table Q.3. Solvent losses - operating mode (at maximum practical throughput)

Electronics	Loss per throughput kg/m^2	Source
Batch	0.50	Fitzgerald, 1990
In-Line	0.10	Osterman, 1991
Metal	Loss per throughput kg/tonne	Source
Batch	0.75	Osterman, 1991
In-Line	0.35	Osterman, 1991

Table Q.4. Solvent losses assumed for analysis – idling and downtime

Electronics	Mode	Loss Rate kg/hr
Batch	Idling Downtime	0.127[5] 0.076[5]
In-Line	Idling Downtime	0.046[6] 0.046[6]
Metal	Mode	Loss Rate kg/hr
Batch	Idling Downtime	0.127[7] 0.076[7]
In-Line	Idling Downtime	0.046[8] 0.046[8]

[5] idling loss of SOA HCFC batch system iwth high freeboard and freeboard chiller having an open top are of 24 inces by 41 inces or 0.635 m^2 and 0.20 kg/m^2-hr diffusion loss rate (Table Q.2). Downtime loss is based on a roll top type cover being closed, and a loss of 60% of the open top loss at idle (Based on the ratio of the first two entries in Table Q.2).

[6] state of the art in-line, last entry in Table Q.2

[7] identical freeboard configuration as note 5

[8] machine from note 6 used as basis

APPENDIX R: GLOBAL WARMING POTENTIAL

The Intergovernmental Panel on Climate Change (IPCC) has developed a unit of measurement designed to estimate the relative contributions of the various greenhouse gases to global warming[1]. This unit - known as the Global Warming Potential (GWP) - is rapidly being recognized as a convenient tool for measuring the impact of various CFC replacements on a per kilogram basis relative to CO_2.

Three factors determine a GWP for a particular gas:

(1) Its ability to absorb infrared radiation

(2) Its atmospheric lifetime

(3) The time period over which the gas is compared with CO_2

GWPs, by definition, represent the time-integrated commitment to global warming of the instantaneous release of one kg of a gas relative to CO_2. Therefore, the timeframe chosen affects the relative contribution to GWP.

For example, a shorter time frame emphasizes the climate forcing potential of shorter lived gases and is useful for developing short-term delay-oriented policies. The longer time frame is more representative of the cumulative effect of a gas on climate change over its entire lifetime and is therefore more useful for developing long-term strategies and targets to limit global warming, rather than just delay it.

Table R.1 shows the GWPs for various CFC substitutes of interest. The significant differences in GWPs for these CFC substitutes is primarily due to the widely varying lifetimes of the gases. For instance, both HFC-152a and HCFC-123 have lifetimes under two years, while HFC-134a and HFC-125 have lifetimes of 16 and 28, respectively.

It should be noted that though a gas may have a low GWP, the actual warming affect of any gas is the product of its GWP and the amount of gas emitted. Carbon dioxide, though it has the lowest GWP, has by far the highest emission level of any greenhouse gas estimated at 26000 Tg in 1990. (The next highest is methane at approximately 300 Tg). Table R.2 shows estimated manmade emissions for selected greenhouse gases.

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[1] Source: Global Change Division; Office of Air and Radiation; U.S. Environmental Protection Agency

Table R.1. Global warming potentials

Trace Gas	Estimated Lifetime (years[2])	Global Warming Potential		
		Integration Time Horizon (years[2])		
		20	100	500
Carbon Dioxide	-	1	1	1
Methane - includes indirect	10	63	21	9
Nitrous Oxide	150	270	290	190
CFC-11	60	4500	3500	1500
CFC-12	130	7100	7300	4500
HCFC-22	15	4100	1500	510
CFC-113	90	4500	4200	2100
CFC-114	200	6000	6900	5500
CFC-115	400	5500	6900	7400
HCFC-123	1.6	310	85	29
HCFC-124	6.6	1500	430	150
HFC-125	28	4700	2500	860
HFC-134a	16	3200	1200	420
HCFC-141b	8	1500	440	150
HCFC-142b	19	3700	1600	540
HFC-143a	41	4500	2900	1000
HFC-152a	1.7	510	140	47
CCl_4	50	1900	1300	460
CH_3CCl_3 (1,1,1)	6	350	100	34
CF_3Br	110	5800	5800	3200
HCFC-225ca	2.6	NA	162	55
HCFC-225cb	7.7	NA	680	230
Indirect				
Non-methane hydrocarbons	troposhperic	24	8	3
non-methane hydrocarbons	O_3	3	3	3
	CO_2			
TCE	Appendix S	0.67	0.67	0.67

NA - Not Available
Source: IPCC and AFEAS (August 2, 1991) for HCFC-225ca and HCFC-225cb.

[2] lifetimes were not used in assessing TEWI; only GWPs for 100 and 500 years were used.

Table R.2. Estimates of man made emissions

Trace Gas	Current Man Made Emissions Tg/year
CO_2	26000
CH_4	300
N_2O	6
CFC-11	0.3
CFC-12	0.4
HCFC-22	0.1
CFC-113	0.15
CFC-114	0.015
CFC-115	0.005
CCl_4	0.09
CH_3CCl_3	0.81
CO	200
NO_x	66
NMHCs	20

Carbon dioxide emissions given on CO_2 basis; equivalent to 7 Gt C/year

Nitrous oxide emissions given on N_2O bases; equivalte to 4 Mt N/year

NO_x emissions given on NO_2 basis; equivalent to 20 Mt N/year

Source: IPCC (Cambridge University Press, 1990)

APPENDIX S: SHORT LIVED SOLVENTS

S.1 SHORT LIVED CHLORINATED HYDROCARBONS

Of the four commonly used solvents all except 1,1,1-trichloroethane have short atmospheric lifetimes (Hey, 1990). They are decomposed into water, carbon dioxide and hydrogen chloride in the troposphere (lower atmosphere) and are not considered as potential contributors to either greenhouse warming or stratospheric ozone depletion. Both, trichloroethylene and perchloroethylene can take part in photochemical reactions in the troposphere (lower atmosphere), but only to a limited extent.

As for 1,1,1-trichloroethane, about 85% is decomposed in the troposphere (lower atmosphere) whilst the remaining 15% reaches the stratosphere (upper atmosphere). (The Revised Montreal Protocol, June 1990, requires a phase down in production and consumption beginning with a freeze in 1993 and ending with 100% phase out in 2005.)

Per kilogram of solvent the decomposition of these hydrocarbons contributes small amounts of CO_2 to the environment in the range of 0.50 kg to 0.67 kg CO_2/kg of solvent as shown in Table S.1.

Because of the common usage of trichloroethylene we follow Dr. Heys practice in assuming that:

- One kg of any chlorinated hydrocarbon breaks down in the troposphere to produce 0.67 kg CO_2.
- For aqueous processes the contribution to CO_2 emissions from the active chemicals is negligible (see Appendix P).

Reference: D.G. Hey, ICI, Runcorn, Cheshire, England, Personal Correspondence December 7, 1990.

S.2 TERPENES

Terpenes discharged with liquid from the semi-aqueous treatment will eventually decompose into CO_2, water vapor, and possibly other decomposition products in an activated sludge plant or by decomposition in the natural environment. (The reaction chain of terpenes to aerosols to polymers and ultimate decomposition is discussed by Rasmussen, 1964). Alternatively, they may be combusted to CO_2 and water vapor to obtain an estimate of the potential for CO_2 emissions on a weight basis, some typical terpenes were identified based on prior work (EPA, November 1990). Table S.2 shows that the carbon content of these terpenes varies from about 0.78 to 0.88 weight fraction and that the CO_2 evolved are in the order of 3 lbs (kg) of CO_2 per lb (kg) of terpene. Terpene vapor emissions are classified as non-methane hydrocarbons and discussed in Appendix R (having a GWP of 3 in the 500 yr time horizon and 8 in the 100 year time horizon).

Table S.1. GWP of selected chloronated hydrocarbons

Solvent	Molecular Weight	kg CO_2/kg Solvent[1]
1,1,-Trichloroethane[2]	133.42	0.63
Trichloroethylene	131.40	0.67
Perchloroethylene	165.85	0.53
Methylenechloride[3]	84.94	0.52

[1] Molecular weight of CO_2 is 44

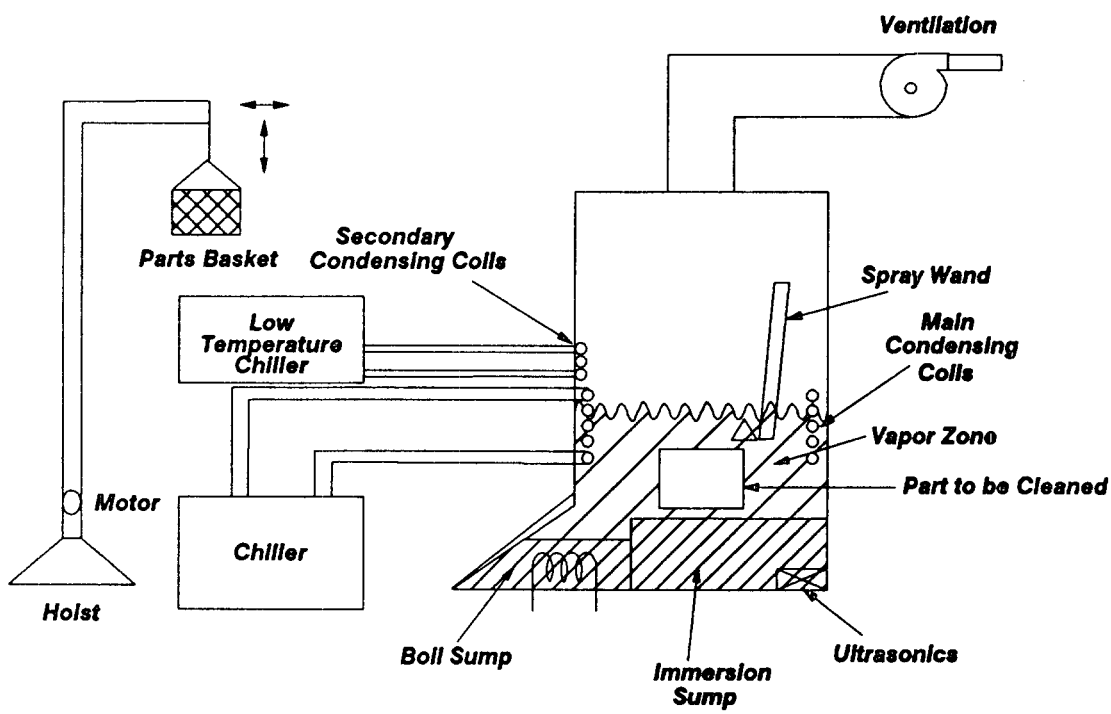
[2] 1,1,1-Trichloroethane; CH_3CCl_3

[3] CH_2Cl_2

APPENDIX T: DESCRIPTION OF BATCH MACHINES FOR METAL CLEANING

T.1 BATCH METAL CLEANING SYSTEM - LOW BOILING POINT SOLVENTS

Figure T.1 shows a system schematic for a batch cleaning system used with low boiling point solvents (those with boiling points less than 65°C (150°F) such as CFC-113, HCFC-141b, HCFC-225ca, HCFC-225cb, and HCFC-123); such a system can be used in a vapor/immersion cleaning process. The system modelled here has 100% freeboard such as found on a Branson model 2024. The system can clean about 0.91 tonnes (2000 lb) of steel per hour (Polhamus, 1991, March 20), basket loads are about 30.3 kg (66.7lb). Based on discussions with manufacturers and users the average rate of throughput is taken to be 50% of its capacity.



Basis: Branson BSD - 2024 standard and Allied Vaportrap

Fig. T.1. Batch metal cleaning system - low boiling point solvents.

Parts are cleaned in a multistage process consisting of:

1) Vapor rinse
2) Immersion with ultrasonic cleaning
3) Distillate spray rinse
4) Drying in the vapor zone.

Parts are placed in a 46 cm x 51 cm x 41 cm (18" x 20" x 16") basket and lowered into the unit at three to eleven feet per minute using an operator-controlled hoist (ASTM, 1989; Radian, 1989). They are held for about 30 to 60 seconds in the vapor zone as vapor condenses on the cooler parts and drips into sumps below. Vapor is formed by heating elements in a boiling sump with sizes shown in Appendix Y. The parts are then immersed in a sump with ultrasonic transducers for about a

minute. About 1.2 kW of transducers are used (Polhamus, 1991, March 20) and they are driven by a generator at 25 kHz or 40 kHz (Branson, 1987, Bulletin 5-975A). The solvent in the sump is replaced periodically depending on the soils to be removed and the operating schedule (typically every month to 6 months depending on duty cycle and soils). The next step in the cleaning process is a distillate spray rinse from a manifold or a hand held wand. Solvent is provided to this spray from a reservoir of freshly distilled solvent. Distilled solvent insures that the part has minimal residue on it after cleaning. Parts are then raised into the vapor zone and held there for about a minute to a minute and a half (Polhamus, 1991, March 20) before being removed.

Solvent emissions from the system are attributable to diffusion from the vapor zone and dragout. Each cleaning system may be specifically designed for the HCFC used. For example in a typical system diffusion losses can be reduced with two sets of condensing coils. The main condenser, at 4° to 7°C (40° to 45°F) (Ramsey, 1990), is located at the top of the vapor zone (61 cm (24 in.) below the top of the unit). A chiller keeps these coils cool (Branson, 1988, Bulletin S-987). A secondary condenser at 0.56 kW (3/4 HP) maintains the second set of coils at -34°C to -28°C (-30° to -20°F) (Allied, 1990, Vaportrap product literature). These coils are located above the primary coils, on one side of the unit. A cover on top of the unit during downtime reduces emissions.

Heaters in the boiling sump account for the majority of the energy used in the process. The chillers used to cool the condenser coils account for the next largest energy use.

Low boiling point solvents may be used in cleaning systems with a different order of process steps (e.g. having a spray station before an immersion step). Other variations include several immersion steps in the process. This would decrease throughput and achieve a higher degree of cleanliness. Corpane offers a heat pump to both boil the solvent in the boiling sump and condense vapor in the vapor zone (Corpane, 1990, High Efficiency literature).

T.2 BATCH METAL CLEANING SYSTEM - HIGH BOILING POINT SOLVENTS

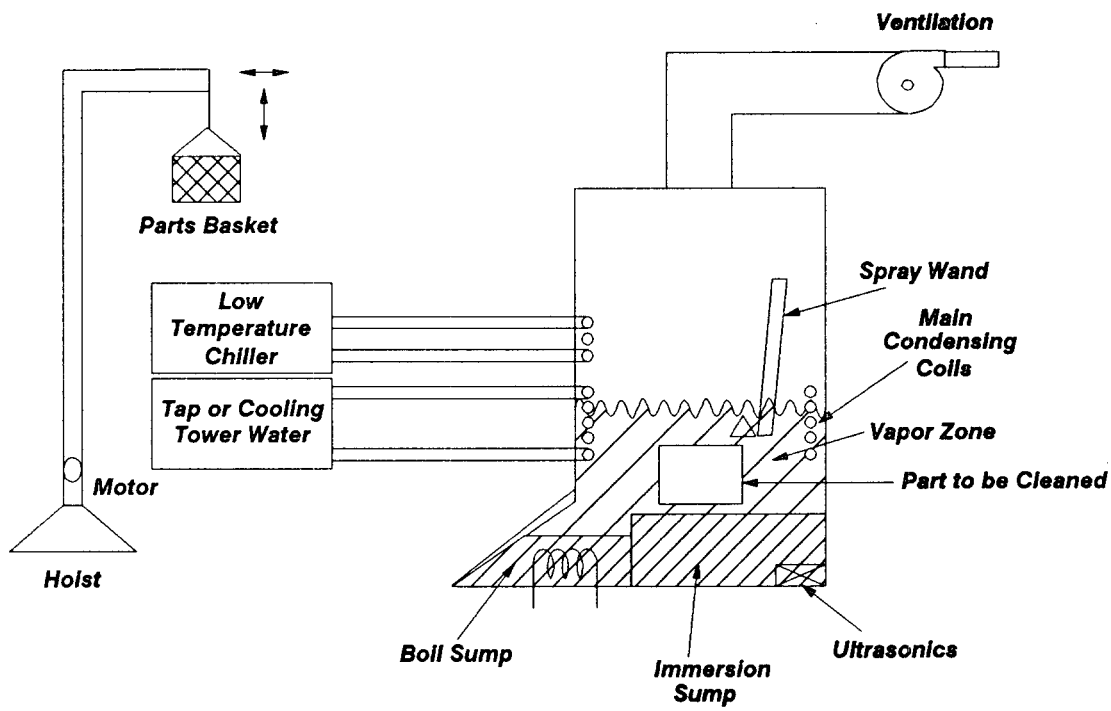
Figure T.2 shows a batch system for use with high boiling point solvents (with boiling points greater than 65°C (150°F) such as 1,1,1-trichloroethane and trichloroethylene) which include the same design principles as those for low boiling points. The major difference between the systems is that the condensing coils are cooled with tap water or water from a cooling tower.

T.3 MODULAR BATCH METAL CLEANING SYSTEMS - AQUEOUS

The aqueous batch model system includes wash, rinse, and dry modules. Each module performs a single process and a hoist lifts and lowers a basket of parts into each module. This system can accommodate about 23 kg (50 lbs) of parts in each basket (Maltby, 1991, March 12). The model shown in Fig. T.3 is based on with 25 cm x 36 cm x 20 cm (10" x 14" x 8") batch such as found on a Crest system.

Parts remain in each station for about 1 1/2 to 2 minutes; they remain in the drying station for about 4 minutes (Maltby, 1991, March 12). In the first process, parts placed in a sump which contains a solution of water and cleaning additives (a mild detergent such as sodium tripolyphosphate, emulsifiers). The solution is maintained at 60° to 70°C (140° to 160°F) with a 1.0 kW (3400 Btu/h) heater (Vasina 1991, March 27) and agitated with a 0.25 kW (1/3 HP) pump and about 0.5 kW of ultrasonics (Maltby, 1991, March 12). The basket is then moved to second wash station with the

same components as the first station. The part is next immersed in a heated spray rinse station. Two heated rinse baths (the first with ultrasonics) come next. Heated water from a separate preheater (5.9 kW (20,000 Btu/h), Arthur D. Little estimate) is added to the final rinse sump and the second wash sump at about 0.03 l/s (0.5 gpm) total to replenish water that is carried out. Water is filtered within the unit. Parts are finally moved to a hot air drying station where air is maintained at about 80° to 120°C (180° to 250°F) (Legg, 1991, January 27) with a 7.5 kW (25,000 Btu/h) heater (Maltby, 1991 March 12) and circulated with a 1 HP blower. Between 10 and 15% of the air from the drying station is carried out through a ventilation system (Polhamus, 1991, March 20); total ventilation is 47 to 71 l/s (100 to 150 cfm) (Maltby, 1991, March 12).



Basis: Branson BSD 2024 standard and Allied Vaportrap

Fig. T.2. Batch metal cleaning system - high boiling point solvents.

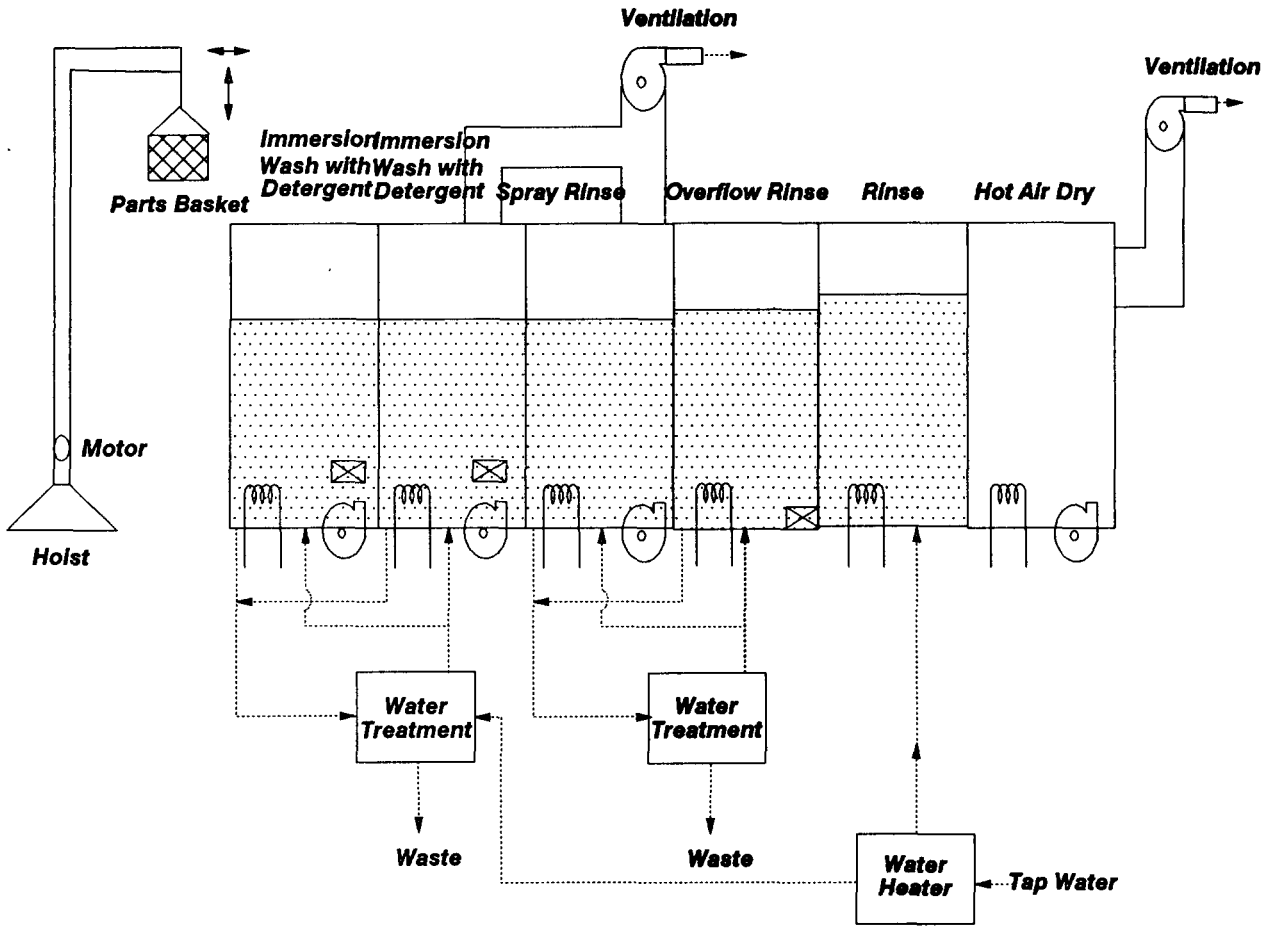
Most of the energy for the process is used to dry parts. Energy to heat incoming water is the other main energy requirement.

There are many variations for aqueous systems due to the wide variety of cleaning applications. Some of these variations include wash solutions with other chemicals (e.g. 10% terpene solution), agitated baskets in the wash and rinse sumps, ultrasonics in the wash sump, additional rinses, and ambient temperature rinses.

T.4 BATCH METAL CLEANING SYSTEMS - SEMI-AQUEOUS

Figure T.4 shows that semi-aqueous batch cleaning systems are similar to aqueous systems in their modularity. The wash station uses an agitated solvent (e.g. formulated hydrocarbon, terpenes, etc.)

instead of a water/detergent solution. The system is modeled with 25 cm x 36 cm x 20 cm (10" x 14" x 8") baths (such as the Crest system).



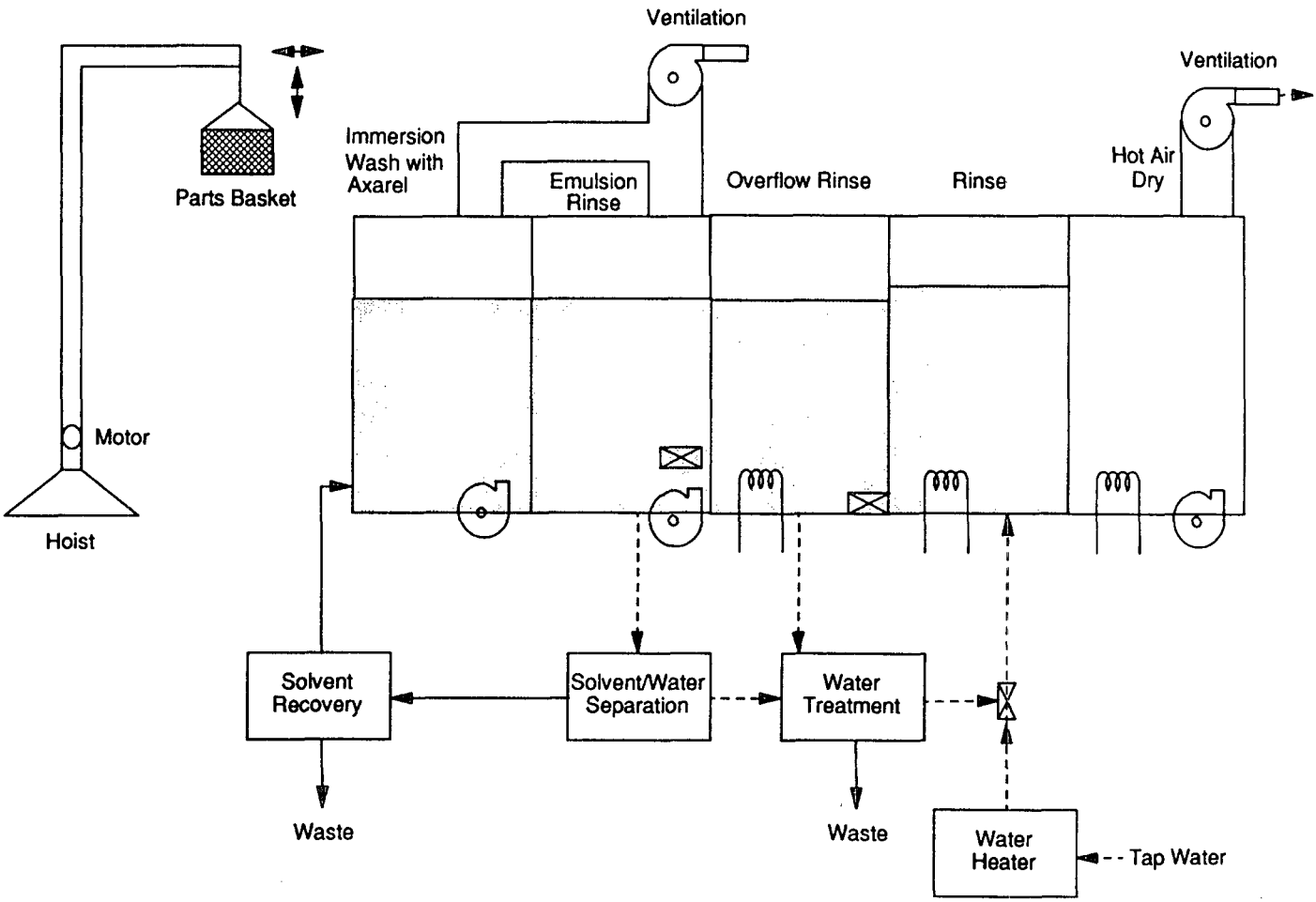
Basis: Crest bench system with 1014 tanks

Fig. T.3. Batch metal cleaning system - aqueous.

Parts are first immersed into a bath of solvent agitated by a 0.25 kW (1/3 HP) pump (Maltby, 1991, March 12). This solvent in the sump needs to be replaced periodically depending on soils to be removed (typically once every one to three months). Parts remain in this and other baths for 1-1/2 to 2 minutes (Maltby, 1991, March 12). They are then immersed in a solvent/water emulsion rinse (about 10% solvent per Maltby, 1991, March 12) and agitated with a 0.25 kW (1/3 HP) pump and 500 W of ultrasonics. Two heated cascaded rinse stages follow, the first of which is agitated with about 0.5 kW of ultrasonics. The rinses are replenished with water heated by a separate preheater at about 0.03 l/s (0.5 gpm) (Maltby, 1991, March 12). A drying station similar to that used in the aqueous batch system is the last step in the process. (It is recognized that the model configuration can vary depending on the cleaning application. Other solvents, such as Alpha EC-7R, Coors BioT, and other terpenes could be used in the wash station. With terpene systems, the wash sump must be cooled to near room temperature because of solvent flammability (Kalmbach, 1991, March 12). The wash bath would typically be cooled by a separate chiller which would require additional energy.)

A solvent/water separation system recovers solvent from the emulsion station and sends water to water filters. These filters are used to clean rinse water - the energy for this is provided by the emulsion rinse pump and shop water pressure.

Most of the energy for the process is used to dry the parts. The other main energy use is water preheating.



Basis: Crest bench system with 1014 tanks

Fig. T.4. Batch metal cleaning system - semi-aqueous.

Solvent emissions occur in the immersion and emulsion steps. Ventilation of these modules reduces emissions to the workspace. About 47 to 71 l/s (100 to 150 cfm) total ventilation is required for the system, including the drying station (Maltby, 1991, March 12). Covers are placed on the two tanks when they are not in operation (i.e. at night) to reduce solvent loss.

APPENDIX U: DESCRIPTION OF BATCH MACHINES FOR ELECTRONICS CLEANING

U.1 BATCH LOW BOILING POINT SOLVENTS - ELECTRONICS

For many years batch cleaners for electronics have been simple in construction being essentially a two step process. In general the printed circuit boards (PCB's) are loaded vertically into a metal basket such that drainage is assisted and dragout is minimized. An operator-controlled hoist controls the speed of movement of the basket into and out of the cleaning area. The cleaner itself consists of, in general, two sumps one boiling and one, cooler, rinse tank. The mode of operation is for the work basket to be lowered by the operator through the vapor at controlled speed into the boiling sump for about a 1.5 minute wash cycle. The basket is then transferred to the rinse tank for approximately 0.5 minutes before exiting the cleaner again at controlled speed, with dwell time in the vapor zone, enabling the majority of the solvent to drain or evaporate. The solvent continuously boils generating a vapor that condenses on a single set of cooling coils. The liquid solvent is returned to the rinse tank via a water separator and/or desiccator constantly overflowing into the boiling sump. Thus, the rinse tank is kept clean with the flux residues concentrating in the boiling sump. Periodically the boiling tank is boiled down to recover as much solvent as possible with the remainder being sent for reclamation or disposal.

With the increasing environmental awareness and escalating cost of solvents companies are now more readily considering the latest generation of "low emission" cleaning systems. Examples of such systems as mentioned elsewhere are the Baron Blakeslee LE range and the ICI Cleanzone and Cleanseal ranges. Typical improvements that have been made include the use of 100% freeboard and a more sophisticated design of the vapor condensation configuration plus more intricate lid arrangements to reduce diffusion losses.

For use with the new generation of HCFC solvents it has become clear that a different approach may be required to cleaning machine design in particular concerning diffusion losses. Because the diffusivity of some of the lower molecular weight HCFC compounds is around 9-16% greater than for CFC-113, a two or three tiered cooling coil system may be needed. In such cases, the lowest tier (nearest the solvent) operates at around 5°C, the second tier operating at sub zero temperatures to further condense the solvent and a final dehumidification zone to prevent moisture from condensing on the lower coil. Automatic hoist arrangements are considered mandatory to avoid excessive mixing of the vapor and air.

Ultrasonics are not widely used largely due to their forbiddance under old US military standards, although this attitude is softening in the light of studies being done to prove that correctly operated ultrasonic tanks do not harm integrated circuit (IC) wire bonds as previously thought. If they are to be used it is either in a warm solvent where a separate tank is needed or in the boiling sump where "streaming" occurs rather than cavitation. The increasing use of surface mount technology and the difficulties associated with removing residues from small gaps has lead to a reappraisal of the benefits of ultrasonic cleaning.

With batch electronic cleaning, the overall volume of soil is low leading to relatively infrequent disposals of soil laden waste and there is less need for a separate solvent regeneration unit as might be found on a metal cleaning unit. However, small solvent recovery stills are beneficial since they continuously remove contaminants from the cleaning unit and concentrate them in the still.

There are newer techniques becoming available such as vacuum drying operating at lower temperatures than conventional thermal drying and thus offering the potential for reducing damage of electronics parts. Moreover, where it can be justified, a heat pump arrangement is used to reduce

operating costs but the higher capital costs still leads to a significant proportion of machines sold with immersion heaters and either water or refrigeration cooling. Such techniques are considered in the best available current technology (BACT) scenario.

U.2 BATCH HIGH BOILING POINT SYSTEMS - ELECTRONICS

For electronics cleaning, these systems are from a technical standpoint a subset of those outlined in U.1 above. They are in general simpler machines with a lower degree of emphasis on solvent conservation measures because of their lower vapor pressures where chilled water is sufficient typically to control vapor losses.

U.3 BATCH AQUEOUS SYSTEMS - ELECTRONICS

This method of flux removal represents a small proportion of systems in use today. Those systems that are available fall into two broad categories. The first is a multiple tank system following the description for metal cleaning - Appendix T.3, where virtually every system is different with no obvious standard existing. The second is a batch cleaner constructed like, for want of a better description, a commercial dishwasher. These systems have very limited capacity by virtue of their very long cycle times (about 30 minutes) and are understood to be relatively ineffective at cleaning surface mount technology (SMT) panels. For the purposes of this exercise we will consider an electronics system to be analogous to its metal cleaning equivalent. The only possible difference of significance would therefore be the fact that printed circuit boards are required to be particularly dry, as this may affect subsequent testing, and therefore, capacity has to be carefully considered.

U.4 BATCH SEMI-AQUEOUS SYSTEMS - ELECTRONICS

This method of cleaning circuit boards is comparatively recent with few systems available or installed (installed base in UK less than 10). Kerry Ultrasonics have such a unit as do Crest in the U.S. They are in overview very similar to those supplied for metal cleaning being based on a wash tank of terpene or hydrocarbon followed by two rinse stages and a vertical dryer. Both systems feature an additional emulsion stage after the hydrocarbon wash, which also have as an option ultrasonics to ensure adequate removal of the solvents. The hydrocarbons present in this emulsion stage are separated from the water and returned to the wash tank. The water is recycled to the rinse stage after being cleaned to a level commensurate with level of cleanliness required - in this case to 200 to 300 ppm of contaminants. If necessary an additional deionized rinse can be added. Transfer is affected by a hoist arrangement to minimize dragout from the wash to rinse stages with dwell times adjustable to suit the product and cleanliness level required.

With hydrocarbon products such as Axarel™ and terpenes such as BioAct™ tests have shown that solvent temperature is fairly crucial to the cleaning performance with some heating being required. Other solvents, however, with a lower flash point may need specific cooling. In either case, thermostatically controlled temperature can prevent potentially dangerous overheating. For surface mount applications, these solvents need some form of agitation despite their relatively high solvency for flux residues. Where possible, this is now being achieved with ultrasonics although there is some question regarding the flammability risk of the fine mist produced by ultrasonic energy. The recent introduction of this system as a cleaning solution means that relatively little data are available

regarding the need for replacing the sump of solvent. It is assumed, therefore, that sufficient solvent is dragged over from the wash tank to enable make-up solvent (either directly recycled or fresh) to keep the concentration of soil below saturation.

Drying of the printed circuit boards is time consuming and energy intensive and as with all aqueous systems not easily achieved. Attention to the way in which the boards are loaded into the carrier helps to create natural drainage but adequate drying under tight spaced surface mount components is never easy. Some energy conservation is afforded by using a shutter system on the drying stage to retain some heat. Being essentially an open top system control of any flammable gasses is not practical and therefore purge gases to reduce this risk are not often used. Cleaning times depend entirely on the cleanliness levels sought and the time delay from soldering.

APPENDIX V: DESCRIPTION OF IN-LINE MACHINES FOR METAL CLEANING

V.1 IN-LINE LOW BOILING POINT SOLVENTS - METAL

Although in-line metal cleaners can be cold cleaners, vapor cleaners, or a combination cold/vapor cleaner, the majority are vapor cleaners using chlorinated/chlorofluorinated solvents. Typically these machines are enclosed except for entrance/exit ports employing a continuous or multiple-batch loading systems. Unlike open top vapor degreasers which are often "off-the-shelf" items, the in-line systems are normally custom-designed for a specific product, production rate, and cleaning time. In-line cleaners are used in a broad spectrum of metal working industries, they are most often found in plants where there is a constant stream of parts to be cleaned, and the advantages of continuous cleaning outweigh the lower capital cost of a batch loaded open top vapor degreaser.

There are a number of configurations of in-line cleaners (Radian, 1989).

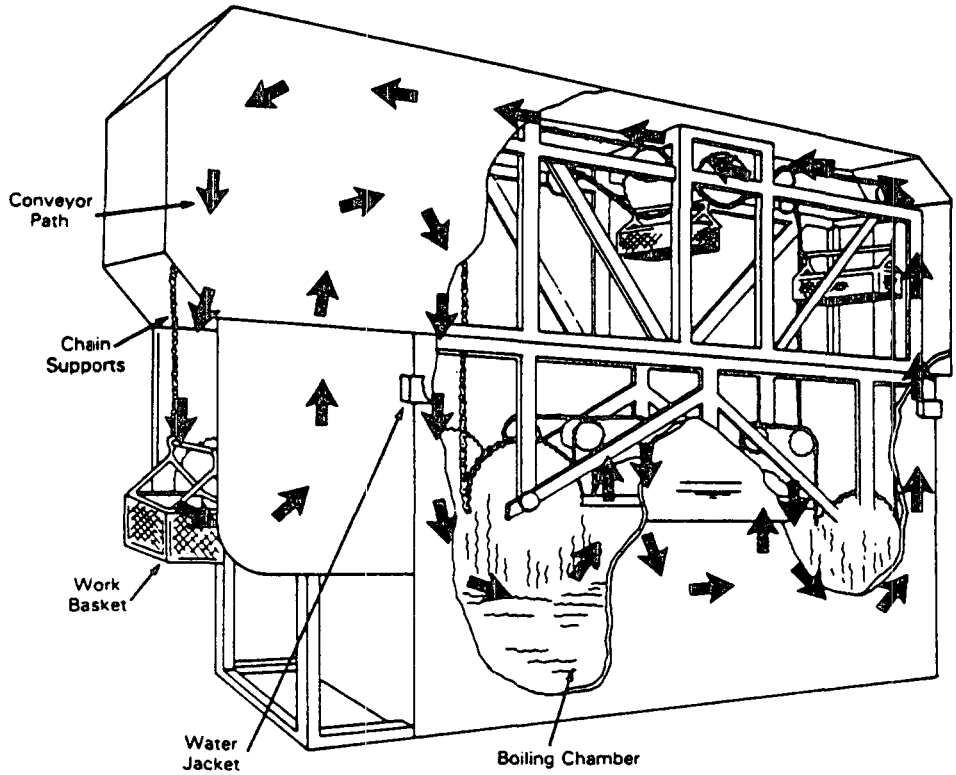
- "The cross-rod cleaner (Fig. V.1) obtains its name from the rods from which parts baskets are suspended as they are conveyed through the machine by a pair of power-driven chains. The parts are contained in pendant baskets, and where tumbling of the parts is desired, perforated or wire mesh cylinders. These cylinders may be rotated within the liquid solvent and/or the vapor zone. This type of equipment lends itself particularly well to handling small parts that need to be immersed in solvent for satisfactory cleaning or which require tumbling to drain solvent from cavities and/or to remove metal chips.

- "A monorail vapor cleaner (shown in Fig. V.2) is usually chosen when the parts to be cleaned are being transported between manufacturing operations on a monorail conveyor. The monorail cleaner is well suited to automatic cleaning with solvent spray and vapor. It can be of the straight-through design illustrated or can incorporate a U-turn within the machine so that parts exit through an opening parallel to the entrance opening. The U-turn monorail cleaner benefits from lower vapor loss because the design eliminates the possibility of drafts flowing through the machine. Other variations include use of superheated vapor to dry out the parts and control solvent emissions (as shown in Fig. V.3).

- "The belt cleaner is designed to allow simple and rapid loading and unloading of parts. A belt cleaner conveys parts through a long and narrow boiling chamber in which the parts are cleaned either by the condensing vapor or by immersion in the solvent sump." These are very commonly found in cleaning circuit boards, but can be used for cleaning metal parts with low profiles, such as television picture tube masks.

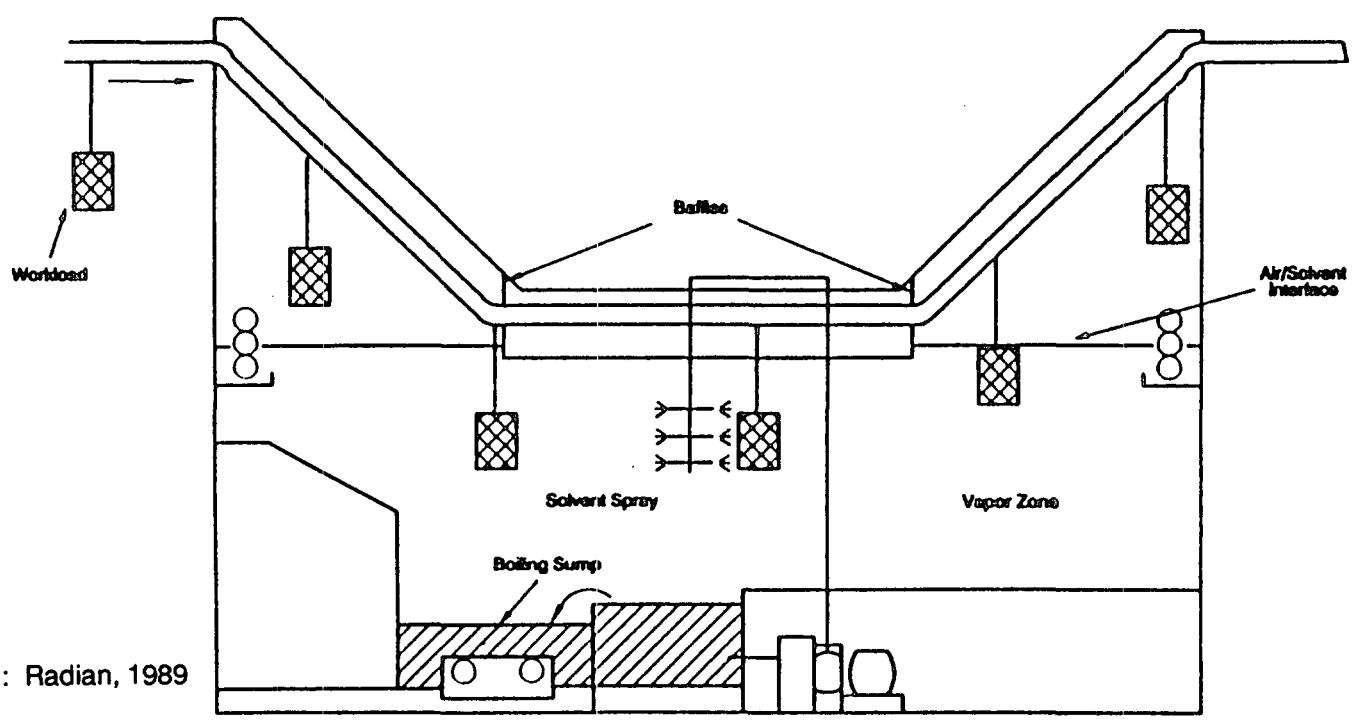
To control vapor emissions, the refrigerated freeboard device on an in-line vapor cleaner functions in the same way as one on an open top vapor degreaser. Refrigeration establishes a cool air layer above the vapor zone which inhibits diffusion and solvent-air mixing.

Cleaning systems using low boiling point solvents are typically used for cleaning circuit boards, but they can be used for cleaning metal parts with low profiles (i.e., disc drive housings). The solvents used include CFC-113, methylene chloride, and HCFC blends. The state of the art process is modeled after Baron-Blakeslee CBC-18LE, Corpane BSI-18RD, and similar systems which are about 7.3 m (24 ft) long (see Fig. V.4).



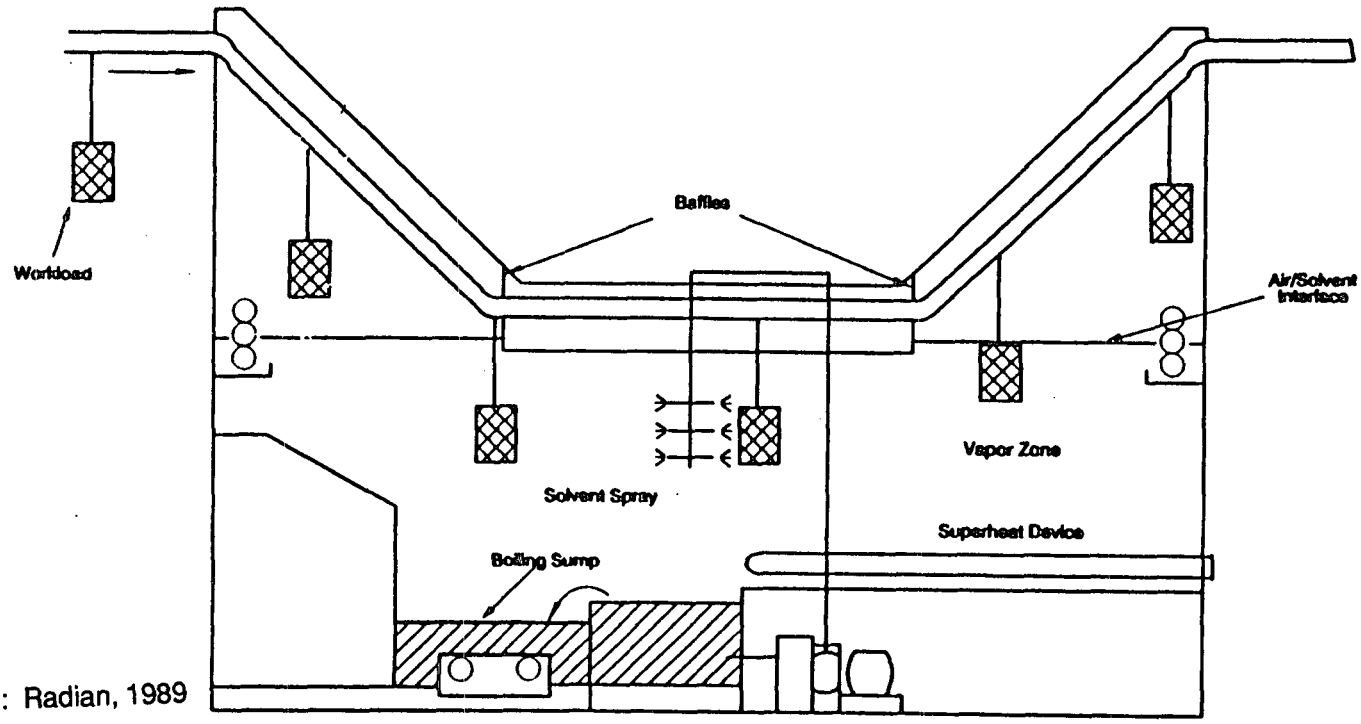
Source: Radian, 1989

Fig. V.1. Cross-rod in-line cleaner.



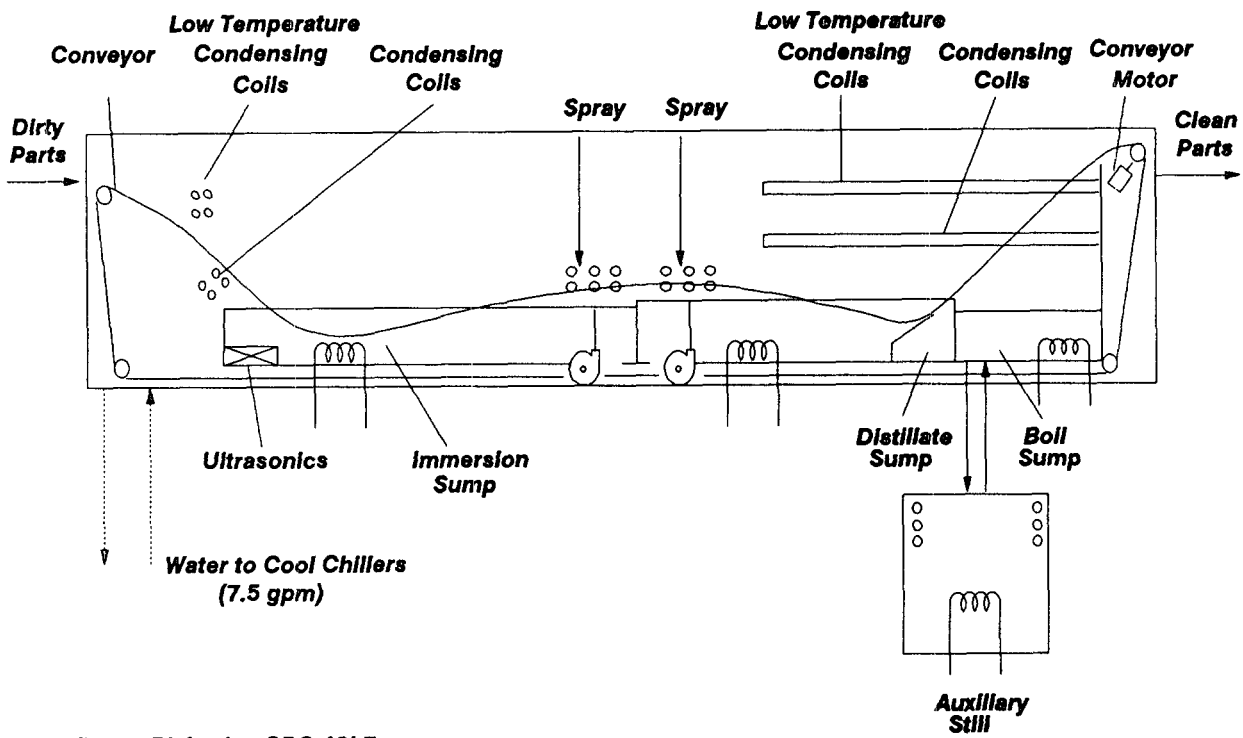
Source: Radian, 1989

Fig. V.2. Baffled monorail in-line cleaner.



Source: Radian, 1989

Fig. V.3. Baffled monorail in-line cleaner with superheat device.



Basis: Baron-Blakeslee CBC-18LE

Fig. V.4. In-line metal cleaning system: low boiling point solvents.

From an energy point of view, the systems generally consist of four components: a cleaning system, a distillation system, a solvent emissions control system, and a cooling system.

- The cleaning system is comprised of the following process steps: immersion, low pressure spray, high pressure spray, immersion, and vapor rinse. The first immersion sump is heated and includes ultrasonics. For example, in the Baron Blakeslee CBC-18LE, the first spray station sprays the parts from the top and bottom at about 5 l/s (80 gpm) and 240 kPa (35 psi). A lower flow and higher pressure, 1.3 l/s, 1400 kPa (20 gpm, 200 psi), spray follows the first spray. The next step is immersion in a sump maintained with fresh distillate solvent. The last step in the cleaning process is a vapor stage, where the parts are dried. Typical belt speeds for cleaning metal parts range from 1.2 to 2.1 meter (4 to 7 feet) per minute (Osterman, 1991c).

- An auxiliary still is assumed to be on continuously to provide clean solvent.

- Solvent emissions are controlled by keeping the vapor-air interface to a minimum and by using two sets of condensing coils. The condensing coils are kept at low temperatures (4° to 10°C (40 to 50°F) for one set and about -30°C to -35°C (-20° to -30°F) for the second) by a vapor compression refrigeration system (Osterman, 1991c). Solvent recovery (i.e. distillation) occurs within the system. It is assumed that typical solvent life is several months and that the product is removed by waste handlers for either solvent recovery or as a fuel. It is assumed that there is no energy use or credits in this step (in any event they are small--see Section P).

- A cooling tower is used for rejecting heat from the refrigeration system's condenser water. The power required is shown in Appendix Y.

V.2 IN-LINE HIGH BOILING POINT SOLVENTS - METAL

These systems are similar in design to the low boiling point solvent systems described in subsection U.1 with the following exceptions (see Figs. V.3 and V.5):

- Higher temperature sumps are required in order to vaporize the higher boiling point solvents;

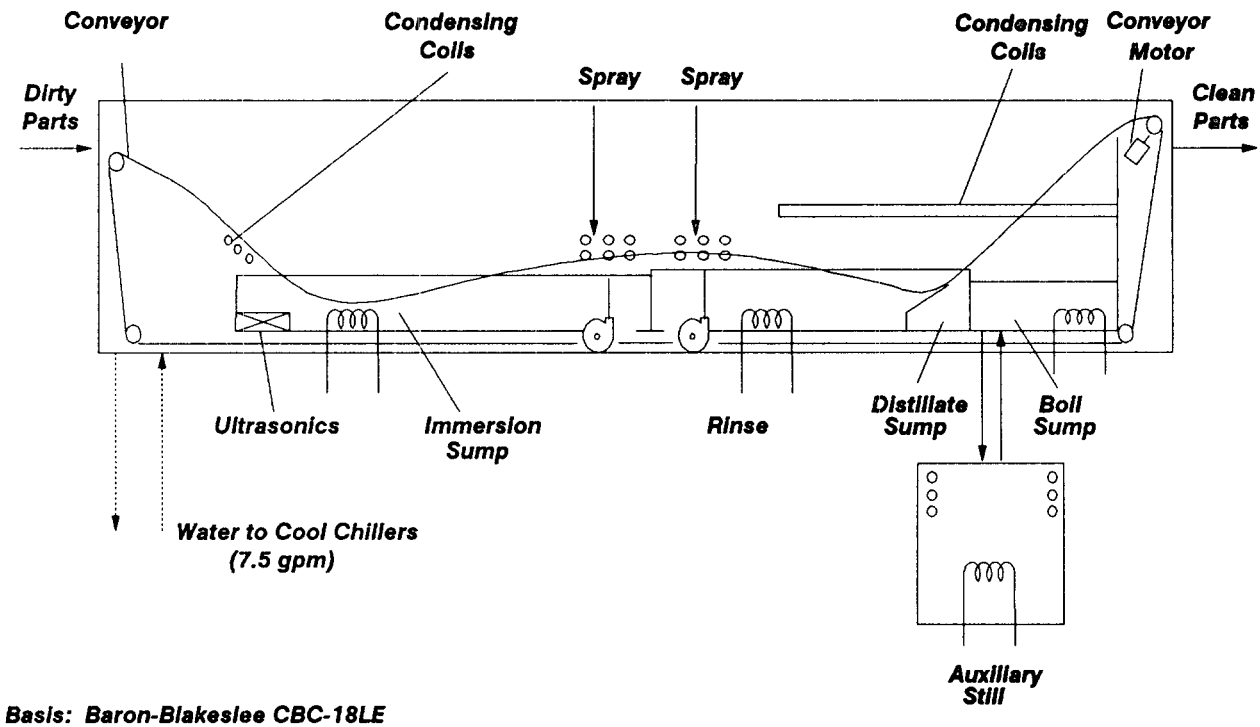
- The emission control system includes water-cooled condensing coils; and

- The solvent recovery system requires more energy due to the higher heats of vaporization necessary to distill these solvents.

The solvents used in the systems examined here are 1,1,1 and TCE.

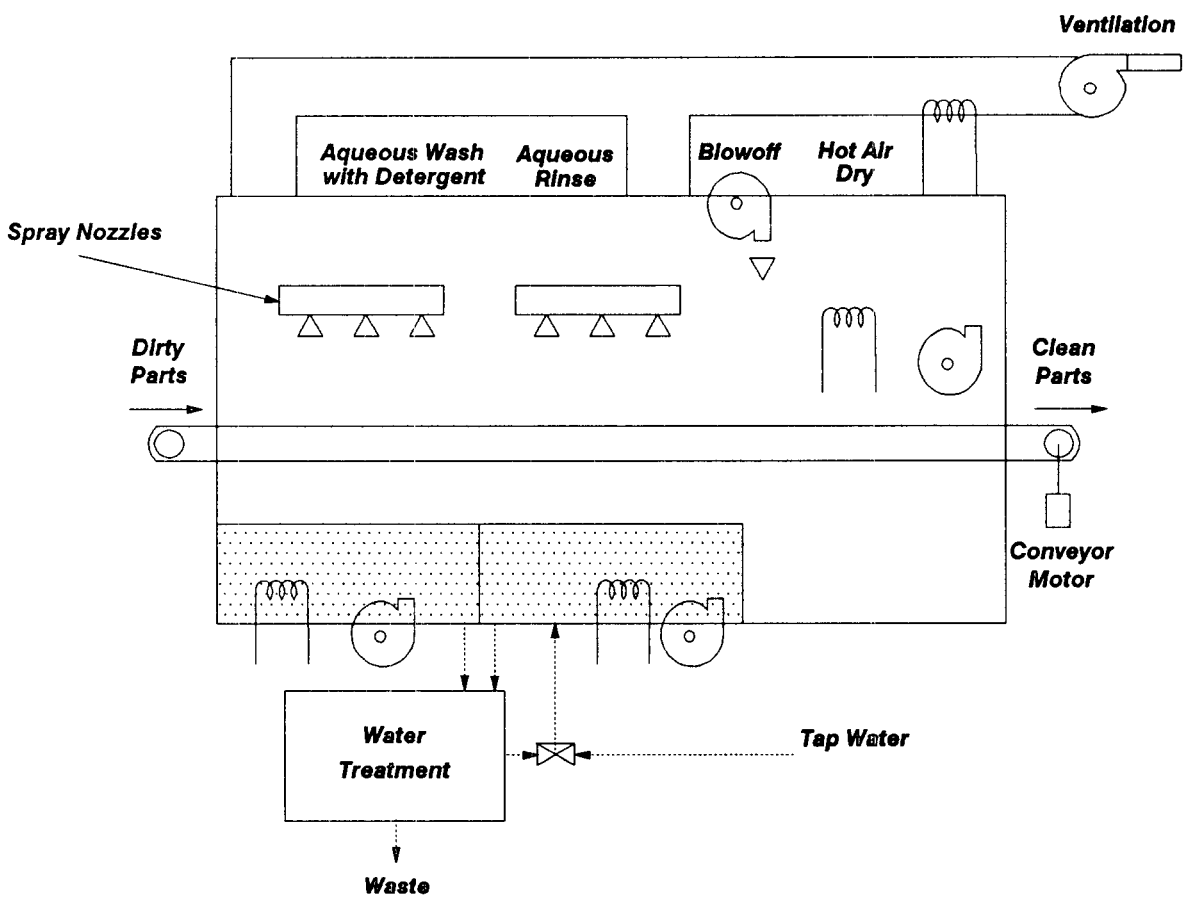
V.3 IN-LINE AQUEOUS SYSTEMS - METAL

This system is based on a belt system such as found in a Stoelting machine. The system includes four basic stations shown in Fig. V.6: wash, rinse, blowoff, and dry. No solvents are emitted from aqueous systems.



Basis: Baron-Blakeslee CBC-18LE

Fig. V.5. In-line metal cleaning system: high boiling point solvents.



Basis: Stoelting BBW series

Fig. V.6. In-line metal cleaning system: aqueous.

Parts enter the system on a conveyer traveling between 1.2 and 1.5 meter (4 and 5 feet) per minute. A high volume spray washes the part in the first station. This spray is comprised of water and additives, such as light detergents, emulsifiers, and surfactants. The wash sump may be replenished six to eight times with a rejuvenator solution before replacing it (Kneen, 1991). The next station, the rinse station, includes a spray with hot (65°C or 150°F) recirculated water. Tap or treated water enters the wash and rinse stations at about 10.5 ml/s (10 gph) to make up water that is carried out (Kneen, 1991). An air knife blows off most of the water from the parts, about 90% for simple part geometries, (Kneen, 1991). The remaining water is removed with another blower and heater in the drying station. Remaining water on the parts will be flashed off due to their high temperature. Hot, moist air is drawn from the wash, rinse, and dry areas in order that it does not increase shop cooling/space conditioning requirements. The system includes a water treatment system that separates oil and water. The wash and rinse sumps may be heated by electric, steam, or gas sources. Energy use for the system goes mostly towards drying the parts (about 50%). The wash and rinse sump heating requirements also require energy.

Alternative configurations for aqueous in line systems may use less or more stations. These range from systems requiring a wash and a blowoff station to those requiring two washes, two rinses, blowoff, and a dry station depending on the application. Water temperatures may also vary depending on the cleaning and the additives used. Some applications may trade off a large blowoff because of their geometrical configuration against heat requirements.

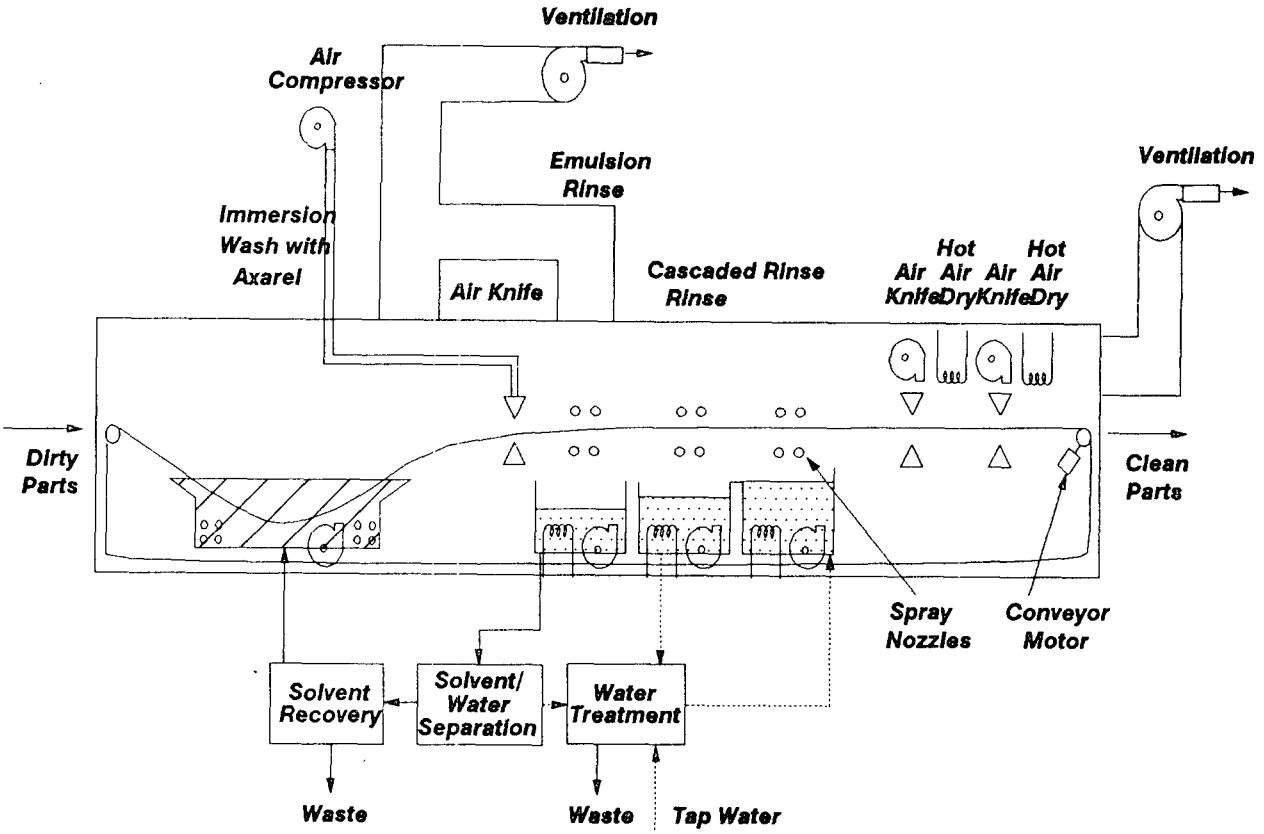
V.4 IN-LINE SEMI-AQUEOUS SYSTEM - METALS

A limited number of in-line semi-aqueous systems are in use; those that are in use are used in electronic cleaning and can be potentially adapted to metals cleaning. Parts with low profiles (10 cm (4 in.) high or lower) are able to be used in this type of system. Better information about system operation will be available as this technology is developed. The model shown in Fig. V.7 is based on a Corpane SAI 18RD (25 ft. long) using a hydrocarbon solvent such as AXAREL™.

Process steps include immersion wash, emulsion rinse, cascaded rinses, and drying. Parts travel on a belt at speeds between 1.2 and 1.5 meter (4 and 5 feet) per minute. They are immersed into an agitated sump that is heated to about 50°C (125°F) by rejected heat from a heat pump. This sump would be replaced infrequently (possibly once per year, Kalmbach, 1991). An air knife removes most of the solvent from the parts before they enter a spray solvent/water emulsion rinse station at about 60°C (140°F). Two additional spray rinse stations follow, one cascaded into the other. Water enters the second final rinse station at about 0.2 l/s (3 gpm) to make up water that gets carried out. Parts then enter the last stations, two drying areas, each with an air knife and infrared heater.

Additional components include a separation system that separates solvent and water from the emulsion rinse and carries it into immersion sump and water treatment systems respectively. A water treatment system moves soluble and insoluble solids from the cascaded rinse water and from water from the water separating system. Waste from this system, potentially removed within ultrafiltration system will be small. A solvent recovery system removes impurities from solvent that exits the separator. Ventilation is required at both the immersion and emulsion stations and the drying stations.

Solvent is emitted at the entering and exiting points of the system. Emissions, controlled by minimizing the vapor-air interface, are expected to be small, between 1 and 6 kg (2.2 to 13 lb) per hour.



Basis: Corpane SAI18RD system

Fig. V.7. In-line metal cleaning process: semi-aqueous.

The model may be different if another solvent is used (e.g. EC 7R™) with this solvent, the immersion sump would need to be cooled to about 25°C (80°F) to keep it about 20°C (40°F) below the flash point. Estimated energy use would be approximately the same for this configuration as for an AXAREL™ configuration.

Most of the energy that is used in the system is for the drying and rinsing stations. The relatively high flow rate of 0.2 l/s (3 gpm) necessitates high heating energy inputs. The drying stages require energy for their high velocity air knives and the infrared heaters for a small portion of the energy used.

Some variations from this state-of-the-art design include a different order of process steps (e.g. having a spray station before an immersion step). Another variation is to include several immersion steps in the process. This would affect throughput, while achieving a higher degree of cleanliness. At least one manufacturer incorporates a heat pump in the system (Corpane).

CITATIONS

Radian Corporation, Alternative Control Technology Document. Halogenated Solvent Cleaners, EPA-450/3-89-030 August, 1989.

APPENDIX W: DESCRIPTION OF IN-LINE EQUIPMENT FOR CIRCUIT BOARD CLEANING

W.1 IN-LINE HIGH BOILING POINT SYSTEMS - ELECTRONICS

These systems represent a subset of in-line solvent cleaning systems generally described in Section W.2 below. Their range of applicability is limited to printed circuit board (PCB) cleaning where the materials are able to withstand (mainly) 1,1,1 Trichloroethane. In practice, this means reflow soldered surface mount technology (SMT) and through hole panels, but even here blends of CFC-113 and various alcohols have been preferred or even stipulated by standards.

The electronics system has been taken to be broadly the same as that for metal cleaning for the purposes of this exercise. Of the currently installed systems many feature immersion heating occasionally using steam as a heating media (to avoid local hot spots) and recirculated water cooling. In considering current equipment, it is assumed that immersion heating, primary coils cooled with water from a cooling tower, and refrigerated low temperature cooling coils. In general, it has been true to say that environmental issues have not been the predominant motive for solvent conservation measures within these systems - the main objective has been to reduce the cost of circuit board cleaning and maintain an adequate working environment for the operatives. It is not uncommon, therefore, to see a greater emphasis on controlled extraction rather than elaborate vapor control measures.

W.2 IN-LINE LOW BOILING SOLVENTS - ELECTRONICS

This type of PCB defluxing system is very common throughout the world. It has been the standard method of achieving high cleanliness levels particularly for military/aerospace products and gained wider acceptance still as the primary method of defluxing SMT panels especially when reflow soldered. The only solvents used commercially in these systems has been CFC-113 in the form of stabilized blends with various alcohols. As a result of the phase-out schedule for these solvents under the Montreal Protocol, the larger companies are reconsidering the use of this method as alternatives (HCFC's, semi-aqueous, etc.) become more widely available.

For this exercise, an in-line system for electronics cleaning can be considered as virtually the same as the in-line system for metals. Ultrasonics is gaining greater acceptance and is included as in any case its use has relatively little impact on energy consumption. The typical throughput of such a system depends on the type of product being cleaned (conventional, reflowed or wave soldered SMT); the cleanliness level sought and the degree of matching to the throughput of the previous process. For example, cleaning of freshly wave soldered conventional boards with current systems may be processed at 1.8 to 2.4 meters (6 to 8 ft) per minute, where as a reflowed panel with tight component - substrate stand-off (less than 0.1 mm (0.005 in.)) soldered may require belt speeds of 0.9 to 1.2 meters (3 to 4 ft) per minute; there is a whole range of throughputs in between. Clearly this does not take account of all of these factors so a median figure has been used based on a theoretically average panel.

Similarly, solvent consumption figures will also vary according to the type of product and the duty cycle with Appendix Q showing average solvent emission values used.

Within the cleaning equipment, the majority of the energy usage is in the solvent regeneration cycle where the dirty solvent is boiled to form a vapor which is condensed to provide clean distillate. This basic process is combined in various ways with additional solvent conservation measures but the

fundamental process is to boil solvent and condense it in the most energy efficient manner. This aspect is considered carefully in the analysis when selecting state of the art systems for evaluation.

W.3 IN-LINE AQUEOUS SYSTEMS - ELECTRONICS

A standard aqueous system is not simply determined, as it depends on many factors, such as type of product, cleanliness level, throughput and the type of flux used. Typically these factors will affect the following parameters:

- Incoming and recirculating water quality
- Saponifier concentration (which also varies with the type of saponifier)
- Water temperatures, pressures and flow rates
- Air temperatures, pressures and flow rates
- Line speed
- Incoming PCB temperature

In selecting a system for this investigation therefore, an attempt was made to choose a machine that has typical features and would be appropriate for cleaning moderately dense mixed technology printed wiring assemblies soldered with a rosin based flux.

To clean such an assembly it is necessary to use mechanical agitation. Here it is high pressure, high flow rate sprays. For reflow soldered PCB's additional very high intensity sprays are also needed such as Hollis' "Hurricane" wash. The flow of water around such a system is rather complex but essentially consists of three stages: pre-wash, recirculating wash and rinse (possibly deionized). In the wash tanks, the saponifier concentration (when used with rosin based fluxes) is controlled to 6-7% by volume with a cascade system being present to ensure that the cleanest solution sprays the panels last. The rinse tank is assumed to use de-ionized water as is common practice and an air knife is present to minimize the carry over of saponified water. From an energy point of view the flow of water is not particularly significant except that the water is required to be heated.

One of the largest energy consuming steps is in drying. The main difficulties are in the adequate drying of connectors and open wound components where subsequent electronic testing is very problematic if water is still present. Consequently, much effort has been put in by IBM and others to achieve a method which overcomes this problem. To date the solution is still to apply in increasingly imaginative ways air knives and large volumes of hot air in conjunction with infrared panel heaters. This has a major impact as the energy is almost entirely lost either as damp air or in the form of higher product temperature. The system considered has these features. Note that it is not possible to superheat the PCB's as several electronic components cannot withstand temperatures in excess of 85°C (185°F) (e.g., electrolytic capacitors).

W.4 IN-LINE SEMI-AQUEOUS SYSTEMS - ELECTRONICS

At present, the use of semi-aqueous defluxing systems is rather new but likely to become of increasing importance due to excellent cleaning performance. More and more equipment suppliers are offering in-line systems including Vitronics, Corpane, Detrex, Electrovert and OSL with others having equipment under development. The Corpane system has been take as the as the model example for this exercise - the generic description can be found in Appendix V.4. The solvent selected could easily have been a number of solvents (e.g. Axarel™, terpenes such as EC-7™, etc.) with only minor modifications to the overall system. The potential fire hazard is dealt with by operating at sufficiently low temperatures (15 to 20°C (27 to 36°F) below the flashpoint) and fitting appropriate fire detection and extinguishing equipment.

The cleaning stage consists of high flow rate sprays and/or sprays under immersion in several stages and to a length that is governed by throughput. Carry out of solvent is controlled by air knives; despite these, some solvent is carried over into the rinse stage. It is not yet clear whether the makeup solvent to replace this loss is adequate to ensure a reasonably clean wash stage. With Axarel™, the cleaning efficiency is enhanced by slightly elevated temperatures.

The rinse stages are essentially a cascading system of progressively cleaner water which is heated and recirculated to separate the hydrocarbon from the water and deionize it for the final rinse. Significant amounts of energy are used to heat the water.

As with fully aqueous systems, the drying operation represents the most important use of electrical energy with similar problems being found.

APPENDIX X: OTHER MACHINES AND EQUIPMENT

X.1 LOW SOLIDS/LOW RESIDUE FLUXES FOR "NO-CLEAN" SOLDERING

For many years, the primary method of ensuring adequate solder joint formation was to use a high solids flux often around the 15-20% range with some form of halide activator. Such systems were established as having good soldering yield and tolerance to variations to component quality. Largely through the military specifications post solder defluxing was conducted since:

- for critical applications these residues are unacceptable from a reliability standpoint,
- the thick rosin residue lead to poor bed-of-nails tests,
- the residues were often tacky leading to adhesion of undesirable matter and difficulty in materials handling, and
- residues caused poor conformal coating and adhesion.

Recent developments, however, have lead to flux systems that overcome the need for defluxing whilst retaining good soldering performance especially when wave-soldering conventional assemblies. To achieve these challenging requirements the manufacturers have developed the so-called low solids or low residue fluxes. They center on an ability to contain activator elements which are active only at elevated temperature whilst being broadly inert at normal electronics operating temperatures. In addition, residues are quantatively reduced by employing a lower solids content in the region of 1 to 5%. Much work has been done both by the users and the manufacturers to identify the precise formulation commensurate with the longer term reliability of the product. Developments have also occurred in the method of application as it has been established that a key measure of the long term reliability -- surface insulation resistance -- is governed by the quantity of flux applied.

The application of such systems has been significant in those areas not bound by the current military standard, for example, consumer, telecoms and computing and especially for conventional assemblies. Their use for wave soldered surface mount assemblies is lagging somewhat due to the more demanding soldering requirements particularly in avoiding bridges and obtaining adequate wetting on certain components. For reflow soldered surface mount no-clean solder paste is still further behind because of the fundamentally inconsistent requirements of a printable tacky paste and an inert residue. Much research and development effort however, is being devoted to resolving this issue. In summary, "no clean" technologies do not now universally meet reliability requirements; moreover "no clean" is not no-residue and problems have been reported with conformal coating adhesion.

From an energy point of view, the only impact is in the need to provide extra preheating, although the additional electrical demand is not great. There is some evidence that component solderability needs to be better controlled to successfully use these systems, possibly leading to some limited up-stream energy requirement. It would be, however, a large task to quantify them at this time, if indeed it is possible at all.

X.2 CONTROLLED ATMOSPHERE SOLDERING

Overview

Inert gas wave soldering is a relatively new soldering process as described by EPA (1990). The process operates under a nitrogen atmosphere and applies finely divided activators via ultrasonic injection. The carboxylic acid activators include formic acid, acetic acid, citric acid, and adipic acid. Other processes are also being developed that function on the same principle except that soldering is carried out in vacuum instead of a nitrogen atmosphere.

The particular features that make this process attractive to the well established and widely used method of soldering under atmospheric conditions (i.e., in the presence of oxygen) are (EPA, 1990):

- soldering takes place with metallically pure solder (i.e., in an oxide-free soldering module, oxygen levels in and above the bath are monitored by solid electrolytes at less than two ppm);
- oxide formation is greatly reduced on the printed circuit boards both before and after soldering (dross formation is reported to be only 10% of that generated in normal soldering machines, i.e., 0.5 to 1.0 kg/day (1.1 to 2.2 lb/day));
- the system operates without conventional rosin or resin fluxes; and
- post-cleaning required for assemblies wave soldered on equipment currently in use and utilizing conventional fluxes (rosin, inorganic or synthetic fluxes) is eliminated for many applications. The residues remaining on the printed circuit boards after soldering have been reported to be less than 3.5 micrograms/cm^2 NaCl equivalent.

Several such systems are now available including units from Seho, Soltec and Electrovert which are fully in line systems. Because of the high capital cost associated with such system, retrofits are also becoming available to provide a constant purge of nitrogen through the machine to, mainly, reduce the quantity of dross produced.

Lock Box Concept

For the purposes of this exercise, the lock box concept is assumted to be a fully enclosed air locked system capable of processing PCB carriers of 400 mm by 500 mm (15.75 x 19.7 in.). The "flux" is adipic acid/alcohol solution sprayed onto the PCB within the machine. The high content of alcohol means additional preheating to achieve a reasonably dry board at the solder bath. This has been included in the calculations. To ensure low dross formation and promote low surface tension at the exit point from the wave, the oxygen content of the atmosphere within the machine is kept to 5 ppm. This is achieved by having air locks at both the entrance and exit of the machine. The carriers enter the air locks singly and are subjected to two cycles of vacuum and nitrogen refill before entering the main processing chamber.

The increased energy requirements are therefore concerned with pulling a vacuum and the incremental energy cost of generating high purity nitrogen. The energy calculations are presented in Appendix AA.

Nitrogen Retrofit Equipment

Hanaway (1991) describes an inert gas wave soldering system at DELCO in which "the nitrogen retrofit hood was designed and fabricated by Linde to inert the wave and preheat areas of an Electrovert Econopak II machine to low ppm oxygen levels. Nitrogen is injected into the hood at multiple locations and air entry is minimized through a series of curtains and controlled exhausts. Adjustable flow controls allowed optimization of nitrogen consumption. Gas sample ports are located at the entry, pre-heat, wave, and exit sections of the hood to allow measurement of oxygen levels.

"The production rates on the retrofitted machine were maintained following hood installation. In addition, the Linde hood design allowed the board temperature profile to remain the same.

"The inerting performance of the nitrogen retrofit hood was monitored periodically over the first three months of operation. Oxygen levels were measured at part per million levels with a trace oxygen analyzer. Less than 10 ppm oxygen at the solder wave was achieved at all times during board processing. The oxygen readings were substantiated by the visual appearance of the oxide-free solder wave. Nitrogen flow rates and exhaust settings were set to counter the effects of air drafts." Calculational details are found in Appendix AA. Further improvements are possible since preliminary evaluations have shown that most of the benefits of nitrogen inerting may be achieved by inerting just the wave. Linde and Delco plan to test wave-only inerting as the next step in minimizing design and equipment cost of nitrogen retrofits.

X.3 ALCOHOL-PERFLUOROCARBON DEFLUXING FOR ELECTRONICS

Recent developments have occurred in the UK through a collaborative research program involving ISC Chemicals and British Aerospace which has lead to the specification of an alcohol cleaner using a perfluorocarbon as a mechanism for reducing the risk of flammability. Although the system can be adapted for in-line use, it was originally developed as a two stage batch cleaner not dissimilar to batch solvent systems in principle. In overview, the principle of operation is that the lower boiling point perfluorocarbon will boil through the alcohol forming a vapor at about 45°C (113°F) in the non-flammable range for alcohol content, recondense on the cooling coils and return to the rinse sump. The rinse continuously overflows into the dirty boiling sump completing the cycle. As the work basket exits the tank, it is sprayed with hot fluorocarbon to displace residual alcohol and enable rapid drying. Some perspectives on TEWI are provided in Appendix AC.

Prototype equipment is understood to have been developed and demonstrated and commercialization is imminent. It is difficult to predict whether this system can achieve significant market penetration over the period of CFC phaseout. Moreover, perfluorocarbons are also greenhouse gases with potential global warming impacts. These, however, can be controlled substantially by refrigerated recovery systems.

X.4 ENCLOSED BATCH SPRAY CLEANERS

Enclosed batch spray cleaners are sold primarily for defluxing printed circuit boards and are manufactured by a number of companies including Protonique (Switzerland) and ECD, Milwaukee, Oregon (USA). These systems are very similar to a residential dishwasher in terms of appearance, size, and function.

The ECD machines each carry out one step (e.g., semi-aqueous wash) such as with a terpene aqueous wash, aqueous rinse, alcohol wash, drying. The racks used to hold the boards fit all of the machines; a complete cleaning, rinsing, and drying process is implemented by the use of several individual machines and manually moving the rack full of boards through each of the machines. A typical wash or rinse step takes about 5 minutes. The alcohol water concept is discussed below.

X.5 ALCOHOL - WATER DEFLUXING FOR ELECTRONICS

Various systems have been developed based on high alcohol content solutions with water. One such system supplied by ECD is essentially a batch aqueous cleaner using either a saponified or straight water wash with a final rinse/wash of water and alcohol. The cited advantage is that the final stage is not only an efficient cleaning operation but also provides an indication or final cleanliness levels. This latter benefit is derived from the use of a similar technique as part of several contamination testing systems. As a safety measure the wash chamber is constantly purged with nitrogen.

X.6 ACCEL MACHINE

The Accel machine, manufactured by Accel, Plano, Texas is designed specifically for cleaning PC boards. Cleaning and rinsing is carried out by spinning the board in its own plane while submerged in the cleaning solution. It is claimed by the manufacturer that this process is able to provide particularly effective cleaning of surface mounted assemblies having very close clearances between the component and the board.

X.7 OTHER ELECTRONICS CLEANING SYSTEMS

A variety of miscellaneous methods of achieving a reliable electrical connection have been considered and discounted from this investigation on the basis of their commercialization status and range of applicability. These include ice scrubbing using frozen carbon dioxide; supercritical cleaning; reactive gas atmospheres; reactive plasma pretreatment and conductive polymer device attachment.

X.8 HYDROCARBON METAL CLEANING

Hydrocarbon cleaning processes may be used for precision cleaning; equipment and process design is presently under development.

Exxon has a variety of fluids available for this process. According to Miasek (1990), "There are numerous ways to utilize hydrocarbon products like the ACTREL or EXXATE fluids in a cleaning process. In all cases, properly designed equipment is needed to avoid the risks associated with flammability. Some process options are shown in Fig. X.1. These can be combined or modified to suit the particular application. For example, multi-stage processes can be employed to increase the degree of cleanliness.

"All processes involve liquid-phase cleaning at temperatures sufficiently below the flash point of the fluid. Ultrasonics or other agitation processes such as immersion spraying can be used to augment

cleaning action. Spraying or misting processes, where fine droplets are formed, should be employed only in an inert environment or with equipment otherwise protected from ignition conditions. This is because fine droplets can be ignited at temperatures below bulk fluid flash point.

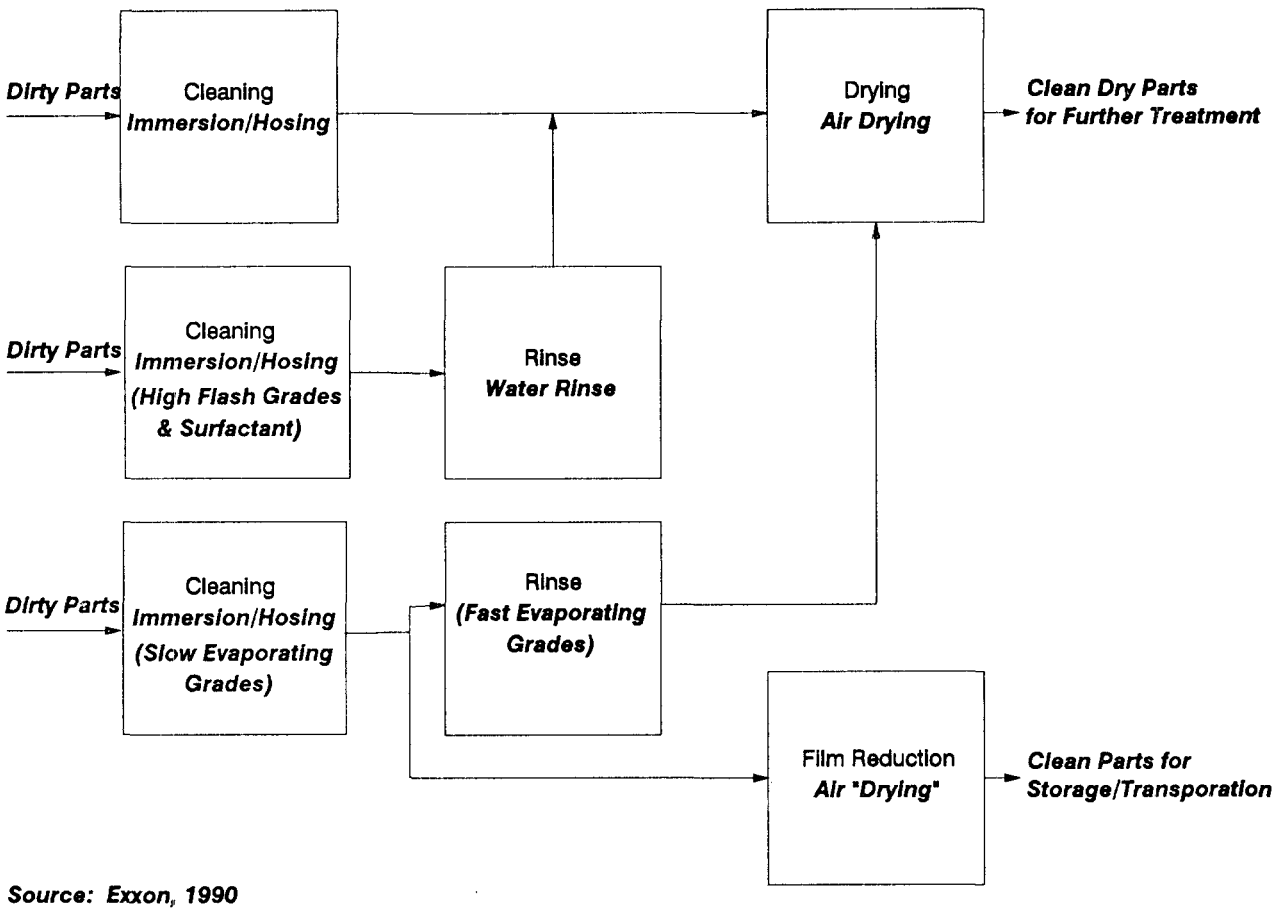


Fig. X.1. Hydrocarbon metal cleaning process.

"Fluids with flash points near 40°C (104°F) should be operated in unheated equipment, operating at ambient temperatures. A typical process is shown in the figure. More than one stage can be employed to increase the degree of cleanliness.

"In the ambient temperature process, drying is most commonly done by forced air drying at ambient temperatures.

"Another approach is hot cleaning. This can be employed to boost cleaning action. This process is only suitable for higher flash fluids. For systems with good temperature control (independent temperature sensors, cutouts, level indicators, etc.), Exxon Chemical recommends a safety margin of 15°C (27°F) between the fluid flash point and the cleaning temperature. For systems with poorer temperature control, a higher margin should be employed. Again, more than one cleaning stage is possible.

"To dry the part following hot cleaning, a number of techniques can be employed. The simplest is to utilize a heated forced air dryer. The dryer should either operate at 15°C (27°F) below the flash point of the fluid, or sufficient air flow should be provided so that the effluent air composition is well

below the Lower Explosive Limit of the system. Alternatively, an ambient temperature rinse with a faster evaporating grade can be employed. Finally, some applications require that a thin film of protective material be left on the part for corrosion protection. There are various cleaning machine manufacturers across the world working on designing cleaning machines using this hot cleaning concept."

CITATIONS

Exxon, 1991. Exxon Chemical Co., Houston, TX, Performance Products for Industrial Cleaning, Product Literature.

Hanaway, E., et al., Optimizing a No-Clean Circuit Board Process Using Nitrogen Inerting of a Conventional Wave Solder Machine, NEPCOM West Technical Session 14, Anaheim, CA, February 25, 1991.

Miasek, P.G., 1990. (November 27) Development of Advanced Hydrocarbon Fluid Alternatives for Precision and Metal Cleaning, 1990. International Conference on CFC and Halon Alternatives, Baltimore, MD.

APPENDIX Y: METAL CLEANING - ENERGY AND CO_2 EMISSIONS

This appendix includes background data for batch and in-line metal cleaning systems modeled in Appendices T and V. The methodology for determining the Total Equivalent Warming Impact (kg equivalent CO_2/tonne metal cleaned) of the systems is described in Section 12. Results are presented in two subsections:

- Appendix Y.1 for batch systems
- Appendix Y.2 for in-line systems

In each of these subsections the information is presented in hierarchical order, namely:

- *Level 1*: at this level a comparative overview is presented of the Total Equivalent Warming impact of the various systems
- *Level 2*: this level backs up the information provided in Level 1 and shows the various contributions to the Total Equivalent Warming Impact from energy use, solvent emissions, embodied energy in materials consumed, etc. during the operating mode.
- *Level 3*: this level backs up Level 2 by disaggregating the energy uses in a given machine (heating, drying, cooling, etc.). The model systems consider low boiling solvents, high boiling solvents, aqueous and semi-aqueous systems.

Y.1 BATCH MACHINES

Appendix Y.1 includes information regarding batch metal cleaning systems. Figure Y.1 shows the absolute TEWI for each system using 500 year GWP's; data used to create this figure is shown in Fig. Y.4 in the rows marked "composite". Note that the contribution to TEWI from energy comprises the bottom portion of each bar. Figure Y.2 shows the TEWI of each system relative to the CFC-113 baseline system. Figure Y.3 shows the absolute TEWI of the BACT systems using 500 year GWP's as compared to baseline CFC-113 systems, based on the energy and emissions savings shown in Table AB.1.

Figure Y.4 is a table showing kg of equivalent CO_2 per tonne of metal throughput using 500 year GWP's in the operating mode, idling mode, downtime mode, and composite. Values for the operating mode are derived from Figs. Y.6 to Y.12. Energy and emissions values per tonne of total daily operating mode throughput for the idling mode are determined as below (using batch metal CFC-113 as an example).

Energy Consumed in Cleaning Process:

- Total operating mode daily throughput is .45 tonne/operating hour times 12 operating hours = 5.4 tonnes
- Equivalent CO_2 during idling mode is 17.3 kWh/idling hour (Fig. Y.13) times 0.67 kg CO_2/kWh x 4 idling hours = 46.3 kg CO_2

- Idling mode CO_2 per daily throughput is 46.3 kg CO_2 ÷ 5.4 tonnes= 8.6 kg CO_2/tonne

Embodied Energy:

- Equivalent CO_2 value is found under Embodied Energy column of Figure Y.6.

Auxiliary Processes:

- Energy value found under "Other" column of Y.6.

Emissions:

- Equivalent CO_2 due to solvent emissions during the idling mode is 0.127 kg solvent/hr (Table Q.4) times 2100 kg CO_2/kg 113 (Table E-1) times 4 hrs in idling mode = 1066.8 kg CO_2

- The equivalent CO_2 per tonne of metal processed is 1066.8 kg CO_2 ÷ 5.4 tonne = 197.6 kg CO_2/tonne

The same procedure is followed to calculate equivalent CO_2 per tonne values for energy and emissions in the downtime mode. Energy demand in the downtime mode is shown in the energy use tables by a double asterisk (Table Y.12 et seq.).

Composite values are determined by summing the operating, idling, and downtime mode values. (Displayed values are rounded.)

Figure Y.5 is similar to Fig. Y.4 except GWP values for the 100 year time horizon are used.

The Level 2 tables show total energy use, chemicals consumed, and emissions for each system in operating mode. Equivalent kg of CO_2 emitted are shown both for each system and per tonne of steel cleaned in Figs. Y.6 to Y.12.

The Level 3 tables detailing the energy use for each system are found in Figs. Y.13 to Y.16. The total energy contribution of each component in the system is listed here (note that these total values back up the "Electric Energy" column of in Figs. Y.6 to Y.12).

Table Y.1. Figures and tabular values for metal cleaning

Comparative TEWI (bar graphs)	Batch	In-Line
TEWI for systems (500 year GWP)	Y.1	Y.17
TEWI relative to baseline CFC-113 systems (500 year GWP)	Y.2	Y.18
TEWI for BACT compared to baseline CFC-113 systems (500 year GWP)	Y.3	Y.19
Comparative Level 1 tabular values (by mode) of Total Equivalent Warming Impact		
500 year GWP	Y.4	Y.20
100 year GWP	Y.5	Y.21
Total Equivalent Warming Impact in Operating Mode (Level 2)		
CFC-113	Y.6	Y.22
HCFC-141b	Y.7	Y.23
HCFC-225ca	Y.8a	Y.24a
HCFC-225cb	Y.8b	Y.24b
HCFC-123	Y.8c	Y.24c
1,1,1 Trichloroethane	Y.9	Y.25
Trichloroethylene	Y.10	Y.26
Aqueous	Y.11	Y.27
Semi-Aqueous	Y.12	Y.28
Energy use breakdown (Level 3: operating mode)		
Low boiling solvents	Y.13	Y.29
Low boiling solvents (water cooling) showing effect of heat pump	Y.13a	-
High boiling solvents	Y.14	Y.30
Aqueous	Y.15	Y.31
Semi-Aqueous	Y.16	Y.32

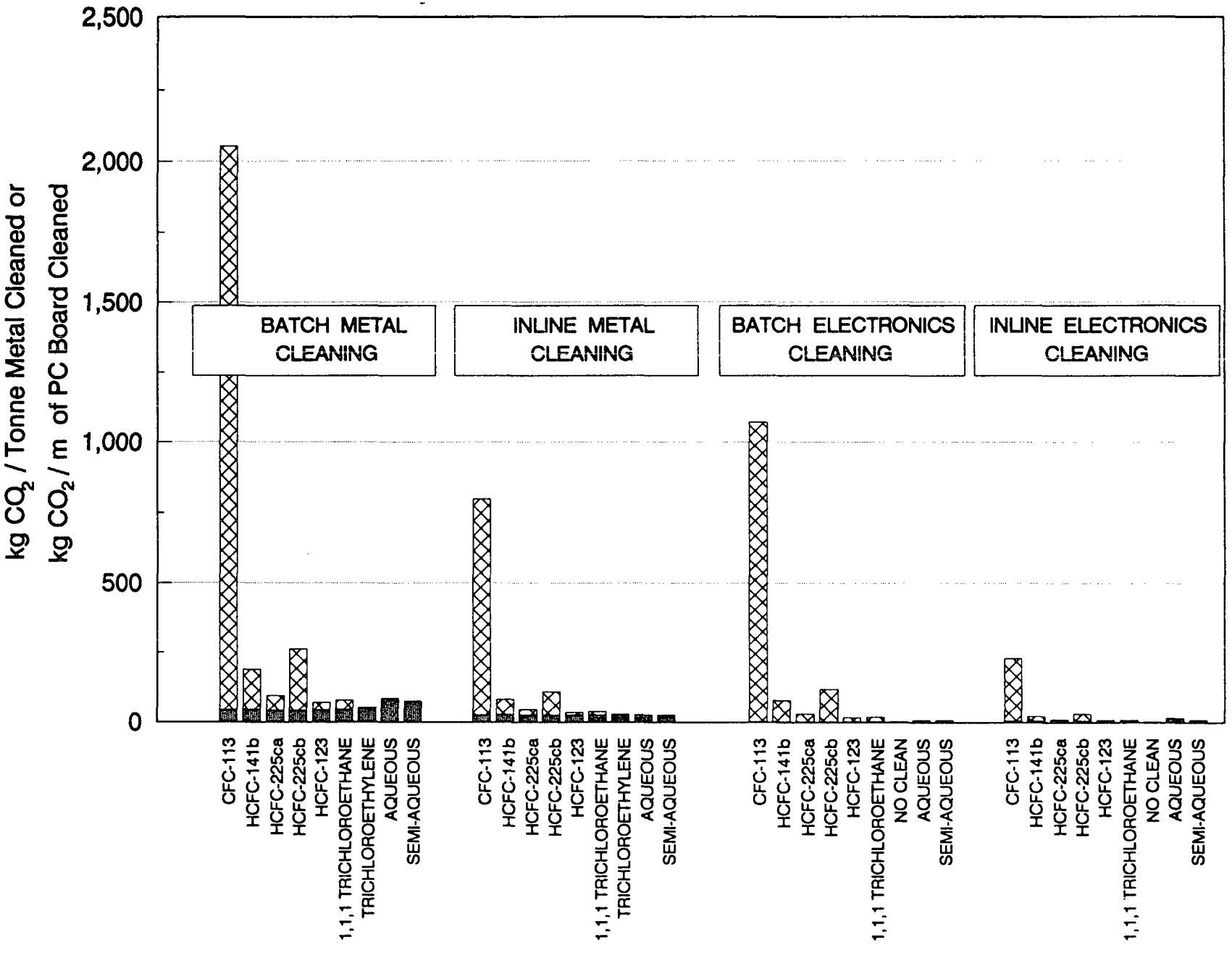


Fig. Y.1. TEWI of baseline technologies (500 year GWP).

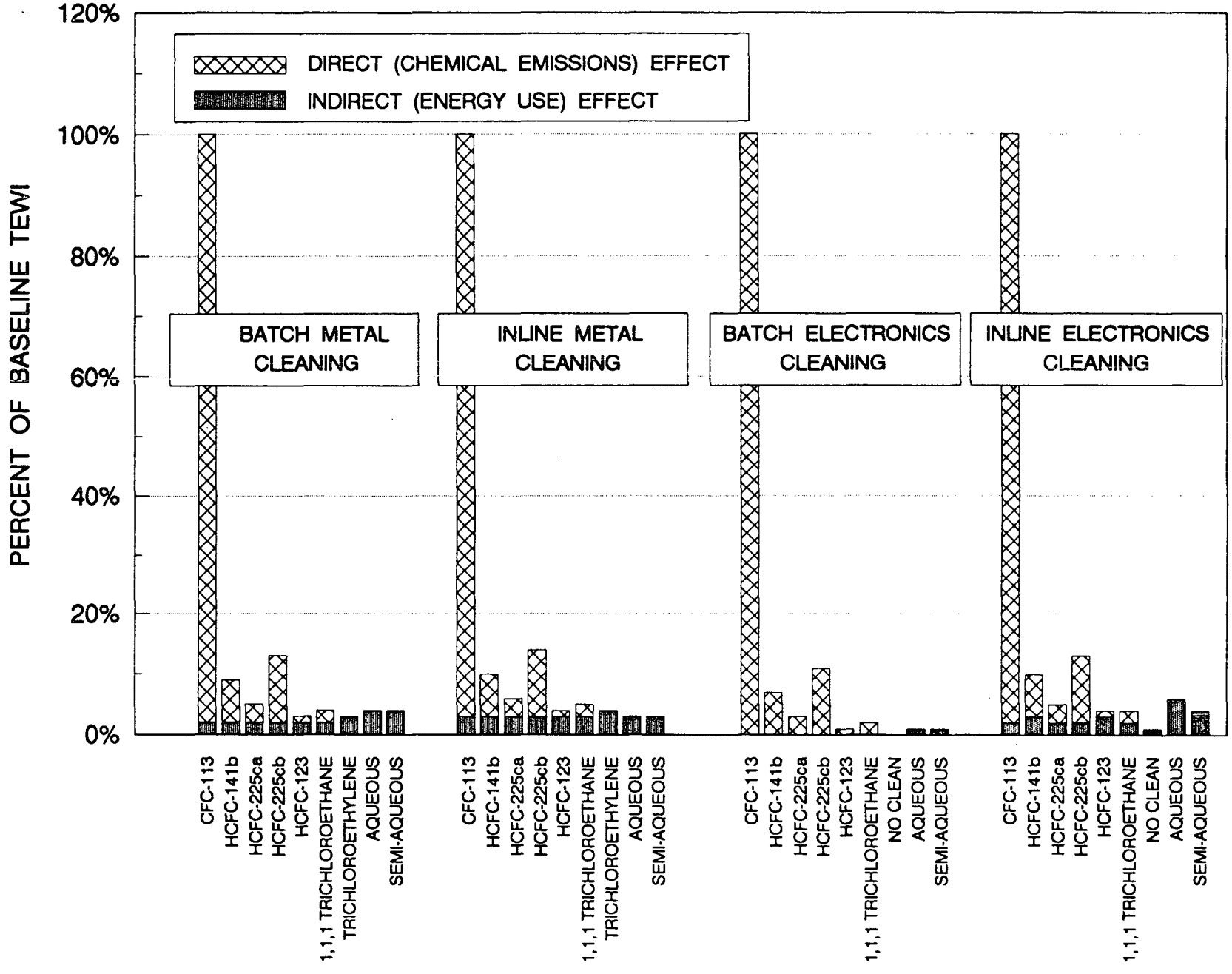


Fig. Y.2. Relative TEWI of baseline technologies (500 year GWP).

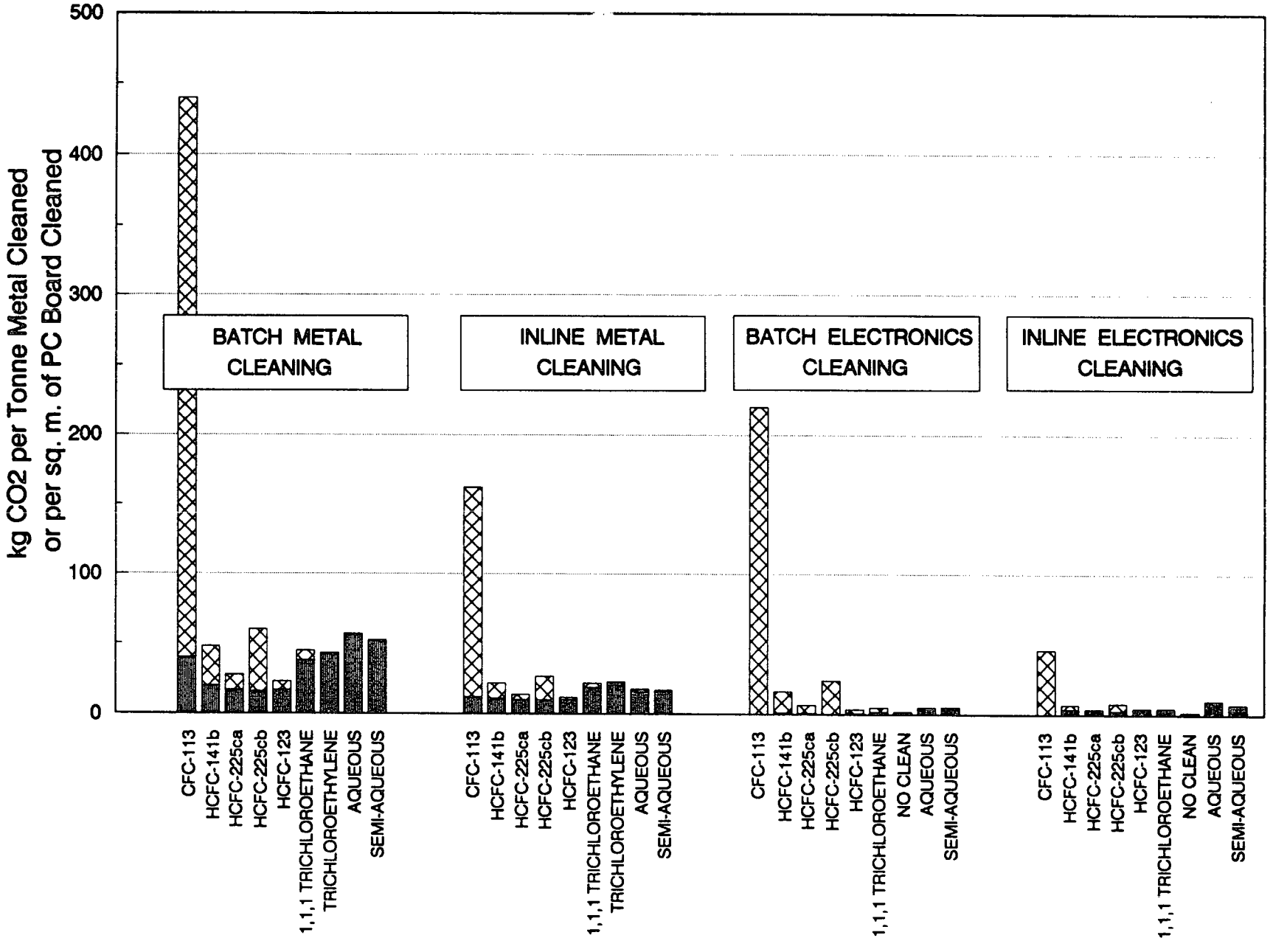


Fig. Y.3. TEWI of BACT (500 year GWP).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	TCE	AQ	SAQ
Operating: 12 Hours									
Energy consumed in cleaning process	27.1	29.9	26.4	26.7	27.7	28.9	32.8	79.6	70.6
Embodied energy in solvent chemicals	2.37	1.94	2.37	2.34	2.23	2.02	2.25	0.00	0.54
Auxilliary processes**	1.84	1.46	1.92	1.99	1.36	2.49	2.82	0.84	0.84
Solvent emissions	1575.0	112.5	41.3	172.5	21.8	25.5	0.5	0.0	0.4
Total Operating	1606.3	145.8	71.9	203.5	53.0	58.9	38.3	80.4	72.5
Idling: 4 hours									
Energy consumed in cleaning process	8.6	9.5	8.3	8.4	8.8	9.2	10.5	4.0	2.0
Embodied energy in solvent chemicals	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00
Auxilliary processes	0.44	0.43	0.44	0.42	0.42	0.47	0.48	0.02	0.02
Solvent emissions	197.6	14.1	5.2	21.6	2.7	3.2	0.1	0.0	0.0
Total Idling	206.6	24.1	14.0	30.5	12.0	12.9	11.1	4.1	2.0
Downtime: 8 hours									
Energy consumed in cleaning process	1.49	1.49	1.49	1.49	1.49	1.49	1.49	0.00	0.00
Embodied energy in solvent chemicals	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.00	0.00
Auxilliary processes	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.00	0.00
Solvent emissions	236.4	16.9	6.2	25.9	3.3	3.8	0.1	0.0	0.0
Total Downtime	238.8	19.3	8.6	28.3	5.7	6.2	2.5	0.0	0.0
Composite: kg eq. CO2/te metal cleaned									
Energy consumed in cleaning process	37.2	40.9	36.2	36.6	38.0	39.6	44.7	83.6	72.6
Embodied energy in solvent chemicals	2.5	2.1	2.5	2.5	2.3	2.1	2.4	0.0	0.5
Auxilliary processes	3.1	2.7	3.2	3.3	2.6	3.8	4.2	0.9	0.9
Solvent emissions	2009.0	143.5	52.6	220.0	27.7	32.5	0.6	0.0	0.4
TOTAL	2051.8	189.2	94.5	262.3	70.7	78.0	51.9	84.5	74.4

** additional HVAC requirements due to cleaning system

Fig. Y.4. Batch metal cleaning processes, 500 year time horizon (kg equivalent CO_2/te metal).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	TCE	AQ	SAQ
Operating: 12 Hours									
Energy consumed in cleaning process	27.1	29.9	26.4	26.7	27.7	28.9	32.8	79.6	70.6
Embodied energy in solvent chemicals	2.37	1.94	2.37	2.34	2.23	2.02	2.25	0.00	0.54
Auxilliary processes**	1.84	1.46	1.92	1.99	1.36	2.49	2.82	0.84	0.84
Solvent emissions	3150.0	330.0	121.5	510.0	63.8	75.0	0.5	0.0	1.0
Total Operating	3181.3	363.3	152.1	541.0	95.0	108.4	38.3	80.4	73.1
Idling: 4 hours									
Energy consumed in cleaning process	8.6	9.5	8.3	8.4	8.8	9.2	10.5	4.0	2.0
Embodied energy in solvent chemicals	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00
Auxilliary processes	0.44	0.43	0.44	0.42	0.42	0.47	0.48	0.02	0.02
Solvent emissions	395.1	41.4	15.2	64.0	8.0	9.4	0.1	0.0	0.6
Total Idling	404.2	51.4	24.1	72.9	17.2	19.1	11.1	4.1	2.6
Downtime: 8 hours									
Energy consumed in cleaning process	1.49	1.49	1.49	1.49	1.49	1.49	1.49	0.00	0.00
Embodied energy in solvent chemicals	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.00	0.00
Auxilliary processes	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.00	0.00
Solvent emissions	472.9	49.5	18.2	76.6	9.6	11.3	0.1	0.0	1.2
Total Downtime	475.3	51.9	20.6	79.0	12.0	13.7	2.5	0.0	1.2
Composite: kg eq. CO2/te metal cleaned									
Energy consumed in cleaning process	37.2	40.9	36.2	36.6	38.0	39.6	44.7	83.6	72.6
Embodied energy in solvent chemicals	2.5	2.1	2.5	2.5	2.3	2.1	2.4	0.0	0.5
Auxilliary processes	3.1	2.7	3.2	3.3	2.6	3.8	4.2	0.9	0.9
Solvent emissions	4018.0	420.9	155.0	650.5	81.3	95.7	0.6	0.0	2.8
TOTAL	4060.8	466.6	196.8	692.8	124.3	141.2	51.9	84.5	76.9

** additional HVAC requirements due to cleaning system

Fig. Y.5. Batch metal cleaning processes, 100 year time horizon (kg equivalent CO_2/te metal).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy Chemicals Consumed Name	Embodied Energy Chemicals Consumed (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	12.1			CFC-113	2.1 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Air Pollution	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.7							1.2		
TOTAL	18.2	0.0	0.0		2.1	0.0	0.3	1.2		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	2100 (e)	0.67	500 year GWP= 2100 (e)	
Equivalent CO2 Emissions, N.A.	12.2	0.0	0.0		1.1 (d)	0.0	708.8	0.8	722.8	1606.3
Emissions, Europe	9.3	0.0	0.0		1.1 (d)	0.0	708.8	0.8	719.9	1599.8
Emissions, Japan	10.6	0.0	0.0		1.1 (d)	0.0	708.8	0.8	721.2	1602.6

	100 year GWP= 4200 (e)	
Equivalent CO2 Emissions, N.A.	1431.6	3181.3
Emissions, Europe	1428.7	3174.8
Emissions, Japan	1429.9	3177.6

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch consumed*2.86 kWh/kg chemicals produced 1.000 kg*0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.6. Batch metal cleaning system - CFC-113 operating mode (low boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	13.2			HCFC-141b	1.70 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	6.5							1.0		
TOTAL	20.1	0.0	0.0		1.7	0.0	0.3	1.0		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	150 (e)	0.67	500 year GWP= 150 (e)	
Equivalent CO2 Emissions, N.A.	13.5	0.0	0.0		0.9 (d)	0.0	50.6	0.6	65.6	145.8
Emissions, Europe	10.3	0.0	0.0		0.9 (d)	0.0	50.6	0.6	62.4	138.6
Emissions, Japan	11.7	0.0	0.0		0.9 (d)	0.0	50.6	0.6	63.8	141.8

	100 year GWP= 440 (e)	
Equivalent CO2 Emissions, N.A.	163.5	363.3
Emissions, Europe	160.3	356.1
Emissions, Japan	161.7	359.3

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.7. Batch metal cleaning system - HCFC-141b, operating mode (low boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	11.8			HCFC-225ca	2.07 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.5							1.3		
TOTAL	17.7	0.0	0.0		2.1	0.0	0.3	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	55 (e)	0.67	500 year GWP= 55 (e)	
Equivalent CO2 Emissions, N.A.	11.9	0.0	0.0		1.1 (d)	0.0	18.6	0.9	32.3	71.9
Emissions, Europe	9.0	0.0	0.0		1.1 (d)	0.0	18.6	0.9	29.5	65.6
Emissions, Japan	10.3	0.0	0.0		1.1 (d)	0.0	18.6	0.9	30.7	68.3

	100 year GWP= 162 (e)	
Equivalent CO2 Emissions, N.A.	68.5	152.1
Emissions, Europe	65.6	145.8
Emissions, Japan	66.9	148.6

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL est.)
(h) see Appendix D

Fig. Y.8a. Batch metal cleaning system - HCFC-225ca, operating mode (low boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	12.0			HCFC-225cb	2.0 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.5							1.3		
TOTAL	17.9	0.0	0.0		2.0	0.0	0.3	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	230 (e)	0.67	500 year GWP= 230 (e)	
Equivalent CO2 Emissions, N.A.	12.0	0.0	0.0		1.1 (d)	0.0	77.6	0.9	91.6	203.5
Emissions, Europe	9.1	0.0	0.0		1.1 (d)	0.0	77.6	0.9	88.7	197.1
Emissions, Japan	10.4	0.0	0.0		1.1 (d)	0.0	77.6	0.9	90.0	199.9

	100 year GWP= 680 (e)	
Equivalent CO2 Emissions, N.A.	243.4	541.0
Emissions, Europe	240.6	534.6
Emissions, Japan	241.8	537.4

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.8b. Batch metal cleaning system - HCFC-225cb, operating mode (low boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	12.1			HCFC-123	2.0 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	6.1							0.9		
TOTAL	18.6	0.0	0.0		2.0	0.0	0.3	0.9		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	29 (e)	0.67	500 year GWP= 29 (e)	
Equivalent CO2 Emissions, N.A.	12.5	0.0	0.0		1.0 (d)	0.0	9.8	0.6	23.9	53.0
Emissions, Europe	9.5	0.0	0.0		1.0 (d)	0.0	9.8	0.6	20.9	46.4
Emissions, Japan	10.8	0.0	0.0		1.0 (d)	0.0	9.8	0.6	22.2	49.3

	100 year GWP= 85 (e)	
Equivalent CO2 Emissions, N.A.	42.8	95.0
Emissions, Europe	39.8	88.4
Emissions, Japan	41.1	91.3

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.8c. Batch metal cleaning system - HCFC-123, operating mode (low boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	17.3			1,1,1	1.8 (g)	0.00	0.34 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	1.7							1.7		
TOTAL	19.4	0.0	0.0		1.8	0.0	0.3	1.7		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	34 (e)	0.67	500 year GWP= 34 (e)	
Equivalent CO2 Emissions, N.A.	13.0	0.0	0.0		0.9 (d)	0.0	11.5	1.1	26.5	58.9
Emissions, Europe	9.9	0.0	0.0		0.9 (d)	0.0	11.5	1.1	23.4	52.0
Emissions, Japan	11.3	0.0	0.0		0.9 (d)	0.0	11.5	1.1	24.8	55.0

	100 year GWP= 100 (e)	
Equivalent CO2 Emissions, N.A.	48.8	108.4
Emissions, Europe	45.7	101.5
Emissions, Japan	47.0	104.5

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.9. Batch metal cleaning system - 1,1,1 trichloroethane, operating mode (high boiling point solvent).

0.45 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	19.9			TCE	2.0 (g)	0.34 (h)				
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	1.7							1.9		
TOTAL	22.0	0.0	0.0		2.0	0.3	0.0	1.9		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0.67 (e)		0.67	500 year GWP= 0.67 (e)	
Equivalent CO2 Emissions, N.A.	14.7	0.0	0.0		1.0 (d)	0.2	0.0	1.3	17.2	38.3
Emissions, Europe	11.2	0.0	0.0		1.0 (d)	0.2	0.0	1.3	13.7	30.5
Emissions, Japan	12.8	0.0	0.0		1.0 (d)	0.2	0.0	1.3	15.3	33.9

	100 year GWP= 0.67 (e)	
Equivalent CO2 Emissions, N.A.	17.2	38.3
Emissions, Europe	13.7	30.5
Emissions, Japan	15.3	33.9

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) Polhamus, 1991, March 20
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 2 weeks (ADL estimate)
(h) see Appendix D

Fig. Y.10. Batch metal cleaning system - trichloroethylene, operating mode (high boiling point solvent).

0.16 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	2.1			detergent	0.25 (g)	0.00	0.00			
Rinse	8.0									
Dry	8.4									
Exhaust	0.4									
Pretreatment (h)	0.0									
Waste Treatment	0.0									
Other	0.1							0.2		
TOTAL	19.0	0.0	0.0		0.3	0.0	0.0	0.2		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	0	0.67	500 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	12.7	0.0	0.0		0.0 (d)	0.0	0.0	0.1	12.9	80.4
Emissions, Europe	9.7	0.0	0.0		0.0 (d)	0.0	0.0	0.1	9.8	61.4
Emissions, Japan	11.0	0.0	0.0		0.0 (d)	0.0	0.0	0.1	11.2	69.7

	100 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	12.9	80.4
Emissions, Europe	9.8	61.4
Emissions, Japan	11.2	69.7

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate based on engineering judgement
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) 0.25 kg*0.01 kWh/kg ch. produced 1.000 kg*0.000050*3600 kJ/kWh
(e) GWP of detergent estimated to be 0.0 in 100 year time frame (ADL est.)
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) 0.25 kg detergent (ADL estimate)
(h) no consideration for pretreatment

Fig. Y.11. Batch metal cleaning system, operating mode (aqueous system).

0.16 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	0.3			AXAREL	0.15 (g)	0.02 (h)	0.00			
Rinse	7.7									
Dry	8.4									
Exhaust	0.4									
Pretreatment (i)	0.0									
Waste Treatment	0.0									
Other	0.1							0.2		
TOTAL	16.9	0.0	0.0		0.2	0.02	0.0	0.2		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	2.4 (e)	0	0.67	500 year GWP= 2.4 (e)	
Equivalent CO2 Emissions, N.A.	11.3	0.0	0.0		0.1 (d)	0.1	0.0	0.1	11.6	72.5
Emissions, Europe	8.6	0.0	0.0		0.1 (d)	0.1	0.0	0.1	8.9	55.6
Emissions, Japan	9.8	0.0	0.0		0.1 (d)	0.1	0.0	0.1	10.1	63.0

	100 year GWP= 6.4 (e)	
Equivalent CO2 Emissions, N.A.	11.7	73.1
Emissions, Europe	9.0	56.2
Emissions, Japan	10.2	63.6

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate based on engineering judgement
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) dragout + change sump every 3 months (ADL estimate)
(h) 0.15 kg solvent /te steel (ADL est.)
(i) no consideration for pretreatment

Fig. Y.12. Batch metal cleaning system, operating mode (semi-aqueous system).

Station/ Component	Operating Power (kWh/h)				
	113	141b	123	225ca	225cb
Wash					
Heater	11.5 (a)*	12.6	11.5	11.2	11.4
Ultrasonics, 1.2 kW	0.6 (b)	0.6	0.6	0.6	0.6
Total, Wash	12.1	13.2	12.1	11.8	12.0
Rinse					
Pump, 0.3 HP, spray	0.1 (b)	0.1	0.1	0.1	0.1
Total, Rinse	0.1	0.1	0.1	0.1	0.1
Dry					
Total, Dry	0.0	0.0	0.0	0.0	0.0
Exhaust					
Total, Exhaust	0.0	0.0	0.0	0.0	0.0
Waste Treatment					
Pump, 0.3 HP	0.3 (b)*	0.3	0.3	0.3	0.3
Total, Waste Treatment	0.3	0.3	0.3	0.3	0.3
Other					
Chiller	4.0 (c)*	4.8	4.4	3.8	3.8
Chiller, low temp. 0.75 HP**	1.5 (e)*	1.5	1.5	1.5	1.5
Hoist, 0.2 HP	0.2 (d)	0.2	0.2	0.2	0.2
Total, Other	5.7	6.5	6.1	5.5	5.5
TOTAL, SYSTEM	18.2	20.1	18.6	17.7	17.9
kg CO2, operating	27.10	29.93	27.69	26.35	26.65
kW idling	17.30	19.20	17.70	16.80	17.00

Basis: Branson model BSD 2024 standard, 0.45 te/hr
(a) Branson, 1988, Bulletin S-984
(b) Polhamus, 1991, March 20
(c) Branson, 1988, Bulletin S-987
(d) ADL estimate based on engineering judgement
(e) Allied, 1990, Vaportrap product literature
* = included in idling mode
** = included in downtime mode

Fig. Y.13. Energy use breakdown, operating mode, batch metal cleaning systems (low boiling point solvents).

Station/ Component	Operating Power (kWh/h)
Wash	
Heater, 14 kW	11.5 (a)
Ultrasonics, 1.2 kW	0.6 (b)
Total, Wash	12.1
Rinse	
Pump, 0.3 HP, spray	0.1 (b)
Total, Rinse	0.1
Dry	
Total, Dry	0.0
Exhaust	
Total, Exhaust	0.0
Waste Treatment	
Pump, 0.3 HP	0.3 (b)
Total, Waste Treatment	0.3
Other	
Chiller, 5 HP	5.5 (f)
Chiller, low temp., 0.75 HP	1.5 (e)
Hoist, 0.2 HP	0.2 (d)
Total, Other	7.2
TOTAL, SYSTEM	19.7
Heat Pump Savings (if used)	11.5 (f)
TOTAL, System with Heat Pump	8.2

Basis: Branson model BSD 2024 standard, 0.45 te/hr

(a) Branson, 1988, Bulletin S-984

(b) Polhamus, 1991, March 20

(c) Branson, 1988, Bulletin S-987

(d) ADL estimate based on engineering judgement

(e) Allied, 1990, Vaportrap product literature

(f) Osterman, 1991, April 23

Fig. Y.13a. Energy use breakdown, operating mode batch metal cleaning system with water cooled chiller or heat pump (low boiling point solvents).

Station/Component	Operating Power (kWh/h)	
Wash	1,1,1 Trichloroethane	Trichloroethylene
Heater, 14 kW	16.7 (a)*	19.3
Ultrasonics, 1.2 kW	0.6 (b)	0.6
Total, Wash	17.3	19.9
Rinse		
Pump, 0.3 HP, spray	0.1 (b)	0.1
Total, Rinse	0.1	0.1
Dry		
Total, Dry	0.0	0.0
Exhaust		
Total, Exhaust	0.0	0.0
Waste Treatment		
Pump, 0.3 HP	0.3 (b)*	0.3
Total, Waste Treatment	0.0	0.0
Other		
Chiller, low temp**	1.5 (c)*	1.5
Hoist, 0.2 HP	0.2 (d)	0.2
Total, Other	1.7	1.7
TOTAL, SYSTEM	19.4	22.0

kg CO2, operating	28.88	32.76
kW idling	18.50	21.10

Basis: Branson model BSD 2024 standard, 0.45 te/hr
(a) Branson, 1988, Bulletin S-984
(b) Polhamus, 1991, March 20
(c) Allied, 1990, Vaportrap product literature
(d) ADL estimate based on engineering judgement
*=included in idling mode
**=included in downtime mode

Fig. Y.14. Energy use breakdown, operating mode batch metal cleaning system (high boiling solvents).

Station/ Component	Operating Power (kWh/h)
Wash	
Heaters, 2 @ 1 kw	1.0 (a)
Pumps, 2 @ 0.3 HP	0.6 (a)
Ultrasonics, 1.0 kW	0.5 (a)
Total, Wash	2.1
Rinse	
Heaters, water, 10 kW	5.9 (b)
Heaters, 3 @ 1 kW	1.5 (a)
Ultrasonics, 0.5 kW	0.3 (a)
Pumps, 0.3 HP	0.3 (a)
Total, Rinse	8.0
Dry	
Heater, 7.5 kW	7.5 (a)
Blowers, 1 HP	0.9 (a)
Total, Dry	8.4
Exhaust	
Blower, 0.5 HP	0.4 (b)
Total, Exhaust	0.4
Waste Treatment	
Total, Waste Treatment	0.0 (c)
Other	
Hoist, 0.12 HP	0.1 (a)
Total, Other	0.1
TOTAL, SYSTEM	19.0

Basis: Crest bench system with 1014 tanks, 0.16 te/hr

(a) Maltby, 1991 March 12

(b) ADL estimate based on engineering judgement

(c) water separation powered by wash and rinse pumps.

* = included in operating mode

Fig. Y.15. **Energy use breakdown, operating mode batch metal cleaning (aqueous system).**

Station/ Component	Operating Power (kWh/h)
Wash	
Pump, 0.3 HP	0.3 (a)
Total, Wash	0.3
Rinse	
Heater, water, 10 kW	5.9 (b)
Heaters, 2 @ 1 kW	1.0 (a)
Pumps, 0.3 HP	0.3 (a)
Ultrasonics, 1.0 kW	0.5 (a)
Total, Rinse	7.7
Dry	
Heater, 7.5 kW	7.5 (a)
Blowers, 1 HP	0.9 (a)
Total, Dry	8.4
Exhaust	
Blower, 0.5 HP	0.4 (b)
Total, Exhaust	0.4
Waste Treatment	
Total, Waste Treatment	0.0 (c)
Other	
Hoist, 0.12 HP	0.1 (b)
Total, Other	0.1
TOTAL, SYSTEM	16.9

Basis: Crest bench system with 1014 tanks, AXAREL 52, 0.16 te/hr

(a) Maltby, 1991 March 12

(b) ADL estimate based on engineering judgement

(c) water separation powered by wash and rinse pumps.

* = included in operating mode

Fig. Y.16. Energy use breakdown, operating mode batch metal cleaning system (semi-aqueous system.)

Y.2 IN-LINE MACHINES

Appendix Y.2 uses the same format for in-line metal cleaning systems as is used in Appendix Y.1 for batch metal cleaning systems. There is parallelism in the cases examined as shown in Table Y.1.

The in-line metal solvent cleaning system was especially difficult to model because these machines tend to be built for specific applications as described in Section 6 of the body of the main report. Thus, the model machine was thought of as one having the following major heat sinks: heating the metal, vaporizing solvent, solvent condensation, and control of vapor emissions. Based on examining a number of systems, the energy involved in the drive mechanisms is small and the system could as easily be a crossrod, monorail, or belt system involving:

1) Heating in a vapor zone

2) An immersion wash

3) A vapor rinse

4) A second immersion

5) A second vapor rinse evaporation step

Based on such considerations and discussions with vendors and users of equipment, it was felt that solvent losses in any of these systems would be the same (for similar parts being cleaned). Nevertheless, it should be recognized that there is a need for confirmatory data on operational systems.

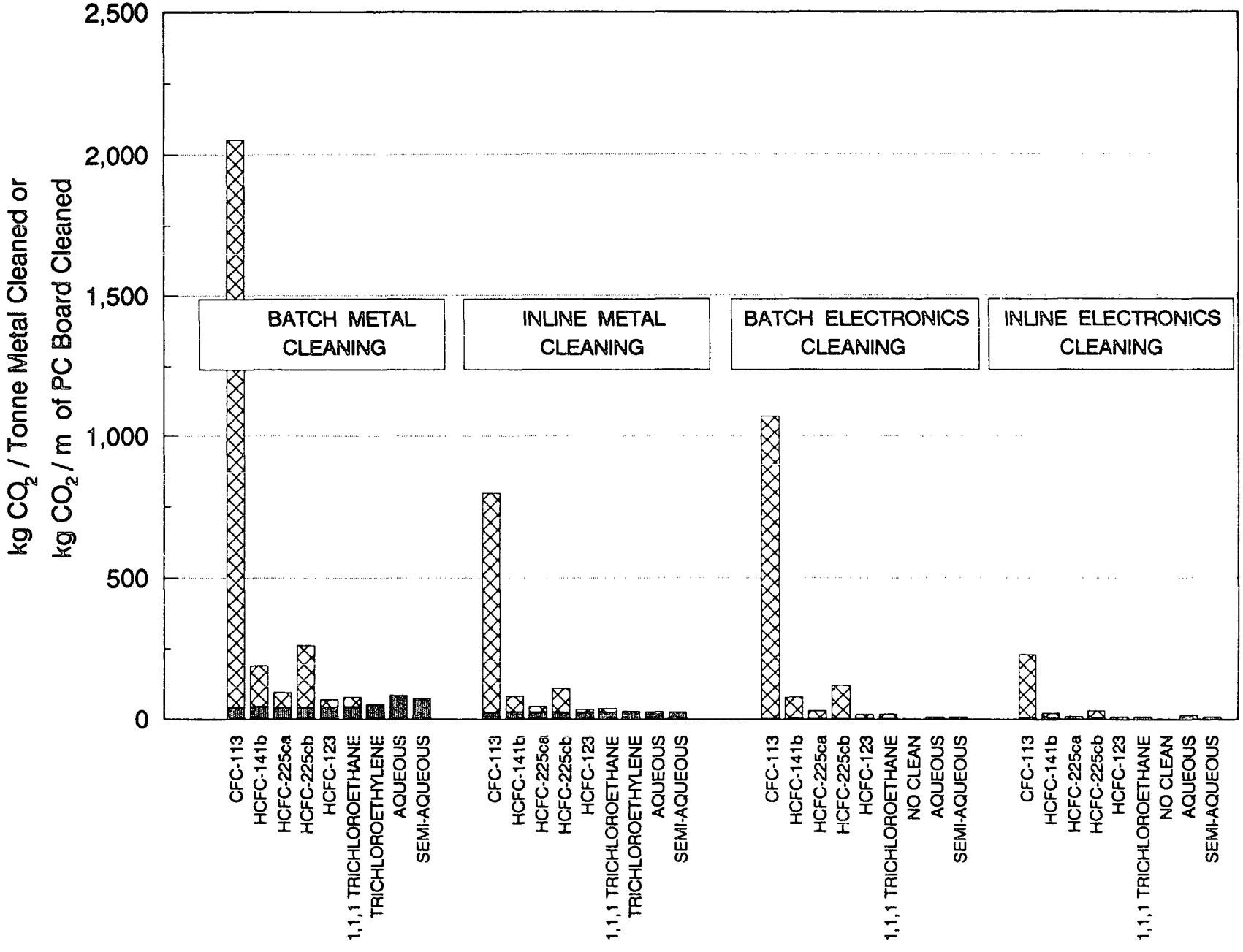


Fig. Y.17. TEWI of baseline technologies (500 year GWP).

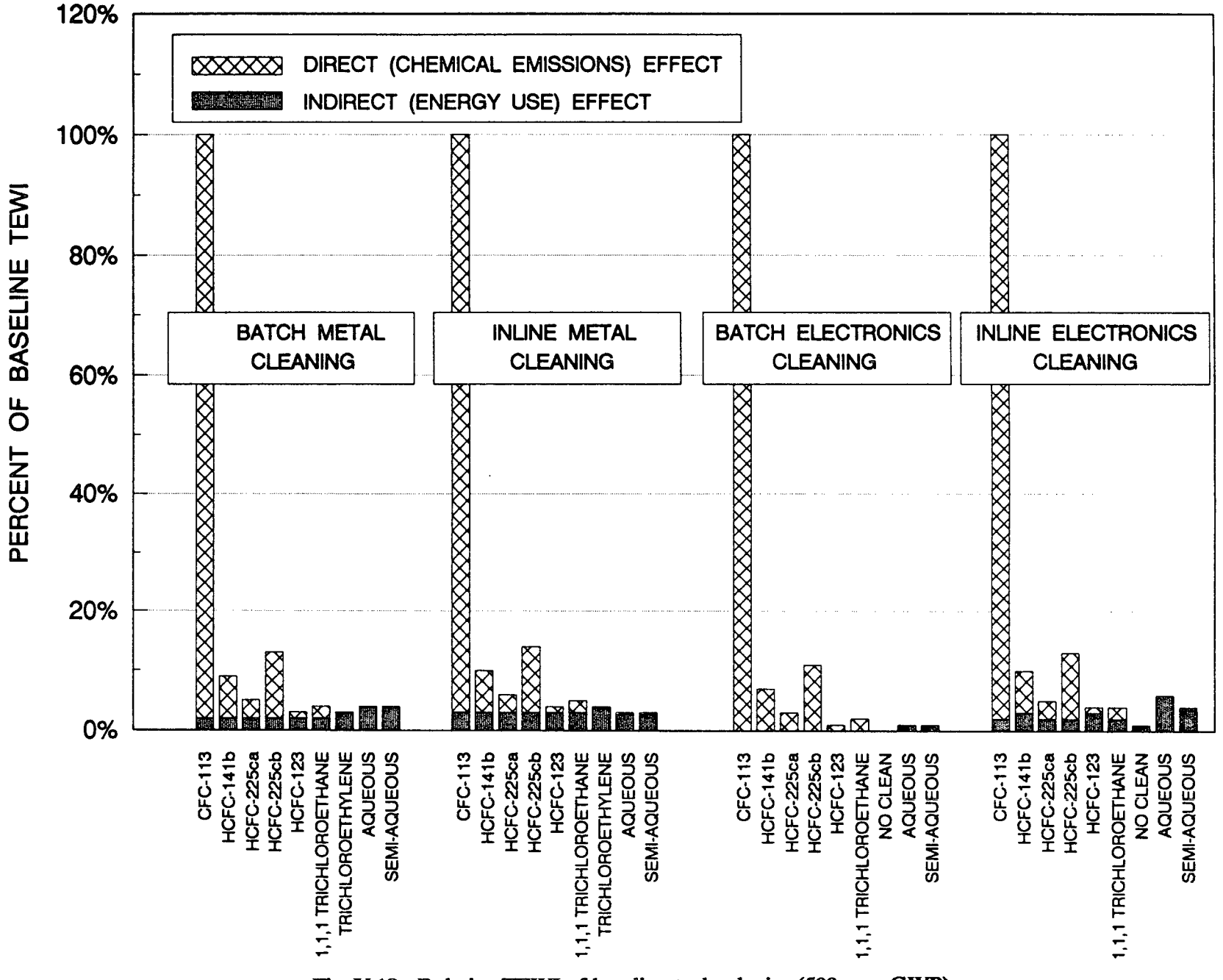


Fig. Y.18. Relative TEWI of baseline technologies (500 year GWP).

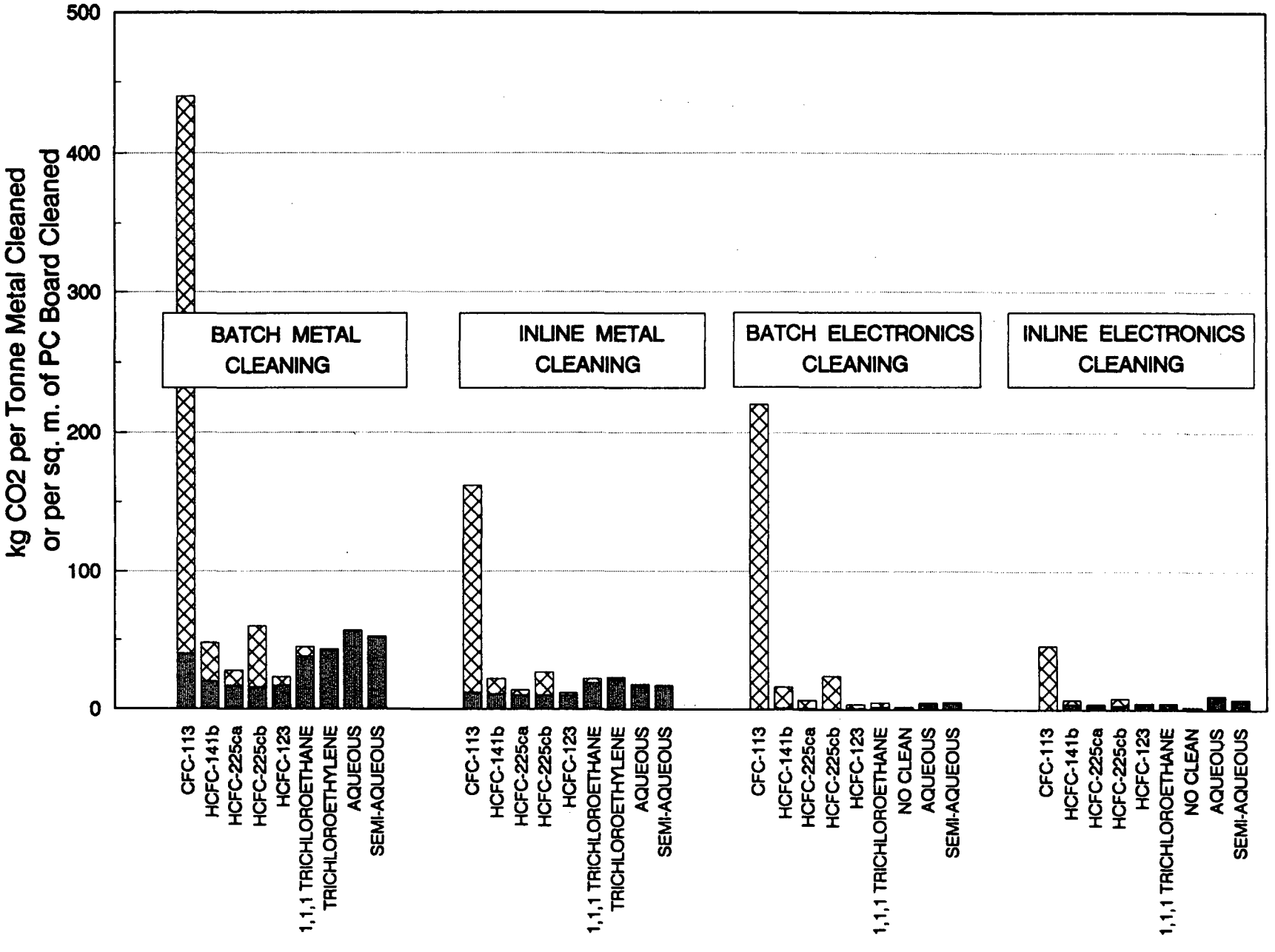


Fig. Y.19. TEWI of BACT (500 year GWP).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	TCE	AQ	SAQ
Operating: 12 Hours									
Energy consumed in cleaning process	16.8	18.3	16.4	16.8	16.7	16.7	19.3	25.4	23.0
Embodied energy in solvent chemicals	1.81	1.46	1.81	1.79	1.70	1.52	1.71	0.00	0.10
Auxilliary processes**	0.80	0.45	0.88	1.00	0.35	1.41	1.72	0.74	0.74
Solvent emissions	735.0	52.5	19.3	80.5	10.2	11.9	0.2	0.0	0.4
Total Operating	754.5	72.8	38.3	100.1	28.9	31.5	22.9	26.2	24.2
Idling: 4 hours									
Energy consumed in cleaning process	5.3	5.8	5.2	5.4	5.3	5.3	6.2	1.1	0.9
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.09	0.09	0.09	0.09	0.09	0.10	0.11	0.01	0.01
Solvent emissions	12.9	0.9	0.3	1.4	0.2	0.2	0.0	0.0	0.0
Total Idling	18.3	6.8	5.6	6.9	5.6	5.6	6.3	1.2	0.9
Downtime: 8 hours									
Energy consumed in cleaning process	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.00	0.00
Embodied energy in solvent chemicals	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Auxilliary processes	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.00	0.00
Solvent emissions	25.8	1.8	0.7	2.8	0.4	0.4	0.0	0.0	0.0
Total Downtime	26.2	2.3	1.2	3.3	0.8	0.9	0.5	0.0	0.0
Composite: kg eq. CO2/te metal cleaned									
Energy consumed in cleaning process	22.4	24.4	21.9	22.5	22.3	22.3	25.7	26.6	23.8
Embodied energy in solvent chemicals	1.8	1.5	1.8	1.8	1.7	1.5	1.7	0.0	0.1
Auxilliary processes	1.1	0.7	1.1	1.3	0.6	1.7	2.0	0.8	0.8
Solvent emissions	773.6	55.3	20.3	84.7	10.7	12.5	0.2	0.0	0.4
TOTAL	799.0	81.9	45.1	110.3	35.3	38.0	29.7	27.3	25.1

** additional HVAC requirements due to cleaning system

Fig. Y.20. In-line metal cleaning processes, 500 year time horizon (kg equivalent CO_2/te metal).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	TCE	AQ	SAQ
Operating: 12 Hours									
Energy consumed in cleaning process	16.8	18.3	16.4	16.8	16.7	16.7	19.3	25.4	23.0
Embodied energy in solvent chemicals	1.81	1.46	1.81	1.79	1.70	1.52	1.71	0.00	0.10
Auxilliary processes**	0.80	0.45	0.88	1.00	0.35	1.41	1.72	0.74	0.74
Solvent emissions	1470.0	154.0	56.7	238.0	29.8	35.0	0.2	0.0	1.0
Total Operating	1489.5	174.3	75.8	257.6	48.5	54.6	22.9	26.2	24.8
Idling: 4 hours									
Energy consumed in cleaning process	5.3	5.8	5.2	5.4	5.3	5.3	6.2	1.1	0.9
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.09	0.09	0.09	0.09	0.09	0.10	0.11	0.01	0.01
Solvent emissions	25.8	2.7	1.0	4.2	0.5	0.6	0.0	0.0	0.0
Total Idling	31.2	8.6	6.3	9.7	5.9	6.0	6.3	1.1	0.9
Downtime: 8 hours									
Energy consumed in cleaning process	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.00	0.00
Embodied energy in solvent chemicals	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Auxilliary processes	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.00	0.00
Solvent emissions	51.5	5.4	2.0	8.3	1.0	1.2	0.0	0.0	0.1
Total Downtime	52.0	5.9	2.5	8.8	1.5	1.7	0.5	0.0	0.1
Composite: kg eq. CO2/te metal cleaned									
Energy consumed in cleaning process	22.4	24.4	21.9	22.5	22.3	22.3	25.7	26.6	23.8
Embodied energy in solvent chemicals	1.8	1.5	1.8	1.8	1.7	1.5	1.7	0.0	0.1
Auxilliary processes	1.1	0.7	1.1	1.3	0.6	1.7	2.0	0.8	0.8
Solvent emissions	1547.3	162.1	59.7	250.5	31.3	36.8	0.2	0.0	1.1
TOTAL	1572.6	188.7	84.5	276.1	55.9	62.4	29.7	27.3	25.8

** additional HVAC requirements due to cleaning system

Fig. Y.21. In-line metal cleaning processes, 100 year time horizon (kg equivalent CO_2/te metal).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	3.0			CFC-113	8.8 (g)	0.00	0.88 (h)			
Rinse	18.9									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	41.0							3.0		
TOTAL	62.9	0.0	0.0		8.8	0.0	0.9	3.0		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	2100 (e)	0.67	500 year GWP= 2100 (e)	
Equivalent CO2 Emissions, N.A.	42.1	0.0	0.0		4.5 (d)	0.0	1837.5	2.0	1886.2	754.5
Emissions, Europe	32.1	0.0	0.0		4.5 (d)	0.0	1837.5	2.0	1876.1	750.4
Emissions, Japan	36.5	0.0	0.0		4.5 (d)	0.0	1837.5	2.0	1880.5	752.2

	100 year GWP= 4200 (e)	
Equivalent CO2 Emissions, N.A.	3723.7	1489.5
Emissions, Europe	3713.6	1485.4
Emissions, Japan	3718.0	1487.2

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.22. In-line metal cleaning system - CFC-113 operating mode (low boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	3.0			HCFC-	7.1 (g)	0.00	0.88 (h)			
Rinse	17.1			141b						
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	48.2							1.9		
TOTAL	68.3	0.0	0.0		7.1	0.0	0.9	1.9		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	150 (e)	0.67	500 year GWP= 150 (e)	
Equivalent CO2 Emissions, N.A.	45.8	0.0	0.0		3.6 (d)	0.0	131.3	1.2	181.9	72.8
Emissions, Europe	34.8	0.0	0.0		3.6 (d)	0.0	131.3	1.2	171.0	68.4
Emissions, Japan	39.6	0.0	0.0		3.6 (d)	0.0	131.3	1.2	175.7	70.3

	100 year GWP= 440 (e)	
Equivalent CO2 Emissions, N.A.	435.6	174.3
Emissions, Europe	424.7	169.9
Emissions, Japan	429.5	171.8

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.23. In-line metal cleaning system - HCFC-141b, operating mode (low boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	3.0			HCFC-	8.8 (g)	0.00	0.88 (h)			
Rinse	19.1			225ca						
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	39.0							3.4		
TOTAL	61.1	0.0	0.0		8.8	0.0	0.9	3.4		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	55 (e)	0.67	500 year GWP= 55 (e)	
Equivalent CO2 Emissions, N.A.	40.9	0.0	0.0		4.5 (d)	0.0	48.1	2.2	95.8	38.3
Emissions, Europe	31.1	0.0	0.0		4.5 (d)	0.0	48.1	2.2	86.0	34.4
Emissions, Japan	35.4	0.0	0.0		4.5 (d)	0.0	48.1	2.2	90.3	36.1

	100 year GWP= 162 (e)	
Equivalent CO2 Emissions, N.A.	189.4	75.8
Emissions, Europe	179.6	71.9
Emissions, Japan	183.9	73.6

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.24a. In-line metal cleaning system - HCFC-225ca, operating mode (low boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	3.0			HCFC-	8.7 (g)	0.00	0.88 (h)			
Rinse	20.7			225cb						
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	39.2							3.7		
TOTAL	62.9	0.0	0.0		8.7	0.0	0.9	3.7		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	230 (e)	0.67	500 year GWP= 230 (e)	
Equivalent CO2 Emissions, N.A.	42.1	0.0	0.0		4.5 (d)	0.0	201.3	2.5	250.4	100.1
Emissions, Europe	32.1	0.0	0.0		4.5 (d)	0.0	201.3	2.5	240.3	96.1
Emissions, Japan	36.5	0.0	0.0		4.5 (d)	0.0	201.3	2.5	244.7	97.9

	100 year GWP= 680 (e)	
Equivalent CO2 Emissions, N.A.	644.1	257.6
Emissions, Europe	634.0	253.6
Emissions, Japan	638.4	255.4

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.24b. In-line metal cleaning system - HCFC-225cb, operating mode (low boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	3.0			HCFC-123	8.2 (g)	0.00	0.88 (h)			
Rinse	14.6									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	44.8							1.5		
TOTAL	62.4	0.0	0.0		8.2	0.0	0.9	1.5		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	29 (e)	0.67	500 year GWP= 29 (e)	
Equivalent CO2 Emissions, N.A.	41.8	0.0	0.0		4.2 (d)	0.0	25.4	1.0	72.4	28.9
Emissions, Europe	31.8	0.0	0.0		4.2 (d)	0.0	25.4	1.0	62.4	24.9
Emissions, Japan	36.2	0.0	0.0		4.2 (d)	0.0	25.4	1.0	66.7	26.7

	100 year GWP= 85 (e)	
Equivalent CO2 Emissions, N.A.	121.4	48.5
Emissions, Europe	111.4	44.5
Emissions, Japan	115.7	46.3

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.24c. In-line metal cleaning system - HCFC-123, operating mode (low boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	3.0			1,1,1	7.4 (g)	0.00	0.88 (h)			
Rinse	32.2									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	27.0							5.2		
TOTAL	62.2	0.0	0.0		7.4	0.0	0.9	5.2		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	34 (e)	0.67	500 year GWP= 34 (e)	
Equivalent CO2 Emissions, N.A.	41.7	0.0	0.0		3.8 (d)	0.0	29.8	3.5	78.7	31.5
Emissions, Europe	31.7	0.0	0.0		3.8 (d)	0.0	29.8	3.5	68.8	27.5
Emissions, Japan	36.1	0.0	0.0		3.8 (d)	0.0	29.8	3.5	73.1	29.3

	100 year GWP= 100 (e)	
Equivalent CO2 Emissions, N.A.	136.5	54.6
Emissions, Europe	126.5	50.6
Emissions, Japan	130.9	52.4

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.25. In-line metal cleaning system - 1,1,1 trichloroethane, operating mode (high boiling point solvent).

2.50 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
Wash	3.0			TCE	8.3 (g)	0.88 (h)	0.0			
Rinse	38.7									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	30.2							5.7		
TOTAL	71.9	0.0	0.0		8.3	0.9	0.0	6.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0.67 (e)	0	0.67	500 year GWP= 0.67 (e)	
Equivalent CO2 Emissions, N.A.	48.2	0.0	0.0		4.3 (d)	0.6	0.0	4.2	57.3	22.9
Emissions, Europe	36.7	0.0	0.0		4.3 (d)	0.6	0.0	4.2	45.8	18.3
Emissions, Japan	41.7	0.0	0.0		4.3 (d)	0.6	0.0	4.2	50.8	20.3

	100 year GWP= 0.67 (e)	
Equivalent CO2 Emissions, N.A.	57.3	22.9
Emissions, Europe	45.8	18.3
Emissions, Japan	50.8	20.3

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement twice per week (ADL estimate)
(h) see Appendix D

Fig. Y.26. In-line metal cleaning system - trichloroethylene, operating mode (high boiling point solvent).

2.5 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	32.4			detergent	0.20 (b)	0.00	0.00			
Rinse	32.4									
Dry	27.2									
Exhaust	2.6									
Pretreatment (g)	0.0									
Waste Treatment	0.0									
Other	0.3							2.8		
TOTAL	94.9	0.0	0.0		0.2	0.0	0.0	2.8		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	0	0.67	500 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	63.6	0.0	0.0		0.0 (d)	0.0	0.0	1.9	65.5	26.2
Emissions, Europe	48.4	0.0	0.0		0.0 (d)	0.0	0.0	1.9	50.3	20.1
Emissions, Japan	55.0	0.0	0.0		0.0 (d)	0.0	0.0	1.9	56.9	22.8

	100 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	65.5	26.2
Emissions, Europe	50.3	20.1
Emissions, Japan	56.9	22.8

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate based on engineering judgement
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) GWP of detergent is 0.0 in 100 year time frame (ADL est.)
(f) auxilliary energy needed to condition shop space (ADL est.)
(g) no consideration for pretreatment

Fig. Y.27. In-line metal cleaning system, operating mode (aqueous system).

2.5 te/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other(f) (kWh/h)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ te steel)
				Name	(kg/hr)					
Wash	7.5			AXAREL	0.60 (g)	0.38 (h)	0.00			
Rinse	50.9									
Dry	24.3									
Exhaust	2.6									
Pretreatment (i)	0.0									
Waste Treatment	0.0									
Other	0.3							2.8		
TOTAL	85.6	0.0	0.0		0.6	0.4	0.0	2.8		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	2.4 (e)	0	0.67	500 year GWP= 2.4 (e)	
Equivalent CO2 Emissions, N.A.	57.4	0.0	0.0		0.3 (d)	0.9	0.0	1.9	60.4	24.2
Emissions, Europe	43.7	0.0	0.0		0.3 (d)	0.9	0.0	1.9	46.7	18.7
Emissions, Japan	49.6	0.0	0.0		0.3 (d)	0.9	0.0	1.9	52.7	21.1

	100 year GWP= 6.4 (e)	
Equivalent CO2 Emissions, N.A.	61.9	24.8
Emissions, Europe	48.2	19.3
Emissions, Japan	54.2	21.7

(a) kg CO2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate based on engineering judgement
(c) 0.000050 kg CO2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced *0.000050*3600 kJ/kWh
(e) see Appendix E
(f) auxilliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement every week (ADL estimate)
(h) Osterman, 1990, Jan. 24
(i) no consideration for pretreatment

Fig. Y.28. In-line metal cleaning system, operating mode (semi-aqueous system).

Station/ Component	Operating Power (kWh/h)				
Wash	CFC-113	HCFC-141b	HCFC-123	HCFC225ca	HCFC-225cb
Heater, 3 kW	0.2 (f)*	0.2	0.2	0.2	0.2
Pump, 1.5 HP (45 gpm, 30 psi)	1.3 (c)	1.3	1.3	1.3	1.3
Heater, 3 kW	0.2 (f)*	0.2	0.2	0.2	0.2
Pump, 1.5 HP (45 gpm, 30 psi)	1.3 (c)	1.3	1.3	1.3	1.3
Total, Wash	3.0	3.0	3.0	3.0	3.0
Rinse					
Heater	18.9 (c)*	17.1	14.6	19.1	20.7
Total, Rinse	18.9	17.1	14.6	19.1	20.7
Dry					
Total, Dry	0.0	0.0	0.0	0.0	0.0
Exhaust					
Total, Exhaust	0.0	0.0	0.0	0.0	0.0
Waste Treatment					
Total, Waste Treat.	0.0	0.0	0.0	0.0	0.0
Other					
Chiller	6.9 (a)*	8.2	7.6	6.5	6.6
Chiller, low temp., 1 HP**	1.7 (a)*	1.7	1.7	1.7	1.7
Still, 60 gal/hr	30.8 (c)*	36.7	33.9	29.1	29.3
Cooling Tower	1.3 (d)*	1.3	1.3	1.3	1.3
Conveyor, 0.3 HP	0.3 (c)	0.3	0.3	0.3	0.3
Total, Other	41.0	48.2	44.8	39.0	39.2
TOTAL, SYSTEM	62.9	68.3	62.4	61.1	62.9
kg CO2, operating	16.85	18.31	16.7	16.4	16.8
KW idling	60.0	65.4	59.5	58.2	60.0

Basis: 2.5 te/hr (see text)
(a) Osterman, 1991, Feb. 13
(b) Allied, 1990, CBC-18LE product literature
(c) ADL estimate based on engineering judgement
(d) Osterman, 1991, March 6
(e) Osterman, 1991, April 9
* included in idling mode
** included in downtime mode

Fig. Y.29. Energy use breakdown, operating mode, in-line metal cleaning systems (low boiling point solvents).

Station/ Component	Operating Power (kWh/h)	
Wash	1,1,1	TCE
Heater, 3 kW	0.2 (f)*	0.2
Pump, 1.5 HP (45 gpm, 30 psi)	1.3 (c)	1.3
Heater, 3 kW	0.2 (f)*	0.2
Pump, 1.5 HP (45 gpm, 30 psi)	1.3 (c)	1.3
Total, Wash	3.0	3.0
Rinse		
Heater, boil	32.2 (e)*	38.7
Total, Rinse	32.2	38.7
Dry		
Total, Dry	0.0	0.0
Exhaust		
Total, Exhaust	0.0	0.0
Waste Treatment		
Total, Waste Treatment	0.0	0.0
Other		
Chiller,low temp.,1 HP **	1.7 (a)*	1.7
Cooling Tower	0.9 (d)*	0.9
Still, 60 gal/hr	24.1 (c)*	27.3
Conveyor, 0.3 HP	0.3 (c)	0.3
Total, Other	27.0	30.2
TOTAL, SYSTEM	62.2	71.9
kg CO2, operating	16.67	19.27
kW idling	59.3	69.0

Basis: 2.5 te/hr (see text)
(a) Osterman, 1991, Feb. 13
(b) Allied, 1990, CBC-18LE product literature
(c) ADL estimate based on engineering judgement
(d) Osterman, 1991, March 6
(e) ADL estimate based on about 4 times solvent rate condensed on parts
(f) Osterman, 1991, April 9
* = included in idling mode
** = included in downtime mode

Fig. Y.30. Energy use breakdown, operating mode in-line metal cleaning system (high boiling solvents).

Station/ Component	Operating Power (kWh/h)
Wash	
Heater, 40 kW	28.0 (a)*
Pump, 5 HP	4.4 (a)
Total, Wash	32.4
Rinse	
Heater, 40 kW	28.0 (a)*
Pump, 5 HP	4.4 (a)
Total, Rinse	32.4
Dry	
Blower, blowoff, 7.5 HP	6.6 (a)
Heater, 20 kW	14.0 (a)
Blower, 7.5 HP	6.6 (a)
Total, Dry	27.2
Exhaust	
Blower, 3 HP	2.6 (d)*
Total, Exhaust	2.6
Waste Treatment	
Total, Waste Treatment	0.0 (c)
Other	
Conveyor, 0.3 HP	0.3 (b)
Total, Other	0.3
TOTAL, SYSTEM	94.9

Basis: Stoelting BBW series washer, 4.5 feet per minute, 2.5 te/hr

(a) Kneen, 1991, March 12

(b) ADL estimate based on engineering judgement

(c) water separation powered by wash pump

(d) ADL estimate based on Eltech visit

* = included in idling mode

Fig. Y.31. Energy use breakdown, operating mode in-line metal cleaning (aqueous system).

Station/ Component	Operating Power (kWh/h)
Wash	
Heat Pump, 1.5 HP	2.2 (b)
Pump, 2 @ 3 HP	5.3 (a)
Compressed Air, 5 HP, 20 cfm, 40 psi	4.4 (c)
Total, Wash	7.5
Rinse	
Heater, 15 kW	12.9 (c)*
Heater, 2 @ 18 kW	30.1 (c)
Pump, 3 @ 3 HP	7.9 (a)
Total, Rinse	50.9
Dry	
Heater, 12 kW	12.0 (a)
Blowers, air knife, 2 @ 7 HP	12.3 (a)
Total, Dry	24.3
Exhaust	
Blower, 3 HP	2.6 (e)*
Total, Exhaust	2.6
Waste Treatment	
Total, Waste Treatment	0.0 (d)
Other	
Conveyor, 0.3 HP	0.3 (c)
Total, Other	0.3
TOTAL, SYSTEM	85.6

Basis: Corpane model SAI18RD with AXAREL 52, 4.5 feet per minute
2.5 te/hr
(a) Kalmbach, 1991, March 12
(b) Kalmbach, 1991, March 13
(c) ADL estimate based on engineering judgement
(d) water separation powered by wash pump
(e) ADL estimate based on Eltech visit
* = included in operating mode

Fig. Y.32. Energy use breakdown, operating mode in-line metal cleaning system (semi-aqueous system.)

APPENDIX Z: ELECTRONICS CLEANING: ENERGY AND CO_2 EMISSIONS

This appendix includes background data for batch and in-line electronics cleaning systems modeled in Appendices U and W. The methodology for determining the Total Equivalent Warming Impact (kg equivalent CO_2) of the systems is described in Section 11. Results are presented in two subsections:

- Appendix Z.1 for batch systems
- Appendix Z.2 for in-line systems

In each of these subsections the information is presented in hierarchical order, namely:

- *Level 1*: at this level a comparative overview is presented of the global warming impact of the various systems
- *Level 2*: this level backs up the information provided in Level 1 and shows the various contributions to the global warming impact from energy use, solvent emissions, embodied in energy materials consumed, etc.
- *Level 3*: this level backs up Level 2 by disaggregating the energy uses in a given machine (heating, drying, cooling, etc.). The model systems consider low boiling solvents, high boiling solvents, aqueous and semi-aqueous systems.

Z.1 BATCH MACHINES

Appendix Z.1 includes information regarding batch electronics cleaning systems. Figure Z.1 shows the absolute TEWI for each system using 500 year GWP's; data used to create this figure is shown in Fig. Z.1.4 in the rows marked "composite". Note that the contribution to TEWI from energy comprises the bottom portion of each bar. Figure Z.2 shows the TEWI of each system relative to the CFC-113 baseline system. Figure Z.3 shows the absolute TEWI of the BACT systems using 500 year GWP's as compared to baseline CFC-113 systems, based on the energy and emissions savings shown in Table AB.1.

Figure Z.4 is a table showing kg of equivalent CO_2 per square meter of PC board throughput using 500 year GWP's in the operating mode, idling mode, downtime mode, and composite. Values for the operating mode are derived from Figs. Z.6 to Z.13. Energy and emissions values per square meter of total daily operating mode throughput for the idling mode are determined as below (using batch electronic CFC-113 as an example).

Energy:

- Total operating mode daily throughput is 10 m^2/operating hour times 12 operating hours = 120 m^2
- Equivalent CO_2 during idling mode is 17.4 kWh/idling hour (Fig. Z.13) times 0.67 kg CO_2/kWh x 4 idling hours = 46.6 kg CO_2
- Ilding mode CO_2 per daily throughput is 46.6 kg CO_2 ÷ 120 m^2 = 0.39 kg CO_2/m^2 = 8.6 kg CO_2/tonne

Emissions:

- Equivalent CO_2 due to solvent emissions during the idling mode is 0.127 kg solvent/hr (Table Q.4) times 2100 kg CO_2/kg 113 (Table R.1) times 4 hrs in idling mode = 1066.8 kg CO_2

- The equivalent CO_2 per tonne of metal processed is 1066.8 kg CO_2 + 120 m^2 = 197.6 kg CO_2/m^2

The same procedure is followed to calculate equivalent CO_2 per m^2 values for energy and emissions in the downtime mode.

Composite values are determined by summing the operating, idling, and downtime mode values.

Figure Z.5 is similar to Fig. Z.4 except GWP values for the 100 year time horizon are used.

The Level 2 tables show total energy use, chemicals consumed, and emissions for each system in operating mode. Equivalent kg of CO_2 emitted are shown both for each system and per m^2 of PCM cleaned in Figs. Z.6 to Z.13.

The Level 3 tables detailing the energy use for each system are found in Figs. Z.14 to Z.17. The total energy contribution of each component in the system is listed here (note that these total values back up the "Electric Energy" column of in Figs. Z.6 to Z.13).

Z.2 IN-LINE MACHINES

Appendix Z.2 uses the same format for in-line electronic cleaning systems and there is complete parallelism in the cases examined as shown in Table Z.1.

The model machine was thought of as one having the following major heat sinks: heating the PCBs, vaporizing solvent, solvent condensation, and control of vapor emissions. The energy involved in the drive mechanisms is small and the system process steps include:

1) Heating in a vapor zone

2) An immersion wash

3) A vapor rinse

4) A second immersion

5) A second vapor rinse evaporation step

Table Z.1. Figures and tabular values for electronic cleaning

	Batch	In-Line
Comparative TEWI (bar graphs)		
TEWI for systems (500 year GWP)	Z.1	Z.18
TEWI relative to baseline CFC-113 systems (500 year GWP)	Z.2	Z.19
TEWI for BACT compared to baseline CFC-113 system (500 year GWP)	Z.3	Z.20
Comparative Level 1 tabular values (by mode) of Total Equivalent Warming Impact		
500 year GWP	Z.4	Z.21
100 year GWP	Z.5	Z.22
Total Equivalent Warming Impact in Operating Mode (Level 2)		
CFC-113	Z.6	Z.23
HCFC-141b	Z.7	Z.24
HCFC-225ca	Z.8	Z.25
HCFC-225cb	Z.9	Z.26
HCFC-123	Z.10	Z.27
1,1,1 Trichloroethane	Z.11	Z.28
Aqueous (tank)	Z.12	Z.29
Semi-Aqueous	Z.13	Z.30
Energy Use breakdown (Level 3; operating mode)		
Low boiling solvents	Z.14	Z.31
High boiling solvents	Z.15	Z.32
Aqueous	Z.16	Z.33
Semi-Aqueous	Z.17	Z.34

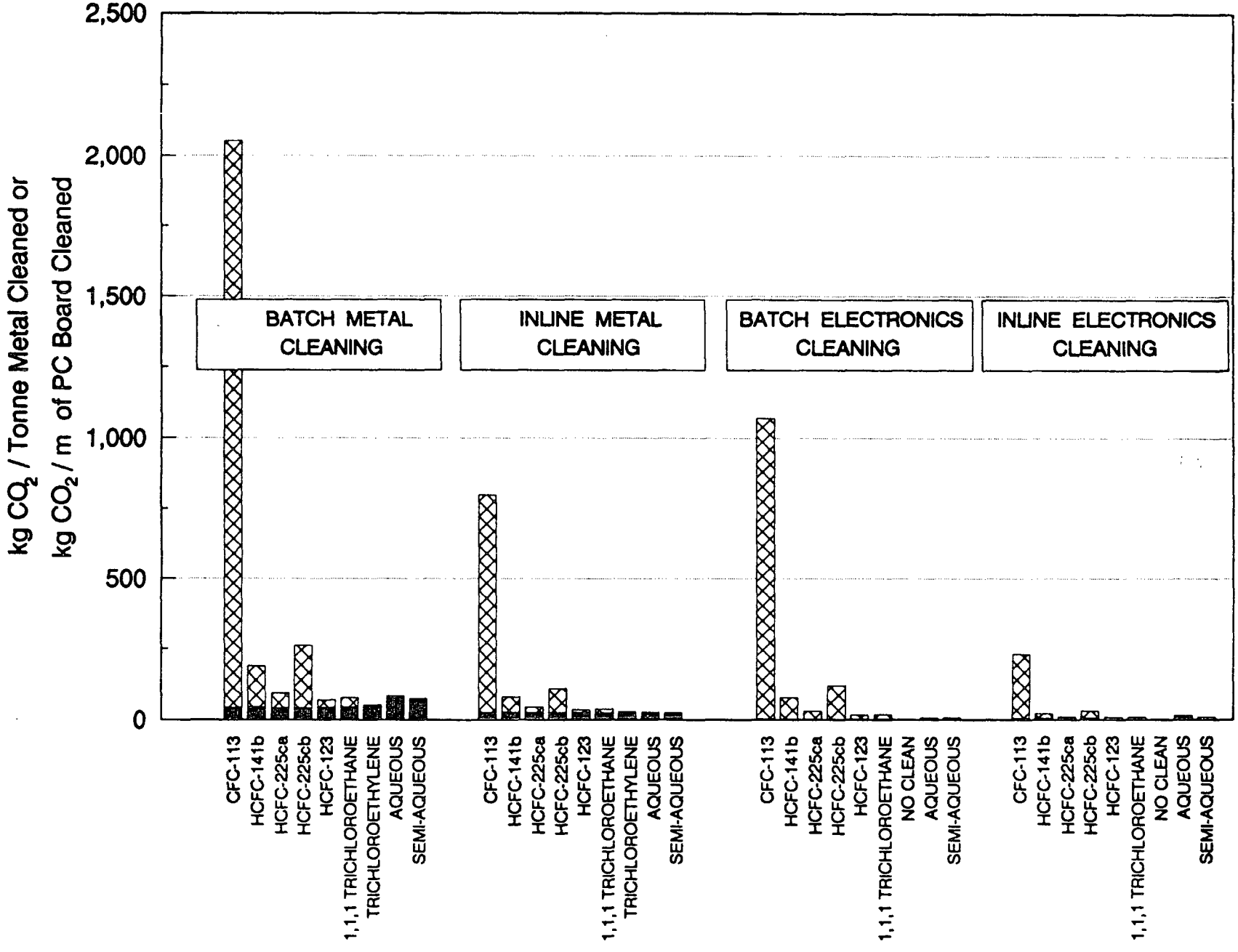


Fig. Z.1. TEWI of baseline technologies (500 year GWP).

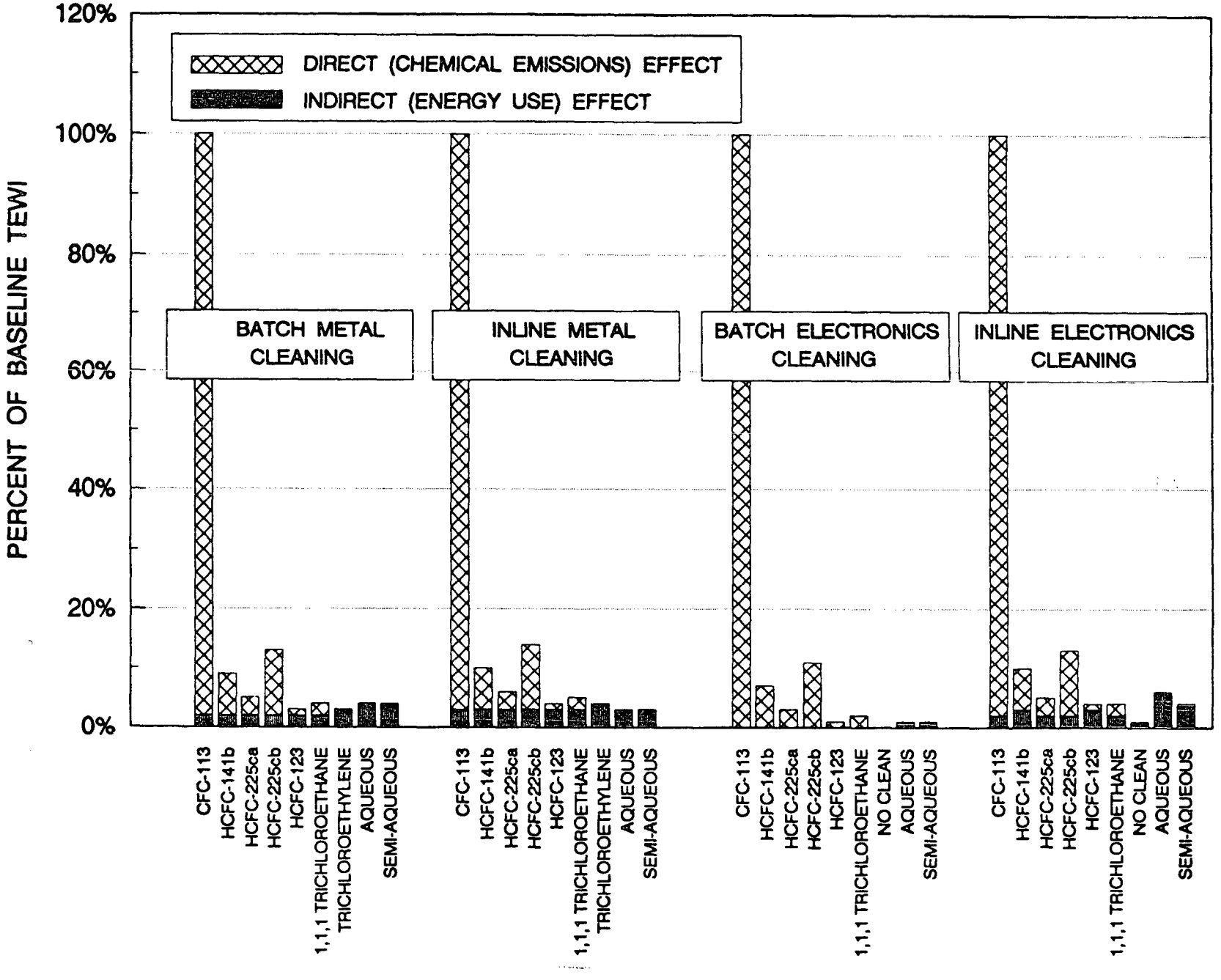


Fig. Z.2. Relative TEWI of baseline technologies (500 year GWP).

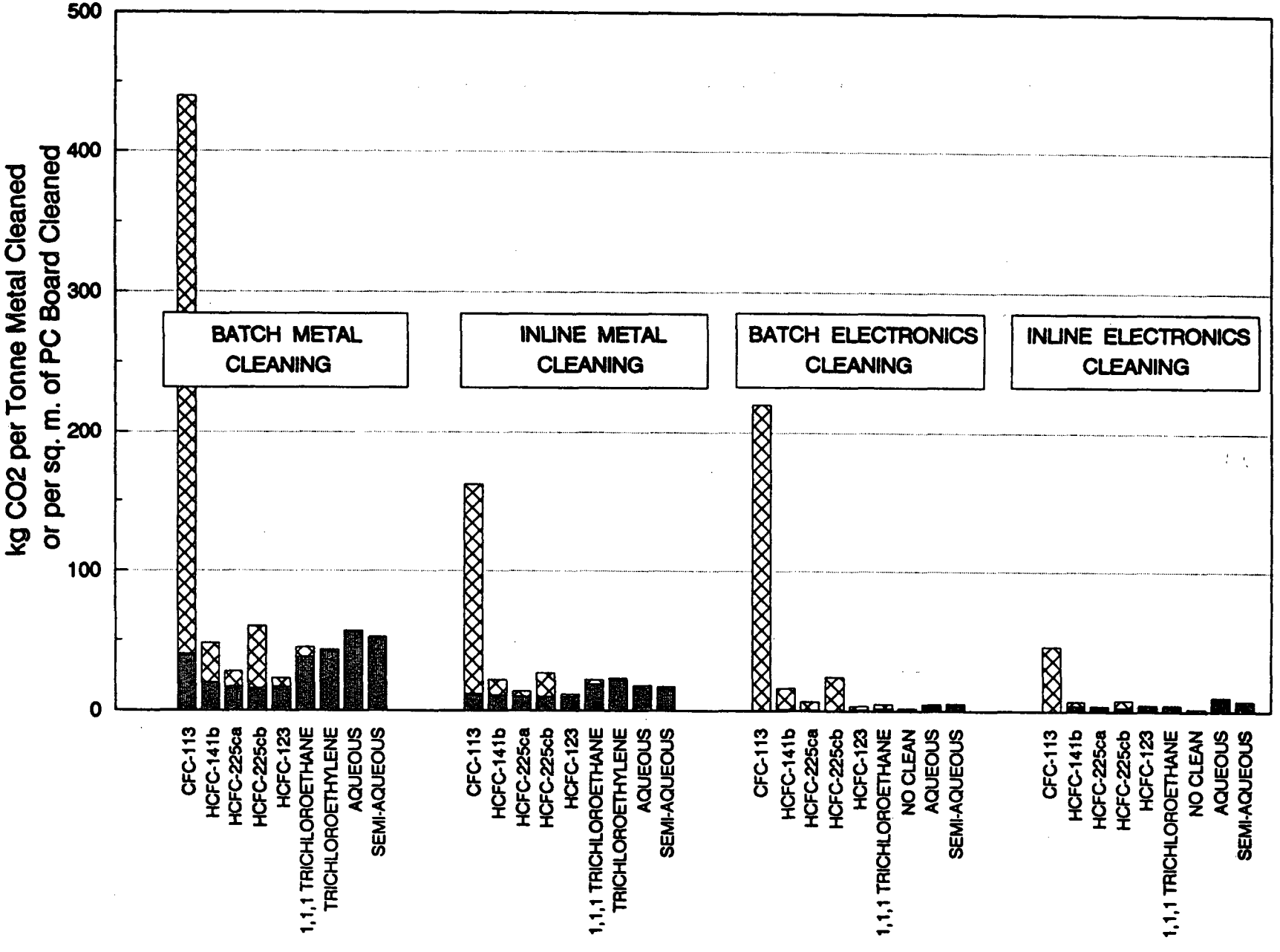


Fig. Z.3. TEWI of BACT (500 year GWP).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	AQ	SAQ
Operating: 12 Hours								
Energy consumed in cleaning process	1.23	1.35	1.19	1.20	1.25	1.31	7.07	6.29
Embodied energy in solvent chemicals	0.29	0.28	0.29	0.29	0.29	0.28	0.00	0.10
Auxilliary processes**	0.08	0.07	0.09	0.09	0.06	0.11	0.48	0.48
Solvent emissions	1050.00	75.00	27.50	115.00	14.50	17.00	0.00	0.36
Total Operating	1051.60	76.70	29.07	116.58	16.10	18.70	7.55	7.23
Idling: 4 hours								
Energy consumed in cleaning process	0.39	0.43	0.38	0.38	0.40	0.42	0.36	0.17
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.00
Solvent emissions	8.89	0.64	0.23	0.97	0.12	0.14	0.00	0.04
Total Idling	9.30	1.09	0.63	1.37	0.54	0.58	0.36	0.21
Downtime: 8 hours								
Energy consumed in cleaning process	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.04	0.04	0.04	0.04	0.04	0.04	0.00	0.00
Solvent emissions	10.64	0.76	0.28	1.17	0.15	0.17	0.00	0.00
Total Downtime	10.75	0.87	0.39	1.28	0.26	0.28	0.00	0.00
Composite: kg eq. CO2/m2 board cleaned								
Energy consumed in cleaning process	1.69	1.85	1.64	1.65	1.72	1.80	7.43	6.46
Embodied energy in solvent chemicals	0.29	0.28	0.29	0.29	0.29	0.28	0.00	0.10
Auxilliary processes	0.14	0.13	0.15	0.15	0.12	0.17	0.48	0.48
Solvent emissions	1069.53	76.40	28.01	117.14	14.77	17.32	0.00	0.40
TOTAL	1071.65	78.66	30.09	119.23	16.90	19.56	7.91	7.44

** additional HVAC requirements due to cleaning system

Fig. Z.4. Batch electronics cleaning processes, 500 year time horizon (kg equivalent CO_2/m^2 board).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	AQ	SAQ
Operating: 12 Hours								
Energy consumed in cleaning process	1.23	1.35	1.19	1.20	1.25	1.31	7.07	6.29
Embodied energy in solvent chemicals	0.29	0.28	0.29	0.29	0.29	0.28	0.00	0.10
Auxilliary processes**	0.08	0.07	0.09	0.09	0.06	0.11	0.48	0.48
Solvent emissions	2100.00	220.00	81.00	340.00	42.50	50.00	0.00	0.96
Total Operating	2101.60	221.70	82.57	341.58	44.10	51.70	7.55	7.83
Idling: 4 hours								
Energy consumed in cleaning process	0.39	0.43	0.38	0.38	0.40	0.42	0.36	0.17
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.00
Solvent emissions	17.78	1.86	0.69	2.88	0.36	0.42	0.00	0.01
Total Idling	18.19	2.31	1.08	3.28	0.78	0.86	0.36	0.18
Downtime: 8 hours								
Energy consumed in cleaning process	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.04	0.04	0.04	0.04	0.04	0.04	0.00	0.00
Solvent emissions	21.28	2.23	0.82	3.45	0.43	0.51	0.00	0.01
Total Downtime	21.39	2.34	0.93	3.56	0.54	0.62	0.00	0.01
Composite: kg eq. CO2/m2 board cleaned								
Energy consumed in cleaning process	1.69	1.85	1.64	1.65	1.72	1.80	7.43	6.46
Embodied energy in solvent chemicals	0.29	0.28	0.29	0.29	0.29	0.28	0.00	0.10
Auxilliary processes	0.14	0.13	0.15	0.15	0.12	0.17	0.48	0.48
Solvent emissions	2139.06	224.09	82.51	346.32	43.29	50.93	0.00	0.98
TOTAL	2141.18	226.35	84.58	348.41	45.42	53.18	7.91	8.03

** additional HVAC requirements due to cleaning system

Fig. Z.5. Batch electronics cleaning processes, 100 year time horizon (kg equivalent CO_2/m^2 board).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	12.2			CFC-113	5.6 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.7							1.2 (f)		
TOTAL	18.3	0.0	0.0		5.6	0.0	5.0	0.5		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	2100 (e)	0.67	500 year GWP= 2100 (e)	
Equivalent CO2 Emissions, N.A.	12.3	0.0	0.0		2.9 (d)	0.0	10500.0	0.4	10515.5	1051.6
Emissions, Europe	9.4	0.0	0.0		2.9 (d)	0.0	10500.0	0.3	10512.5	1051.3
Emissions, Japan	10.6	0.0	0.0		2.9 (d)	0.0	10500.0	0.3	10513.8	1051.4

	100 year GWP= 4200 (e)	
Equivalent CO2 Emissions, N.A.	21015.5	2101.6
Emissions, Europe	21012.5	2101.3
Emissions, Japan	21013.8	2101.4

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 6 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.6. Batch electronics cleaning system - CFC-113, operating mode (low boiling point solvent).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	13.2			HCFC-141b	5.5 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	6.5							1.0 (f)		
TOTAL	20.1	0.0	0.0		5.5	0.0	5.0	0.5		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	150 (e)	0.67	500 year GWP= 150 (e)	
Equivalent CO2 Emissions, N.A.	13.5	0.0	0.0		2.8 (d)	0.0	750.0	0.3	766.6	76.7
Emissions, Europe	10.3	0.0	0.0		2.8 (d)	0.0	750.0	0.2	763.3	76.3
Emissions, Japan	11.7	0.0	0.0		2.8 (d)	0.0	750.0	0.3	764.7	76.5

	100 year GWP= 440 (e)	
Equivalent CO2 Emissions, N.A.	2216.6	221.7
Emissions, Europe	2213.3	221.3
Emissions, Japan	2214.7	221.5

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 6 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.7. Batch electronics cleaning system - HCFC-141b, operating mode (low boiling point solvent).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	11.8			HCFC-225ca	5.6 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.5							1.3 (f)		
TOTAL	17.7	0.0	0.0		5.6	0.0	5.0	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	55 (e)	0.67	500 year GWP= 55 (e)	
Equivalent CO2 Emissions, N.A.	11.9	0.0	0.0		2.9 (d)	0.0	275.0	0.9	290.6	29.1
Emissions, Europe	9.0	0.0	0.0		2.9 (d)	0.0	275.0	0.7	287.6	28.8
Emissions, Japan	10.3	0.0	0.0		2.9 (d)	0.0	275.0	0.8	288.9	28.9

	100 year GWP= 162 (e)	
Equivalent CO2 Emissions, N.A.	825.6	82.6
Emissions, Europe	822.6	82.3
Emissions, Japan	823.9	82.4

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 6 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.8. Batch electronics cleaning system - HCFC-225ca, operating mode (low boiling point solvent).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	12.0			HCFC-225cb	5.6 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	5.5							1.3 (f)		
TOTAL	17.9	0.0	0.0		5.6	0.0	5.0	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	230 (e)	0.67	500 year GWP= 230 (e)	
Equivalent CO2 Emissions, N.A.	12.0	0.0	0.0		2.9 (d)	0.0	1150.0	0.9	1165.8	116.6
Emissions, Europe	9.1	0.0	0.0		2.9 (d)	0.0	1150.0	0.7	1162.7	116.3
Emissions, Japan	10.4	0.0	0.0		2.9 (d)	0.0	1150.0	0.8	1164.1	116.4

	100 year GWP= 680 (e)	
Equivalent CO2 Emissions, N.A.	3415.8	341.6
Emissions, Europe	3412.7	341.3
Emissions, Japan	3414.1	341.4

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 6 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.9. Batch electronics cleaning system - HCFC-225cb, operating mode (low boiling point solvent).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	12.1			HCFC-123	6.10 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	6.1							0.9 (f)		
TOTAL	18.6	0.0	0.0		6.1	0.0	5.0	0.9		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	29 (e)	0.67	500 year GWP= 29 (e)	
Equivalent CO2 Emissions, N.A.	12.5	0.0	0.0		3.1 (d)	0.0	145.0	0.6	161.2	16.1
Emissions, Europe	9.5	0.0	0.0		3.1 (d)	0.0	145.0	0.4	158.1	15.8
Emissions, Japan	10.8	0.0	0.0		3.1 (d)	0.0	145.0	0.5	159.4	15.9

	100 year GWP= 85 (e)	
Equivalent CO2 Emissions, N.A.	441.2	44.1
Emissions, Europe	438.1	43.8
Emissions, Japan	439.4	43.9

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 6 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.10. Batch electronics cleaning system - HCFC-123, operating mode (low boiling point solvent).

10.0 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	17.4			1,1,1	6.10 (g)	0.00	5.00 (h)			
Rinse	0.1									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.3									
Other	1.7							0.9 (f)		
TOTAL	19.5	0.0	0.0		6.1	0.0	5.0	0.9		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	34 (e)	0.67	500 year GWP= 34 (e)	
Equivalent CO2 Emissions, N.A.	13.1	0.0	0.0		3.1 (d)	0.0	170.0	0.6	186.8	18.7
Emissions, Europe	9.9	0.0	0.0		3.1 (d)	0.0	170.0	0.4	183.5	18.4
Emissions, Japan	11.3	0.0	0.0		3.1 (d)	0.0	170.0	0.5	184.9	18.5

	100 year GWP= 100 (e)	
Equivalent CO2 Emissions, N.A.	516.8	51.7
Emissions, Europe	513.5	51.4
Emissions, Japan	514.9	51.5

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + sump replacement every 5 weeks (ADL estimate)
(h) see Appendix Q

Fig. Z.11. Batch electronics cleaning system - 1,1,1 trichloroethane operating mode (high boiling point solvent.)

1.8 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr	TOTAL (kg CO2/ m2 board)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	2.1			detergent	0.10 (g)	0.00	0.00			
Rinse	8.0									
Dry	8.4									
Exhaust	0.4									
Pretreatment (h)	0.0									
Waste Treatment	0.0									
Other	0.1							1.3		
TOTAL	19.0	0.0	0.0		0.1	0.0	0.0	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	0	0.67	500 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	12.7	0.0	0.0		0.0 (d)	0.0	0.0	0.9	13.6	7.6
Emissions, Europe	9.7	0.0	0.0		0.0 (d)	0.0	0.0	0.7	10.4	5.8
Emissions, Japan	11.0	0.0	0.0		0.0 (d)	0.0	0.0	0.8	11.8	6.5

	100 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	13.6	7.6
Emissions, Europe	10.4	5.8
Emissions, Japan	11.8	6.5

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) change tank once per week (ADL estimate)
(h) no consideration for pretreatment

Fig. Z.12. Batch electronics cleaning system - operating mode (aqueous system).

1.8 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	0.3			AXAREL	0.37 (g)	0.27 (h)	0.00			
Rinse	7.7			38						
Dry	8.4									
Exhaust	0.4									
Pretreatment (i)	0.0									
Waste Treatment	0.0									
Other	0.1							1.3 (f)		
TOTAL	16.9	0.0	0.0		0.4	0.3	0.0	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	2.4 (e)	0	0.67	500 year GWP= 2.4 (e)	
Equivalent CO2 Emissions, N.A.	11.3	0.0	0.0		0.1 (d)	0.6	0.0	0.9	12.9	7.2
Emissions, Europe	8.6	0.0	0.0		0.1 (d)	0.6	0.0	0.7	10.0	5.6
Basis: Crest system	9.8	0.0	0.0		0.1 (d)	0.6	0.0	0.8	11.3	6.3

	100 year GWP= 6.4 (e)	
Equivalent CO2 Emissions, N.A.	14.0	7.8
Emissions, Europe	11.1	6.2
Emissions, Japan	12.4	6.9

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)

(g) dragout + change immersion pump every 3 months (ADL estimate)
(h) 0.15 kg solvent/m^2 board (Hamblett, 1990)

Fig. Z.13. Batch electronics cleaning system - CFC-113, operating mode (semi-aqueous system).

Station/ Component	Operating Power (kWh/h)				
Wash	113	141b	123	225ca	225cb
Heater, 7.6 kW	11.6 (a)*	12.6	11.5	11.2	11.4
Ultrasonics, 1.2 kW	0.6 (b)	0.6	0.6	0.6	0.6
Total, Wash	12.2	13.2	12.1	11.8	12.0
Rinse					
Pump, 0.3 HP, spray	0.1 (b)	0.1	0.1	0.1	0.1
Total, Rinse	0.1	0.1	0.1	0.1	0.1
Dry					
Total, Dry	0.0	0.0	0.0	0.0	0.0
Exhaust					
Total, Exhaust	0.0	0.0	0.0	0.0	0.0
Waste Treatment					
Pump, 0.3 HP	0.3 (b)*	0.3	0.3	0.3	0.3
Total, Waste Treatment	0.3	0.3	0.3	0.3	0.3
Other					
Chiller	4.0 (d)*	4.8	4.4	3.8	3.8
Chiller, low temp. 0.75 HP**	1.5 (e)*	1.5	1.5	1.5	1.5
Hoist, 0.2 HP	0.2 (d)	0.2	0.2	0.2	0.2
Total, Other	5.7	6.5	6.1	5.5	5.5
TOTAL, SYSTEM	18.3	20.1	18.6	17.7	17.9
kg CO2, operating	1.23	1.35	1.25	1.19	1.20
kW, idling	17.4	19.2	17.7	16.8	17.0

Basis: Baron Blakeslee MSR-280 LE and Branson BSD 2024 low, 10.0 m2/hr

(a) Allied-Signal, 1990, MSR-LE product lit. and Branson, 1988, Bulletin S-984.

(b) Polhamus, 1991, March 20

(c) Branson, 1988, Bulletin S-987

(d) ADL estimate based on engineering judgement

(e) Allied, 1990, Vaportrap product literature

* = included in idling mode

** = included in downtime mode

Fig. Z.14. Energy use breakdown, operating mode batch electronics cleaning system (low boiling point solvents).

Station/ Component	Operating Power (kWh/h)
Wash	1,1,1
Heater, 7.6 kW	16.8 (a)*
Ultrasonics, 1.2 kW	0.6 (b)
Total, Wash	17.4
Rinse	
Pump, 0.3 HP, spray	0.1 (b)
Total, Rinse	0.1
Dry	
Total, Dry	0.0
Exhaust	
Total, Exhaust	0.0
Waste Treatment	
Pump, 0.3 HP	0.3 (b)*
Total, Waste Treatment	0.3
Other	
Chiller, Low Temp **	1.5 (c)*
Hoist, 0.2 HP	0.2 (d)
Total, Other	1.7
TOTAL, SYSTEM	19.5
kg CO2, operating	1.31
kW, idling	18.6

Basis: Baron Blakeslee MSR-280 LE and Branson BSD 2024, 10.0 m2/hr

(a) Allied-Signal, 1990, MSR-LE product lit. and Branson, 1988, Bulletin S-984.

(b) Polhamus, 1991, March 20

(c) Allied, 1990, Vaportrap product literature

(d) ADL estimate based on engineering judgement

* = included in idling mode

** = included in downtime mode

Fig. Z.15. Energy use breakdown, operating mode batch electronics cleaning system (high boiling point solvents).

Station/ Component	Operating Power (kWh/h)
Wash	
Heaters, 2 @ 1 kw	1.0 (a)*
Pumps, 2 @ 0.3 HP	0.6 (a)
Ultrasonics, 1.0 kW	0.5 (a)
Total, Wash	2.1
Rinse	
Heaters, water, 10 kW	5.9 (b)
Heaters, 3 @ 1 kW	1.5 (a)*
Ultrasonics, 0.5 kW	0.3 (a)
Pumps, 0.3 HP	0.3 (a)
Total, Rinse	8.0
Dry	
Heater, 7.5 kW	7.5 (a)
Blowers, 1 HP	0.9 (a)
Total, Dry	8.4
Exhaust	
Blower, 0.5 HP	0.4 (b)*
Total, Exhaust	0.4
Waste Treatment	
Total, Waste Treatment	0.0 (c)
Other	
Hoist, 0.12 HP	0.1 (a)
Total, Other	0.1
TOTAL, SYSTEM	19.0
kg CO2, operating	7.07
kW, idling	2.90

Basis: Crest bench system with 1014 tanks, 1.8 m2/hr

(a) Maltby, 1991 March 12

(b) ADL estimate based on engineering judgement

(c) water separation powered by wash and rinse pumps.

* = included in idling mode

Fig. Z.16. Energy use breakdown, operating mode batch electronics cleaning system (aqueous system).

Station/ Component	Operating Power (kWh/h)
Wash	
Pump, 0.3 HP	0.3 (a)
Total, Wash	0.3
Rinse	
Heater, water, 10 kW	5.9 (b)
Heaters, 2 @ 1 kW	1.0 (a)*
Pumps, 0.3 HP	0.3 (a)
Ultrasonics, 1.0 kW	0.5 (a)
Total, Rinse	7.7
Dry	
Heater, 7.5 kW	7.5 (a)
Blowers, 1 HP	0.9 (a)
Total, Dry	8.4
Exhaust	
Blower, 0.5 HP	0.4 (b)*
Total, Exhaust	0.4
Waste Treatment	
Total, Waste Treatment	0.0 (c)
Other	
Hoist, 0.12 HP	0.1 (b)
Total, Other	0.1
TOTAL, SYSTEM	16.9
kg CO2, operating	6.29
kW, idling	1.40

Basis: Crest bench system with 1014 tanks, AXAREL 38, 1.8 m2/hr

(a) Maltby, 1991 March 12

(b) ADL estimate based on engineering judgement

(c) water separation powered by wash and rinse pumps.

* = included in idling mode

Fig. Z.17. Energy use breakdown, operating mode batch electronics cleaning system (semi-aqueous system).

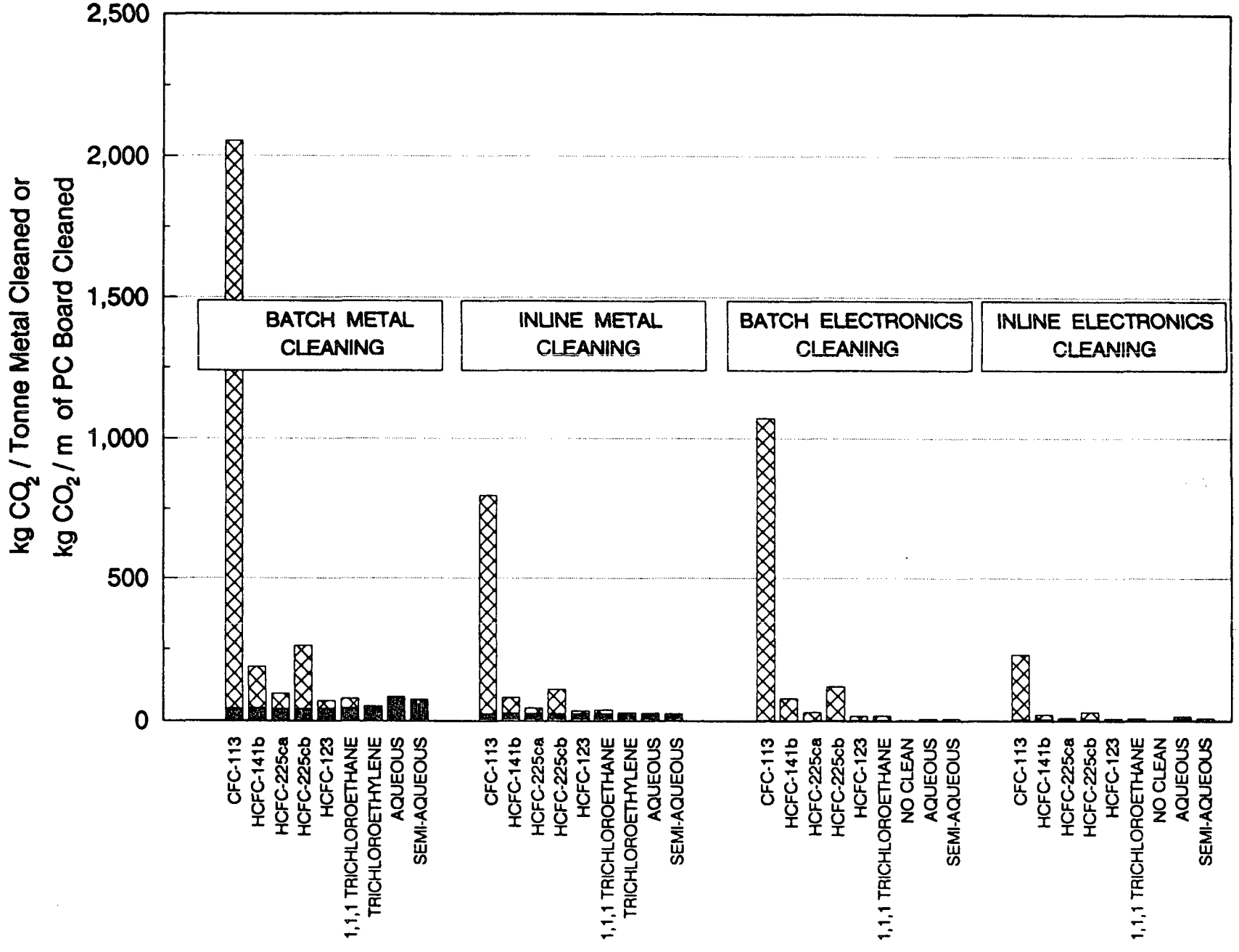


Fig. Z.18. TEWI of baseline technologies (500 year GWP).

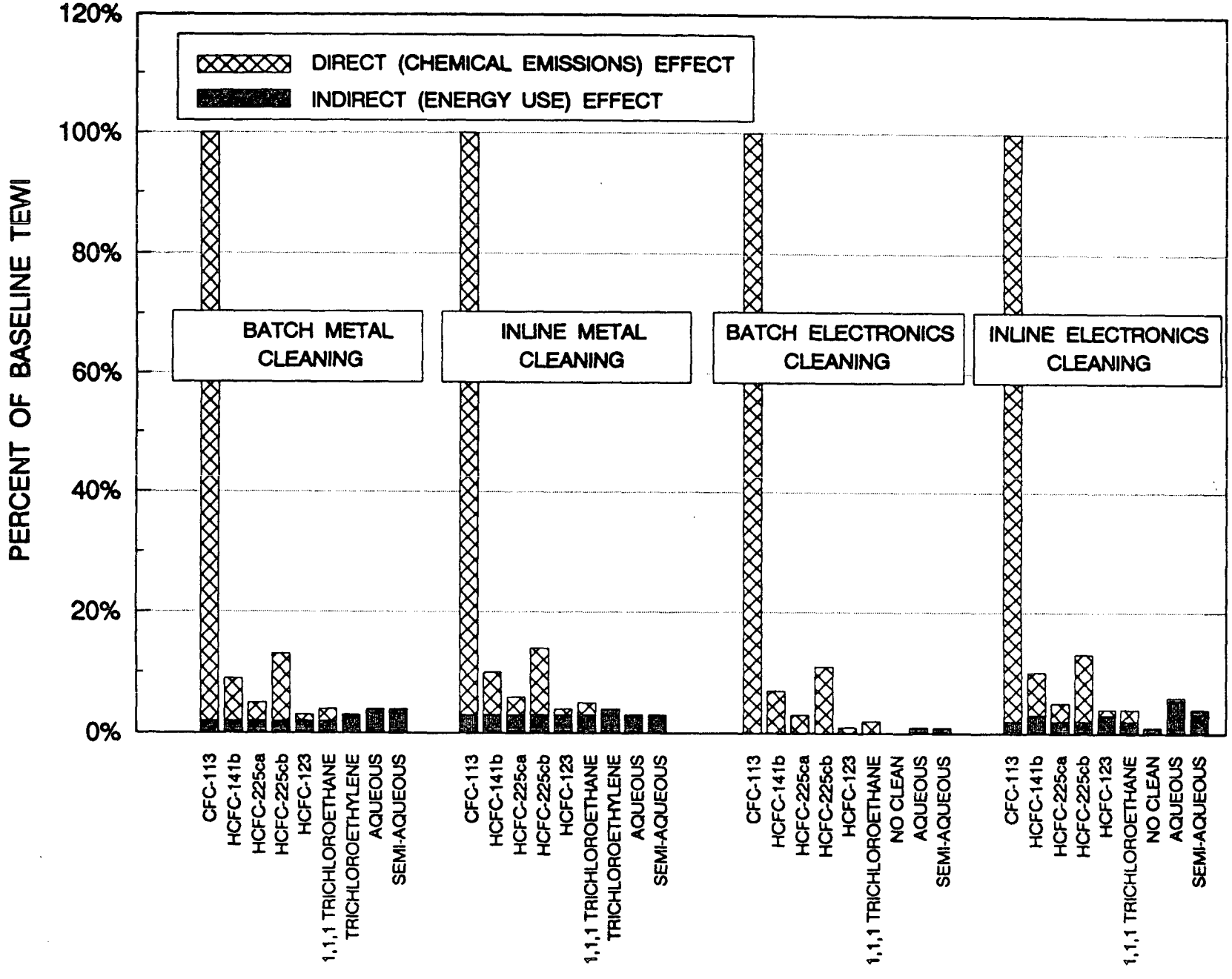


Fig. Z.19. Relative TEWI of baseline technologies (500 year GWP).

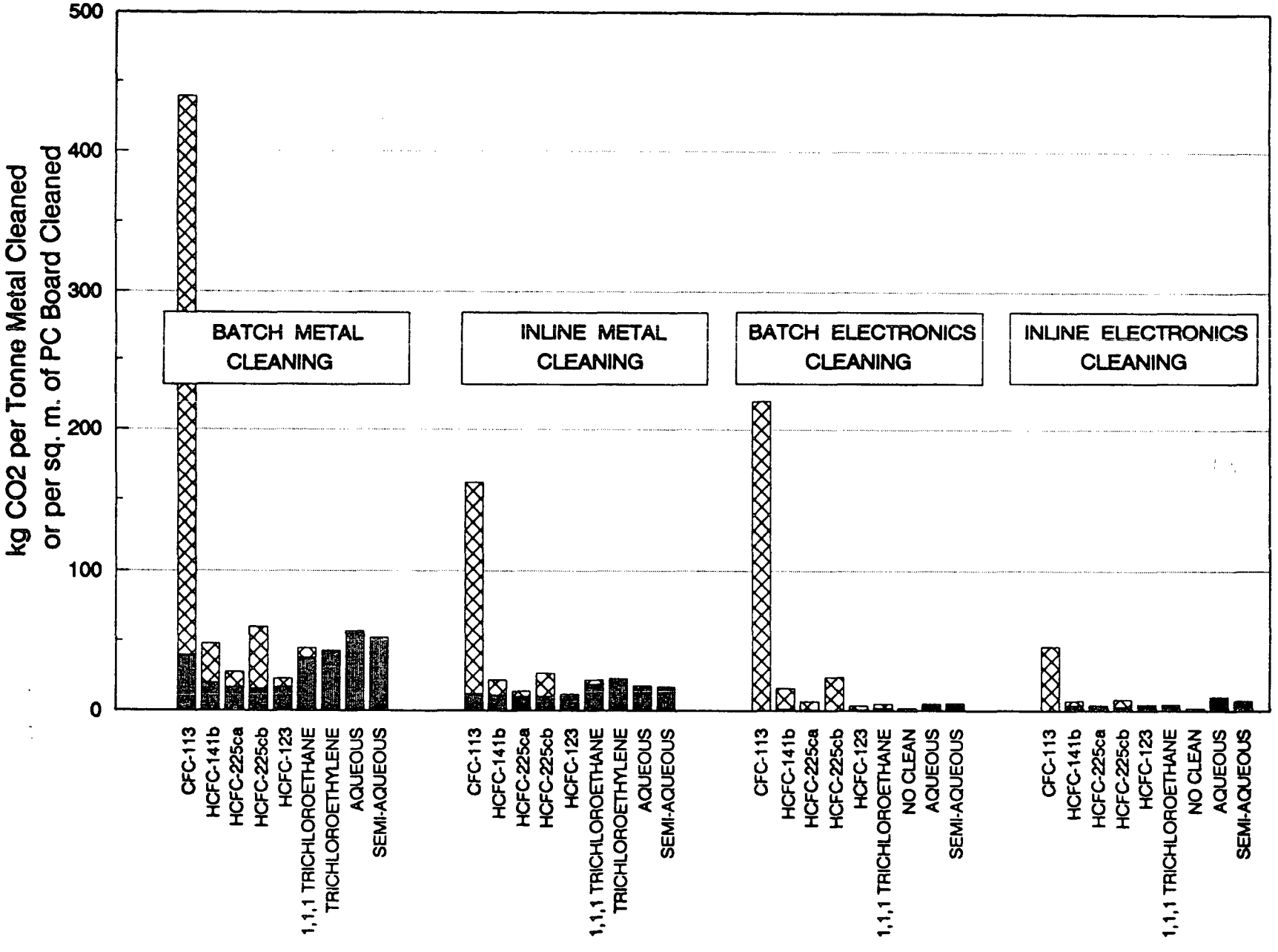


Fig. Z.20. TEWI of BACT (500 year GWP).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	AQ	SAQ
Operating: 12 Hours								
Energy consumed in cleaning process	4.17	4.62	4.04	4.05	4.40	4.00	14.39	8.39
Embodied energy in solvent chemicals	0.08	0.07	0.08	0.08	0.07	0.07	0.00	0.32
Auxilliary processes**	0.13	0.11	0.14	0.15	0.11	0.17	0.04	0.04
Solvent emissions	210.00	14.99	5.50	23.00	2.90	3.41	0.00	0.36
Total Operating	214.38	19.79	9.76	27.28	7.48	7.65	14.43	9.11
Idling: 4 hours								
Energy consumed in cleaning process	0.90	1.05	0.85	0.86	0.97	0.84	0.45	0.35
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.04	0.04	0.04	0.04	0.04	0.04	0.01	0.01
Solvent emissions	5.11	0.37	0.13	0.56	0.07	0.08	0.00	0.04
Total Idling	6.05	1.45	1.03	1.46	1.08	0.96	0.46	0.40
Downtime: 8 hours								
Energy consumed in cleaning process	0.12	0.12	0.12	0.12	0.12	0.12	0.00	0.00
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00
Solvent emissions	10.22	0.73	0.27	1.12	0.14	0.17	0.00	0.01
Total Downtime	10.41	0.92	0.46	1.31	0.33	0.36	0.00	0.01
Composite: kg eq. CO2/m2 board cleaned								
Energy consumed in cleaning process	5.19	5.79	5.01	5.03	5.49	4.96	14.84	8.74
Embodied energy in solvent chemicals	0.08	0.07	0.08	0.08	0.07	0.07	0.00	0.32
Auxilliary processes	0.24	0.22	0.25	0.26	0.22	0.28	0.05	0.05
Solvent emissions	225.33	16.09	5.90	24.68	3.11	3.66	0.00	0.41
TOTAL	230.84	22.16	11.24	30.05	8.90	8.97	14.89	9.52

** additional HVAC requirements due to cleaning system

Fig. Z.21. In-line electronics cleaning processes, 500 year time horizon (kg equivalent CO_2/m^2 board).

U.S. Energy Mix

	CFC-113	HCFC-141b	HCFC-225ca	HCFC-225cb	HCFC-123	1,1,1	AQ	SAQ
Operating: 12 Hours								
Energy consumed in cleaning process	4.17	4.62	4.04	4.05	4.40	4.00	14.39	8.39
Embodied energy in solvent chemicals	0.08	0.07	0.08	0.08	0.07	0.07	0.00	0.32
Auxilliary processes**	0.13	0.11	0.14	0.15	0.11	0.17	0.04	0.04
Solvent emissions	420.00	44.00	16.20	68.00	8.50	10.00	0.00	0.96
Total Operating	424.38	48.80	20.46	72.28	13.08	14.25	14.43	9.71
Idling: 4 hours								
Energy consumed in cleaning process	0.90	1.05	0.85	0.86	0.97	0.84	0.45	0.35
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.04	0.04	0.04	0.04	0.04	0.04	0.01	0.01
Solvent emissions	10.22	1.07	0.39	1.66	0.21	0.24	0.00	0.02
Total Idling	11.16	2.16	1.29	2.55	1.22	1.12	0.46	0.37
Downtime: 8 hours								
Energy consumed in cleaning process	0.12	0.12	0.12	0.12	0.12	0.12	0.00	0.00
Embodied energy in solvent chemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Auxilliary processes	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00
Solvent emissions	20.44	2.14	0.79	3.31	0.41	0.49	0.00	0.03
Total Downtime	20.63	2.33	0.98	3.50	0.60	0.68	0.00	0.03
Composite: kg eq. CO2/m2 board cleaned								
Energy consumed in cleaning process	5.19	5.79	5.01	5.03	5.49	4.96	14.84	8.74
Embodied energy in solvent chemicals	0.08	0.07	0.08	0.08	0.07	0.07	0.00	0.32
Auxilliary processes	0.24	0.22	0.25	0.26	0.22	0.28	0.05	0.05
Solvent emissions	450.67	47.21	17.38	72.97	9.12	10.73	0.00	1.01
TOTAL	456.18	53.29	22.73	78.33	14.90	16.05	14.89	10.11

** additional HVAC requirements due to cleaning system

Fig. Z.22. In-line electronics cleaning processes, 100 year time horizon (kg equivalent CO_2/m^2 board).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			CFC-113	1.33 (g)	0.00	0.63 (h)			
Rinse	15.0									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	10.2							1.3 (f)		
TOTAL	39.2	0.0	0.0		1.3	0.0	0.6	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	2100 (e)	0.67	500 year GWP= 2100 (e)	
Equivalent CO2 Emissions, N.A.	26.3	0.0	0.0		0.7 (d)	0.0	1323.0	0.8	1350.8	214.4
Emissions, Europe	20.0	0.0	0.0		0.7 (d)	0.0	1323.0	0.6	1344.3	213.4
Emissions, Japan	22.7	0.0	0.0		0.7 (d)	0.0	1323.0	0.7	1347.2	213.8

	100 year GWP= 4200 (e)	
Equivalent CO2 Emissions, N.A.	2673.8	424.4
Emissions, Europe	2667.3	423.4
Emissions, Japan	2670.2	423.8

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)

(g) emissions + 40 gal sump replacement every month (Jordan, 1991, March 27)
(h) see Appendix Q

Fig. Z.23. In-line electronics cleaning system - CFC-113, operating mode (low boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			HCFC-	1.33 (g)	0.00	0.63 (h)			
Rinse	17.9			141b						
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	11.5							1.1 (f)		
TOTAL	43.4	0.0	0.0		1.3	0.0	0.6	1.1		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA			
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	150 (e)	0.67	500 year GWP= 150 (e)	
Equivalent CO2 Emissions, N.A.	29.1	0.0	0.0		0.7 (d)	0.0	94.5	0.7	125.0	19.8
Emissions, Europe	22.1	0.0	0.0		0.7 (d)	0.0	94.5	0.6	117.9	18.7
Emissions, Japan	25.2	0.0	0.0		0.7 (d)	0.0	94.5	0.6	121.0	19.2

	100 year GWP= 440 (e)	
Equivalent CO2 Emissions, N.A.	307.7	48.8
Emissions, Europe	300.6	47.7
Emissions, Japan	303.7	48.2

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement every month (Jordan, 1991, March 27)
(h) see Appendix Q

Fig. Z.24. In-line electronics cleaning system - HCFC-141b, operating mode (low boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			HCFC-225ca	1.4 (g)	0.00	0.63 (h)			
Rinse	14.2									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	9.8							1.3 (f)		
TOTAL	38.0	0.0	0.0		1.4	0.0	0.6	1.3		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	55 (e)	0.67	500 year GWP= 55 (e)	
Equivalent CO2 Emissions, N.A.	25.5	0.0	0.0		0.7 (d)	0.0	34.7	0.9	61.7	9.8
Emissions, Europe	19.4	0.0	0.0		0.7 (d)	0.0	34.7	0.7	55.4	8.8
Emissions, Japan	22.0	0.0	0.0		0.7 (d)	0.0	34.7	0.8	58.1	9.2

Equivalent CO2	100 year GWP= 162 (e)	
Emissions, N.A.	129.1	20.5
Emissions, Europe	122.8	19.5
Emissions, Japan	125.5	19.9

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement every 3 months (ADL estimate)
(h) see Appendix Q

Fig. Z.25. In-line electronics cleaning system - HCFC-225ca, operating mode (low boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			HCFC-225cb	1.4 (g)	0.00	0.63 (h)			
Rinse	14.2									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	9.9							1.5 (f)		
TOTAL	38.1	0.0	0.0		1.4	0.0	0.6	1.5		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	230 (e)	0.67	500 year GWP= 230 (e)	
Equivalent CO2 Emissions, N.A.	25.5	0.0	0.0		0.7 (d)	0.0	144.9	1.0	172.1	27.3
Emissions, Europe	19.4	0.0	0.0		0.7 (d)	0.0	144.9	0.8	165.8	26.3
Emissions, Japan	22.1	0.0	0.0		0.7 (d)	0.0	144.9	0.9	168.6	26.8

	100 year GWP= 680 (e)	
Equivalent CO2 Emissions, N.A.	455.6	72.3
Emissions, Europe	449.3	71.3
Emissions, Japan	452.1	71.8

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement every 3 months (ADL estimate)
(h) see Appendix Q

Fig. Z.26. In-line electronics cleaning system - HCFC-225cb, operating mode (low boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			HCFC-123	1.33 (g)	0.00	0.63 (h)			
Rinse	16.5									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	10.9							1.1 (f)		
TOTAL	41.4	0.0	0.0		1.3	0.0	0.6	1.1		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	29 (e)	0.67	500 year GWP= 29 (e)	
Equivalent CO2 Emissions, N.A.	27.7	0.0	0.0		0.7 (d)	0.0	18.3	0.7	47.4	7.5
Emissions, Europe	21.1	0.0	0.0		0.7 (d)	0.0	18.3	0.6	40.6	6.4
Emissions, Japan	24.0	0.0	0.0		0.7 (d)	0.0	18.3	0.6	43.6	6.9

	100 year GWP= 85 (e)	
Equivalent CO2 Emissions, N.A.	82.7	13.1
Emissions, Europe	75.9	12.0
Emissions, Japan	78.9	12.5

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)

(g) emissions + 40 gal sump replacement every month (Jordan, 1991, March 27)
(h) see Appendix Q

Fig. Z.27. In-line electronics cleaning system - HCFC-123, operating mode (low boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	14.0			1,1,1	1.33 (g)	0.00	0.63 (h)			
Rinse	20.3									
Dry	0.0									
Exhaust	0.0									
Pretreatment	0.0									
Waste Treatment	0.0									
Other	3.3							1.7 (f)		
TOTAL	37.6	0.0	0.0		1.3	0.0	0.6	1.7		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	34 (e)	0.67	500 year GWP= 34 (e)	
Equivalent CO2 Emissions, N.A.	25.2	0.0	0.0		0.7 (d)	0.0	21.4	1.1	48.4	7.7
Emissions, Europe	19.2	0.0	0.0		0.7 (d)	0.0	21.4	0.9	42.1	6.7
Emissions, Japan	21.8	0.0	0.0		0.7 (d)	0.0	21.4	1.0	44.9	7.1

	100 year GWP= 100 (e)	
Equivalent CO2 Emissions, N.A.	90.0	14.3
Emissions, Europe	83.7	13.3
Emissions, Japan	86.5	13.7

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) emissions + 40 gal sump replacement every month (Jordan, 1991, March 27)
(h) see Appendix Q

Fig. Z.28. In-line electronics cleaning system - 1,1,1 trichlorethane operating mode (high boiling point solvent).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals Name	Embodied Energy in Chemicals (kg/hr)	Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
Wash	31.0			detergent	0.10 (e,g	0.00	0.00			
Rinse	82.4									
Dry	19.0									
Exhaust	2.6									
Pretreatment	0.0			beads	0.3 (h)					
Waste Treatment	0.0									
Other	0.3							0.4 (f)		
TOTAL	135.3	0.0	0.0		0.4	0.0	0.0	0.4		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	0	0	0.7	500 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	90.7	0.0	0.0		0.1 (d)	0.0	0.0	0.2	91.0	14.4
Emissions, Europe	69.0	0.0	0.0		0.1 (d)	0.0	0.0	0.2	69.3	11.0
Emissions, Japan	78.5	0.0	0.0		0.1 (d)	0.0	0.0	0.2	78.8	12.5

	100 year GWP= 0 (e)	
Equivalent CO2 Emissions, N.A.	91.0	14.4
Emissions, Europe	69.3	11.0
Emissions, Japan	78.8	12.5

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) ADL estimate based on engineering judgement
(h) 0.28 kg beads/hr (Eltech, 1991)

Fig. Z.29. In-line electronics cleaning system - operating mode (aqueous system).

6.3 m2/hr (b)

Unit Process	Electric Energy (kWh/hr)	Steam (kJ/hr)	Direct Fuels (kJ/hr)	Embodied Energy in Chemicals		Short-lived Solvents Emitted (kg/hr)	Long-lived Solvents Emitted (kg/hr)	Other (kWh/hr)	TOTAL (kg CO2/ system)	TOTAL (kg CO2/ m2 board)
				Name	(kg/hr)					
Wash	7.5			AXAREL	3.68 (g)	0.95 (h)				
Rinse	44.2									
Dry	24.3									
Exhaust	2.6									
Pretreatment (i)	0.0			beads	0.3 (j)					
Waste Treatment	0.0									
Other	0.3							0.4 (f)		
TOTAL	78.9	0.0	0.0		4.0	0.9	0.0	0.4		
Efficiency Factor	NA	0.80	1.00	NA	1.00	1.00	1.00			
Equivalent Primary Fuels (kJ/hr)	NA	0.0	0.0			NA	NA	NA		
CO2 Factor	0.67 (a)	0.00005	0.0		0.00005 (c)	2.4 (e)		0.7	500 year GWP= 2.4 (e)	
Equivalent CO2 Emissions, N.A.	52.9	0.0	0.0		2.0 (d)	2.3	0.0	0.2	57.4	9.1
Emissions, Europe	40.2	0.0	0.0		2.0 (d)	2.3	0.0	0.2	44.7	7.1
Emissions, Japan	45.8	0.0	0.0		2.0 (d)	2.3	0.0	0.2	50.2	8.0

	100 year GWP= 6.4 (e)	
Equivalent CO2 Emissions, N.A.	61.1	9.7
Emissions, Europe	48.5	7.7
Emissions, Japan	54.0	8.6

(a) kg CO_2/kWh delivered: 0.67, N. America; 0.51, Europe; 0.58, Japan (Fischer, ORNL)
(b) ADL estimate
(c) 0.000050 kg CO_2/kJ energy produced (ADL estimate)
(d) ch. consumed*2.86 kWh/kg ch. produced*0.000050*3600 kJ/kWh
(e) see Appendix R
(f) auxiliary energy needed to condition shop space (ADL estimate)
(g) dragout + change sump every 6 months(ADL estimate)
(h) 0.15 kg solvent/m^2 board (ADL estimate)
(i) no consideration for pretreatment
(j) 0.28 kg beads/hr (Eltech, 1991)

Fig. Z.30. In-line electronics cleaning system - operating mode (semi-aqueous).

Station/ Component	Operating Power (kWh/h)				
Wash	CFC-113	HCFC-141b	HCFC-123	HCFC225ca	HCFC-225cb
Heater, 3 kW	0.2 (e)*	0.2	0.2	0.2	0.2
Pump, 5 HP (80 gpm, 35 psi)	6.8 (a)	6.8	6.8	6.8	6.8
Heater, 3 kW	0.2 (e)*	0.2	0.2	0.2	0.2
Pump, 5 HP (80 gpm, 35 psi)	6.8 (a)	6.8	6.8	6.8	6.8
Total, Wash	14.0	14.0	14.0	14.0	14.0
Rinse					
Heater	15.0 (c)*	17.9	16.5	14.2	14.2
Total, Rinse	15.0	17.9	16.5	14.2	14.2
Dry					
Total, Dry	0.0	0.0	0.0	0.0	0.0
Exhaust					
Total, Exhaust	0.0	0.0	0.0	0.0	0.0
Waste Treatment					
Total, Waste Treat.	0.0	0.0	0.0	0.0	0.0
Other					
Chiller	6.9 (a)*	8.2	7.6	6.5	6.6
Chiller, low temp., 1 HP**	1.7 (a)*	1.7	1.7	1.7	1.7
Cooling Tower	1.3 (d)*	1.3	1.3	1.3	1.3
Conveyor, 0.3 HP	0.3 (c)	0.3	0.3	0.3	0.3
Total, Other	10.2	11.5	10.9	9.8	9.9
TOTAL, SYSTEM	39.2	43.4	41.4	38.0	38.1
kg CO2, operating	4.17	4.62	4.40	4.04	4.05
KW idling	25.29	29.51	27.48	24.09	24.18

Basis: Baron-Blakeslee model CBC-18LE, 6.3 m2/hr
(a) Osterman, 1991, Feb. 13
(b) Allied, 1990, CBC-18LE product literature
(c) ADL estimate based on engineering judgement
(d) Osterman, 1991, March 6
(e) Osterman, 1991, April 9
* included in idling mode
** included in downtime mode

Fig. Z.31. Energy use breakdown, operating mode in-line electronics cleaning (low boiling point solvents).

Station/ Component	Operating Power (kWh/h)
Wash	**1,1,1**
Heater, 3 kW	0.2 (e)*
Pump, 5 HP (80 gpm, 35 psi)	6.8 (a)
Heater, 3 kW	0.2 (e)*
Pump, 5 HP (20 gpm, 200 psi)	6.8 (a)
Total, Wash	14.0
Rinse	
Heater, boil	20.3 (b)*
Total, Rinse	20.3
Dry	
Total, Dry	0.0
Exhaust	
Total, Exhaust	0.0
Waste Treatment	
Total, Waste Treatment	0.0
Other	
Chiller, Low Temp **	1.7 (a)*
Cooling Tower	1.3 (d)*
Conveyor, 0.3 HP	0.3 (c)
Total, Other	3.3
TOTAL, SYSTEM	37.6
kg CO2, operating	4.00
kW idling	23.70

Basis: Baron-Blakeslee model CBC-18LE, 6.3 m2/hr
(a) Osterman, 1991, Feb. 13
(b) Allied, 1989, CBC-18LE product literature
(c) ADL estimate based on engineering judgement
(d) Osterman, 1991, March 6
(e) Osterman, 1991, April 9
* = included in idling mode
** = included in downtime mode

Fig. Z.32. Energy use breakdown, operating mode in-line electronics cleaning system (high boiling point solvents).

Station/ Component	Operating Power (kWh/h)
Wash	
Pump, recirculating, 3 HP	2.6 (b)
Heater, recirculating, 30 kW	15.0 (b)*
Pump, power, 7.5 HP	6.6 (b)
Blower, isolation, 7.7 HP	6.8 (b)
Total, Wash	31.0
Rinse	
Heater, water, 100 kW	58.2 (c)*
Pump, recirculating, 3 HP	2.6 (b)
Heater, recirculating, 30 kW	15.0 (b)
Pump, power, 7.5 HP	6.6 (b)
Total, Rinse	82.4
Dry	
Blower, blowoff, 3.7 HP	3.3 (b)
Blowers, 2@ 7.5	13.2 (b)
Heater, 3.6 kW	2.5 (b)
Total, Dry	19.0
Exhaust	
Blower, 3 HP	2.6 (d)*
Total, Exhaust	2.6
Waste Treatment	
Total, Waste Treatment	0.0
Other	
Conveyor, 0.3 HP	0.3 (c)
Total, Other	0.3
TOTAL, SYSTEM	135.3

Basis: Hollis 332, open loop, 4.5 feet per minute, 6.3 m2/hr

(a) Eltech, 1991, Feb. visit

(b) Andrus, 1991, PWA paper

(c) ADL estimate based on engineering judgement

(d) ADL estimate based on Eltech visit

* included in idling mode

Fig. Z.33. Energy use breakdown, operating mode in-line electronics cleaning system (aqueous system).

Station/ Component	Operating Power (kWh/h)
Wash	
Heat Pump, 1.5 HP	2.2 (b)*
Pump, 2 @ 3 HP	5.3 (a)
Compressed Air, 5 HP, 20 cfm, 40 psi	4.4 (c)
Total, Wash	7.5
Rinse	
Heater, 15 kW	10.7 (c)*
Heater, 2 @ 18 kW	25.6 (c)
Pump, 3 @ 3 HP	7.9 (a)
Total, Rinse	44.2
Dry	
Heater, 12 kW	12.0 (a)
Blowers, air knife, 2 @ 7 HP	12.3 (a)
Total, Dry	24.3
Exhaust	
Blower, 3 HP	2.6 (e)*
Total, Exhaust	2.6
Waste Treatment	
Total, Waste Treatment	0.0 (d)
Other	
Conveyor, 0.3 HP	0.3 (c)
Total, Other	0.3
TOTAL, SYSTEM	78.9

Basis: Corpane model SAI18RD with AXAREL 38, 4.5 feet per minute, 6.3 m2/hr

(a) Kalmbach, 1991, March 12

(b) Kalmbach, 1991, March 13

(c) ADL estimate based on engineering judgement

(d) water separation powered by wash pump

(e) ADL estimate based on Eltech visit

* included in idling mode

Fig. Z.34. Energy use breakdown, operating mode in-line electronics cleaning system (semi-aqueous system).

APPENDIX AA: NO CLEAN: INERT GAS SOLDERING

AA.1 INERT GAS SOLDERING WITH NITROGEN PURGE

The electrovert Econopak II machine described by Hanaway (1991) and summarized in Appendix X, uses a continuous nitrogen purge to reduce oxygen levels to the parts per million (ppm) range. The major additional energy consuming steps for this concept over conventional soldering can be attributed to nitrogen use which is estimated to be 42.4 to 56.7 m^3/hr or 1500 to 2000 standard ft^3/hr (SCFH) (Hagerty, 1991). An average value of 50 m^3/hr (1750 SCFH) is used for the analysis in this report.

Energy is consumed in:

- Manufacture of liquid nitrogen estimated to be 893 Wh/kg (810 kWh/short ton) (Battelle, 1975; Hagerty, 1991). This amounts to 1.04 kWh/m^3 or 52 kWh/hr of operating time.

- Heating nitrogen purge gas to exit gas temperatures. If one assumes that all of the nitrogen is heated from 21°C to 204°C (70°F to 400°F), the energy required is about 3 kWh (= 6.8 Btu/mol°F x (400-70°F) x (1750/385 S.ft^3 at 20°C). If a heater is required to vaporize the nitrogen, this could add another 20 to 30 kWh/hr. Total energy use is thus in the order of 55 to 85 kWh/hr with the estimated range depending on whether a heater for vaporization is required.

Since the throughput of the machine (maximum) is estimated to be 24.2m^2/hr (based on covering 67% of a 33 cm (13 in.) wide track moving at 1.8 m/min. (6 ft/min.)), energy use is calculated to be 2.3 to 3.5 kWh per m^2 of board. An intermediate rounded value of 3.0 kWh/m^2 is used.

Nitrogen use is expected to be relatively independent of board throughput, thus nitrogen use (and related energy used) is inversely proportional to throughput. Thus, if on the average only 33% of the belt area was occupied, energy use would rise from 3 to 6 kwh/m^2 of board.

AA.2 INERT GAS SOLDERING WITH VACUUM EVACUATION AND NITROGEN (LOCK BOX)

The second system being modeled is based on using a vacuum and "flushing" out the oxygen using nitrogen much as practiced in the lamp industry (Roth, 1986). The following sequence of operations are considered:

Step 1: Printed wire circuit boards are placed in a carrier (tray). The maximum board area (100% coverage) is 0.175 m^2.

Step 2: The carriers (trays) are placed in a vacuum lock chamber of 0.05 m^3 in volume.

Step 3: The chamber is evacuated, purged with nitrogen, evacuated again, and filled with nitrogen again to bring oxygen levels down to the ppm range. Total nitrogen required for two purge cycles in O.1 m^3.

Step 4: The carrier is moved through the soldering operation which is in a nitrogen atmosphere.

Step 5: The carrier is moved into a second vacuum chamber (also of 0.05 m^3 in volume) which is then sealed off from the soldering chamber; the tray is discharged.

Step 6: The second chamber is then sealed (while empty) and evacuated, filled with nitrogen, evacuated again and filled with nitrogen.

The major energy (direct or indirect) consuming steps are:

- Operation of the vacuum system. It is assumed that the vacuum system is operating between 101 Pa and 101 kPa (0.76 torr and 760 torr). The volume of gas to be pumped in Step 2 is 0.1 m^3 and in Step 6 another 0.1 m^3 for a total of 0.2 m^3/cycle. Estimated energy use is under 0.1 kWh.

- Energy to produce nitrogen: it is assumed that nitrogen is purchased as a liquid and vaporized at the cleaning site. As above in Section AA.1, production of liquid nitrogen requires about 893 W/kg (810 kWh/s ton) which corresponds to about 1.04 kWh/m^3 of gas at 20° C. Since 0.2 m^3 of gas are used, energy requirements for nitrogen production are 0.21 kWh.

- Incremental energy in soldering to evaporate alcohol used in this system. This value is rather difficult to determine but a calculation indicates this is small. For example, if the board were wetted with alcohol at 0.5 kg per m^2 (which is about equivalent to solvent losses by dragout and diffusion and other losses in batch solvent systems), the total amount of alcohol on 0.175 m^2 of board is less than 0.1 kg (0.5 x 0.175). Upon vaporization of solvent and heating to a temperatures of 150° C (302° F) it would require less than 1200 kJ/kg. The estimated energy requirements are less than 120 kJ (1200 x 0.1). This is less than 0.03 kWh and is then seen to be small.

As a result, the energy use is dominated by nitrogen production (0.21 kWh), vacuum system (0.1 kWh) and a small amount for alcohol evaporation of 0.03 kWh for a total of 0.34 kWh for 0.175 m^2 of board with 100% coverage of the carrier area by PC boards. This amounts to about 2 kWh/m^2 (0.34/0.175).

If the relatively small tray area is only 50% covered by boards, then the energy consumption is about 4 kWh/m^2 which is believed to be a more reasonable average operating value and is used in the summary tables and figures. As with the previous example, energy use rises inversely with how much of the tray area is covered by boards. Thus, if the tray area is only 25% covered, the energy use is roughly doubled from 4 to 8 kWh/m^2. Similarly if boards are soldered twice, energy use will double. Interestingly enough, if the carrier area remains 50% covered by boards but hourly throughput is reduced by half, the energy use remains at about 4 kWh/m^2. In other words, nitrogen (and energy) use are dictated by the number of times the carrier enters the vacuum chamber. This system is of advantage to a smaller operator with a widely varying work load and is more like a batch operation in nitrogen use. By contrast, the in-line system described in Section AA.1 consumes nitrogen at a rate almost independent of throughput.

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APPENDIX AB: BEST AVAILABLE CURRENT TECHNOLOGY SCENARIO AND EFFECT ON TEWI

As noted in the body of this report, there are two major contributors to TEWI in the solvent cleaning processes examined, namely energy used in the process and solvent emissions. Embodied energy in materials used and auxiliary processes typically contribute little to TEWI. There are a number of technologies developed that have yet to be widely adopted in PCB and metal cleaning. Such technologies, including new tight equipment, can reduce energy consumption and emission losses significantly. In addition, several technologies are capable of being retrofitted on existing solvent cleaning systems. Reductions in TEWI due to energy conservation techniques are also applicable to aqueous and semi-aqueous systems. Typical energy and emission savings that can be achieved are shown in Table AB.1.

Table AB.1. Scenario of energy and emissions savings for BACT (best available current technology)

Change in Cleaning System from Baseline Technology	Electronic		Metals	
	Batch	In-Line	Batch	In-Line
Energy Savings				
Solvent, low boiling point	0.60	0.40	0.60	0.60
Solvent, high boiling point	0.18	0.18	0.16	0.23
Aqueous	0.33	0.33	0.33	0.33
Semi-Aqueous	0.30	0.30	0.30	0.30
Solvent Emission Loss Reduction				
Solvent, low boiling point	0.8	0.8	0.8	0.8
Solvent, high boiling point	0.8	0.8	0.8	0.8

The reduced TEWI levels that result from these energy and emission savings are presented in Fig. AB.1 for the 500 year GPW and in Fig. AB.2 for the 100 year GWP.

These savings can be realized by a variety of technologies used alone or in combination, such as:

- For solvent systems:

  - Low boiling point solvents: Use of heat pumps that can reduce energy requirements by up to 75%. Conservative values of 60% are used in this analysis for metals systems and batch electronics, (see Fig. X.13a) and 40% for in-line electronics.

  - High boiling solvents: Use of control systems, "economizers", to reduce the distillation rates in the idling mode by 67% compared to the baseline case (Osterman, 1991). These economizers can provide energy savings of 10 to 85% (Hey, 1991), depending on throughput, operating cycle, and the required clean solvent distillation rate. This is most applicable to single stage vapor degreasers.

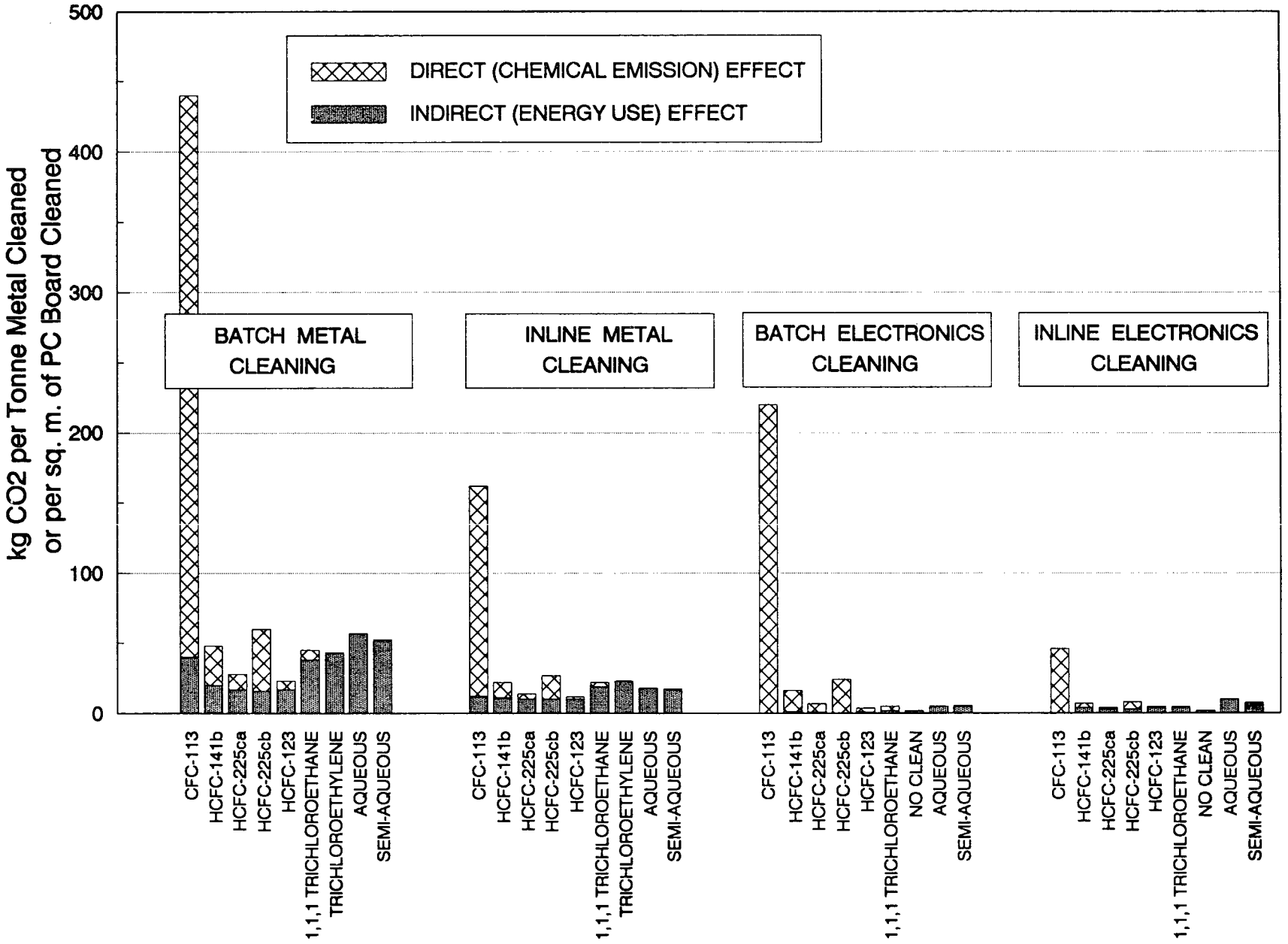

Fig. AB.1. TEWI of BACT (500 year GWP).

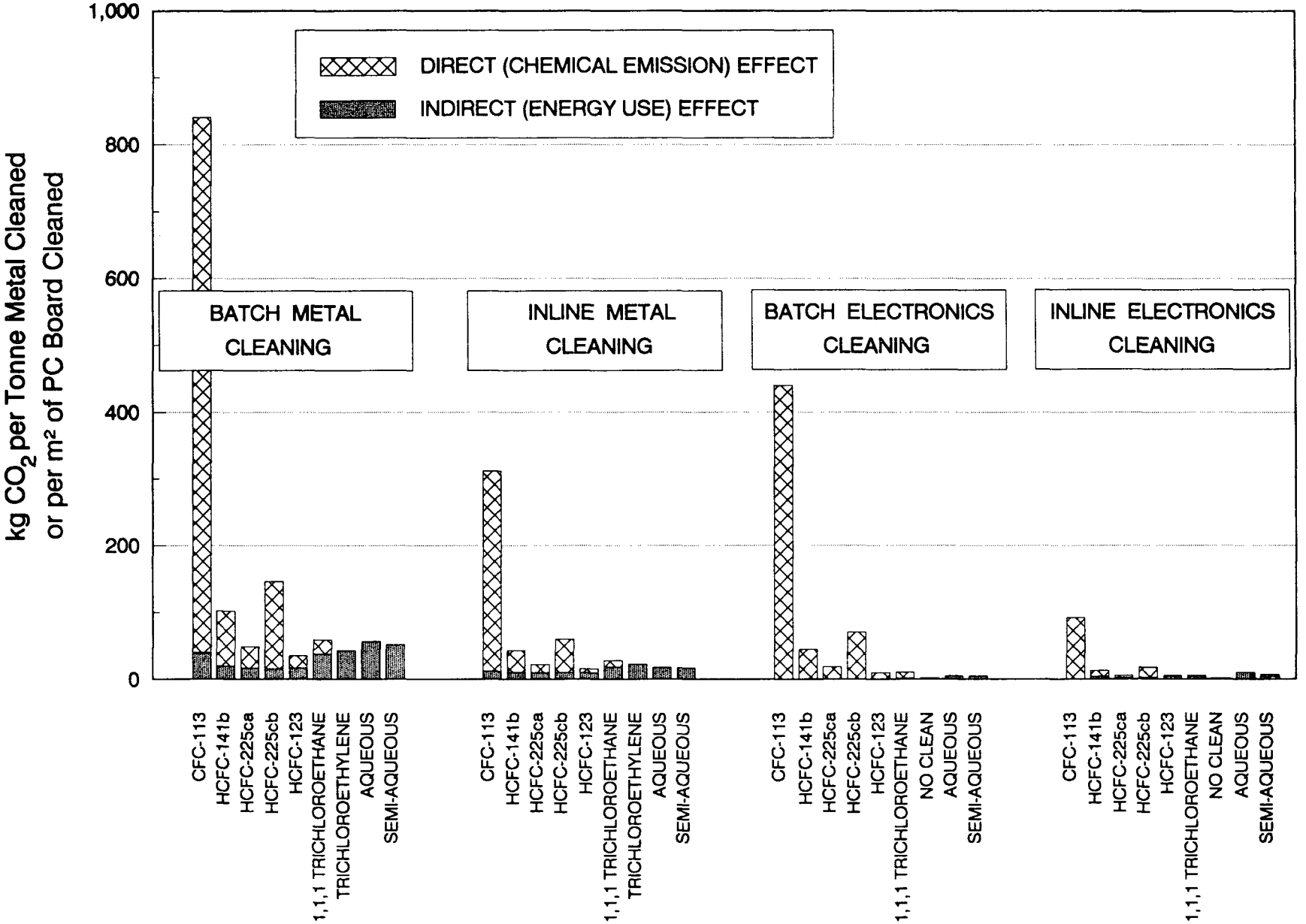

Fig. AB.2. TEWI of BACT (100 year GWP).

- The use of specifically designed low emission equipment, such as ICI's "Clean Zone" equipment can reduce idling emissions by up to 80% and operating emissions significantly (Hey, 1991).

- Use of superheated vapor for drying that has the potential to reduce solvent drag out losses to zero and reduce total emission losses by 90% of the baseline solvent based systems.

- Use of carbon adsorption systems that can reduce emission losses by 75% to 95% (ASAHI, 1991). See Appendix AC for details.

- Use of higher freeboard on batch solvent degreasers can reduce emission losses.

- Use of hoists to lower and raise parts with batch solvent degreasers can greatly reduce emission losses. Hoists provide controlled dwell time in the vapor and freeboard zones.

Energy demand in the downtime is shown in the tables by a double asterisk.

A conservative estimate of solvent emission reduction of 80% is used in the calculations, which includes one or more of the above technologies.

- For aqueous and semi-aqueous systems:

  - Use of closed loop systems and/or heat exchangers for aqueous and semi-aqueous systems which can provide energy savings of approximately 30 to 35% (Andrus, 1990). Energy is saved mainly by not losing the heat value in discharged water.

  - Advances in closed batch aqueous electronic cleaning.

APPENDIX AC: ESTIMATED TEWI OF OTHER TECHNOLOGIES

AC.1 CLOSED BATCH AQUEOUS MACHINES FOR PCBS

As mentioned in Appendix X, batch aqueous machines are manufactured by a number of vendors. An example is a high throughput batch aqueous machine by Protonique (Model APL-5) and described by Ellis (1990) who notes that only a few machines fall into this category while offering good quality cleaning. Generally these units have separate machines for washing and drying although they may be combined into one housing. The following information is provided by Ellis:

"The baskets to hold the circuits can handle 11 assemblies up to 500 x 400 mm with a maximum thickness of 35 mm.

"The cleaning machine consists of a 50 litre tank holding wash water or solution. This is pumped with a typically 2 HP pump to two spray arms, top and bottom.

"The washing action in closed circuit lasts for two to four minutes (conventional circuits)."

The rinse cycle (with a 5-10% isopropanol option) takes about 30 to 45 seconds. Drying uses rotary air knives supplemented by heating. Drying time is about equivalent to the cleaning time so that the possible throughput of the machine of cleaned and dried circuits can be up to five to ten basket loads per hour. Ellis reports substantial improvements in the energy efficiency of Protonique machines in the past two decades with present models using 500 to 800 watt hr/m^2. Estimated TEWI is about 0.5 kg CO_2/m^2 or less ((500-800) x 0.67). Being a closed batch machine, idling and downtime contributions to TEWI are expected to be small.

AC.2 CLOSED BATCH ALCOHOL MACHINES WITH INERT GAS

Closed batch machines for PCBs can be aqueous or semi-aqueous (e.g., terpenes or formulated hydrocarbons) and are offered by a number of vendors. For rosin fluxes, one machine using alcohol is described by ECD (Model 7300) which is programmed though a saponifier cycle followed by a water rinse and a final wash in a continuously purified solution of 75% alcohol and 25% water at an elevated temperature. The used alcohol water mixture is recirculated through a de-ionizing column and a filter and back to a holding tank for re-use. Alcohol loss is reported to be minimal. The alcohol is stored in an external double-walled enclosure. Nitrogen is used to purge the wash chamber thus reducing the oxygen content and the flammability of the contents.

The following shows estimates of energy and nitrogen use (Breunsbach, 1991; Appendix AA) for once through use of water. Maximum throughput is 3 m^2 of PCBs. An average of 2 m^2 in a 40 minute cycle (or 3 m^2/hr) is used in this analysis.

Being a closed batch machine, idling and downtime energy and TEWI effects are expected to be small.

Item	kg CO_2/hr
Energy for pumps, heaters, heated water (15 gal/cycle): 4 kW x 0.67 kg CO_2/kWh	2.7
Nitrogen: 1.7 m^3/hr x 1.04 kWh/m^3 x 0.67 kg CO_2/kWh	1.2
Alcohol: Embodied energy 1.6 kg/hr x 2.86 kWh/kg x 3600 joules/kWh x 0.00005 kg CO_2/joule	0.8
Alcohol emissions based on losses of 0.5 kg/m^2 (0.5 kg/m^2 x 3 m^2/hr x 3 kg CO_2/kg (500 year GWP)	4.5
Total	9.2
Square meters of board per hour	3.0
TEWI (kg CO_2/m^2 of board)	3.1

AC.3 MULTIPLE TANK FLAMMABLE SOLVENT CLEANING SYSTEM FOR PCBS

Because of the nature of flammable solvents and vapor control for explosion proofing and vapor control, multiple tank batch cleaning (rather than in-line conveyer machines) are suggested by Forward Technologies, Inc. (Minneapolis, Minn) and KLN Ultraschall (Heppenheim, Germany). Based on information supplied (Musselman, 1991), the system may consist of two to four tanks ranging from 350x250x300 mm to 1000x500x500 mm. Throughput of up to 150 m^2 per hour is claimed with

- energy use of 10 to 55 kW
- nitrogen use of 40 to 250 l/hr (0.04 to 0.25 m^3/hr)
- alcohol consumption of 0.3 to 1.5 kg/hr.

To provide an estimate of TEWI, the maximum sized machine, throughput, energy use, and solvent losses are used based on one hour throughput shown in the following table.

Item	kg equivalent CO_2/m^2
Energy Use: 55 kWh x 0.67 kg CO_2/kWh	37
Nitrogen Use: 0.25 m^3/hr x 1 kWh/m^3	--
Alcohol (embodied energy)	
$\frac{1.5\ kg}{hr} \times \frac{2.86\ kWh_t}{kg} \times \frac{3600\ joules}{kWh} \times \frac{0.00005}{jou}$	< 1
Alcohol Emissions: 1.5 x GWP of 3 (500 year)	4.5
Total	43
Square meters/hour throughput (maximum)	150
TEWI (working mode): kg CO_2/m^2	0.28

Alcohol losses during idling are estimated to be 0.7 kg/hr of tank liquid surface area (Musselman, 1991) or under 0.5 kg/hr for the larger tanks. This contribution (embodied energy) to TEWI is seen to be negligible assuming 12 operating hours and 4 idling hours. Similarly, emissions contribution to TEWI is small. If energy use in idling/downtime is similar to that of other batch systems, the composite TEWI is expected to be under 0.6 kg CO_2/m^2 (0.28 working mode + (<0.28) in idling/operating modes) assuming a 12-4-8 duty cycle.

AC.4 OPEN TOP BATCH ALCOHOL SYSTEM WITH PERFLUOROCARBON INERTING

A novel method for alcohol cleaning involves using a perfluorocarbon (PFC) to provide a non-flammable vapour blanket over the flammable solvent. An example is an open top batch type machine (with a cover) being developed by Rhone-Poulenc (Slinn, 1991). A machine with a typical throughput of 2.3 m^2 of PCB per hour would require about 6 kW or 2.6 kW/m^2 of PCB, 0.35 kg/hr of alcohol (0.15 kg/m^2) and 0.012 kg/hr of perfluorocarbon (0.005 kg/m^2; Slinn, 1991). The contributions to TEWI are then calculated:

Item	kg equivalent CO_2
Energy Use: 6 kWh x 0.67 kg CO_2/kWh	4.0
Embodied Energy in Organic Chemicals: (0.35 + 0.012 kg) 0.362 kg/hr x 2.86 kWh/kg x 3600 joules/kWh x 0.00005 kg CO_2/kg	0.19
Alcohol Losses: 0.35 kg x GWP of 3 (500 year)	1.1
Total	< 5.29
Square meters of board/hour	2.3
TEWI/m^2	> 2.3

To this TEWI one should add the TEWI due to perfluorocarbon emissions (GWP x emission rate/m^2 PCB)

AC.5 CARBON ADSORPTION SYSTEM

A well-known technique for capturing solvent vapors is carbon adsorption systems. ASAHI Glass (Munekata, 1991) has commercialized (in 20 installations) a fixed bed system in which the solvents are desorbed and recovered in a pressure swing adsorption system. The unit has been designed mainly for batch open top cleaning systems with the gas containing solvent collected in a hood. The technology may be applied to other systems as well.

Energy use for the recovery system is about 14 kW. To relate this to other TEWI calculations, typical installation configuration might involve a batch system cleaning 1000 boards in eight hours (i.e., 125 boards/hr) with each board having an area of 300 cm^2 (0.03 m^2). Energy used for solvent capture and recovery is thus calculated to be 3.7 kWh/m^2 of board (14 kWh/125 boards/0.03 m^2). Since the energy is all electrical, the TEWI is 2.5 kg CO_2/m^2 of board (3.7 kWh x 0.67 kg CO_2/kWh).

The efficiency of the adsorption column is estimated at more than 95% recovery of the solvent vapors (Munekata, 1991; Samejima, 1991). System efficiency (from vapor release to collection in hoods to adsorption and desorption) is estimated to be in the order of 70 to 75% (Osterman, 1991).

In conclusion, this adsorption system has the potential to lower solvent emissions (and TEWI) very significantly with only a modest increase in energy use (and concomittant TEWI).

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