The Treatment by LEED® of the Environmental Impact of HVAC Refrigerants

APROVED BY LEED STEERING COMMITTEE
OCTOBER 25, 2004

APPROVED BY USGBC BOARD
NOVEMBER 8, 2004

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Prepared by

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reviewed and accepted by TSAC, October 10, 2004

LEED™
LEADERSHIP IN ENERGY & ENVIRONMENTAL DESIGN
TSAC
TECHNICAL & SCIENTIFIC ADVISORY COMMITTEE

September 28, 2004

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PREFACE

This report has been prepared under the auspices of the U.S. Green Building Council's LEED™ Technical and Scientific Advisory Committee (TSAC), in response to a charge given TSAC by the LEED Steering Committee to review the atmospheric environmental impacts arising from the use of halocarbons as refrigerants in building heating, ventilating, and air conditioning (HVAC) equipment. To undertake this assignment, the TSAC impaneled an *ad hoc* HCFC Task Group (HCFC TG), consisting of Reva Rubenstein, Ph.D. (Chair), David Didion, D.Eng., P.E., and Jeff Dozier, Ph.D.; biographical data on the TG appear in Appendix A of this report. TSAC members, Malcolm Lewis, D.Eng, P.E., Nigel Howard, Bruce Hunn, Ph.D., and Joel Ann Todd, reviewed drafts and provided technical input into the report.

TSAC has developed a nine-step process for preparing reports on technical issues. One of the most important elements of this process is obtaining input from the various stakeholders on an issue. Stakeholder input on a preliminary report was obtained in February 2004. Subsequently the TSAC released a revised draft final report in July 2004 that took into account the comments from stakeholders. Public comments on that revision were accepted through August 2004. Incorporating input from these later comments, this document is now the final report of this task given TSAC by the LEED Steering Committee.

The January draft of the report focused only on the refrigerants used in centrifugal water chillers. In this final phase of the work, the methodologies are expanded to the other major classes of HVAC equipment and the refrigerants used in them.

This report recommends a basis for the long-term evolution of LEED credits dealing with the atmospheric impacts of refrigerants, as well as for an interim approach that can be applied to the existing Energy & Atmosphere Credit 4.

EXECUTIVE SUMMARY

This report addresses the tradeoff between ozone depletion and global warming caused by anthropogenic release of refrigerants commonly used in HVAC systems. Our analysis considers refrigerants used now and in the past in both centrifugal water chillers and unitary equipment: a range of chlorofluorocarbons (CFCs, now banned under the Montreal Protocol), hydrochlorofluorocarbons (HCFCs, scheduled for phase-out under terms of the Montreal Protocol), and hydrofluorocarbons (HFCs).

The ozone-depletion potential (ODP) of the HCFCs (e.g., HCFC-123, HCFC-22) is much smaller than the ODP of the CFCs, but is not negligible. In contrast, the HFCs (e.g., HFC-134a, HFC-410a) have an ODP that is essentially zero, but their global warming potential (GWP) is substantially greater than some of the HCFCs, leading to a *direct* global warming mechanism when the compound leaks into the atmosphere. Moreover, thermodynamic properties make the HFCs slightly less efficient refrigerants than the HCFCs given idealized equipment design, so the same amount of cooling may require more electricity and thereby causes the *indirect* release of more CO_2 in generating that electricity. The dilemma, therefore, is that some refrigerants cause more ozone depletion than others, but the most ozone-friendly refrigerants cause more global warming.

A complete analysis of the relative harms of ozone depletion and global warming is beyond the scope of this report, because the full implications of both anthropogenic effects are not known. We know that both are critically important issues, and LEED has attempted to address both—ozone depletion through Energy and Atmosphere (E&A) Credit 4, Ozone Depletion, and global warming through E&A Credit 1, Optimize Energy Performance. Version 2.1 of the LEED rating system awards one point for avoiding the use of any chlorine-containing refrigerants in buildings in E&A Credit 4. It also awards credits for varying amounts of energy savings, hence rewarding the use of a more efficient refrigerant in Credit 1. The current LEED system thereby reflects the dilemma described in the previous paragraph: there is no clear win-win solution, and an architect or builder must choose between competing environmental damages.

The charge to TSAC was *"To review the atmospheric environmental impacts arising from the use of halocarbons in HVAC equipment and recommend a basis for LEED credits that gives appropriate credit to the alternatives."* Both direct and indirect effects were to be included in the analysis. To assess the relative differences for chillers and air conditioners, we normalize ozone depletion and global warming by cooling capacity, and we compare those values with total U.S. emission of ozone depleting and greenhouse gases, both from direct and indirect emissions. Although no single refrigerant is "best" when we consider both ozone depletion and global warming, we identify those that score well in both categories.

Our analysis suggests changes within the existing LEED credit structure, as well as in future versions of LEED, to better address these issues. The best approach is to devise a new credit structure that considers both ozone depletion and *direct* global warming impacts of refrigerants, as well as their *indirect* global warming impacts.

The current LEED structure awards credit for energy savings in E&A Credit 1 and thereby addresses *indirect* global warming effects, but it ignores the *direct* emission of greenhouse gases. Moreover, although the direct global warming effects of the refrigerants analyzed are smaller than the indirect effects resulting from energy generation to operate the HVAC equipment, they are not negligible and for some refrigerants they are as large as the indirect contribution.

Moreover, the near-term strategy to address global warming should consider other greenhouse gases along with CO_2 [1].The current E&A Credit 4 should be changed now to address this gap, but it is not feasible in the near term to change the number of credits dealing with refrigerants' atmospheric impacts, and the LEED credit structure cannot handle fractional credits. Therefore, we suggest that the existing single point in Credit 4 can be modified to accommodate both ozone depletion and direct global warming impacts, by awarding a credit to compounds that score "very well" in one of the categories and "well" on the other. There are no compounds that score "very well" in both.

This approach does not single out any refrigerant *per se*, but focuses on the impacts on the atmosphere of that refrigerant as applied in specific HVAC equipment configurations. This technically robust approach to considering refrigerant alternatives will encourage LEED users to evaluate both critical atmospheric effects. We also recommend that the credit be renamed from its current "Ozone Protection Credit" to "Refrigerant Selection Credit" to reflect its broadened purview.

In future versions of LEED, we recommend that all emissions of ozone depleting substances and greenhouse gases—not just from refrigerants—be considered in the credit structure. This could involve separate credits for ozone depletion and global warming.

1.0 INTRODUCTION

As the scientific community discovers new environmental problems, the desire to live with a minimal impact on our environment becomes more complex. Some choices have inherent environmental tradeoffs. Technologies, materials, or practices designed to ameliorate one problem may exacerbate another.

To make matters worse, the political recognition that one pollutant represents a societal threat, as compared to another, is not always timely. Such is the case with ozone depletion and global warming. While the legal protection of the ozone layer is well in place throughout most of the international community via the Montreal Protocol, the same nations lack agreement that global warming is a comparable threat. Therefore, the current regulatory program to protect stratospheric ozone was established without consideration of any impact on global warming. Although many governments, non-governmental organizations, and companies *do* believe the evidence of the magnitude and consequences of global warming is compelling enough to warrant action, a similar regulatory framework is not in place in the U.S.

The U.S. Green Building Council recognizes the critical importance of both issues and addresses them in its LEED™ rating system (Leadership in Energy and Environmental Design). Global warming is addressed in Energy & Atmosphere (E&A) Credit 1, which awards points for energy efficiency, and in other credits, which also contain provisions for proximity to public transportation, local energy generation, and use of energy from renewable sources. Ozone depletion is addressed in E&A Credit 4, which awards one point for avoidance of HCFCs and halons in HVAC and refrigeration equipment and fire suppression systems, and in E&A Prerequisite 3, which prohibits the use of CFC-based refrigerants.

The specific issue addressed in this report is a tradeoff between anthropogenic ozone depletion and global warming in the choice of refrigerants. The chlorine-based halogen refrigerants (e.g., HCFC-123) often represent the most efficient working fluids for the air conditioning industry, but their ozone-depleting effect is about 2% of that of CFC-11, which is no longer produced under the terms of the Montreal Protocol. HCFCs will be phased out in 2020 for new equipment under terms of the Montreal Protocol; production can continue until 2030 for servicing purposes. Some alternative compounds, such as HFC-134a, have virtually no effect on stratospheric ozone, but they are themselves greenhouse gases, so their leakage into the atmosphere exacerbates global warming. For thermodynamic reasons, they are also slightly less efficient than HCFCs, thereby requiring more power (with similar ideal equipment) and thus causing more carbon dioxide emission for the same amount of cooling.

Because of these considerations, the LEED Steering Committee charged its Technical Scientific Advisory Committee with the following tasks (see Appendix B):

> *"To review the atmospheric environmental impacts arising from the use of halocarbons in HVAC equipment and recommend a basis for LEED credits that gives appropriate credit to the alternatives. The review should consider:*
>
> - *"The direct effect of leaked halocarbons on the atmosphere (including but not necessarily limited to ozone depletion and global warming potential).*
> - *"The indirect effects on the energy efficiency of equipment in operation and the consequential effects on atmospheric emissions and impacts (including but not necessarily limited to global warming potential)."*

1.1 Current Status

The current LEED Version 2.1 rating system [2] addresses ozone depletion and global warming related to HVAC equipment as follows:

- E&A Credit 4 addresses the negative impact that a halocarbon has on the ozone layer. It awards one point for elimination of HCFCs and halons in HVAC and refrigeration equipment and fire suppression systems.
- E&A Credit 1 addresses global warming indirectly by awarding points for improved energy performance. If one refrigerant system is more efficient than another, it can contribute to the variety of ways a building designer can save energy.

LEED does not currently consider direct global warming effects of refrigerants from release into the atmosphere.

1.2 Significance

The credit system implicitly assumes that designers have the ability to make a trade-off between the building's impact on ozone depletion and indirect global warming as they select the HVAC refrigerant.

The current LEED rating system recognizes the merit of a reduction in a building's contribution toward global warming but it only addresses global warming *indirectly* as a function of energy consumption. If a more efficient refrigeration system is selected, LEED credits might be earned for the energy benefits in E&A Credit 1, but not earned in E&A Credit 4 if the refrigerant depletes ozone, even slightly. Therefore, if a cooling system achieves greater efficiency only at the environmental price of using a chlorine-containing refrigerant, an inevitable environmental conflict exists. Further, the current LEED system does not include direct impacts on global warming of refrigerant use. Is there a way to establish a quantitative description of a cooling system's *total environmental impact*, and should the assignment of LEED credits be revised? This issue is the focus of the study.

2.0 REFRIGERANT TYPES

A "refrigerant" is a working fluid that flows through a machine that is designed to pump heat from a lower temperature to a higher temperature. The overwhelming majority of such machines operate on the vapor compression cycle principle, and the fluids that meet all necessary criteria for a stable, safe, inexpensive, efficient performance are mostly in the halogen family. This means they are usually halogenated hydrocarbons. Ammonia is the most common exception. This family of chemicals fall into the following categories: CFC, HCFC, HFC, and a non-halogen refrigerants group called Natural Refrigerants. Table 1 lists the ozone-depletion (ODP) and global-warming potentials (GWP) of these chemicals used in this analysis. Over the last decade, estimates of some of these values have changed because of new knowledge, typically about atmospheric lifetimes. Values are published by the Environmental Protection Agency [3-6] and the World Meteorological Organization (WMO) [7]. Because the WMO values are better documented, we use that publication [7] as the preferred source, supplemented with values from EPA where necessary.

2.1 CFC (ChloroFluoroCarbons)

The molecules have one or more carbons, with *all* of the hydrogen atoms replaced by either chlorine or fluorine atoms. Because they are extremely stable, most of the refrigerants developed prior to the ozone crisis were of this group. However, their stability gives them a very long atmospheric life, allowing them to migrate to the stratosphere where they break up, and the free chlorine atoms reduce the amount of ozone. Manufacture of these chemicals is now banned in the developed countries that signed the Montreal Protocol. Developing countries who signed the protocol can produce CFCs until 2010, and significant amounts are still manufactured in some countries that did not sign the protocol.

2.2 HCFC (HydroChloroFluoroCarbons)

The molecules have one or more carbons, with *some* of the hydrogen atoms replaced by either chlorine or fluorine atoms. Typically these refrigerants are designed to be sufficiently stable within the machine but have a relatively short atmospheric life, thereby minimizing their damage to the ozone layer. Nevertheless, they are scheduled to be phased out in the future under

Table 1. Ozone-depletion and global-warming potentials of refrigerants (100-yr values)

Refrigerant	ODP	GWP	Building Applications
Chlorofluorocarbons			
CFC-11	1.0	4,680	Centrifugal chillers
CFC-12	1.0	10,720	Refrigerators, chillers
CFC-114	0.94	9,800	centrifugal chillers
CFC-500	0.605	7,900	centrifugal chillers, humidifiers
CFC-502	0.221	4,600	low-temperature refrigeration
Hydrochlorofluorocarbons			
HCFC-22	0.04	1,780	air conditioning, chillers,
HCFC-123	0.02	76	CFC-11 replacement
Hydrofluorocarbons			
HFC-23	$< 4\times10^{-4}$	12,240	ultra-low-temperature refrigeration
HFC-134a	$<1.5\times10^{-5}$	1,320	CFC-12 or HCFC-22 replacement
HFC-245fa	$\sim10^{-5}$	1,020	Insulation agent, centrifugal chillers
HFC-404A	$\sim10^{-5}$	3,900	low-temperature refrigeration
HFC-407C	$\sim10^{-5}$	1,700	HCFC-22 replacement
HFC-410A	$< 2\times10^{-5}$	1,890	air conditioning
HFC-507A	$\sim10^{-5}$	3,900	low-temperature refrigeration
Natural Refrigerants			
CO_2	0	1.0	
NH_3	0	0	
Propane	0	3	

Data sources: [3-7], with [7] considered the most reliable source to resolve differences terms of the Montreal Protocol, so that even those refrigerants in this group that have a short enough atmospheric life that they do little ozone damage (less than 2% compared to CFC-11) are to be eliminated.

2.3 HFC (HydroFluoroCarbons)

The molecules have one or more carbons, with *some* of the hydrogen atoms replaced by fluorine atoms. HFCs typically have a negligible impact on the ozone layer, but many have a significant GWP value. There is a strong movement in Europe to expand their areas of application.

2.4 Natural Refrigerants (CO_2, H_2O, NH_3, HC, Air)

Five refrigerants, arbitrarily grouped under this title in the early 1990s, are environmentally benign to the atmosphere. They were and are used as refrigerants in various applications, but all have significant limitations for buildings. There is a strong movement in Europe to expand their areas of application.

2.4.1 CO_2 (carbon dioxide)

Currently being considered for automotive air conditioning, it is inherently inefficient for building applications. Moreover, its operation at a pressure of 100 atmospheres may raise safety concerns. As the gas to which other compounds are normalized, its GWP is 1.0 mass unit CO_2 equivalent.

2.4.2 H_2O (water)

Water is used for making ice for some limited industrial applications. Because of its very low vapor pressure, machine size per unit capacity is of an order of magnitude larger than current building machinery. Although it is the main gas responsible for absorption of infrared radiation in the atmosphere, its very short atmospheric lifetime (9 days) makes any anthropogenic emission completely benign.

2.4.3 NH_3 (ammonia)

Ammonia is widely used in industrial applications because of its excellent thermodynamic performance. Building, fire, and hazardous materials codes apply limitations because of safety concerns.

2.4.4 HC (hydrocarbons)

Propane, butane, ethane, isobutene, and isopentane are good refrigerants thermodynamically, but their flammability limits capacity inside buildings to be not much larger than a home refrigerator. HCs are sometimes used as blend components in service fluids to avoid the need for lubricant change with conversions to HFCs.

2.4.5 Air (78% N_2, 21% O_2, 1% H_2O, + trace gases)

Inherently inefficient compared to all other refrigerants, air is being considered in Europe for railway air conditioning.

2.5 Other Building Applications

Halocarbons are also used in buildings for applications other than working fluids in cooling equipment. In particular, they are used in the cells of foamed insulation and in fire fighting systems. Although these fluids are of the same chemical family as the machinery fluids, such applications are beyond the scope of the current assignment to the TSAC. Since their use causes emission to the atmosphere, with consequences for both ozone depletion and global warming, future versions of LEED should consider the building's total effects, including those of the non-refrigeration applications.

3.0 MARKET DISTRIBUTION FOR VARIOUS REFRIGERANT TYPES AND HVAC EQUIPMENT TYPES

The LEED E&A Credit 4 applies to all types of HVAC systems, including unitary (direct expansion package rooftop equipment, split system, through-the-wall, and heat pumps) and water chillers (centrifugal, reciprocating, screw, and absorption). There is significantly more unitary HVAC equipment specified and installed than water chillers, both in terms of number of units and total amount of refrigerant charge [8]. However, our analysis is similar for all types of cooling strategies and therefore applies to both small and large units.

Approximately 50% of the water chillers in existing buildings still use CFC-11 as refrigerant [8], and many of these remaining chillers are old, inefficient and often leaky; retrofitting them is not cost-effective. Of particular significance for *LEED for Existing Buildings*, it makes sense to encourage the retrofitting of existing chillers using CFC-11 to HCFC-123 only for the newer CFC-11 chillers [9]. Replacement with new energy-efficient chillers is the choice most owners should make now. The annual volume of refrigerants sold for replacement in existing building equipment is four times that sold for new equipment, so the significance of the existing buildings market cannot be ignored.

4.0 DIRECT AND INDIRECT EFFECTS OF HVAC EQUIPMENT AND REFRIGERANTS ON OZONE DEPLETION AND GLOBAL WARMING

To compare the environmental impacts on ozone depletion and global warming of all refrigerants, we adapt a simple model, based on one developed for EPRI [10], to calculate *life cycle* values for an *ozone depletion index* and a *global warming index*. The impacts occur through two mechanisms:

- *direct* impacts from the leakage of gases that deplete ozone through stratospheric chemical reactions or warm the atmosphere through their absorption of Earth's thermal emission, and
- *indirect* global warming impacts, which occur through the amount of electricity consumed as a function of the chiller's operating efficiency—the lower the chiller's efficiency, the more electricity is consumed and consequently the more CO_2 emissions are generated.

However, because LEED E&A Credit 1 addresses the indirect global warming impacts, we focus on a comparison of the direct impacts, which are not currently addressed in LEED, although we show how both would be calculated.

4.1 Direct Effects

Metrics for Analysis of Direct Effects. Our analysis of direct effects uses performance-based metrics of the *life-cycle ozone depletion index* and *life-cycle direct global warming index* of the refrigerant used by HVAC for a building, normalized per Ton of Cooling Capacity and per Year of Equipment Life for the HVAC equipment. The equations describing these two factors are:

$$LCODI = \frac{ODP_r \times R_c \times (L_r \times Life + M_r)}{Life} \tag{1}$$

$$LCGWI_d = \frac{GWP_r \times R_c \times (L_r \times Life + M_r)}{Life} \tag{2}$$

Note that the equations are identical for all variables except ODP_r and GWP_r and that only the direct effect of the refrigerant on global warming is included. The variables are:

> *LCODI*: Life-Cycle Ozone Depletion Index [lb CFC-11/(ton-year)].
> $LCGWI_d$: Life-Cycle Direct Global Warming Index [lb CO_2/(ton-year)].
> ODP_r: Ozone Depletion Potential of Refrigerant $0 < ODP_r < 0.2$ lb CFC-11/lb_r.
> GWP_r: Global Warming Potential of Refrigerant $0 < GWP_r < 12{,}000$ lb CO_2/lb_r.
> L_r: Refrigerant Leakage Rate (% of charge per year) $0.5\% < L_r < 3\%$/Year.
> M_r: End-of-life Loss (% of charge) $2\% < M_r < 10\%$.
> R_c: Refrigerant Charge (lb refrigerant per ton of cooling capacity) $0.9 < R_c < 3.3$.
> *Life*: Equipment Life (Years) 20 < *Life* < 35 Years.

The task group has evaluated the range of actual values of *LCODI* and $LCGWI_d$ for a uniform random sample of the various types of HVAC equipment and refrigerants on the market, using the ODP_r and GWP_r values from Table 1 and values for L_r, M_r, and R_c for a wide range of equipment on the market, as listed in the tabulation of values below Equations (1) and (2) and

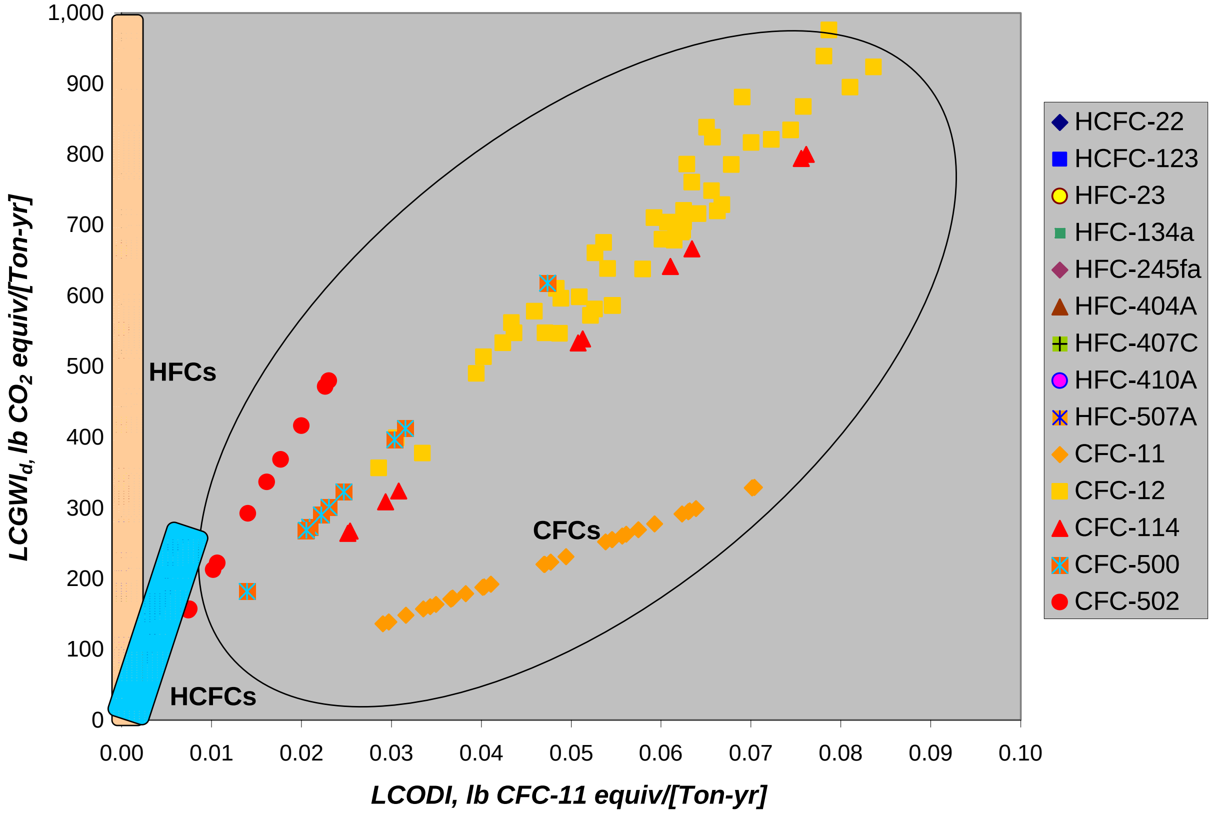

Figure 1. Life-cycle direct global warming & ozone depletion for all refrigerants

provided by manufacturers. The samples for each refrigerant were drawn from the values in Appendix C. The numbers of samples used in the simulation reflected each refrigerant's approximate market share, in high, medium, and low categories, and these numbers are also in Appendix C. Plotting these data against each other as $LCGWI_d$ vs. *LCODI* provides an instructive depiction of the atmospheric impacts of refrigerants—both ozone depletion and direct global warming—that occurs for different equipment and refrigerants (Figure 1). It also illustrates the inherent trade-off between these two impacts that exists for each possible choice: some deplete less ozone but cause more global warming, and *vice versa*. These variations are a function not only of the refrigerant but also of the performance of the specific refrigeration equipment. Note that Figure 1 should not be misinterpreted as representing a dependent relationship between the two axes: the two axes are entirely independent variables. Choices of refrigerants inevitably represent a mix of these two factors, and the figure merely shows this mix.

The analysis recognizes that the leakage values L_r and M_r are not uniform for a given piece of HVAC equipment. For example, an annual leakage rate of 1% refers only to the machine that remains closed but under normal operation throughout the year. In addition, refrigerants escape to the atmosphere through poor service practices, accidents, and, albeit rare, assembly line or shipping mishaps. End-of-life recovery and service reclaim practices contribute to the value of M_r. Data on refrigerant replacement sales could help quantify these leakage rates.

Figure 2 shows the same information as in Figure 1, but with the axes rescaled to better

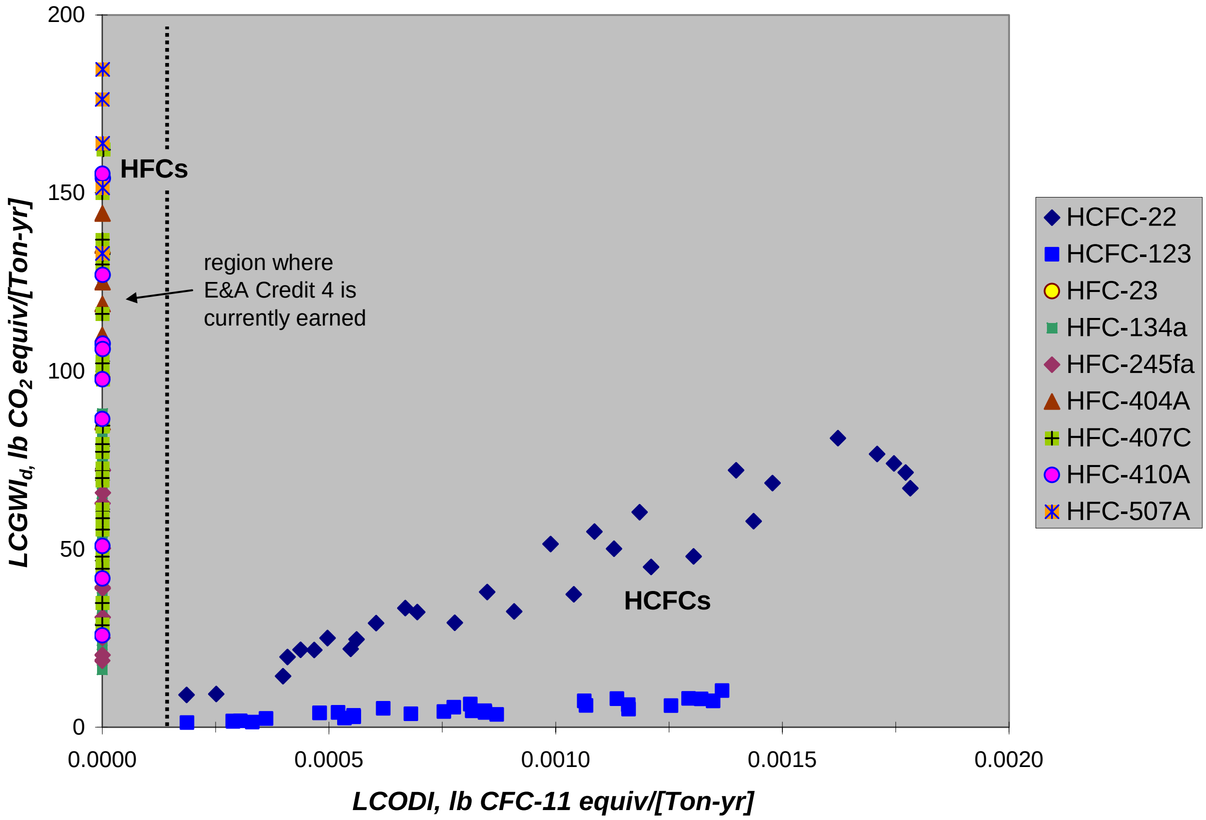

Figure 2. Life-cycle direct global warming & ozone depletion for all refrigerants, showing current coverage of E&A Credit 4

show the differences between the HFCs and the HCFCs. It also shows the current coverage of E&A Credit 4, which is a prescriptive credit that only includes HFC refrigerants and excludes HCFCs. While the HFCs deplete less ozone, HCFC-123 in particular causes less global warming than the HFCs. In the current credit structure there is no penalty for unbounded direct global warming through leakage of HFCs. Compared to CFCs, *all* current mainstream refrigerants have relatively low ozone depletion and direct global warming impacts. This is properly reflected in the LEED E&A Prerequisite 3, which bans CFC refrigerants.

Table 2. Direct (non-combustion) U.S. emissions of greenhouse gases

Gas	**2002 U.S.emission (lb CO_2 equivalent)**
CO_2	3.77×10^{11}
CH_4	1.04×10^{12}
N_2O	7.98×10^{11}
HFCs, PFCs, SF_6	3.04×10^{11}
Total	$\mathbf{2.52 \times 10^{12}}$
Data source: [6]	

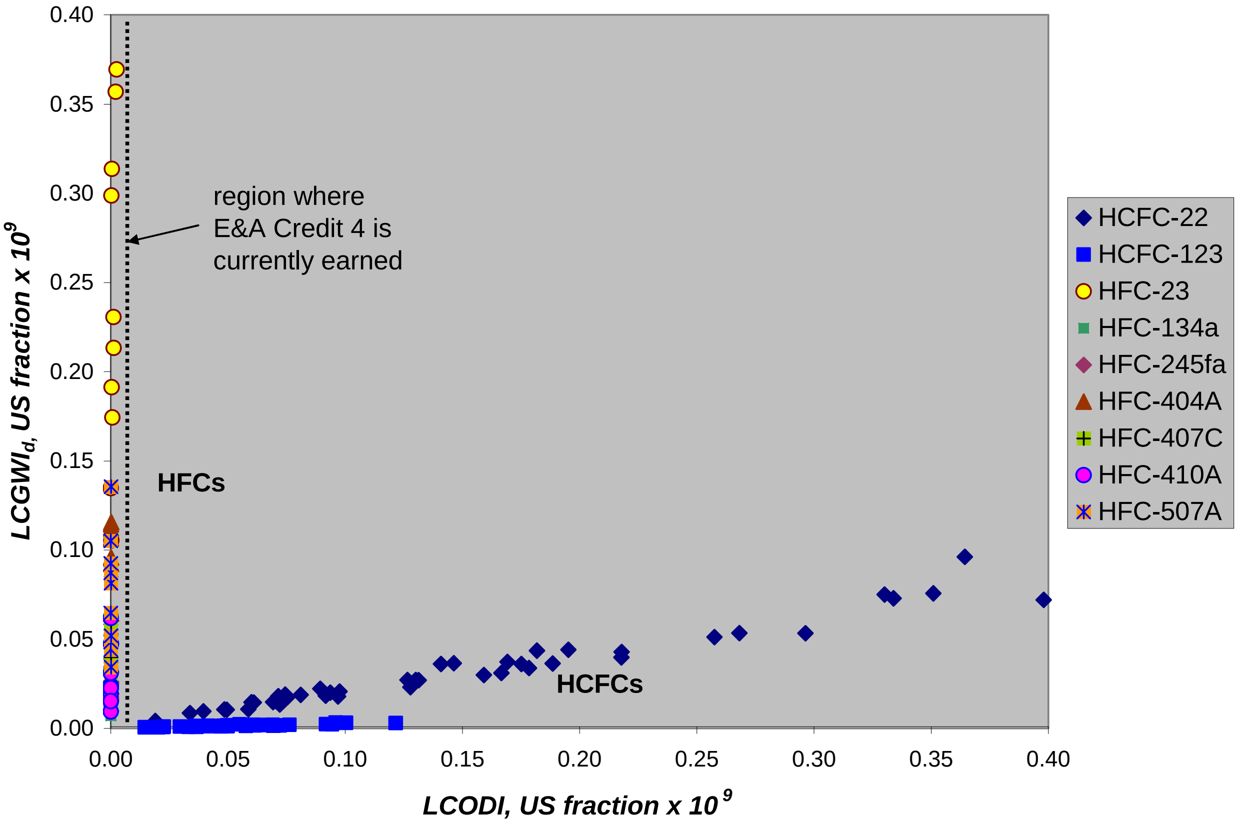

Figure 3. Life-cycle direct global warming & ozone depletion, expressed as fraction of U.S. total, per ton of cooling capacity

Normalizing Against U.S. Totals. The total annual U.S. emission of ozone depleting chemicals is 1.27×10^7 lb CFC-11 equivalent [11], whereas the total annual *direct* U.S. emission of global warming gases is 2.52×10^{12} lb CO_2 equivalent [6] in 2002 (Table 2). Using these totals, we compare the relative magnitudes of the life-cycle ozone depletion and direct global warming impacts of refrigerants considered in this report, by expressing them as a fraction of annual U.S. emissions. Figure 3 expresses the data in Figure 1 in this fashion, dividing the *LCODI* and

$LCGWI_d$ values by the U.S. totals and multiplying by 10^9 to present them as “nano-fractions,” i.e. the fraction of the U.S. total direct emission of either ozone depleting or global warming substances that results from a ton of cooling capacity with a specific refrigerant. The relative magnitudes, expressed in this way, are similar. For ozone depletion, the nano-fractions for the HCFCs range from 0.02 to 0.50. For global warming, the nano-fractions range from 0.01 to 0.40. Note that although CO_2 is the major gas contributing to anthropogenic global warming, most of its emission results from fossil fuel combustion. CH_4 and N_2O account for most of the non-combustion emissions of greenhouse gases.

4.2 Indirect Effects

The *indirect* life-cycle global warming index, based on CO_2 emitted in producing the energy to operate the chiller, may be estimated using [10]:

$$LCGWI_i = EFL \times P \times \sum_j f_j \times CDF_j \qquad (3)$$

The variables are:

$LCGWI_i$ has the same units as $LCGWI_d$, lb CO_2/(ton-year).
CDF_j is the CO_2 produced per kilowatt-hr of power generated from source j .
EFL is the equivalent full load of operation (hr/yr).
P is the equipment performance (kW/ton).
f_j is the fraction of power generated with fuel source j.

The Carbon Dioxide Factor, *CDF*, is the conversion factor for determining the amount of CO_2 released into the atmosphere from the electric power plant. Of course this factor varies with the type of plant (i.e., coal, gas, hydropower, etc.). For hydropower, wind, solar, and nuclear power, the value is zero. For fossil fuels, *CDF* ranges from 1.25 to 4.0 lb CO_2 per kWh [12].

The only variable in Equation (3) that depends on the refrigerant is *P*, the chiller performance rating, which is defined as the ratio of power in (kW) to cooling capacity (ton). Therefore, a lower value of *P* indicates a higher efficiency. For the determination of these values for both the HFC-134a and HCFC-123 chillers, we use the NIST Standard Reference Database 49 [13]. This database was developed specifically for the comparison of refrigerants and refrigerant mixtures performance within the theoretical vapor compression cycle without the encumbrances of specific hardware specifications. The program consists of a simulation of the vapor compression cycle that can call upon the NIST Reference Database 23:REFPROP, a program that contains the world’s most authoritative thermophysical properties of refrigerants [14]. Analyses of two commonly used refrigerants give theoretical full-load results of 0.509 kW/ton for HCFC-123 and 0.533 kW/ton for HFC-134a, illustrating the maximum differences between refrigerants. Therefore a theoretical chiller running at full load 1500 hr/yr, with electricity generated by fossil fuel combustion, would have $LCGWI_i$ values as shown in Figure 4.

Note that the energy source for electricity generation causes far greater variability in CO_2 emissions than the choice of refrigerant, hence the need for LEED to expressly consider carbon emissions in future versions, rather than just energy cost.

Total U.S. emission of greenhouse gases for energy production, including transportation, is 1.27×10^{13} lb CO_2 equivalent per year (in 2002) [6]. The right-hand axis of Figure 4 shows the “nano-fractions” of the indirect emissions from energy production per ton-year of cooling, as compared to the emissions from all energy production. Note that although the amount of global

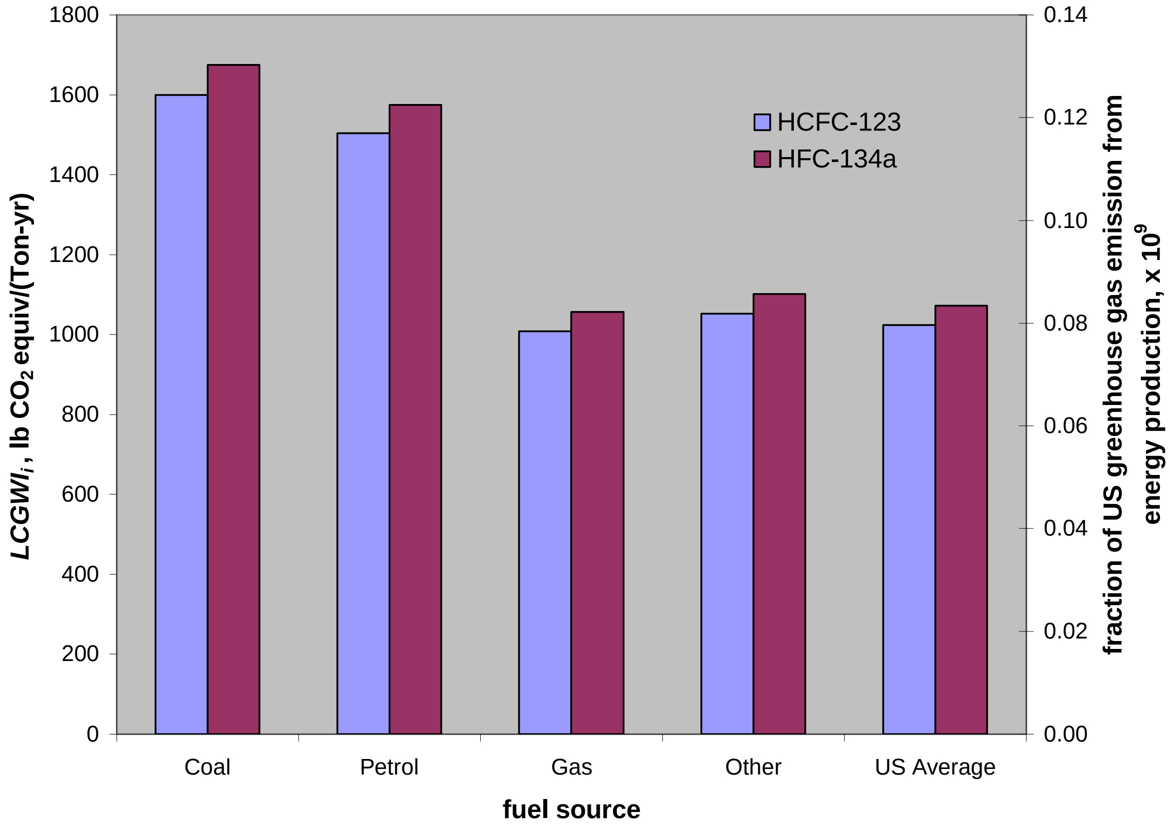

Figure 4. Indirect global warming from theoretical full-load operation of air conditioning equipment

warming from energy production is greater than for direct emissions, the fraction of the respective totals from direct emission of refrigerants (from Figure 3, 0.02-0.40 nano-fractions per ton of cooling) is very similar to the fraction for energy production (from Figure 4, 0.08-0.13 nano-fractions per ton of cooling).

We are not proposing that LEED use Equation 3 for calculating energy performance. LEED-NC (New Construction) uses ASHRAE/IESNA Standard 90.1 to determine energy savings and takes into account part-load operation. Because this report does not recommend a change in LEED E&A Credit 1, we leave this consideration to further study for LEED Version 3.0 or later. Thus the recommendations in the next section address only direct effects,

5.0 RECOMMENDED CONCEPT FOR RECOGNIZING ENVIRONMENTAL IMPACTS

Figures 1 through 3 show clearly that the *relative shares* of the refrigerants' effects on ozone depletion and global warming are similar, and that the direct global warming effect is a significant part of the U.S. total. Therefore, it is important to develop a credit structure that considers both direct global warming and ozone depletion. In the current structure, additional credits are not an option, and LEED does not allow award of fractional credits. In the future, the credit structure could be modified in several ways, including changing the number of credits available under E&A Credit 4 to address direct global warming and ozone depletion explicitly, addressing all global warming in a separate credit, or perhaps by some other approach. This recommendation addresses both ozone depletion and direct global warming under the current credit structure and only considers refrigerants. We do not address indirect global warming, which is covered under E&A Credit 1.

5.1 Concept for a Combined Refrigerant Selection Credit

Figure 5 has the same data as Figure 2, but shows the proposed mechanism for providing a performance-based credit based on the combined values of *LCODI* and $LCGWI_d$ for the various refrigerant options to earn the Credit 4: *any HVAC equipment selection whose impact on the atmosphere falls to the left of the diagonal line (towards the origin of the graph) would earn the credit.* The generalized equation for the proposed credit criterion is thus:

$$A \times LCGWI_d + B \times LCODI \leq C \tag{4}$$

The challenge is that the location of the diagonal line defining the “credit earned” zone in Figure 5 is subjective and should be guided by USGBC policies. Lacking a scientific basis for setting the limit, LEED could follow its established policy, used in other LEED credits, of rewarding the top 25% of the market with eligibility for the credit. To accomplish this, the line could be located so that the top quartile (25%) of HVAC equipment performers (on the combined ODP/GWP metrics) earns the credit. Based upon the limited data sample available and on our understanding of the current market mix of HVAC refrigerants and equipment, we suggest setting the line as shown, with *A*=1, *B*=100,000, and *C*=100. If other data are made available by manufacturers, the precise location of the “credit earned” line could be adjusted accordingly. Likewise, if the performance of available equipment improves over time, the line

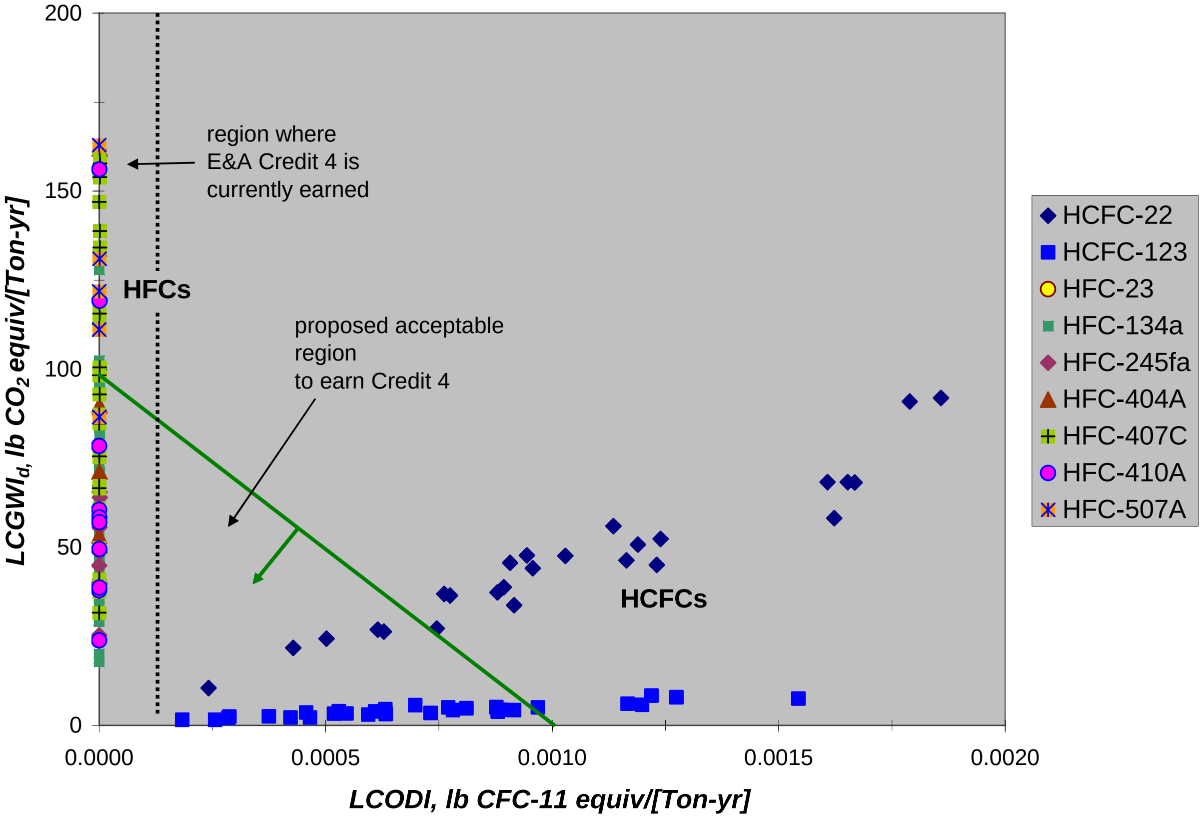

Figure 5. Illustration of proposed credit concept

could shift (in subsequent versions of LEED) closer to the origin, so that it continues to give credit to the top 25% of performance.

We recommend that this concept be developed into revised credit language for E&A Credit 4 for the upcoming releases of LEED products. Longer term, USGBC may consider alternative ways of accommodating these principles within different credit structures. The arguments in favor of this approach include:

- Both global warming and ozone depletion impacts of refrigerants are critical issues and should be addressed in LEED. Indirect global warming is addressed in E&A Credit 1, while direct warming through emission of greenhouse gases is not. The scientific analysis indicates that candidate refrigerants, e.g. HCFC-123 and HFC-134a, contribute similarly either to ozone depletion or direct global warming (although their absolute magnitudes are quite different). Moreover, the direct global warming from leaking refrigerants is of similar magnitude to their indirect warming through energy generation. Therefore, it is important to consider the direct global warming impacts as well. E&A Credit 4 is the obvious place to do so.
- Figure 5 shows that trade offs between refrigerants in terms of ozone depletion and direct global warming can be meaningfully considered together in a single credit. There are refrigerants and configurations that score *very well* on one parameter and *well* on the other – and *vice versa*. Refrigerants with very small impacts on either ozone depletion or global warming can be distinguished from other refrigerants which only do *well* on both. There are none that do *very well* on both.
- It does not single out any refrigerant *per se*, but focuses on the *impacts on the atmosphere* of that refrigerant as applied in specific HVAC equipment configurations. Not all configurations of HFCs and HCFCs will qualify; those with relatively high specific charge or leakage rate would not. It would be possible for specific equipment to earn the credit even if other equipment using the same refrigerant does not. This would properly create incentives for manufacturers to offer improved equipment performance, and more benign atmospheric impacts, even within differing classes of refrigerants.
- It reflects the importance of the *direct* emissions that leaking refrigerants contribute to global warming. U.S. non-combustion emission of greenhouse gases is 2.52×10^{12} lb CO_2 equivalent, vs. 1.27×10^{13} lb CO_2 from combustion. Therefore direct emission causes about 16% of the combined direct and indirect contribution to global warming. The emission from refrigerants are significant parts of both the direct warming (0.02-0.40 nano-fractions per ton of cooling) and the indirect warming (0.08-0.13 nano-fractions per ton of cooling).

5.2 Critical Leakage Rates and Refrigerant Charges

Once one chooses a refrigerant, the values for ODP_r and GWP_r are fixed, with the values shown in Table 1. Thus the only variables anyone can adjust, through choice and maintenance of the equipment, are the leakage rates (L_r and M_r), the charge (R_c), and the equipment life (*Life*). Combining Equation (4) with (1) and (2) and rearranging terms yields

$$A\times GWP_r + B\times ODP_r \le C\left[\frac{Life}{R_C\times\left(L_r\times Life + M_r\right)}\right] \qquad (5)$$

Using Equation (5), a designer can tell what leakage rates and charge would achieve the credit, given a choice of refrigerant, whose values for GWP_r and ODP_r are in Table 1. We believe that manufacturers' and suppliers' data must be supplied to document values of L_r, M_r, *Life*, and (of course) R_c. LEED should provide default values for L_r, M_r, and *Life*, perhaps at 1%, 3%, and 30 yr. A project or manufacturer must provide convincing evidence to support values other than the defaults. Manufacturers' assertions of low leakage rates based on testing of joints under laboratory conditions would not be considered convincing, because most of the leakage occurs during servicing, rather than as some gradual diffusion process in every installation.

6.0 CONCLUSIONS

An objective scientific analysis of trade-offs between global warming and ozone depletion is extremely complex, and will only come from a full understanding of all interacting pathways and the effects on economic activities, human health, and terrestrial and oceanic ecosystems. Any quantitative credit scheme addressing both must involve some subjectivity in the relative weight given to each issue, at least where the final credit values are concerned. There is enough scientific evidence that global warming is a problem that it should be included in LEED.

We recommend that the E&A Technical Advisory Group and the LEED Product Committees consider introducing the approach presented here to E&A Credit 4 in the versions and refinements now being developed, as an alternative to the existing ozone-only structure. We believe that it is a more technically robust approach to considering refrigerant alternatives and that it will encourage LEED users to evaluate both critical atmospheric effects. We also recommend that the credit be renamed from its current "Ozone Protection Credit" to "Refrigerant Selection Credit" to reflect its broadened purview.

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APPENDIX A: AUTHORS' BIOGRAPHICAL DATA

Reva Rubenstein, Ph.D, Task Group Chair

Dr. Rubenstein has more than 40 years experience in the technical sciences, including chemistry, public policy, science education, toxicology, and environmental management, and specializes in matters related to the health and environmental impacts of chlorofluorocarbon (CFC) substitutes. She acted as the Science Advisor to the Director of the Stratospheric Protection Division (now Global Programs Division) of the U.S. Environmental Protection Agency (EPA) until her retirement in March 2001. Her duties included analysis of toxicity and exposure reports submitted to the EPA under the Significant New Alternatives Policy (SNAP) program for both new and existing chemical alternatives. During her tenure as Science Advisor and Toxicologist for the U.S. EPA, she served on a variety of honorary committees and won awards for her knowledge and dedication. In 1997, she received the U.S.EPA Bronze Medal for Commendable Service for contributions to the research strategies for protection of stratospheric ozone. Since 1995, she has served as a member of the United Nations Environmental Programme Halon Technical Options Committee. She is also serving a term from 1999 to 2002 as a member of the Halon Alternative Protection Options HAO-AAA Technical Committee, which is responsible for clean agent fire extinguishing systems (NFPA 2001). In 1996, she served as a member of the Committee on Fire Suppression Substitutes and Alternatives to Halon 1301. This committee was a committee of the National Research Council's Naval Studies Board. She was a member of the United States Coast Guard delegation to the Fire Protection Subcommittee of the International Maritime Organization from 1998 to 2000. This subcommittee reports to the Maritime Safety Committee and the Maritime Environmental Protection Committee in furtherance of its responsibility to develop regulations under the Safety of Life at Sea Treaty, (SOLAS).

David A. Didion, D.Eng., P.E.

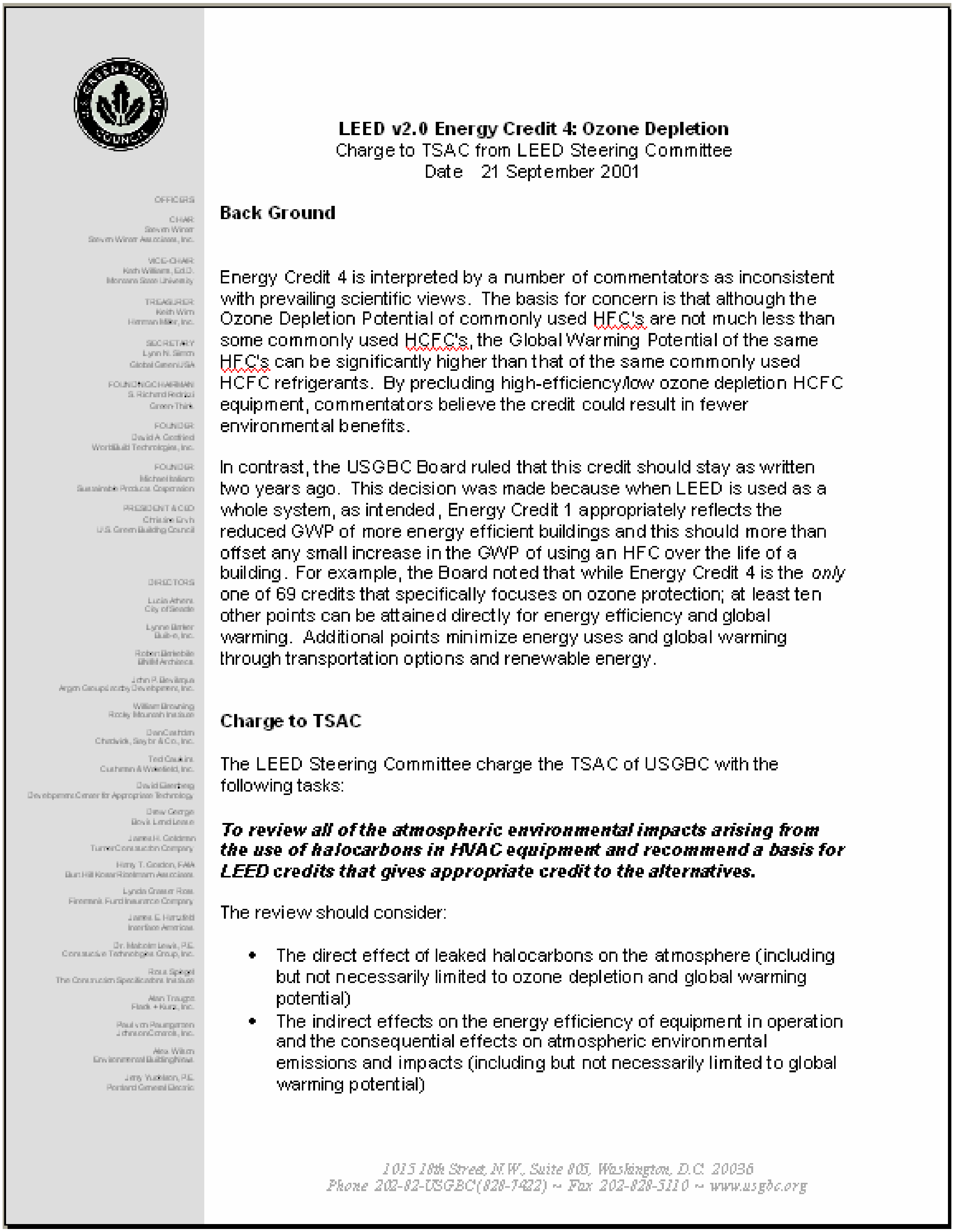
David Didion is a retired Fellow of the National Institute of Standards and Technology (NIST). He began the refrigeration engineering phase of his career as a project engineer in the Building and Fire Research Laboratory in 1971. By 1974, he had become the leader of the Thermal Machinery Group and began a 10 year program to develop a series of laboratory test methodologies for seasonal efficiency ratings of various vapor compression cycle machines (e.g., air conditioners and heat pumps). These procedures are in use throughout the manufacturing industry, today. In 1981, he started a research program in zeotropic refrigerant mixtures. This program's modeling and laboratory efforts focused on the interaction between the machinery and their working fluids. This work helped point the way for the world-wide industrial effort to develop the new, chlorine-free, refrigerant mixtures that are compatible with the earth's ozone layer. For this 15 year effort, he has received several honors and awards from the U.S. Department of Commerce, the DuPont Corporation, the Air Conditioning and Refrigeration Institute, the American Society of Mechanical Engineers, and the American Society of Heating, Refrigeration, and Air Conditioning Engineers, the U.K.'s Institute of Refrigeration's 2001 Gold Medal, and the International Institute of Refrigeration's highest honor: the Lorentzen Prize. Throughout this period, he has maintained a teaching career in the graduate engineering evening programs at the University of Maryland and Johns Hopkins University, where he is a 'Fellow by Courtesy'. Since his retirement from NIST, in 2002, he has remained active in his field through the continuation of engineering graduate school teaching, as the USA Regional Editor of the

International Journal of Refrigeration, and selected private consulting projects in the field of vapor compression cycles and refrigerants. He also remains active member of ASHRAE's Standards Committee 34. This committee determines if a new refrigerant has satisfied all the tests for flammability and toxicity and is thus qualified to be assigned a number (e.g. R-134a, etc.) and a safety rating category.

Jeff Dozier, Ph.D.

Jeff Dozier's research and teaching interests are in the fields of snow hydrology, Earth system science, remote sensing, and information systems. He has pioneered interdisciplinary studies in two areas: one involves the hydrology, hydrochemistry, and remote sensing of mountainous drainage basins; the other is in the integration of environmental science and computer science and technology. In addition, he has played a role in development of the educational and scientific infrastructure. He founded UCSB's Donald Bren School of Environmental Science & Management and served as its first Dean for six years. During that time he inspired and supervised the design of Bren Hall, the first LEED Platinum-award laboratory building. He was also the Senior Project Scientist for NASA's Earth Observing System in its formative stages when the configuration for the system was established. Professor Dozier received his B.A. from California State University, Hayward in 1968 and his Ph.D. from the University of Michigan in 1973. He has been a faculty member at UC Santa Barbara since 1974. He is a Fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the UK's National Institute for Environmental *e*Science. He is also an Honorary Professor of the Chinese Academy of Sciences and a recipient of the NASA Public Service Medal.

APPENDIX B: CHARGE TO TSAC



LEED v2.0 Energy Credit 4: Ozone Depletion

Charge to TSAC from LEED Steering Committee
Date 21 September 2001

Back Ground

Energy Credit 4 is interpreted by a number of commentators as inconsistent with prevailing scientific views. The basis for concern is that although the Ozone Depletion Potential of commonly used HFC's are not much less than some commonly used HCFC's, the Global Warming Potential of the same HFC's can be significantly higher than that of the same commonly used HCFC refrigerants. By precluding high-efficiency/low ozone depletion HCFC equipment, commentators believe the credit could result in fewer environmental benefits.

In contrast, the USGBC Board ruled that this credit should stay as written two years ago. This decision was made because when LEED is used as a whole system, as intended, Energy Credit 1 appropriately reflects the reduced GWP of more energy efficient buildings and this should more than offset any small increase in the GWP of using an HFC over the life of a building. For example, the Board noted that while Energy Credit 4 is the *only* one of 69 credits that specifically focuses on ozone protection; at least ten other points can be attained directly for energy efficiency and global warming. Additional points minimize energy uses and global warming through transportation options and renewable energy.

Charge to TSAC

The LEED Steering Committee charge the TSAC of USGBC with the following tasks:

To review all of the atmospheric environmental impacts arising from the use of halocarbons in HVAC equipment and recommend a basis for LEED credits that gives appropriate credit to the alternatives.

The review should consider:

- The direct effect of leaked halocarbons on the atmosphere (including but not necessarily limited to ozone depletion and global warming potential)
- The indirect effects on the energy efficiency of equipment in operation and the consequential effects on atmospheric environmental emissions and impacts (including but not necessarily limited to global warming potential)

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APPENDIX C: REFRIGERANT LEAKAGE & CHARGE DATA

These are the model parameters used to generate Figures 1-3 and Figure 5. Data are from the sources identified in Table 1.

	ODP, lb CFC-11 equiv	GWP, lb CO_2 equiv	Leakage per yr		End-of-Life Leakage		Life (yr)		Charge (lb/ton)		No. Simu-lations
CFC-11	1.0	4,680	1.0%	3.0%	2.0%	10.0%	20	35	2.0	2.4	30
CFC-12	0.82-1.0	10,720	1.0%	3.0%	2.0%	10.0%	20	35	2.5	3.0	50
CFC-114	0.94	9,880	1.0%	3.0%	2.0%	10.0%	20	35	1.4	3.3	10
CFC-500	0.605	7,900	1.0%	3.0%	2.0%	10.0%	20	35	1.4	3.3	10
CFC-502	0.221	4,600	1.0%	3.0%	2.0%	10.0%	20	35	1.4	3.3	10
HCFC-22	0.034-0.05	1,780	0.5%	2.0%	2.0%	10.0%	20	35	0.4	5.0	50
HCFC-123	0.012-0.02	76-120	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	30
HFC-23	$<4\times10^{-4}$	11,700	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	10
HFC-134a	$<1.5\times10^{-5}$	1,320	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	50
HFC-245fa	$\sim10^{-5}$	1,020	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	10
HFC-404A	$\sim10^{-5}$	3,900	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	10
HFC-407C	$\sim10^{-5}$	1,700	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	30
HFC-410A	$<2\times10^{-5}$	1,890	0.5%	2.0%	2.0%	10.0%	20	35	1.6	3.5	50
HFC-507A	$\sim10^{-5}$	3,900	0.5%	2.0%	2.0%	10.0%	20	35	1.4	3.3	10