Energy and Global Warming Impacts of CFC Alternative Technologies for Foam Building Insulations

S.K. Fischer **P.D. Fairchild** **P.J. Hughes**

ABSTRACT

Since their introduction in the 1930s, chlorofluorocarbons (CFCs) have been used as blowing agents in foam insulation, as the working fluids in cooling and refrigerating equipment, and as solvents in general and precision cleaning applications. The number of applications and volume of CFCs used grew at a tremendous pace during the 1960s and 1970s, but in the mid-1980s it was confirmed that these extremely useful chemicals contribute to the destruction of stratospheric ozone and that they are the primary cause of the Antarctic ozone hole (Zurer 1988). The Montreal Protocol of 1987 is a landmark agreement to protect the global environment by phasing out the production and use of CFCs. CFCs have also been found to be second only to carbon dioxide as a factor causing increased greenhouse warming. These chemicals are being phased out of use rapidly to protect the ozone layer, and it is very important that the replacements for CFCs do not result in a net increase in global warming by introducing less efficient processes that lead to higher energy use and increased carbon dioxide emissions.

A study was conducted to identify those alternative chemicals and technologies that could replace CFCs in energy-related applications before the year 2000 and to assess the total potential impact of those alternatives on global warming. The analysis for this project included an estimate of the direct effects from the release of blowing agents, refrigerants, and solvents into the atmosphere and the indirect effects of carbon dioxide emissions resulting from energy use for commercial and residential building insulation, household and commercial refrigeration, building and automotive air conditioning, and general metal and electronics solvent cleaning. The discussion in this paper focuses on those aspects of the study relevant to building insulation. In general, the hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) alternatives for CFCs lead to large and sometimes dramatic reductions in total equivalent warming impact, lifetime equivalent CO_2 emissions (TEWI). Most of the reductions result from decreased direct effects without significant changes in energy use.

INTRODUCTION

Since their introduction in the 1930s, chlorofluorocarbons (CFCs) have been used as blowing agents in foam insulation, as the working fluids in cooling and refrigerating equipment, and as solvents in general and precision cleaning applications. The number of applications and volume of CFCs used grew at a tremendous pace during the 1960s and 1970s, but in the mid-1980s it was confirmed that these extremely useful chemicals contribute to the destruction of stratospheric ozone and are the primary cause of the Antarctic ozone hole. The Montreal Protocol was drafted as an international agreement to phase out the use of CFCs in an effort to reduce future ozone losses and to permit stratospheric ozone levels to be restored to pre-1986 levels. CFCs have also been found to be second only to carbon dioxide as a factor causing increased greenhouse warming. It is very important that the compounds and technologies developed as replacements for CFCs do not result in a net increase in global warming by introducing less efficient processes that lead to higher energy use and increased carbon dioxide emissions. A study was conducted to identify those alternative chemicals and technologies that could replace CFCs in energy-related applications before the year 2000 and to assess the total potential impact of those alternatives on global warming (Fischer et al. 1992; Fairchild 1991). The analysis includes an estimate of the direct effects from the release of blowing agents, refrigerants, and solvents into the atmosphere and the indirect effects of carbon dioxide emissions resulting from energy use for commercial and residential building insulation, household and commercial refrigeration, building and automotive air conditioning, and general metal and electronics solvent cleaning. The emphasis of this paper is on the alternatives to R-11 and R-12, both CFCs, in building foam insulation.

TOTAL EQUIVALENT WARMING IMPACT

The impacts that greenhouse gases have on global warming are frequently quantified and compared with each other by using their global warming potentials (GWPs).

S.K. Fischer and **P.J. Hughes** are research engineers and **P.D. Fairchild** is manager of the Building Equipment Research Program in the Energy Division of Oak Ridge National Laboratory, Oak Ridge, TN.

Tables of these values are often presented expressing the contributions of a trace gas to global warming relative to the impact of either R-11 or R-12; one of the most useful sets of values for GWPs is that compiled by the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO) (IPCC/WMO 1990). These data express the impact of a single pound or kilogram release of a greenhouse gas relative to the impact of an instantaneous release of the same mass of carbon dioxide, CO_2. In this context, the GWP of a gas is equal to the mass of CO_2 that would have the same net impact on global warming as the release of a single unit (pound or kilogram) of the gas in question. Some of the GWP values using CO_2 as the reference gas are listed in Table 1.

The concept of the "integration time horizon" for the GWP values is an important idea that needs to be explained in order to understand the numbers in Table 1 and some of the results from this study. The time horizon arises because the GWPs are related to CO_2, and the atmospheric lifetimes of the different greenhouse gases are not the same as that of CO_2. The GWPs represent a cumulative impact on global warming over a specified period of time relative to the cumulative impact of an equal mass of CO_2 over the same period of time. If that gas is removed from the atmosphere more rapidly than is CO_2, then its GWP will decrease as the time horizon under consideration increases. An examination of the numbers for R-11 in Table 1 shows that over a 20-year period, an instantaneous release of one kilogram of R-11 has the same impact on global warming as the release of 4,500 kg of CO_2. Over a 100-year period, the impact is equivalent to the release of 3,500 kg of CO_2, and over a 500-year period it has the impact of 1,500 kg of CO_2. No single time horizon is clearly the "right" one, and the choice is often controversial.

TABLE 1
Global Warming Potentials Relative to CO_2

Greenhouse Gas	Integration Time Horizon		
	20 years	100 years	500 years
Carbon Dioxide	1	1	1
CFC-11	4500	3500	1500
CFC-12	7100	7300	4500
CFC-113	4500	4200	2100
CFC-114	6000	6900	5500
CFC-115	5500	6900	7400
HCFC-22	4100	1500	510
HCFC-123	310	85	29
HCFC-124	1500	430	150
HCFC-141b	1500	440	150
HCFC-142b	3700	1600	540
HFC-125	4700	2500	860
HFC-134a	3200	1200	420
HFC-143a	4500	2900	1000
HFC-152a	510	140	47

A drawback of the GWPs is that they cannot take into account changing system efficiencies when one of these gases replaces another in an application that uses energy. An advantage of using GWPs that are based on CO_2 is that it allows a "composite" value or total equivalent warming impact (TEWI) to be computed for buildings and systems that use both a greenhouse gas and also indirectly cause emissions of carbon dioxide due to energy use. For example, consider a 2,000-ft^2 (186-m^2), two-story home in Chicago that has 119 ft^3 (3.37 m^3) of 0.83-in. (21-mm) polyisocyanurate foam sheathing (about 1,900 ft^2 or 180 m^2). At 12.5 weight percent blowing agent, the foam contains approximately 30 lb (13.5 kg) of R-11 that will eventually escape to the atmosphere. This home, however, will consume 9,900 ft^3 (280 m^3) of natural gas each year to replace the heat losses through the insulated wall surfaces, and the combustion of natural gas will release 1,200 lbs (548 kg) of CO_2 into the air each year.

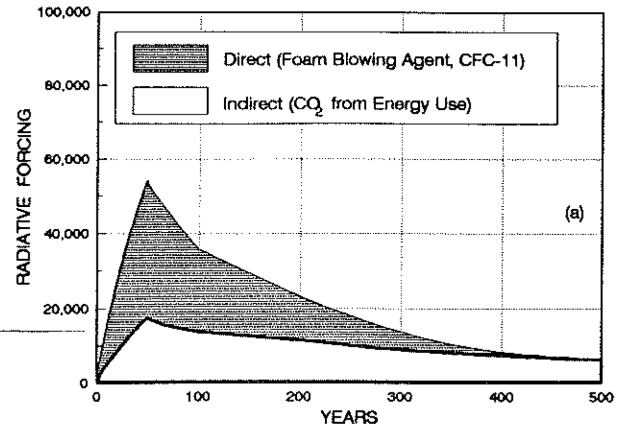
The combination of the two contributions to global warming are illustrated in Figure 1a, where it has been assumed that the R-11 trapped in the foam escapes at a constant rate over the lifetime of the building (50 years). The unshaded portion of the curves corresponds to the radiative forcing effects on temperature change resulting from the CO_2 emissions each year, and the shaded portion represents the effects of the blowing agent when it escapes to the atmosphere. It can be seen that the impacts of R-11 in this case are significant whether the cumulative effect is considered over 50, 100, 300, or 500 years. Figure 1b has a similar set of curves using the corresponding assumptions for foam sheathing that could be formed using R-123, an HCFC (it is assumed that 25% more gas will be required to create the foam due to the lower blowing efficiency of R-123 and that CO_2 emissions are higher because of an assumed lower R-value for the foam). In this case, the impact of the foam blowing agent is barely discernible in the graph, and it is an insignificant portion of the cumulative effect over almost any time horizon. The total effect, corresponding to the area beneath both curves in Figure 1b, is much less than the total effect with the R-11 blown foam in Figure 1a.

The computation of the areas under the curves in Figure 1 is an unnecessarily tedious calculation. The TEWI can be calculated using Equation 1:

$$\text{TEWI} = M \cdot \text{GWP} + \alpha_{CO_2} \cdot L_{years} \cdot E_{annual}, \quad (1)$$

where

M	=	total kilograms of the gas released to the atmosphere,
GWP	=	global warming potential using CO_2 as the reference gas,
α	=	a factor to convert energy use to CO_2 emissions from the combustion of fossil fuels,
L	=	lifetime of the system, and
E	=	annual energy use.



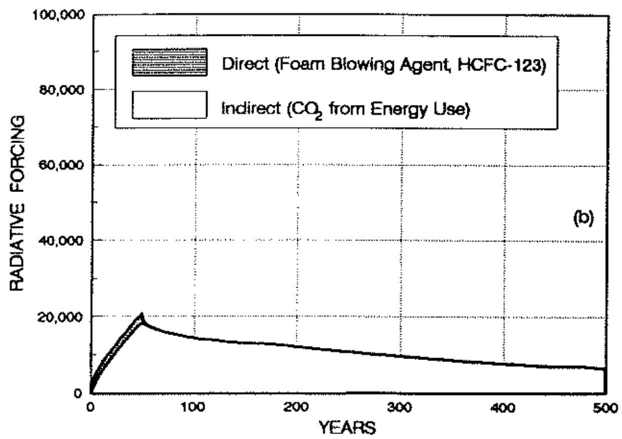


Figure 1 *Potential radiative forcing from gases associated with polyisocyanurate foam sheathing in a single-family home in Chicago: (a) baseline case using R-11 and (b) alternative case using R-123.*

The TEWI is a very good approximation of the total impact on global warming for energy-using systems and is within a few percentage points of the area under the curves except when the lifetime of emissions is of the same order of magnitude as the time horizon. Naturally, the TEWI is going to depend on the GWP and the integration time horizon chosen. For the two cases pictured in Figure 1, the 100-year TEWI for the home using R-11 is 74,600 kg equivalent of CO_2, while that for the R-123 foam sheathing is 30,300 kg. The 500-year TEWIs are 47,600 kg and 29,400 kg, respectively.

BASELINE BUILDINGS

Residential Buildings

Polyurethane, polyisocyanurate, and extruded polystyrene plastic foam insulation are all used in the wall structures of residential buildings in North America and northern Europe because of their excellent thermal properties. One common practice in wood-frame construction is to use the foam material as a layer of sheathing underneath the external siding of the building in conjunction with fiberglass batts of insulation in the cavities between the vertical studs of the building frame, as shown in Figure 2. This combination of foam and batts forms a wall with high thermal resistance. Foam insulation is also used in the cavities of masonry construction between a brick veneer on the outside of the building and the cement blocks of the building wall. In this case, the foam insulation provides almost all of the thermal resistance of the wall.

Although the study evaluated impacts of building insulation for both frame and masonry construction in North America and Europe, only the results for frame construction in Chicago, Illinois, are presented here because of the space limitations. The results for frame construction in Atlanta, Georgia, and Frankfurt, Germany, and masonry construction in Millington, U.K., are similar. The "baseline" home is a 2,000-ft^2 (186-m^2) dwelling with a high-efficiency, forced-air, natural gas furnace. Two separate cases are considered: (1) sheathing thickness selected to give an R-19 (3.35 m^{2}K/W) wall between the studs using R-11 blown polyurethane foam and (2) sheathing thickness selected to give an R-19 (3.35 m^{2}K/W) wall with R-12 blown extruded polystyrene. These thicknesses are then used with the best data available on the thermal properties of CFC-free sheathing materials. These data are listed in Table 2.

Alternative Sheathing Materials

The thickness of the alternative sheathing material is assumed to be the same as the thickness of the corresponding CFC-blown sheathing. The thermal resistance of each type of polyurethane/polyisocyanurate sheathing is chosen based on the thickness and estimates for the 50-year time-averaged R-values (McElroy et al. 1990; McElroy 1991). Thermal properties data for extruded polystyrene (XEPS) foam insulation blown with R-12 were provided by an industry source.[1] Insufficient data were available for the thermal properties of alternative XEPS products, and they were assumed to be the same as for R-12 blown foam.

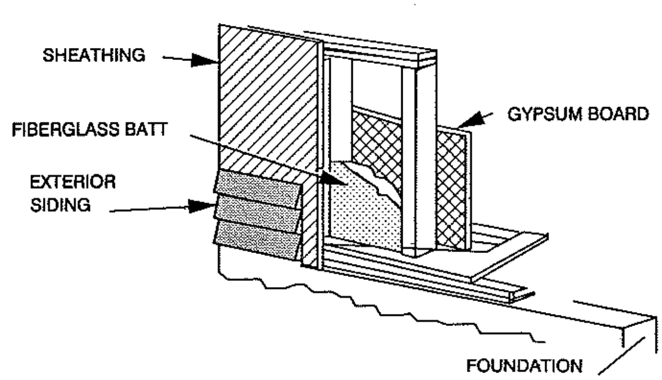


Figure 2 *Cutaway diagram of wood-frame cavity wall construction.*

[1]Private communication from John Minsker.

TABLE 2
Thermal Properties of Baseline and Alternative Sheathing Materials

Wall Sheathing (material and foam blowing agents)	Thermal Resistance ($h \cdot ft^2 \cdot {}^\circ F/Btu$)		Thermal Resistance ($m^2 \cdot K/W$)	
	foam sheathing (per inch)	wall (total)	foam sheathing (per m)	wall (total)
0.83 in. (21 mm)				
Polyurethane/ Polyisocyanurate Sheathing				
CFC-11	7.03	17.5	49	3.09
HCFC-123	6.43	17.0	44	3.00
HCFC-141b	6.12	16.7	43	2.95
Isopropylchloride	5.61	16.3	39	2.87
Non-Foam Sheathing Materials				
Bead Board	3.80	14.7	26	2.60
Glass Fiber Board	4.08	15.0	28	2.64
1.44 in. (37 mm)				
Extruded Polystyrene Sheathing				
CFC-12	3.99	17.4	28	3.07
HCFC-142b	3.99	17.4	28	3.07
HCFC-124	3.99	17.4	28	3.07
HFC-134a	3.99	17.4	28	3.07
Non-Foam Sheathing Materials				
Bead Board	3.80	17.2	26	3.02
Glass Fiber Board	4.08	17.6	28	3.09

The masses of blowing agent used for the foam in the baseline building are computed using estimates for the volume, density, and weight percent of blowing agent for the baseline gases and for each alternative. Differences in blowing efficiency were taken into account. The direct effects from emissions of blowing agents are computed from the estimated masses and the GWP values for each gas. The total direct effects on greenhouse warming are thus the mass of blowing agent for each alternative times the corresponding GWP.

These direct effects are shown in Table 3 for each of the alternative materials for polyurethane/polyisocyanurate sheathing along with the estimates for thermal losses through the insulated walls, fuel use, and annual CO_2 emissions. Building heating loads were computed using binned temperature data for an average weather year (Ballou et al. 1981). The TEWI for each of the alternatives is graphed in Figure 3, where the contributions from energy use are represented by the heavily shaded portion of each bar and the part due to emissions of the blowing agent are in the lightly shaded areas. Each of the non-CFC materials has significantly lower total contributions to global warming than the R-11 and R-12 baseline materials even though some have higher indirect effects. Another conclusion to draw from these results is that the differences between some alternatives, such as R-123 and R- 141b, both HCFCs, are relatively small when the total impact is evaluated. Similar results were observed for foam insulation in the walls of commercial buildings and essentially the same conclusions could be drawn.

Although the results shown in Table 3 and Figure 3 are calculated using 500-year GWP values, similar information can be put together using the 100-year values in Table 1. If this is done, the direct contribution of the blowing agent is a larger proportion of the total for each of the blown insulations. Some of the nonfoam alternatives are more attractive under these assumptions than they are using the 500-year GWP values. The general conclusions, however, do not change: all of the alternatives have significantly lower TEWI than do the CFC-blown foams and there are only small differences between the TEWI for R-123 and R-141b blown foams.

Commercial Roof Insulation

Analysis was also performed for alternatives to CFC-blown foam insulation in low-slope roofs of commercial buildings. In this case, the lifetime of the roof has been assumed to be 15 years, and 15-year, time-integrated, average R-values are used for computing heat losses. The results are shown in Figures 4a and 4b. Both the large volume of foam used and the relatively short lifetime of the roof are reflected in the large proportion of the TEWI due to the blowing agent. This is shown in the bars for both

TABLE 3
Total Equivalent Warming Impact of R-11 Blown Polyurethane/Polyisocyanurate Sheathing and CFC-free Alternative Insulations for a 2000 ft^2 (186 m^2) Residence in Chicago

Components	PUR/PIR Foam Sheathing Materials				Other Sheathing Materials	
	CFC-11	HCFC-123	HCFC-141b	Isopropyl-chloride	bead board	glass fiber board
Direct Effects						
volume of insulation (ft^3)	119	119	119	119	119	119
mass of insulation (lbs)	238	238	238	238	238	238
mass of blowing agent (lbs)	30	37	25	19	30	NA
GWP (500 year)	1500	29	150	15	6	NA
direct effect (equ. lbs CO_2)	45,000	1100	3750	285	180	0
Indirect Effects						
energy losses (KBtu/yr)	8450	8900	9120	9530	11,200	10,900
fuel use (ft^3)	9920	10,500	10,700	11,200	13,200	12,800
CO_2 emissions (lb/yr)	1200	1270	1300	1360	1600	1560
lifetime (yr)	50	50	50	50	50	50
indirect effect	60,000	63,500	65,000	68,000	80,000	78,000
TEWI	105,000	64,600	68,750	68,300	80,200	78,000
% Direct	43%	2%	5%	0%	0%	0%
% Indirect	57%	98%	95%	100%	100%	100%

R-11 and R-12, and it is also a factor for R-141b, R-134a, an HFC, and some of the other fluorocarbon alternatives.

CONCLUSIONS

There are several conclusions that can be drawn from these results. Foremost among these is that each of the non-CFC insulations considered is a significant improvement over the CFC-based foams with regard to their contributions to global warming. Second, in low-volume, long-life applications such as residential wall sheathing, the direct contributions from the blowing agent are only a small fraction of the TEWI, and greater reductions in future global warming contributions can be achieved through improving the thermal resistance of the wall than by focusing solely on the blowing agent with the lowest GWP. Third, low-slope roofs will have dramatically lower TEWI with any of the alternative materials, but the direct contributions from the blowing agents of plastic foams can still be a significant fraction of the total. This is a result of the assumed 15-year useful lifetime of the roof; the benefits of the large quantities of insulation and blowing agent used are enjoyed for a relatively short period of time.

Finally, recent findings are throwing some doubt on whether or not CFCs actually have a net warming effect on the atmosphere (WMO/UNEP 1991). Ozone is itself a greenhouse gas, and the destruction of ozone by CFCs has a cooling effect that partially or completely offsets the global warming from the CFCs depending on latitude and altitude. At this time, the magnitude of the net effect is uncertain, although the GWPs of the CFCs and HCFCs listed in Table 1 are likely to be reduced when this effect is taken into account. The consequence of this work is that the energy contributions to TEWI will be even more dominant than they are now, which only emphasizes the fact that the most effective way to reduce contributions to global warming will be to improve building thermal envelopes and reduce energy use.

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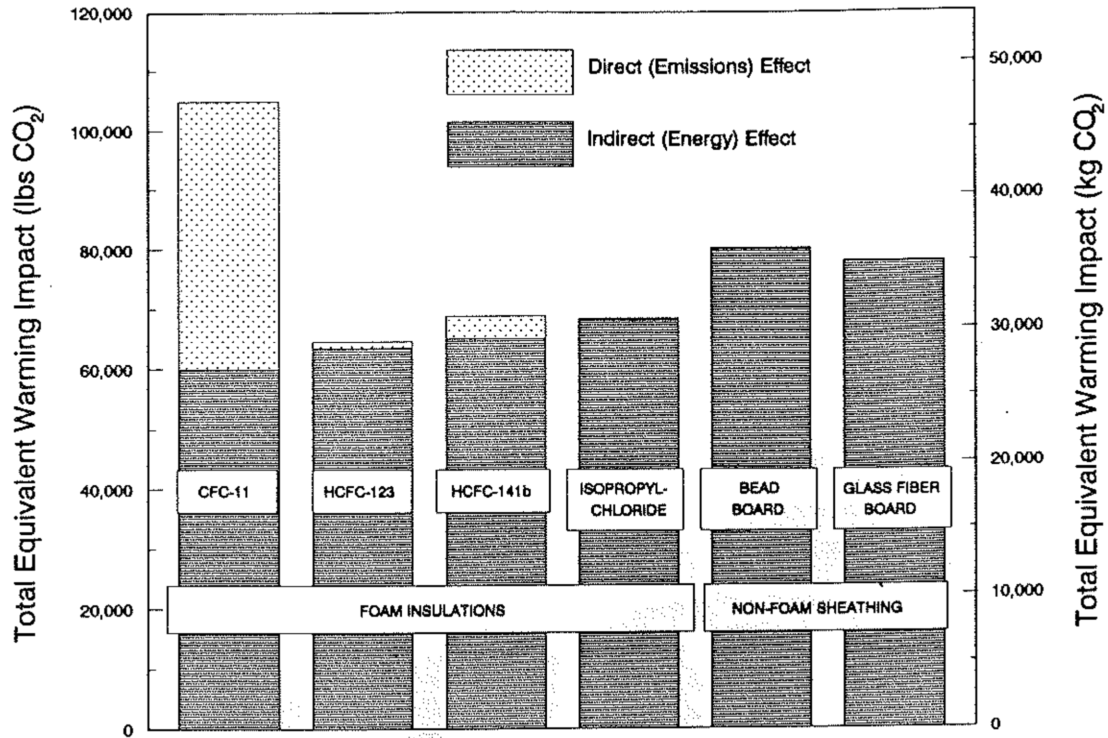

Figure 3a *TEWI for single-family home in Chicago using 0.83 in. (21 mm) polyurethane/polyisocyanurate foam and nonfoam sheathing materials (50-year building useful lifetime).*

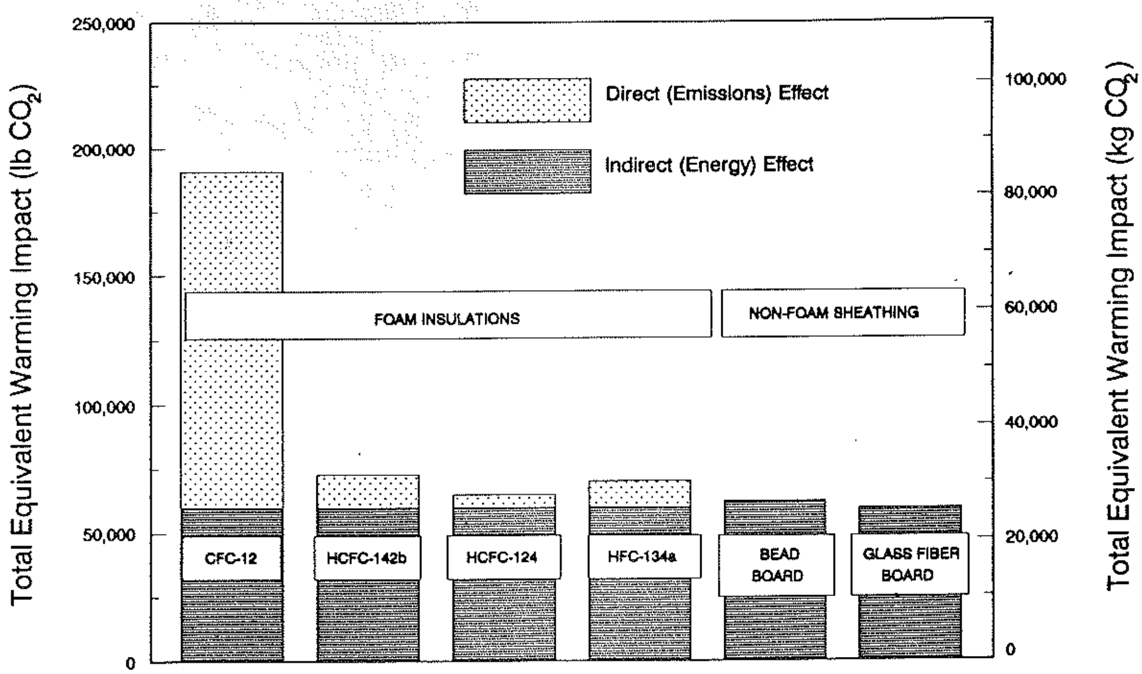

Figure 3b *TEWI for a single-family home in Chicago using 1.44 in. (37 mm) extruded polystyrene and nonfoam sheathing materials (50-year useful building lifetime).*

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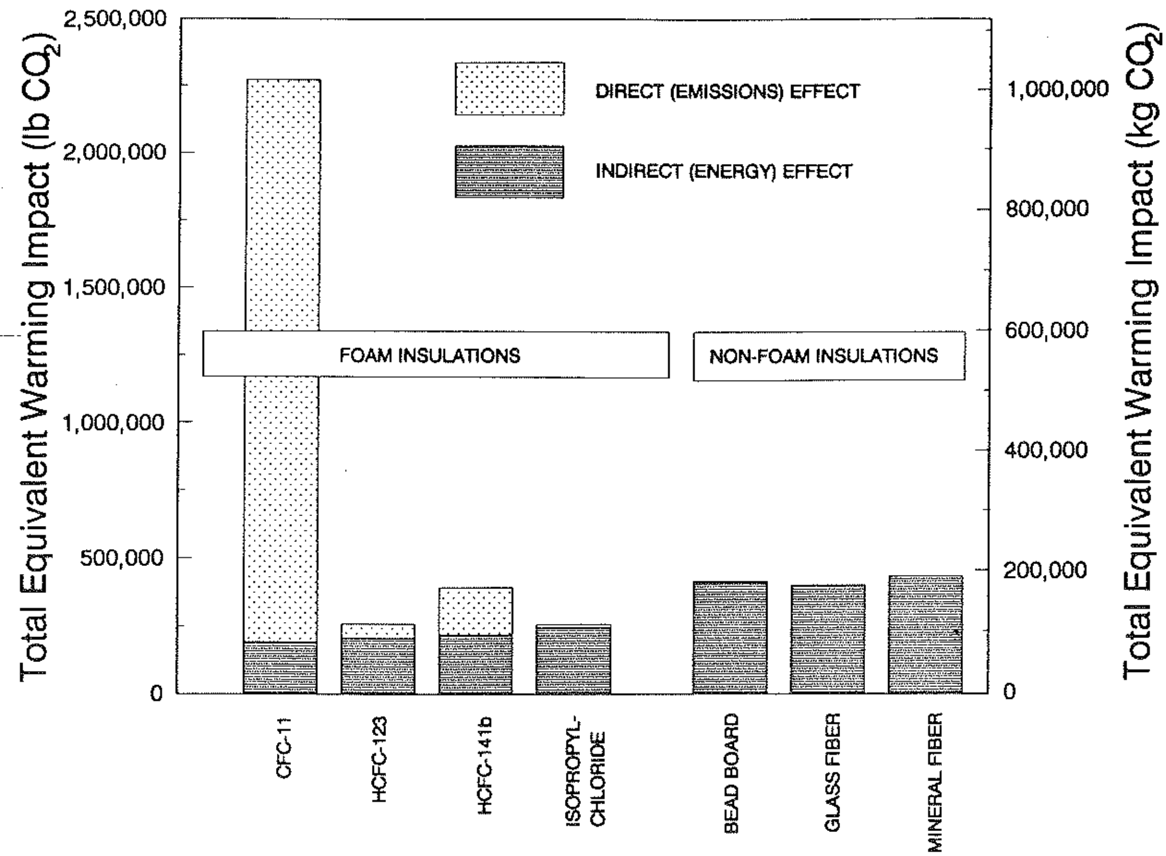

Figure 4a *TEWI for low-slope roofs of a 23,000 ft^2 (2170 m^2) commercial building in North America using 2.4 in. (61 mm) polyurethane and nonfoam roof insulation (15-year useful lifetime).*

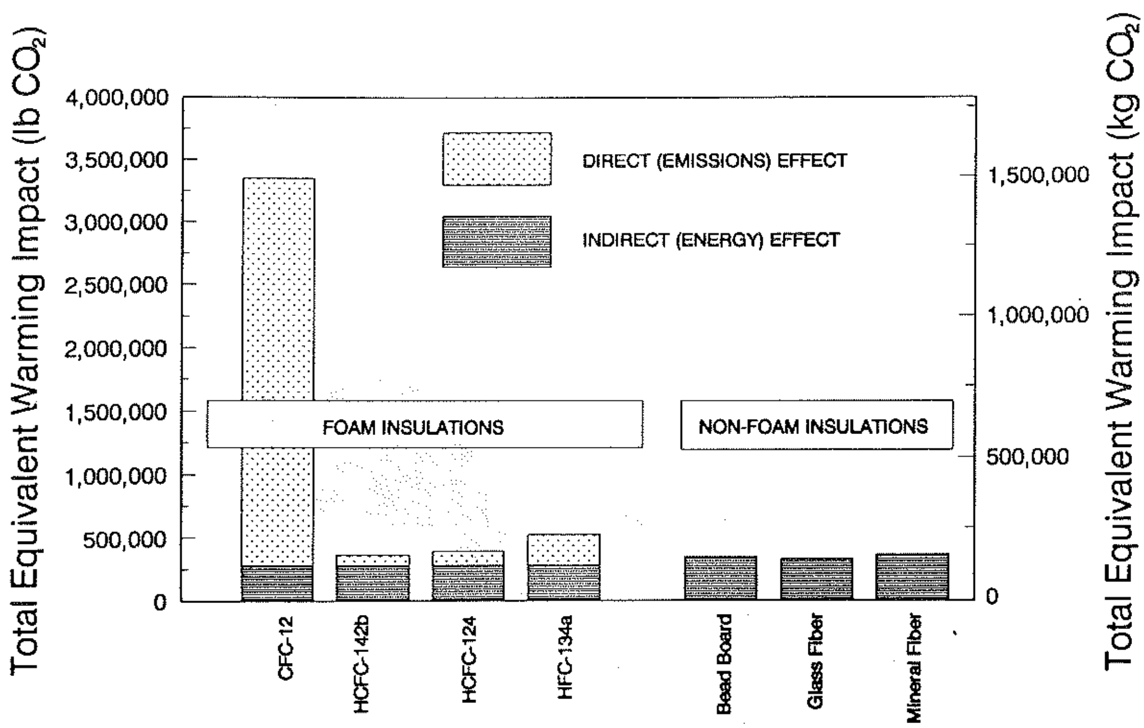

Figure 4b *TEWI for low-slope roofs of a 23,000 ft^2 (2170 m^2) commercial building in North America using 2.9 in. (74 mm) extruded polystyrene and nonfoam roof insulation (15-year useful lifetime).*