A Procedure for Analyzing Energy and Global Warming Impacts of Foam Insulation in U.S. Commercial Buildings

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ABSTRACT

The objective of this paper is to develop a procedure for evaluating the energy and global warming impacts of alternative insulation technologies for U.S. commercial building applications. The analysis is focused on the sum of the direct contribution of greenhouse gas emissions from a system and the indirect contribution of the carbon dioxide emission resulting from the energy required to operate the system over its expected lifetime. In this paper, parametric analysis was used to calculate building related CO_2 emission in two U.S. locations. A retail mall building has been used as a model building for this analysis. For the analyzed building, minimal R-values of insulation are estimated using ASHRAE 90.1 requirements.

Introduction

An evaluation of the energy and global warming impacts of alternative insulation technologies for U.S. commercial building applications is presented in this paper. It is a product of the Total Equivalent Warming Impact (TEWI) research project cofounded by Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) and U.S. Department of Energy. Due to the fact that current stage of this research is continuation of the TEWI research project established in 1991 (AFEAS 1991, 1994), the research procedure presented in this paper is a modification of the previously used methodology. Also, the analyzed retail mall was used as a model building in previous TEWI studies. Generated results are based on the limited foam aged thermal conductivity data of foam insulations publicly available in 1997.

This analysis is based on the sum of the direct and indirect contributions of greenhouse gas emissions generated by a model building. Direct contribution of greenhouse gas emissions from the insulation used and the indirect contribution of the carbon dioxide emission resulting from the energy required to run the building over its expected lifetime are examined. DOE-2.1E was used for the whole building energy analysis of a retail mall building. Two types of wall (masonry and steel-framed) and low-slope roof were assumed for model building.

Similarly to the previous TEWI studies (AFEAS 1991, 1994) the constant thickness of insulation was used for all analyzed insulation end-uses. For the retail mall, minimal R-values of insulation were estimated using ASHRAE 90.1 requirements (ASHRAE 1989). The insulation thickness was calculated by using the average aged resistivity of 5.6 $hft^2F/Btu\text{-}in.$ (39.2 mK/W) for roofs and 6.8 $hft^2F/Btu\text{-}in.$ (47.5 mK/W) for walls. This establishes a constant thickness used to generate the indirect CO_2 emissions for the whole range of foam thermal resistivities used in parametric analysis. Three foam board end-uses have been identified for the analysis: masonry walls, metal panel walls, and low-slope roofs.

For all insulation alternatives and for model building considered here, TEWI values were calculated for two U.S. locations (Atlanta and Chicago). Also, the difference between Total Equivalent Warming Impact (ΔTEWI) calculated for uninsulated and insulated buildings is analyzed for each wall material configuration. Total equivalent CO_2 emission is a sum of indirect CO_2 emission and direct equivalent CO_2 emission. ΔTEWI is a measure of the positive impacts of using building envelope insulation to reduce building-related CO_2 emissions. The larger the ΔTEWI, the more effective is the building envelope system, and the lower the building-related CO_2 emission.

Parametric analysis is utilized to compare insulating foams in this paper. A more detailed study which include analysis of aged thermal resistivities for insulating foams will be published in January 1999 (AFEAS 1999). Not-in-kind alternative types of insulation like expanded polystyrene (EPS) and fiber glass will be also evaluated.

Building Simulation Model and Climates

The whole building computer code DOE-2.1E (Winkelmann at al. 1993) was used for energy analysis of the considered commercial building. TMY climate data for Chicago and Atlanta were used for whole-building thermal modeling. The basic climate characteristics for the geographic locations are presented in Table 1.

Table 1. Basic climate characteristics for geographic locations considered in DOE-2.1E modeling

Location	Latitude	Heating Degree Days @65 °F	Cooling Degree Days @65 °F
Atlanta	33.6 °North	3070	1566
Chicago	41.8 °North	6151	1015

Equivalent Warming Impact Calculation Methodology

The global warming impacts of alternative types of insulation that can replace current HCFC blown insulation are compared for commercial building application in this analysis. For all insulation alternatives considered in this paper, Total Equivalent Warming Impact (TEWI) values were estimated. The Total Equivalent Warming Impact is a sum of Indirect CO_2 Emissions and Direct Equivalent CO_2 Emissions (AFEAS 1991). Also, ΔTEWI values were calculated. ΔTEWI was defined as a difference in Total Equivalent Warming Impact between uninsulated and insulated buildings. ΔTEWI is a measure of positive impacts of using building envelope insulation on the reduction of the building related CO_2 emissions. The larger the ΔTEWI, the more effective is the building envelope system, and the lower the building related CO_2 emission.

The methods used to estimate the direct and indirect equivalent CO_2 emissions for the various insulation alternatives are described in this section. The parametric analysis compares insulating foams represented by the wide range of thermal resistivities, Global Warming Potentials, and % weights of blowing agent. For the analyzed commercial building, minimal R-values of insulation were estimated using ASHRAE 90.1 requirements (ASHRAE 1989). Based on the standard requirements for Atlanta and Chicago, insulation thickness was calculated by using the average aged resistivity of 5.6 hft^{2}F/Btu-in. (39.2 mK/W) for roofs and 6.8 hft^{2}F/Btu-in. (47.5 mK/W) for walls. The insulation R-values were derived by subtracting the thermal resistances of the other wall or roof materials in series with the insulation in each assembly. The steady thickness for all types of insulation has been a standard for all TEWI studies (AFEAS 1991, 1994). In current work, this thickness was selected using 0.1-in. increments and it remains constant for all types of insulation. The resulting foam thicknesses are listed in Table 2. This established a constant thickness used to generate the Indirect Equivalent CO_2 Emissions for all insulation types evaluated.

Table 2. Roof and wall insulation R-values and thicknesses for a North American retail mall.

	Chicago		Atlanta	
	Foam R-value [h·ft·²F/Btu] (m·²K/W)	Thickness for all insulations -in.(cm.)*	Foam R-value [h·ft·²F/Btu] (m·²K/W)	Thickness for all insulations -in.(cm.)*
Roof:	14.9 (2.62)	2.7(6.9)	9.91(1.75)	1.8 (4.6)
Masonry wall	6.39 (1.12)	0.9 (2.3)	1.29 (0.23)	0.2 (0.5)
Metal panel wall	11.35 (2.0)	1.7 (4.3)	6.84 (1.20)	1.0 (2.5)

* *Selected thickness is in 0.1-in. increments.*

During the statistical analysis of the data from DOE-2.1E runs it was assumed that the whole building envelope (roof and wall) was insulated using a specific foam. Three foam board end-uses have been identified for the analysis: masonry walls, metal panel walls, and low-slope roofs shown in Figures 1, 2, and 3. They are the same as used for the 1991 Total Equivalent Warming Impact (TEWI) study (AFEAS 1991). All comparisons were made for the constant insulation thicknesses.

The masonry wall consists of eight-inch-thick (20.3 cm.) heavyweight concrete blocks partially filled with reinforced concrete with foam board on the outside, covered with a 0.5-in. (1.3-cm.) thick layer of stucco. The masonry wall has high thermal mass and placing the insulation on the outside maximizes the thermal mass effect.

The foam-core metal panel wall 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 surfaces.

Low-slope roof construction was chosen for the example retail mall building, as is common construction practice in North America. Retail malls typically have dropped ceilings. The steel deck is covered with insulation and then a roofing membrane is applied above the insulation.

The following design parameters were used for the retail strip mall in the computer analysis:

- *gross floor area - 1093m²,*
- *length/width - 36.6/24.4 m.;*
- *gross external wall area -648.1m²;*
- *window area - 16.4%;*
- *roof construction - low-slope;*
- *wall construction - masonry or metal panel;*
- *HVAC equipment - packaged rooftop;*
- *heating fuel - gas; oil; or electric;*
- *building occupied 4140 hours per year.*

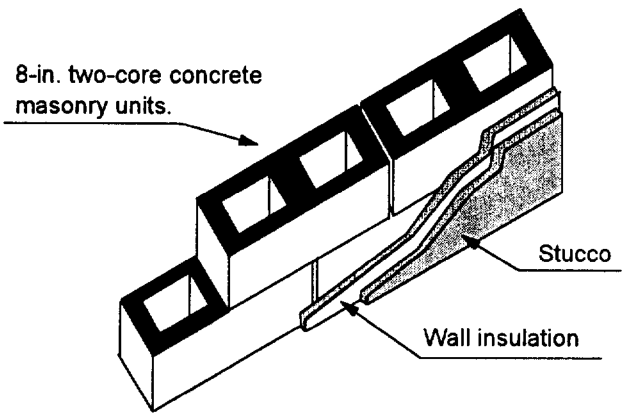

Figure.1. Typical masonry wall in retail mall.

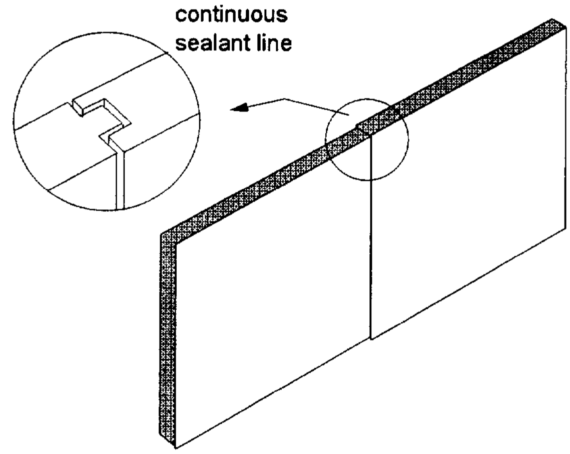

Figure.2. Typical foam core metal panel wall.

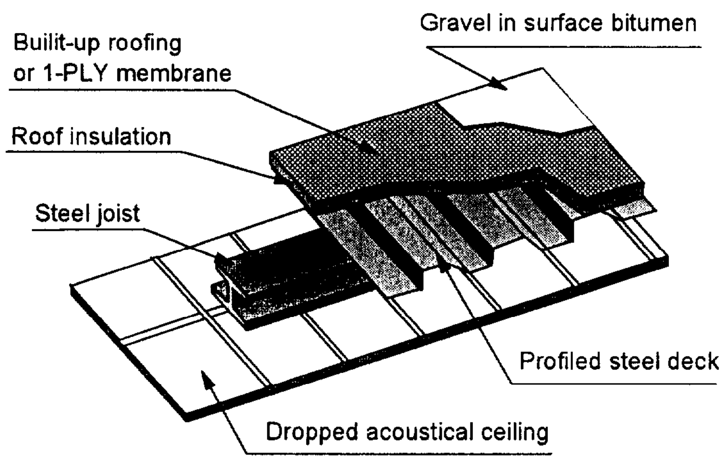

Figure.3. Typical low-slope roof.

Direct CO_2 Emission

The equivalent direct CO_2 emission is caused by the eventual release of the blowing agent into the atmosphere. For all foam insulations it is assumed that the blowing agent is lost to the environment either while in service or at retirement. The calculations to estimate the direct CO_2 emissions were performed using the 100-year Global Warming Potential (GWP) data and the weight of blowing agent contained in the commercial building insulation end-uses for each location. Calculation of the lifetime equivalent CO_2 emission was based on the equation (1):

$$Eqv\ Dir\ CO_2\ Em. = [\%\ Weight\ of\ BA] * GWP * [Compst\ Bldg\ Insul\ W] \quad (1)$$

where:

- $Eqv\ Dir\ CO_2\ Em.$ - Equivalent Direct CO_2 Emission,
- BA - Blowing Agent,
- GWP - 100 years Global Warming Potential, and
- $Compst\ Bldg\ Insul$ - Weight of Composite Building Insulation.

Considered range of 100-year Global Warming Potential (GWP) for insulating foams is between 1 and 2000. Table 3 shows minimal and maximal values for the weight percent of blowing agent in the insulations and assumed uniform density of insulation materials.

Table 3. Weights percent blowing agent (BA) and densities for insulating foams (AFEAS 1997).

	minimum	maximum
% weight (BA)	4.5	14
density lb/ft^3 [kg/m^3]	2 [32]	3.1 [50]

Indirect CO_2 Emission

Estimation of indirect CO_2 emission is based on the building lifetime insulation-related energy consumption analysis. For the low-slope roof, masonry wall, and metal panel wall the R-values used in the energy analysis were displayed in Table 1 above. The whole-building energy modeling was performed using the DOE-2.1E computer program for two North American locations (Atlanta and Chicago).

The example retail mall has one possible roof and two possible walls. For each location and insulation application, the ASHRAE 90.1 standard was used to calculate the required minimum R-value of the roof or wall insulation based on heating and cooling degree days. Calculated thicknesses of roof and wall insulation materials were listed in Table 2.

To minimize the number of DOE-2.1E simulations required to perform the energy analysis, six nominal thermal resistivities ranging from 3 to 8 hft^{2}F/Btu-in. (21 to 56 mK/W) were assumed for dynamic modeling. The results of this regression analysis are depicted in Figure 4. Regression equations can serve to calculate energies for other insulation alternatives. The results of the regression analysis will be used in the next stage of this project (ASHRAE 1989).

The decrease in thermal resistivity with time of thermal insulations manufactured with low thermal conductivity gases is widely recognized. A procedure for determining the long-term thermal performance has been developed for unfaced homogeneous foam insulation, and an ASTM consensus standard has been written (ASTM C-1303) (ASTM 1995). A number of papers contain vapor-phase thermal conductivity data for gases (Creazzo at al. 1993, Doerge 1995, Knopeck at al. 1993, McElroy at al. 1991, Murphy & Costa 1994, Rossito & McGregor 1995, Walker at al. 1993, Williams at al. 1995) and measured initial thermal resistivity for foam insulations (Albrecht & Zehendner , Czarnecki at al. 1994, Doerge 1995, Fabian at al. 1997, Knopeck at al. 1993, McElroy at al. 1991, Rossito & McGregor 1995, Volkert 1995, Walker at al. 1993, Wiedermann at al. 1991). The data in the cited papers can be used to calculate time-average thermal properties.

The time-averaged thermal resistivities were calculated for several insulating foams. The average difference between foam aged thermal resistivities calculated for 15 year and 50 year time periods is about 0.15 hft^{2}F/Btu-in. (1.0 mK/W). These time intervals have not been changed since the first TEWI study (AFEAS 1991). Since the error caused by using only one thermal resistivity (of 15 year old foam) for each simulated building configuration was less than 1.5%, each foam was represented in parametric analysis by one thermal resistivity without compromising accuracy. More experimental data will be available in January 1999 (AFEAS 1999).

For all foams, Fully Insulated Building Energies E(fib) were calculated. E(fib) was defined as heating or cooling energy for a fully insulated building. Next, the sum of heating and cooling energies E(fib) for specific foams were converted into indirect life-time CO_2 emissions. Conversion factors are presented in Table 4.

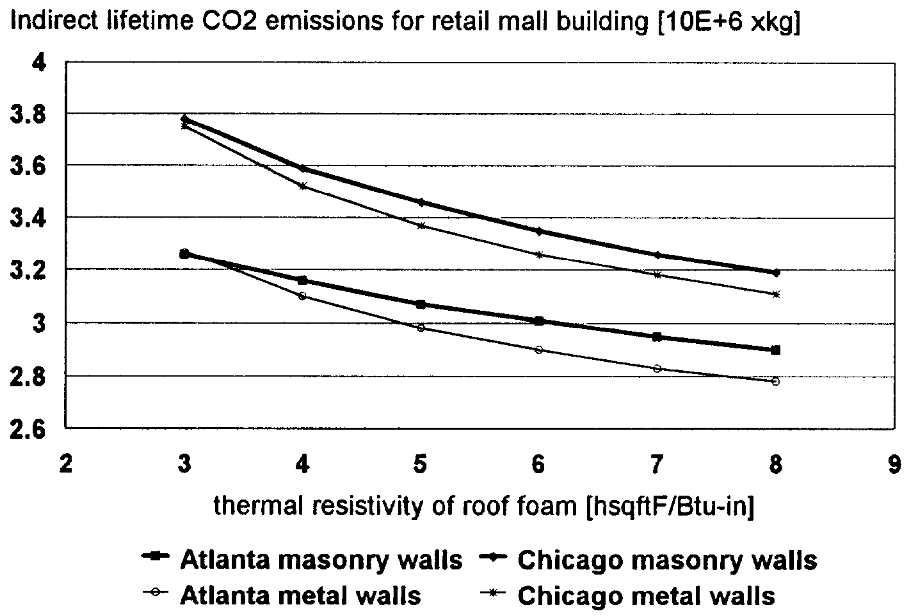

Figure 4. Generated by DOE-2.1E modeling, approximate indirect lifetime CO2 emissions for the retail mall building.

To convert heating and cooling energies into lifetime CO_2 emission, insulation material lifetimes of 50 years for walls and 15 years in roofs were assumed. Conversion to lifetime CO_2 emission was performed using the fuel mixes listed in Table 5.

Table 4. Heating and cooling energies conversion factors into indirect life-time CO_2 emission (AFEAS 1997).

	kg CO_2 / kWh	kg CO_2 / MBTU
electricity	0.65	190
gas	0.184	53.9
oil	0.257	75.4

Table 5. North American retail mall building assumptions and conversion factors (AFEAS 1997).

Weighting factors:		retail mall
Heating fuel:	gas	68% of total
	oil	15% of total
	electricity	17% of total
HVAC system:	heat/cool	100% of total

Results

For the retail mall building, heating and cooling energies for all considered types of insulation were estimated using regression analysis. Nonlinear regression equations served later for indirect lifetime CO_2 emission calculations. The weight of insulation represented in the composite whole-building insulation end-uses for each region was used to estimate the direct life-time CO_2 emissions. These results enabled calculation of TEWI values.

Indirect CO_2 Emission

As shown in Figure 5, an uninsulated retail mall building with massive masonry walls generates 14 to18% less indirect CO_2 emission than the same building with metal panel walls. For the range of foam thermal resistivities - 4 to 7 hft^{2}F/Btu-in. (28.0 to 48.9 mK/W), indirect CO_2 emissions vary from 7 to11% comparing to the building with installed R-4 per in. insulation.

Direct CO_2 Emission

The estimation of the direct lifetime CO_2 emission was performed with 100-year Global Warming Potential (GWP) data and the weight of insulation represented in the whole-building insulation end-uses for each region. As presented in Figure 6, maximum values of direct lifetime CO_2 emissions range from about 0.5 to 1.0 [10E+6 kg CO_2], when the lowest values are close to zero. Values of direct lifetime CO_2 emission are significantly lower than indirect lifetime CO_2 emissions. They represent about 15 to 30% of indirect lifetime CO_2 emissions.

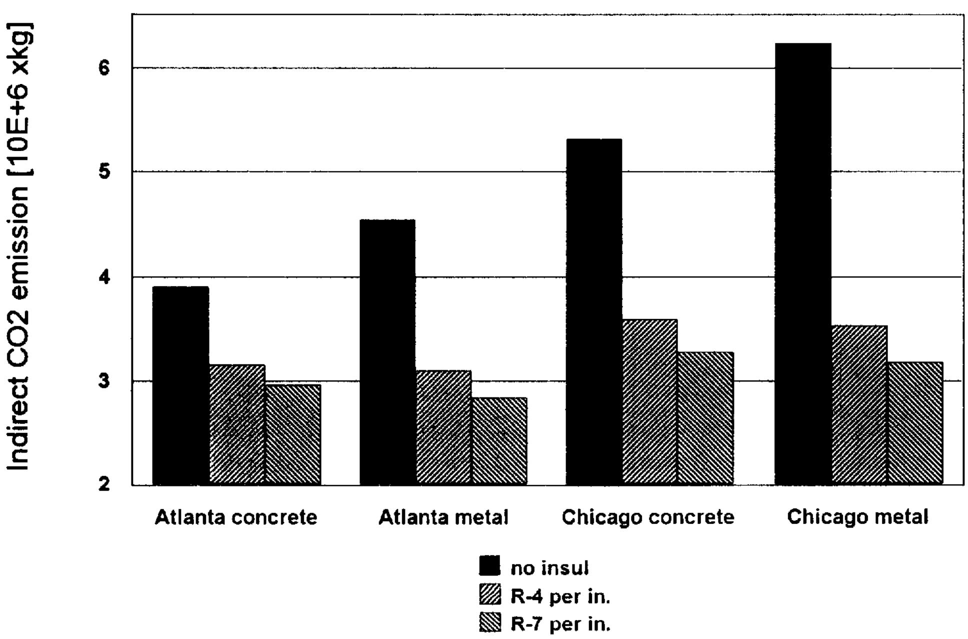

Figure 5. Indirect CO2 emissions for retail mall building.

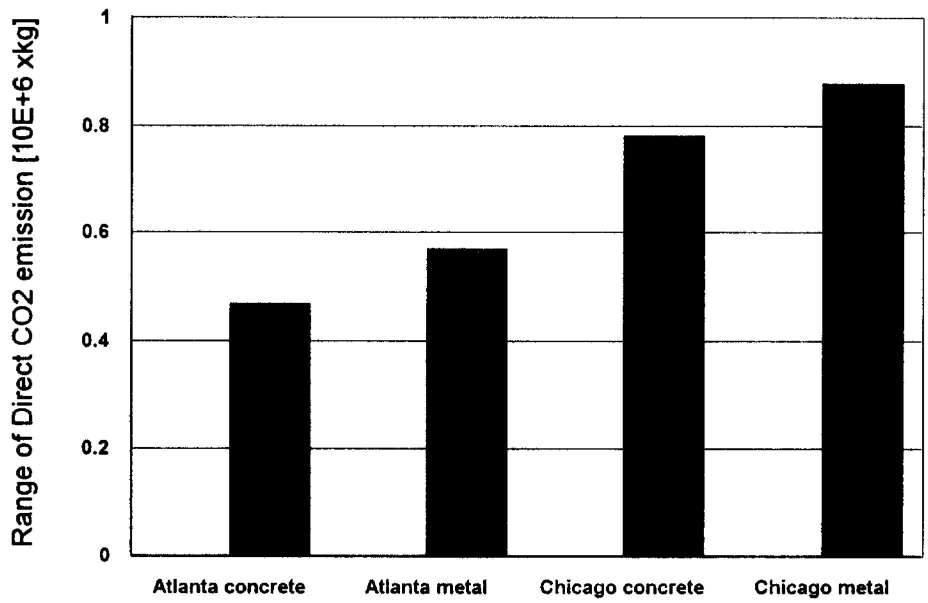

Figure 6. Range of direct CO2 emissions for insulating foams.

Commercial Building TEWI and ΔTEWI

For all considered foam parameters for the retail mall building, Total Equivalent Warming Impact (TEWI) values were calculated. Total Equivalent CO_2 Emission was defined as a sum of two components: CO_2 Emissions, caused by energy consumption of the building to provide heating and cooling, and Direct CO_2 Emission. For uninsulated and insulated commercial buildings, Total Equivalent CO_2 Emissions are presented on Figure 7.

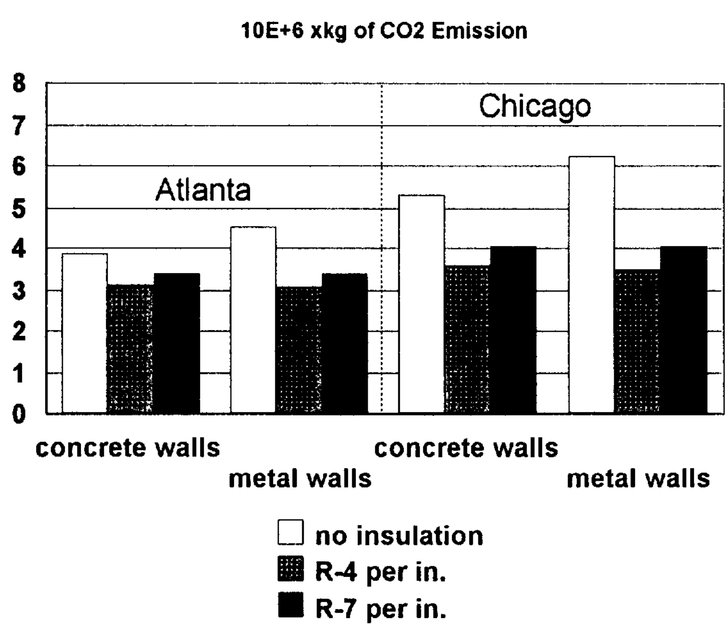

Figure 7. Total equivalent CO2 emissions for a retail mall building.

As shown in Figure 7, for the range of foam thermal resistivities - 4 to 7 hft²F/Btu-in. (28.0 to 48.9 mK/W), TEWI values vary from 7.7 and 9% for Atlanta to 11.4 and 13.2% for Chicago as compare to the building with installed R-4 per in. insulation. The retail mall containing metal walls is more sensitive to the changes in building envelope thermal insulation than the same building having concrete masonry walls. This can be explained by the affect of thermal mass on the whole building energy performance.

$$\Delta TEWI = \frac{\text{Total Equivalent CO2 Emission (uninsul. building)} - \text{Total Equivalent C02 Emission (insul. building)}}{\text{Total Equivalent CO2 Emission (uninsul. building)}}$$

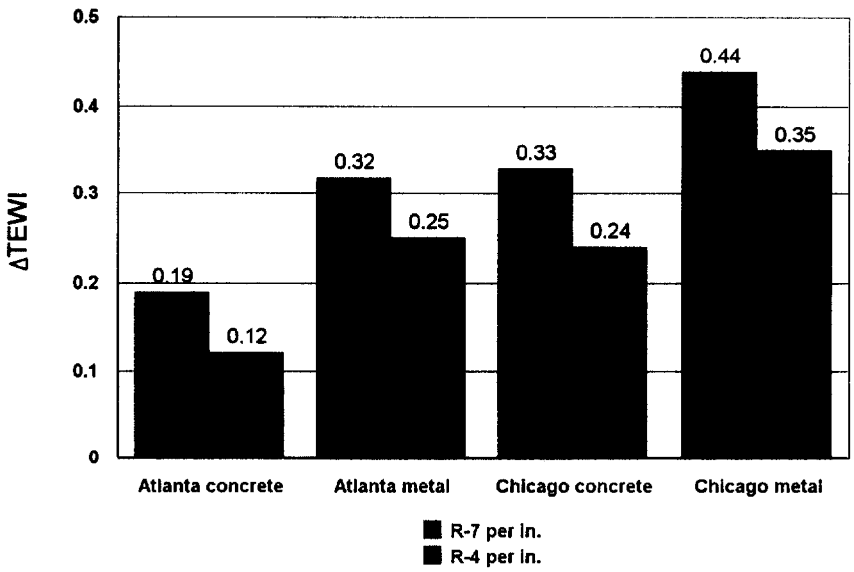

Figure 8. ΔTEWI values for insulating foams.

ΔTEWI values are presented in Figure 8. ΔTEWI is a measure of the positive impacts of using building envelope insulations on the reduction of building related CO_2 emissions. The larger the ΔTEWI, the more effective is the building envelope system, and the lower is the building related CO_2 emission. As shown on Figure 8, TEWI value can be reduced by 12 to 32% for Atlanta and 24 to 44% for Chicago when ASHRAE 90.1 required amounts of thermal insulation are installed on the retail mall roof and walls.

Taking in to account a very fast development of new, more thermally efficient insulating foams, it is very likely that data presented in Figures 7 and 8 under the label "R-7 per in." are very realistic. More detailed study comparing several types of foams blown with different blowing agents will be available in January 1999 (AFEAS 1999).

Conclusions

In this study, Total Equivalent Warming Impact (TEWI) was used for performance comparison of insulating foams. ΔTEWI was used as a measure of the positive impacts of using building envelope insulations to reduce building related CO_2 emissions. The following set of conclusions can be derived:

1. Total Equivalent CO_2 Emission can be reduced by 20 to 30% for Atlanta and 30 to 45% for Chicago if insulation required by ASHRAE 90.1 is install on commercial building similar to that analyzed in this study.

2. Adding insulation to the building is more valuable for reducing TEWI in heating dominated climates.
3. Low-mass commercial buildings are more sensitive to the changes in building envelope thermal insulation than the buildings containing massive masonry walls. Relatively more Equivalent CO_2 Emission can be saved if insulation is installed in low mass buildings.
4. Direct CO_2 emissions represent about 15 to 30% of indirect lifetime CO_2 emissions and they cannot be neglected in TEWI analysis.

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