PARAMETRIC ANALYSIS OF IMPACT OF REFLECTIVE/ABSORPTIVE GLAZING AND MOVABLE WINDOW INSULATION ON HEATING AND COOLING LOADS IN RESIDENTIAL BUILDINGS

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ABSTRACT

We studied the impact of reflective glazing and movable window insulation on heating and cooling loads in single-family and multifamily buildings for many U.S. locations. Regressions between loads and appropriate climatic variables allowed extension of our results to other climates where computer simulations were not performed but where climatic data are available. We calculated space conditioning fuel cost for each location studied and plotted the fuel cost savings for reflective glazing on a map of the U.S. This procedure allows easy determination of the cost-effectiveness of these conservation measures in various climatic regions. For warm climates with large cooling loads and small or moderate heating loads, reflective glazing produces a substantial decrease in space conditioning cost (assuming gas heating and electric cooling). We found the use of movable insulation over windows to be economically justified in cold climates with electric heating.

INTRODUCTION

The Lawrence Berkeley Laboratory has extensively analyzed the influence of various energy conservation options on residential energy use in prototypical residences in the United States. To represent the energy use characteristics of site-built single-family housing, we defined five prototypical buildings that encompassed the majority of new residences built in the U.S. We studied the following building types: one-story, two-story, split-level, and middle-unit and end-unit townhouse. The construction details of the five prototypical buildings are reported elsewhere (Huang et al. 1985). We also developed a two-story, six-unit multifamily prototype in order to perform energy analyses of new low-rise multifamily buildings (Turiel et al. 1985).

In this report, we discuss the impact of reflective glazing and movable window insulation on heating and cooling loads in single-family and multifamily residential buildings. We also estimated the cost-effectiveness of these measures in various climatic regions and developed a graphical technique for presenting our results.

METHODOLOGY AND ASSUMPTIONS

For each building prototype, we identified and simulated a full range of energy conservation options. These options included various combinations of insulation (ceiling, floor, and walls), window glazings, and infiltration levels. We considered three building foundation types (slab-on-grade, ventilated crawl space, and unheated basement) depending on the location. For each location, the most common foundation type was chosen for simulation. The simulations described in this report produced a data base for 11 cities. We expanded this data base to 45 cities as described below.

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For these energy analyses, we used the DOE 2.1A computer program (DOC, 1980). We used Test Reference Year (TRY) weather tapes for all locations except for Juneau, Alaska, and Las Vegas, Nevada. For these two locations, we used Typical Meteorological Year (TMY) weather tapes since TRY tapes were unavailable. The climatic input data included dry- and wet-bulb temperatures, wind speed and direction, barometric pressure, cloud cover, and atmospheric clearness index.

Standard building operating conditions refer to those operations that are under the control of the homeowner, such as temperature settings, night thermostat setback, whole house ventilation, day shading devices, internal loads due to average house occupancy and use of appliances, and the type and operation of space conditioning equipment in the building. For the purpose of this analysis, we kept these operating conditions constant to provide a basis for comparing different physical and climatic conditions. In addition, we tested many of these assumptions in various sensitivity analyses in which a particular parameter was varied from the assumed value.

We assumed that the whole building (living space) consisted of one zone, and the basement area, if there is one, constituted a second zone. The first zone was thermostatically controlled, whereas the second zone was allowed to have a floating temperature (no control). Thus, in all cases, only one thermostat was required to control temperatures in the living space. For heating, we assumed the thermostat setting to be 70 F (21.1 °C) and for cooling, 78 F (25.6 °C). We also assumed a night setback to 60 F (15.6 °C) between the hours of 12 midnight and 6 a.m.

We assumed that natural window venting was utilized when both the outdoor temperature in the summer was lower than the indoor temperature but not higher than 78 F (25.6 °C) and the enthalpy of the outdoor air was less than that of the indoor air. We imposed the second requirement so that the indoor humidity would not be adversely affected by window venting. We assumed a single venting schedule for all climates (May 15 through September 30).

Under the conditions of normal occupancy, the interior space of a house collects heat, termed the "internal load", released by people, appliances, and lighting. We assumed 3.2 persons as the average single-family and apartment unit household size. In addition, our analysis assumed internal loads due to heat gain from the following appliances: range, refrigerator, freezer, clothes dryer, water heater, and television and from lights and occupants. Huang (1985) and Turiel (1984) contain the hourly internal loads schedule used in the analyses for the one-story ranch house and the multifamily units, respectively.

We modeled three types of space conditioning systems:

- Gas or oil furnace (heating)—modeled for all options
- Electric air conditioner (cooling)—modeled for all options
- Electric heat pump (heating and cooling)—modeled for selected options

We assumed that the furnace had a fixed efficiency of 0.70, which corresponds to a gas furnace with an intermittent ignition device and a tight stack damper. The rated capacity of the furnace modeled was 50,000 Btu/h (14,650 W). The rated capacity of the air conditioner was 33,000 Btu/h (9670 W). It had an EER of 9.2 at 95 F(35 °C) outdoor dry-bulb and 67 F (19.4 °C) wet-bulb temperatures. A full-load efficiency curve (COP) versus outdoor dry-bulb and indoor wet-bulb and a part-load efficiency curve can be found in another report (Huang et al. 1985).

WINDOW CHARACTERISTICS

An NAHB survey (1981) found window area in new construction to equal 8% to 10% of the floor area. For these analyses, we performed simulations for 10%, 15%, and 20% window to floor ratios. For the single-story prototype, we modeled windows in the base case as being equally distributed on all four sides. For the multifamily prototype, windows were equally distributed on two sides for the mid-units and unequally distributed on three sides for the end-units.

In these analyses, we modeled windows with no sash. The number of window glazings or panes ranged from one to three with a 0.5 inch (12.7 mm) gap between consecutive panes. We use the following conductances, which reflect the ASHRAE winter U-values with outside film coefficient subtracted, to calculate conductive heat loss or gain through the windows:

Single glazing: 1.35 Btu/ft^2·F h (7.52 W/m^2·°C)

Double glazing: 0.54 Btu/ft^2·F h (3.01 W/m^2·°C)

Triple glazing: 0.33 Btu/ft^2·F h (1.84 W/m^2·°C)

We used these values with both regular and reflective glazing simulations. Converted winter values are appropriate for the entire year, since the main difference between the winter and summer seasons is the outside air film, which is simulated hourly by DOE-2.

Table 1 shows the transmittance and reflectance values for solar radiation at normal incidence for regular glass (base case building) and reflective glass (DOE, 1980). The reflectance values for the reflective glazing are at the high end of what is commercially available. The DOE-2.1A program uses precalculated transmission and absorption coefficients to determine solar gain as a function of angle of incidence of solar radiation.

We performed many of the simulations with two alternate shading assumptions. The simpler assumption is that drapes, or some other shading device, with a fixed shading coefficient of 0.63 are in place at all hours and that they do not affect the thermal conductivity of the windows. For the second assumption , we assume that the occupants manage the window shading more actively. In this case, we modeled a window covering with a shading coefficient of 0.63 over half the windows during all the daylight hours in the summer. This is approximately equivalent to a constant shading coefficient of 0.82 during all the daytime hours. We assumed that during winter days drapes do not cover the windows (shading coefficient equals 1.0). In both the winter and summer, drapes cover the windows at night, and the conductivity of the windows is reduced accordingly. In the winter (October 1-April 30), we assumed the drapes to be in place from 5 p.m. to 7 a.m. each day. We modeled the thermal resistance of the drapes to be equal to 0.9 h·^{2}·F/Btu (5.01 m^2·°C/W), which corresponds to a dead air space between the windows and drapes. If, in practice, convective heat flows are present between the windows and drapes, then the actual thermal resistance will be lower. We specify the particular shading assumption used in each analysis in the results section.

ANALYSIS OF RESULTS

Reflective Glazing

The influence of glass solar transmittance on cooling load can be quite significant. For example, the results from computer simulations for Miami indicated that the decrease in cooling load due to installation of reflective glass was as high as 20% of the total cooling load (ranch house, 15% window-to-floor-area ratio, 231 ft^2 or 21.5 m^2, single-glazing). However, heating loads are increased by installation of reflective glass, and the net energy effect varies with location and equipment efficiencies. Our initial objective was to determine which climatic variables, if any, would correlate with heating and cooling load changes resulting from the use of reflective glazing. If successful, this procedure allows extrapolation of our results to any location for which we have access to appropriate climatic data. Our final step was to estimate the cost-effectiveness of reflective glazing in different locations.

Cooling Load. A series of initial simulations established that the changes in cooling load per square foot of window area did not vary significantly with window area when the number of panes remained constant. Therefore, we needed to perform regression analyses with only one set of window area simulations and could express the results in load changes per square foot. We performed regression analyses with cooling load savings per square foot (separately for single-, double-, and triple-glazed windows) as the dependent variable and the average vertical insolation (S) that occurs during periods when cooling is needed as the independent variable. We obtained the average vertical solar insolation (see Table 2) from the weather tape for each location considered. Insolation is counted only during those hours for which the outdoor dry-bulb temperature is greater than 65 F (18.3 °C) and venting is not possible.

Figure 1 shows cooling load savings due to the use of single-pane reflective glazing for the single-family ranch house plotted against average vertical solar insolation during hours cooling is required. Each point represents a different location. We used the constant shading assumption for all ranch simulations. The ranch house simulated in these analyses had 231 ft^2 (21.5 m^2) of window area and 1540 ft^2 (143 m^2) of floor area. Figure 2 shows a similar graph for an average end-unit in a two story multifamily building. Each end-unit apartment had 180 ft^2 (16.7 m^2) of glazing and 1200 ft^2 (111.5 m^2) of floor area. The simulations used to plot the graph in Figure 2 were performed with the constant shading assumption. As these two figures show, the correlation between cooling load reductions and solar insolation during cooling load hours is quite good. For all cooling load regressions, the correlation coefficient was greater than or equal to 0.99. The cooling load reduction regression equations for reflective glazing in single-family ranch houses and end-unit apartments obtained from this analysis are given below (after the heating load section).

Heating Load. For the heating loads analyses, the general approach remained the same, i.e., we related increases in heating load to a vertical insolation level (W) for the heating period. The climatic information used in the reflective glazing analysis for 11 locations is summarized in Table 2. We obtained the values of W shown in Table 2 by calculating the solar insolation for hours when the outdoor dry-bulb temperature is less than 65 F (18.3 °C). Figure 3 illustrates the fit obtained for heating load increases as a function of insolation for single-pane reflective glass with 15% glazing. We obtained similar fits for all combinations of glazing type and glazing area. The correlation coefficients changed only slightly when the assumed balance point temperature was lowered from 65 F (18.3 °C) to 60 F (15.6 °C) or 57 F (13.9 °C).

For all cases considered, we performed linear regression analyses. There was generally a strong linear relationship (correlation coefficient >0.91) between insolation and heating load increase, although not as strong as for cooling load decreases. The correlation coefficient was greater than 0.96 for the ranch house and multifamily regressions with constant shading assumption. The multifamily regressions with variable shading assumptions yielded correlation coefficients of 0.97, 0.93, and 0.91 for single-pane, double-pane, and triple-pane respectively.

We used the linear regression equations derived from the analyses for 11 cities to predict cooling load decreases and heating load increases due to reflective glass for 45 locations. The following formulas were used to obtain the cooling and heating load deltas per square foot for the other 34 cities. We have multiplied them by 1000 for ease of presentation.

1. Reflective Glass, Single-Family Ranch, Constant Shading
   - a. single-glazing: $C = .0876 + 0.2887 * S$, $H = 1.377 + 0.2208 * W$
   - c. triple-glazing: $C = -.9636 + 0.2820 * S$, $H = 0.922 + 0.1688 * W$
2. Reflective Glass, Multifamily End-Unit, Constant Shading
   - a. single-glazing: $C = 1.013 + 0.3102 * S$, $H = 1.616 + 0.2004 * W$
   - b. double-glazing: $C = 1.496 + 0.3082 * S$, $H = -0.280 + 0.1770 * W$
   - c. triple-glazing: $C = 1.146 + 0.2984 * S$, $H = -2.329 + 0.1677 * W$
3. Reflective Glass, Multifamily End-Unit, Variable Shading
   - a. single-glazing: $C = 1.442 + 0.4448 * S$, $H = 0.565 + 0.2787 * W$
   - b. double-glazing: $C = 0.614 + 0.4401 * S$, $H = 0.234 + 0.2396 * W$
   - c. triple-glazing: $C = 0.099 + 0.4221 * S$, $H = 2.853 + 0.2208 * W$

where

S = average vertical insolation (kBtu/ft^2) during hours cooling required
W = average vertical insolation (kBtu/ft^2) during hours heating required.
C = cooling load savings (MBtu/ft^2),
H = heating load increase (MBtu/ft^2).

In S.I. Units these become:

1. Reflective Glass, Single-Family Ranch, Constant Shading

a. Single-glazing: $C = 276.18 + 288.95 * S$
$H = 4341.27 + 220.99 * W$

c. triple-glazing: $C = -3037.94 + 282.27 * S$
$H = 2906.79 + 168.95 * W$

2. Reflective Glass, Multifamily End-unit, Constant Shading

a. single-glazing: $C = 3193.68 + 310.47 * S$
$H = 5096.02 + 200.57 * W$

b. double-glazing: $C = 4716.44 + 308.47 * S$
$H = -883.07 + 177.15 * W$

c. triple-glazing: $C = 3613.0 + 298.66 * S$
$H = -7341.7 + 167.84 * W$

3. Reflective Glass, Multifamily End-Unit, Variable Shading

a. single-glazing: $C = 4546.19 + 445.18 * S$
$H = 1782.54 + 278.94 * W$

b. double-glazing: $C = 1935.44 + 440.48 * S$
$H = 736.47 + 239.81 * W$

c. triple-glazing: $C = 311.17 + 422.46 * S$
$H = 8994.34 + 220.99 * W$

where

S = average vertical insolation (kWh/m^2) during hours cooling required
W = average vertical insolation (kWh/m^2) during hours heating required.
C = cooling load savings (kWh/m^2),
H = heating load increase (kWh/m^2).

Since single-pane reflective glazing is more likely to be used in warmer climates than double- or triple-pane, we confine our comparison of ranch and multifamily buildings to single-pane windows. We compare the single-family and multifamily regression equations obtained for reflective glazing under the constant shading assumption. For large values of S (>130 $kBtu/ft^2$), the ratio of cooling load reductions for the end-unit to the reductions for the ranch house is approximately equal to the ratio of the slopes (.3102/.2887) in the regression equations. Thus, for locations where reflective glazing is likely to be cost-effective, end-unit apartments will achieve about a 7% greater cooling load reduction per square foot than similar ranch houses. Heating load increases resulting from the use of reflective glazing are greater for the ranch house than for the end-unit apartment. The heating load increase for ranch houses ranges from about 7% to 10% greater than the increase for end-unit apartments.

We also compared the multifamily regressions obtained under the two shading assumptions. The cooling load decrease resulting from the use of reflective glazing (single- and double-pane) is greater by a factor of 1.43 for variable shading relative to fixed shading. This result is roughly consistent with the fact that the shading coefficient, during the summer months, is about 30% greater for the variable shading case compared to the fixed shading case. The heating load increase resulting from the use of reflective glazing (single- and double-pane) is greater by a factor of 1.37 for variable shading relative to fixed shading. This result can be partially explained by the higher wintertime shading coefficient for variable shading (1.0) relative to fixed shading (0.63). This factor alone would produce a ratio of about 1.59 for variable shading heating load increase relative to the fixed shading heating load increase. However, the nighttime window conductance is lower in the variable case, which brings down the heating loads and lowers the heating load increase for the variable shading assumption case.

Other quantities of interest can be derived from these data by making some assumptions about equipment efficiencies and obtaining local fuel prices. We calculated changes in the annual cost of space conditioning with the following equation:

$$\text{Change in cost of space conditioning} = \Delta\text{C.L.} * \frac{\text{PFC}}{\text{SCOP}_{\text{cool}}} - \Delta\text{H.L.} * \frac{\text{PFH}}{\text{SCOP}_{\text{heat}}}$$

where

PFC = price of cooling fuel

PFH = price of heating fuel

$\Delta C.L.$ = decrease in cooling load

$\Delta H.L.$ = increase in heating load

$SCOP_{cool}$ = seasonal COP for cooling equipment

$SCOP_{heat}$ = seasonal COP for heating equipment

We used the output from the equation above, that is, the change in space conditioning cost in 1985 dollars/year for the first year of reflective glazing use, to calculate the simple payback period (SPP) for an investment in reflective glazing. In order to calculate other economic indicators, such as benefit-to-cost ratio or net present value, this result has to be modified for future years taking into account the time value of money and changing fuel prices.

Figure 4 shows on a map of the United States the change in annual space conditioning cost (1985 \$/yr) for reflective single-pane glass relative to the single-pane glass described for the base-case ranch house. It is important to note that the values shown on the map are approximate for locations between the 45 cities for which space conditioning costs were calculated. The map should be used to determine which regions of the U.S. are likely to have reasonably short (10 yr) simple payback periods for the use of reflective glazing. A rough estimate of the SPP can be obtained by dividing the additional capital cost of reflective glazing by the annual dollar savings shown on the map. The values shown on the graph are for a 1540 ft^2 (143 m^2) house with 100 square feet (9.3 m^2) of window area and are for the first year only. We assumed a gas space heating system with a seasonal COP of 0.7 and an electrical cooling system with a seasonal COP of 2.4. We assumed the cost of electricity and natural gas to be \$0.08/kWh and \$0.50/therm (\$0.017/kWh), respectively, for all locations. These are average values, which need to be adjusted to local fuel prices. We plan to gather such data and produce new maps in the near future.

The savings are substantial (40-80 \$/yr) in climates with warm summers and mild winters, e.g., the southwestern and southern parts of the U.S. These savings would be greater for houses with more than 100 ft^2 (9.3 m^2) of window area. The savings moderate as one moves north to cooler locations. In the Pacific Northwest and parts of California, Idaho, Montana, and Nevada, space conditioning costs increase with the use of reflective glazing. For a 1540 ft^2 (143 m^2) ranch house with 10% window area, the additional capital cost of reflective glazing is about \$4.00/ft^2 (\$43/m^2) or \$616 (Means, 1984). Therefore, the simple payback period is 5 to 10 years for such a house with gas space heating in the southwestern or southern parts of the U.S.

We also computed the energy cost savings from the use of reflective glazing in houses that use electric resistance or heat pump space heating. For such houses, the cost of heating fuel and the heating COP are higher than for houses with gas space heating. For heat pumps (HCOP=2.0), there is a small decrease in the energy cost savings except in the warmest locations where there are essentially no heating loads. For electric resistance heating, there is a larger decrease in the energy cost savings, and the savings are positive only in locations south of a line running from mid-Texas to mid-Alabama. We also compared the use of double-pane windows with reflective and regular glass. In general, the increase in the cost of heating decreased in magnitude and the cost of cooling was essentially unchanged. The net effect was generally a small decrease in the cost of space conditioning compared to single-pane windows. Since the cost of double-pane reflective glass compared to regular double-pane glass is about \$4.00/ft^2 (\$43./m^2), the cost effectiveness of reflective glazing increases slightly with double-pane windows relative to single-pane windows (Means, 1984).

One of the questions we did not attempt to answer is whether consumers will accept the use of reflective glazing based on esthetic criteria. The outside appearance and the indoor light availability will both be affected by the use of reflective glazing. Although these are important considerations, we decided to focus our paper on energy and economic calculations.

Movable Window Insulation

Products that are moved into place over the windows in the evening hours to reduce winter time heat losses are called movable insulation. We simulated one R-value in this study. We modeled a standard off-the-shelf product with a material R-value of 2 $ft^2 \cdot h \cdot F/Btu$ ($11.14\ m^2 \cdot {}^\circ C/W$). We assumed that the total component R-value for this product is R-3 $ft^2 \cdot h \cdot F/Btu$ ($16.7\ m^2 \cdot {}^\circ C/W$). We attributed the additional R-1 $ft^2 \cdot h \cdot F/Btu$ ($5.57\ m^2 \cdot {}^\circ C/W$) to the air space between the product and window. In order to achieve that additional resistance, the window covering must be tightly fit and sealed around all edges of the window. Although such a window covering will reduce infiltration somewhat, we did not attempt to model such a reduction in infiltration in our simulations. A previous study (Selkowitz and Bazjanac 1979) considered the effect on heating load of such a reduction in infiltration. It found that a tight-fitting shutter of low R-value will outperform higher R shutters that do not reduce air leakage. We assumed that the movable insulation was in place between the hours of 10 p.m. and 8 a.m. during the heating season. Of course, greater benefits would result if the insulation were in place earlier in the evening. We did not perform sensitivity analyses to determine the impact of variations in the scheduling of movable insulation use. We varied the assumed length of the heating season depending upon local climate. Thus, the assumed heating season was from October 1 through April 30 for cities typified by cool climates; from November 1 through March 31 in cities in temperate climatic zones; and from December 1 through February 28 for cities in hot climates.

For both ranch and multifamily prototypes, we selected 11 cities representing the range of characteristic climates in the United States to examine the impact of movable insulation on the annual heating load. Table 3 summarizes the results of the DOE 2.1A simulations for the three glazing types for the ranch house prototype. It shows the annual heating load reduction (in millions Btu and millions kWh) achieved from the use of movable insulation for each of three window glazing types in 11 locations.

We found a good correlation between heating load reduction and nighttime heating degree-days (NHDD). Nighttime heating degree-days are summed from 10 p.m. to 8 a.m., the hours during which the insulation covered all windows. Figure 5 shows heating load reduction plotted as a function of nighttime heating degree-days (base 59 F [(15 °C)] for ranch-style houses with single-pane windows in 11 cities. These houses have windows evenly distributed among all four wall orientations with a 15% window-to-floor area ratio. Because of its extremely small heating load, we excluded Miami from the regressions.

We obtained similar fits for double- and triple-pane simulations. The correlation coefficient was 0.99 for all three regressions. Using test runs, we showed that the ratio of heating load reduction to window area was not constant for the three window areas studied but decreased as the window area increased. For example, for double-glazed windows, the average heating load reduction for 15% window area was 1.42 times the average reduction for 10% window area. For 20% window area, the average heating load reduction was 1.78 times the average reduction for 10% window area. Therefore, when using 15% window area simulation results to compute regression equations for prediction of heating load reductions in other locations, we must note that they are not strictly extendable without a correction factor to other window areas. We performed similar analyses for multifamily buildings. The results for the ranch house and multifamily end-units are shown below for the constant shading assumption. These equations are most accurate for values of NHDD above 200 F days (111 °C days). The correlation coefficient is 0.97 for all three multifamily regressions.

1. Movable Insulation, Single-Family Ranch

single–pane (1) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .00202 + 1.706 \text{ x}10^{-5} \text{ NHDD}$

double–pane (2) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .00113 + 0.794 \text{ x}10^{-5} \text{ NHDD}$

triple–pane (3) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .00034 + 0.422 \text{ x}10^{-5} \text{ NHDD}$

2. Movable Insulation, End-Unit, Constant Shading

single–pane (1) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .01213 + 1.600 \text{ x}10^{-5} \text{ NHDD}$

double–pane (2) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .00329 + 0.6389 \text{ x}10^{-5} \text{ NHDD}$

triple–pane (3) $\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = .00150 + 0.3389 \text{ x}10^{-5} \text{ NHDD}$

where

NHDD = nighttime heating degree days (F)

ΔL = change in heating load (MBtu)

A = window area (ft^2)

In SI Units:

1. Movable Insulation, Single-Family Ranch

single–pane (1) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.00637 + 9.673 \text{ x } 10^{5} \text{ NHDD}$

double–pane (2) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.00356 + 4.502 \text{ x } 10^{-5} \text{ NHDD}$

triple–pane (3) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.00107 + 2.393 \text{ x } 10^{-5} \text{ NHDD}$

2. Movable Insulation, End-Unit, Apartment, Constant Shading

single–pane (1) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.03821 + 9.072 \text{ x } 10^{-5} \text{ NHDD}$

double–pane (2) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.01036 + 3.623 \text{ x } 10^{-5} \text{ NHDD}$

triple–pane (3) $\frac{\Delta L}{A}\left(\frac{\text{MWh}}{\text{ft}^2}\right) = 0.00473 + 1.922 \text{ x } 10^{-5} \text{ NHDD}$

where

NHDD = nighttime heating degree-days ($^\circ$C)

ΔL = change in heating load (MWh)

A = window area (m^2)

We tabulated nighttime heating degree-days (NHDD) for 45 cities in Table 4 for three different balance point temperatures. These values can be inserted in the regression equations to obtain predictions of heating load reductions for single-, double-, and triple-pane windows. We found that the goodness of fit depended weakly on the balance point temperature chosen.

We compared the heating load savings per square foot derived from movable insulation for ranches and apartment prototypes. For the purpose of this comparison, we assumed that double-pane windows are likely to be in use in the cold locations where movable insulation may be cost-effective. For NHDD values between 1200 and 3500 (F), the ratio of savings for a ranch house compared to an end-unit apartment ranges from 1.0 to 1.15. There are a number of reasons why the load reduction per square foot of window area is somewhat different for the ranch prototype than for the end-unit apartment. One of the differences between the two sets of simulations is that the apartment prototype simulations were performed with custom weighting factors, while the ranch simulations were performed with a fixed set of weighting factors. Additionally, the ranch prototype simulations allowed for somewhat more external shading than the apartment simulations. Lower solar gain would result in slightly lower indoor temperatures during times when the temperature is floating (swing seasons) and thus, in some climates, slightly greater benefits from the use of movable insulation at night.

All of the DOE 2.1A simulations we used to generate the load reductions found in Table 3 assumed R-3 $ft^2{\cdot}F/Btu$ (16.7 $m^{2\cdot}{}^\circ C/W$) insulation and no window sash. In order to be able to predict heating-load reductions for various window sash types and for various movable insulation R-values, we calculated sash correction factors and R-value correction factors. These correction factors are shown in Tables 5 and 6 respectively. We derived sash correction factors by calculating U-values for the various combinations of sash type and insulation. We used ASHRAE adjustment factors to obtain U-values for single-, double-, and triple-pane windows with various sash types. R-value correction factors were obtained in a similar manner.

Table 7 lists the simple payback period resulting from the use of movable insulation for a ranch house with gas heating appliances in 10 locations and with three different types of glazing. We assumed a cost of natural gas of \$0.50/therm (\$0.017/kWh). Our analysis used a combined value of R-3 $ft^2{\cdot}h{\cdot}F/Btu$ (16.7 $m^2{\cdot}{}^\circ C/W$) for the insulation and air space. We obtained the cost of the conservation measure from an extensive list of movable insulation devices (New Shelter 1985). One example of a lower priced material is a translucent shade, with polyester batting and a clear polyethylene vapor barrier, sealed on all sides. The cost of the material is \$4/ft^2 (\$43/m^2), and its reported (measured in place with a single-pane window) R-value is 3.4 $ft^2{\cdot}h{\cdot}F/Btu$ (18.9 $m^{2\cdot}{}^\circ C/W$). We assumed that the movable insulation is manually operated so there is no extra cost for timing devices. We assumed that the base case house has no internal shading and therefore have used the full cost of the movable insulation in our calculations. If loose drapes were originally in place, then most of the energy savings would still be achieved, but the differential in cost of the conservation measure would be lower. The net effect would be a lower SPP. The following equation was used to get the results in Table 7:

$$SPP = \frac{PM \times S \times HCOP}{HLS \times PF}$$

where

PM = Price of the movable insulation

S = Surface area of the moveable insulation

HLS = Heating load savings (see Table 3)

PF = Fuel price

SPP = Simple payback period (years)

HCOP = Coefficient of performance for heating

We found, as shown in Table 7, a long payback period even with single-glazing in very cold locations such as Bismarck (8.7 years) or Omaha (12.3 years). For double- or triple-pane windows, the payback period is even greater. With present prices of movable insulation and natural gas, movable insulation in houses with gas space heating should be considered only in very cold climates. We added several cold locations and removed some warm ones from Table 7 (as compared to Table 3) in order to provide more useful information to potential users of movable insulation.

We also calculated the simple payback period for electric resistance (see Table 8) and electric heat pump heating systems. We assumed that the cost of electricity was \$23.4/MBtu (\$0.08/kWh). For electric resistance heating, the payback period decreases substantially (by a factor of 3.26) to six years or less in all the cold climates for houses with single-pane windows. With double-pane windows, movable insulation should be considered for implementation only in the coldest climates (e.g., Bismarck and Minneapolis). For heat pump systems, the payback period decreases by a factor of 1.64 relative to the values for gas space heating systems. Therefore, the simple payback periods fall between the values for gas space heating and electric resistance heating. It is important to consider electric resistance and electric heat pump space heating because they are often used in new residential construction, particularly in multifamily housing. For example, in recent years, more than twice as many new units have used electric heat as all other fuels combined. In 1983, electric heat pumps were installed in 28% of new multifamily units (HUD, 1984).

CONCLUSION

Our analysis shows that the use of reflective glazing, relative to regular glazing, reduces cooling loads and increases heating loads in all climates. For warm climates (with large cooling loads and small or moderate heating loads) reflective glazing produces a decrease in both total space conditioning resource energy use (assuming gas heating and electric cooling) and space conditioning cost. Simple payback periods range from 5 to 10 years in the southwestern and southern parts of the United States when single-pane windows are used in houses with gas space heating and electric air conditioning.

DOE-2.1A simulations of movable insulation show substantial reductions in heating loads for cold climates. However, due to the high capital cost of movable insulation (\$4/ft^2 or \$43/m^2), the payback period is quite high (10 years) even in cold locations when gas space heating is utilized. When electric resistance or heat pump heating is used (common in new multifamily buildings), the cost of heating is much higher and the use of movable insulation is more cost-effective. For electric resistance heating in cold locations (e.g., Chicago and Denver), the simple payback period is about five years when single-glazing is used. However, the cost-effectiveness of double-glazed windows and other conservation measures should be compared to that of movable insulation rather than deciding in isolation whether to use movable insulation. This can be done by calculating marginal benefit-to-cost ratios (B/C) for individual measures. The measure with the highest B/C (greater than 1.0) should be installed first and then new marginal B/C should be calculated and the process repeated.

There are several conservation measures (related to windows) that we have not yet assessed. These include: external window shading, movable interior shading under varying operator schedules, and reflective/absorptive glazing for selective orientations. We also intend to explore the interactive effect of carrying out two or more measures simultaneously.

In conclusion, the cost-effectiveness of various energy conservation measures for windows is highly dependent upon climate, heating equipment choice, local fuel prices, and capital cost of the conservation measure. However, energy conservation opportunities for glazing can be tailored to specific local conditions by using the results of parametric analyses such as those described here.

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TABLE 1

Transmittance and Reflectance of Regular and Reflective Glass

	Regular Glass		Reflective Glass	
	% T	% R	% T	% R
Single-pane	88	7	20	45
Double-pane	75	16	19	45
Triple-pane	68	18	17	45

T = Transmittance

R = Reflectance

TABLE 2

Climate Information for 45 Locations

Location	W vert.insol. $\left(\frac{kBtu}{ft^2}\right)$	S vert. insol. $\left(\frac{kBtu}{ft^2}\right)$	W vert. insol. $\left(\frac{kWh}{m^2}\right)$	S vert. insol. $\left(\frac{kWH}{m^2}\right)$
Albuquerque	175	91	551.2	286.6
Atlanta	105	140	330.7	441.0
Birmingham	98	154	308.7	485.1
Bismarck	157	67	494.5	211.0
Boise	154	69	485.1	217.3
Boston	164	69	516.6	217.3
Brownsville	28	248	88.2	781.2
Buffalo	145	44	456.7	138.6
Burlington	156	41	491.4	129.1
Charleston	76	177	239.4	557.5
Cheyenne	196	44	617.4	138.6
Chicago	151	66	475.6	207.9
Cincinnati	121	106	381.1	333.9
Denver	180	54	567.0	170.1
El Paso	112	132	352.8	415.8
Fort Worth	99	167	311.8	526.0
Fresno	114	116	359.1	365.4
Great Falls	163	38	513.4	119.7
Hononulu	0	323	-	1017.4
Jacksonville	62	196	195.3	617.4
Juneau	175	0	551.2	-
Kansas City	127	107	400.0	337.0
Lake Charles	65	182	204.7	573.3
Las Vegas	107	164	337.0	516.6
Los Angeles	134	26	422.1	81.9
Medford	115	60	362.2	189.0
Memphis	108	141	340.2	444.1
Miami	12	269	37.8	847.3
Minneapolis	150	81	472.5	255.1
Nashville	104	136	327.6	428.4
New York	144	82	453.6	258.3
Oklahoma City	126	128	396.3	403.2
Omaha	147	92	463.0	289.8
Philadelphia	133	97	418.9	305.5
Phoenix	73	189	229.9	595.3
Pittsburg	132	79	415.8	248.8
Portland,Me	179	44	563.8	138.6
Portland,Or	157	24	494.5	75.6
Reno	149	64	469.3	201.6
Salt Lake	155	92	488.2	289.8
San Antonio	72	187	226.8	589.0
San Diego	119	35	374.8	110.2
San Francisco	215	8	677.2	25.2
Seattle	171	12	538.6	37.8
Washington	125	105	393.7	330.7

W = average vertical insolation during heating periods.
S = average vertical insolation during cooling periods.

TABLE 3a

Ranch House Movable Insulation Annual Heating Load Reduction (MBtu)

City	Window Type SG	DG	TG
Albuquerque	6.20	2.29	1.17
Atlanta	3.01	1.08	0.54
Chicago	7.47	2.72	1.41
Denver	7.67	2.76	1.42
Lake Charles	2.24	0.83	0.43
Miami	0.27	0.09	0.05
Minneapolis	12.15	4.52	2.37
New York	6.60	2.29	1.18
Phoenix	2.65	0.97	0.50
San Francisco	2.57	0.97	0.49
Seattle	5.34	2.00	0.96

SG = single-glazing
DG = double-glazing
TG = triple-glazing

TABLE 3b

Ranch House Movable Insulation Annual Heating Load Reduction (kWh)

City	Window Type SG	DG	TG
Albuquerque	1816.6	670.9	342.8
Atlanta	881.9	316.4	158.2
Chicago	2188.7	796.9	413.1
Denver	13.8	808.7	416.1
Lake Charles	656.3	243.2	126.0
Miami	79.1	26.4	14.7
Minneapolis	3533.3	1324.4	694.4
New York	1933.8	690.9	345.7
Phoenix	776.4	284.2	146.5
San Francisco	753.0	284.2	143.6
Seattle	1564.6	586.0	281.3

TABLE 4
Nighttime Heating Degree-Days

City	59F	61F	63F	32.8 ° C	33.3 ° C	35 ° C
	Base Temperature					
Albuquerque (5)+	1525	1650	1776	847.2	916.7	986.7
Atlanta GA (3)	649	722	797	360.6	401.1	442.8
Birmingham (3)	705	775	846	391.7	430.6	470.0
Bismarck (7)	3447	3624	3799	1915.0	2013.4	2110.6
Boise (5)	1622	1748	1875	901.1	971.1	1041.7
Boston (5)	1658	1784	1911	921.1	991.1	1061.7
Brownsville (3)	135	172	216	75.0	95.6	120.0
Buffalo (7)	2255	2426	2599	1252.8	1347.8	1443.9
Burlington (7)	2703	2877	3051	1501.7	1598.3	1695.0
Charleston (3)	582	651	723	323.3	361.7	401.7
Cheyenne (7)	2565	2741	2919	1425.0	1522.8	1621.7
Chicago (5)	1783	1906	2031	990.6	1058.9	1128.4
Cincinnati (5)	1482	1606	1733	823.4	892.3	962.8
Denver (5)	1825	1950	2076	1013.9	1083.4	1153.3
El Paso (3)	824	898	973	457.8	498.9	540.6
Fort Worth (3)	604	673	743	335.6	373.9	412.8
Fresno (3)	677	751	827	376.1	417.2	459.5
Great Falls (7)	2537	2714	2890	1409.5	1507.8	1605.6
Honolulu (3)	0	0	0	-	-	-
Jacksonville (3)	345	407	471	191.7	226.1	261.7
Juneau (7)	2440	2615	2792	1355.6	1452.8	1511.1
Kansas City	1660	1781	1904	922.2	989.4	1057.8
Lake Charles (5)	465	529	597	258.3	293.9	331.7
Las Vegas (3)	427	495	566	237.22	275.0	314.5
Los Angeles (3)	242	315	389	134.4	175.0	216.1
Medford (5)	1442	1569	1695	801.1	871.7	941.7
Memphis (5)	1097	1211	1327	609.4	672.8	737.2
Miami (3)	46	62	81	25.56	34.4	45.0
Minneapolis (7)	3010	3183	3358	1672.2	1768.3	1865.6
Nashville (5)	1144	1262	1385	635.6	701.1	769.4
New York (5)	1368	1492	1618	760.0	828.9	898.9
Oklahoma City (5)	1374	1494	1616	930.0	830.0	897.7
Omaha (7)	2401	2572	2745	1333.9	1428.9	1525.0
Philadelphia (5)	1639	1764	1891	910.6	980.0	1050.6
Phoenix (3)	535	610	685	297.2	338.9	380.5
Pittsburgh (5)	1661	1786	1911	922.8	992.2	1061.7
Portland, ME (7)	2658	2834	3011	1476.7	1574.4	1672.8
Portland, OR (5)	1250	1376	1501	694.5	764.4	833.9
Reno (5)	1856	1982	2109	1031.1	1101.1	1171.7
Salt Lake City (5)	1914	2040	2167	1063.3	1133.3	1203.9
San Antonio (3)	528	595	663	293.3	330.6	368.3
San Diego (3)	251	323	397	139.4	179.4	220.6
San Francisco (3)	490	565	639	272.2	313.9	355.0
Seattle (5)	1241	1367	1492	689.5	759.4	828.9
Washington (5)	1259	1383	1508	699.5	768.3	837.8

+The number in parenthesis is the number of months comprising the winter heating season for each city.

TABLE 5

Sash Correction Factors+

	Sash Type		
	Wood	AL	AL/TB
Single-Glazed	.945	1.12	.994
Double-Glazed 1/2" air gap	1.03	1.48	1.18
Triple-Glazed 1.2" air gap	1.09	1.83	1.35

AL = aluminum
AL/TB = aluminum window thermal break

+These factors are multiplied by the heating load reductions for windows without sash (Table 3) to obtain the heating load reductions for windows with the sash types such as wood, aluminum, and aluminum with a thermal break.

TABLE 6

R-Value Correction Factors+

	R-1	R-5
Single-pane	.68	1.10
Double-pane	.55	1.19
Triple-pane	.49	1.26

+These factors are multiplied by the heating load reductions for R-3 insulation (Table 3) to obtain the heating load reductions for windows with either R-1 or R-5 insulation.

TABLE 7

Ranch House Movable Insulation Simple Payback Period (Years) Gas Heating 10% Window Area

	Window Type		
City	SG	DG	TG
Albuquerque	19.7	53.7	105
Atlanta	40.7	113.4	226
Bismarck	8.7	18.6	29.8
Boise	17.9	38.2	52.6
Chicago	16.6	44.9	86.8
Denver	16.0	44.5	86.1
Minneapolis	10.1	27.1	51.6
New York	18.5	53.6	104
Omaha	12.3	26.4	39.6
Seattle	30.5	48.7	61.6

TABLE 8

Ranch House Movable Insulation Simple Payback Period (Years) Electric Resistance 10% Window Area

	Window Type		
City	SG	DG	TG
Albuquerque	6.0	16.4	32.1
Atlanta	12.4	34.6	69.2
Bismarck	2.7	5.7	9.1
Boise	5.5	11.7	16.0
Chicago	5.0	13.7	26.6
Denver	4.9	13.6	26.6
Minneapolis	3.1	8.3	15.8
New York	5.7	16.4	31.8
Omaha	3.8	8.1	12.1
Seattle	9.3	14.9	18.8

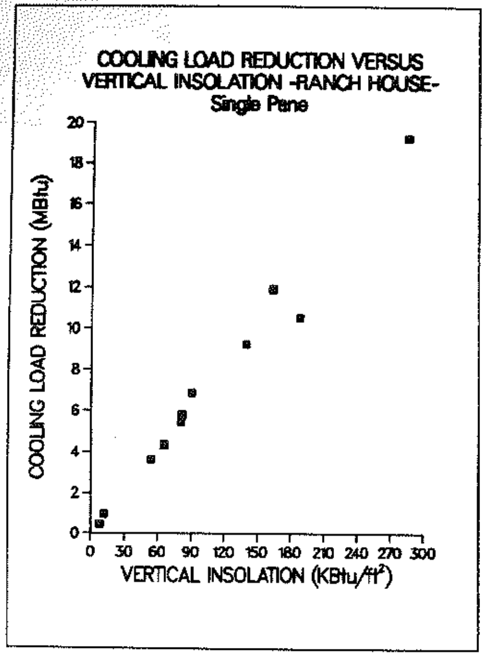

Figure 1. Reduction in cooling load (millions of Btu) achieved by use of reflective glass vs. average vertical insolation for 11 cities. Simulations are for a 143 m^2 (1540 ft^2) ranch house with 21.5 m^2 (231 ft^2) single-pane windows

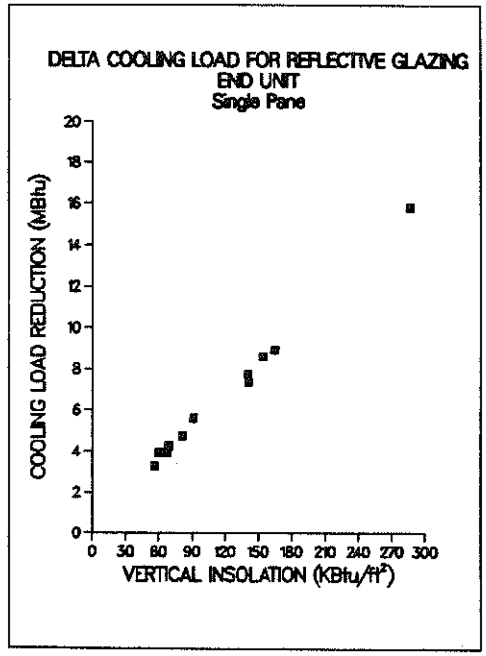

Figure 2. Reduction in cooling load (millions of Btu) achieved by use of reflective glass vs. average vertical insolation for 11 cities. Simulations are for a 111.5 m^2 (1200 ft^2) end-unit apartment with 16.7 m^2 (180 ft^2) of single-pane windows

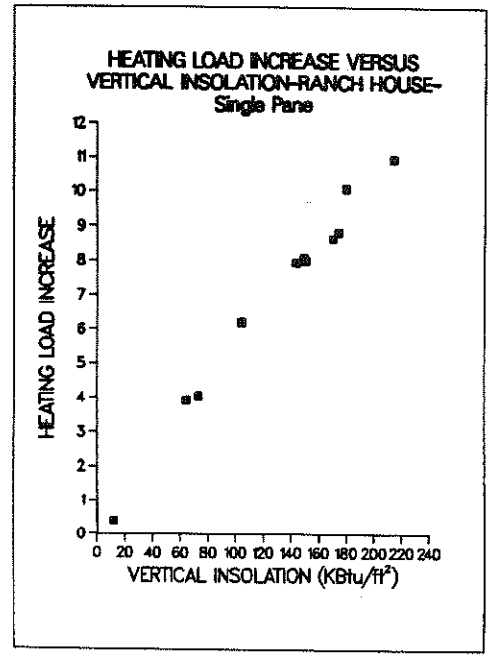

Figure 3. Increase in heating load (millions of Btu) resulting from use of reflective glass vs. average vertical insolation for 11 locations. Simulations are for a 143 m^2 (1540 ft^2) ranch house with 21.5 m^2 (231 ft^2) of single-pane windows

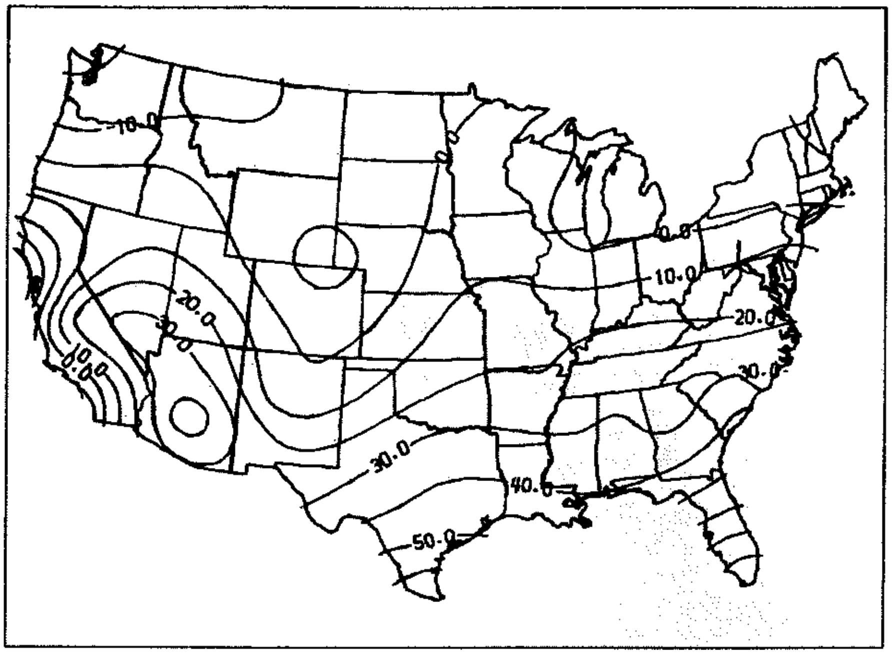

Figure 4. Impact of reflective glazing on annual cost of space conditioning a 143 m^2 (1540 ft^2) ranch house with 9.3 m^2 (100 ft^2) of single-pane windows is shown on a map of the U.S. The cost changes are for a house heated with natural gas and cooled with an electric air conditioner

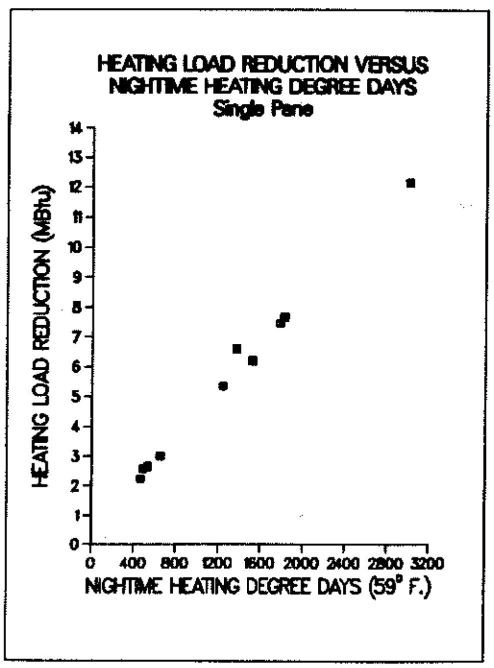

Figure 5. Heating load reduction (millions of Btu) achieved by use of movable insulation vs. nighttime heating degree days base 59 F (15°C) for 10 locations. Simulations are for a 243 m^2 (1540 ft^2) ranch house with 21.5 m^2 (231 ft^2) of single-pane windows