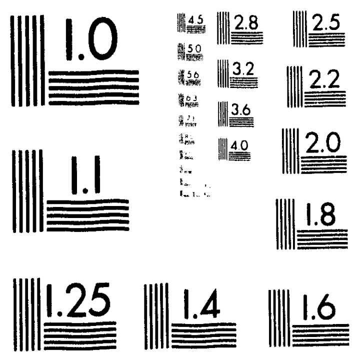
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Window U-Value Effects on Residential Cooling Load

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Window U-Value Effects on Residential Cooling Load

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Abstract

This paper presents the results of a study investigating the effects of window U-value changes on residential cooling loads. We used the DOE-2.1D energy analysis simulation program to analyze the hourly, daily, monthly, and annual cooling loads as a function of window U-value. The performance of a prototypical single-story house was examined in three locations: hot and humid, Miami FL; hot and dry, Phoenix AZ; and a heating-dominated location with a mildly hot and humid summer, Madison WI. Our results show that when comparing windows with identical orientation, size, and shading coefficient, higher U-value windows often yield lower *annual* cooling loads, but lower U-value windows yield lower *peak* cooling loads. This occurs because the window with the higher U-value conducts more heat from inside the residence to the outside during morning and evening hours when the outside air temperature is often lower than the inside air temperature; and, a lower U-value window conducts less heat from outside to inside during summer afternoon peak cooling hours. The absolute effects are relatively small when compared to total annual cooling which is typically dominated by window solar heat gain effects, latent loads, and internal loads. The U-value effect on cooling is also small when compared to both the effects of U-value and solar heat gain on heating load. Our modeling assumed that U-value and solar heat gain could be independently controlled. In fact, reducing window conductance to the levels used in this study implies adding a second glazing layer which always reduces solar heat gain, thus reducing annual cooling. Thus, when we compare realistic options, e.g., single pane clear to double pane clear, or single pane tinted to double pane tinted, the double pane unit shows lower annual cooling, as well as lower peak loads.

Introduction

Analyzing the thermal load and energy performance of a residence involves understanding the complex heat transfer relationships between the parameters that define the residence and the external environmental characteristics associated with the residence's geographic location. When heating is required, conductance (U-values of wall-roof-floor-windows) is one of the more important parameters that determine performance. For example, steady-state $UA\Delta T$ calculations are often used to quickly estimate heating loads in buildings. The conductance heat losses that occur during daytime heating hours can be balanced by solar heat gains through windows which are directly influenced by the window glazing's shading coefficient or solar heat gain. During heating hours, the outside air temperature is usually lower than the indoor air temperature. Therefore, to reduce heating loads, conductance or U-value is decreased (R-value or amount of insulation is increased) and solar gains are increased. These rules are very straightforward and relatively easy to understand.

One would expect a similar analysis to be valid when cooling is required; i.e., reduced cooling loads require lower conductances, but also lower solar gains. However, the climatic and environmental conditions during which cooling is necessary are more diverse and variable than heating situations. Unlike heating, where there is usually a well-defined temperature difference between the outside and inside which thus establishes a distinct conductance loss that adds to the total heating required in a building, cooling may occur during hours when the outside air temperature fluctuates between values that are less than or greater than the inside air temperature since solar gain typically dominates cooling performance. We cannot easily categorize conductance effects on cooling because they may occur quite often during periods when the inside air temperature is within the thermostat deadband. However, we can say with confidence that lower solar gains yield lower cooling loads. Another parameter that complicates the analysis of cooling is humidity which is introduced through the infiltration of outside air through cracks and leaks in the building. Latent cooling loads as well as sensible loads are often introduced. Humidity is also a factor if natural ventilation through openable windows is used in residences to reduce cooling.

This paper presents the results of a study undertaken to better understand the nature of thermal conductance effects under conditions when cooling is required. It complements and explains the results reported in Gueymard and McCluney (1992) which presented annual cooling and peak cooling and heating loads for parametrically varying window frame and glazing conductances and shading coefficients. In that study it was shown that for windows with identical orientation, size, and shading coefficient, higher U-value windows yielded lower annual cooling loads. On the other hand, lower U-value windows yielded lower peak cooling loads. This study also extends previous studies by Sullivan and Selkowitz (1986, 1985) which focused on the annual cooling and heating energy performance of specific window products with an emphasis on orientation, window size, and shading coefficient for cooling and orientation, window size, and conductance on heating.

We used the DOE-2 (Simulation Research Group 1989) hour-by-hour program to simulate the thermal load and energy performance in three geographic locations: hot and humid, Miami FL; hot and dry, Phoenix AZ; and a heating-dominated location with a mildly hot and humid summer, Madison WI. Table 1 gives heating- and cooling-degree-day information as well as humidity and solar radiation data for these locations. Specific configuration parameters investigated included window conductance and shading coefficient, internal load levels, and residence thermostat setting.

This work is part of a process to verify a computer program called RESFEN (Sullivan, Chin, Arasteh, and Selkowitz 1992) being developed by the Building Technologies Program at the Lawrence Berkeley Laboratory. RESFEN calculates the heating and cooling energy use and cost of residential fenestration systems. The algorithms used by the program were derived by a regression analysis of thousands of hour-by-hour DOE-2 building energy simulations of a prototypical residential building.

Residential Model Description

We modeled a single-story, slab-on-grade, one-zone house of wood-frame construction (R19 walls and R34 roof) with a floor area of 1540 ft^2 (143 m^2). Window sizes were fixed on all four facades at 4% (61.6 ft^2, 5.72 m^2,) of the floor area. The total residential window area was therefore 16% of the floor area. Window U-values investigated were 1.11 Btu/hr-ft^2°F (6.24 W/m^2°C) and 0.47 Btu/hr-ft^2°F (2.67 W/m^2°C). In addition, we also varied the shading coefficient from 1.0 to 0.4 to better understand the interactions that occur with reduced solar gains.

Internal loads for occupants, lights, and appliances were modeled by considering a composite process heat gain input with a maximum value of 10163 Btu/hr (10721 KJ/hr) which is equivalent to a daily heat input of 53963 Btu/day (56932 KJ/day) sensible and 12156 Btu/day (12875 KJ/day) latent. Infiltration was calculated using an average level of building leakage area, 0.77 ft^2($0.071m^2$). The leakage area is a parameter that describes the tightness of the structure which is obtained from pressurization tests. Both temperature-induced and wind-induced infiltration components were calculated on an hourly basis.

Natural ventilation of ten air-changes per hour was also provided by opening the windows. The windows were opened only if the following conditions were both met: (1) if the act of opening the windows provided more cooling than would be provided by the mechanical system with the windows closed; and (2) the enthalpy of the outside air was less than the enthalpy of the inside air (this condition eliminates the possibility of introducing a latent load into the house.

A dual setpoint thermostat was used to control the space conditioning system. Heating was set at 70°F (21.1°F) from 7 a.m. to 11 p.m. with a night setback to 60°F (15.6°C) from 12 p.m. to 6 a.m. Cooling was set at 78°F (25.6°C) for all hours. A direct-expansion air-cooled air-conditioning unit was used for cooling and a forced-air gas furnace for heating. Cooling system COP was 2.2 and furnace steady state efficiency was 0.74.

Discussion

Figure 1 presents annual and monthly cooling loads for Miami, Florida for two window U-values at shading coefficients of 1.0 and 0.4. Miami requires both sensible and latent cooling most of the year (see Table 1). Cooling load values are shown for thermostat settings of 70°F (21.1°C) and 78°F (25.6°C). We see in Figure 1 for a shading coefficient equal to 1.0 at the 70°F (21.1°C) thermostat setting, that the low U-value window has a slightly smaller annual cooling load than the high U-value window. On a monthly basis, the low U-value window outperforms the high U-value window from late spring through fall; whereas, the high U-value window has a lower monthly cooling load during winter months. At the 78°F (25.6°C) thermostat setting, the high U-value window annual and monthly loads are lower than the loads due to the low U-value window.

Windows with a lower shading coefficient, SC=0.40, reduce the amount of solar heat gain and consequently the total amount of annual and monthly cooling loads. However, the relative difference in performance between high and low U-value windows in Miami is the same as the higher shading coefficient configuration. Comparable results occur by reducing the internal loads due to occupants and appliances.

Figures 2 and 3 show results for Madison, Wisconsin and Phoenix, Arizona (see Table 1). Madison's climate is characterized as cold in winter with a short hot and humid summer; however, summer temperatures do not get as high as in Miami. Cooling takes place from late May until September. Phoenix is hotter than Miami in the summer but it is very dry with almost no humidity, resulting in high sensible cooling loads from spring through fall. Most homes in Madison, because of its cold climate and the importance of heating load reduction, use windows with low U-values. However, we still compared the high and low U-value alternatives, with the result that the high U-value windows yield lower cooling loads both monthly and annually at both thermostat settings. In Phoenix, for windows with high shading coefficients, annual cooling for both U-values is about the same for the two thermostat settings; however, on a monthly basis, high U-value windows have lower cooling loads from late fall through winter and spring.

The results for all three locations appear to indicate that cooling loads are lower with high U-value windows during transition months; i.e., fall through spring or when the ambient air temperature is lower than what one would expect on a hot summer day. Low U-value windows are best when the ambient temperature is high. Cooling loads for high U-value windows are also lower in Madison during summer when ambient temperatures are mild compared to Miami or Phoenix. We can further validate these results by examining hourly cooling load and temperature profiles.

Figure 4 shows hourly cooling load variations at the 78°F (25.6°C) setpoint in Miami during peak cooling days in January and August for varying window U-values at a fixed shading coefficient of 1.0. In January, cooling for the high U-value window is lower than the low U-value window throughout the 24-hour period; whereas, in August, the low U-value window is best during daylight hours.

Figure 5 presents the inside and outside air temperatures for the same January and August days. Notice that the inside temperature is essentially fixed at the setpoint. Annotated on each figure is an arrow indicating the direction of heat flow. We see that on the peak day in January, with the exception of 2-3 hours at midday, the flow of heat is from inside the residence to the outside. In August, the flow of heat is from the outside to the inside. The daily ambient temperatures for the peak cooling day of every month in Miami is shown in Figure 6. From October through March, the conductive heat flow is from inside to outside during early morning and evening hours. During the late spring through summer, May to August, this situation reversed. Note that we are only addressing the peak cooling day; the outside temperature during other days of each month would be less than that shown.

This flow of heat gives an indication of what level of window conductance results in lower cooling loads; i.e., when the outside air temperature is lower than the inside air temperature, such as during morning and evening hours and during other hours in transition months, the conduction of heat is from inside to outside and a window with a high U-value best facilitates the conduction of heat to the outside which reduces the amount of cooling required; when the flow of heat is from the outside to inside such as during daytime hours, particularly in the summer months, a window with a low U-value is best to prevent excess heat buildup in the residence. This latter condition also means that low U-value windows are best for peak cooling load reduction.

Another way of observing the effect of window conductance is seen in Figure 7. In this instance, we have allowed the inside temperature to float; i.e., there is no cooling. The inside temperature with the high U-value window for both January and August peak days is approximately 6°F (3.3°C) less than the inside temperature using the low U-value window, and this is true for all hours. The flow of heat is from the inside to the outside which is better facilitated by the high U-value windows resulting in a lower temperature at all times. We present these results for illustrative purposes only, since homeowners would not normally permit the inside air temperature to rise to the levels shown.

Several important qualifiers need to be added to the above analysis. We have used identical shading coefficients for the high and low conductance windows that we compared. In fact, in switching from, for example, a single glazed high conductance window to a double glazed low conductance window, the solar heat gain will normally be reduced by 10-15%. In addition, there is a great deal of freedom in selecting a shading coefficient for a window and the magnitude of the shading coefficient more strongly effects cooling load than U-value. For example, Figure 8 shows results for windows that have the same U-values as above, but the high U-value window's shading coefficient is 0.72 and the low U-value window's shading coefficient is 0.58, each corresponding to a green tint on the glazing. This small decrease in shading coefficient for the low U-value window yields a sufficient reduction in solar gain so that the annual and most monthly cooling loads are smaller than the high U-value window. This data should be compared with that contained in Figure 1.

Most importantly, the magnitudes of the cooling load differences due to window conductance variations are not very large. Greater control in cooling load reduction can be obtained by looking closely at the solar gain characteristics of the glazing element and frame size and type, or by considering various exterior or interior shading system options such as overhangs, blinds or drapes, deciduous trees, etc. Also, in geographic locations which have moderate or substantial heating, window U-value selection should be based primarily on heating load reduction and secondarily on cooling load reduction. Furthermore, window selection to improve thermal comfort and minimize condensation will normally favor a lower conductance solution.

We have not specifically addressed peak cooling loads in our analysis. However, our results indicate that lower U-value windows yield lower summer peak cooling loads (Figure 4). Peak cooling usually occurs during the mid-afternoon when the outside air temperature exceeds the inside air temperature; and, therefore, a well-insulated glazing conducts less heat into the house. Lower peak cooling loads should result in lower peak electric demand which is important to electric utilities whose generating and transmission investments are driven by peak electric loads.

Conclusions

The effects of window conductance variations on residential cooling load has been discussed in this paper. We have seen that for windows with equal areas and shading coefficients, high U-value windows conduct more heat from inside the house to the outside during those hours of the day when it is cooler outside than inside, thus reducing excess heat buildup which must be removed by the cooling system. During hot summer months, on the other hand, when it is hotter outside than inside, a low U-value window prevents conduction of heat from outside to the inside. Also a low U-value window results in lower peak cooling loads.

The magnitude of the difference in annual cooling loads due to high and low conductance windows is small, particularly when compared to cooling load differences due to shading coefficient variations. From the standpoint of an individual homeowner, the solar gain characteristics of windows are more important in evaluating a window system; however, from a utility standpoint, both solar gain and conductance are important because of each parameter's effect on peak cooling load.

It has been suggested that single glazed windows are better than double glazed solutions in southern climates because of the annual cooling load performance discussed above. However, window selection must also be tied to overall performance. The lower conductance window will always reduce peak cooling load and thus peak electric demand, an issue of growing importance to summer peaking utilities. It will also reduce peak electric demand for heating in those areas where electricity is used for heating as well as cooling. A lower conductance window also improves thermal comfort under winter conditions and most summer conditions, and reduces interior and exterior condensation. Thus although there will be times when lower conductance windows show very small total energy savings, a design decision based on total performance will typically still favor their selection.

Acknowledgment

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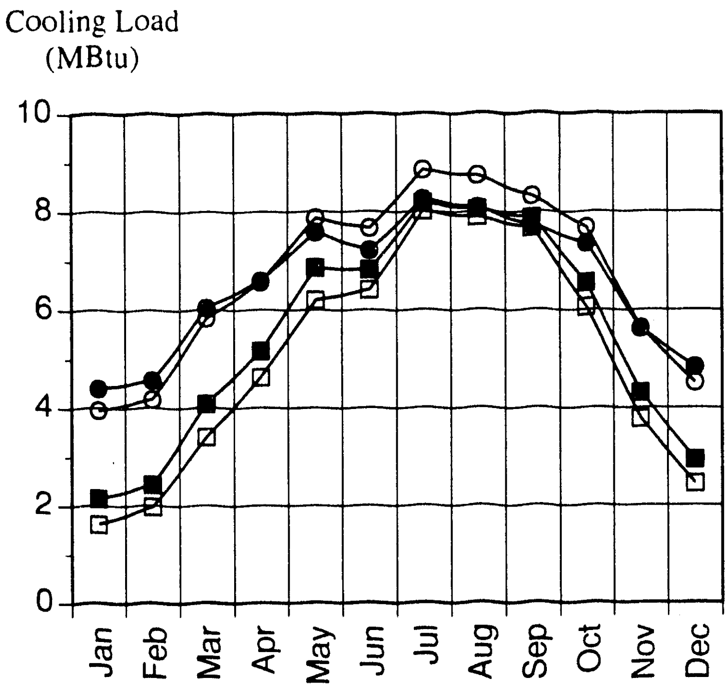
Table 1
Representative Heating Load and Cooling Load Parameters for the Cities Used in the Analysis

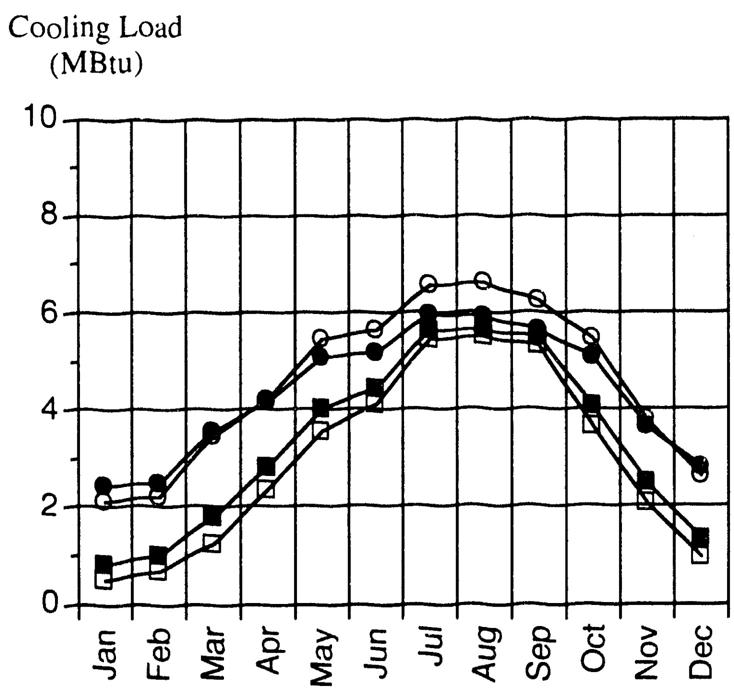
City	Lat	Long	Alt	TZ	HDD	CDD (65)	LED (75)	CID
Madison	43.02	89.03	858	6	7825	135	92	99
Miami	25.80	80.3	7	5	185	1264	1183	280
Phoenix	33.05	112.0	1117	7	1918	1989	135	227

Notes:
(1) LEH is Latent Enthalpy-Days at a base temp of 78 degrees and base humidity of .0116 and gives an indication of the effect of latent cooling. Defines the amount of energy that must be removed from the air each hour to lower it to the a reference humidity ratio without changing the drybulb temperature.
(2) CID is Cooling Insolation-Days at a base temperature of 70 degrees. Represents the total insulation hitting an average one square foot vertical surface (sum of N, E, S, W) when temperatures are above a designated value. Correlates with cooling load penalties due to unwanted solar gain.



Room Setpoint	Ug	Annual Cooling MBtu (MWh)
—o— 70	1.11	79.75 (23.37)
—●— 70	0.47	78.22 (22.92)
—□— 78	1.11	60.06 (17.60)
—■— 78	0.47	65.39 (19.16)

SC = 1.0



Room Setpoint	Ug	Annual Cooling MBtu (MWh)
—o— 70	1.11	54.27 (15.90)
—●— 70	0.47	51.83 (15.19)
—□— 78	1.11	35.32 (10.35)
—■— 78	0.47	39.45 (11.56)

SC = 0.4

Figure 1: Monthly cooling loads in Miami, Florida for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for varying room thermostat settings and window U-values for fixed window shading coefficients. The house internal load is 54 kBtu/day (15.8 kWh/day)

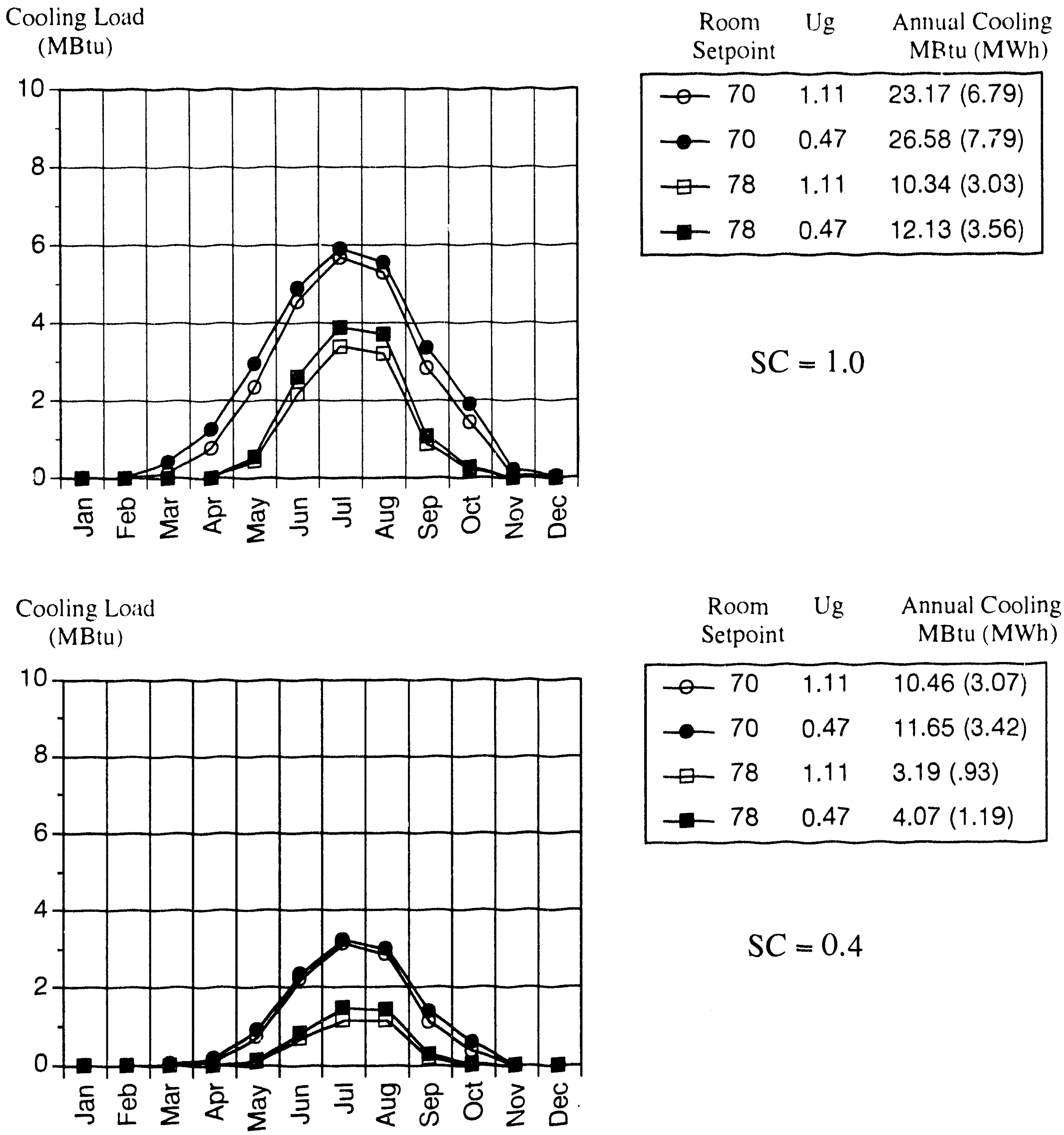


Figure 2: Monthly cooling loads in Madison, Wisconsin for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for varying room thermostat settings and window U-values for fixed window shading coefficients. The house internal load is 54 kBtu/day (15.8 kWh/day)

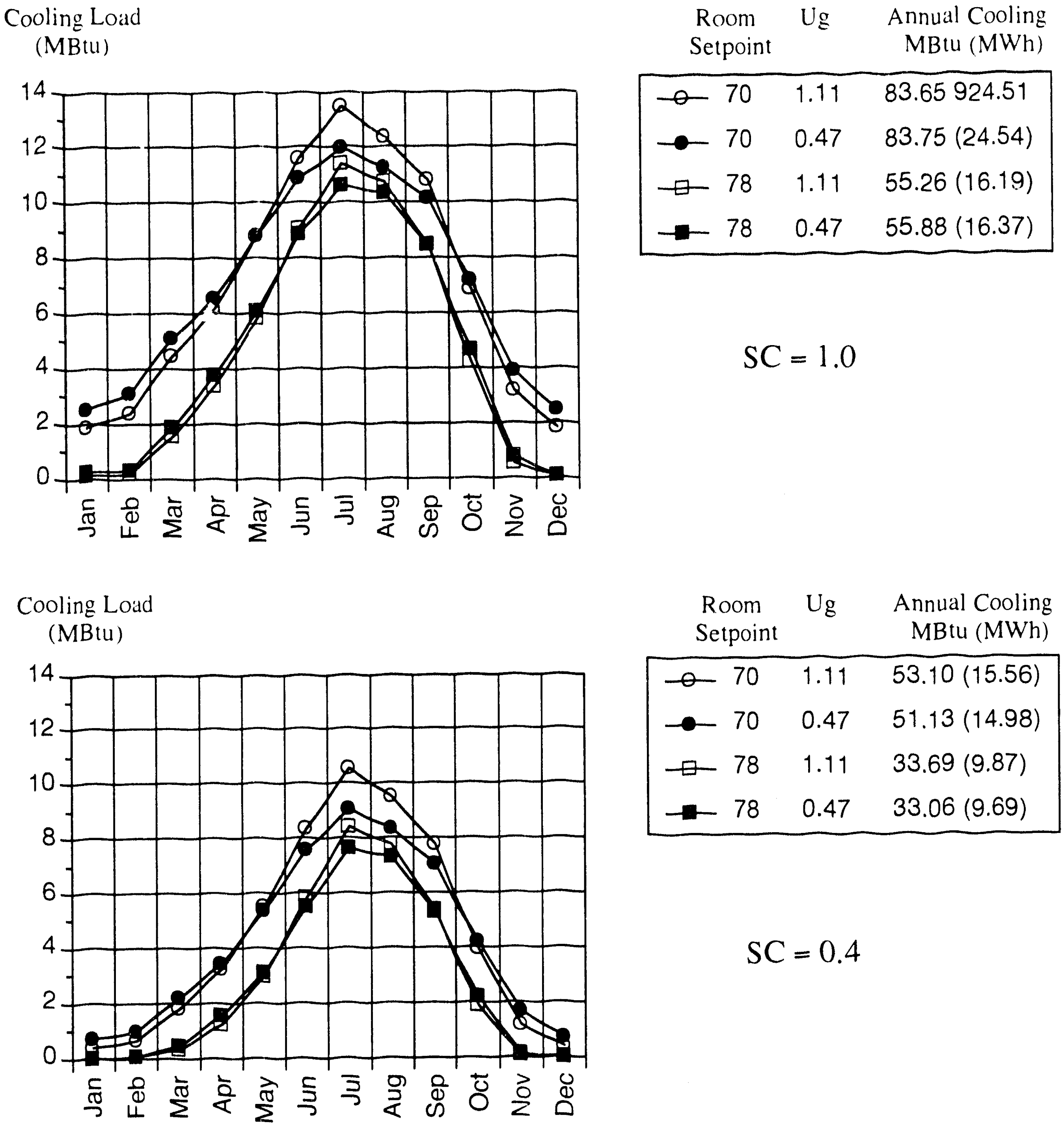


Figure 3: Monthly cooling loads in Phoenix, Arizona for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for varying room thermostat settings and window U-values for fixed window shading coefficients. The house internal load is 54 kBtu/day (15.8 kWh/day)

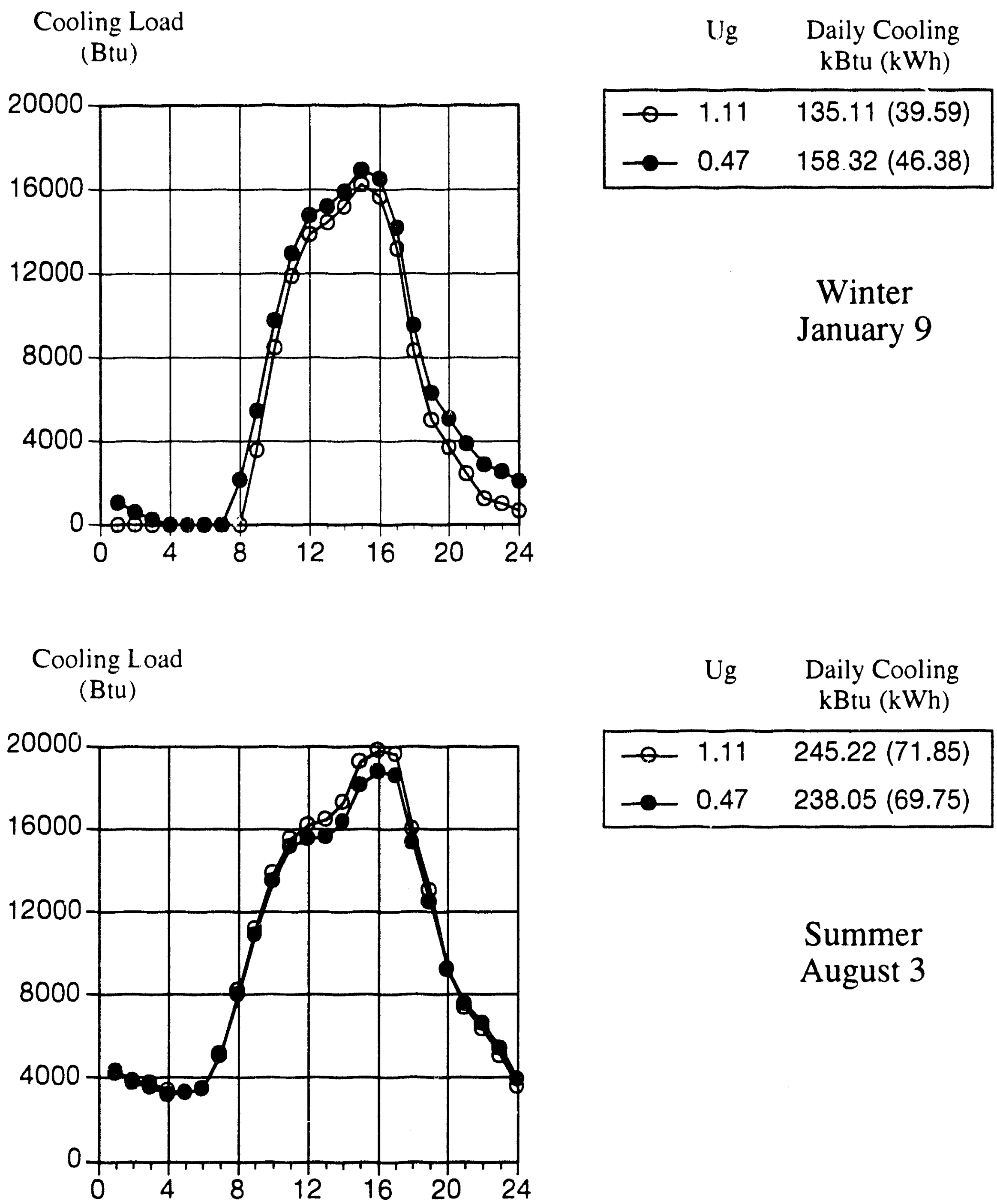


Figure 4: Hourly cooling load variation on peak cooling days in January and August in Miami, Florida for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Thermostat setpoint is 78F(25.5C). Results are shown for varying window U-values for a fixed window shading coefficient of 1.0.

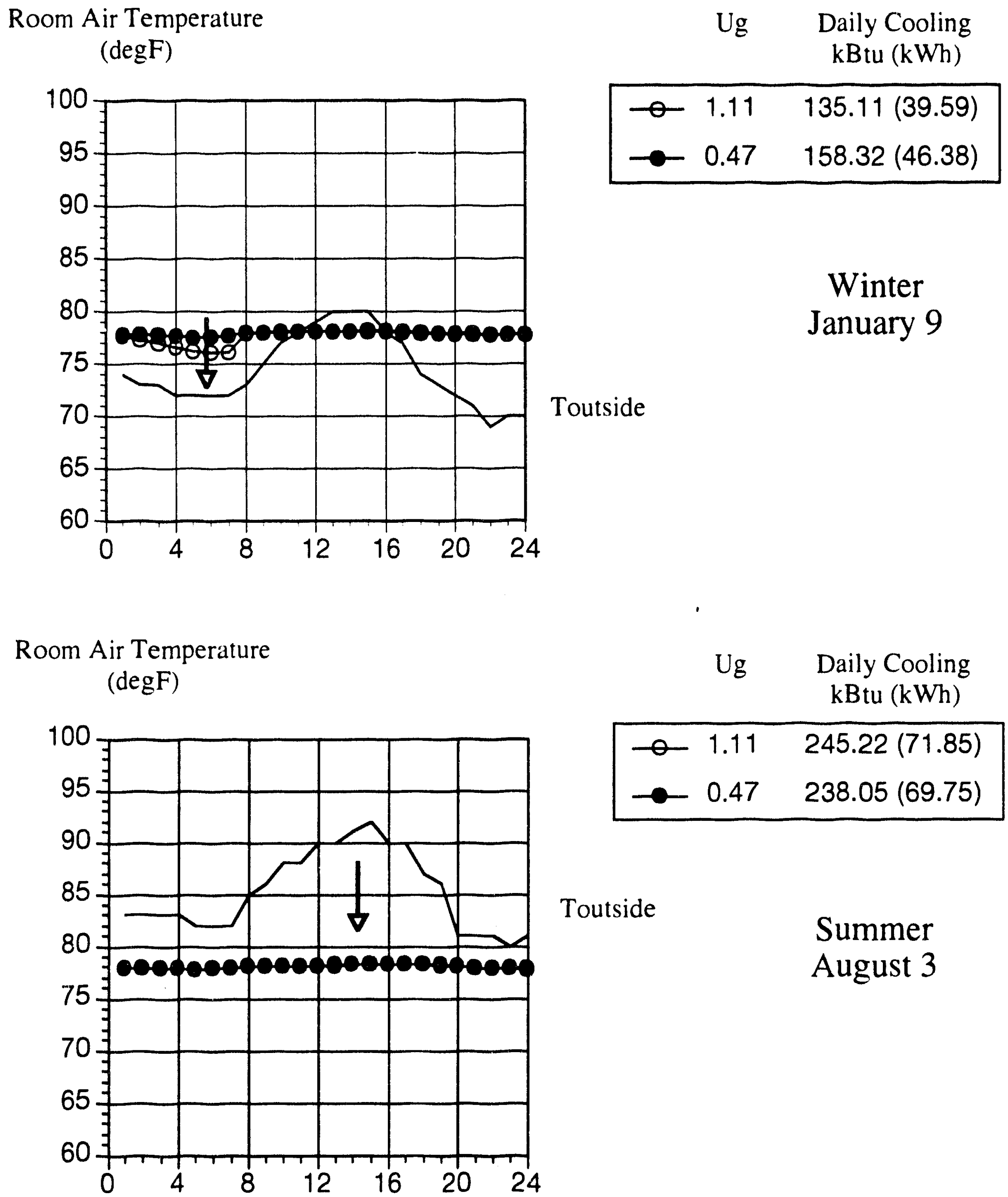


Figure 5: Hourly house air temperature on peak cooling days in January and August in Miami, Florida for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for varying window U-values for a fixed window shading coefficient of 1.0. Also shown is the outside air temperature.

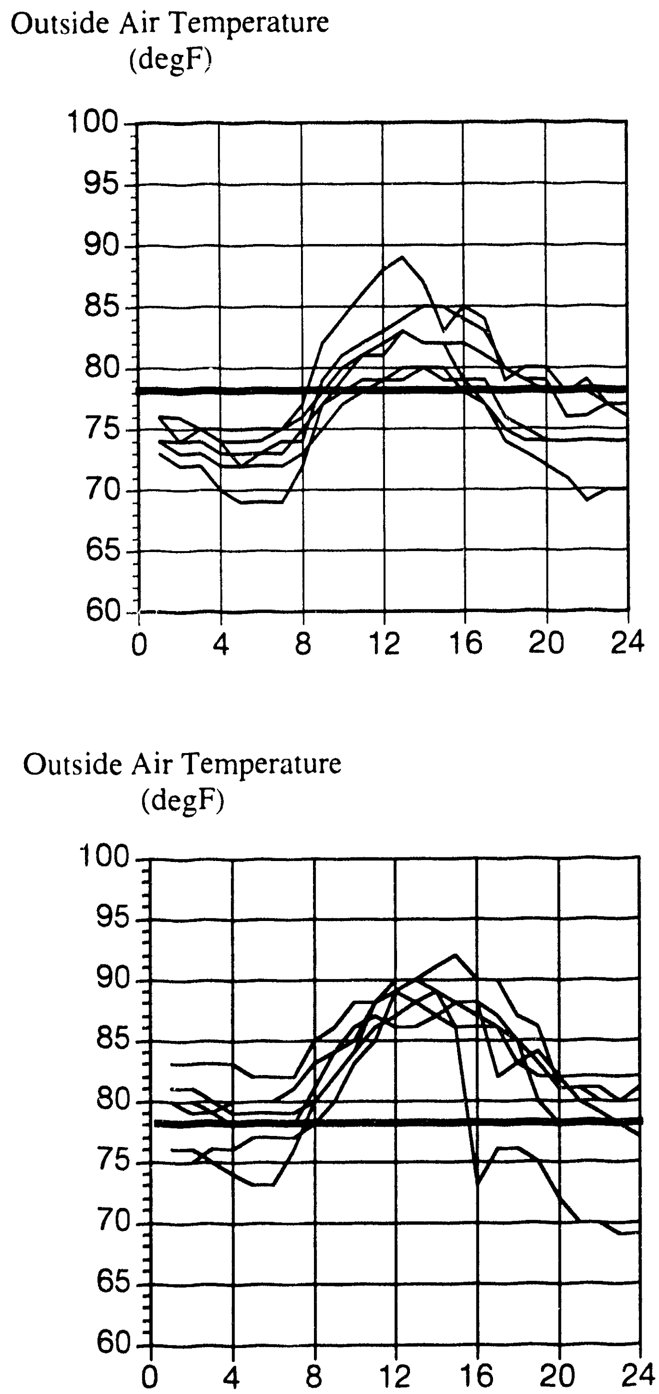


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Figure 6: Hourly outside air temperature on peak cooling days for each month of the year in Miami, Florida.

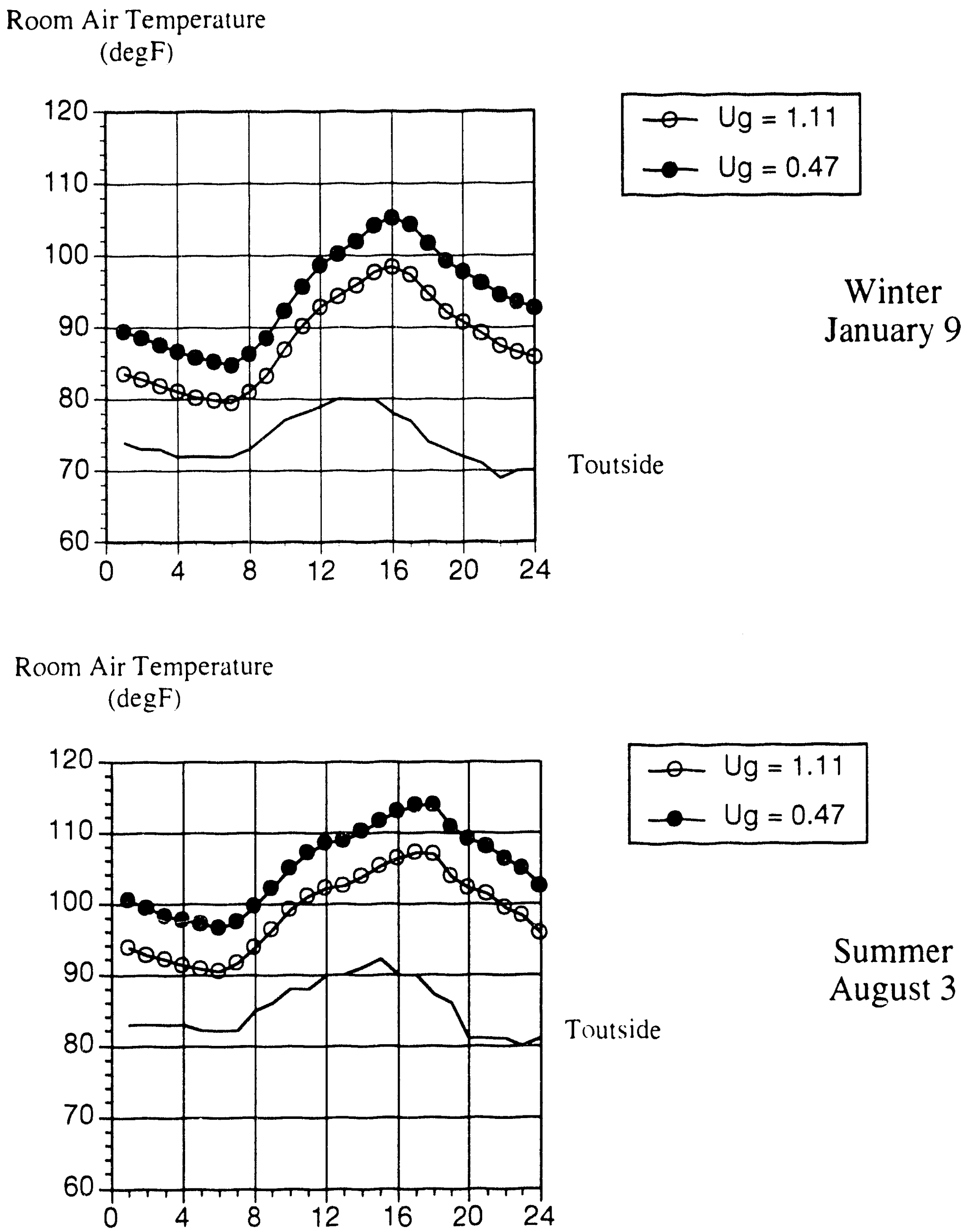
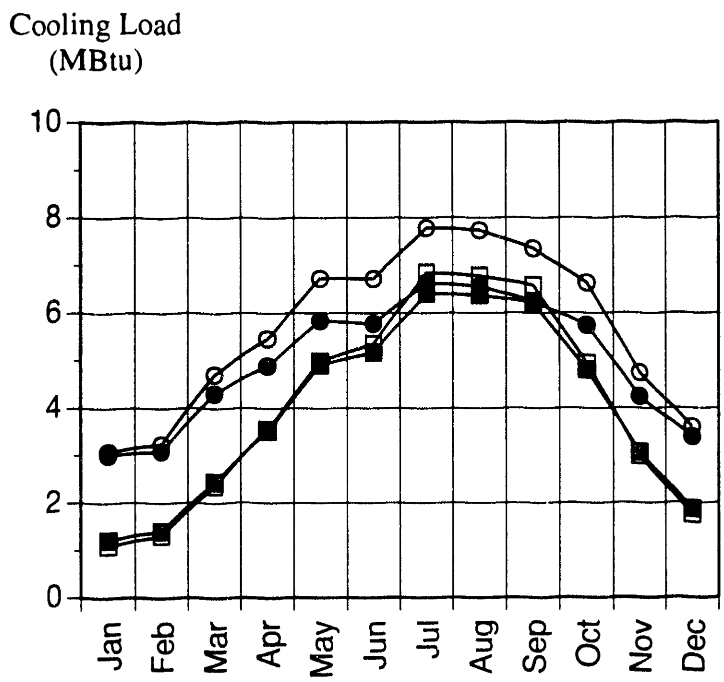


Figure 7: Hourly house air temperature with no cooling on winter and summer peak cooling days in Miami, Florida for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for varying window U-values for a fixed window shading coefficient of 1.0. Also shown is the outside air temperature.



	Room Setpoint	Ug	Shading Coeff	Annual Cooling MBtu (MWh)
—o—	70	1.11	0.72	67.79 (19.86)
—●—	70	0.47	0.58	59.71 (17.50)
—□—	78	1.11	0.72	48.54 (14.22)
—■—	78	0.47	0.58	47.40 (13.89)

Figure 8: Monthly cooling loads in Miami, Florida for a prototypical residential single-story house. The floor area is 1540 sqft (143 sqm). Total window area is 246.4 sqft (22.9 sqm) corresponding to 4% floor area along each facade facing north, east, south, and west. Results are shown for single and double pane windows for varying room thermostat settings. The house internal load is 54 kBtu/day (15.8 kWh/day)

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