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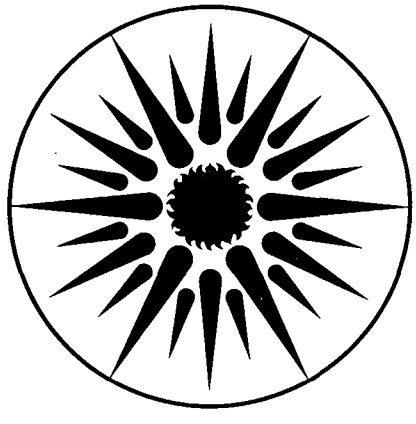

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Energy Performance of Evacuated Glazings in Residential Buildings

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Abstract

This paper presents the results of a study investigating the energy performance of evacuated glazings or glazings which maintain a vacuum between two panes of glass. Their performance is determined by comparing results to prototype highly insulated superwindows as well as a more conventional insulating glass unit with a low-E coating and argon gas fill. We used the DOE-2.1E energy analysis simulation program to analyze the annual and hourly heating energy use due to the windows of a prototypical single-story house located in Madison, Wisconsin. Cooling energy performance was also investigated. Our results show that for highly insulating windows, the solar heat gain coefficient is as important as the window's U-factor in determining heating performance for window orientations facing west-south-east. For other orientations in which there is not much direct solar radiation, the window's U-factor primarily governs performance. The vacuum glazings had lower heating requirements than the superwindows for most window orientations. The conventional low-E window outperformed the superwindows for southwest-south-southeast orientations. These performance differences are directly related to the solar heat gain coefficients of the various windows analyzed. The cooling performance of the windows was inversely related to the heating performance. The lower solar heat gain coefficients of the superwindows resulted in the best cooling performance. However, we were able to mitigate the cooling differences of the windows by using an interior shading device that reduced the amount of solar gain at appropriate times.

Introduction

Currently, new window products are being developed for use under a variety of environmental conditions. For example, in climates which are dominated by cooling loads, conventional window research focuses on developing films that reduce the amount of near-infrared solar energy that penetrates a window while maintaining adequate visibility. Advanced controllable windows are also being developed in which the solar and optical properties of the window change as a function of a particular control variable such as the amount of incident solar radiation. Electrochromic windows are one type of window that use such technology.

In climates which are dominated by heating loads, however, research has been more concerned with window heat loss by conduction, convection, and radiation rather than with the window's solar/optical performance. This has usually entailed the addition of more panes of glass with

low-emissive coatings or films and the use of low-conductive gas fills such as argon or krypton. Another technique involves the creation of a vacuum space between two pane of glass to eliminate the internee heat transfer by conduction and convection. In conjunction with a low-E coating on one or both gap surfaces, this process can result in center-of-glass U-factors on the order of 1.0 W/m^2-K (0.18 Btu/h-ft^2F).

Recently, researchers at the University of Sydney in Australia (Ref. 1) have developed a prototype vacuum glazing consisting of two 4mm (0.16 in) thick low-E coated glass panes (e=0.27) separated by a 0.2mm (0.007 in) thick evacuated gap. The unit has a solder glass hermetic edge seal and a grid of small ceramic pillars to maintain the spacing of the evacuated gap. The Lawrence Berkeley Laboratory is participating in a joint effort with the University of Sydney to evaluate the performance of this prototype and this paper documents the results of a first study aimed at heating and cooling energy performance. It extends previous studies (Refs. 2, 3, 4) which focused on the annual heating and cooling energy performance of specific window products with an emphasis on orientation, window size, and conductance on heating and orientation, window size, and solar heat gain for cooling. We used the DOE-2 (Ref. 5) hour-by-hour program to simulate the annual and hourly energy performance in a heating-dominated location, Madison, Wisconsin. Madison is located at 43N latitude and has 4347 (7825) heating degree-days at a base temperature of 18C (65F) and is characterized by having cold winters and hot and humid summers.

Residential Model Description

We modeled a single-story, slab-on-grade, one-zone house of wood-frame construction with a wall U-factor of 0.30 W/m^2K (0.05 Btu/hr-ft^2F, R19] and a roof U-factor of 0.17 W/m^2K (0.03 Btu/hr-ft^2F, R34) with a floor area of 143 m^2 (1540 ft^2). Internal loads for occupants, lights, and appliances were modeled by considering a composite process heat gain input with a maximum value of 107^{2}1 KJ/hr (10163 Btu/hr) which is equivalent to a daily heat input of 56932 KJ/day (53963 Btu/day) sensible and 12875 KJ/day (12156 Btu/day) latent. Infiltration was calculated using an average level of building leakage area, 0.071m^2 (0.77 ft^2).

In order to reduce increasing cooling system operation, natural ventilation of 10 air-changes per hour was provided by opening the windows during the cooling season. 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 latter condition eliminates the possibility of introducing a latent load into the house. These strategies are meant to facilitate best-operating conditions and not necessarily the actions of house residents

A dual setpoint thermostat was used to control the space conditioning system. Heating was set at 21.1C (70F) from 7am to 11pm with a night setback to15.6C (60F) from 12pm to 6am. Cooling was set at 25.6C (78F) for all hours. A direct-expansion air-cooled airconditioning unit was used for cooling and a forced-air gas furnace for heating. Cooling system COP under peak conditions was 2.2 and furnace steady state efficiency was 0.74.

Window performance was determined by considering different configurations using a base window size of 0.91m x 1.22m (3ft x 4ft) including a frame width of 0.064m (0.21ft, 2.5 in). We varied the numbers of windows from 1 to 10 on one facade and rotated the building through 360 degrees in 45 degree increments. This facilitated an analysis of the effects of orientation as well as size. For 10 windows, the ratio of window area-to-wall area was 38.2% and window-to-floor area was 7.8%. We modified this approach by placing 1 to 10 windows on all facades simultaneously. This enabled an analysis of a configuration with a large window-to-floor area ratio of 31%.

Although this study is mainly concerned with the heating energy performance of windows, we also examined cooling performance since even in heating-dominated locations such as Madison, WI, there can be substantial cooling required during the summer months. As part of this effort, we investigated the performance of interior diffusing shades during the months of April through September in which the solar heat gain through the windows was reduced by 35% if the transmitted direct solar radiation was greater than or equal to 95 W/m^2 (30 $Btu/hr\text{-}ft^2$). There were no overhangs or exterior shading obstructions modeled in the study.

Glazing Model Descriptions

Four high thermal performance windows (Figure 1 and Table 1) were modeled using WINDOW4 (Ref. 6) and FRAME3 (Ref. 7) for use in the DOE-2 building energy simulation program. The models were constructed using a generic wood-framed casement sill profile for each of the four windows. A fifth highly insulating window was defined to represent conventional windows that are currently in use in heating-dominated locations. In addition, we also present results for a double pane clear glass to give insight into the performance differences associated with each glazing type.

(1) Vacuum glazing #1, developed by the University of Sydney (Ref. 1), consists of two 4mm (0.16 in) thick low-E coated glass panes (e=0.24) separated by a 0.15mm (0.006 in) thick evacuated gap. The unit has a solder glass hermetic seal that acts as a significant thermal bridge between the warm and cold side panes of the glass. A grid of small ceramic pillars maintains the spacing of the evacuated gap. The center-of-glass U-factor was 1.0 W/m^2K (0.18 $Btu/hr\text{-}ft^2F$) with a solar heat gain coefficient of 0.68; frame U-factor was 2.27 W/m^2K (0.40 $Btu/hr\text{-}ft^2F$).

(2) We modified the base vacuum glazing by adding a 3mm (0.12 in) thick low-E pane (e=0.197) to the warm side of the glazing to mitigate edge effects due to edge seal thermal bridging. A 12.7mm (0.50 in) thick wood spacer was used to separate the third pane from the vacuum glazing, creating a 12.7mm (0.50 in) thick air gap between the vacuum glazing and the third pane. The center-of-glass U-factor was 0.73 W/m^2K (0.13 $Btu/hr\text{-}ft^2F$) with a solar heat gain coefficient of 0.58; frame U-factor was 1.69 W/m^2K (0.430$Btu/hr\text{-}ft^2F$).

(3) The above vacuum glazings were compared to two superwindows of more conventional design. The first, designated R8 superwindow, consisted of a three layer glazing with a thermally-broken spacer employing two 3.2mm (0.13 in) thick clear glass layers and one suspended double-coated low-E film (e=0.11 and 0.13). Gaps were 6.4mm (0.25 in) with a 50%

krypton/50% xenon gas fill. The center-of-glass U-factor was 0.73 W/m^{2}K (0.13 Btu/hr-ft^{2}F) with a solar heat gain coefficient of 0.51; frame U-factor was 1.65 W/m^{2}K (0.29 Btu/hr-ft^{2}F).

(4) A second superwindow was designated R12.5 and consisted of a four layer glazing assembly with a thermally-broken spacer employing two 3.2mm (0.13 in) thick clear glass layers, one suspended low-E film (e=0.126), and one suspended double-coated low-E film (e=0.11 and 0.13). Gaps were 6.4mm (0.25 in) with a 100% xenon gas fill. The center-of-glass U-factor was 0.45 W/m^{2}K (0.08 Btu/hr-ft^{2}F) with a solar heat gain coefficient of 0.40; frame U-factor was 1.63 W/m^{2}K (0.29 Btu/hr-ft^{2}F).

(5) We compared these high performance windows to a more conventional highly insulating double pane clear low-E (e=0.20) window with argon gas fill and wood frame. The center-of-glass U-factor was 1.70 W/m^{2}K (0.30 Btu/hr-ft^{2}F) with a solar heat gain coefficient of 0.74.; frame U-factor was 1.82 W/m^{2}K (0.32 Btu/hr-ft^{2}F). In order to provide some reference point for our tabulated results, we also generated data for a double pane clear insulating glass with wood frame that had a center-of-glass U-factor was 2.79 W/m^{2}K (0.49 Btu/hr-ft^{2}F) with a solar heat gain coefficient of 0.76.

Discussion: Heating Energy Performance

Figure 2 shows the incremental heating energy due to the windows for the residential configuration in which ten windows are on one facade and the building rotated 360 degrees. The heating energy use for the building without windows was 73.2 GJ (69.4 MBtu). We see that vacuum glazing #1, the prototype designed by the University of Sydney in Australia, has the lowest required heating for all orientations. For orientations west-south-east, vacuum glazing #2 is the next best performer. Although the U-factor for these glazings is higher than the superwindow prototypes, their solar heat gain coefficient is also higher resulting in more beneficial solar heat gain and lower required heating.

This is especially apparent when viewing the results for the conventional double-pane low-E window for a south-facing orientation. Its performance is equivalent to vacuum glazing #2 although its U-factor is more than double the value of the vacuum glazing; the conventional window's solar heat gain coefficient is 28% greater than the value of the vacuum glazing.

For orientations approaching north where the amount of solar gain is reduced, we see that the U-factor becomes more important in determining performance. However, for these high performance, low U-factor windows, there is not much difference in heating performance for windows directly facing the north. Vacuum glazing #1 (the University of Sydney prototype) is equivalent to the R12.5 superwindow, followed by vacuum glazing #2 and the R8 superwindow. The relatively large U-factor of the double pane clear window results in a substantial heating energy increment when compared to the high performance windows. In general, for orientations west-south-east, one can expect a negative seasonal heating energy increment for most windows designed for heating-dominated locations, i.e. U-factors less than 1.70 W/m^2-K (0.30 Btu/h-ft^{2}F); as window orientations approach northwest-north-northeast, we begin to see positive heating energy increments.

The importance of solar gain is also apparent on Figure 3 which shows incremental heating energy as a function of facade window-to-wall area ratio. The largest window-to-wall ratio represents a configuration with ten windows on each facade. Figure 3 clearly shows that vacuum glazing #1 is the best performer, followed by vacuum glazing #2. At larger window-to-wall ratios, vacuum glazing #2 is equivalent to the R12.5 superwindow, which is better than the R8 superwindow. For smaller window-to-wall ratios, the R12.5 and R8 superwindows are equivalent. The conventional double pane low-E window does not compare favorably with any of the other high performance windows studied except at small window-to-wall ratios. In this case, the much larger U-factor of the conventional glazing is governing performance. The differences are even more dramatic for the double pane clear window.

As seen on Figure 3, negative incremental heating energy (net useful solar heat gain) is mostly obtained for all the high performance glazings regardless of the number of windows. The only exception occurs for the configuration with the largest number of windows using the R8 superwindow. For window-to-wall ratios lower than 0.20, the conventional low-E window also yields a negative heating increment. At smaller window sizes, all the solar gain is used to offset thermal losses; with large windows, there is too much solar gain to be "used" for a given house thermal capacity, and so the benefits tend to level off and the losses increase.

We present on Figure 4 hourly conductive loss and solar heat gain data through the window for a winter day in January for the windows to better understand the tradeoff between U-factor and solar heat gain coefficient. The data is for the configuration which has ten windows on one facade. For south-facing windows, we see that the difference in solar heat gain through the window during the day exceeds the difference in conductive heat loss occurring at night (there is also conductive heat loss during the day, but the values are much less than at nighttime because the daytime temperature differential between the inside and outside is smaller). The sum over the course of the day, which represents the day's heating energy requirement of the window, follows a pattern similar to the annual data shown on Figure 2 in which vacuum glazing #1 is the best performer, followed by vacuum glazing #2 and the conventional low-E window. The R12.5 superwindow is not a good performer primarily because its solar heat gain coefficient is so low.

For windows facing north, nighttime conductive heat loss exceeds daytime solar gain and therefore the relative performance of the glazings is different than for south-facing windows. The summed daily heating energy, however, is similar for all the high performance glazings.

In summary, we can say that for high performance windows in heating-dominated locations in which the focus is having a low U-factor, one must also consider the solar heat gain coefficient of the window system. This is especially true for residential configurations that have windows facing west-south-east. For windows approaching a north-facing orientation, in which there is not much solar heat gain, the importance of the window's solar heat gain coefficient in determining performance is reduced and the U-factor is of primary importance.

Discussion: Cooling Energy Performance

Figure 5 presents the annual incremental cooling energy due to the window systems as a function of orientation. Data are shown for the building with ten windows on one facade. The average

cooling energy use for the building without windows was 2.0 GJ (562 kWh, 1.9 MBtu). Required cooling is primarily influenced by window solar heat gain and the results indicate a relatively proportional relationship between the two quantities. Although U-factor does have some minimal contribution to cooling (Ref. 2), its effect is second order and can be ignored for high performance glazings. We see from these results that the R12.5 and R8 superwindows outperform the vacuum glazings which in turn outperform the conventional low-E window and double pane clear unit. The R12.5 superwindow has the lowest solar heat gain coefficient (SHGC=0.40), while the double pane clear window has the largest, SHGC=0.76. The low-E conventional window has a SHGC of 0.74. Using a spectrally-selective low-E coating with a lower SHGC would improve the cooling performance of the conventional low-E window; however, the heating performance would be adversely effected.

The design and development of the high performance windows reported in this study are mostly related to heating performance. One would desire that the cooling performance differences seen in Figure 5 be eliminated or minimized so that the evaluation and comparison is simplified. To mitigate these cooling differences, we simulated a interior shading device that was implemented during the months April to September if the amount of transmitted direct solar radiation was equal to or greater than 95 W/m^2 (30 $Btu/hr\text{-}ft^2$). Under such a condition the solar heat gain through the window was reduced by 35%. Figure 6 shows the same data as Figure 5 with an interior shade. Other shading devices such as overhangs or exterior obstructions would also tend to reduce the performance differences among the different window types.

There is a significant reduction in required cooling for the conventional low-E, vacuum glazing #1, and double pane clear windows for orientations south-southwest-west. Their performance approaches that of the R12.5 superwindow and is better than the R8 superwindow. The performance of vacuum glazing #2 for southwest-west orientations is almost the same as the R12.5 superwindow. For orientations northwest-north-northeast-east, there is only a hardly any reduction in required cooling indicative of the shading device not being use very often.

An anomaly occurs for several windows facing southwest-west when using interior shades. For example, the incremental cooling of a west-facing R12.5 superwindow shown on Figure 6 with the shade is greater than the results shown on Figure 5 which is without shading. This is not to be expected, since the purpose of using a shading device is to reduce cooling. The explanation for this is related to peak cooling being used for air conditioner sizing. The peak cooling requirement for a west-facing window occurs for the configuration in this study at 5pm on an August afternoon with an outdoor temperature of 35C (88F). The amount of transmitted direct solar radiation does not exceed the shade deployment setpoint and so the peak cooling without and with shades is very similar, and thus the air conditioners have almost the same capacity. The air conditioner will be running at part-load during those hours when required cooling is not at the peak condition. This situation occurs more often with the building that uses interior shades; also the difference between peak and part-load condition is greater. Therefore, air conditioning performance is more inefficient and results in higher required cooling for the residence with interior shades.

For residential buildings in which there are windows on more than one facade, the peak cooling condition will be different without and with shades and the above condition does not occur. Figure 7 shows required cooling without a shading device as a function of window-to-wall ratio.

Windows are placed simultaneously on all facades and at the largest window-to-wall ratio, we have ten windows on each facade. Performance, as before, is proportional to window solar heat gain coefficient, with the R12.5 superwindow performing the best; about 28% better than the R8 superwindow; 38% better than vacuum glazing #2; 45% better than vacuum glazing #1; and 47% better than the conventional low-E window. Figure 8 shows the same data, but with the interior shading device. The performance difference between the R12.5 window and the others have been reduced to 26%, 28%, 31%, and 33% respectively.

Conclusions

This study was aimed at comparing the performance of newly developed evacuated or vacuum windows to prototype superwindows and also to a more conventional insulating glass units. Such high performance windows are being designed for use in heating-dominated climates and that was the primary focus of our analysis. However, these geographic locations can also have large cooling requirements at certain times of the year and therefore, we have also documented the cooling energy performance as well. There was no winter shading system operation and no overhangs or exterior shading obstructions. In addition, the results focus on window performance in a prototypical residence in which the inside air temperature was controlled at all times by a typical thermostatic controller. This eliminates the possibility of overheating in wintertime which is sometimes a concern to homeowners who do not use airconditioning at that time of year. Conclusions reached are as follows:

Heating Performance

1. Both window U-Factor and solar heat gain characteristics are important.

2. Vacuum glazing #1 outperforms vacuum glazing #2 and the superwindow prototypes for all orientations even though its U-factor is higher. This is primarily because its solar heat gain coefficient is higher which results in more beneficial solar heat gain.

3. Vacuum glazing #2 outperforms the R8 and R12.5 superwindow prototypes for east-, south-, and west-facing orientations. This is also due to the higher solar heat gain coefficient.

4. The double pane low-E conventional glazing outperforms the prototype superwindows for south-facing orientations. The liability of its modest U-factor, 1.0 W/m^2-K (0.18 $Btu/h\text{-}ft^2F$, is more than offset by its higher solar heat gain coefficient.

5. All the high performance windows analyzed result in negative incremental heating energy (net seasonal energy benefits relative to an insulated wall) when facing west-south-east.

Cooling Performance

1. The window solar heat gain characteristics are most important.

2. Required cooling is directly proportional to the window solar heat gain coefficient.

3. R12.5 superwindow (SHGC=0.40) requires the least amount of cooling for all orientations, followed by the R8 superwindow (SHGC=0.51).

4. The double pane low-E conventional glazing (SHGC=0.74) and the double pane clear glazing (SHGC=0.76) require the most cooling.

5. Use of shading devices mitigates the cooling performance differences associated with the glazings analyzed.

Our future simulation efforts of high performance glazings will be extended to account for additional effects. Of particular importance is how these windows perform in passive solar homes which have significant amounts of thermal mass and direct gain. In addition, we intend to analyze the performance of such windows without the use of night-setback. In such situations, the magnitude of the differences between window types may be more pronounced than was the case in this study.

We will also investigate the relative utility cost differences associated with heating (gas) and cooling (electricity). The benefits associated with reduced winter heating of these glazings may be somewhat offset by the increased summer cooling costs. For many orientations, window heating and cooling performance are inversely related and it would be desirable to define relationships between U-factor and solar heat gain coefficient that minimize energy cost as well as energy itself.

In addition, condensation, which can be a problem with vacuum glazings because thermal bridging through the uninsulated edge is of the same order as thermal bridging through windows with aluminum spacers, will be studied. Condensation can be mitigated by recessing the vacuum glazing edge into the sash, or by adding a third pane to the unit. Finally, development of high performance glazings is being continued by several organizations and we intend to assist these efforts by determining the annual energy performance of such new window systems.

Acknowledgment

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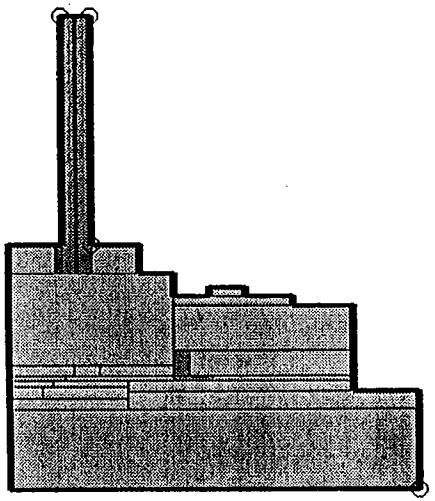
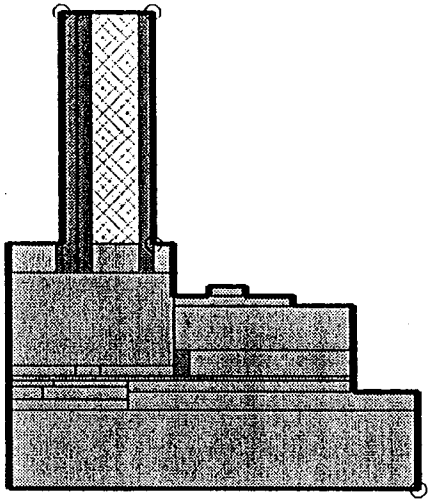
TABLE 1
Glazing Properties: Thermal/Solar/Optical

	U-Factor COG, Total W/m^2-K (Btu/h-ft^{2}F)	SHGC COG, Total	SC COG, Total	Tvis
Vacuum #1	1.00 (0.18), 1.29 (0.23)	0.68 (0.53)	0.78 (0.61)	0.71
Vacuum #2	0.73 (0.13), 0.95 (0.17)	0.58 (0.45)	0.67 (0.52)	0.60
Superwindow #1	0.73 (0.13), 0.95 (0.17)	0.51 (0.39)	0.59 (0.45)	0.66
Superwindow #2	0.45 (0.08), 0.72 (0.13)	0.40 (0.30)	0.46 (0.35)	0.59
DP Clear Low-E Argon	1.70 (0.30), 1.72 (0.30)	0.74 (0.57)	0.86 (0.66)	0.74
DP Clear Air	2.79 (0.49), 2.67 (0.47)	0.76 (0.59)	0.87 (0.67)	0.81

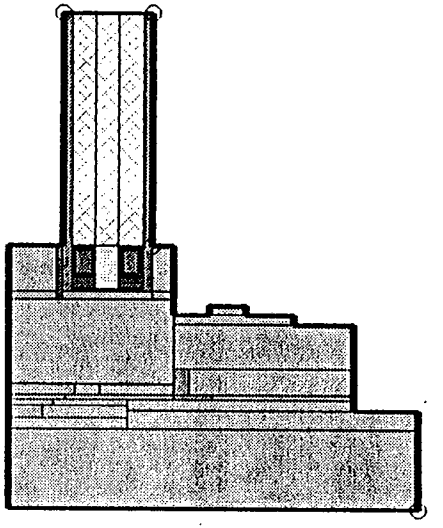
Note: U-factor are values at ASHRAE winter conditions: -17.8C (0F) outside temperature, and 21.1C (70F) inside temperature, 6.71 m/s (15 mph) wind speed, and zero incident solar radiation. Solar Heat Gain Coefficient (SHGC) and Shading Coefficient (SC) are values at ASHRAE summer conditions: 35C (95F) outside temperature, and 24C (75F) insidetemperature, 3.3 m/s (7.5 mph) wind speed, and near-normal incident solar radiation of 783 W/m^2 (248 Btu/h-ft^2).



Vacuum glazing mounted in a wood casement frame.



Vacuum glazing with an additional low-E third pane mounted in a wood casement frame. A 12.7 mm.-thick wood spacer reduces thermal bridging through the evacuated glazing edge seal.



Configuration for the R12.5 super glazing mounted in a wood casement frame. Spacer is steel with a polystyrene foam thermal break. The configuration for the R8 superglazing is similar except that there is only one suspended low-E film.

Figure 1: Window cross sections used in the study of evacuated glazings and superwindows.

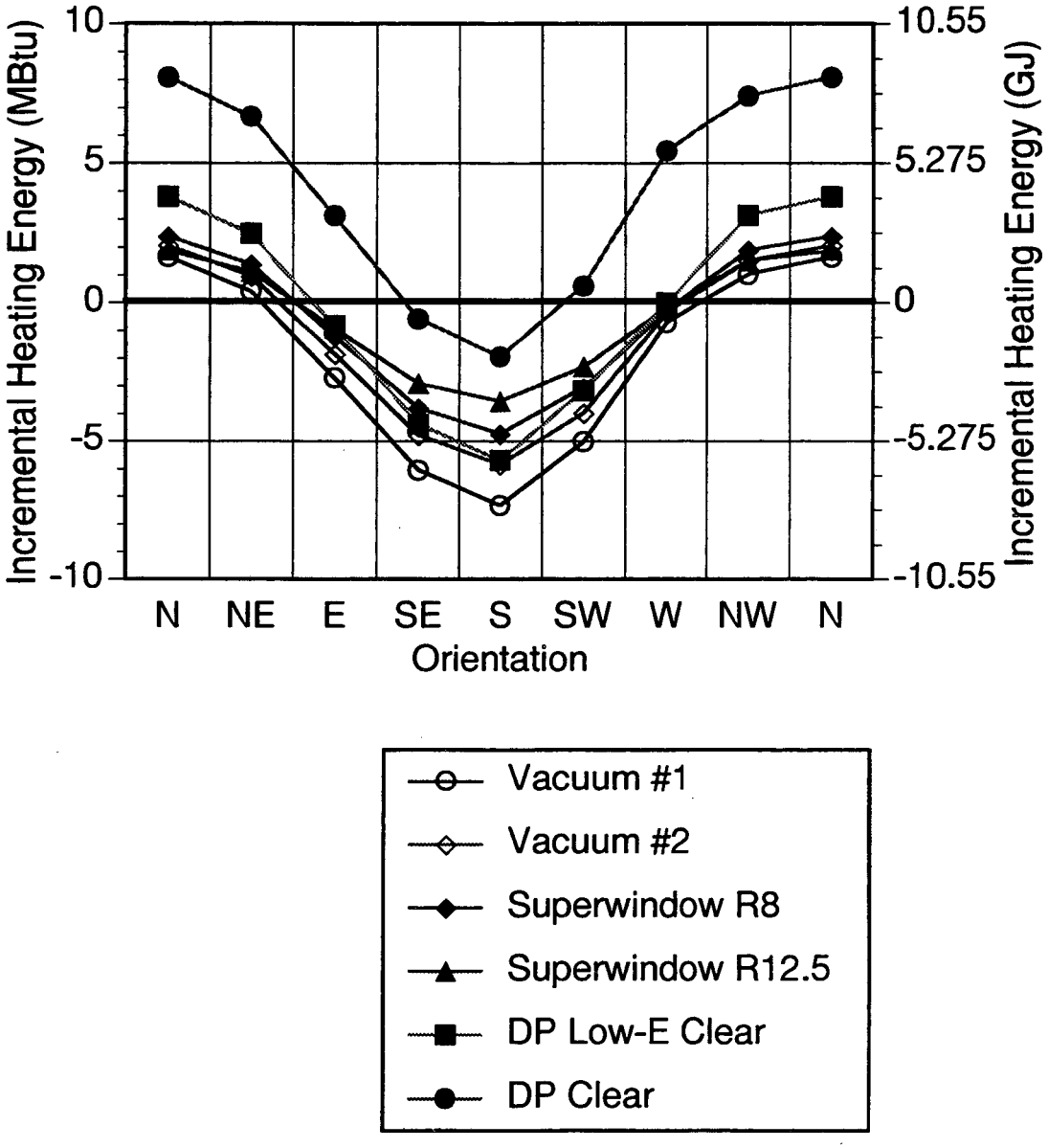


Figure 2: Incremental heating energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window orientation and type. There are 10 - 0.91m x 1.21m (3ft x 4ft) windows on one facade which represents a window-to-floor area ratio of 7.8% and a window-to-wall area ratio of 38.3%.

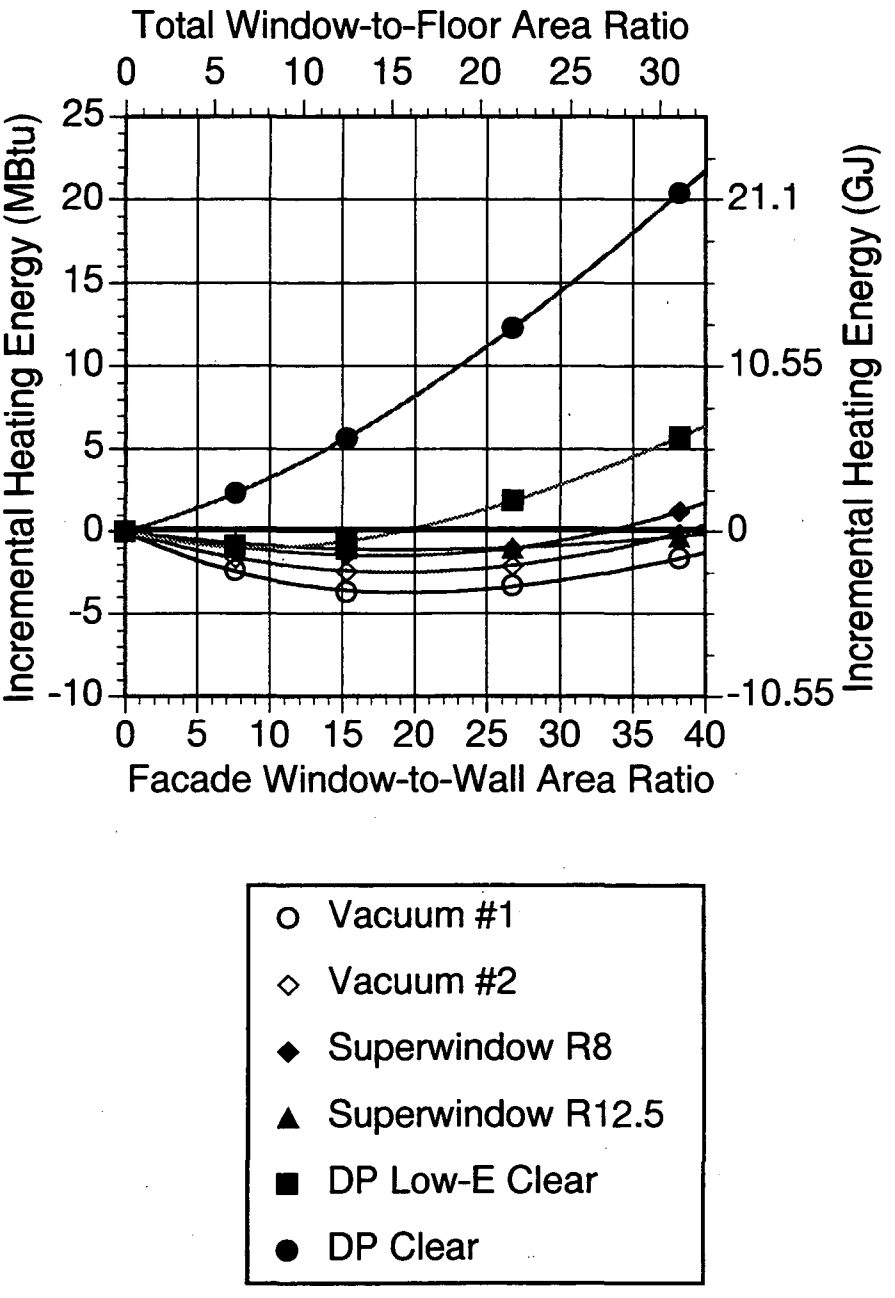
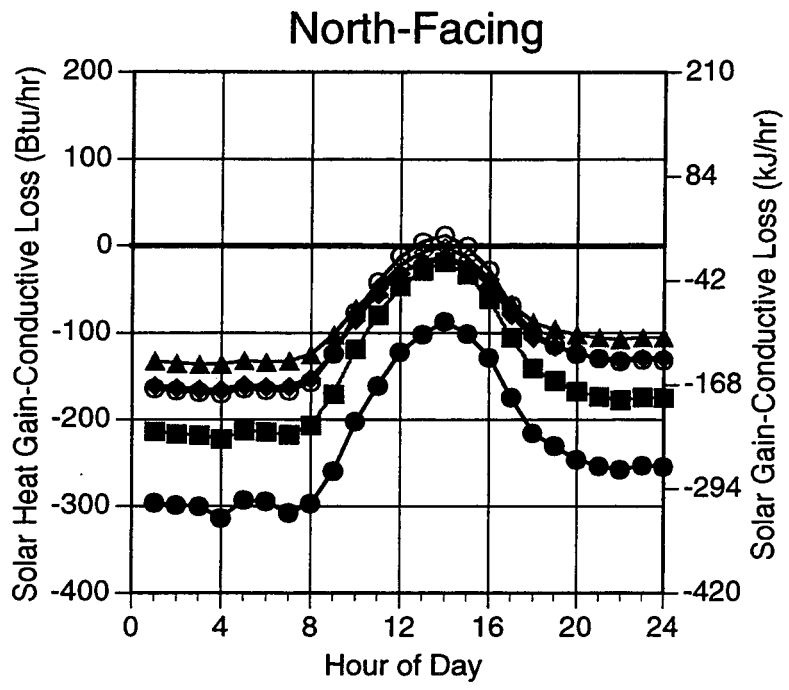
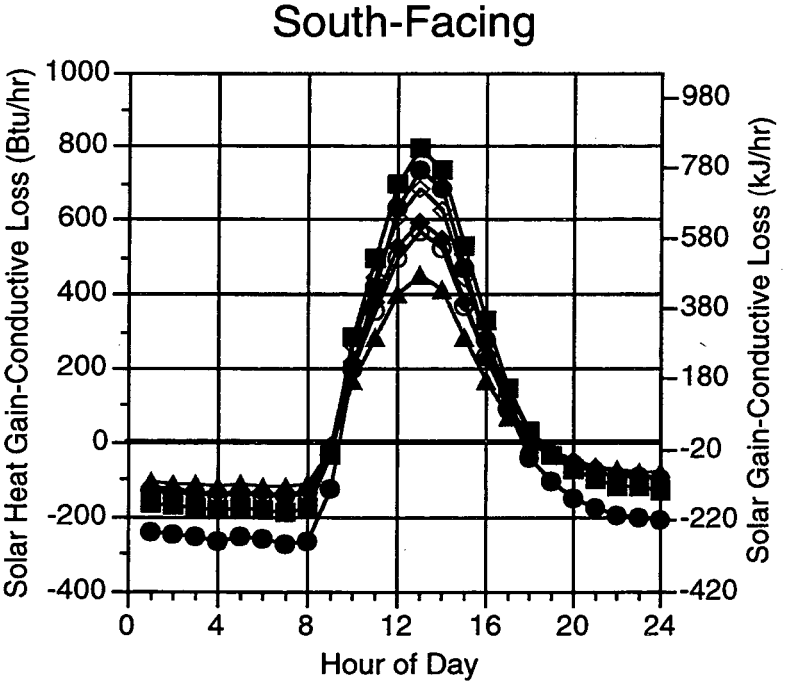


Figure 3: Incremental heating energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window type, and size. Numbers of 0.91m x 1.21m (3ft x4ft) windows are placed simultaneously on each facade. Total window-to-floor area ratio for 10 windows on each facade is 31%.



Glazing	Daily Sum kJ (kBtu)
Vacuum #1	-2.66 (-2.52)
Vacuum #2	-2.70 (-2.56)
Superwindow R8	-2.75 (-2.61)
Superwindow R12.5	-2.30 (-2.18)
DP Low-E Clear	-3.73 (-3.54)
DP Clear	-5.74 (-5.44)



Glazing	Daily Sum kJ (kBtu)
Vacuum #1	2.92 (2.77)
Vacuum #2	2.17 (2.06)
Superwindow R8	1.57 (1.49)
Superwindow R12.5	0.99 (0.94)
DP Low-E Clear	2.17 (2.06)
DP Clear	0.80 (0.76)

Figure 4: Window solar heat gain less conductive heat loss during a 24 hour period in January in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window type. Results are shown for 0.91m x 1.21m (3ft x 4ft) north- and south-facing windows.

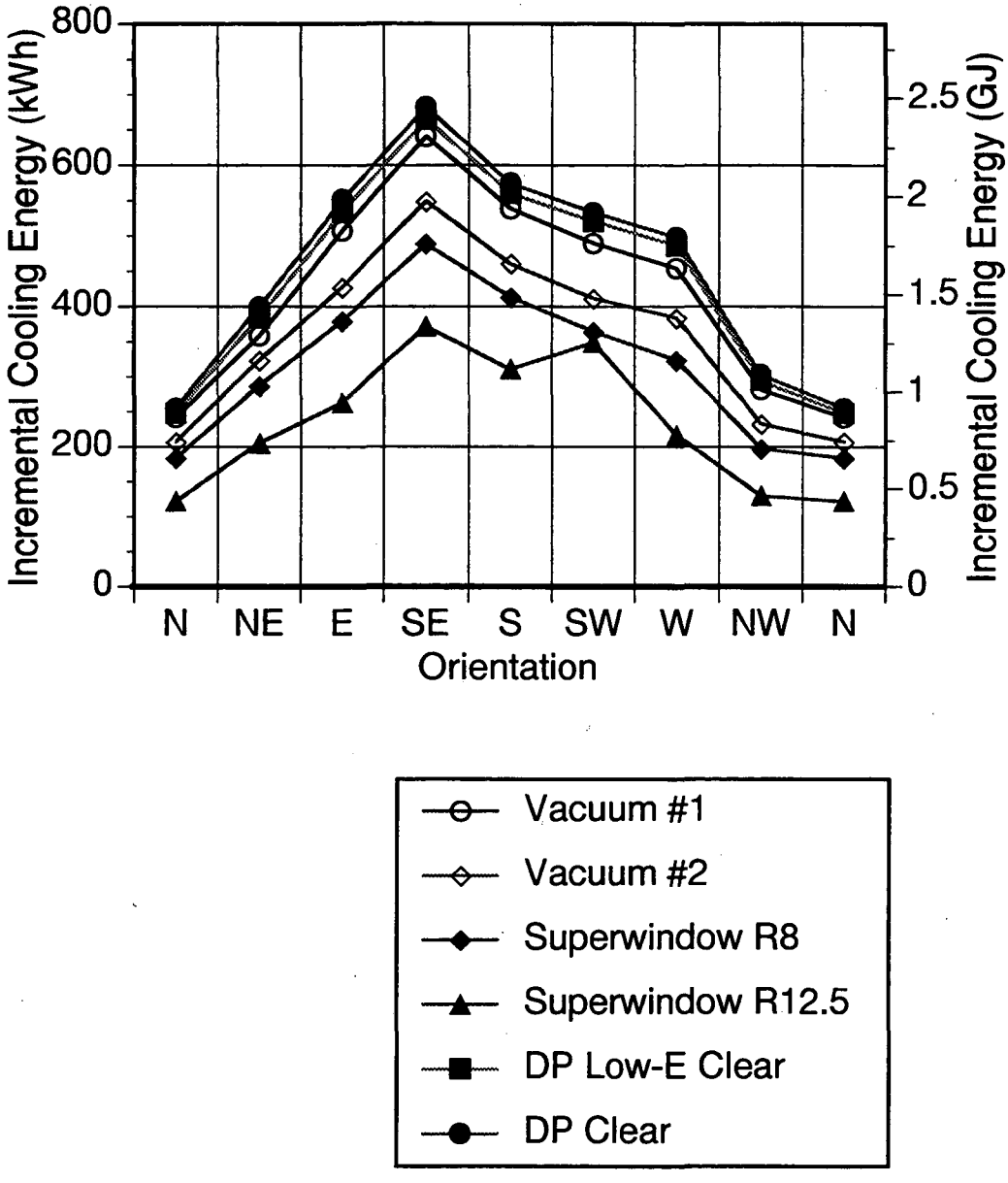


Figure 5: Incremental cooling energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window orientation and type. There are 10 - 0.91m x 1.21m (3ft x 4ft) windows on one facade which represents a window-to-floor area ratio of 7.8% and a window-to-wall area ratio of 38.3%.

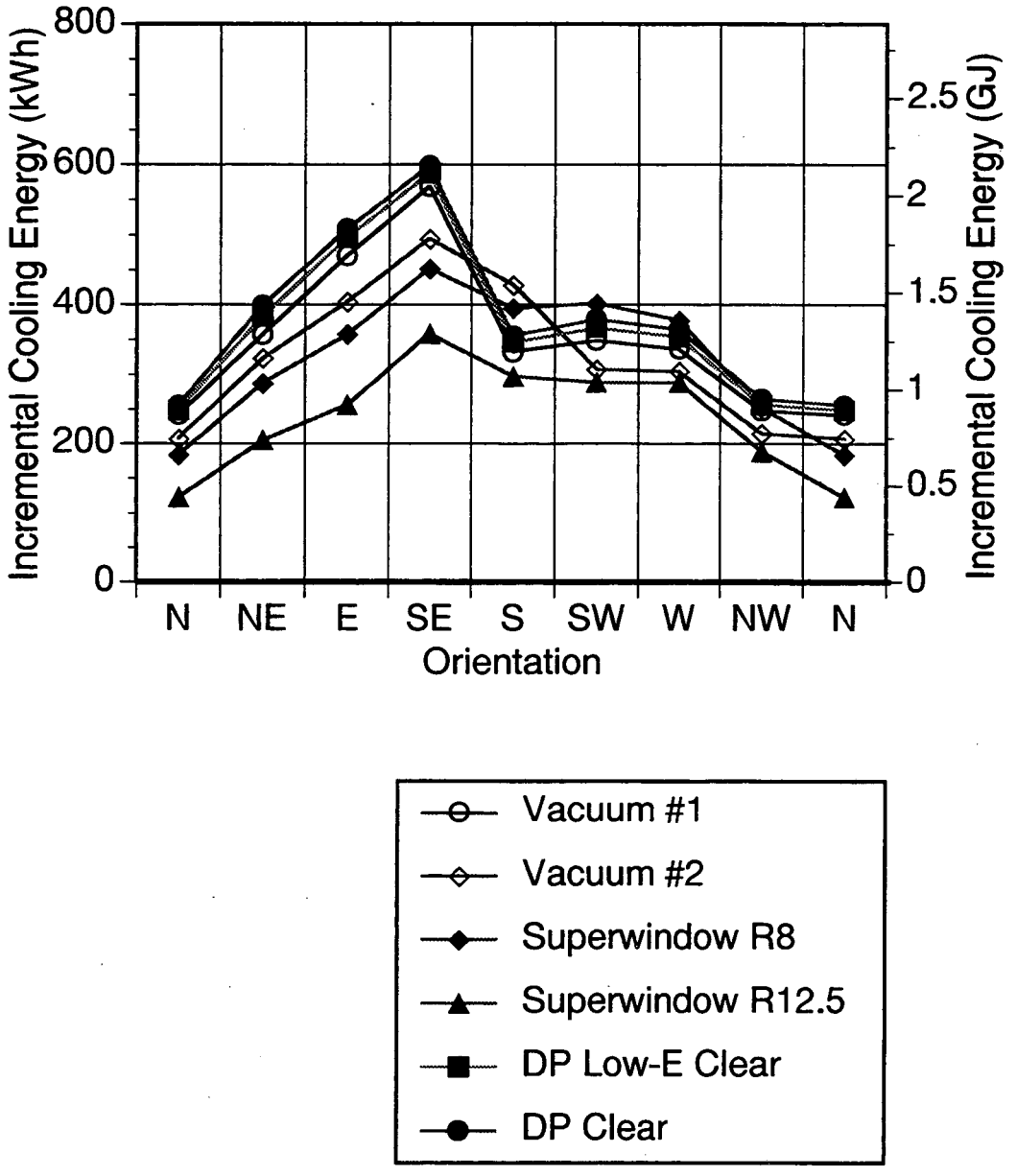


Figure 6: Incremental cooling energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window orientation and type. There are 10 - 0.91m x 1.21m (3ft x 4ft) windows on one facade which represents a window-to-floor area ratio of 7.8% and a window-to-wall area ratio of 38.3%. Results are shown for windows using an interior shading in which the solar heat gain through the windows is reduced by 35% if the transmitted direct solar radiation is greater than or equal to 95 W/m2 (30 Btu/hr-ft2).

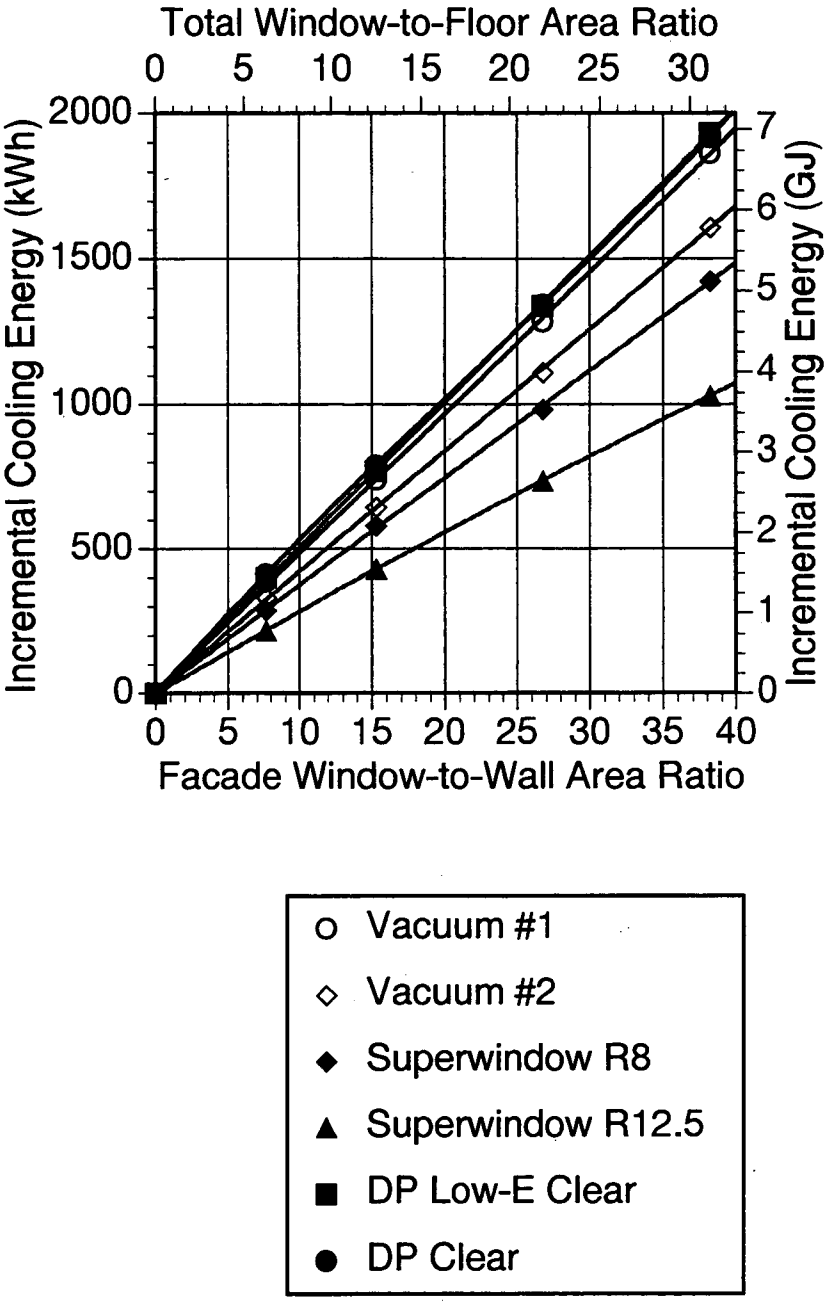


Figure 7: Incremental cooling energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window type, and size. Numbers of 0.91m x 1.21m (3ft x 4ft) windows are placed simultaneously on each facade. Total window-to-floor area ratio for 10 windows on each facade is 31%.

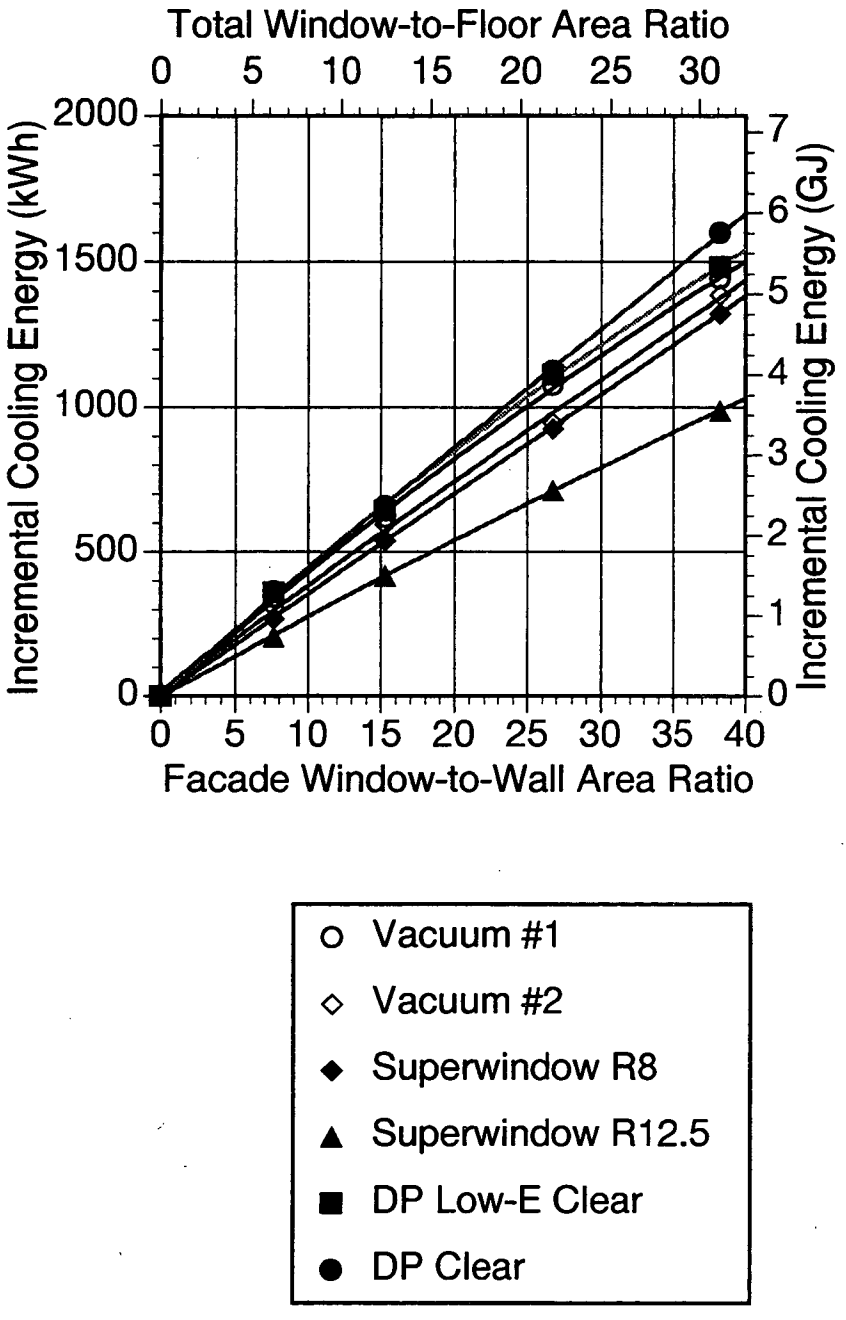


Figure 8: Incremental cooling energy required in Madison, Wi for a single-story residential house with a floor area of 143.1 m2 (1540 ft2) as a function of window type, and size. Numbers of 0.91m x 1.21m (3ft x 4ft) windows are placed simultaneously on each facade. Results are shown for windows using an interior shading in which the solar heat gain through the windows is reduced by 35% if the transmitted direct solar radiation is greater than or equal to 95 W/m2 (30 Btu/hr-ft2).

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