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AN ANALOG EVALUATION OF METHODS FOR CONTROLLING SOLAR HEAT GAIN THROUGH WINDOWS

BY

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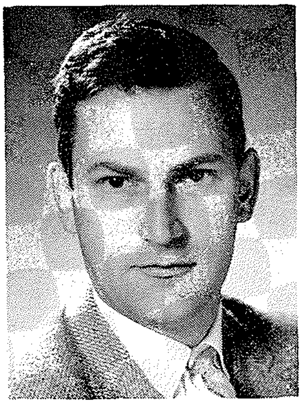

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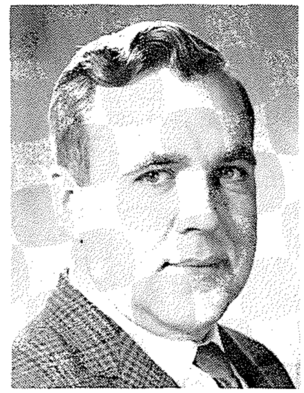

G. P. MITALAS

Current trends in the architecture of office buildings are to curtain wall systems with large transparent areas. One effect of this increasing use of glass is that the solar energy absorbed and transmitted by the transparent sections is a major component of the building cooling load. It is important, therefore, both in the selection of glass and shading arrangements and in the design of air conditioning systems to be able to compute accurately the cooling load imposed by glass areas. In this paper, the heat gain resulting from the window in a typical office module, calculated by the ASHRAE GUIDE method, is compared with the cooling load associated with the window, computed by an electronic analog computer. A comparison also is made of the relative effectiveness of different glass and shading arrangements on the cooling load caused by solar radiation.

The GUIDE method of calculating the instantaneous heat gain through sunlit glass is the result of an extensive research program carried out at the ASHRAE Research Laboratory.[1,2,3] The method combines the heat transfer from glass to the room air by convection with the radiant energy exchanged between the glass and the other surfaces which enclose the space. This is valid only when surfaces in radiant exchange with the glass are at the same temperature as the room air. The difference between surface temperature and room air temperature can be large for the surfaces that are exposed to the direct sunshine transmitted through the transparent walls. Mackey and Gay[4,5] have pointed out that the instantaneous rate of heat gain is not the same as the instantaneous cooling load, since the energy transferred by radiation can only affect the cooling load after the receiving surfaces have been heated to a temperature higher than the room air temperature.

The radiant energy exchange between the various surfaces enclosing a space and the effect of the heat storage capacity of the walls and floor can be allowed for by using a thermal circuit representation of a room. Nottage and Parmelee[6,7] described this approach to cooling load calculation in their papers in 1954 and 1955. The thermal circuit is simply a schematic diagram of the heat transfer processes occurring in a room. The cooling load imposed by any assumed cycle of outside and inside conditions can be evaluated by applying the techniques of electrical circuit analysis. An alternate approach is to use an analog to simulate the heat transfer situation in the room. In the latter case, the thermal circuit is a schematic diagram for the analog circuit.

A hydraulic analog for the solution of air conditioning problems was reported by Leopold[8] in 1948. Leopold's analog was used subsequently by Mackey and Gay[5,9] to calculate the cooling load from a single-pane window of ordinary glass. The first application of a general-purpose electronic analog computer to the calculation of cooling loads was the work of Parmelee, Vance and Cerny[10] in 1956. In 1960 the present authors[11] set up a somewhat more elaborate simulation of an air conditioned room on a medium-sized electronic analog computer. The work now reported is an application of the methods described in References 11 and 12, and is an extension of the work of Mackey and Gay[9] on the cooling loads resulting from the use of glass.

DETAILS OF THE ROOM AND AMBIENT CLIMATE

The cooling load has been computed for a typical office module with many different arrangements of glass and shading for the trans-

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parent section of the outside wall. The office has inside dimensions 20 x 20 x 10 ft high and the outside wall is assumed to be 80% glass. The partition walls are taken as the thermal equivalent of 3 in. of light-weight concrete. It is assumed that the room is surrounded by other identical rooms so that there is never any heat transfer across the mid-planes of the partitions. The floor is a 6-in. slab of ordinary concrete and a light-weight ceiling is suspended from the floor above, forming an unventilated air space above the ceiling. The floor-ceiling is treated as a combined unit. This allows for heat transfer through the ceiling from the room above, and a corresponding transfer from the floor to the room below. Two floor-ceiling sections are included: one represents the floor area that is exposed to solar radiation transmitted through the transparent wall area; the other represents the remainder of the floor. The opaque section of the outside wall is assumed to be a 2-in. outer layer of ordinary concrete backed by a 4-in. slab of lightweight concrete.

Heat transfer through this wall is negligible compared with that through the glass area. The results are valid, therefore, for a room with any type of insulated opaque outer wall comprising 20% of the total wall area. The emissivity of glass for thermal radiation is taken as 0.95 and the emissivity of all the other surfaces is assumed to be 0.90. A coefficient of 0.8 Btu/ft²/hr/F is used for the convection heat transfer between all inside surfaces and the room air; the outside convection coefficient is 4.0 Btu/ft²/hr/F. No allowance is made for furnishings, people or lights in the room.

The solar radiation incident on the outside surface of the outside wall is considered as two parts: the beam from the solar disc and the diffuse radiation scattered from the sky and reflected from the ground. The direct beam strikes the outer surface of the glass and is partially reflected, partially absorbed by the glass; the remainder is assumed to be absorbed by the part of the floor near the glass wall. The fraction of the solar energy absorbed and reflected depends on the angle of incidence and on the type and arrangement of the glass. Tables are given in Reference 13 to facilitate calculation of these quantities. Diffuse radiation is assumed to have uniform intensity for all angles of incidence. The appropriate transmission and absorption values are, therefore, the average for angles of incidence from 0 to 90 deg. These average values are included in the tables of Reference 13. Diffuse radiation transmitted through the glass is assumed to be absorbed by the other room surfaces in proportion to the geometric view factors between the surfaces and the glass.

Outside air temperature and intensities of direct and diffuse components of the solar radiation are the same as those used to prepare the GUIDE tables for instantaneous heat gains. The outside surface of the opaque wall area absorbs half the solar radiation falling on it (i. e. a light-colored surface).

The long wave radiation falling on the outside surface comes partly from the ground and partly from the sky. The ground is assumed to radiate as a black body at air temperature (actually higher temperature during the day and lower at night) and the sky is taken as a grey body at air temperature. The emissivity of the sky depends on the water vapor content. Parmelee and Aubele[14] give the intensity of long wave radiation from the sky falling on a vertical wall as

$$R_{sky} = \sigma T_a^4 (0.30 + 0.165 \sqrt{P_w})$$

where P_w is the partial pressure of water vapor at ground level in in. of mercury

σT_a^4 is the radiation emitted by a black body at air temperature.

The total long wave radiation received by a vertical wall is the $R_{sky} + \frac{1}{2} \sigma T_a^4$, since a vertical wall has a view factor of ½ with the infinite horizontal plane. Thus, for a clear atmosphere with a dew-point of 40 F the total long wave radiation incident on a vertical surface is 0.88 σT_a^4. This is the value used for this investigation.

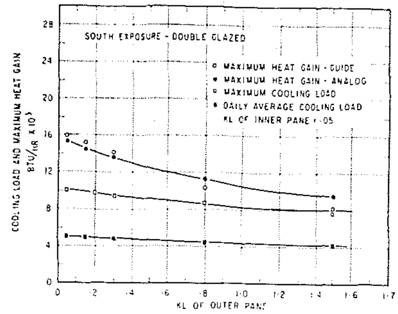


Fig. 1 Maximum heat gain calculated by ASHRAE GUIDE method and by analog computer, maximum cooling load and daily average cooling load versus KL for south exposed double-pane window

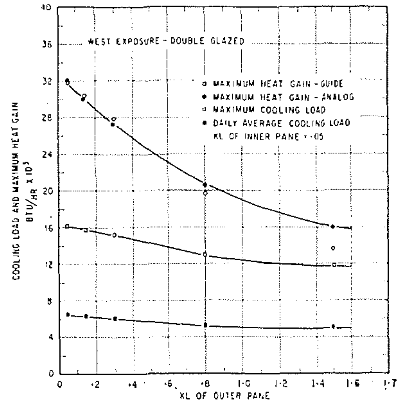


Fig. 2 Maximum heat gain calculated by ASHRAE GUIDE method and by analog computer, maximum cooling load and daily average cooling load versus KL for west exposed double-pane window

Table I

Type of Glass	KL	Transmission For Normal Incidence (Per Cent)
Ordinary Window Glass	0.05	85
Ordinary Plate Glass	0.20	75
Heat Absorbing Plate	0.80	40

THE ANALOG SIMULATION

The room and its environment were simulated on a PACE analog computer, using a time scale of 1 sec computer time to represent 1 hr real time. The daily cycles of out-

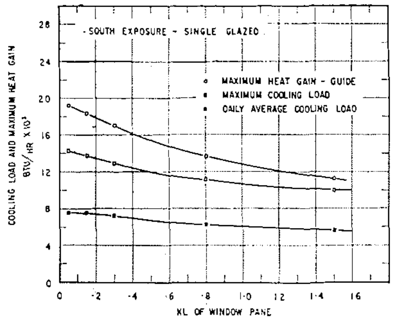


Fig. 3 Maximum heat gain calculated by ASHRAE GUIDE method, maximum cooling load and daily average cooling load versus KL for south exposed single-pane window

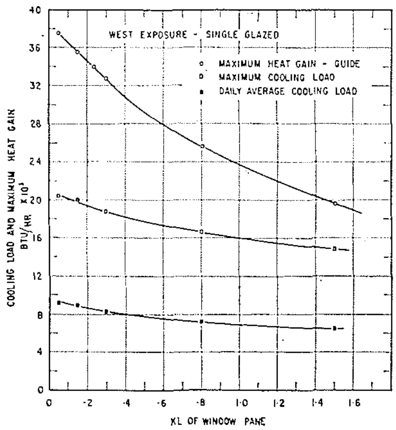


Fig. 4 Maximum heat gain calculated by ASHRAE GUIDE method, maximum cooling load and daily average cooling load versus KL for west exposed single-pane window

side air temperature, solar radiation transmitted through the window, solar radiation absorbed by the window and the long wave thermal radiation were set up on diode function generators. It was assumed that these design conditions recurred on successive days so that the resulting cooling loads and surface temperatures were recorded only after the steady periodic condition was established.

The analog circuit was essentially the same as the one described in Reference 11. Partition walls were assumed to be at the same temperature and were considered as a single surface; the floor was divided into two parts; one of which was exposed to the direct sunshine and the rest of which was not. Since the floor-ceiling combination was considered as a unit, the ceiling also was divided into two parts corresponding to the two floor sections. The opaque outer wall and the window area completed the enclosure, so that the room was enclosed by seven isothermal surfaces.

The model used for this study differed from the one described by Nottage and Parmelee[6, 7] only in the way in which the lumped circuits were designed and the radiation coupling conductances were calculated.

DESIGN OF LUMPED CIRCUITS

The number of lumps required to model the floor, outside wall and partitions was selected by the method of Reference 12. The error in the cooling loads resulting from lumping was less than 1% for frequencies up to 4 cycles per day. This method of designing lumped circuits usually requires more lumps than the simple ⅛ wave length rule recommended by Nottage. The Nottage method, however, is of indeterminate accuracy when several lumps are in series.

RADIATION COUPLING

Heat transfer by radiation between any two surfaces forming part of the enclosure of a room is represented by a conductance multiplied by the difference of the temperatures of the two surfaces, i. e.

$$q_{a \to b} = h_{a \to b} (T_a - T_b)$$

Hottel has shown[15] that the expression for the radiant energy transfer between two isothermal surfaces is

$$q_{a \to b} = A_a \cdot F_{a \to b} \cdot \sigma (T_a^4 - T_b^4)$$

where $F_{a \to b}$ is the over-all interchange factor between a and b.

The calculation of the over-all interchange factors requires the evaluation of N N^{th} order determinants where N is the number of isothermal surfaces forming the enclosure. This arithmetic was performed on a small digital computer using a program available for this specific task[14]. The conductances were calculated from the relationship

$$h_{a \to b} = (1.076)\, A_a \cdot F_{a \to b}$$

which corresponds to

$$\frac{T_a + T_b}{2} = 540 \text{ R}$$

If the true average temperature differs from 540 R by 5F, the conductances calculated by this equation will be in error by about 3%.

Nottage[6, 7] approximated the over-all interchange factors by

$$F_{a \to b} = \epsilon_a \cdot \epsilon_b \cdot \mathrm{F}_{a \to b}$$

where ϵ is the emissive power of a surface and $\mathrm{F}_{a \to b}$ is the geometric view factor. This approximation is reasonably accurate as long as the emissivity of all the surfaces is close to unity, but for lower emissivities it underestimates the over-all interchange factors.

Table II

Shading	No. of Panes	Max Cooling Load Btu/hr x 103	Daily Average Cooling Load Btu/hr x 103	Max Window Inside Surface Temperatures F
No Shading	1	20.5	9.1	102
	2	16.2	6.5	93
Inside	1	25.8	8.7	128
	2	20.0	5.9	118
Interpane	2	12.2	4.6	125

Maximum cooling load, daily average cooling load and maximum window inside surface temperature for west-exposed ordinary glass (KL = 0.05) single and double-pane windows with no shading, inside shading and interpane shading.

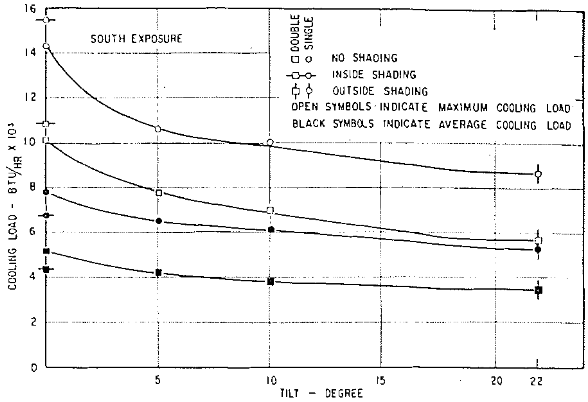


Fig. 5 Maximum cooling load and daily average cooling load versus tilt angle, inside and outside shading for ordinary glass (KL = 0.05) south exposed single and double-pane windows

WINDOW ARRANGEMENTS

The most useful parameter to specify the absorption properties of glass is the dimensionless number KL, where K is the absorption coefficient and L is the thickness of the pane. When a ray of light passes through a layer of glass of thickness t, the fraction of the incident energy absorbed is $1 - e^{-Kt}$. This should not be confused with the absorptivity of a pane of glass that includes the effects of multiple reflections. The significance of the magnitude of KL can be seen from Table I.

The following arrangements of glass and shading were considered as forming the window area of the outer wall:

1. a single sheet of unshaded glass (KL = 0.05 to 1.5), south and west exposures;
2. two sheets of unshaded glass, the outer sheet having the same range of KL as the single sheet, and the inner sheet with a KL of 0.05, south and west exposures;
3. single and double sheets of ordinary glass (KL = 0.05) with outside shading, south exposure only;
4. single and double windows of ordinary glass with venetian blinds on the room side, south and west exposures;
5. double window of ordinary glass with a blind between the panes, west exposure only;
6. single and double sheets of ordinary glass tilted 5 and 10 deg from the vertical, south exposure only.

The peak value of the instantaneous heat gain was calculated by the GUIDE method for as many of the above listed cases as the GUIDE data permitted. An instantaneous heat gain also was evaluated from the computer results for all cases with double windows, but it was not convenient to obtain a value of instantaneous heat gain for single windows. The results given in Figs. 1 through 5 show the peak and average (i.e. 1/24 of daily total) values of cooling load for the various arrangements.

DISCUSSION OF RESULTS

Heat gain through a window can be considered in two parts:

1. solar radiation transmitted through the window;
2. heat transfer from the inside surface of the window.

All the techniques for reducing heat gain through a window depend on reducing either or both of these components. In some cases, however, a reduction in solar transmission results in an increase in the other component so that it is less effective than the reduction in transmission would indicate.

HEAT ABSORBING GLASS

Results of computations for heat-absorbing glass shown in Figs. 1, 2, 3 and 4 demonstrate the counteracting effect. As the KL of the window is increased from 0.05 (ordinary glass) to 1.00 (heat-absorbing) the transmission of a single sheet for an incident angle of 70 deg changes from 68% to only 20%, but the energy absorbed by the glass increases from 6 to 62%[13]. Heat-absorbing glass reflects 18% compared with 26% for ordinary plate. Thus, transmission through the window is reduced by 48% of the energy incident on it, but energy absorbed by the window is increased 56% of the incident radiation. The absorbed energy is dissipated partly to the outside air and the remainder is transferred to the room air and thus still forms part of the heat gain. The amount transferred to the outside air depends on the magnitude of the heat transfer coefficient for the outside surface. Since the temperature of the absorbing glass is usually higher than the ambient air temperature, the highest heat transfer to the room will occur when the outside film coefficient is a minimum. Results shown in Figs. 1, 2, 3 and 4 were computed for an outside film coefficient of 4.0 Btu/ft²/hr/F, corresponding to 10-mph wind speed. For calm conditions the heat gain and the cooling load would have been higher.

The difference between maximum heat gain and maximum cooling load is smaller for heat-absorbing glass than for clear glass because a part of the absorbed energy is transferred to the room air by convection and has an immediate effect on cooling load. The transmitted solar heat is absorbed by the floor slab and only affects the cooling load as the floor is heated. For the room considered in this study the net effect of increasing KL is small, as is shown by the plot of peak cooling load vs KL for a single sheet of glass in the outer wall.

DOUBLE PANES

The addition of an inner pane of ordinary glass increases the thermal resistance between the absorbing pane and the interior of the room. This always will reduce the heat gain and the cooling load, although it increases the energy absorbed in the outer pane and greatly increases its peak temperature (Figs. 6, 7).

REFLECTING WINDOWS

Heat gain will be smaller for a specific window transmission factor if solar energy is reflected rather than absorbed. Reflection from an air-glass interface increases with increase in angle of incidence. Energy transmitted through a unit area of windows also is reduced as the incident angle is increased, because the energy falling on unit

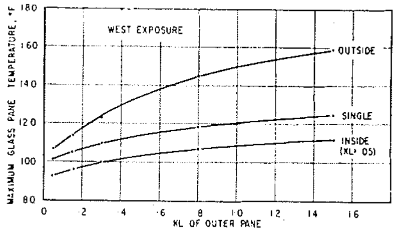


Fig. 6 Maximum glass pane temperatures versus KL for west exposed single and double-pane windows

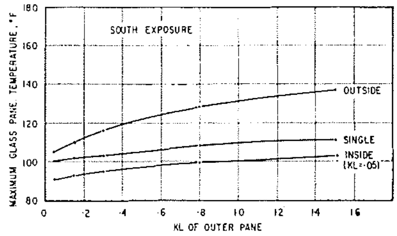
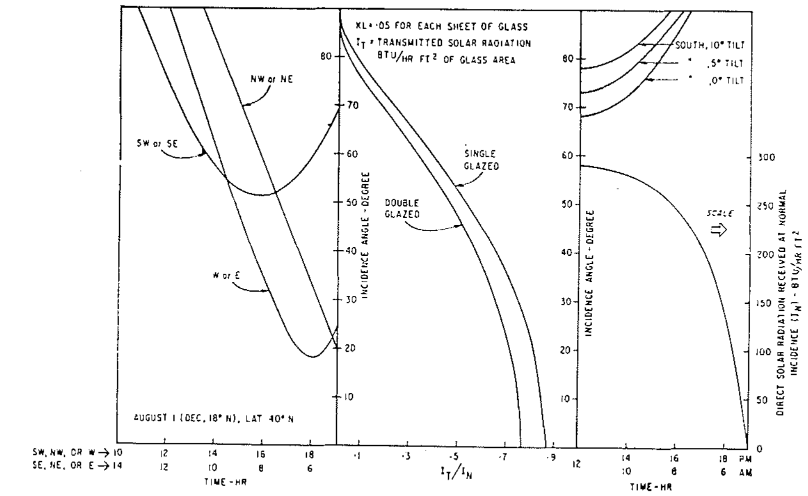


Fig. 7 Maximum glass pane temperatures versus KL for south exposed single and double-pane windows

Fig. 8 Data for the calculation of the solar transmission through ordinary glass windows with several different orientations or tilt angles



area of the glass is proportional to the cosine of the incident angle. The ratio of the energy transmitted through unit area of glass to the energy incident on a unit area with normal incidence is shown in Fig. 8 as a function of the incident angle. This shows that the maximum rate of change of transmission with incident angle occurs at incident angles between 60 and 80 deg. This fact can be used to decrease heat gain from a south-facing window since the minimum incident angle is in the 60 to 80-deg range for temperate latitudes during the summer. Thus, tilting a window to increase the incident angle will reduce solar transmission in summer but has a much smaller effect in winter.

Fig. 8, right panel, shows the angle of incidence vs time for a vertical window facing south and for windows with 5 and 10-deg tilt. The energy incident on a unit area with normal incidence at 40° N latitude on August 1 is shown as a function of time in the right panel of Fig. 8. Curves in this figure can be used to give the energy transmitted by a vertical or tilted window.

The left panel in Fig. 8 presents the angle of incidence vs time for a vertical window with southwest, west and northwest orientation. It shows that changing from south to southwest orientation reduces solar gain until about 12:30 p.m.; thereafter it increases it. Similarly, a west window has a lower gain than a south window until 1:30 p.m. but the peak value during the afternoon is much greater. A further 45-deg increase in the window azimuth from west to northwest considerably reduces solar heat gain.

Maximum cooling loads computed for the standard room with a southern exposure and windows with 5 and 10-deg tilt are shown in Fig. 5. The maximum cooling loads for an unshaded vertical window and a window with complete outside shading are shown for comparison. The latter corresponds to a tilt angle of 22 deg. This graph shows that the first 5 deg of tilt cause a marked reduction in cooling load, but the change per deg of increase in tilt diminishes so that there is little point in tilting more than 10 deg.

The reflectivity of glass can be increased for all angles of incidence by coating the surface with either a dielectric material with a high index of refraction or a quite thin layer of a conducting material such as silver or gold. The thickness of a dielectric film can be selected so that reflectivity will be maximum for wave lengths in the infra-red part of the solar spectrum.

The use of an analog to compute cooling load requires an average transmission and absorption factor for glass whether it is treated or not. Reference 13 describes how the appropriate average can be computed when absorptivity and transmissivity are known as functions of wave length. The results shown in Fig. 5 for tilted windows represent the combined effects of increased reflectivity and the reduction in intensity of radiation incident on unit area of the window (resulting from increased angle of incidence). If a window is treated to increase its reflectivity it will be necessary to prepare a new curve for the center panel in Fig. 8.

SHADING

A 22-deg tilt is equivalent to complete outside shading, because the peak cooling load for this case is less than for any other arrangement. For comparison, the maximum cooling load for a vertical window facing south, with an inside blind, also is plotted on Fig. 5. The window with the inside shade has a higher peak cooling load than the window without a blind. The daily average cooling load is less, however, since some energy is reflected from the blind.

For a west orientation, complete shading is only possible with a shutter or blind which covers the whole window. A movable outside shade sometimes is used, but a shade which does not have to stand exposure to the outside climate is preferable in many instances. Since it is desirable to have as large a thermal resistance as possible between the surface which intercepts the radiation and the room air, it is preferable to have a shade between the panes of a double window rather than inside the room. The maximum cooling loads and inside surface temperatures for the two arrangements are given in Table II, together with results for a bare west window for comparison. The inside shade gives higher peak cooling loads than those for a window without shading and a much higher inside surface temperature. Interpane shading produces a significantly lower peak cooling load than prevails with a blind, but gives an inner pane temperature almost the same as the temperature with a venetian blind on the inside of a single sheet of glass. These results indicate, therefore, that interpane shading is preferable to the use of an inside blind for a west window. For a west exposure, a double window with an outer pane of heat-absorbing glass shows small reduction in peak cooling load as the absorptivity of the outer pane is increased, and requires a quite dark window to equal the performance of an interpane shade.

Results in Figs. 1 and 2 show that the computer values of peak instantaneous heat gain are in quite good agreement with the results of GUIDE method calculations. The corresponding peak cooling loads, however, are of the order of 60% of the peak heat gain values.

CONCLUSION

This study has considered only the component of the cooling load resulting from heat gain through the outside wall of a building; all other heat gains have been assumed to be zero. It has been shown that the peak value of the instantaneous heat gain through a largely transparent wall may exceed the corresponding component of the cooling load by from 20 to 40%. The significance of this difference depends, of course, on the relative magnitudes of the other heat sources. It is hazardous to generalize from the present results since the ratio of peak cooling load to peak heat gain depends on the thermal capacity of a building, the ratio of the transparent to opaque wall area, the orientation of the transparent wall sections, as well as the method used to limit solar heat gain. This study has considered but one type of building, one size of room and one ratio of transparent to opaque wall area. It has, however, demonstrated again the feasibility of using an analog computer to simulate complex heat transfer phenomena that occur in an air conditioned space. It is quite clear that further work must be done before the GUIDE method of calculating cooling load can be extended satisfactorily to include the effect of the heat storage capacity of interior elements in a building.

The study has shown also that the designer of a system for reducing solar heat gain must take into account the heat storage capacity of a building. For instance, the use of heat-absorbing glass can lead to increased peak values of the cooling load for buildings with large internal heat storage capacity. Heat-absorbing glass can be useful, however, in reducing the cooling load for a light building.

Maximum heat gain through heat-absorbing glass will occur on clear calm days when the outside film coefficient is minimum. Hence, the design value of the outside film coefficient for heat absorbing glass should be about 2 Btu/ft^2/hr/F rather than the value of 4, which is used in the current GUIDE. This will lead to higher calculated values of the glass temperature, and a greater proportion of the energy absorbed by the glass will be transferred to the room air. When heat-absorbing glass is used, its effectiveness is increased much by the use of an inner pane of ordinary glass.

Outside shading or tilting are quite effective means for reducing the cooling load of windows facing south, and an inside blind is most effective if placed between the panes of a double window.

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