The Effect of Building Envelopes on Cooling Loads Due to Lighting

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ABSTRACT

The interaction between the building envelope and lighting and HVAC systems is examined based on full-scale measurements and computer modeling of a lighting interaction test facility. Cooling loads due to lighting, in particular peak cooling loads during transient operation of the lighting system, are influenced by the building thermal environment and heat storage characteristics. Variations in building envelope performance and exterior conditions can affect both lighting system performance and cooling load due to lighting.

INTRODUCTION

Two of the major contributors to commercial building cooling loads are heat gains from lighting and exterior envelope heat transfer. An accurate estimate of building cooling loads is needed in order to determine the proper cooling and fan equipment sizes. In order to size HVAC systems, peak heating and cooling loads must be predicted. In the case of cooling, the concurrent peak load is what is of interest. This is the maximum rate of cooling taking into consideration all heat gains. It is important to note that the peak cooling load does not necessarily occur when any of the individual heat gains are maximum, due to heat storage effects, or even when the associated individual cooling loads are maximum. Rather, peak building cooling load occurs when the sum of the cooling loads due to individual sources is maximum.

In actuality, building cooling loads tend to be maximum on hot, summer afternoons, at time that usually coincides with peak electrical demand. During these periods of high demand, the cost of electric power is greatest, and the utilities are not always able to provide all the power needed by their customers, a situation which results in voltage reductions and brownouts.

It is because of concerns regarding proper sizing of building HVAC systems, and the search for means to reduce peak electrical demand for electric utilities, that the control of cooling loads due to lighting is of interest. Lighting can account for 25% or more of commercial buildings' annual energy requirements. All of the energy used by the lighting system is typically dissipated into the building space. A large fraction, if not all, of the dissipated lighting energy eventually becomes cooling load. The cost of commercial building lighting was more than $40 billion in 1980, with cooling due to lighting accounting for another $15 billion (DOE 1985). Thus, improvements of only a few percent can have a significant impact.

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This paper focuses on the effect of the building envelope on cooling loads due to lighting and vice versa. Interactions between the lighting and cooling systems and the building envelope are examined, based on full-scale measurements and computer modeling conducted at the lighting test facility.

THE INTERACTION BETWEEN LIGHTING AND HVAC SYSTEMS AND THE BUILDING ENVELOPE

In the process of estimating cooling loads, building designers frequently consider each heat source individually, without regard to interactions between different heat sources and the potential impact on the resulting combined cooling load (ASHRAE 1981). For example, the cooling load due to lighting will be determined, typically using weighting factors, assuming that the lighting system is the only source of heat within the room. Then, the cooling load due to exterior heat gain will be computed separately. The combined cooling load is assumed to be the sum of the individual components, by application of the principle of superposition. However, the total cooling load due to lighting and exterior heat gain occurring together is not the same as the sum of the individual components. This is because the presence of other heat sources alters the thermal conditions within the building. Both transient and equilibrium temperatures are affected. In particular, the transient cooling load is affected because both the heat from lighting and from the exterior compete for the same storage. Once the heat storage components, such as walls, floors, and furnishings, are saturated, any additional heat gain represents an instantaneous cooling load.

There are three main effects that can be caused by the interaction of the lighting system and the building envelope. They are:

1. The presence of the exterior wall and exterior boundary condition can alter the shape of the cooling load profile due to lighting by changing heat storage characteristics of the wall.

2. The steady-state cooling load due to lighting and exterior wall heat transfer can be altered.

3. The equilibrium lighting system temperatures and efficiency can be altered due to the exterior wall.

In addition to these three effects, solar radiant heat gain through envelope fenestration elements can also potentially influence the thermal performance of the lighting system; this possibility is not addressed in this paper, but awaits further study.

DESCRIPTION OF MEASUREMENTS AND COMPUTER SIMULATIONS

Detailed measurements were made of cooling load for a typical office space due to lighting with a hot and cool exterior condition across one wall. The test facility has been previously described in detail (Treado and Bean 1988). A schematic figure of the test facility is shown in Figure 1. To summarize, the test room is 12 ft by 14 ft by 8 ft high with a 2.5 ft plenum above a suspended ceiling. The lighting system consisted of 4 2-lamp luminaires (2.1 W/ft^2) with open-cell prismatic diffusers. Supply air was introduced from a ceiling register and extracted through the plenum space by means of a ceiling grille. A duplicate lighting and HVAC system was beneath the floor slab, which was 2 1/2 in of concrete on a steel deck. The exterior wall was lightweight and insulated, while the three interior walls were also lightweight, but only the corridor wall was insulated separately guard air spaces surrounding the test room simulated adjacent similar spaces by maintaining equal wall surface temperatures on both sides of the wall, this allows heat storage in the interior walls, but no net heat flow. The exterior guard air was maintained at 85°F or 65°F. The room was held at 75°F. The area of the exterior wall was approximately equal to the floor area.

Both steady-state and transient (step) tests were conducted with the lighting system and exterior conditions independently and then together. The measured results were used to calibrate and validate a detailed finite-difference computer model (Treado and Bean 1988). The computer model was then used to extend the results to a wider range of test conditions.

Eight exterior wall configurations were simulated, as shown in Table 1.

TABLE 1
Exterior Wall Configurations

	Exterior Condition	Wall Type
1	Interior condition,	Lightweight insulated
2	Interior condition,	Heavyweight insulated
3	90°F, summer	Lightweight insulated
4	30°F, winter	Lightweight insulated
5	90°F, summer	Heavyweight insulated
6	30°F, winter	Heavyweight insulated
7	90°F, summer	Lightweight uninsulated
8	30°F, winter	Heavyweight uninsulated

The lightweight walls were gypsum board with steel studs; the heavyweight walls were concrete 2 in thick (140 lb/ft^3). The insulated walls had an R=11 rating, with the insulation located on the exterior side of the wall.

The response of the cooling load (Q) due to a step change in lighting (W) can be evaluated to determine ASHRAE-type weighting factors in the following manner. The cooling load curve is approximated by a exponential function:

$$\frac{Q(t)}{W} = 1 - Ae^{-Bt} \qquad (1)$$

<u>where</u>

t = time
A,B = regression coefficients

The weighting factors are given by:

$$a_1 = Q(1) = 1 - Ae^{-B}$$

$$b_1 = e^{-B}$$

$$a_2 = 1-b_1-a_1 \qquad (2)$$

Cooling load at discrete time intervals due to an arbitrary lighting schedule can then be expressed as [2]:

$$Q(t) = a_1\ W(t-\Delta) + a_2 W(t-2\Delta) + b_1\ Q(t-\Delta) \qquad (3)$$

<u>where</u>

Δ = time step

Equation 3 is the basis for the calculation of cooling load profiles due to cyclic operation of the lights, and assumes zero instantaneous cooling load due to lights, which reflects experimental observations.

The total heat storage (S) is given by: $S = \frac{A}{B}$ (4)

RESULTS

The first series of figures show the simulated cooling load that would result from a step operation of the lighting system with the interior boundary condition or the exterior conditions. This type of step operation is bounded by two steady-state conditions - lights off and lights on. During the transient stage, the shape of the cooling load curve is determined by the heat storage occurring in the room components. In the case of an interior room, the cooling load due to lighting eventually equals the lighting power. The shape of the cooling load curve determines the weighting factors that are used for design.

Figure 2 compares cooling loads due to a step change in lighting for lightweight vs. heavyweight insulated exterior walls. In this case, the wall construction is of an exterior type but there is no exterior condition, thus, heat can be stored in the walls, but no net flow can occur. The heavyweight wall noticeably reduces the pick-up of the cooling load due to lighting. This is due, of course, to the additional heat storage in the room with the more massive heavyweight wall, which stores 31% more heat than the room with the lightweight wall. This additional heat storage reduces peak cooling loads with cyclic lighting, as will be shown later.

The effect of an exterior condition on cooling load is shown in Figures 3 and 4 for a lightweight insulated wall. Figure 3 shows the total cooling load for the interior, summer exterior and winter exterior condition, with the lighting system switched on midway through the simulation. The exterior condition is held constant throughout the test, and the room is initially at a uniform temperature of 75°F. While the lights are off, the exterior conditions cause steady cooling or heating (negative cooling) loads. When the lights are energized, cooling loads increase to a new equilibrium condition. Both the shape of the cooling load curves and the values of their asymptotes are influenced by the exterior conditions, as shown in Figure 4. In this figure, the cooling load curves have been adjusted by subtracting the steady lights-off cooling load (i.e. the exterior heat transfer). The steady combined cooling load is 1% to 2% less with the exterior conditions than without. These effects can have two alternate interpretations - either that the operation of the lighting systems alters the exterior wall heat transfer, or that the exterior condition alters the cooling load due to lights.

The influence of the exterior wall construction is highlighted in figure 5, which shows cooling load, adjusted as described above, for an uninsulated wall. The steady cooling load with lights on is 3.5% less for summer condition and 4.2% less for the winter condition than for the interior condition. This is because for the winter condition, some of the lighting power is lost through the exterior wall, while for the summer condition, the heating of the wall by the lighting system reduces the temperature difference across the wall, thereby reducing exterior heat gain.

The net effect is that for either the summer or winter condition, steady-state cooling loads due to lighting and the exterior condition are less than for no exterior condition. Similar results are shown for the heavyweight exterior wall in Figure 6. Table 2 summarizes the ratio of steady cooling load due to lights and exterior condition to the sum of the individual lighting and exterior wall cooling loads. Also included in this table are the regression coefficients A and B and the total heat storage, S, as determined from Equation 4.

TABLE 2
Combined Cooling Load Ratio and Heat Storage

Case	Combined Cooling Load / Sum of Cooling Loads	A	B	S
1. Interior, Light Wall	1	.584	.235	2.479
2. Interior, Heavy Wall	1	.643	.198	3.247
3. Summer, Light Wall	.988	.521	.238	2.188
4. Winter, Light Wall	.981	.588	.221	2.659
5. Summer, Heavy Wall	.995	.621	.216	2.875
6. Winter, Heavy Wall	.974	.605	.187	3.229
7. Summer, Uninsulated Wall	.965	.445	.236	1.882
8. Winter, Uninsulated Wall	.958	.400	.198	2.019

A considerable range in storage of lighting energy is seen in Table 2. Maximum heat storage, shown in units of total energy stored per lighting power input, is greatest for the heavyweight wall with interior or winter condition, while for the summer condition, heavyweight wall, only 88.5% of the heat storage occurs. This is because the hot exterior condition increases the wall temperature, thereby using some of the heat storage capacity which would otherwise be available for lighting energy. Similarly, minimum heat storage occurred for the summer condition, uninsulated wall, which stored only 75.9% of the energy stored by a similar interior wall. The insulated lightweight wall stored 88.3% for summer and 107.3% for winter compared to a similar interior insulated wall.

The differences in heat storage and steady combined cooling load noted above influence cooling load profiles and peak cooling loads during cyclic lighting operation. The regression coefficients listed in Table 2 can be used to compute ASHRAE-type weighting factors according to Equation 2. Table 3 lists the weighting factors.

TABLE 3
Weighting Factors for Lighting Cooling Load

Case	a_1	a_2	b_1
1. Interior, Light Wall	0.539	-0.329	0.790
2. Interior, Heavy Wall	0.473	-0.293	0.820
3. Summer, Light Wall	0.589	-0.377	0.788
4. Winter, Light Wall	0.528	-0.330	0.801
5. Summer, Heavy Wall	0.500	-0.306	0.806
6. Winter, Heavy Wall	0.499	-0.328	0.829
7. Summer, Uninsulated Wall	0.649	-0.439	0.790
8. Winter, Uninsulated Wall	0.672	-0.493	0.820

These weighting factors were used along with a 12-hour daily lighting schedule to determine the resulting cooling load profile due to lighting and the actual cooling load due to lighting. The difference between these two quantities is due to the differences in steady cooling load with exterior conditions, as described above. The cooling load profile is based on the assumption that cooling load due to lighting eventually equals the lighting power at steady state, while the actual cooling load takes into consideration the reduction in cooling load caused by the exterior condition. For the two interior conditions, lightweight and heavyweight walls, there is no difference between the cooling load profile and the actual cooling load. However, as shown in Figure 7, the cooling load profile and peak cooling loads are significantly less for the heavyweight wall. Peak cooling load is 2.2% less for the heavy wall at 94.5% of the lighting power, while the two cooling load profiles differ by as much as 5% throughout the day.

The cooling load profiles for the lightweight wall are compared in Figure 8. The cooling load profile is greatest for the summer condition, but the peak cooling loads converge at 96% to 97% of the lighting power. However, as shown in Figure 9, the actual cooling load is significantly less for the winter condition - only 94.3% of the lighting power due to loss of lighting energy through the exterior wall. Actual peak cooling load is 0.7% less for the summer condition than for the interior condition.

Figures 10 and 11 show similar results for the heavyweight walls under interior and exterior conditions. The lowest actual peak cooling loads are least for the winter condition, at 91.8% of lighting power, while the summer actual peak cooling load is 0.7% greater than the interior heavyweight wall, at 95.2% of the lighting power. The additional wall mass combines with the summer condition to slightly increase peak cooling loads relative to an interior wall condition.

The most dramatic results are shown in Figures 12 and 13 for the uninsulated wall. The actual cooling loads for the uninsulated wall case initially exceed those for the interior condition, then cross over near midday and remain below it. The actual peak cooling load is 94.1% of the lighting power for the cooling condition and 92.5% for the winter, about 2% less than the similar insulated wall and 2% to 4% less than the interior condition.

Table 4 lists the peak cooling load due to lighting for 12-hour cyclic operation for each wall condition. The actual cooling load is least for the heavy wall, winter condition, with the uninsulated wall, winter condition a close second at approximately 92% of lighting power. At the other extreme, the cooling load for the lightweight interior wall, summer conditions is about 96% of the lighting power.

The reductions in peak cooling load, while not overwhelming, are significant for several reasons. First, the savings are due to the effect of a single wall; rooms with more exterior surface area would have a greater effect. Second, any reduction in peak cooling load allows equipment sizes to be less, or alternatively, provides additional capacity to meet unexpected or additional cooling loads. Third, electrical power is expensive during peak cooling hours due to demand charges and ratchet clauses, which tie the unit cost of electrical power for the entire year to the peak demand at any instant in time. This can have a tremendous amplifying effect where a 1% reduction in peak cooling load can save an equivalent percentage of total building electrical power expense.

TABLE 4
Peak Cooling Load, 12-Hour Lighting Cycle

Case	Cooling Load Profile	Actual Cooling Load
1. Interior, Light Wall	0.967	0.967
2. Interior, Heavy Wall	0.945	0.945
3. Summer, Light Wall	0.972	0.960
4. Winter, Light Wall	0.961	0.943
5. Summer, Heavy Wall	0.957	0.952
6. Winter, Heavy Wall	0.942	0.918
7. Summer, Uninsulated Wall	0.975	0.941
8. Winter, Uninsulated Wall	0.966	0.925

Regarding the effect of the exterior wall and condition on lighting system temperatures and efficiency, the analysis indicated only a very small effect, with lamp temperatures varying by only 1°F or less. This is due to the decoupling of the lighting system from the exterior wall. Since room air temperature is held constant, convective heat transfer at the lamps is not affected by the exterior wall. Only the infrared heat transfer is dependent on wall temperatures, and the single exterior wall is one of six surfaces interacting radiatively with the lighting system. Thus, the differences in the radiant heat transfer are small, but are responsible for the changes in lamp temperature.

CONCLUSIONS

Evaluation of the effects of exterior wall type and exterior condition on the cooling load due to lights showed that cooling loads vary by as much as 8% of lighting power, depending on the exterior wall condition. This variation was due to changes in heat storage in the exterior wall and changes in the net heat transfer through the wall due to operation of the lighting system with winter or summer exterior conditions adjacent to one wall of a room. The effect of the exterior condition compared to an interior condition was similar in magnitude to the effect of substituting a heavyweight exterior wall for a lightweight wall. The reduction in actual peak cooling load due to lighting was greatest for an uninsulated, lightweight exterior wall, and an insulated heavyweight exterior wall, both for winter condition. Peak cooling loads for the summer condition were reduced 1% to 3% due to the exterior wall.

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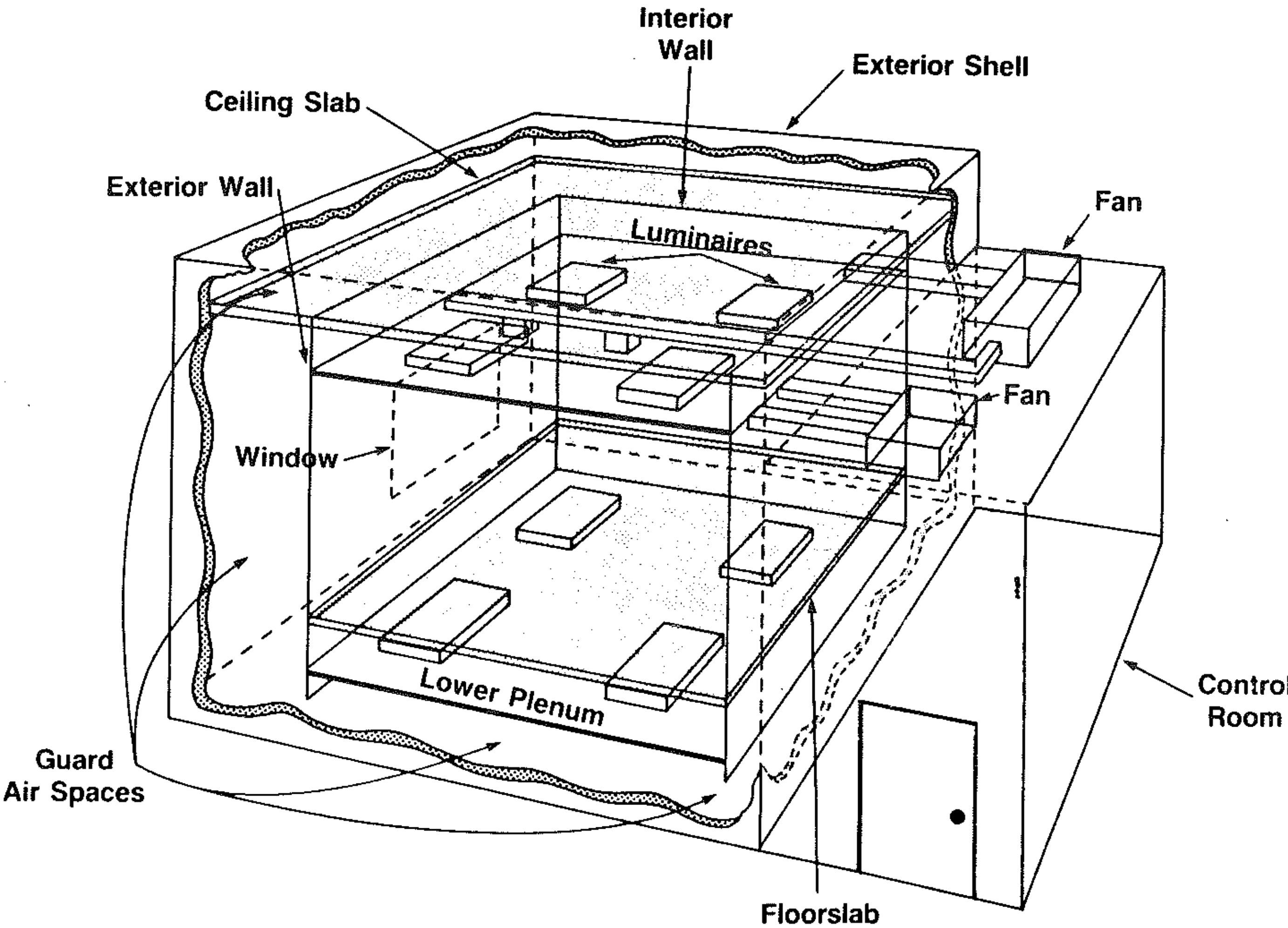

Figure 1. Schematic diagram of the lighting test facility

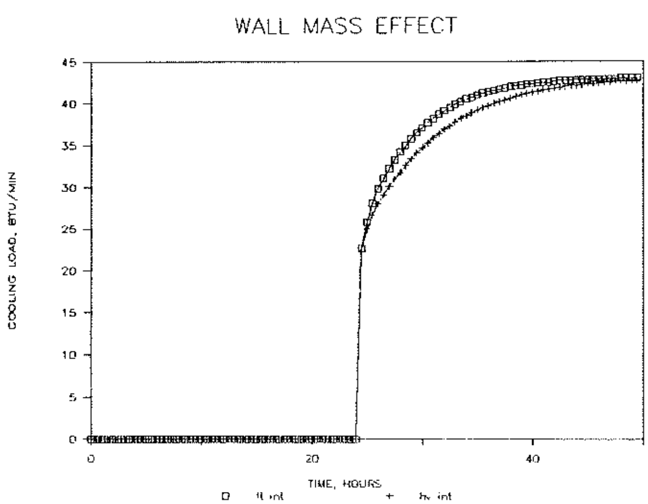

Figure 2. Cooling load due to step change in lighting effect of wall mass

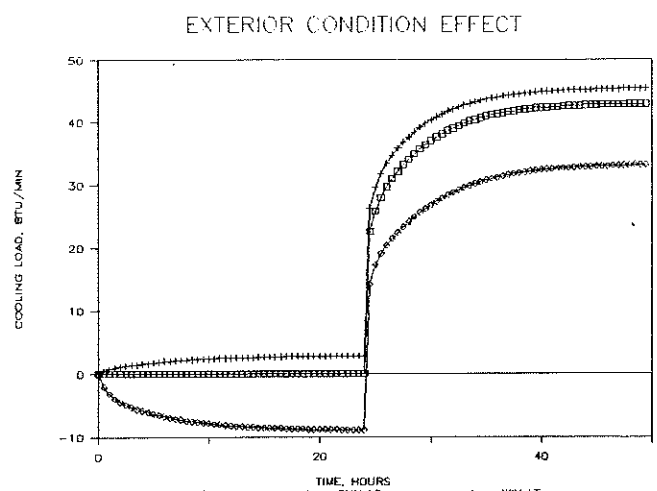

Figure 3. Cooling load due to exterior condition and step change in lighting

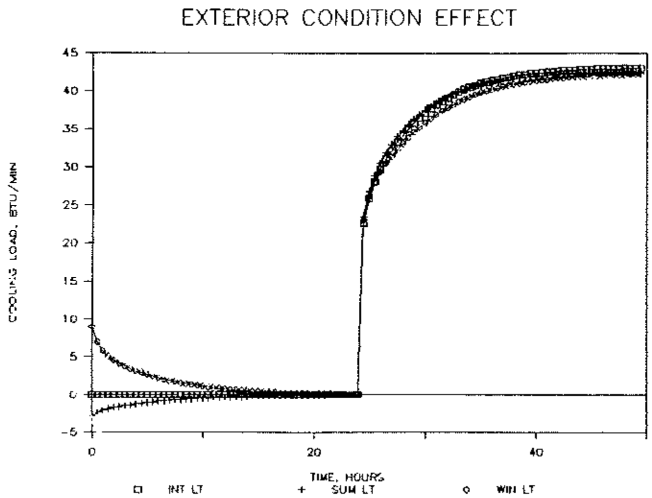

Figure 4. *Adjusted cooling load due to step change in lighting effect of exterior condition*

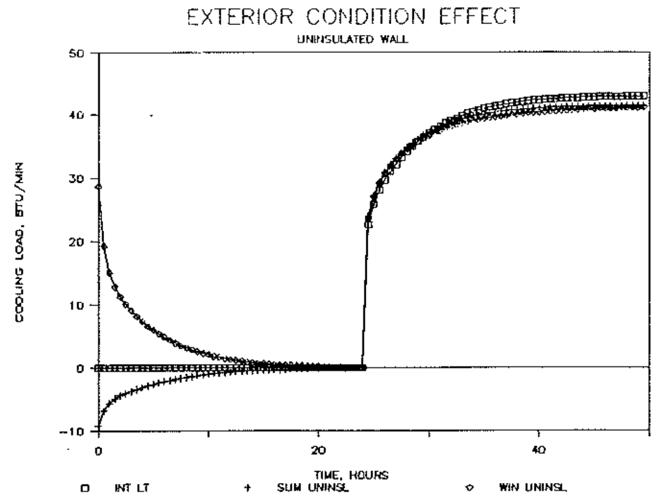

Figure 5. *Adjusted cooling load due to step change in lighting effect of uninsulated wall*

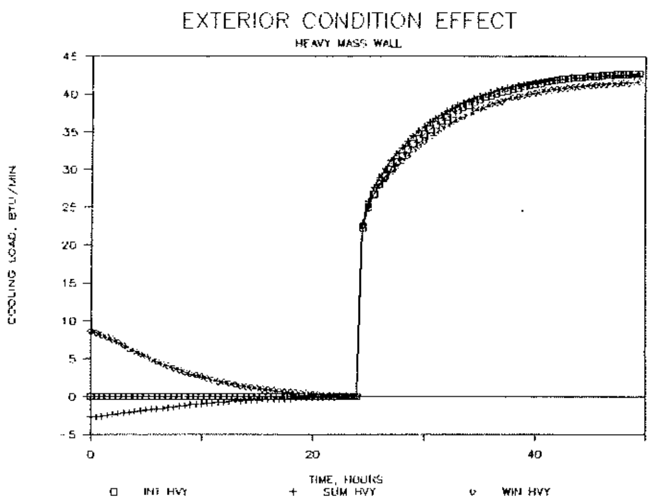

Figure 6. *Adjusted cooling load due to step change in lighting effect of wall mass and exterior condition*

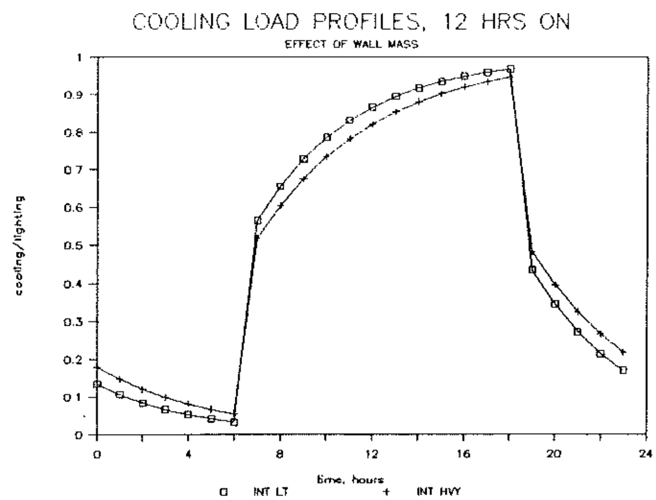

Figure 7. *Cooling load profile due to cyclic lighting effect of wall mass*

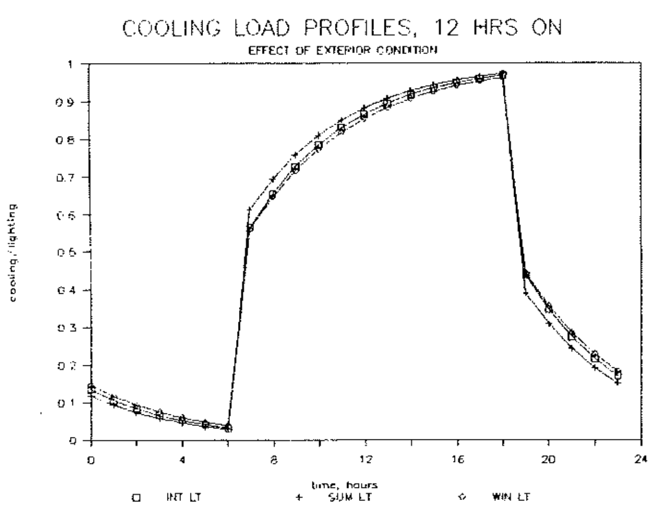

Figure 8. *Cooling load profile due to cyclic lighting effect of exterior condition*

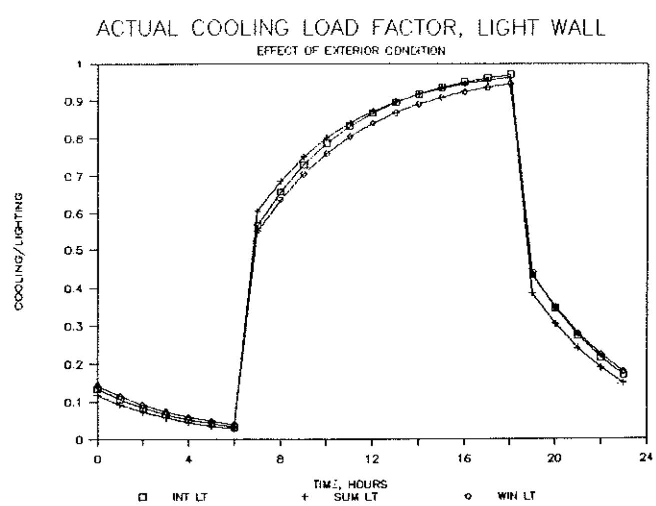

Figure 9. *Actual cooling load due to cyclic lighting effect of exterior condition*

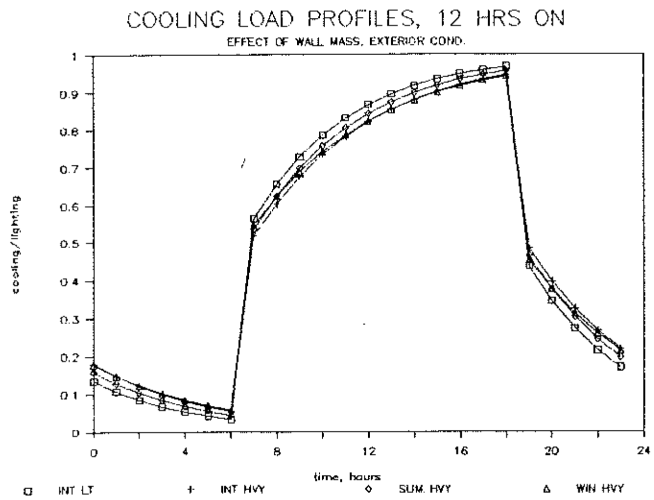

Figure 10. *Cooling load profile due to cyclic lighting effect of wall mass and exterior condition*

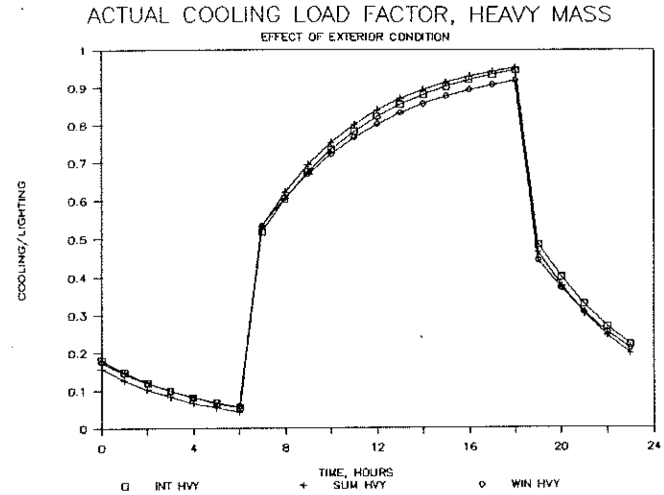

Figure 11. *Actual cooling load due to cyclic lighting effect of exterior condition*

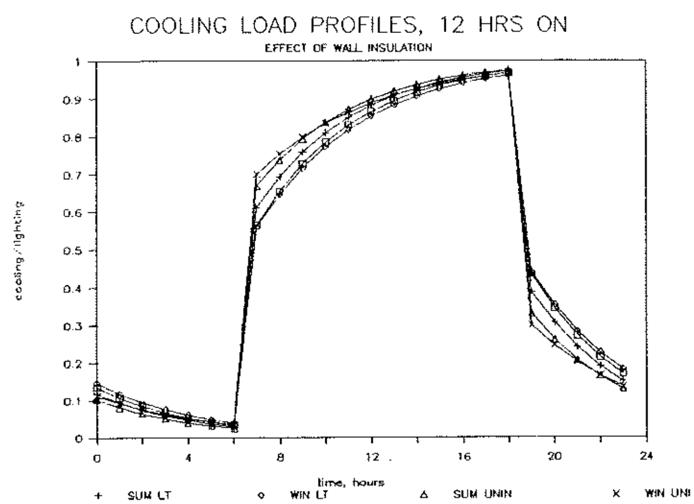

Figure 12. *Cooling load profile due to cyclic lighting effect of uninsulated wall and exterior condition*

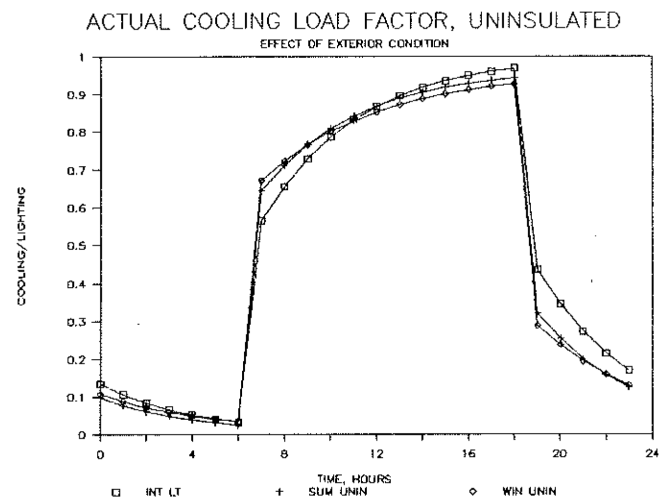

Figure 13. *Actual cooling load due to cyclic lighting effect of uninsulated wall and exterior condition*