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ABSTRACT

The primary factors that determine the net thermal performance of a window system are its overall heat transfer rate (U-value), its air leakage characteristics and its sun control capability. With managed window systems these basic properties may be drastically altered on an hourly basis as movable insulating and shading devices are deployed over the prime windows. A large building energy analysis computer program, DOE-2, has been modified to model the thermal performance of a variety of window management devices. The deployment of these devices is simulated based upon fixed hourly schedules or the value of critical climatic factors such as solar intensity. Automatic operation may be modeled or manual operation with varying degrees of human fallibility may be simulated. The model couples reductions in infiltration rate to the deployment of an insulating or shading device. Results of heating load calculations are presented for the cases of single-and double-glazed windows in a typical house with glass-to-floor area ratios of 15 to 40%, and for window management devices with varying thermal resistance, air leakage rates and different modes of operation.

INTRODUCTION

Windows are unique among major elements of the building envelope. They can be characterized by large convective/conductive heat transfer rates, high rates of radiant transfer, and high mass transfer rates. For these reasons, windows are frequently portrayed as villains in the national effort to reduce unnecessary energy consumption attributable to buildings. This has resulted in the promulgation of design guidelines and building codes which seek to reduce window area.

Because they treat window thermal performance from the simplest perspective, these directives are misleading at best and frequently wrong. By moving away from a static view of window performance under the worst design conditions (a cold winter night) and by examining the timing and magnitude of the various energy flows through windows, it can be shown that the actual energy performance of windows, departs significantly from the rather simplistic view presented above.

The window properties that create potential summer cooling load problems (high transmittance) allow the window to collect useful solar gain during the winter months and daylight throughout the year. Window characteristics that create heat loss problems in winter (relatively high U-values) may be advantageous in cooling a building under some summer night conditions. The operable capability of a window that allows undesired air leakage also provides a large open cross section to promote cooling and increased thermal comfort from natural ventilation. The problem, then, is one of managing the thermal/optical properties of window systems to filter or magnify the appropriate energy flux under a broad range of building, climatic, and site conditions. This collection of approaches to effective window use has been termed "window management strategies."

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The departure from a simple static model of a window to one in which thermal/optical properties vary over time requires new tools to assess performance. While the U-value is a good indicator of the relative heat transfer rates of different window systems under steady-state, night-time conditions, it tells us little about the annual energy consumption of the window system. This may be measured empirically in actual buildings (with some difficulty) or may be calculated using computer-based building simulation models. The latter approach has the advantage of allowing numerous comparative evaluations of many different window systems in different climates to be made at relatively low cost. The model must, however, be sufficiently flexible and "realistic" to allow simulation of all significant window characteristics that will impact actual performance.

The window's importance to net annual building energy performance is based upon its contributions (positive and negative) to heating, cooling and lighting loads. In this paper we report on analysis of the impact of window management strategies on building heating loads for a class of devices known as movable insulating systems. Work now in progress extends this analysis to include the use of sun control devices and the cumulative impact on heating, cooling and lighting loads. The basic approach of this study was to use a quantitative simulation of building performance to determine the comparative performance of movable insulating devices. The intrinsic characteristics of movable insulation that determine energy consumption during the heating season are the thermal resistance of the device and its impact on the air leakage rate of the prime window it covers. Actual device characteristics vary widely so we have evaluated performance of devices with a thermal resistance of R0, R.35, R.85 and R.17 m^2 K/W (R0, R2, R5, and R10 hr-ft^2 F/Btu). An R0 device is one which has no intrinsic insulating value but improves window performance by creating an insulating air space. These insulating devices are assumed to reduce the air leakage rate of the prime window. A loose fitting device will result in no reduction in air leakage while a device which seals tightly may result in complete elimination of air leakage. The relative importance of each of these parameters is of some significance. Heat loss by air leakage in a poorly weatherstripped window may exceed conductive/convective losses. Thus, tight fitting single shades may outperform thick insulating shutters that do not seal effectively to the window. These concerns do not appear to have been adequately addressed in the literature.

In addition to the issues of intrinsic performance characteristics, the operating characteristics of the insulating device are subject to considerable uncertainty. We have modeled devices which are operated on different time schedules or whose operation is based upon a climatic parameter (e.g., solar intensity). Once the nominal "schedule" is selected, automatic operation (an "ideal" occupant or automatic actuator) may be modeled or a fallible human being may be simulated in several different modes.

To more accurately assess the performance of movable insulating devices, we simulate their behavior in the context of a small building. The glass-to-floor ratio is varied from 15 to 40%; the glazing is either distributed evenly on all four orientations (25%N, 25%E, 25%S, 25%W) or favoring a southerly orientation (10%N, 20%E, 50%S, 20%W). The insulating devices are used with single- and double glazing. Results have been obtained for three varied climates but this paper limits discussion to a single location, Minneapolis. Although monthly heating and cooling loads are calculated, we discuss only heating loads since the device operation was simulated to reduce winter heating loads and is thus neither optimal nor realistic as an accurate measure of summer performance.

Not only are the annual performance values of interest, but the timing and magnitude of peak loads and the time-varying patterns of load contributions from major building components provide additional useful information. We have modified the output of the building simulation program to provide this information in several different tabular and graphic formats.

BUILDING SIMULATION MODEL

The ultimate proof of the effectiveness of any energy conservation strategy is convincing results from real buildings. However, it is time-consuming, technically difficult, and thus expensive to collect such data and virtually impossible to compare all the parametric variations of interest in real buildings.* A more versatile approach to field testing of window management systems is embodied in the Mobile Window Thermal Test (MoWiTT) Facility now being designed and built at LBL. This facility will allow comparative testing of different managed

*The DOE/LBL Energy Efficient Windows Program is sponsoring a test demonstration of the effectiveness of 200 insulating shades in a college dormitory but results will not be available until mid-1980.

window systems with building thermal characteristics, orientation, and climate as controlled variables.[1]

At the present time, the most powerful and versatile simulation tool is not a physical experiment but an energy performance simulation computer model. A modified version of the DOE 1.4 computer model was used for this study.** The DOE 1.4 program is a computer simulation model which simulates the energy performance of a building. It was developed with support from the U.S. Department of Energy by a consortium of national laboratories and consultants over the past three and a half years. The program has been used extensively for research purposes and to demonstrate compliance with energy performance standards.

The model accepts a detailed description of the building design features, information about the location and orientation of the buildings, and reads all pertinent weather information from a weather tape for the region in which the building is located. DOE-1.4 was originally designed to simulate the performance of office buildings, but it can be effectively used with virtually any other type of building. Hourly thermal loads are calculated for the building, as well as the energy consumption of mechanical systems. The model will also calculate life-cycle costs.

DOE-1.4 is written in FORTRAN and has a modular structure. The modules (BDL, LOADS, SYSTEMS, PLANT, and ECONOMICS) are separate entities which may be used individually. Thus, it is possible to run a full-scale simulation of the energy performance or simulate only some of its aspects. The simulation can be run hour by hour for a full year, or for only a few days.[3]

The building can be described in great architectural detail. This description is accomplished using the Building Design Language (BDL), an English-like set of commands which are related to the components of a building and are easy to use. If the user does not specify the value of a particular parameter for energy analysis, the model assumes a preset value. A building is divided into coherent thermal zones. Orientation, boundary conditions shared with other zones, the make-up of each wall, floor, roof, window, skylight, and door are defined for each zone. External shading (or surrounding buildings casting shadow) can be defined precisely. Schedules of building use, the use of artificial lighting and the use of occupant-operated equipment describe the operation of the building. The model contains a library of typical building materials and make-up of typical walls, floors, and roof, but the user may also specify materials and wall, floor, and roof sections for use in simulation. The execution of BDL creates a complete data base which describes the building for thermal and economic analyses performed in other modules.

BDL offers great flexibility in the description of buildings. With a little ingenuity, experience with the simulation, and understanding of how the building works, many levels of architectural detail can be described. Complex buildings, rich in architectural detail, can be described as well as simple box-like buildings. The model presents some limitations on the size of the building that can be simulated because of the size of computer memory. This can be circumvented by the simulation of repetitive zones as one, or through subdivision of the building into parts.

The LOADS module calculates thermal transfer by conduction and radiation for each thermal zone in the building for every hour. Calculations are based on the building's architectural characteristics, its thermal mass, orientation, location, weather, and solar conditions, and the delaying effect of the building structure. LOADS' algorithms follow ASHRAE methods of calculation whenever possible.[4,5] Latent and sensible heat from occupants, lighting fixtures, and occupant-operated equipment are taken into account. Infiltration loads are calculated using the air-change method or the crack method. The results from calculations in LOADS are hourly heating and cooling loads based upon a fixed design temperature for each thermal zone in the building, and loads for the entire building. These represent thermal loads for the architectural solution before the performance of mechanical systems in the building is taken into consideration.

The actual thermal loads based on hourly variation of internal temperature are calculated in SYSTEMS. This module also simulates thermostat schedules, ventilation requirements and the performance of mechanical equipment used to control the temperature and humidity in the building.

**This paper refers to DOE-1.4 because this version was used in this study. The program is continuously updated, and the current version is DOE-2.[2]

PLANT simulates the performance of primary energy conversion equipment. The simulated operation of each plant component is based on operating conditions and part-load performance characteristics. ECONOMICS calculates the life-cycle cost of operating the building. The calculation of cost is based on a projected interest rate, labor inflation rate, energy inflation rate, cost of fuel, cost of labor, cost of equipment and site cost factors.

The output from simulation with DOE-1.4 provides a wealth of data useful in assessing the energy performance of the building. The model offers flexibility in its reporting, and virtually any information used in the analysis can be retrieved.

DOE-1.4 relies on weather data provided by the National Oceanic and Atmospheric Administration (NOAA). These data are collected by weather stations across the country, compiled on magnetic tapes, and distributed by NOAA. The tapes (so-called "weather tapes") contain information about solar radiation, dry-bulb and wet-bulb temperature, cloud coverage, wind direction and velocity, atmospheric pressure, ground temperature, etc., for a given weather station for a full calendar year. The data can be examined and modified within the simulation model before their use in the simulation.

THE TEST HOUSE

A single-family residence of 113 m^2 (1,196 ft^2) (gross) was designed and used as the subject building in the study of managed window systems. It is a one-story building on a flat site. The particular design has several features important to the analysis of window performance:

a) It contains characteristics representative of buildings of this type and size which can be found in houses across the country (e.g., building materials, cost of construction, resident amenity, etc.)

b) Flexibility in elevation design permits variation of fenestration form, size and distribution

The floor plan and thermal characteristics of the test house are shown in Figure 1. Four people are assumed to live in the house. During the day, one stays at home, one works, and two go to school. All four spend their evenings and nights in the house. The use of artificial lighting (all incandescent) reflects the assumed occupancy of the house in the evening; connected lighting load is 1.0 W/ft^2, modulated by the schedule of use. No resident-operated equipment is used in the house.

Infiltration is simulated using the air-change method in DOE-1.4. Infiltration in the house is composed of air leakage from the windows and air leakage from all other sources which we assume is 0.75 air changes/hour (ach). This represents a typical stud-wall house of current construction quality. We assume air leakage from the windows varies with the total window area from a contribution of 0.25 ach for windows corresponding to 15% window-to-floor ratio, to a contribution of 0.40 ach for windows corresponding to a 40% window-to-floor ratio. Air leakage rate does not increase linearly with window area because the ratio of window perimeter/window area is reduced as total window area increases (i.e., we assume larger window units) and because we assume that some of the additional window area is likely to be fixed glazing. The contribution of windows (or any other single building element) to total infiltration is still not well understood and its modeling in DOE-1.4 is imperfect at best. However, our interest in comparative rather than absolute results reduces the significance of possible error in the modeling of infiltration processes.

All calculations of thermal loads resulting from the building envelope are initially based on an interior design temperature of 70 ^{o}F. Loads are then adjusted assuming the floating of inside temperature between 69° and 78 ^{o}F. An "ideal" mechanical system (with 100% efficiency) provides the heat and conditioning to maintain this temperature.*

*This study is concerned with the performance of thermal shutters and their effects on loads resulting from "architectural" features of buildings. The assumption about an "ideal" mechanical system is used to avoid the intricacies of simulating the performance of a real mechanical system inside the building. It does not significantly affect the calculations of "architectural" thermal loads.

SIMULATION OF MANAGED WINDOW SYSTEMS

The publicly distributed version of DOE-1.4 did not simulate the dynamic performance of movable insulating or shading devices (e.g., blinds and curtains). To allow the careful study of managed window systems, algorithms in BDL and LOADS modules were modified and appended so that this class of devices could be simulated.

Movable shutters and shades (we use shutters and shades as representative of a much broader family of similar devices) affect the thermal performance of windows in three ways:

1) They reduce or eliminate direct solar gain during the hours when the window is exposed to the sun;

2) They increase thermal resistance of the window by adding the resistance of the shutter or the shading device and the resistance of the air space between the device and the window;

3) They reduce or eliminate air leakage at the perimeter of the window.

Modifications and additions were made to DOE-1.4 to allow the simulation of all three effects. The user defines the type of the device through the definition of its transmissivity, thermal resistance, position, and distance from glazing. If the device reduces infiltration, the user specifies the expected level of reduction.

The user also defines how the movable shutters and shades are used in the building. In one option, a schedule defines the hours when these devices are in operation and the extent to which they are used (e.g., whether shutters are closed fully or only partially). This schedule represents a "reasonable" or expected plan of use of devices; it may be adjusted to account for human behavior. The user can also describe a uniform probability distribution which defines on an hourly basis the chance of use of the devices by occupants. It is also possible to simulate automatic closing and opening of shutters and shades. This is accomplished by specifying a critical solar gain level which, when reached in the simulation, will automatically activate or deactivate the devices.

The data resulting from the simulation of managed window systems performance are displayed in special reports. These reports contain specific information about the conditions of shutter closure or shading, weather conditions (i.e., sun and cloud coverage, wind direction and velocity), direct and delayed solar gain, and latent and sensible infiltration. Data may be reported for each hour of the simulation period. Printed maps and plotted charts show hourly changes in the value of any parameter of interest to the analysis and make the comprehension of data easier and faster. Figure 2 shows a plot of sample hourly data illustrating the impact of shutter performance for each hour over a two-day period. Figure 3 shows a graphic plot of net window performance for every hour in the year. Each symbol location is one hour of a single day (hours run top to bottom; days from left to right). An "´" signifies that the cumulative impact of all windows at that time was a net energy loss to the building. "X" indicates that the windows are providing net energy to the building at that hour. A contour line divides the region of net gain from that of net loss. Changes in window type, area, management, etc., can then be viewed from the perspective of their impact on the shape and size of the net gain/net loss performance regions.

MOVABLE INSULATING SYSTEMS

When the insulating devices are closed, the program computes the thermal conductance of the composite window system, which includes both the prime window and the shutter. The total fenestration thermal resistance is approximately equal to the shutter resistance plus .35 m^2 K/W (2 hr ft^2 F/Btu) for single-glazing, and the shutter resistance plus .52 m^2-K/W (2 hr-ft^2-F/Btu) for double-glazing, assuming that an additional air space between window and shutter is created in each case.

The parametric variation of insulating device properties allows us to ignore the details of device construction and operation. However, a broad survey was made of all classes of window insulating systems to ensure that resistance and air leakage characteristics used were representative (6). Most thermal insulators have some common characteristics and a common set of potential flaws. An insulating layer (rigid board, flexible batt, multi-layer films, granular materials, etc.) reduces heat loss associated with conductive, convective, and radiative

thermal flows. If the device fits tightly to the window frame, air leakage will be reduced. The insulating layer may be located in three positions relative to glazing: internal, external, or between glass. When not in use, the insulating material slides, rolls, collapses, folds, or is otherwise removed from the window. Control and deployment of the devices may be initiated by automatic or manual means. "Shutters" as used in this context include blinds, shades, and drapes, and frequently provide solar control as well as thermal control. In addition, these devices may fulfill the need for privacy, security, and aesthetics. We restrict our discussion to those devices designed primarily to reduce winter thermal losses.

Several important issues arise in any discussion of insulating shutters. Some influence thermal performance directly while others mainly influence consumer acceptance. They are identified briefly below:

1) Condensation: Insulating shutters placed on the interior will reduce glass temperatures and increase the likelihood of condensation. The magnitude of this effect will depend in part on the degree of air leakage around the insulating device and the tightness of the prime window. With a tight prime window, a leaky shutter and high relative humidity, condensation is likely to be a severe problem.

2) Infiltration/Air Leakage: Infiltration through poorly fitted windows is a major energy loss factor in many buildings. Tight-fitting shutters will reduce this loss substantially. Significant air leakage around the edge of the insulating shutter may create a thermal bypass and negate the nominal insulating value of the device. Since most of these devices have extensive moving surfaces, seals and air leakage at the edges are critical design problems. Initial seal properties are important but durability of seals over time is also a critical unknown in many cases.

3) Overheating: Many insulation devices may be left in place or utilized year round. If the device seals to the window effectively, overheating may occur when the sun strikes the window with the shutter closed. Unless provision is made to vent the heat buildup, the shutter, window and all adjacent components must be designed to withstand the resultant high temperatures without failure or degradation. Since many devices incorporate plastics and synthetic fabrics that are temperature sensitive, the shutter must be designed to minimize high stagnation temperatures.

4) Fire Safety: Many movable insulating devices incorporate substantial quantities of plastic foams, plastic films and synthetic fibers. If used improperly, these may constitute a smoke and fire hazard.

5) Operational Reliability: Although many movable insulating devices might be automated and motorized, cost constraints make it unlikely that single windows will be operated in this manner. Thus, if potential savings are to be fully realized, insulating devices must be closed and opened conscientiously. The degree of user responsibility is critical because a fixed permanent solution with lower thermal resistance will perform better than a device with higher thermal resistance which is deployed only occasionally, as discussed later. One solution is to couple the deployment of the thermal insulating device with an action that will be routinely taken to achieve thermal comfort or privacy. For example, if the rollup shade that is pulled to provide privacy as the sun sets is also designed to provide good insulating qualities, the thermal benefits will accrue on a regular basis. Effective energy conservation will be promoted and accelerated by coupling new thermal control functions to existing habits and lifestyles wherever possible.

6) Thermal Comfort: Like any other window with good insulating properties, if air leakage is reduced and interior surface temperatures rise, thermal comfort will be increased, particularly in the vicinity of the window. A draft-free environment with higher mean radiant temperature will allow equivalent thermal comfort to be achieved at correspondingly lower air temperatures, resulting in additional energy savings.

From the perspective of effective energy utilization, indirect factors such as convenience, aesthetics, fire safety, etc., will quickly be translated by occupants into direct impact on energy use. A device which is not acceptable for any reason and is thus not deployed will

produce no energy savings and may actually require additional energy use if it was selected at the "expense" of a non-movable option, such as a storm window.

DISCUSSION

A large number of parametric calculations were completed in order to better understand the variety of performance issues which are relevant to an intelligent selection of movable insulating shutters. Note again that the term "shutter" is used generally to refer to any window covering which reduces thermal losses. Results are presented in a series of performance graphs and discussed below.

1) Effect of Increasing Thermal Resistance: Figure 4 shows the load reductions with the use of R0, R.35, R.85 and R1.7 m^2-K/W (R0, R2, R5 and R10 hr-ft^2 F/Btu) shutters for single- and double-glazed prime windows as a function of window-to-floor area ratio. In this figure, it is assumed that the shutters do not reduce the prime window infiltration rates and that they are deployed 12 hours/day (6 P.M. to 6 A.M.). Savings for insulating shutters with R greater than .85 m^2-K/W (5 hr-ft^2-F/Btu) diminish rapidly and would be even smaller in less severe climates. Cost and thermal resistance figures are being gathered for several devices now on the market to examine their relative cost effectiveness.

   Double-glazing without an insulating device is preferable to most single-glazing with shutter combinations. This results from the severe nature of the Minneapolis climate in which the daytime thermal losses are very substantial. Thus, double-glazing with a resistance of R.35 (R2) for 24 hours/day is preferable to single-glazing with R.17 (R1) for 12 hours and R1.2 (R7) (single-glazing plus an R.85 (R5) shutter) for 12 hours. In milder climates where daytime winter temperatures rise sharply above night average temperatures, the single-glazing with night shutter is a better choice than the double-glazing without shutter.

   Even with the best shutters, single-glazing (evenly distributed on the four building sides) results in increased loads as glass area is increased. The slight upward curvature of the graphs results from the decreasing useful solar gain contribution of each incremental glass area. In addition, although the conduction loss per unit area is constant, the infiltration loss per unit area decreases slightly as glass area is increased, due to the decreasing ratio of glazing perimeter to glazing area. With double-glazing, beyond about R1.7 (R10) the net contribution of incremental glass area is zero, i.e., gains and losses balance. With further increases in shutter R value, total building energy consumption would then drop with increasing window area.

   Imperfect operation of the shutters (i.e., leaving them open at night) will increase loads beyond those shown here for the idealized case of "automatic" operation. Conversely, more intelligent operation may reduce loads further. Shutters might be closed all day and night on east-west and north elevations on particularly cold and cloudy days. Some increase in lighting energy consumption would be expected but in a house with low daytime occupancy this would probably not offset savings. If one assumes that failure to operate the shutters properly occurs in a statistically random manner, the degradation of performance can be estimated from the graph. For a given window area, first estimate the differential load between the curve with the desired shutter R value and the non-shuttered glass case. Failure to operate the shutters properly 25% of the time (or failure to close 25% of the total number of window shutters in a house) would thus increase the load by 25% of that estimated differential. This is illustrated in more detail in Figure 8.

2) Effect of Glass Orientation: For a glass distribution that favors south (50% south, 20% east, 20% west, 10% north) the clusters of curves shown in Figure 4 are generally shifted lower as shown in Figure 5. For the unshuttered cases the typical savings relative to evenly distributed glass (Fig. 4) are approximately 341,000 kJ/m^2-yr (30,000 Btu/ft^2-yr) for single glazing and 273,000 kJ/m^2-yr (24,000 Btu/ft^2-yr) for double glazing. These savings are given per square meter of all glass in the building so that the actual savings per square meter for glass shifted to the south are much higher as one would expect since the majority of glass shifted was moved from north to south. Note that even the orientation averaged glazing shown in Figure 4 shows a winter solar gain of about 795,000 kJ/m^2-yr (70,000 Btu/ft^2-yr) which helps to offset the somewhat larger thermal losses.

The case of very large south glass area resulting from the higher window-to-floor ratios must be examined carefully from an architectural and thermal comfort perspective. In the present house model with little exposed thermal mass this large south glazed area would tend to overheat the space, particularly in the milder swing seasons. Well developed techniques exist in the passive solar heating literature for sizing thermal storage to available glass area. A properly designed passive system would make better use of daytime solar gains for subsequent use at night and reduce heating loads below those reported here. Subsequent work will examine and compare these simple non-mass cases to a proper passive solar design.

Several additional interesting comparisons may be made between results for uniform glass distribution compared to those where the distribution favors a southerly orientation. Starting with an assumption of uniform distribution of single glazing for a given window-to-floor ratio, we can ask: how can we best reduce building losses by altering the windows? As mentioned earlier, adding any insulating shutter (which does not alter the windows' air leakage characteristics) for 12 hours per night will still not attain a performance equal to that of double-glazing. However, if window area is shifted from north to south, single-glazing plus an R.35 (R2) shutter will result in an annual building heat loss approximately equal to double-glazing for the uniformly distributed glass case. The increased gain per square foot obtained by shifting orientation plus the use of a modest shutter at night is equal to the reduction in heat loss obtained by shifting from single to double-glazing in the case of uniform window distribution. Quantitatively, we seek to minimize the sum

$$\sum_{\substack{\text{Heating}\\ \text{Season}}} (U_w \times HDD_d + U_{w+s} \times HDD_n - Q_{solar})$$

where U_w and U_{w+s} are U values of the window and window-shutter combination respectively; HDD_d and HDD_n are heating degree days during the day (no shutter) and night (shutter) respectively; and Q_{solar} is the solar gain for a specific orientation.

The choice of glazing type and shutter type may reduce U_w and U_{w+s} whereas a change in orientation will alter Q_{solar}. The relative importance of these options (which are not mutually exclusive) will depend upon location and climate. Since the change in net heat load per unit window area is approximately linear as shown in Figures 4 and 5, a simple comparison of the relative slopes identifies the most advantageous strategy.

3) Effect of Air Leakage Rates: The effect of air leakage rates on the performance of movable insulating devices is shown by some representative results in Figure 6 for single-pane and Figure 7 for double-pane windows. Three different air leakage scenarios are examined. In case 1 (labeled "100%" leakage) it is assumed that the application of a movable insulating device has no effect on the air leakage rate previously described (1.0 ach for 15% window-to-floor ratio and 1.15 ach for 40% window-to-floor ratio). For case 3 (labeled "0%" leakage) we assume a perfectly tight seal on the shutter which eliminates all window air leakage when the shutters are deployed. Case 2 is the intermediate situation where the shutters, when deployed, reduce the nominal air leakage rate by 50%.

The results show the importance of considering air leakage characteristics as well as thermal resistance in selection of movable insulating devices. In Figure 6, an R.35 (R2) shutter which reduces air leakage by 50% is seen to be as effective as an R.85 (R5) shutter which has no impact on air leakage. Similarly, a tightly sealed R.35 (R2) shutter (no leakage) performs as well as an R.85 (R5) shutter which reduces leakage by 50% or an R.17 (R10) shutter with no impact on air leakage. Thus in selection of movable insulation, great care should be taken to determine the relative importance of shutter thermal resistance and air leakage rates.

The figures also provide a quantitative estimate of the heating loads attributable to air leakage in windows based upon the rates selected and the nature of the DOE-1.4 infiltration algorithms. For example, tight shutters for large window areas (operating 12 hours/day) reduce heating loads by approximately 227,000 kJ/m^2-yr (20,000 Btu/ft^2-yr). If we make the simplifying assumption that the average wind velocity during the day and night are equal, then window air leakage contributes about 454,000 kJ/m^2-yr (40,000 Btu/ft^2-yr) to the building loads. This is substantially less than conductive/convection losses alone (2,385,000 kJ/m^2-yr (210,000 Btu/ft^2-yr) for

single, 1,294,000 kJ/m^2-yr (114,000 Btu/ft^2-yr) for double, based on a simple degree day model) but it is an appreciable fraction of the net losses of managed window systems. In absolute magnitude it represents approximately 10% of the entire building heat loss for the case of large double glazed windows with R.85 (R5) shutters (Figure 7).

Two notes of caution must be added concerning conclusions drawn from Figures 6 and 7. First, additional work is required to improve the modeling of infiltration in building simulations. Second, this analysis of window management strategies assumes that the conductive loss and air leakage losses are separable and operate in parallel whereas this will not generally be the case. Additional laboratory and field testing is required to better define these interactions. Despite these uncertainties it is apparent that air leakage characteristics of window-shutter systems are significant determinants of overall thermal performance.

4) Probability and Timing of Use of Movable Insulation: Analyses resulting in Figures 4-7 assume that the insulating shutters are in use 12 hours/day (6 P.M. to 6 A.M.) on all windows and that they are operated correctly at all times. In practice, some movable insulating devices may not be moved at the proper time or at all. In Figure 8 we simulate the effect of varying hours of usage (6 P.M. to 6 A.M and 12 midnight to 6 A.M.) for an R.35 (R2) shutter with single- and double-glazing.

Two additional curves show the projected loads if shutters are properly closed only 75% of the nights or 50% of the nights. Note that this is essentially equivalent to closing shutters on 75% or 50% of the windows in the house on a given night. In reality, the thermal effect of proper use of shutters will vary from night to night depending on which shutter is not operated for what duration on a given night.

Several observations can be made. The hours of use have a major influence on total energy consumption. Reducing the hours by 50% (from 12 hrs/day to 6 hrs/day) reduces the savings by slightly less than half because the coldest hours still lie in the shuttered time period (midnight to 6 A.M.). Missed operation (which occurs on a random basis) will reduce overall savings proportionately as shown in the case of double-glazing 12 hours/day use. Since faithful operation is essential to realizing energy savings, shutter design and operation must be developed with ease of use as a key parameter. To reiterate, a simple device with low R value, used conscientiously, will outperform a shutter with higher R value which might be more complex and time-consuming to deploy, thus inhibiting its routine use.

If shutters are inadvertently left closed during the day, they may increase energy consumption by blocking the entry of more useful solar heat than they save by reduced conduction losses. These conditions are now being studied.

The present understanding of the patterns of human use and operation of insulating shutters is extremely limited. No studies of the subject matter have been reported in the literature. Therefore, at this time the modelling of human use of shutters can only be very crude at best. An analysis of the daytime use of venetian blinds in office buildings has been started at the National Bureau of Standards[7]. Since the actual human deployment of shutters is one of the most critical factors in obtaining energy savings from insulating shutters, it is important to develop a much better understanding of the subject.

CONCLUSIONS

A comparative study of the annual heating loads for a 113 m^2 (1200 ft^2) residence in several climates has been undertaken using a modified version of DOE-1.4 which simulates the operation of a variety of window management strategies. Movable insulating devices with a range of thermal resistance , differing air leakage characteristics, and differing hours of operation have been simulated as a function of window type (single-or double-glazed), window-to-floor area ratios (15% to 40%) and window distribution (25%N, 25%E, 25%S, 25%W vs. 10%N, 20%E, 50%S, 20%W). Results are reported and discussed for a severe climate (Minneapolis).

1) Effective movable insulation can substantially reduce thermal loads from single-and double-glazed windows. The incremental energy cost of a window of average orientation can be reduced to approximately zero if R1.7 (R10) shutters are used 12 hours per day with double-glazing. Further reductions in building net energy use can be achieved

if some windows are shifted to the south and if air leakage is reduced by shutter operation.

2) For prime windows of average air tightness, tight-fitting insulating shutters save significant energy by reducing infiltration losses. A tight-fitting shutter of low R value is shown to outperform higher R shutters which do not reduce air leakage. Air leakage modeling through window-shutter combinations requires additional study.

3) Hours of operation per day and probability of shutter use have a major impact on projected heating loads. Infrequent use of movable insulation minimizes savings and suggests the use of simple but proven static energy conserving solutions such as storm windows or double and triple glazing to provide effective savings. Design and operating characteristics of movable insulating devices must be conducive to routine manual operations by building occupants.

4) Based on specific physical characteristics of movable insulating devices and product costs, analysis of this type can be used to suggest a series of window management approaches either for new construction or as a retrofit action. Conclusions and recommendations drawn for a severely cold climate may change for moderate or mild climates. Additional computer runs have been completed for other cities and will be compared in a follow-up report.

The modeling of relationships among the various factors that determine the performance of movable shutters is sometimes imperfect in the simulation model used for this study. However, any resultant error in modeling is consistent for all simulations we conducted. Thus, while the specific quantitative predictions of thermal loads obtained from these computer simulations results may be questioned in absolute terms, our simulation results are valid for the comparison of performance of different insulating shutters.

The window management model also simulates the operation of dynamically operated shading devices. Future studies will assess the impact of various window management strategies on both heating and cooling loads, and heating, cooling, and lighting in commercial sector buildings.

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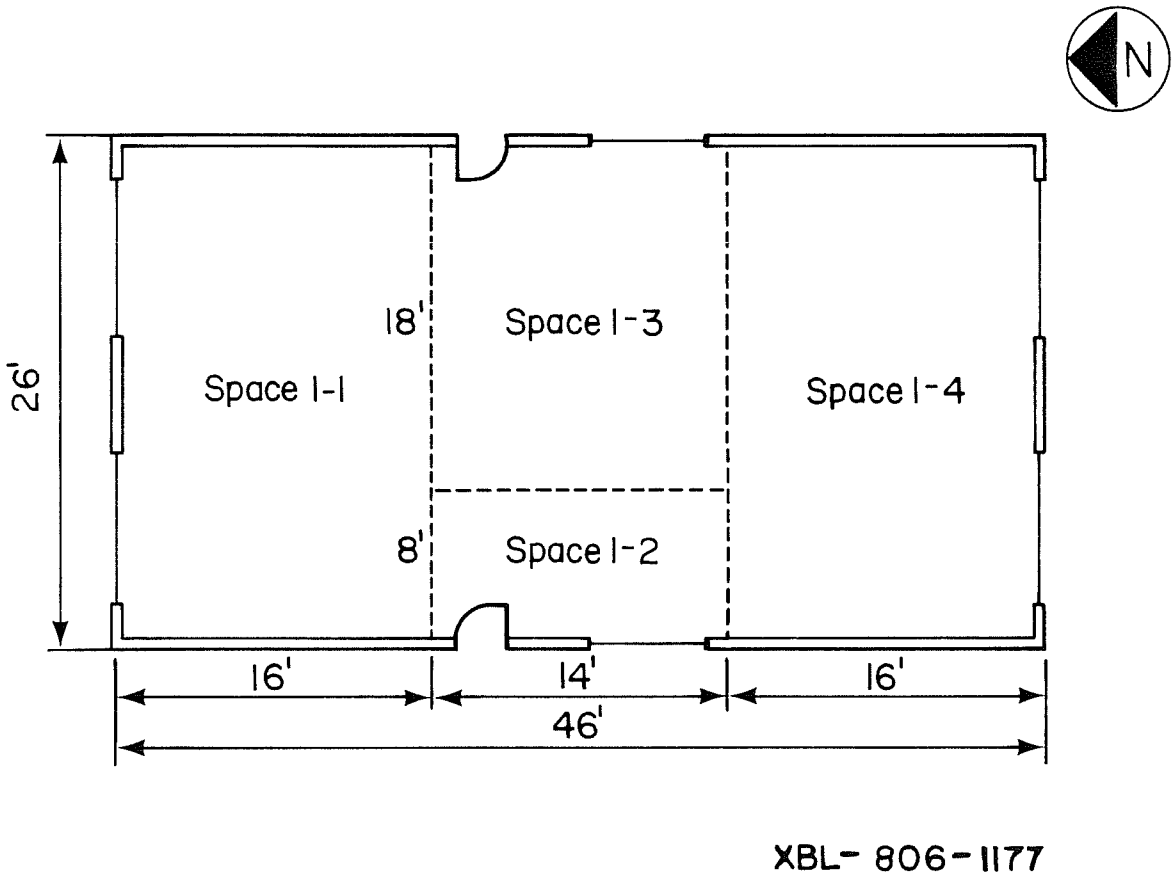

Fig. 1. Test House: Floor Plan and Thermal Zoning

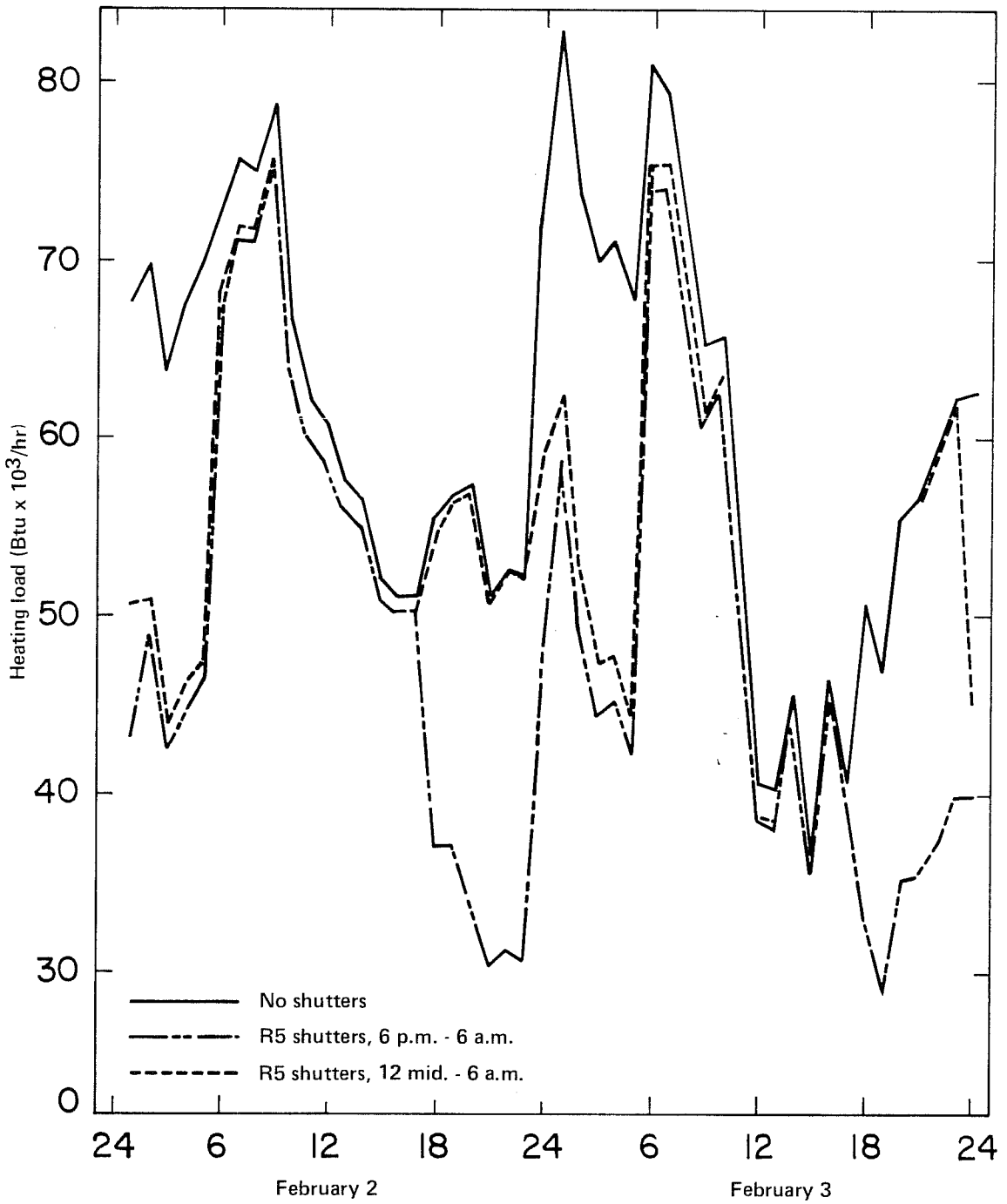

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Fig. 2. Comparison of the Effect of Use of Shutters with Single Glazing on the Building's Total Heating Load

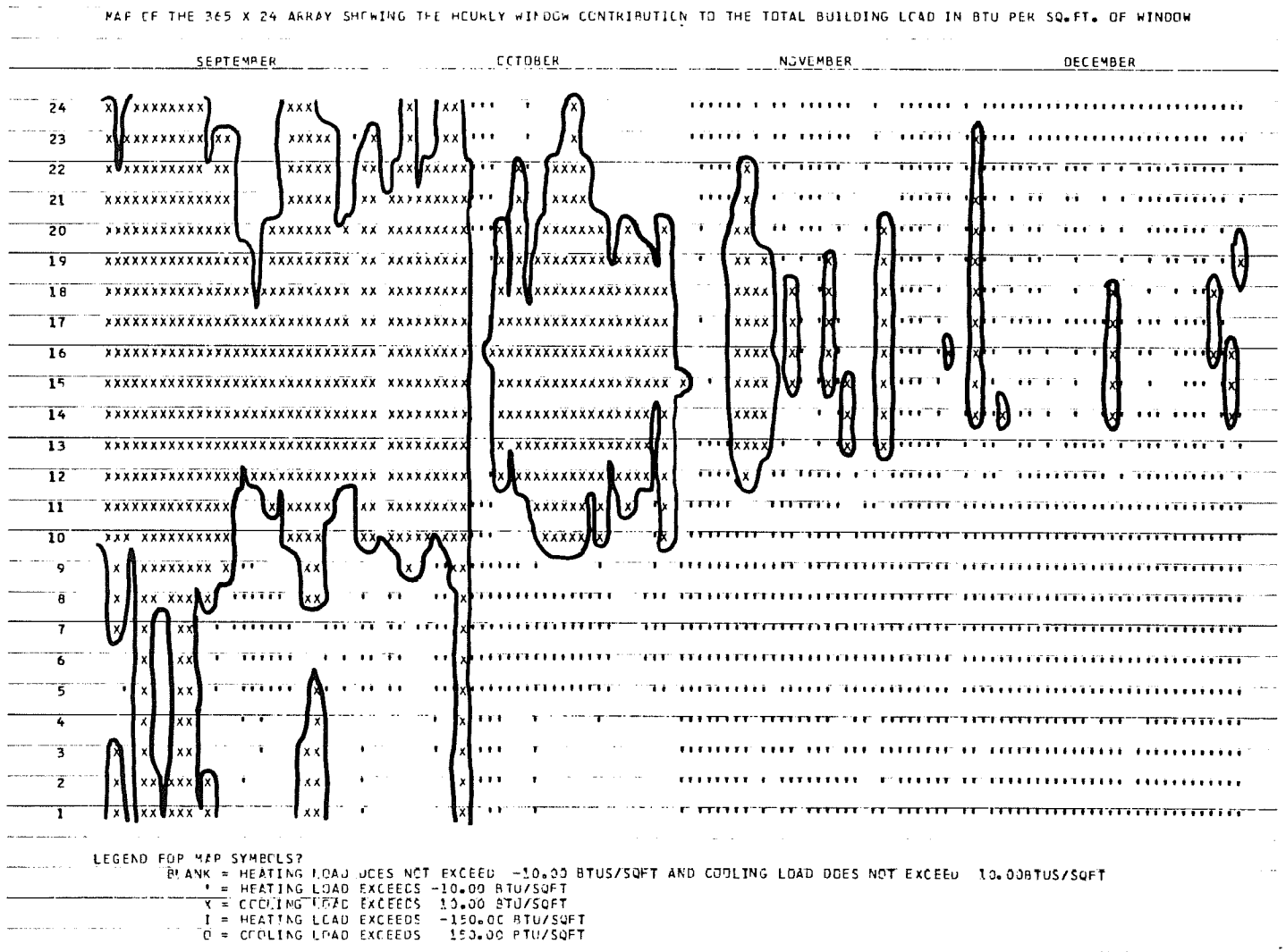

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Fig. 3. Plot of the Hourly Contribution from Windows to the Heating & Cooling Loads

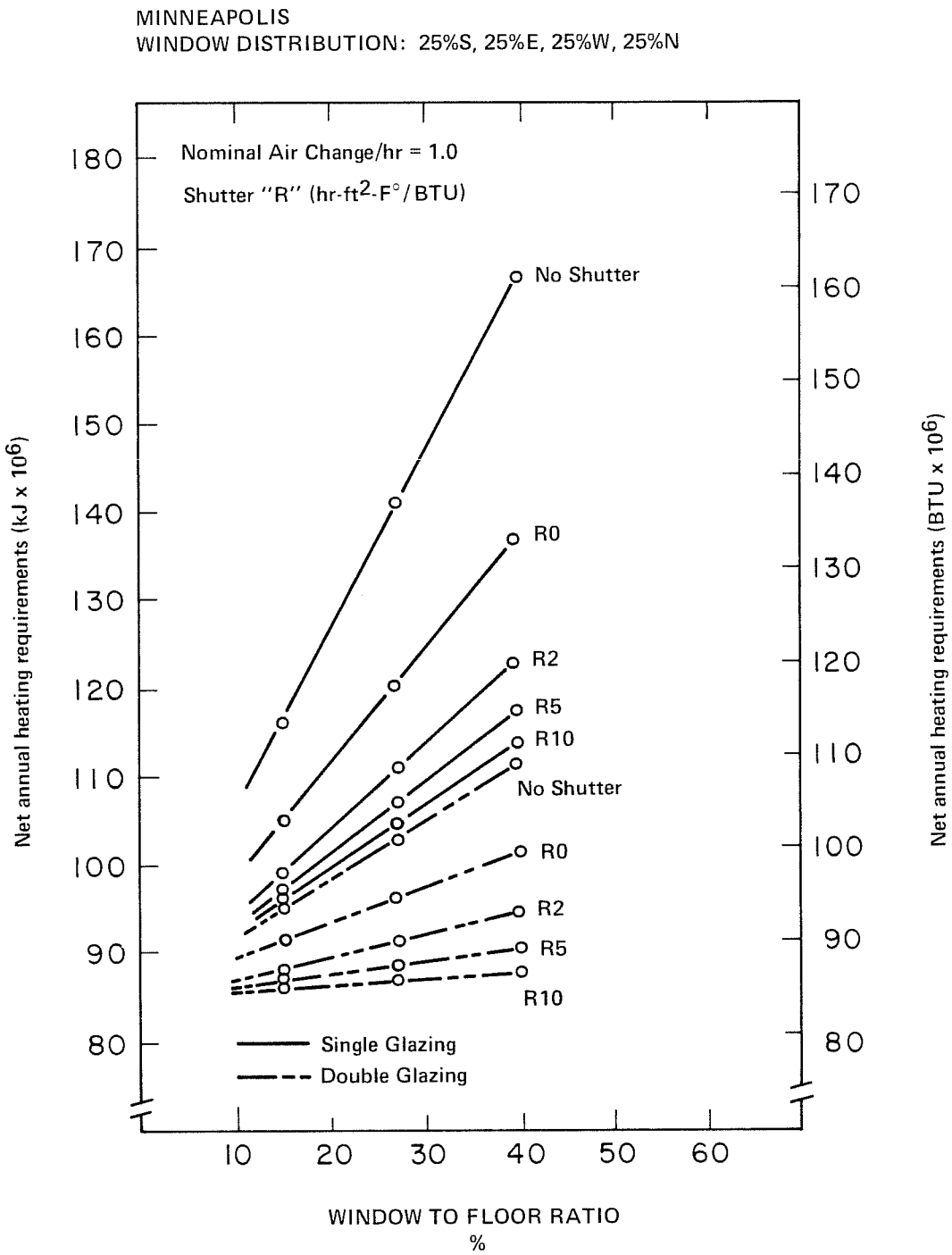

Fig. 4. Effect of Thermal Shutters on Single and Double Pane Windows Evenly Distributed on all Orientations

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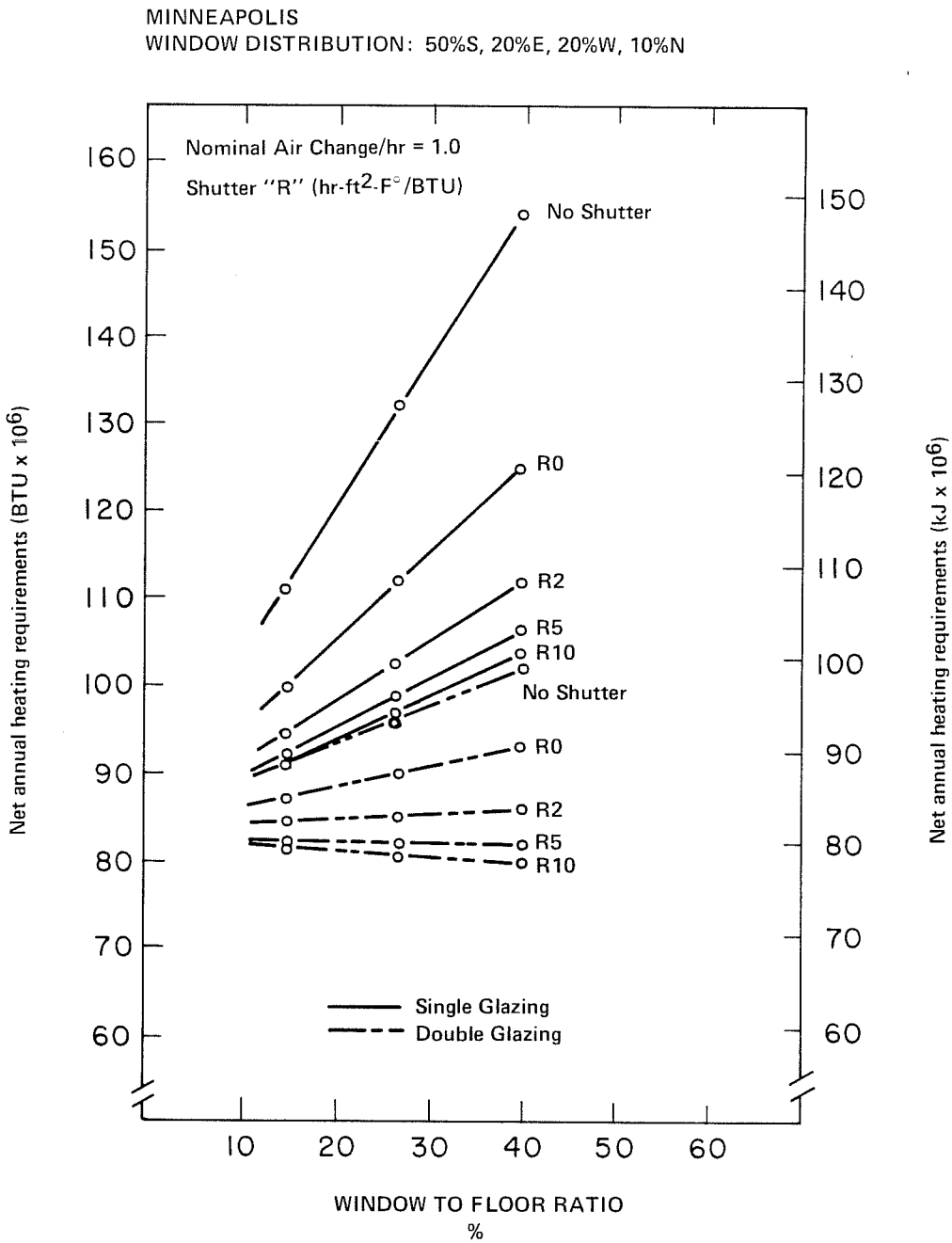

Fig. 5. Effect of Thermal Shutters on Single and Double Pane Windows Concentrated on South Elevation

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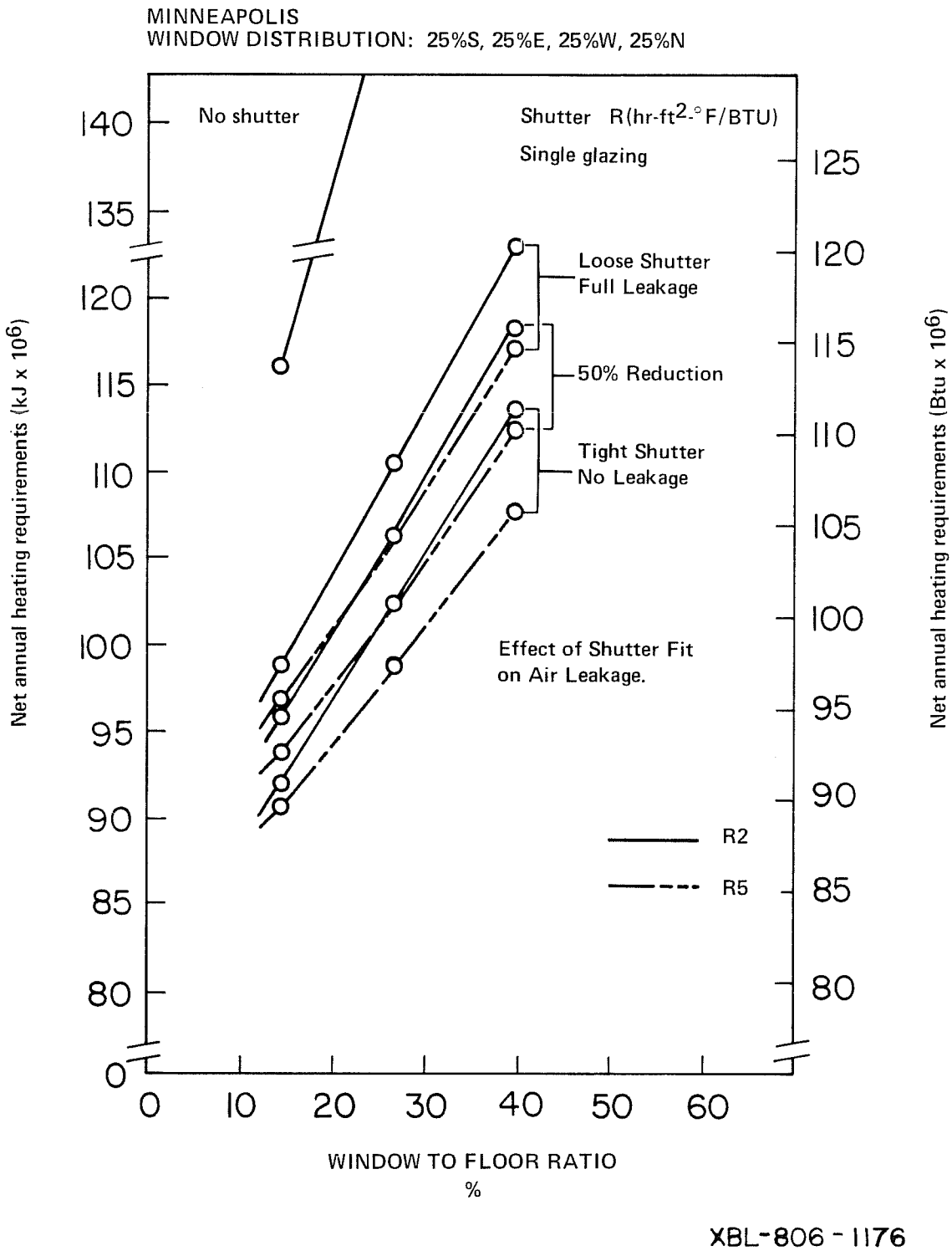

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Fig. 6. Effect of Reduced Air Leakage from Single Pane Windows

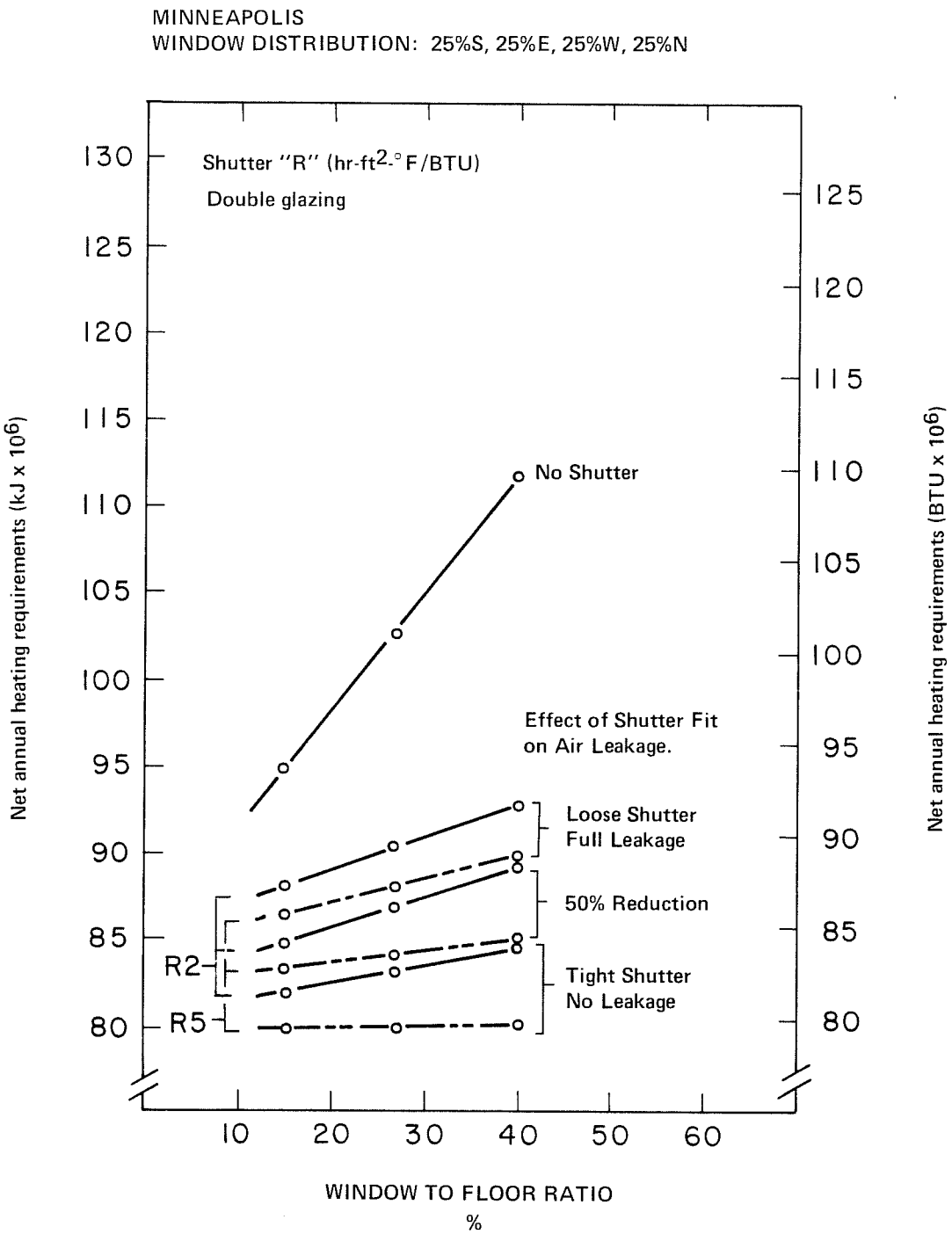

Fig. 7. Effect of Reduced Air Leakage from Double Pane Windows

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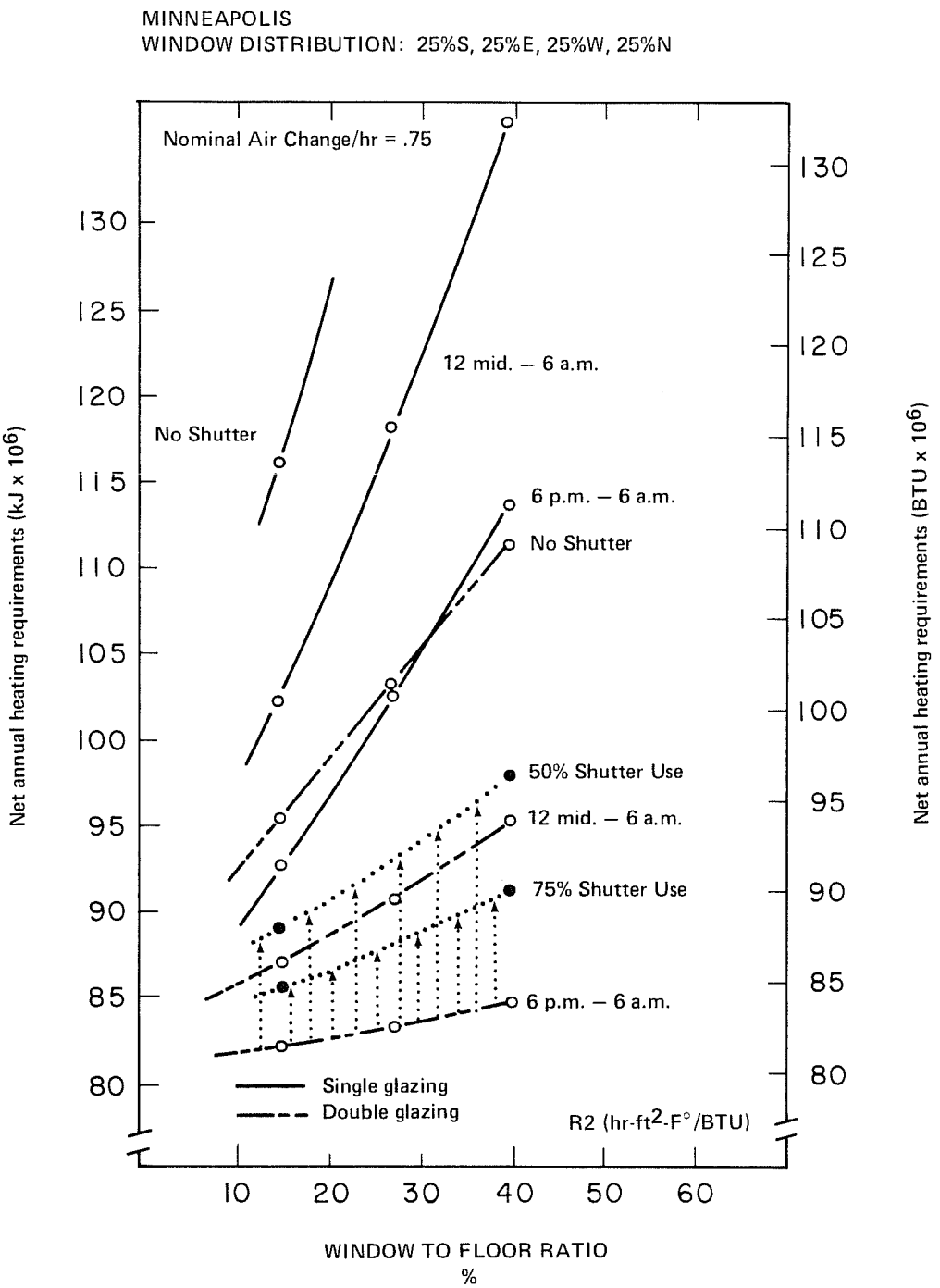

Fig. 8. Effect of Length of Operation of R2 Shutters on Single and Double Pane Windows

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