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# Evaluation of the Daylighting and Energy Performance of Windows, Skylights, and Clerestories

Prepared by:
U.S. DEPARTMENT OF COMMERCE
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Prepared for:

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**Topeka, KS 66611**

**Naval Facilities Engineering Command**
**U.S. Navy**
**Washington, DC 20390**

**Directorate of Civil Engineering**
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and

**Office of Chief of Engineers**
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**Washington, DC 20314**

June 1983

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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# EVALUATION OF THE DAYLIGHTING AND ENERGY PERFORMANCE OF WINDOWS, SKYLIGHTS, AND CLERESTORIES

Stephen Treado, Gary Gillette, Tamami Kusuda

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**U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary***
**NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director***

ABSTRACT

This paper examines the impact of several fenestration options on building space heating, cooling, and lighting loads. The use of skylights, windows, and clerestories is evaluated for a single floor commercial building, using the NBSLD-2 building energy analysis computer program, which posesses a fully integrated daylight model (DALITE). The evaluation focuses on:

a) the impact of daylighting on heating and cooling energy requirements,

b) the potential reduction in electric lighting energy requirements through daylight utilization,

c) the relative daylighting/thermal performance of skylights, clerestories, and windows, and

d) the effect of aperture orientation on fenestration optimization and selection.

The NBSLD-2 computer procedure performs a dynamic simulation of hour-by-hour building thermal performance and energy requirements for a one-year period. The thermal and daylighting characteristics of each fenestration aperture are modeled to enable evaluation of the trade-offs associated with the use of each fenestration type. The results are presented in the form of design guidelines to enable the preliminary design decisions to be made regarding fenestration location, type, configuration, and size. The energy calculations are presented as functions of fenestration characteristics, so that the potential energy advantages can be estimated for different fenestration designs.

Key words: building energy analysis, clerestories, daylighting, skylights, windows.

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## 1. INTRODUCTION

Commercial buildings consume energy primarily in three ways: for heating, cooling, and lighting. When designing a building, various trade-offs among these three must be considered regarding the selection and sizing of fenestration, lighting, equipment, and HVAC systems [1]. Fenestration systems, including windows, skylights, and clerestories, influence building energy requirements also in three main ways. They transmit solar radiant energy, they provide daylight illumination, and they transmit heat by conduction/convection. However, fenestration in buildings has usually been associated with increasing heating loads due to conduction and convection, and increasing cooling loads due to solar gains, with little thought of the decreasing lighting loads and cooling loads possible due to daylighting. The determination of the net effect of a fenestration system requires that the impact of the system on the combined heating, cooling and lighting loads and energy use be examined on an annual basis. This requires the use of a building energy analysis computer program with integrated daylight modeling capabilities. We have chosen to use the NBSLD-2 computer program which has such an integrated daylighting model [2,3]. Other researchers have examined the daylighting and energy performance of fenestration systems [4,5,6], however, the question of relative performance of different sidelighting and toplighting fenestration designs has not been addressed.

The NBSLD-2 computer program is used to perform a dynamic simulation of hour-by-hour building thermal performance and energy requirements for a one-year period. The thermal and daylighting characteristics of several fenestration apertures are modeled to enable evaluation of the trade-offs associated with the use of each fenestration type.

NBSLD-2 is an updated version of the NBSLD building energy analysis computer program. The unique features of the program include a completely coupled hour-by-hour daylight simulation capability to enable evaluation of the performance of windows, skylights and clerestories for all types of sky conditions. The daylighting algorithms have been validated against measured data for a variety of fenestration designs and exterior daylight conditions [3].

The purpose of this paper is to examine the impact of different fenestration options on building energies. Thirty-one options are compared, both with and without daylighting, from six main groups:

I) No fenestration.

II) South facing windows (10, 25, and 50 percent of south wall area).

III) North facing windows (10, 25, and 50 percent of north wall area).

IV) South facing clerestories (10, 25, and 50 percent of south wall area).

V) North facing clerestories (10, 25 and 50 percent of north wall area).

VI) Skylights (2, 5, and 10 percent of roof area).

The analysis was performed using Washington, DC, Test Reference Year (TRY) [7] weather data, since Washington has both significant heating and cooling loads.

Throughout the report, the term "non-daylighting case" is frequently used. By this term, it is meant that daylight is not used to offset electric lighting, even if the building has fenestration which admits daylight. A building without fenestration is a special case, since no potential exists for daylight utilization.

## 2. BACKGROUND

A simple building design was chosen for the analysis, consisting of a detached, one-story, 2500 square foot (232 $m^2$), commercial building. Different fenestration systems were added to the building and the annual energy requirements for heating, cooling, and lighting were determined for each case. The energy requirements were determined by modeling the performance of a simple HVAC and lighting system responding to the calculated heating, cooling, and lighting loads. The HVAC system modeled included a gas furnace and a packaged air conditioner, serving a single zone.

Several factors were considered before choosing this type of building design for evaluating the thermal and lighting performance of fenestration systems. First, it has been found that 58 percent of the total U.S. nonresidential building stock, including 71 percent of the commercial buildings built since 1945, are single storied, and that a large portion of these are relatively small buildings [8]. Furthermore, during the initial design phase, detailed information concerning the building construction is usually not available; consequently, the building should be as generic as possible. In fact, construction details are normally not selected until after the envelope is determined, which, in this case, involves the selection and sizing of the fenestration. Second, since the purpose of the analysis is to evaluate the relative performance of several fenestration options, it is important to have a building configuration which lends itself to side and overhead fenestration indiscriminantly. In addition, it is desirable at this stage of design to consider in detail only those factors which influence the thermal and daylighting performance of the fenestration. This approach will minimize the influence of a particular HVAC system or component on the energy calculations, since the HVAC system can be specified or changed following selection of the fenestration design. Once the fenestration and building envelope design are determined, a more detailed analysis of the HVAC system can be performed to facilitate calculation of energy consumption.

Although the simulated building model need not be excessively detailed, it must include all factors which influence fenestration thermal and daylighting performance. Thus, the thermal resistance and thermal mass of the building envelope, and the geometry of the building components must be carefully modeled. In addition, decisions or assumptions must be made regarding the number of building occupants, the use of office equipment, the building occupancy schedule, the HVAC system control strategies, and, most importantly for our case, the lighting system design.

There are two approaches to modeling the lighting system for the purpose of evaluating fenestration performance. One would be to specify a particular lighting system including luminaire type and its particular photometrics, and for the daylighting case, control strategy and control sensor location. A separate calculation would then be made to determine the illuminance levels due to the electric lighting at the points of interest within the building. While this approach provides detailed information concerning the performance of that particular lighting system, it has the disadvantage of tying the analysis to a single lighting system. That would be appropriate at a later design stage when the details of the lighting system would be known, but at the preliminary design stage, one is seeking to determine the required performance characteristics of the lighting system, and would benefit from a more general approach.

Thus, an alternate approach is used to model the lighting system. A lighting power budget is specified in terms of watts/area, and a general (uniform) lighting system is assumed which would exactly meet the budget at the required illuminance level. In this manner, different lighting systems could be specified based on the performance parameters.

When dimming of the lighting system is modeled in the analysis, it is assumed that the illumination set point is just met when the lighting system is at full power (with no daylight contribution). Thus, any contribution of daylight illuminance results in a corresponding decrease in illuminance from the lighting system. In practice, this would be achieved if the maximum output of the lighting system was adjusted so the work-plane illuminance was at the set-point. The change in lighting power consumption associated with the change in illuminance is not, in general, linear and is determined from a dimmer performance curve (light output vs. power consumption) [9]. Most dimming systems have similar performance curves. The computer model includes a typical dimmer performance curve. It should be noted that the glare conditions and other psychophysical parameters are not included in the analysis. Griffith [10] has noted that the direct glare analysis methods presently in use are not valid for cases where daylighting is coupled with electric lighting, as used here, and Hopkinson [11] has observed that even when they are valid they do not necessarily represent glare problems. Therefore, excluding such an analysis should not be considered a severe weakness.

The details of the building and the operating parameters are contained in the following section.

## 2.1 THE BUILDING

A single floor commercial building in Washington, D.C. is modeled for the analysis. The building is shown in figure 1 and its operating conditions are described in Tables 1 through 3. Table 1 lists a basic description of the building characteristics. Table 2 lists the sizes and construction details of the building envelope components. Table 3 lists the building and HVAC operating parameters, assumptions, and preliminary design choices, used for the analysis.

The assumptions used are representative of modern practice. The building envelope thermal properties meet ASHRAE 90-80 standards for Type B buildings. The wall, floor and roof construction details are typical. The HVAC system controls utilize night-time setback, and the lighting system requires 2.5 watts per $ft^2$ (26.9 watts per $m^2$) when fully energized. A gas heating furnace was simulated.

## 2.2 RESULTS AND DISCUSSION

Lighting, heating, and cooling energy was calculated for each case for a one-year period. The results are plotted for each case as a function of fenestration surface area, both for the daylighting case and for the non-daylighting case. These figures are plots of the annual electric energy, heating energy and cooling energy as a function of fenestration area, for each fenestration type.

For south-facing windows (figure 2), the 50 percent area with daylighting provided the minimum total energy use mainly due to a reduction in electric energy of 44 percent compared to the non-daylighting cases. The lowest cooling energy was also seen to occur at this configuration, indicating that the reduction in cooling energy due to decreased lighting energy more than compensated for the increase in cooling energy due to solar heat gain through the large windows. Daylighting is seen to be favorable for all window areas analyzed, and for the non-daylighting cases the no fenestration option produces the lowest total energy use. Heating energy decreases with increasing window area for both the daylighting and non-daylighting cases, while cooling energy decreases for the daylighting cases and increases for the non-daylighting cases.

Looking now at the peak loads (figure 2a), the peak demand heating load is not significantly influenced by the window area or daylighting strategy, since it occurs in winter during the early morning warm-up of the building. The peak demand cooling load exhibits more variation, with a minimum occurring for the 25 percent area daylighting case. All of the daylighting cases show lower peak demand cooling loads than any non-daylighting case.

For north-facing windows (figure 3), the minimum total energy use also occurs with the 50 percent area daylighting case. A 32 percent reduction in electric energy is seen compared to the non-daylighting case. For the daylighting cases, cooling energy decreases and heating energy increases with increasing window area. For the non-daylighting cases, both cooling and heating energy increase with increasing window area. The lowest peak demand cooling load is seen to occur with the 50 percent area daylighting case, with all of the daylighting cases producing lower peak demand cooling loads than any non-daylighting case.

For the south-facing clerestories (figure 4), the minimum total energy use occurs for the 50 percent area daylighting case, where a reduction in electric energy of 65 percent is seen. Cooling energy increases and heating energy decreases with increasing window area for both the daylighting and non-daylighting cases, however, cooling energy is much lower for the daylighting cases. Peak demand heating and cooling loads are significantly greater at the larger clerestory area for both the daylighting and non-daylighting cases. For each clerestory area, peak demand loads are less for the daylighting case than for the non-daylighting case.

For the north-facing clerestories (figure 5), the minimum total energy use also occurs for the 50 percent area daylighting case, with a reduction in electric energy of 65 percent compared to the non-daylighting case. Cooling energy decreases and heating energy increases with increasing clerestory area for the daylighting cases. This is because larger north-facing clerestories transmit little additional solar heat gain while increasing thermal losses. However, since the total energy use decreases with increasing clerestory area for the daylighting cases, the decreases in cooling and lighting energy more than offset the increases in heating energy. For the non-daylighting cases both heating and cooling energy increase with increasing clerestory areas. The lowest peak demand cooling load occurs for the 25 percent area daylighting case, while the lowest peak demand heating load occurs for the smallest clerestory areas.

Although for the skylight cases (figure 6), the minimum total energy use occurs for the 2 percent area daylighting cases, the curve is essentially flat beyond this value with a reduction in electric energy of 77 percent compared to the non-daylighting case. The minimum electric energy was produced by the 10 percent area daylighting case. However, since for the daylighting cases the cooling energy increases and heating energy decreases with increasing skylight area, the increase in cooling energy for the 10 percent area as compared to the 2 percent area more than offsets the decrease in heating and lighting energy. The skylights are so effective in reducing lighting energy that the total energy for the daylighting cases never exceeded the electric energy alone for the non-daylighting cases. The peak demand heating loads did not vary significantly, except for the 10 percent area daylighting case being larger than the others. The lowest peak demand cooling load occurred for the 2 percent area daylighting case, with the daylighting cases always lower than the non-daylighting cases.

Comparing the total energy of each of the thirty-one fenestration/daylighting options, several results are apparent. The skylights with daylighting produced the lowest total energy use, with the 2 percent area slightly better than the 5 percent area, followed by the south-facing 50 percent area window and the 25 percent area clerestories, all with daylight. Table 4 lists all 31 options studied, in order of increasing total energy use. In figure 7, the total annual building energy use is plotted for all fenestration types as a function of fenestration area, with and without daylighting. This figure clearly shows the energy-savings potential of daylight utilization, and a relative comparison of daylighting performance of different fenestration types and orientations.

## 3. CONCLUSIONS

Several conclusions can be drawn from the foregoing results. These conclusions are limited to buildings similar to the study building, namely single-floor, detached commercial buildings without movable shading or other window management devices subject to weather conditions equivalent to Washington, D.C. While the study building had no internal partitions, similar results would be expected for the skylight and clerestory cases for buildings with a few properly placed internal partitions. For a building with windows on one facade, internal partitions would have to be positioned to provide daylight for all interior zones, to enable the results of the window analyses to be applicable.

The major conclusions are as follows:

- For any fenestration area, the use of daylighting reduces total building energy as compared to the non-daylighting cases;
- Skylights are the most effective fenestration options in terms of minimizing total building energy for heating, cooling, and lighting, with between 2 percent and 10 percent of roof area performing almost equally well;
- Skylights are the most effective daylighting source of the three types studied, reducing electric energy by as much as 77 percent as compared to the non-daylighting cases;
- Clerestories are more effective than windows of the same size, both as daylighting sources and in terms of total building energy;
- South-facing clerestories and windows are more effective than north-facing ones, with the 50 percent clerestory and window areas being the most effective;
- Peak demand cooling loads are less when daylighting is used than for the non-daylighting case, for any fenestration option;
- Peak damand heating loads are not significantly influenced by the use of daylighting, but increase with increasing fenestration area;
- All of the fenestration options with daylighting are more effective than the no fenestration option, in terms of total building energy.

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Table 1. Building Description

| | |
|---|---|
| Building Location | Washington, DC<br>Lat. 38° Long. 77° |
| Building Dimensions | 50 ft (15.2 m) long<br>50 ft (15.2 m) wide<br>10 ft (3.0 m) high |
| Building Type | Single floor<br>Free-standing<br>Medium weight construction<br>No attic space |
| Building Use | Commercial |
| Building Thermal Properties | Meets ASHRAE 90-80 standards for Type B buildings (except 10 percent skylight case, which meets BOCA and Southern Building Code) |

Table 2. Building Envelope Construction Details

| Component | Area | Overall Thermal Conductance | Layer | Thickness | |
|---|---|---|---|---|---|
| | $ft^2$ ($m^2$) | $\frac{Btu}{h \cdot ft^2 \cdot F}$ ($\frac{W}{m^2 \cdot K}$) | | in. | (cm) |
| Floor | 2500 (232) | 0.133 (0.755) | | | |
| | | | Carpet & Pad | 1 | ( 2.5) |
| | | | Concrete Slab | 4 | (10.2) |
| | | | Polystyrene Insulation | 1 | ( 2.5) |
| | | | Earth | 6 | (15.2) |
| Wall | *2000 (186) | 0.155 (0.880) | | | |
| | | | Face Brick | 4 | (10.2) |
| | | | Cement Mortar | 0.5 | ( 1.3) |
| | | | Insulated Hollow Cinder Block | 8 | (20.3) |
| | | | Air Space | 0.75 | ( 1.9) |
| | | | Gypsum Drywall | 0.5 | ( 1.3) |
| Roof | *2500 (232) | 0.092 (.552) | Built-up Roofing | 0.375 | ( 1.0) |
| | | | Rigid Insulation | 2 | ( 5.1) |
| | | | Concrete Slab | 2 | ( 5.1) |
| | | | Air Space | 0.75 | ( 1.9) |
| | | | Metal Lath & Plaster | 0.75 | ( 1.9) |
| Windows | 50, 125, or 250 (5, 12, or 23) | .50 (2.84) | Double glazed clear north or south facing | | |
| Skylights | 50, 125, or 250 (5, 12, or 23) | .43 (2.44) | Double dome clear over white, insulated curb | | |
| Clerestories | 50, 125, or 250 (5, 12, or 23) | .50 (2.84) | Double glazed clear north or south facing | | |

* Assuming no fenestration

Table 3. Parameters Used for Analysis

| | | | |
|---|---|---|---|
| 1) | Thermostat Set-Points | min. 60°F (15.6°C) | Unoccupied |
| | | min. 68°F (20.0°C) | Occupied |
| | | max. 78° (25.6°C) | Occupied |
| | | max. 85° (29.4°C) | Unoccupied |
| 2) | Occupancy Schedule | hours 1-6 | Unoccupied |
| | | hour 7 | 50% occupied |
| | | hours 8-17 | 100% occupied |
| | | hour 18 | 50% occupied |
| | | hours 19-24 | Unoccupied |
| | | weekends | Unoccupied |
| | | holidays | Unoccupied |
| 3) | Number of Occupants | 20 | |
| 4) | Office Equipment | 0.25 watts per $ft^2$<br>2.69 watts per $m^2$ | |
| | | 625 watts total | |
| 5) | Lighting | 0.25 watts per $ft^2$<br>2.69 watts per $m^2$ | Fixed |
| | | 2.5 watts per $ft^2$<br>26.9 watts per $m^2$ | Primary fluorescent luminaires controlled in five banks |
| | | | 100% lighting power dissipated as heat to interior space |
| 6) | HVAC system | | Heating furnace 80% efficiency |
| | | | Cooling COP = 3.0 |

Table 4

Total Building Energy

| Rank | Fenestration | Area | Daylighting? | Total Building Energy |
|---|---|---|---|---|
| 1 | Skylights | 2% | Y | 13718 kwh |
| 2 | Skylights | 5% | Y | 13929 |
| 3 | Skylights | 10% | Y | 14853 |
| 4 | Clerestories, south | 50% | Y | 19065 |
| 5 | Clerestories, north | 50% | Y | 19893 |
| 6 | Window, south | 50% | Y | 21035 |
| 7 | Clerestories, south | 25% | Y | 22008 |
| 8 | Clerestories, north | 25% | Y | 22748 |
| 9 | Window, north | 50% | Y | 24426 |
| 10 | Window, south | 25% | Y | 24631 |
| 11 | Clerestories, south | 10% | Y | 26091 |
| 12 | Clerestories, north | 10% | Y | 26483 |
| 13 | Window, north | 25% | Y | 27827 |
| 14 | Window, south | 10% | Y | 28732 |
| 15 | Window, north | 10% | Y | 30421 |
| 16 | None | 0% | N | 32125 |
| 17 | Window, south | 10% | N | 32312 |
| 18 | Window, north | 10% | N | 32408 |
| 19 | Window, south | 25% | N | 32701 |
| 20 | Skylights | 2% | N | 32734 |
| 21 | Window, north | 25% | N | 32780 |
| 22 | Clerestories, south | 10% | N | 32856 |
| 23 | Clerestories, north | 10% | N | 32947 |
| 24 | Window, north | 50% | N | 33407 |
| 25 | Skylight | 5% | N | 33685 |
| 26 | Window, south | 50% | N | 33687 |
| 27 | Clerestories, north | 25% | N | 34195 |
| 28 | Clerestories, south | 25% | N | 34864 |
| 29 | Skylight | 10% | N | 35486 |
| 30 | Clerestories, north | 50% | N | 36371 |
| 31 | Clerestories, south | 50% | N | 39607 |

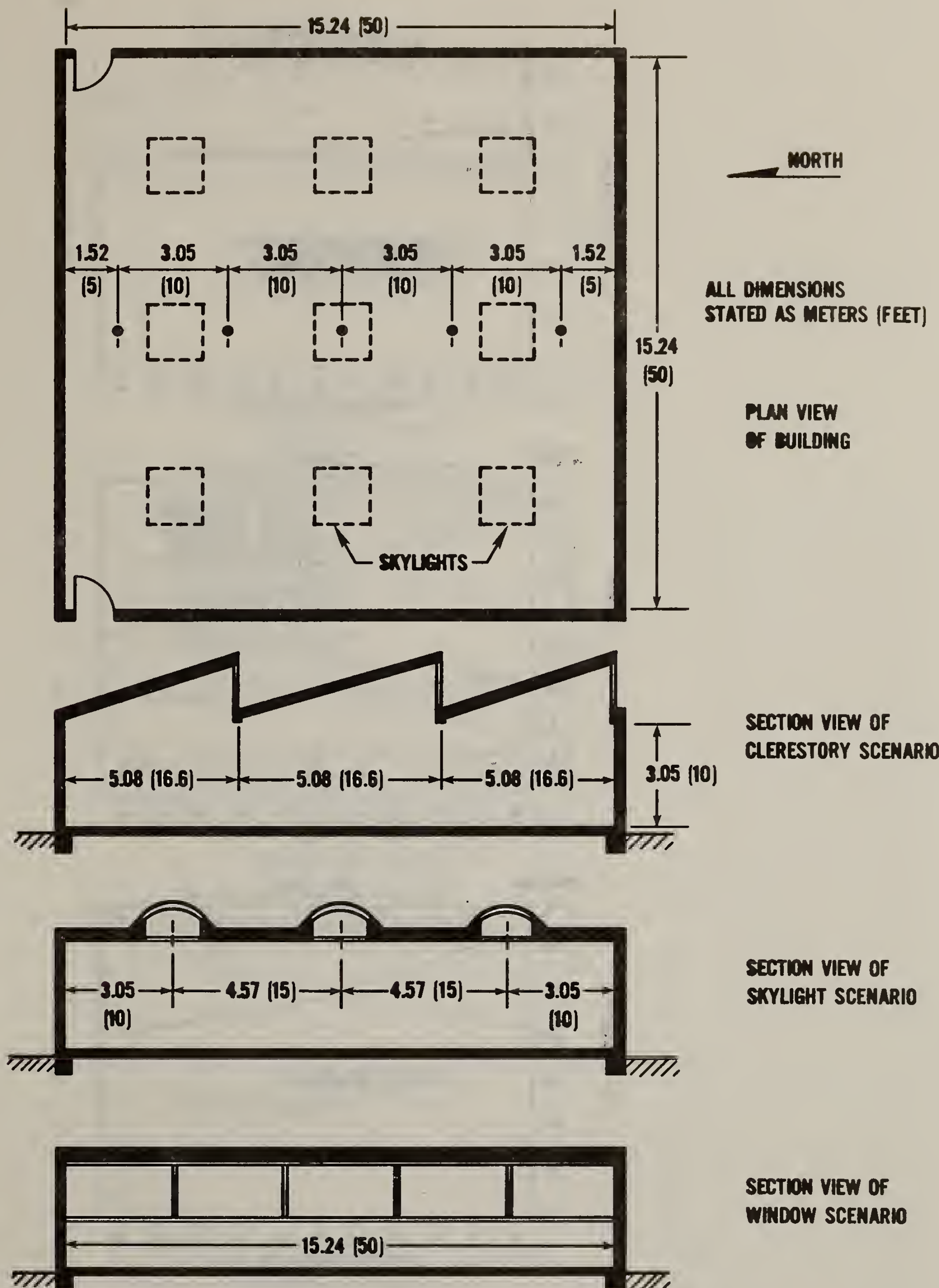



Figure 1. Layout of the fenestration for the window, clerestory and skylight cases

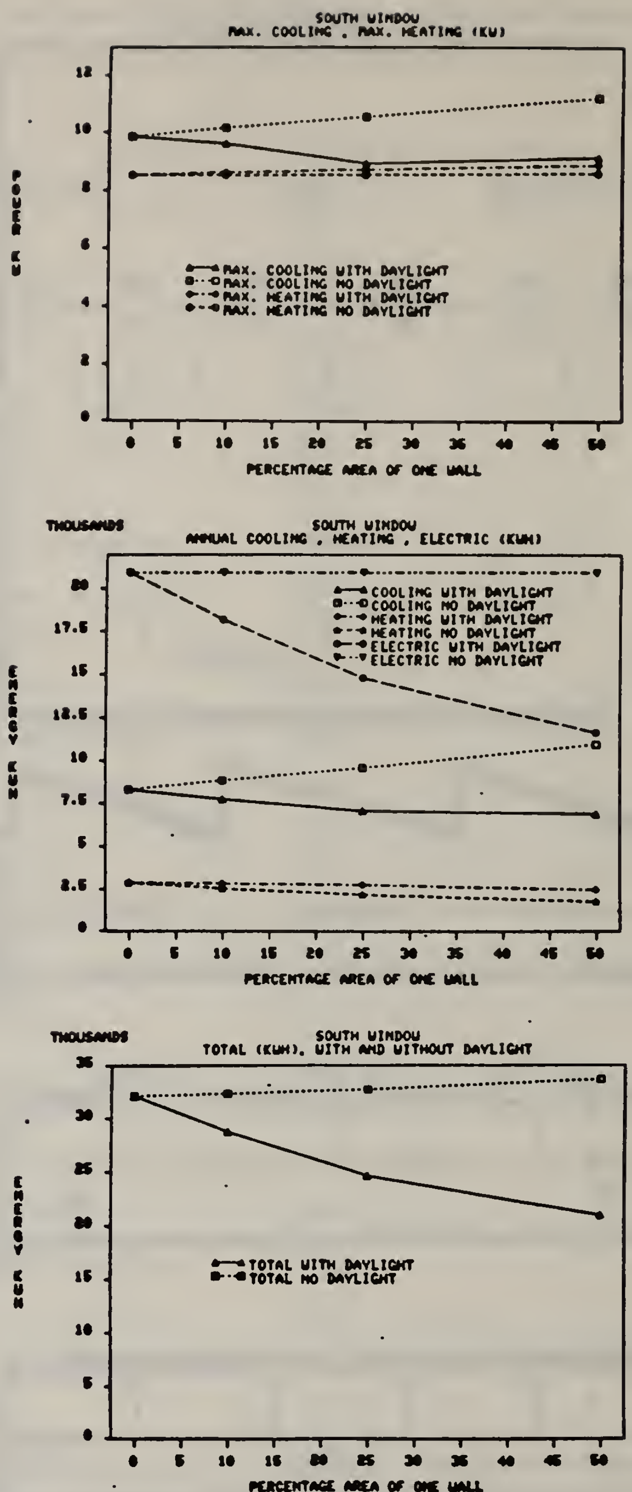



Figure 2. Energy performance of south-facing windows

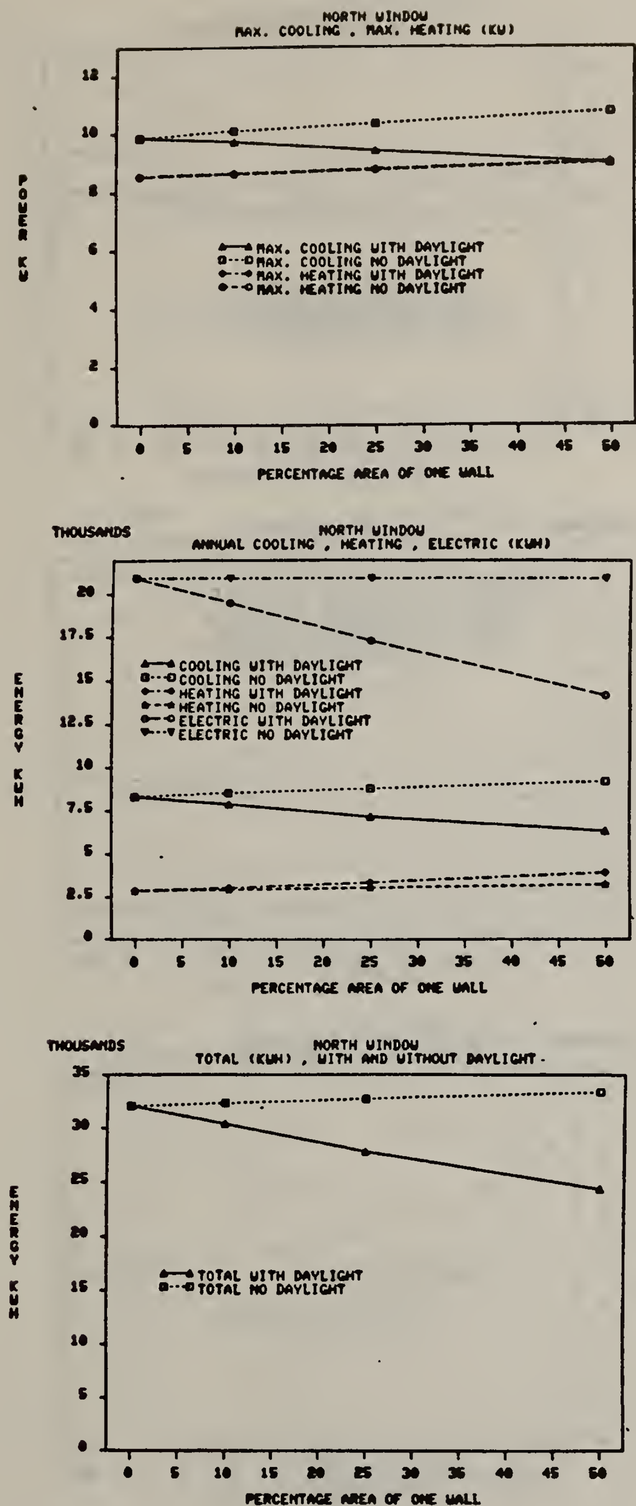



Figure 3. Energy performance of north-facing windows

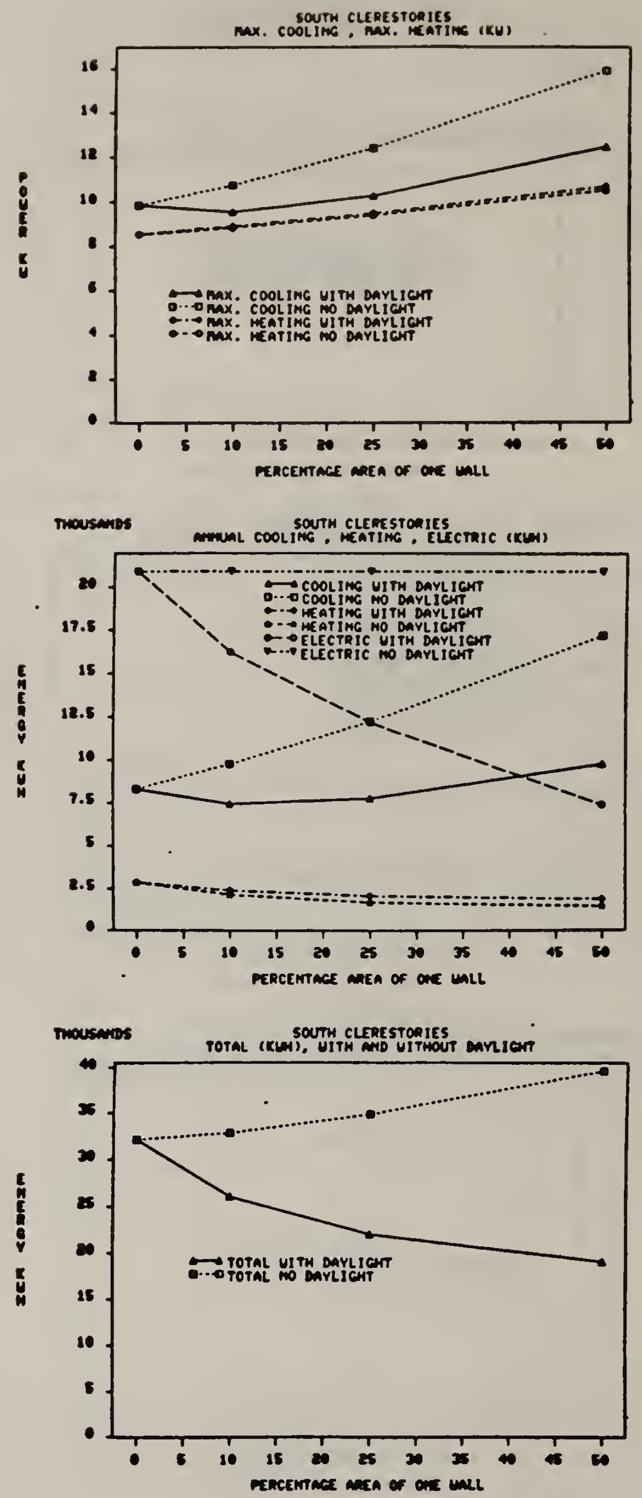
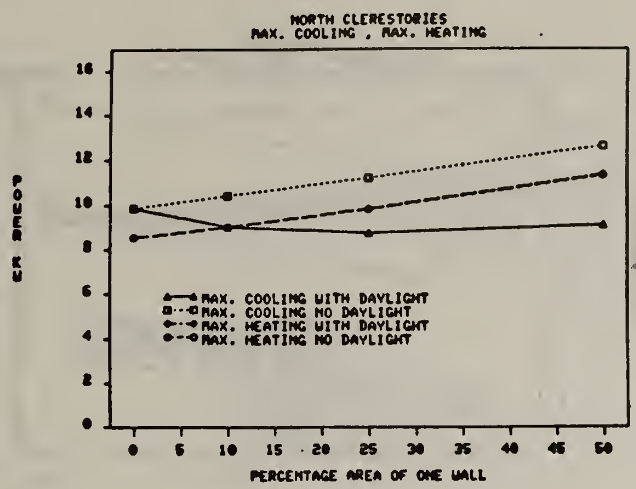
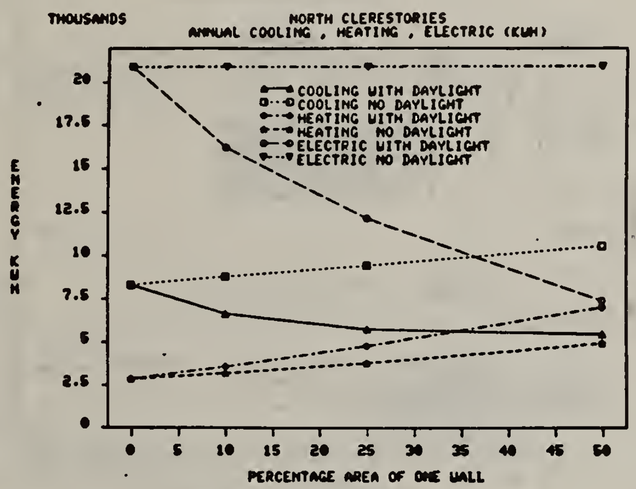



Figure 4. Energy performance of south-facing clerestories



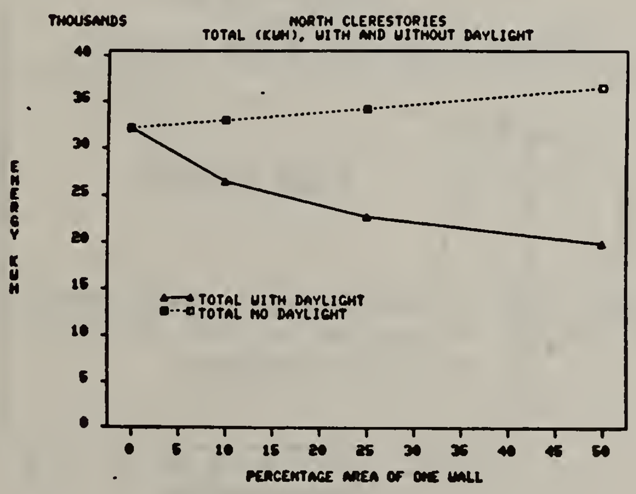




Figure 5. Energy performance of north-facing clerestories

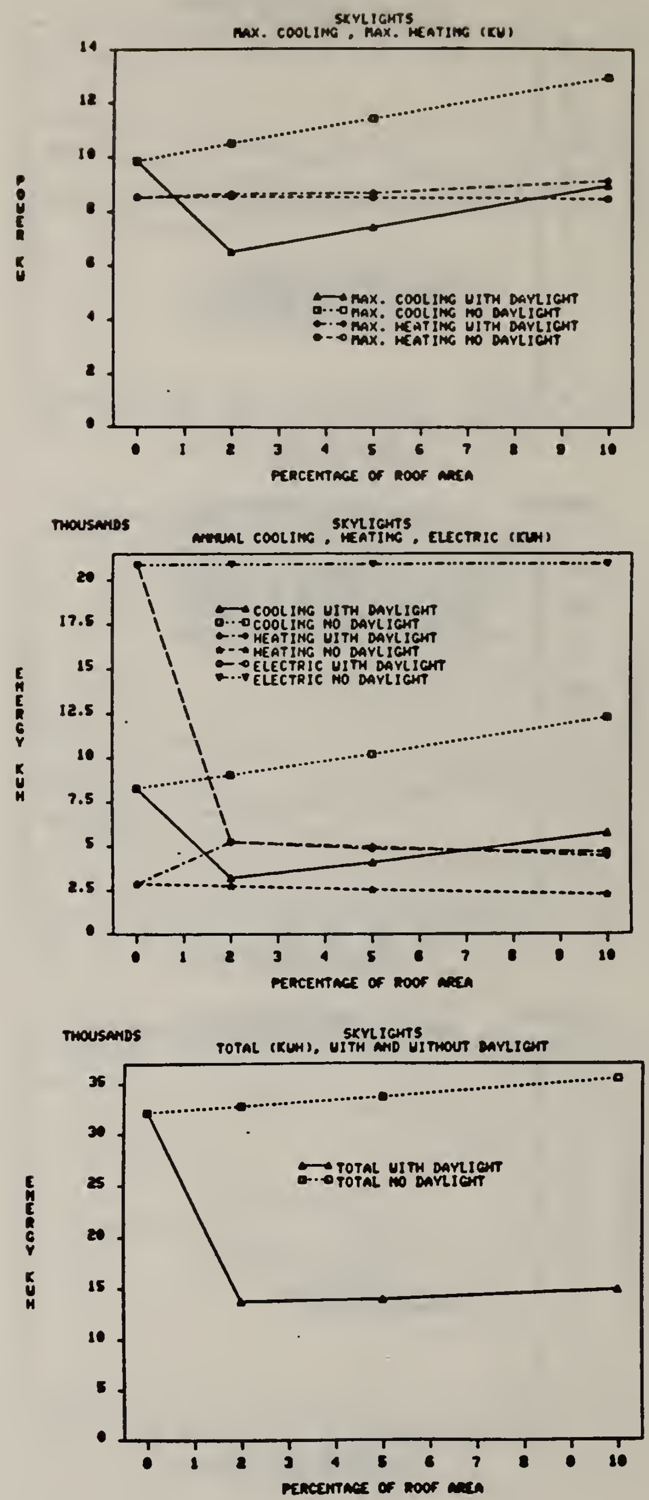



Figure 6. Energy performance of skylights

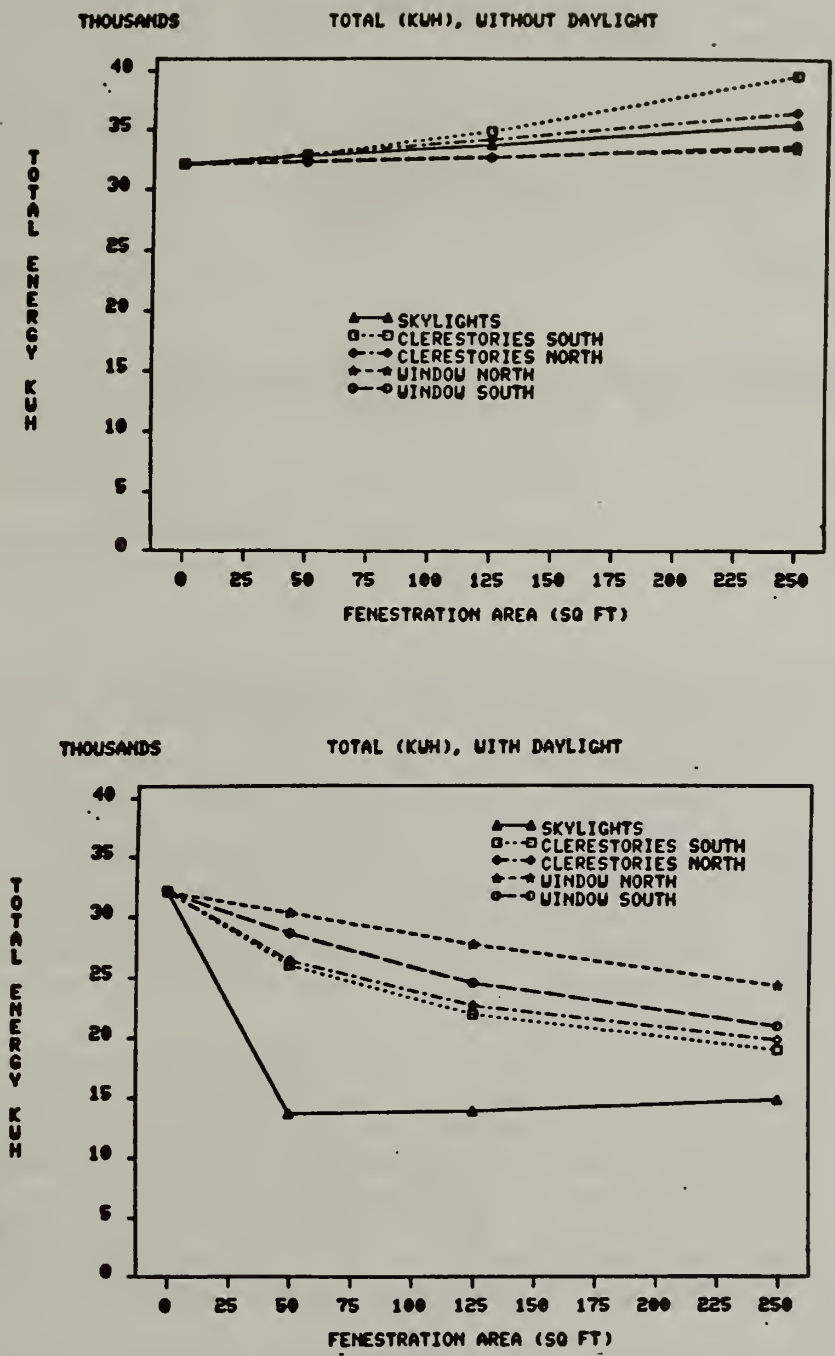



Figure 7. Total energy use for each fenestration option, with and without daylighting

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4. TITLE AND SUBTITLE

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This paper examines the impact of several fenestration options on building space heating, cooling, and lighting loads. The use of skylights, windows, and clerestories is evaluated for a single floor commercial building, using the NBSLD-2 building energy analysis computer program, which possesses a fully integrated daylight model (DALITE). The evaluation focuses on: a) the impact of daylighting on heating and cooling energy and equipment sizing, b) the potential reduction in electric lighting energy requirements through daylight utilization, c) the relative daylighting/thermal performance of skylights, clerestories, and windows, and d) the effect of building orientation on fenestration optimization and selection.

The NBSLD-2 computer procedure performs a dynamic simulation of hour-by-hour building thermal performance and energy requirements for a one-year period. The thermal and daylighting characteristics of each fenestration aperature are modeled to enable evaluation of the trade-offs associated with the use of each fenestration type. The results are correlated in the form of design guidelines to enable the preliminary design decisions to be made regarding fenestration location, type, configuration, and size. The energy calculations are presented as functions of fenestration characteristics, so that the potential energy advantages can be estimated for different fenestration designs.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Building energy analysis; clerestories; daylighting; skylights; windows.

13. AVAILABILITY

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