NBS BUILDING SCIENCE SERIES 109

Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, the Office for Information Programs, and the Office of Experimental Technology Incentives Program.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of the Office of Measurement Services, and the following center and divisions:

> Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Center for Radiation Research — Laboratory Astrophysics[2] — Cryogenics[2] — Electromagnetics[2] — Time and Frequency[2].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials, the Office of Air and Water Measurement, and the following divisions:

> Analytical Chemistry — Polymers — Metallurgy — Inorganic Materials — Reactor Radiation — Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services developing and promoting the use of available technology; cooperates with public and private organizations in developing technological standards, codes, and test methods; and provides technical advice services, and information to Government agencies and the public. The Institute consists of the following divisions and centers:

> Standards Application and Analysis — Electronic Technology — Center for Consumer Product Technology: Product Systems Analysis; Product Engineering — Center for Building Technology: Structures, Materials, and Safety; Building Environment; Technical Evaluation and Application — Center for Fire Research: Fire Science; Fire Safety Engineering.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus wthin the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Institute consist of the following divisions:

> Computer Services — Systems and Software — Computer Systems Engineering — Information Technology.

THE OFFICE OF EXPERIMENTAL TECHNOLOGY INCENTIVES PROGRAM seeks to affect public policy and process to facilitate technological change in the private sector by examining and experimenting with Government policies and practices in order to identify and remove Government-related barriers and to correct inherent market imperfections that impede the innovation process.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

> Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Standards — Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

NBS BUILDING SCIENCE SERIES 109

Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies

Tamani Kusuda
Belinda Lowenhaupt Collins

Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

Sponsored by:

Energy Research and Development Administration
Washington, D.C. 20545
and
U.S. Department of Housing and Urban Development
Washington, D.C. 20410

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary

Dr. Sidney Harman, Under Secretary

Jordan J. Baruch, Assistant Secretary for Science and Technology

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

Issued February 1978

Library of Congress Catalog Card Number: 77-600071

National Bureau of Standards Building Science Series 109
Nat. Bur. Stand. (U.S.), Bldg. Sci. Ser. 109, 113 pages (Feb. 1978)
CODEN: BSSNBV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1978

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.29/2:109). Stock No. 003-003-01892-9 Price $2.75
(Add 25 percent additional for other than U.S. mailing).

PREFACE

The work covered in this report has been conducted within the framework of a National Bureau of Standards (NBS) Interdisciplinary Research project on the energy-related performance of windows. This effort has been supported in part by NBS and by the Energy Research and Development Administration (Mode 2 of Contract E(49-1) 3800), jointly with the Department of Housing and Urban Development (Contract No. RT 193012) as a portion of the Building Energy Performance Standards Program.

SI CONVERSION UNITS

The units and conversion factors given in this table are in agreement with the International System of Units or SI system (Système International d'Unites). Because the United States is a signatory to the 11th General Conference on Weights and Measures which defined and gave official status to the SI system, the following conversion factors are given.

Length

1 in = 0.0254* meter

1 ft = 0.3048* meter

Area

1 in^2 = 6.4516* x 10^{-4} $meter^2$

1 ft^2 = 0.0929 $meter^2$

Volume

1 in^3 = 1.638 x 10^{-5} $meter^3$

1 gal (U.S. liquid) = 3.785 x 10^{-3} $meter^3$

1 liter = 1.000* x 10^{-3} $meter^3$

Energy

1 Btu (International Table) = 1.055 x 10^3 joule

Power

1 Btu/hr = 0.2930 watt

Temperature

$°C = \frac{5}{9} (°F - 32)$

Illumination

1 ft candle = 10.76 lux

---

*Exactly

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies

by

Tamami Kusuda and Belinda Lowenhaupt Collins

Abstract

Results of a simplified analysis for annual heating, cooling, and lighting requirements associated with windows are presented. The analysis includes the effects of window size, heat transfer, solar shading, and compass orientation for typical commercial and residential modules located in a climate typical of Washington, D.C. Three different modes of operation with respect to heating and cooling requirements through windows were assessed: external loads only; external and internal; and external, internal, and daylight. In addition, the effects of selective fenestration heat-transfer management, such as planned employment of thermal shutters and shading devices, and off-hour temperature setback were considered. This analysis assumed that daylight could replace or supplement artificial light whenever it could supply a specified minimum level of illumination. The use of daylight was found to offer the greatest potential for reducing energy costs, particularly when combined with selective fenestration management.

Key Words: Daylighting; energy conservation; fenestration design; solar heat gain; window management.

1. INTRODUCTION

1.1 PURPOSE

Many previous assessments of the energy performance of windows have considered only the heat loss and solar heat gain aspects of windows. Yet, historically, a window's basic functions are more closely related to lighting the interior, providing natural ventilation, and serving as a means of visual communication with the outdoors. In the modern building, however, the lighting and ventilating functions of windows have largely been replaced by electric lighting and by mechanical air handling devices, respectively. Total reliance upon these systems is not necessarily the best way of reducing the energy consumption of a building, however. The possible energy contributions of both natural illumination and ventilation should be reassessed, before design recommendations and energy standards, which require sophisticated illumination and HVAC (heating, ventilating, and air-conditioning) systems are developed.

In this report, a simplified analysis of the thermal and daylighting performance of single- and double-glazed windows of various sizes is used to illustrate ways in which the natural lighting and solar benefits of windows can partially or fully offset the normal heat conduction disadvantages of windows. Although equally important, the effects of natural ventilation are not dealt with in this paper. Window area, orientation, and thermal resistance are evaluated with respect to the seasonal heating and cooling requirements for a limited case in the Washington, D.C. area. In addition, the effects of varying the operation of a window are studied by modeling both the selective management of internal window coverings, and the substitution of natural light for artificial light (whenever practicable). Selected results from these calculations are presented to illustrate the analytical approach employed, as well as the effects on energy requirements and costs.

1.2 SCOPE

Any comprehensive examination of the energy effects of windows must consider many factors, some of which are summarized in Table 1. A more detailed identification of these factors is made in Window Design Strategies to Conserve Energy.[1/]* Only a few of these will be analyzed in this paper, which will consider thermal loads, both internal and external, and daylight. The energy consequences of natural ventilation which should be considered in a comprehensive assessment of windows are not analyzed here because the losses due to air infiltration and benefits due to ventilation and cooling through an openable window must be quantified first. The difficulty of extending this analysis to several building types, and the lack of detailed data on the extent of air infiltration, prompted the investigators to restrict the present study to the thermal, daylight, and management analysis.

An earlier report, Windows and People,[2/] summarized some of the psychological factors associated with windows. The life-cycle costs associated with the computer model presented in this report are treated in an Economic Evaluation of Windows in Buildings.[3/]

---

* Raised figures indicate literature references at the end of this report.

TABLE 1. FACTORS WHICH AFFECT WINDOW PERFORMANCE VARIABLES

<u>Location Factors</u>

1) Climate
2) Cloud cover/sunshine
3) Prevailing winds
4) Latitude
5) Elevation
6) Extent and type of vegetation
7) Ground cover

<u>Building Factors</u>

1) Size
2) Surface/volume ratio
3) Perimeter/area ratio
4) Construction materials
5) Siting
6) Function/use
7) Orientation

<u>Window Factors</u>

1) Size
2) Orientation
3) Number of layers of glazing (thermal resistance)
4) Glazing materials/adhesive films
5) Frame material
6) Operation type
7) Weatherstripping and caulking
8) Quality of construction
9) Shape
10) Position/location in window wall
11) Internal shading devices
12) External shading devices

<u>Variables to be Considered</u>

1) Heat gain
2) Heat loss
3) Insolation
4) Daylight
5) Infiltration losses
6) Ventilation
7) Life-cycle costs
8) Psychological well-being
9) Aesthetic quality of building
10) Occupancy schedules

2. RELATION OF WINDOWS TO TOTAL ENERGY CONSUMPTION

2.1 RELATIONSHIP TO BUILDING HEATING/COOLING SYSTEM

Window heat loss or heat gain is not necessarily directly related to the energy required for heating or cooling. The interrelationship between window heat gain or heat loss and the total energy consumption of a given building for heating and cooling is complex for the following reasons:

1) Solar heat coming through a window will be absorbed by the interior surfaces of the building,

2) Building interior surfaces release a part of the absorbed solar heat into room air by the process of convection,

3) Simultaneously, room air absorbs heat from lighting fixtures, occupants, equipment, and infiltration air, to achieve a temperature balance,

4) Also contributing to this heat balance process is the heat loss or gain through windows and other parts of the building to the ambient air through conduction and infiltration processes.

5) If the room air temperature becomes higher than the cooling thermostat set-point, it will be cooled by a cooling coil. If it becomes lower, for instance during a winter night, than the set-point of the heating thermostat, it will have to be heated by the heating coil.

6) Energy required for heating or cooling room air varies considerably depending upon the heating, ventilating, and air-conditioning system operation. For those who are unfamiliar with HVAC systems (heating, ventilating, and air-conditioning), a brief description of typical systems is presented in Appendix A.

2.2 WINDOW HEAT GAIN/LOSS ANALYSIS

In order to compute the thermal and lighting loads associated with windows, the effects of a large number of variables must be considered simultaneously. One of the most critical factors is window area. Most current designs for energy conservation in buildings have called for reductions in window area. This concept was implemented in the GSA Norris Cotton Building at Manchester, N. H.[4] Yet, the thermal effects of window area need to be assessed in combination with other variables such as orientation, shading devices, glazing materials, and thermal resistance. Any consideration of window performance should involve an assessment of the interactions among these variables for different window areas. Furthermore, an examination of the energy effects of windows must contain an evaluation of the potential gains and losses associated with the use of daylight, as well.

2.3 DAYLIGHT/ARTIFICIAL LIGHT TRADE-OFF

The energy used for the indoor lighting of commercial buildings and schools constitutes a major portion of the electricity consumed in these buildings. Maximum use of natural light can reduce electricity consumption for electric lighting. In addition, the use of daylight can also reduce the cooling loads resulting from electric illumination systems. For approximately the first 15 ft into a room, daylight can be the primary source of illumination,[5] with artificial light needed only on overcast days, at night, or for local task lighting. Beyond this zone, daylight may provide some of the ambient illumination, with artificial lighting providing the task illumination. This second illumination zone extends from about 15 ft to 40 ft into the room. Artificial lighting must be relied upon for interior spaces, unless another source of natural light, such as a skylight, is available.[6]

The utilization of daylight, however, requires larger window areas, which tend to result in increased winter heat loss (especially at night) and summer heat gain (especially during the day).[7] The reduction of electric energy usage for lighting and cooling by using daylight could, therefore, be partly or completely offset by an increase in energy consumption for heating and cooling due to the increased conduction heat loss and solar heat gain. In addition, visual task performance and comfort might be adversely affected by glare or veiling reflections produced by daylight or direct sunshine. Although the adverse conduction heat-loss and solar heat-gain effects can be reduced somewhat by the proper application of controllable shading devices or insulating shutters, studies are needed to determine an optimum amount of fenestration. This optimum would balance the thermal benefits and disadvantages resulting from the increased use of daylighting.

The net contribution of daylight to the energy load upon a building (or a room) is determined by calculation of the amount of light entering through a window, the amount of heat loss or gain induced by the same window, and the amount of heat gain due to the artificial lighting. Calculations of the heat released by occupants and equipment, as well as of conductive heat loss or heat gain, and infiltration heat loss or heat gain, should also be included.

3. ANALYTICAL APPROACH

3.1 COMPUTER MODEL DESCRIPTION

A computer model was developed to study a limited number of variables in a typical situation so that the effects of variations in window parameters upon both thermal performance and lighting levels could be easily calculated. The goal was to isolate the thermal and illumination effects associated with a window and to model these effects in a simplified building situation. Thus, the theoretical performance attributed to each variation in a specific window parameter could be identified and compared.

Because of the differences in internally generated loads between offices and residences, the performance of a window wall in each building type was simulated in some detail. Comparisons were made between a wall with a range of glazed areas and a solid wall for each building type. The office situation is treated first.

3.1.1 Office Module

For the office comparisons, a typical two-person office in a Washington, D.C. building was modeled. The thermal performance of the window wall and of the module was simulated. This analysis does not, however, attempt to model the complex interactions between the module and other rooms within a building, or the total building thermal performance, or the contributions made by a central HVAC system.

The module itself was designed to simulate a two-person office with a width of 12 feet, a depth of 15 feet, and a height of 10 feet. The office was assumed to have only one external facade and to be located in the middle floor of a highrise building. Thus, all the non-facade areas were considered adiabatic (permitting no heat transfer). The module was designed in accordance with good energy-conservation practice with insulated walls, moderate light levels, and tightly fitting windows. The windows were considered to be fixed, to avoid the problems associated with air leakage and draughts around openable windows. Window size was varied from 0 sq ft to 90 sq ft (0% to 75% of the window wall). Table 2 presents a complete list of assumptions used in the analysis of the module while Figure 1 illustrates the design itself.

A fixed thermal load due to human occupancy was set. It was assumed that 1.8 persons occupied the office; in other words, that it was a one-person office with periodic visitors or a two-person office in which each person was present about 90% of the time during the occupied hours.

The lighting was assumed to be fluorescent, as is typical of many offices. The level of illumination used for the calculation is equivalent to 50 fc, in accordance with good energy conservation practices as recommended by GSA. The possible contribution of natural illumination to the overall level of illumination within the office was ignored initially, because it was treated in a later analysis.

A rather nominal equipment load of 0.5 watt/ft^2 was used to simulate office equipment such as typewriters and calculators, but not computers. A low level of air leakage, equivalent to 0.25 Ac/h (air changes per hour) was also assumed, modeling a room with sealed well-fitting windows and minimal air infiltration.

3.1.2 Residential Module

A similar analysis, using somewhat different assumptions was performed for a residence. The residential module was assumed to be a family-room-kitchen with the internal loads and occupancy times typical of such rooms. Again, only the windowed wall was considered exposed to the outdoors, while all the other surfaces of the room were considered to be adiabatic. The external wall was assumed to be 18' long; the room depth was 15'; and the height was 8'. Thus the external wall area was 144 sq. ft. Smaller window sizes, such as those typical in conventional residential construction, were examined, as follows: 0, 8, 12, 20, and 40% of the window wall or 0, 12, 18, 30, and 60 sq. ft.

TABLE 2. OFFICE MODULE DESIGN ASSUMPTIONS

Module

12' wide	window wall area = 120 ft^2
10' high	floor area = 180 ft^2
15' long (deep)	volume = 1800 ft^3

Module Construction

Wall U value = 0.15
Glass thickness = 1/4" plate
Glass strength = double strength
Window operation = none
Frame type = aluminum with thermal break in double-glazed windows

Window Sizes

0% = no window
10% = 12 sq. ft.
25% = 30 sq. ft.
50% = 60 sq. ft.
75% = 90 sq. ft.

Persons

Number = 1.8 (1 per 100 ft^2)
Heat load = 260 BTU/hr/person @ 70-80°F
Occupancy = 8 hr/day, 9 AM - 5 PM: Assumed to be sensible only and based on figures for sedentary adult

Lighting

Type = fluorescent
Output = 3.25 watts/sq. ft.
130 lumens/sq. ft.
40 lumens/watt
50 fc

Equipment

Office = 0.5 watts/sq. ft.

Air Leakage

Leakage = 0.25 air change/hr.
Assume tightly constructed building with fixed windows.

Adiabatic Model

Heat transfer to adjacent spaces is ignored in this calculation.

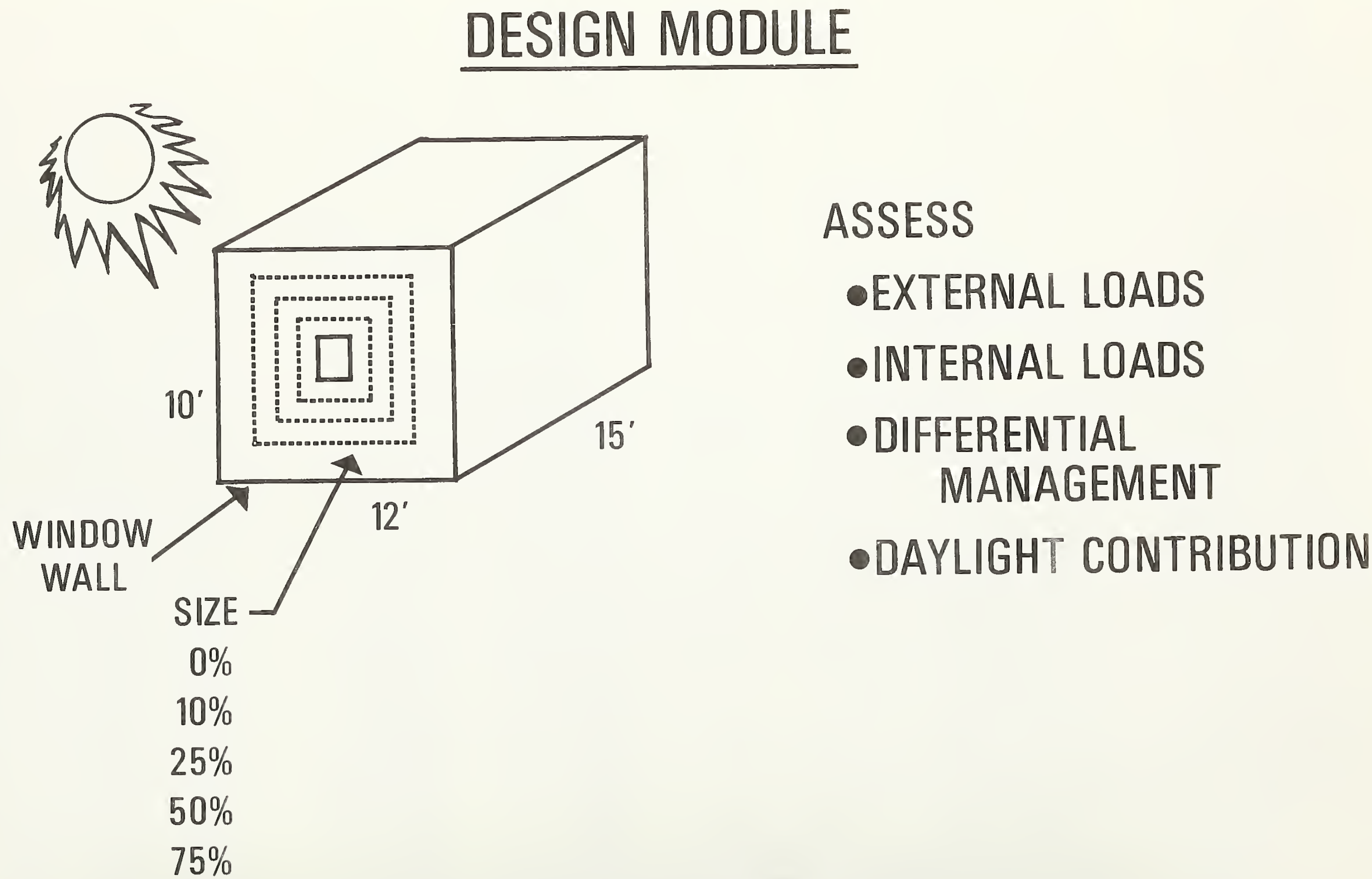


Figure 1. Design Module for a Midrise Office Building in Washington, D.C.

The internal residential loads were assumed to be generally lower than in the office building. Thus the equipment load was about 0.52 watts/sq ft; lighting level about 0.65 watts/sq ft., and person occupancy equal to 0.5. Air leakage was assumed to be 0.5 Ac/hr, a value larger than in the office situation because well-made but operable windows were modeled. No assumptions were made about natural ventilation through these windows.

Lighting in houses is typically incandescent, with the hours of operation at the discretion of the resident. Typical levels of artificial light used either during the day or at night have not yet been determined. As a result, a very low level of illumination, about 6.7 fc or 0.65 watts/sq ft of incandescent light, in terms of daily average value, was assumed in order to simulate as conservative a situation as possible. It was assumed that this level of artificial illumination prevailed even during daylight hours, because at least this level would have been necessary had the room been windowless. See Table 3 for a detailed list of residential assumptions.

In both the office and residential models, the comparisons were extended to include the dollar costs associated with heating, cooling, lighting, and equipment loads. This involved dividing therms (100,000 Btu) by the equipment efficiency and multiplying by the fuel cost. In the residential case two sources of heat were modeled; gas heat, and electric heat. For both, the cooling, lighting, and equipment were assumed to be electric.

3.2 THERMAL CALCULATIONS

In the thermal analysis, calculations were made of the heat gain and loss through each of the five window areas located in a facade of fixed U value for both office and residential modules. In addition to size, the following parameters were varied: building orientation, window U value (single or double glazing), shading coefficient (different glazing materials, internal and external shading devices), and season.

The calculations were made by using the monthly average value of daily total radiation data for Washington, D.C. derived from the Liu-Jordan technique as used in reference 7. Also included in the calculation is a Storage-Load-Factor Concept which approximates the capability of the building structural mass and internal heat distribution system to make use of excess daytime heat gain for nighttime heating. This factor is introduced to account for the fact that not all of the daytime net heat gain (difference between the solar heat gain and conduction loss) through the window is available to reduce the heating requirement during the night. Since specific values for the load factor have not been established, several selected values representing extreme and moderate amounts are used for this calculation.

Each calculation of the thermal loads upon a vertical surface was performed for an average day consisting of average temperatures and solar radiation for each of the twelve months of the year. The effects of varying

TABLE 3. RESIDENTIAL ASSUMPTIONS

I. Building Specifications

Room = 18' wide, 15' long, 8' high
Construction = brick veneer
U value = 0.07
Exterior wall = 144 sq. ft.
Window sizes = 0, 12, 18, 30, and 60 sq. ft. or 0%, 8%, 12%, 20%, 40%
Construction = wood, double-hung, weatherstripped
Interior surfaces were assumed to be adiabatic in this calculation.

II. Internal Loads - Daily Average Basis

Equipment Load = 0.52 watts/sq. ft. = 3511 kWh/year[8/]

dishwasher = 363 watts	blender = 15
stove = 1175	frying pan = 186
refrigerator = 1137	toaster = 39
disposal = 30	clock = 17
TV-color = 440	stereo = 109

Occupancy

Duration = 0.5 for 8 hours occupancy from 0700 to 2300
Load = 260 Btu/hr.

Lights

Type = Incandescent
Output = 0.65 watts/sq. ft.
Illumination = 6.7 fc[*/]

Air Change

0.5 air change/hour

Shading Coefficient

1.0 (0.9) unless window managed

Storage Load Factor

0.1

III. Operating Costs

Electric cooling = 3¢/kWh	Gas heating = 30¢/therm
Electric heating = 3¢/kWh	Electric equipment = 3¢/kWh

---

*/Daylight Level

It is recognized that a reference illumination level of 6.7 fc is too low for many household tasks. This value is chosen, however, to make the average illumination level consistent with the daily average lighting energy consumption figure of 0.65 watts/ft^2 given in Table 3. The average lighting energy figure is equivalent to using one 100 W bulb for 10 hours per day and three 100 W bulbs for 6 hours per day, with no lighting used at night. It is difficult for the type of energy analysis reported here, which is based upon daily average data, to simulate instantaneous and/or dynamic illumination requirements. Using a low level of illumination, such as 6.7 fc, as the reference level for turning off the artificial illumination may increase the calculated benefit of daylighting and could make the daylight analysis appear more favorable than it should.

window shading devices were studied by using several different shading coefficients (from 1.0 to 0.2). By examining the list of options in Table 4, one may pick an existing shading device that corresponds to each of these shading coefficients. Equations, definitions, and assumptions used in the thermal load analysis are given in Table 5.*

The calculations were performed for the average day by balancing the daily total solar heat gain and daily net total conduction heat loss. If, for a typical day, the daily total solar heat gain was greater than the daily total net heat loss, the daily heat balance was termed positive; otherwise it was negative. The calculations were carried out for each of the twelve months for double and single-glazed (vertical) windows for eight compass orientations and over a horizontal surface. The seasonal total values were obtained by summing the products of the number of days in the month times the average-day net heat loss (negative values) or net heat gain (positive values). The heat losses and gains were tallied separately to give the seasonal heating requirement and cooling requirements. Two seasons were modeled; heating (October through April) and cooling (May through September). Although the calculations do take into account the fact that a part of the daytime excess heat gain is made available during winter days to assist the nighttime heating requirement, it was assumed that there was no cooling requirement during the heating season. Likewise, it was assumed that there was no heating requirement during the cooling season. The assumption that there was no cooling during the winter or heating during the summer, may have resulted in the use of slightly less energy to maintain room temperature in both seasons than would otherwise be the case.

3.3 DAYLIGHT CALCULATIONS

The energy calculation associated with daylight dealt only with the usefulness of daylight as the primary lighting source in the zone nearest the window. The artificial lighting was assumed to be dimmable, to enable it to supplement daylight whenever the latter fell below a certain minimum value. No assumptions were made about individual use of task lighting. In addition, the visual performance aspects of daylight, such as glare, ESI (Equivalent Sphere Illumination), and VCP (Visual Comfort Probability) were not considered in this analysis. An exact daylight calculation requires a very comprehensive analysis of light interreflection among all the surfaces in the room as described by DiLaura.[10,11] Since the exact daylight calculation is very laborious and time-consuming, the daylight calculation procedure used in this study is based upon the daylight factor approach.[12,13] This concept, which has been used by European researchers as a simplified method for approximating available daylight within a room, is described in Appendix B. The Daylight Factor is defined as the ratio between the illumination on a horizontal plane at a reference point in the room and the illumination on a horizontal plane under the open sky, both without direct sun beam.

---

*Steady-state heat transfer relationships are used in this analysis because one is dealing strictly with the daily average values. Such simplifications may not be justifiable if one is dealing with the hourly calculations, however.

TABLE 4. SHADING DEVICES AND COEFFICIENTS

	Shading Coefficient	"U" Value		
Glass Type		Summer	Winter	Sp./Fall
Clear single (SG)	1.0	1.06	1.13	1.09
Clear double (DG)	0.9	0.54	0.55	0.54
Reflective single	0.4			
Reflective double	0.3			
Devices				
Venetian Blinds + SG	0.55			
Thermal Drapes + SG	0.2 ~ 0.35			
Fabric Shade + SG	0.4			
External Sunscreens + SG	0.2			
Vertical Fins + SG	0.3			
Horizontal Overhang + SG	0.1 ~ 0.2			
Drapes and Sunscreen + SG	0.1			
Vented Heat Absorbing DG	0.1			
Horizontal Overhang + Venetian Blinds + DG	0.1			

TABLE 5. EQUATIONS FOR WINDOW CALCULATIONS

$q_{facade} = q_{wall} + q_{glass}$

$q_{wall} = U_{wall} (\overline{TOT} - t_i) A_{wall} \cdot 24$ hrs.

$q_{glass} = U_{glass} (\overline{SATG} - t_i) A_{glass} \cdot 24$ hrs $\cdot$ LF

° $\overline{TOT} = TOT + \frac{\alpha}{ho} \times \frac{IDT}{24}$: Average sol-air temperature for walls.

TOT = average outdoor temperature[6/]

α = absorptance of surface for solar radiation

$\alpha = 0.9$

h_o = Coefficient of heat transfer by radiation and convection at the outdoor surface

h_o = 4 in spring, fall (months 4, 5, 10, 11)

h_o = 3 in summer (months 6, 7, 8, 9)

h_o = 5 in winter (months 12, 1, 2, 3)

IDT = Daily total solar insolation upon a specified surface per unit area

t_i = indoor temperature	thermostat setback
t_i = 78°F summer	= 84°F summer
t_i = 72°F winter	= 62° winter

A_{facade} = facade area in square ft

$A_{wall} = A_{facade} - A_{glass}$

A_{glass} = window or glass area in square feet (here equal to A_{facade} x percentage of window wall)

U_{wall} = Overall heat transfer coefficient for wall

U_{glass} = overall heat transfer coefficient for glass

(See specific coefficients on Table 4)

$\overline{SATG}$ = average sol-air temperature for glass

$$\overline{SATG} = TOT + \frac{0.87 \times IDT}{24 \times U_{glass}} \times S.C.^{*/}$$

$\overline{SATG}_s$ = average sol-air temperature for single glass

$\overline{SATG}_d$ = average sol-air temperature for double glass

TOT = average outdoor temperature

0.87 = solar transmittance for single glass

S.C. = Shading coefficient

$$= \frac{\text{Solar heat gain through fenestration}}{\text{Solar heat gain through single-glazed double-strength glass}}$$

LF = storage load factor

$$= \frac{\text{Useful heating obtained from the daytime excess heat gain}}{\text{Total daytime excess heat gain}}$$

*/The equation assumes that there is no heat absorption in the standard double-strength single-glazed window glass.

Daylight Factors were calculated for several areas of glazing, internal and external reflectances, and cloud cover. The amount of illumination within the room at 15 ft from the window was then calculated. In the trade-off analysis, whenever room illumination supplied by daylight fell below a 50 fc minimum (at the reference point) in the office module or 6.7 fc in the residential module, supplementary artificial light was added to maintain the minimum lighting level,* and the electric power saved in lighting was calculated.[14/] See Table 6 for assumptions made in calculating electric power savings.

*In this calculation it is assumed that the artificial illumination level is automatically and perfectly adjusted to maintain the reference level without loss of illumination efficiency.

TABLE 6. DAYLIGHT/ARTIFICIAL LIGHT TRADE-OFF

° Calculate INDOOR illumination = DALITE

° window size h = 8 ft. high

° wall/floor reflectance RFW = 0.4

° ceiling reflectance RCN = 0.6

° exterior obstruction angle α = 0.0

° distance from window = 15 ft.

° height above floor h_1 = 3 ft.

° Indoor Natural Illumination = DALITE

DALITE = (SKYLIT * (SC + XIRC) + SUNLIT * ERC) * M * G * B * SHC/100

SKYLIT : sky illumination

SUNLIT : sun illumination

SC : sky component

ERC : external reflection component

XIRC : internally reflected component

° Task Requirement = DALITE + Supplementary Artificial fc

° Electric Power Saved

	Office	Residential
A = floor area	150 ft^2	270 ft^2
CU = coefficient of utilization	0.55	0.7
LE = lamp efficacy	40 lumens/ watt	19.4 lumens/ watt
LLF = light loss factor	0.7	0.7
Illumination requirement	50 fc	6.7 fc
Watts* = $\frac{\text{A * illumination requirement}}{\text{CU x LE x LLF}}$	3.25 w/ft^2	0.65 w/ft^2

*3.413 Btu/watt

4. COMPARISON CONDITIONS FOR COMPUTER MODEL

4.1 GENERAL REQUIREMENTS

In order to simulate a fairly realistic building situation, three different modes of operation were studied. The first, Mode I, analyzes only the external loads and simulates an unoccupied room with no loads from people, equipment, or lights. The second mode of operation, Mode II, combines internal loads from people, equipment, and electric lights with the external load calculations of Mode I. Finally, Mode III computes the effects of substituting daylighting for artificial light in the calculations described for Mode II. In all three modes, there is assumed to be no heating in the cooling season, or cooling in the heating season. Table 7 depicts the various modes of comparison.

For each of the three modes of operation, four different cases, or patterns of use were studied. In case 1, the internal thermostat setting was maintained at one value all day for each of the two seasons. In case 2, a provision was made for unoccupied-hour temperature setback in

TABLE 7. COMPARISON CONDITIONS

Modes \ Cases	1. Constant Internal Temperature	2. Off-Hour Thermostat Setback	3. Management - Shutters in Winter - Blinds in Summer	4. Management and Setback
I. External Loads	*			
II. External and Internal Loads	*	*	*	*
III. Daylight plus Thermal	*	*	*	*

Window Variables

- ° Window size: 0, 10, 25, 50, 75% for office
  0, 8, 12, 20, 40% for residence
- ° Single and Double Glazing
- ° Building Orientation: N, NE, E, SE, S, SW, W, NW
- ° Average Day in Each of the Twelve Months

Assumptions

- ° Case 1: Constant internal temperatures as specified in Table 5.
- ° Case 2: Thermostat Setback during night and unoccupied hours.

  Setback Temperature (t_i)
  62°F for months 12, 1, 2, 3
  84°F for months 6, 7, 8, 9
  72°F for months 4, 5, 10, 11

- ° Case 3: Management Options

  Winter: Use Thermal Shutters for Months 12, 1, 2, 3 during night hours.

  Vary "U" value as follows:
  Single Glazing = 1.13 for Day
  Single Glazing + Shutters = 0.5 for Night
  Double Glazing = 0.55 for Day
  Double Glazing + Shutters = 0.2 for Night

*Data from these conditions will be reported in detail.

Summer: Use white Venetian Blinds during daylight hours for Months 6, 7, 8, 9

Changes Shading Coefficient during Daylight Hours
SC goes from 1.0 to 0.55 for single glazing
SC goes from 0.9 to 0.5 for double glazing
Blinds set at 45° slat angle

Additional Assumptions

Heating system efficiency = 0.65
Cooling coefficient of performance = 3.0
Energy costs
- gas = 30¢/therm
- electricity = 3¢/kWh

Daylight Calculation Data

Window maintenance factor	1.0
Window material factor	1.0
Window glazing bar factor	1.0
Floor reflectance	0.4
Wall reflectance	0.4
Ceiling reflectance	0.6
Window obstruction angle	0°

each of the seasons. (For offices, the unoccupied hours include weekends and national holidays.) In Case 3, thermal shutters were used during winter nights, and venetian blinds during summer days, to manage the window. In case 4, the window management option was combined with the unoccupied-hour setback option. A more detailed explanation of the assumptions for each of the modes and cases is given in Section 4.1. Each of the four cases was evaluated in each of the three modes so that a comparison could be made of the relative effectiveness of each mode/case combination.

In addition to calculating the thermal loads in each of the three modes, the probable costs of heating, cooling, and lighting for each mode were estimated to determine the total annual expenditures in dollars for energy. The estimate was made by calculating the amount of fuel used for both heating and cooling, as well as the subsequent dollar cost. The heating system was assumed to be gas, at 30¢/therm; the cooling system was electrical, at 3¢/kWh. Non-cooling electrical costs for equipment and lights were also calculated. Costs are based upon 1975 figures and are given for comparison purposes only.[15/]

4.2 SPECIFIC CONDITIONS

Each mode of operation involved modeling a set of specific conditions. A complete description of the conditions appears below. It is important to remember that the data are applicable only to a situation in which each of these conditions is met, before substantive conclusions can be drawn about the results contained in this report. Further experimental assessment of actual thermal and lighting loads is needed to verify these findings.

4.2.1 MODE I: External Loads Only

In Mode I, the calculations given in Table 5 are performed as a reference condition without internal loads. Although not representative of actual use, such calculations have occasionally been used to predict the thermal performance of windows. Modeling is confined to the climatic conditions of Washington, D.C.; and the additional effects of variation in shading coefficient and storage load factor are simulated. In Mode I, the effects of external loads only are studied. The combination of these loads with internal loads is then analyzed in Mode II Case 1 to compare their effects upon seasonal heating and cooling requirements.

4.2.2 MODE II: External Plus Internal Loads

Mode I presents an incomplete picture of the thermal performance of windows. In Mode II, the analysis was extended to include an evaluation of the balance between external and internal loads. Only in rare instances is a building operated without internal equipment, lighting, and people present in its interior. Each of these sources generates heat, which may decrease the need for supplementary heating during the winter, but will increase the demand for air-conditioning during the summer. An understanding of the balance between internal and external loads is essential for determining the contribution of daylight and winter sunshine.

The heat-balance equation involves balancing the transmission loss against the internal heat generation. Ideally, a condition of zero heating energy consumption would result when winter solar heat gain through the window and internally generated heat by the lights, equipment, and occupants could supply the heating requirements, to offset the heat loss due to conduction and infiltration heat losses (at least during daylight hours). During the non-heating seasons, cooling energy consumption would be reduced by minimizing the heat gain, thus lessening the load upon the air-conditioning system. In Mode II, constant internal temperature, thermostat setback, window management, and a combination of both management and setback were simulated to determine the relative effects of each upon window performance.

4.2.3 MODE III: Daylight Plus Thermal Loads

Mode III combines the daylight calculations described before with an assessment of the internal and external loads from the window. In this way, the combined effects of both heat and light could be quantified to determine the extent of energy savings due to the use of natural rather than artificial light for different combinations of window design and operation. The contributions of daylight to room energy use were simulated by assuming that daylight could supplement or replace artificial light, depending upon the amount of external illumination at the reference point. All calculations were determined for one point on a horizontal surface 15 ft (4.2 m) from the window and 3 ft (0.9 m) from the floor to model the edge of the perimeter zone of a larger room. It should be pointed out that use of this particular reference point represents a "worst-case" analysis, because the quantity of daylight increases closer to the window.

The trade-off analysis balances heat loads from the windows against usable daylight. It also calculates the reduction in internal loads due to the absence of heat from the artificial lighting. Thus, the analysis computes possible savings in fuel for both lighting and cooling.

5. RESULTS

Selected results are presented for each of the three modes of operation. Results were obtained for seasonal heating and cooling requirements in therms, and for yearly operating costs in dollars. Yearly operating costs include the cost of energy for lighting and equipment as well as for heating and cooling. Life cycle costs will be treated in a subsequent publication.[37] Results for the office simulation are given first, and for the residential situation, second.

5.1 OFFICE MODULE RESULTS

5.1.1 MODE I: External Loads Only

For the office module, a number of calculations were performed which assessed only the external loads imposed upon the windows, with no consideration of the effects of internal loads. The effect of varying the amount of shading was also assessed, as well as the ability of the building to store any accumulated heat. In all, six runs were made using three shading coefficients (1.0, .55, .25) and two storage load factors (1.0 and 0.5).

An examination of the seasonal heating and cooling requirements given in Figure 2 reveals that, for single glazing, the heating requirement increases steadily with increasing area for north and east/west orientations, but decreases for southern orientations. The addition of double glazing reduces the heating requirement substantially, particularly for north and east/west orientations. The cooling requirement, however, remains about the same. Figure 2 also demonstrates that for both glazing types, the heating requirement for south-facing windows is less than that of a solid wall (0% window), and approaches zero for double-glazed windows that comprise 25% or more of the window wall.

The data depicted in Figure 2 were obtained with a shading coefficient of 1.0 (0.9 for double glazing), indicating no shading. Table 8 presents the effects of varying shading coefficient upon seasonal heating and cooling requirements. Table 8 demonstrates that lowering the shading coefficient from 1 to .25 reduces the cooling requirement below the non-shaded condition for all orientations with both single and double glazing. However, the change in shading coefficient increases the heating requirement for all orientations. For example, reducing the shading coefficient from 1 to 0.25 (Table 8), increases the heating requirement for the largest northern single-glazed window from 101 to 137 therms, and from 10 to 107 therms for a similar south- facing window. Similar, although smaller, increases occur for double glazing. Clearly, the effect of shading in winter is detrimental, because it blocks the solar heat gain which would otherwise reduce the heating requirement. These data suggest that shading is most effective when used only at times of high solar heat gain and high air temperature. Since selective shading appears more effective than year-round use, this approach is subsequently employed as one of the two management options.

In Table 9, the calculations of heating and cooling requirements are repeated using a storage load factor of 0.5 instead of 1.0 to simulate the effects of reducing the storage capacity of the building. A higher load factor represents a building system which is more capable of storing and utilizing excess daytime solar heat gain for nighttime heating requirements.

In brief, a comparison of Tables 8 and 9 demonstrates that reducing the load factor decreases the cooling requirements. This decrease is most noticeable for the two largest window sizes, on all orientations for both types of glazing. The heating requirement was increased slightly, particularly for southern, single-glazed windows. Changing the shading coefficient preserves the same relative relationships as that obtained with a load factor of 1.0. In view of the fact that, in most office buildings, the storage load factor should be less than 1, all subsequent comparisons were run with a load factor of 0.5. A shading coefficient of 0.55 was used except where otherwise stated. Figure 3 depicts seasonal heating and cooling requirements under these circumstances for Mode I.

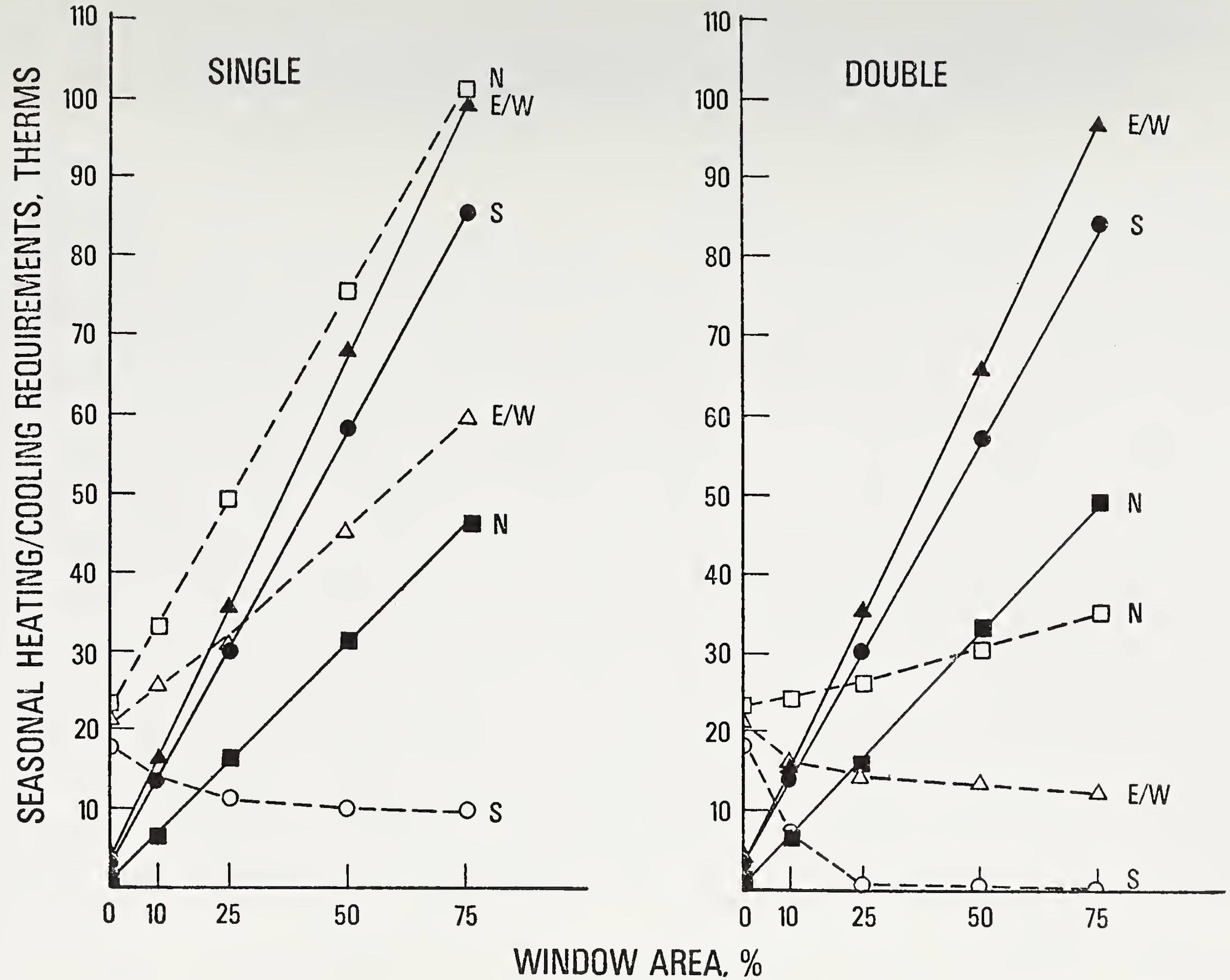


Figure 2. MODE I CASE 1. Seasonal heating and cooling requirements for an office module in Washington, D.C. as a function of percentage of window area with a shading coefficient of 1.0 (0.9) and a load factor of 1 for single and double glazing. Dashed lines and open symbols represent heating requirements. Solid lines and symbols repersent cooling requirements.

Table 8

Comparison of the Effects of Varying Shading Coefficient Upon Seasonal Heating and Cooling Requirements for an Office Module for MODE I CASE 1 and Storage Load Factor of 1.0

	Single Glazing										Double Glazing									
	Heating Requirement*					Cooling Requirement					Heating Requirement					Cooling Requirement				
Area Orientation	0	12	30	60	90	0	12	30	60	90	0	12	30	60	90	0	12	30	60	90
Part A. Shading Coefficient = 1; 0.9																				
South	-22	-14	-11	-10	-10	4	14	31	58	86	-18	-8	0	0	0	4	14	30	58	85
E/W	-21	-25	-32	-46	-59	4	17	36	68	100	-21	-17	-14	-13	-12	4	17	35	66	97
North	-24	-34	-49	-75	-101	2	7	16	31	46	-24	-25	-27	-31	-35	2	7	17	33	49
Part B. Shading Coefficient = 0.55; 0.5																				
South	-18	-23	-31	-45	-59	4	8	15	27	43	-18	-15	-11	-7	-6	4	8	16	30	43
E/W	-21	-31	-46	-70	-95	4	10	18	32	50	-21	-22	-23	-27	-31	4	10	19	34	50
North	-24	-37	-57	-90	-123	2	4	7	12	23	-24	-27	-33	-43	-52	2	4	8	15	23
Part C. Shading Coefficient = 0.25; .23																				
South	-18	-30	-48	-77	-107	4	5	6	8	10	-18	-21	-24	-31	-37	4	5	7	11	15
E/W	-21	-35	-56	-90	-124	4	5	7	10	13	-21	-25	-32	-43	-53	4	6	9	13	18
North	-24	-39	-62	-100	-137	2	2	3	4	5	-24	-29	-37	-51	-65	2	2	3	5	7

*The unit for all entries is the therm (10^5Btu) per season. Negative entries refer to the winter heating requirement in which additional heat must be supplied to the room to maintain a given temperature.

Table 9

Comparison of the Effects of Varying Shading Coefficient for an Office Module for MODE I CASE 1 and Storage Load Factor of 0.5

	Single Glazing										Double Glazing									
	Heating Requirement*					Cooling Requirement					Heating Requirement					Cooling Requirement				
Area	0	12	30	60	90	0	12	30	60	90	0	12	30	60	90	0	12	30	60	90
Part A. Shading Coefficient = 1; 0.9																				
South	-18	-21	-25	-33	-41	4	8	14	25	36	-18	-14	-9	-5	-2	4	8	15	27	39
E/W	-21	-28	-38	-55	-72	4	9	17	30	43	-21	-21	-20	-21	-23	4	10	18	32	46
North	-24	-33	-48	-73	-98	2	4	6	11	16	-24	-26	-29	-35	-41	2	4	8	14	21
Part B. Shading Coefficient = 0.55; 0.5																				
South	-18	-26	-37	-56	-75	4	5	7	10	13	-18	-18	-19	-20	-22	4	5	8	13	18
E/W	-21	-31	-46	-70	-94	4	6	8	13	17	-21	-23	-27	-37	-38	4	7	10	16	22
North	-24	-35	-52	-80	-109	2	2	3	4	6	-24	-27	-33	-42	-51	2	3	4	6	8
Part C. Shading Coefficient = 0.25; 0.23																				
South	-18	-29	-45	-72	-100	4	3	3	2	2	-18	-21	-26	-34	-42	4	4	4	4	5
E/W	-21	-33	-50	-80	-109	4	4	4	4	4	-21	-25	-31	-41	-51	4	4	5	5	6
North	-24	-36	-54	-85	-116	2	1	1	1	1	-24	-28	-35	-46	-57	2	2	2	2	2

*See note for Table 8

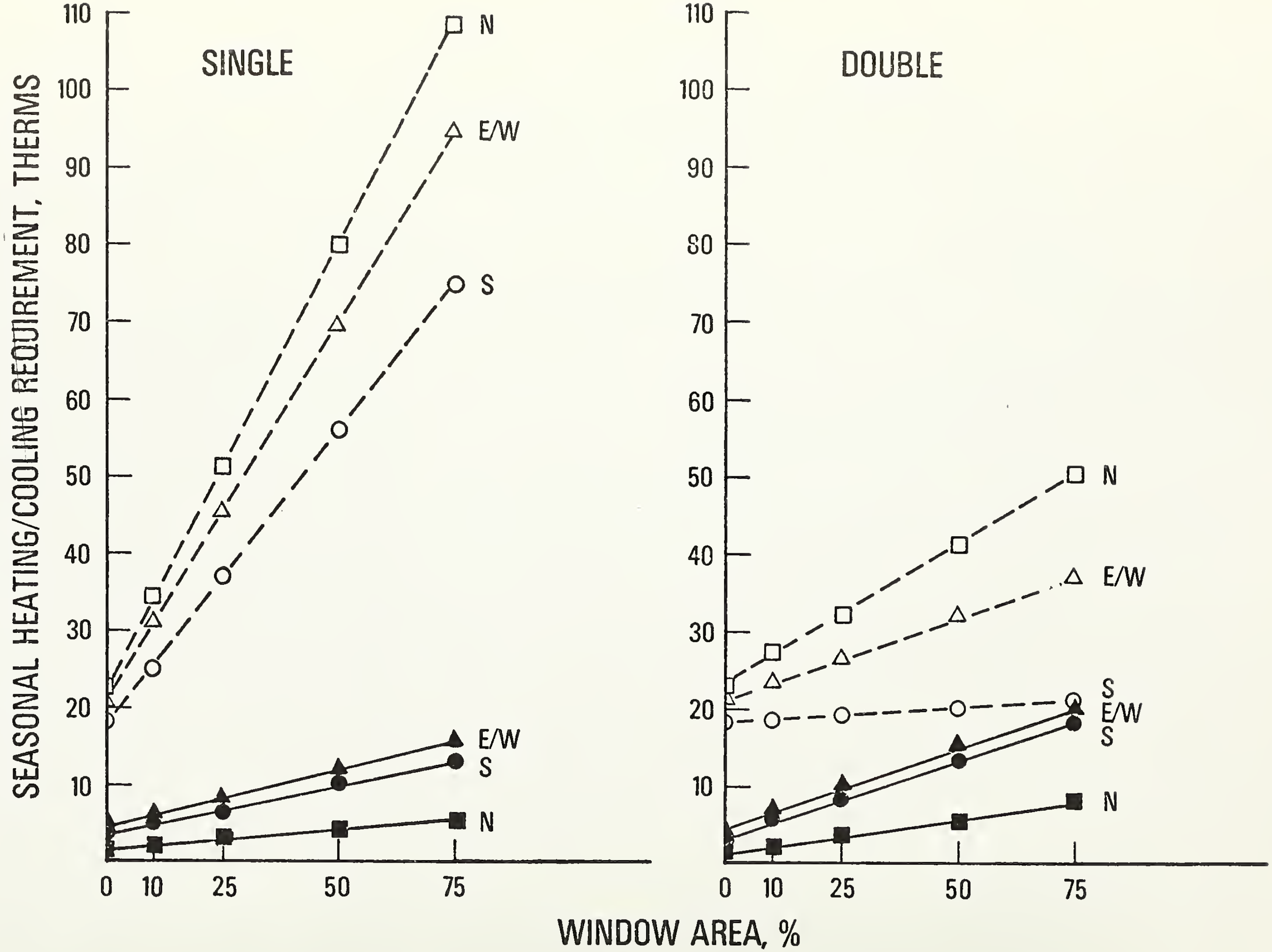


Figure 3. MODE I, CASE 1. External seasonal heating and cooling requirements for an office module in Washington, D.C. as a function of percentage of window area for single and double glazing. Shading coefficient = 0.55, LF = 0.5. Dashed lines and open symbols represent heating requirements. Solid lines and symbols represent cooling requirements.

Data involving off-hour temperature setback and window management (cases 2, 3, and 4) are not presented for Mode I, because this mode represents external loads upon the window, and does not reflect variations in internal conditions.

5.1.2 MODE II: External Plus Internal Loads

Figure 4 represents a situation in which internal loads are added to the external load calculations and a constant internal temperature is maintained. When the external thermal loads depicted in Figure 3 are compared with the combined loads given in Figure 4, it is apparent that the addition of internal loads has increased the cooling requirement while decreasing the heating requirement for a single-glazed window. For a double-glazed window, the cooling requirements exceed the heating requirements for all cases. Data reported in Figure 4 represent a reasonable baseline against which all subsequent data can be compared for the office module.

Annual operating costs were also calculated. These include heating and cooling costs as well as electricity costs for lighting and equipment. Figure 5 shows that dollar costs increase as a function of increasing single-glazed window area by $22 to $35 for different orientations. This increase is much less pronounced for double-glazed windows, however, with an increase of only about $5-$10 per year.

Although the data for cases 2, 3, and 4 are not presented here, the calculated results indicate that the use of thermostat setback decreases operating costs by $5-$10 regardless of window size. Selective management reduces operating costs of the windows somewhat more. A combination of both thermostat setback and window management is even more effective in reducing annual operating costs. These effects are treated in greater detail in the next section.

5.1.3 MODE III: Daylight Plus Thermal Loads

In MODE I a daylight/artificial light trade-off is made along with he assessment of internal and external loads. Daylight is assumed to supplement (or replace) artificial light to maintain an overall light level of 50 fc at the reference station, 15 ft from the window.

Figure 6 depicts the thermal requirements when using daylight in a room with a constant temperature setting. It demonstrates that the use of daylight appears to increase heating requirements noticeably over the baseline case (Figure 4), but to decrease cooling requirements. Using" double glazing cuts the heating requirement in half, but affects the cooling requirement only slightly. Northern orientations exhibit the greatest heating requirement and the least cooling requirement.

Compared with the costs for the baseline case, Figure 5, the use of daylight reduces operating costs substantially. As can be seen in Figure 7, when daylighting is used, increasing single-glazed window area lowers costs for all window sizes except the largest. For double glazing, costs decline up to 50% glazing, but even those for 75% glazing are $20-

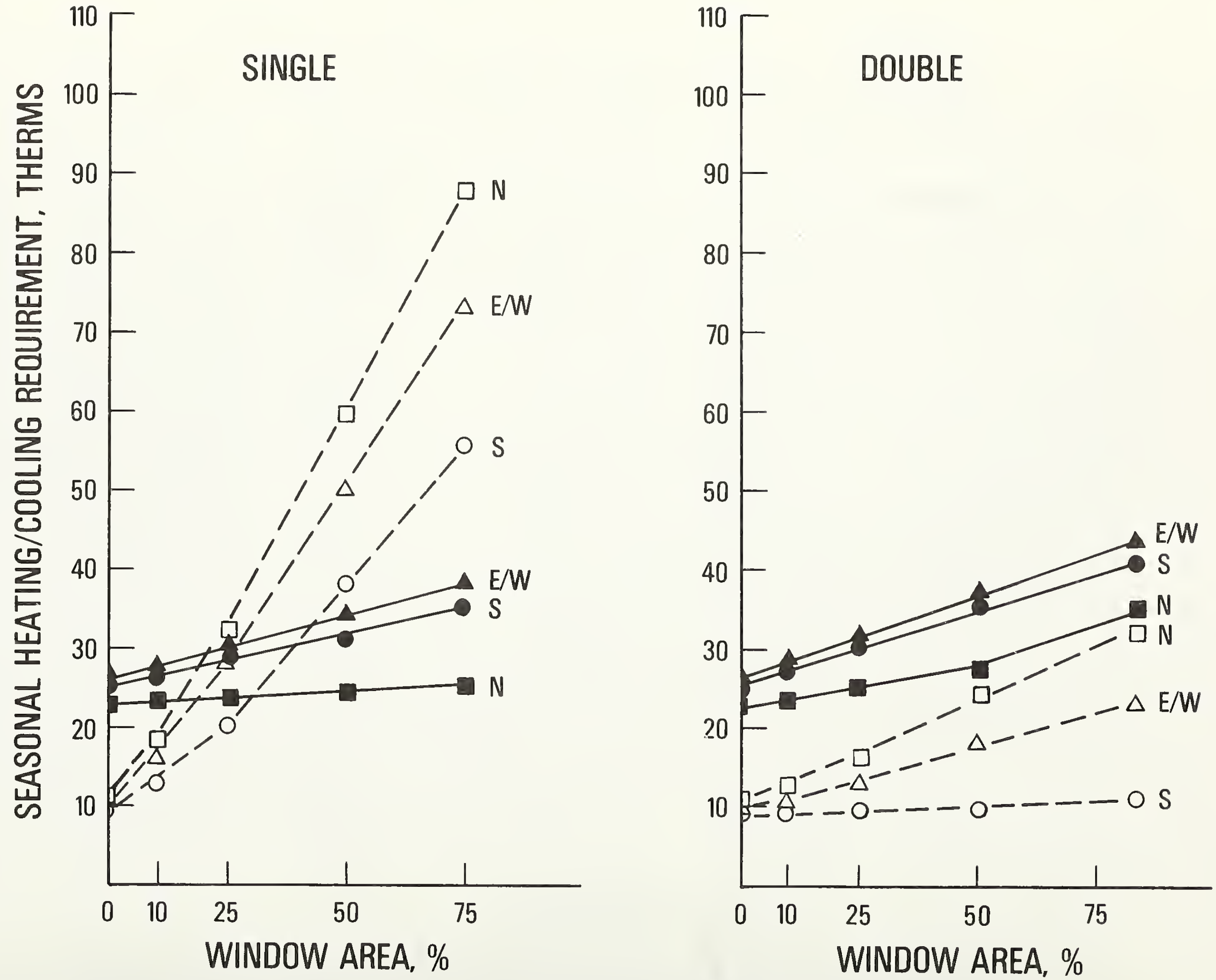


Figure 4. MODE II CASE 1. Seasonal heating and cooling requirements considering both external and internal loads upon an office module in Washington, D.C. for single and double glazing. SC = 0.55, LF = o.5. Dashed lines and open symbols represent heating requirements. Solid lines and symbols represent cooling requirements.

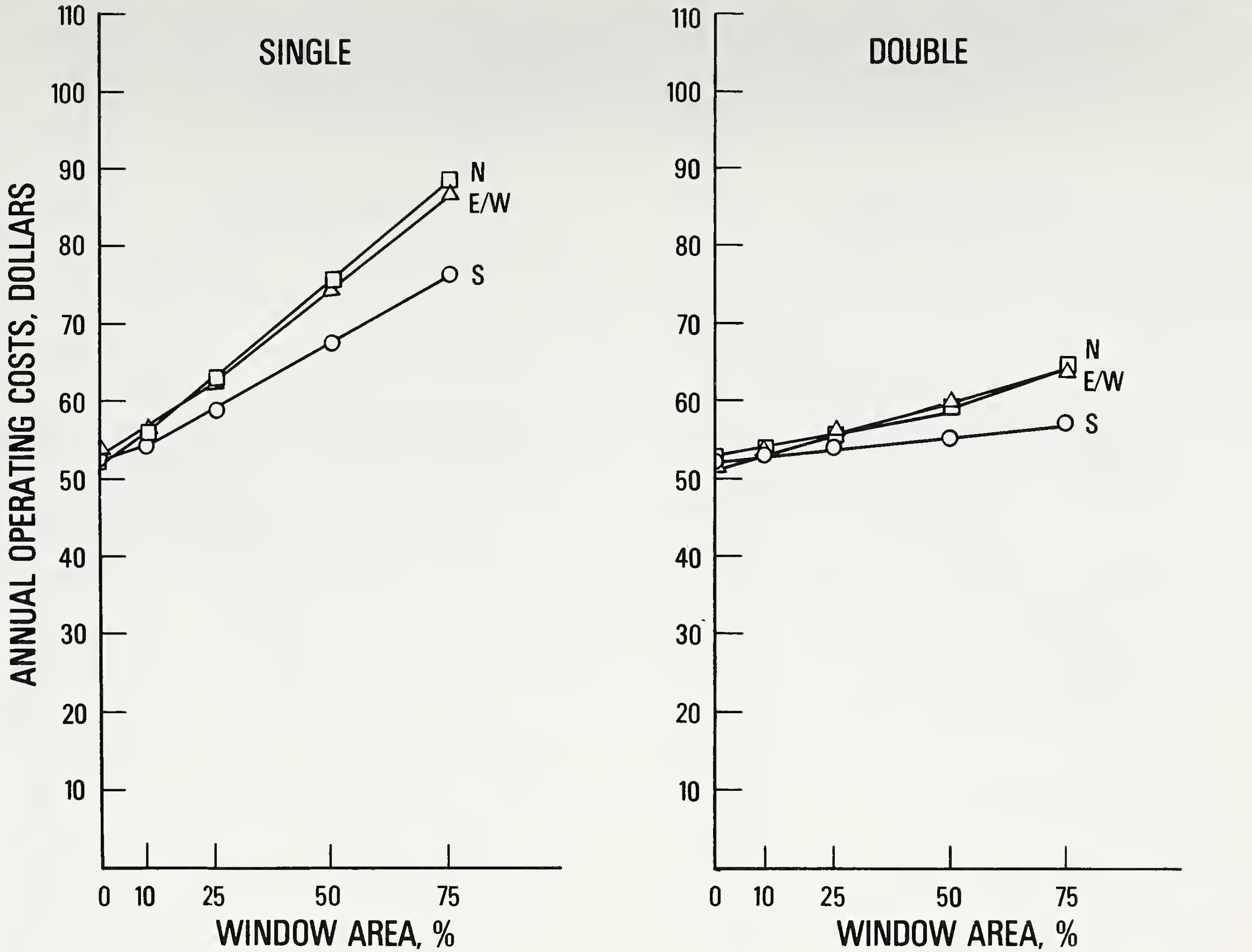


Figure 5. MODE II CASE 1. Estimated annual operating costs for the seasonal heating and cooling requirements of an office module in Washington, D.C. for both single and double glazing. Open symbols represent dollar costs.

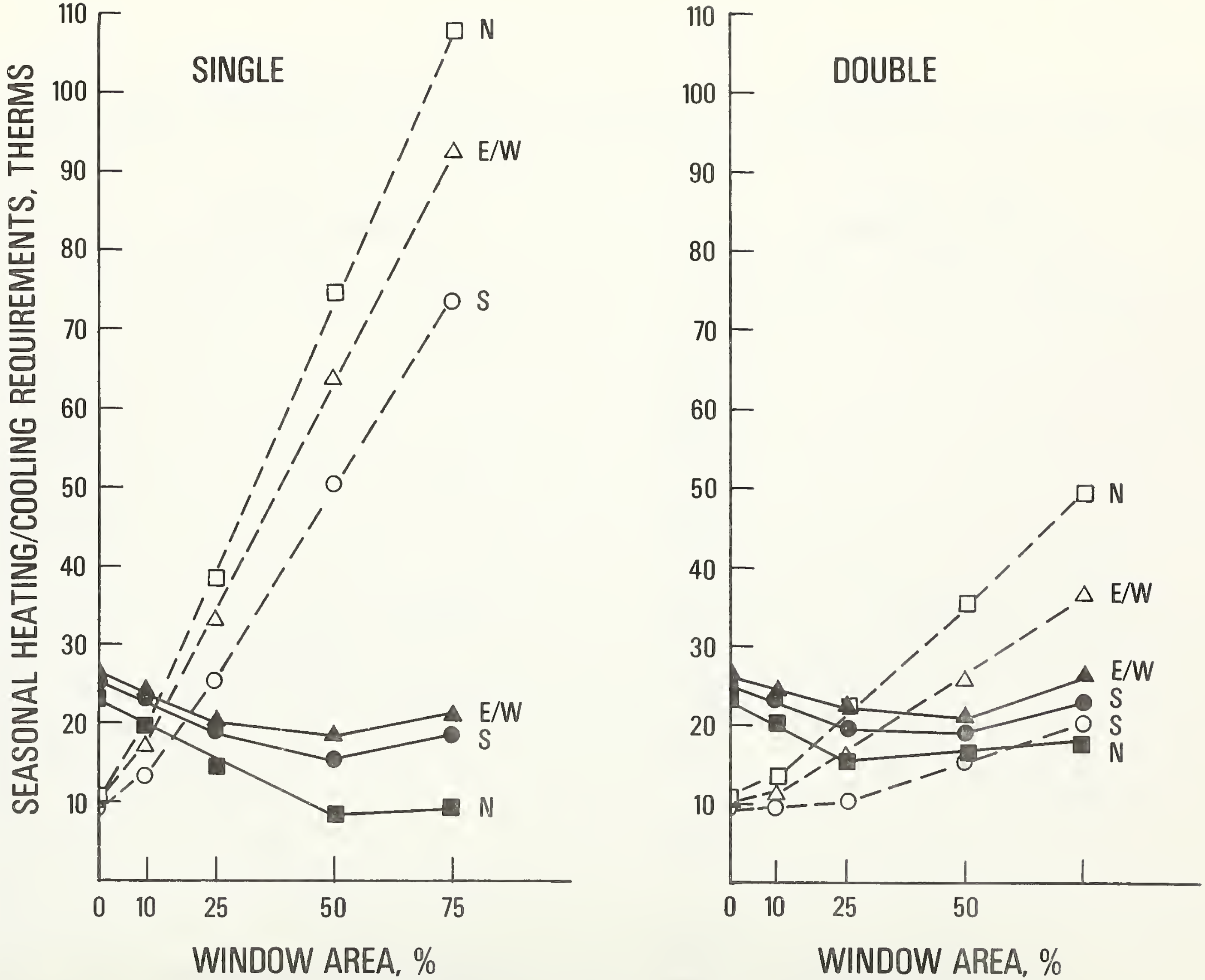


Figure 6. MODE III CASE 1. Seasonal heating and cooling requirements for an office module with daylight utilization in Washington, D.C. as a function of window area and amount of glazing. SC = 0.55, LF = 0.5. Dashed lines and open symbols represent heating requirements. Solid lines and symbols represent cooling requirements.

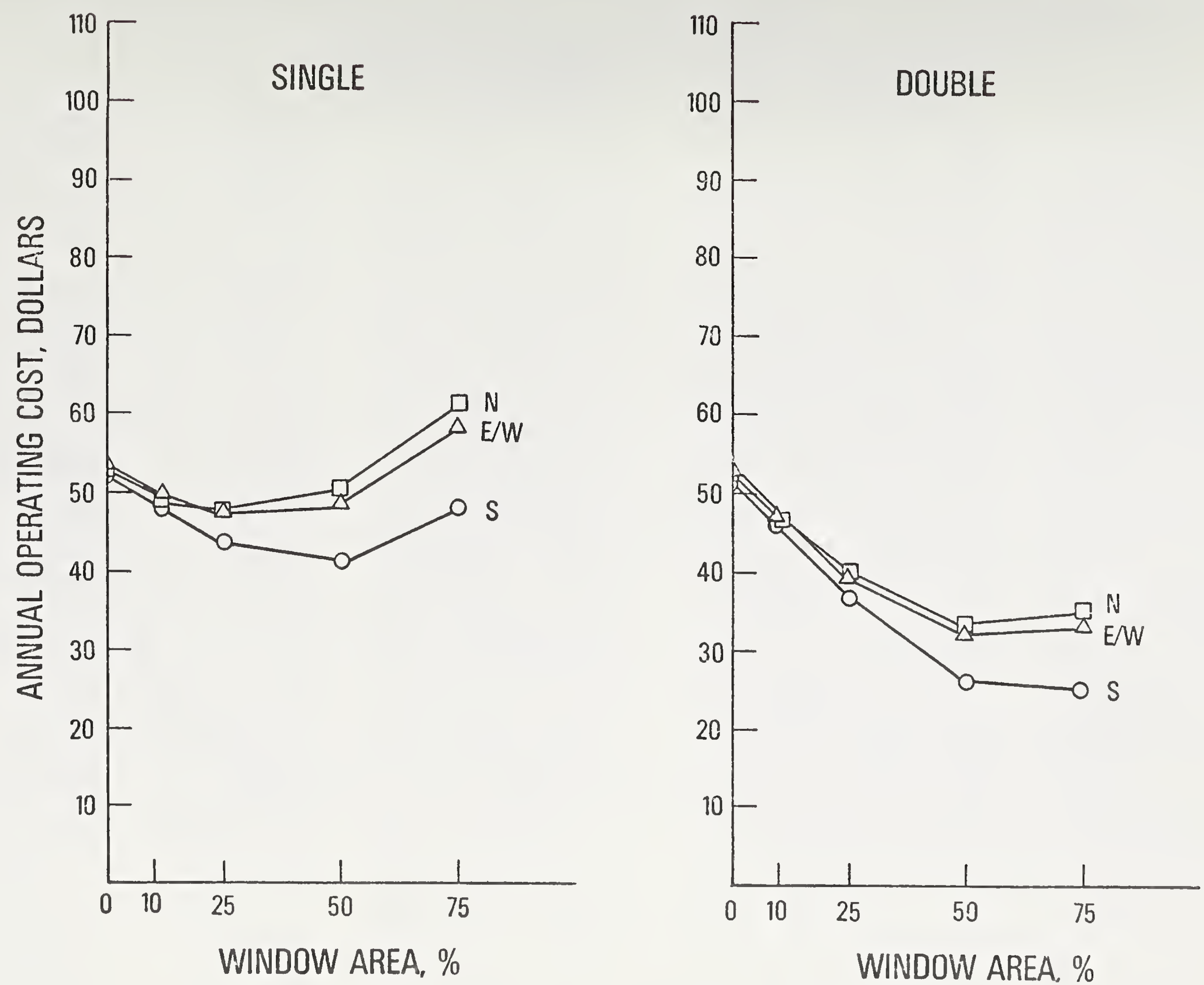


Figure 7. MODE III CASE 1. Estimated annual operating costs for an office module in Washington, D.C. using daylight. Open symbols represent dollar costs.

$25 less than for the 0% window. Again, south-facing windows cost less to operate than windows on the other orientations.

The data in Figures 4 and 6 suggest that the heat generated by the electric lighting can reduce the heating requirement. It is, however, more expensive and less efficient to heat a room with electric lighting than with gas heat. In the summer, of course, removal of the heat from the lights reduces the cooling requirements as well as the demand for electricity. In summary, the use of daylight appears to offer a marked potential for reducing overall energy consumption in buildings.

Figure 8 depicts the use of daylight combined with selective window management and unoccupied-hour temperature setback. When the seasonal heating and cooling requirements for this case, given in Figure 8, are compared with the case in which only daylight is used, Figure 6, it is apparent that the use of window management and temperature setback reduces the heating requirement for single-glazed windows. The cooling requirement is reduced only slightly. Double glazing cuts the heating requirement but does increase the cooling requirement over the single-glazed case. When daylight, management, and double glazing are used, the heating and cooling requirements are less than those for the zero window case for window areas up to 50% glazing on all orientations except north. There, the heating requirement jumps sharply for areas above 25%.

The reduction in yearly operating costs over the baseline condition is most dramatic when daylight and management are both used, as can be seen in the lower portion of Figure 9. Furthermore, costs are reduced below those for a solid wall by as much as $35 for 50% single glazing on the south or $26 for a similar north window. They begin to rise again for 75% glazing for all but the south exposures, but are still well below those for the 0% window. The difference in costs is even more dramatic when compared with the baseline case in which neither management nor daylight are used. These costs are given in the upper portion of Figure 9.

Table 10 demonstrates the effects of lowering wall U value for the different modes of operation. Lowering the wall U value (increasing its thermal resistance) reduces estimated costs slightly. These data are presented to demonstrate that the model can be extended to different design conditions.

5.1.4 Summary of Office Results

In Figures 10 and 11 estimated yearly operating costs for a window in an office module are plotted for four different conditions: bare window (external plus internal loads only); management and setback; daylight; and daylight, management, and setback. Figures 10 and 11 apply to walls with a U value of 0.07, a storage load factor of 0.5, and a shading coefficient of 1.0 (except during summer management conditions). The comparative effectiveness of the various conditions of operation for

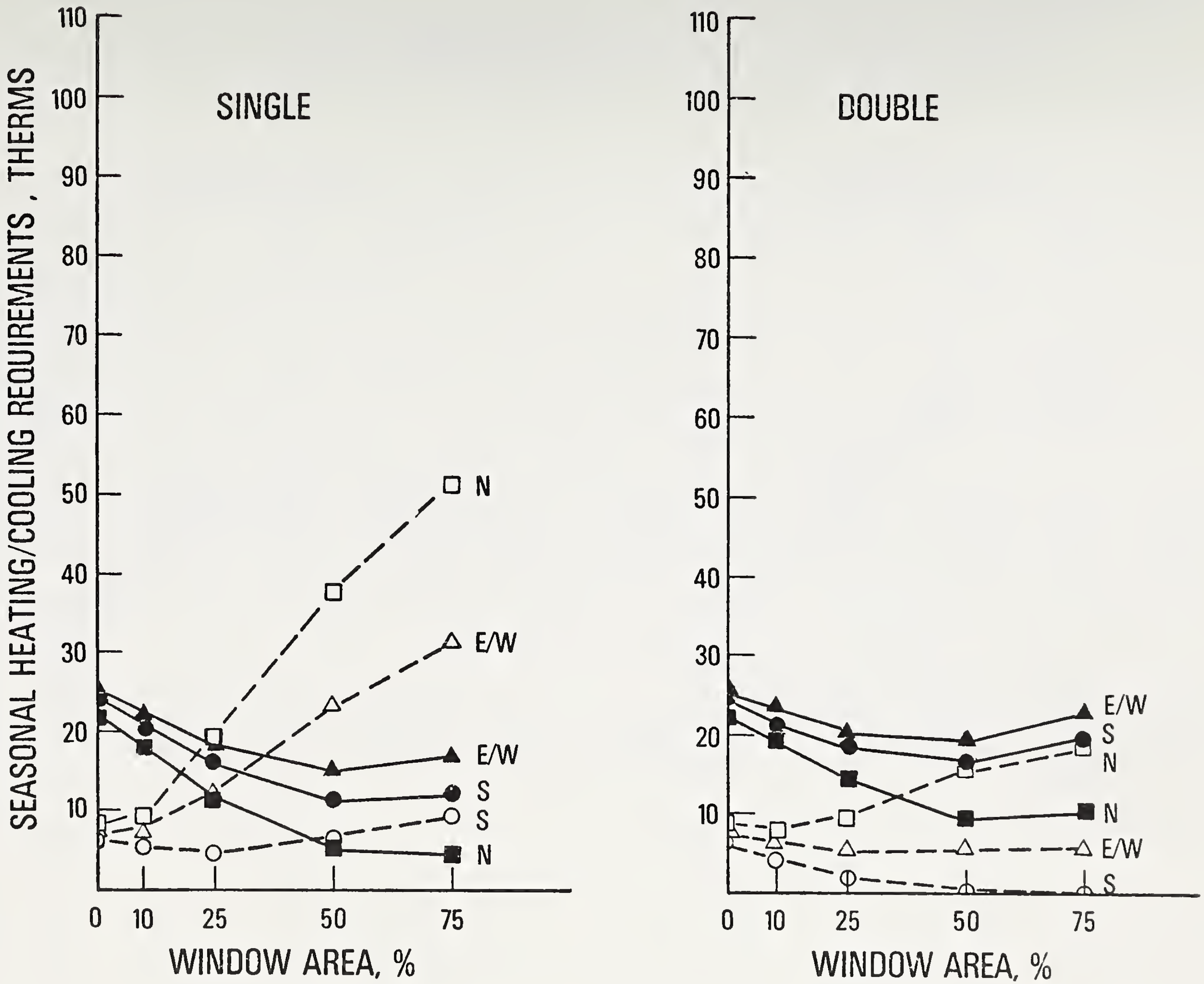


Figure 8. MODE III CASE 4: Seasonal heating and cooling requirements for an office module in Washington, D.C. with selective management, thermostat setback, and daylight. LF = .5, SC varies with season. Open symbols and dashed lines represent heating requirements solid lines and symbols represent cooling requirements.

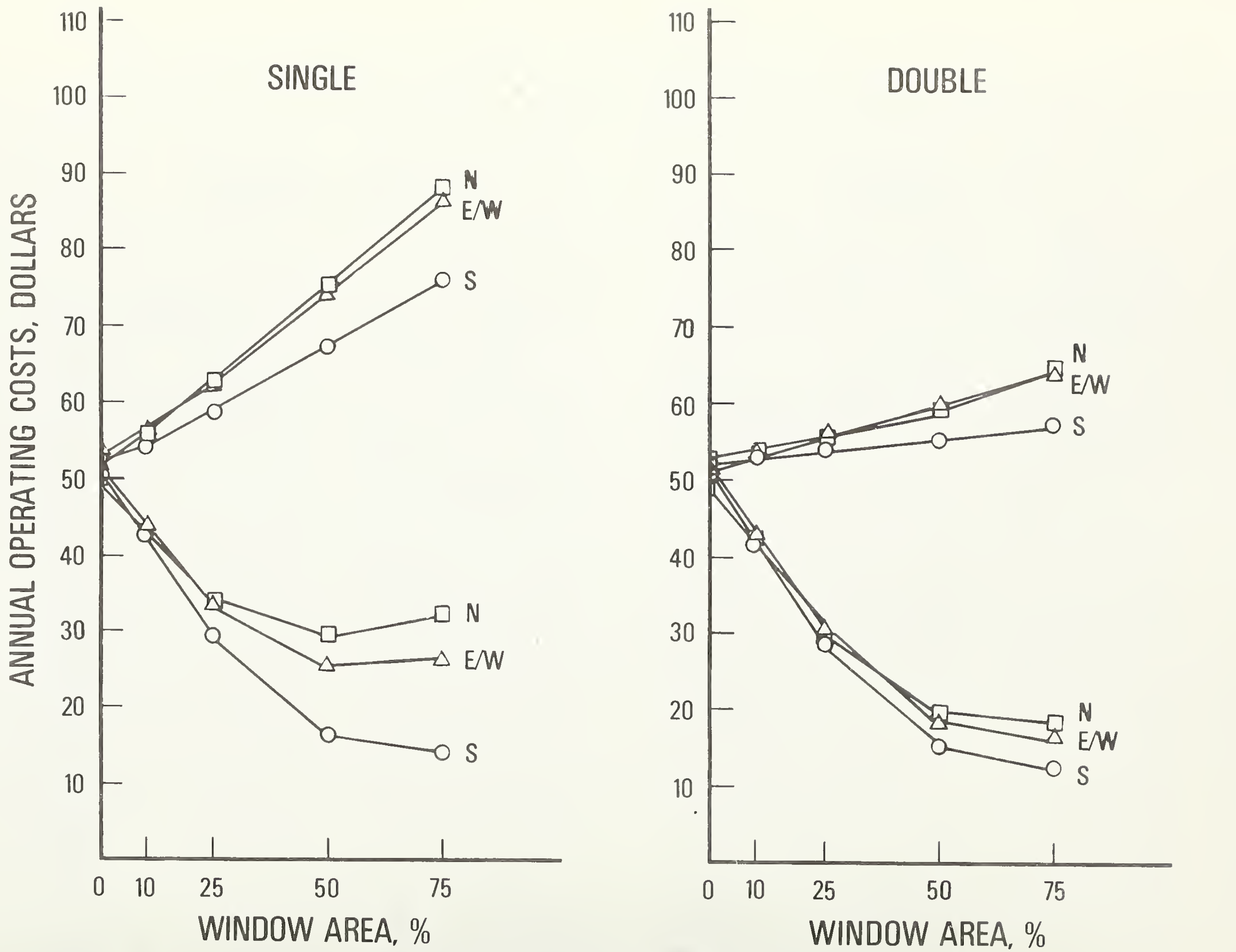


Figure 9. Comparison of estimated costs for MODE II CASE 1, external plus internal loads, represented by the upper three lines with costs for MODE III CASE 4, daylight, management, thermostat setback, represented by the lower three lines.

Table 10

Comparison of Estimated Yearly Energy Costs for a Commercial Module with Two Different Wall U Values with Gas Heating and Electric Load Factor = 0.5, SC = 1.0 (0.9) Cooling

Wall μ value	μ = 0.15					μ = 0.07				
Window area	0	10	25	50	75%	0	10	25	50	75%
Baseline - Single Glazing										
S	52.53	54.19	57.63	63.97	70.39	50.64	52.40	55.21	62.17	69.94
E/W	53.23	56.71	63.03	74.33	85.92	50.97	53.61	59.57	71.67	84.59
N	52.67	56.70	64.19	77.28	91.02	50.72	53.12	60.32	74.66	89.54
Management/Setback - Single Glazing										
S	50.79	50.62	50.45	50.41	51.39	49.58	49.34	49.20	49.87	51.16
E/W	51.47	52.02	53.01	55.51	58.58	49.89	50.38	51.21	53.65	56.29
N	51.01	51.59	53.87	58.78	64.44	49.70	50.23	51.22	54.46	59.61
Daylight - Single Glazing										
S	52.49	41.94	30.39	31.94	38.12	50.60	39.55	27.14	29.57	36.39
E/W	53.19	44.68	36.79	43.45	54.50	50.93	40.86	32.76	40.53	53.05
N	52.63	45.09	39.19	48.50	62.00	50.68	40.96	34.74	45.55	60.52

Daylight, Management, Setback - Single Glazing

S	50.75	42.13	29.12	16.55	14.84	49.54	40.85	27.88	15.80	14.55
E/W	51.43	43.53	33.29	25.25	26.53	49.85	41.89	30.14	20.81	21.93
N	50.97	43.44	35.89	31.38	35.60	49.66	41.73	31.27	26.09	30.03

Baseline - Double Glazing

S	52.53	53.24	54.54	57.05	59.91	50.64	51.52	53.19	56.20	59.57
E/W	53.23	54.73	57.38	62.03	66.87	50.97	52.67	55.35	60.22	66.00
N	52.67	54.05	56.55	60.97	65.65	50.72	51.97	53.91	58.84	64.50

Management/Setback - Double Glazing

S	50.79	50.46	50.17	50.58	51.66	49.58	59.24	49.16	50.29	51.54
E/W	51.47	51.80	52.31	53.34	54.51	49.89	50.24	50.89	52.14	53.65
N	51.01	51.25	51.64	52.39	53.50	49.70	49.96	50.14	51.19	52.32

Daylight - Double Glazing

S	52.49	40.39	24.82	19.99	21.15	50.60	38.67	23.17	18.45	20.65
E/W	53.19	42.46	29.53	28.66	32.75	50.93	39.82	26.06	26.10	31.61
N	52.63	42.02	29.97	29.75	33.90	50.68	39.12	25.83	26.80	32.43

Daylight, Management, Setback - Double Glazing

S	50.75	41.97	28.84	15.12	12.95	49.54	40.76	27.83	14.83	12.83
E/W	51.43	43.31	31.13	19.61	18.00	49.85	41.75	29.56	16.98	15.86
N	50.97	42.76	31.54	21.62	20.66	49.66	41.47	29.08	17.87	17.43

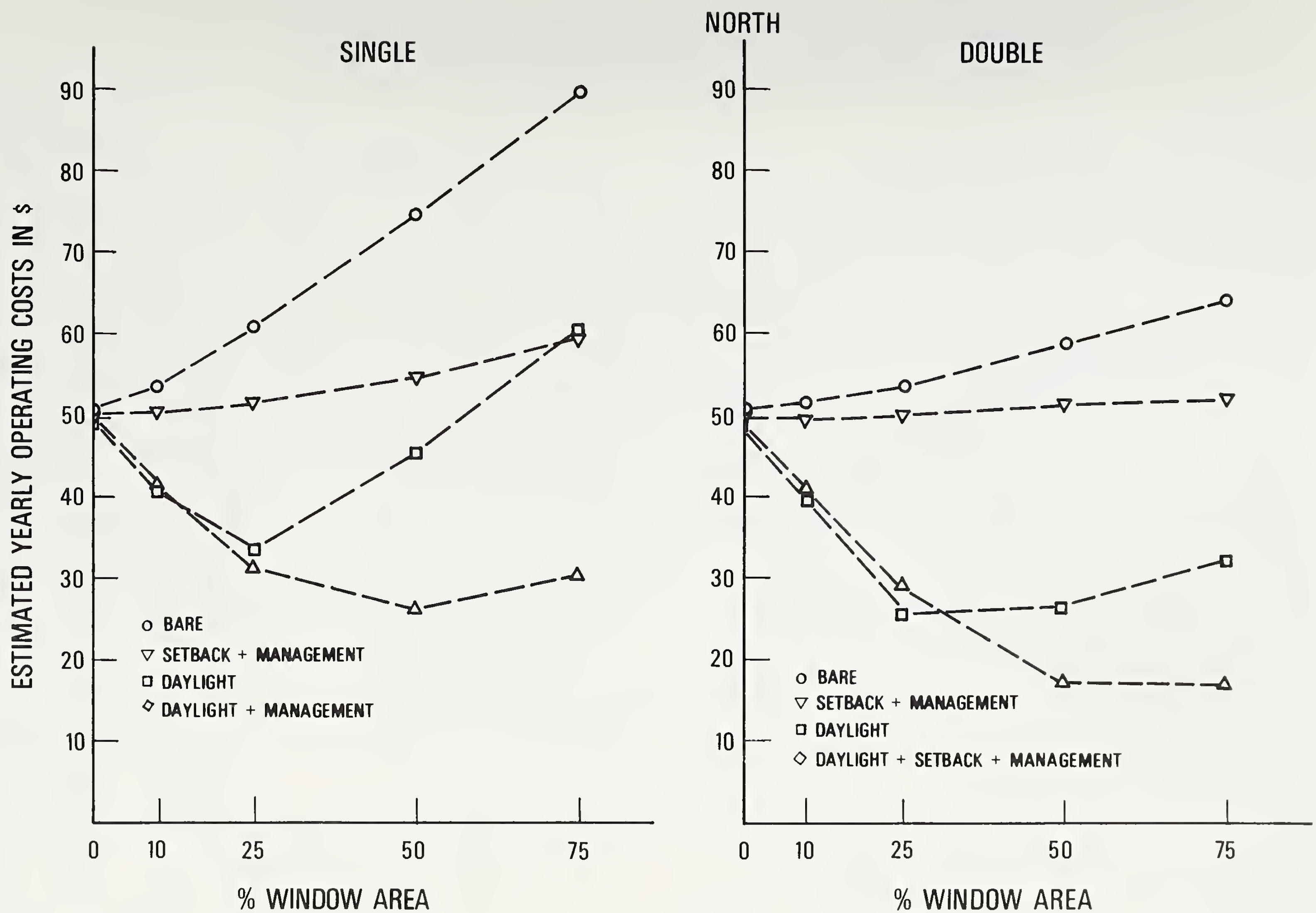


Figure 10. Comparison of estimated yearly operating costs for a north-facing window in a commercial module with a wall U value of 0.07 and storage load factor of 0.5, sc = 1 except when management used.

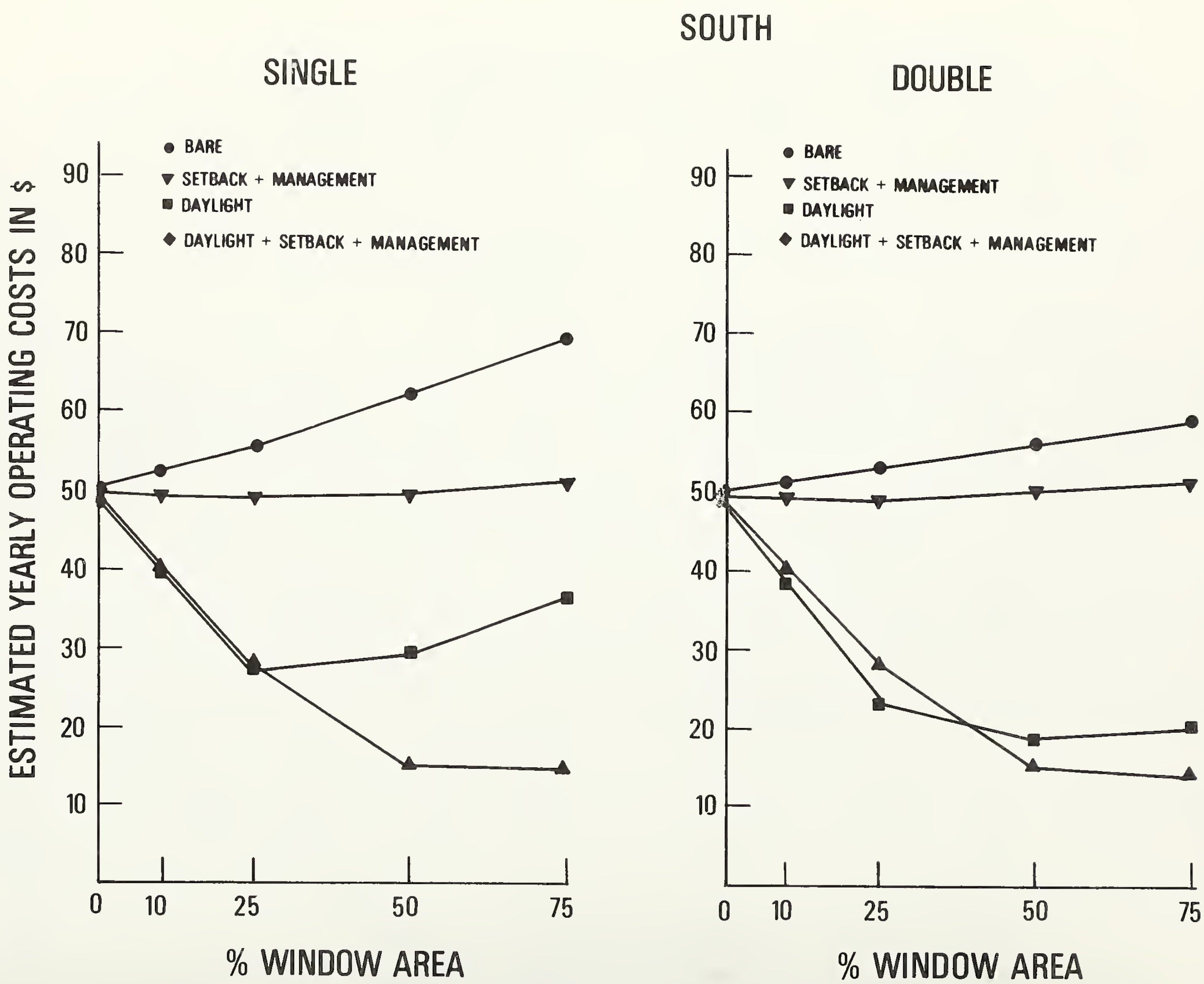


Figure 11. Comparison of estimated yearly operating costs for a south-facing window in a commercial module with a wall U value of 0.07 and storage load factor of 0.5, sc = 1 except when management is used.

both single and double glazing for a north-facing window can be readily seen from Figure 10. The differences between the four conditions indicate the possibilities for reducing energy consumption through different operating practices. The use of daylight, whether with or without management, appears attractive when double glazing is used. Figure 11 demonstrates that orienting the window to the south lowers all costs and improves the effectiveness of daylighting for the single-glazed case.

The calculations reported for the office module for the various modes of operation and cases of study indicate that the energy balance at the window can be reversed. If nothing is done to the window, increasing its area increases both the heating and cooling requirements (except on southern orientations) as well as operating costs. If extra glazing, window management, off-hour thermostat setback, and daylight are utilized, increasing window area no longer increases energy costs, and will, in some instances, actually decrease them.

Shading the window during the winter, however, may actually increase the heating requirement by preventing the use of solar heat gain. Furthermore, failure to use thermal barriers during winter nights can increase energy losses and operating costs substantially. Effective use of daylight also requires that it be substituted for artificial lighting (as long as a minimum level of illumination, such as 50 fc, is maintained). In this trade-off analysis, no attempt was made to assess the quality of the lighting for task performance. Rather, the analysis was based solely on the quantity of light and heat generated by the two sources.

The thermal analysis described for the office module demonstrates that the window can perform better than a solid wall, if the total window system is designed and operated in accordance with the assumptions presented here. There appears to be a range of window sizes occupying 25 to 50% of the window wall which can minimize yearly operating costs for an office module located in a climate similar to Washington, D.C. Additional calculations are needed, however, to extend this analysis to other window sizes, climatic regions, and geographic locations, as well as to a total building. In addition, field verification of the predicted reductions in thermal requirements and operating costs due to the use of daylight and management is necessary.

5.2 RESIDENTIAL MODULE RESULTS

The analysis of the three modes employed for the office situation,, was also used in a typical residential application. As before, the analysis focused on window performance, so that heat flow within and between rooms was not modeled.

The effects of varying window size, thermal resistance, shading, and orientation were assessed for the three modes and four cases in the residential situation. Thus the effects of external loads only (Mode I), external plus internal loads (Mode II), and external, internal, and daylight (Mode III) were modeled for the following cases: constant temperature (Case 1); nighttime setback (Case 2); window management (Case 3); and management plus setback (Case 4).

Results from the calculation of seasonal heating and cooling requirements for several different types of operation are presented first. Then, summary graphs, depicting estimated yearly operating costs for a north-facing and a south-facing window are given to compare the effects of the different operations.

5.2.1 MODE I: External Loads Only

As in the office situation, consideration of only the external loads demonstrates that both the heating and cooling requirements increase substantially with increasing window area for the residential module. The increased heating requirement is greatest on northern exposures and smallest on southern exposures. It is reduced substantially by the addition of double glazing, however. Because the results are very similar to those for the office situation, the data for external loads only are not presented graphically.

5.2.2 MODE II: External Plus Internal Loads

The addition of internal loads to the external loads decreases the heating requirement slightly, but increases the cooling requirement substantially. Yet, Figure 12 demonstrates that the heating requirement still increases rapidly with increasing window area in the single-glazed case. The upper portion of Figure 13 presents seasonal heating and cooling requirements for a window with management. The lower portion presents results for management plus setback. As in the office situation, window management means that wooden thermal shutters cover the window on winter nights, while white venetian blinds are used on summer days. The upper portion of Figure 13 demonstrates that window management decreases the heating requirement from that needed for the load-only case (Fig. 12) but increases the cooling requirement. The lower portion of Figure 13 shows that the addition of thermostat setback to window management reduces the heating and the cooling requirements over those shown in Figure 12 for all window areas.

5.2.3 MODE III: Daylight Plus Thermal Loads

In Mode III, Case 1 daylight replaces artificial light whenever about 6.7 fc of daylight falls on a horizontal surface 3 ft from the floor and 15 ft from the window. The artificial light is turned off, removing 0.65 watts/sq ft of heat load and the electricity for burning the light. Brief inspection of Figure 14 reveals that the cooling requirement is reduced well below that for the bare window (Figure 12), in which no daylight replacement occurred. However, the heating requirement is substantially higher for both single and double glazing.

Figure 15 represents the case in which the window is used most effectively. In addition to daylighting, window management and nighttime temperature setback are used. The result is to reduce the heating and cooling requirements compared with the baseline case (Figure 12). Furthermore, the heating requirement noted for the daylight-only case (Figure 14) is

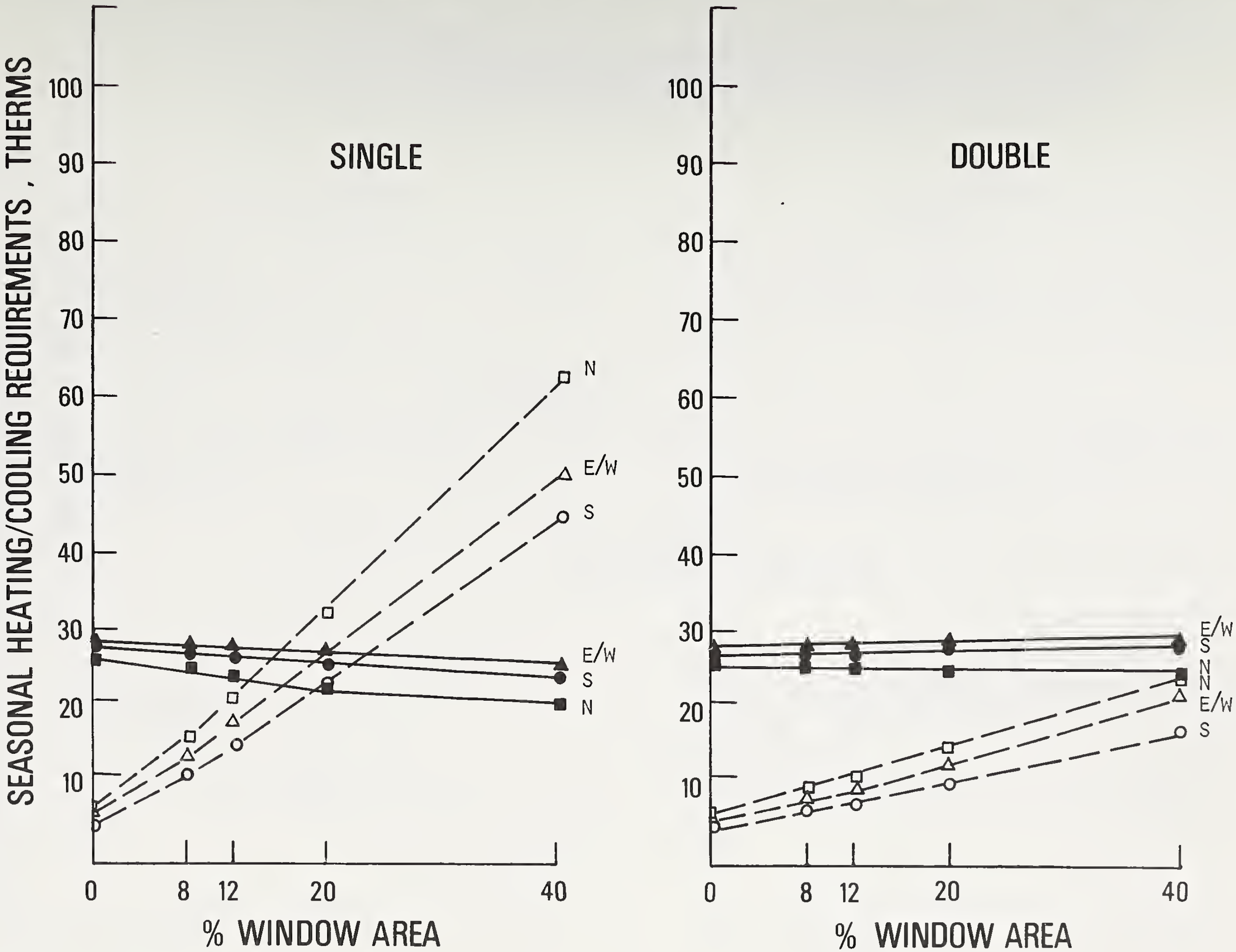


Figure 12. Mode II Case 1. Seasonal heating and cooling requirements for internal and external loads for a residential module; Wall U value = 0.07, LF = 0.1; Open symbols = heating requirements; Solid = cooling requirements.

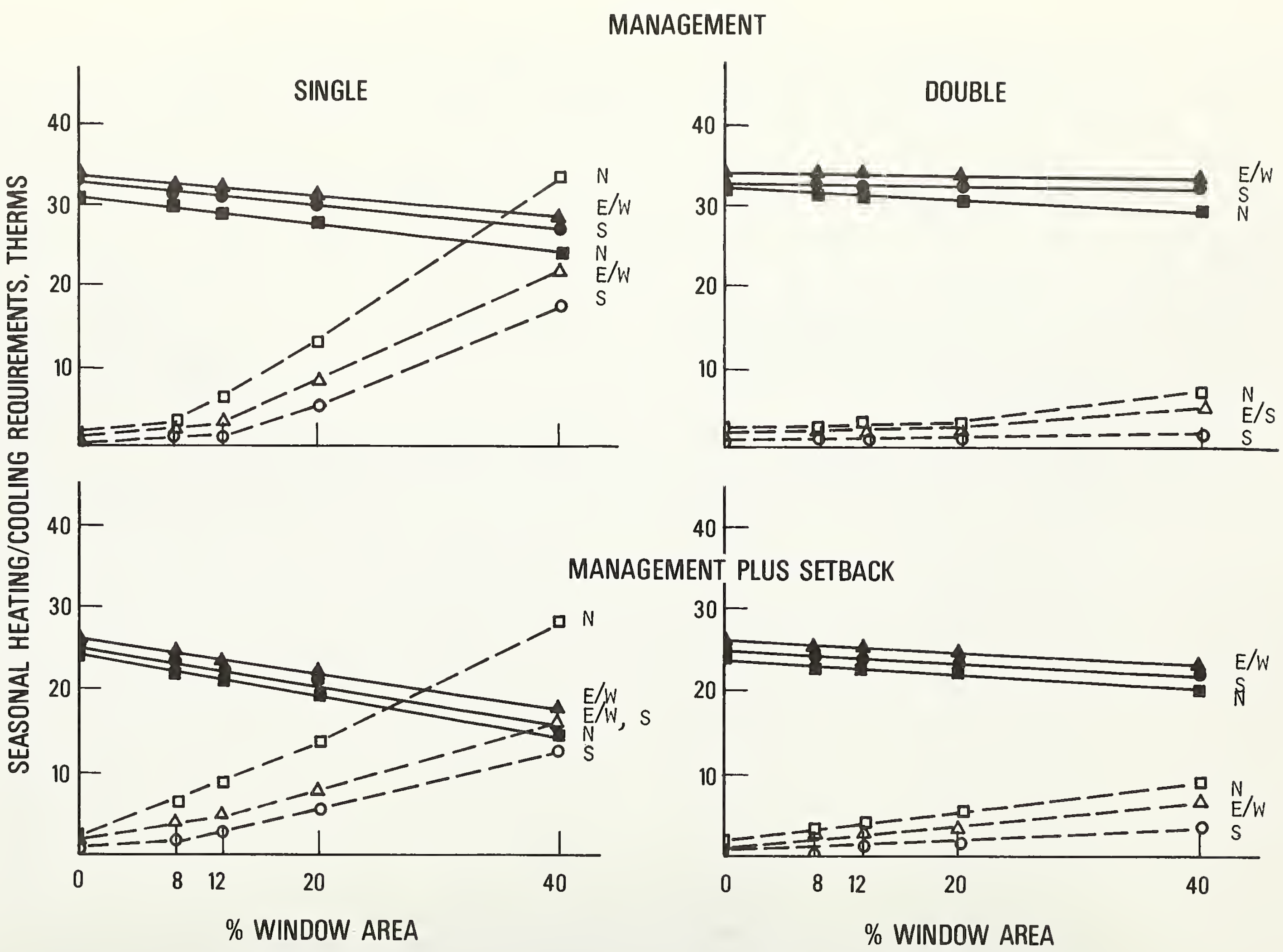


Figure 13. Mode II Case 3 and 4. Seasonal heating and cooling requirements for a residential module with management, and management plus setback, open symbols represent heating requirement; solid symbols represent cooling requirement.

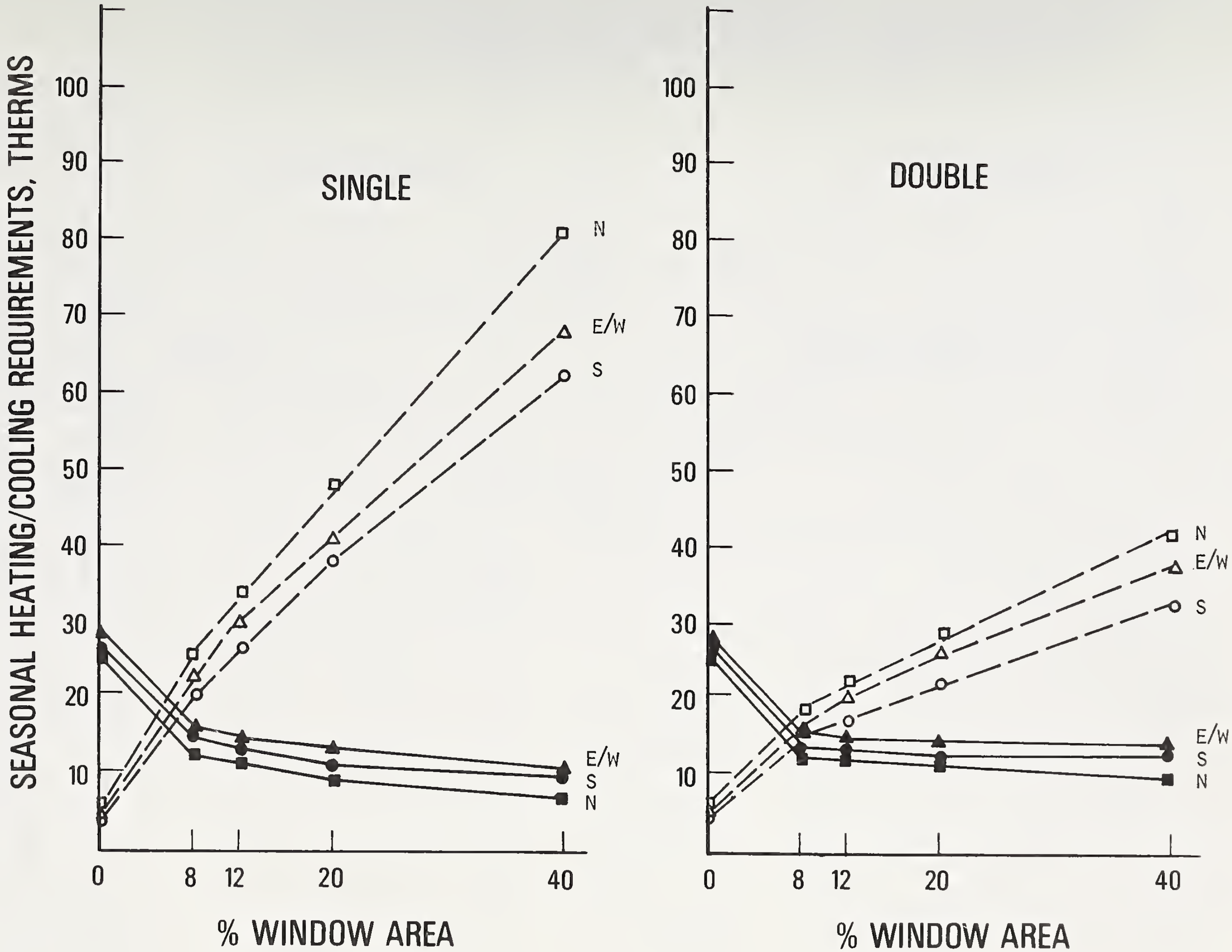


Figure 14. Mode III Case 1. Seasonal heating and cooling requirements for a residential module with daylight; open symbols = heating requirements; solid symbols = cooling requirements.

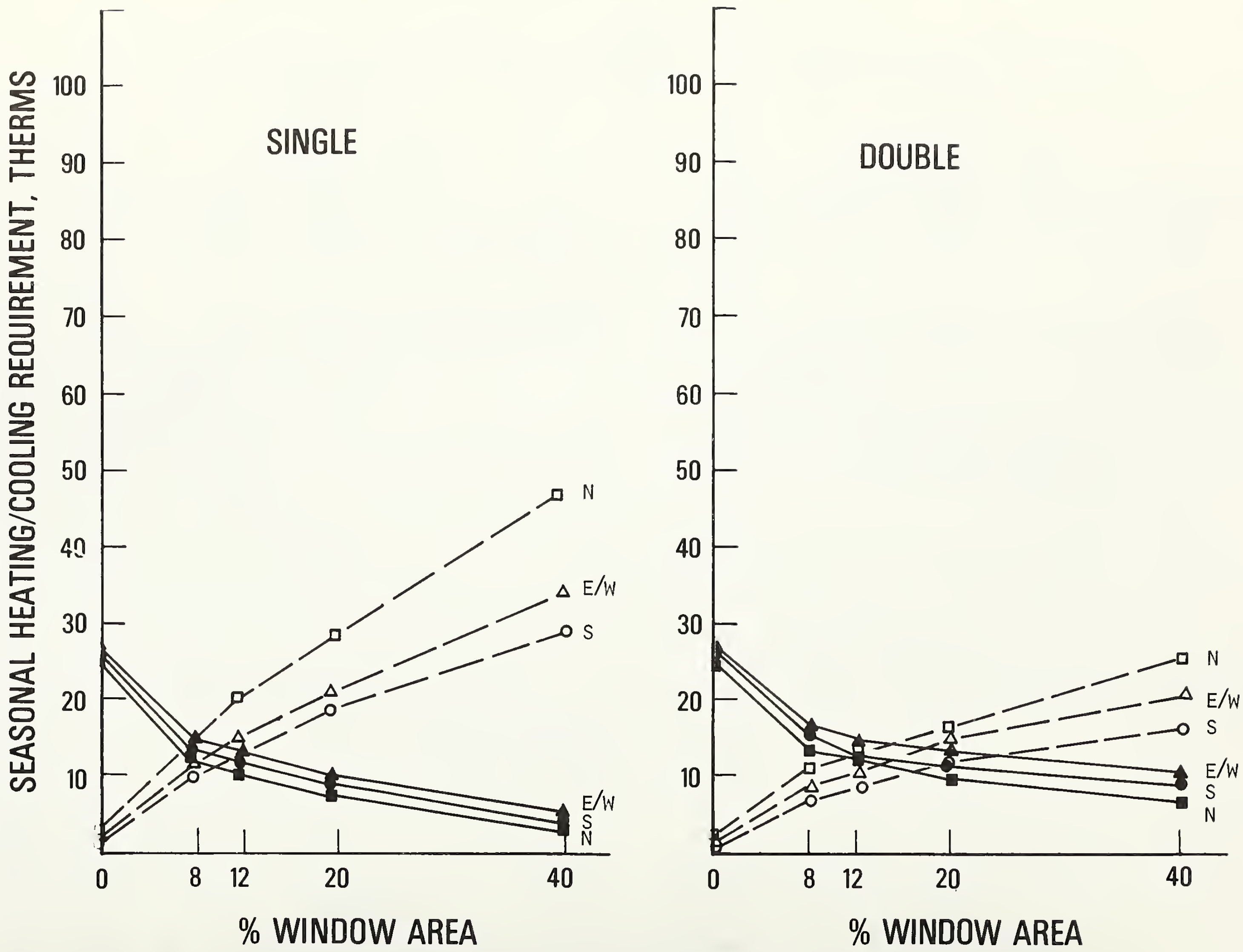


Figure 15. Mode III Case 4. Seasonal heating and cooling requirements for a residential module with daylight utilization, window management, and thermostat setback, open symbols represent heating requirements; solid symbols represent cooling requirements.

cut substantially while the cooling requirement is reduced slightly.

5.2.4 Summary: Operating Costs

Figure 16 summarizes the estimated yearly costs for six types of operation for a north-facing window in a residential module for both single and double glazing. Comparison of the various curves reveals that, if nothing is done to the window, operating costs increase by about $25 for single glazing and by $10 for double glazing as window size increases. Window management reduces this increase, as does a combination of thermostat setback and management. In fact, with double glazing the detrimental cost effects of increasing window area are just about removed for management or management/setback. Figure 16 also demonstrates the beneficial energy effects of substituting daylight for incandescent light. Costs are reduced by $15-20 over the case in which setback and management are used -- for all single-glazed areas. Similar results hold for double glazing. Further reduction in costs, in the order of $5-10, are possible through the use of management and setback. In the most dramatic example, costs are cut in half for the largest single-glazed window area by the use of daylight, management, and setback. In fact, costs are even about $25 lower than they are with a solid wall.

Figure 16 also demonstrates that double glazing is most effective in reducing overall costs when the window is unmanaged -- e.g., in the bare window case, and the daylight only case. This occurs because the management conditions assume that the thermal resistance of the window is increased on winter nights to about that of a double-glazed window through the use of tightly-fitting wooden shutters.

Figure 17 summarizes the overall operating costs obtained for a south-facing window. Simply orienting a window to the south reduces yearly costs by $2-10 for single-glazed windows for all 6 types of operation. Costs are also reduced slightly for double-glazed windows. The pattern of results is very similar to that obtained with north-facing windows with costs increasing with area for bare windows, and remaining level for management and setback. Use of daylight causes all costs to remain lower than those incurred with a solid wall. With the use of daylight, there is some indication of a window size, of 8-12% for single glazing, and 20% with double glazing, which minimizes operating costs. When daylight, management, and setback are all used, estimated costs continue to decline for double glazing, even for the largest window area.

Figure 18 presents a comparison of costs for two different types of operation for a residential module with electric heating and cooling. Costs for the bare window are given by the upper two curves while costs for a window with daylight, management, and setback are given by the lower two curves. Because these graphs represent a situation in which a more expensive fuel is used for heating, costs are higher than those obtained for Figures 16 and 17 in which a less expensive fuel (gas) was used. Differences between north and south orientations appear particularly pronounced for the situation in which daylight, management, and setback are used.

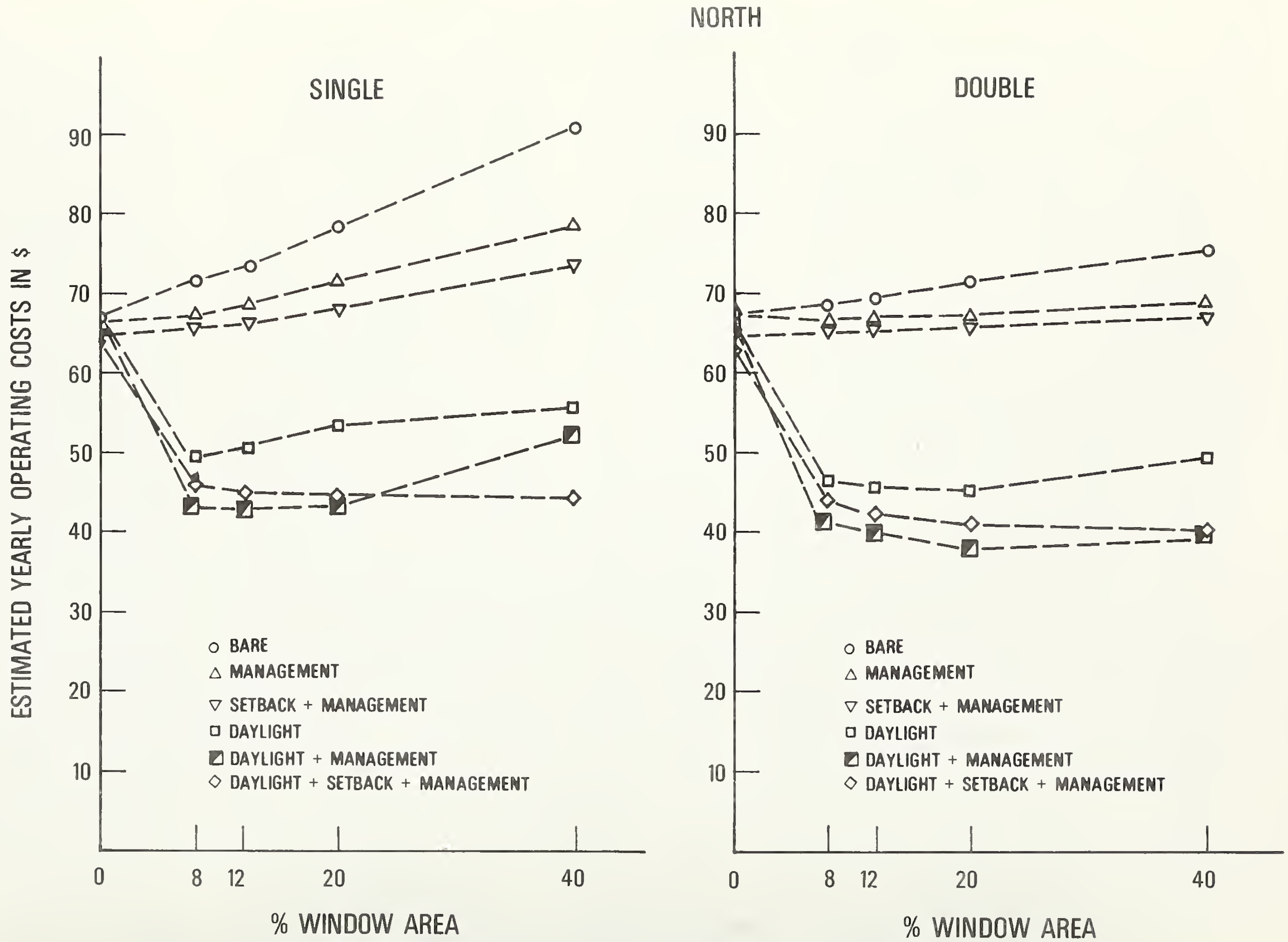


Figure 16. Comparison of estimated yearly operating costs for a north-facing window in a residential module with a wall U value = 0.07, load factor of 0.1, and shading coefficient of 1.0 for different modes and cases of operation.

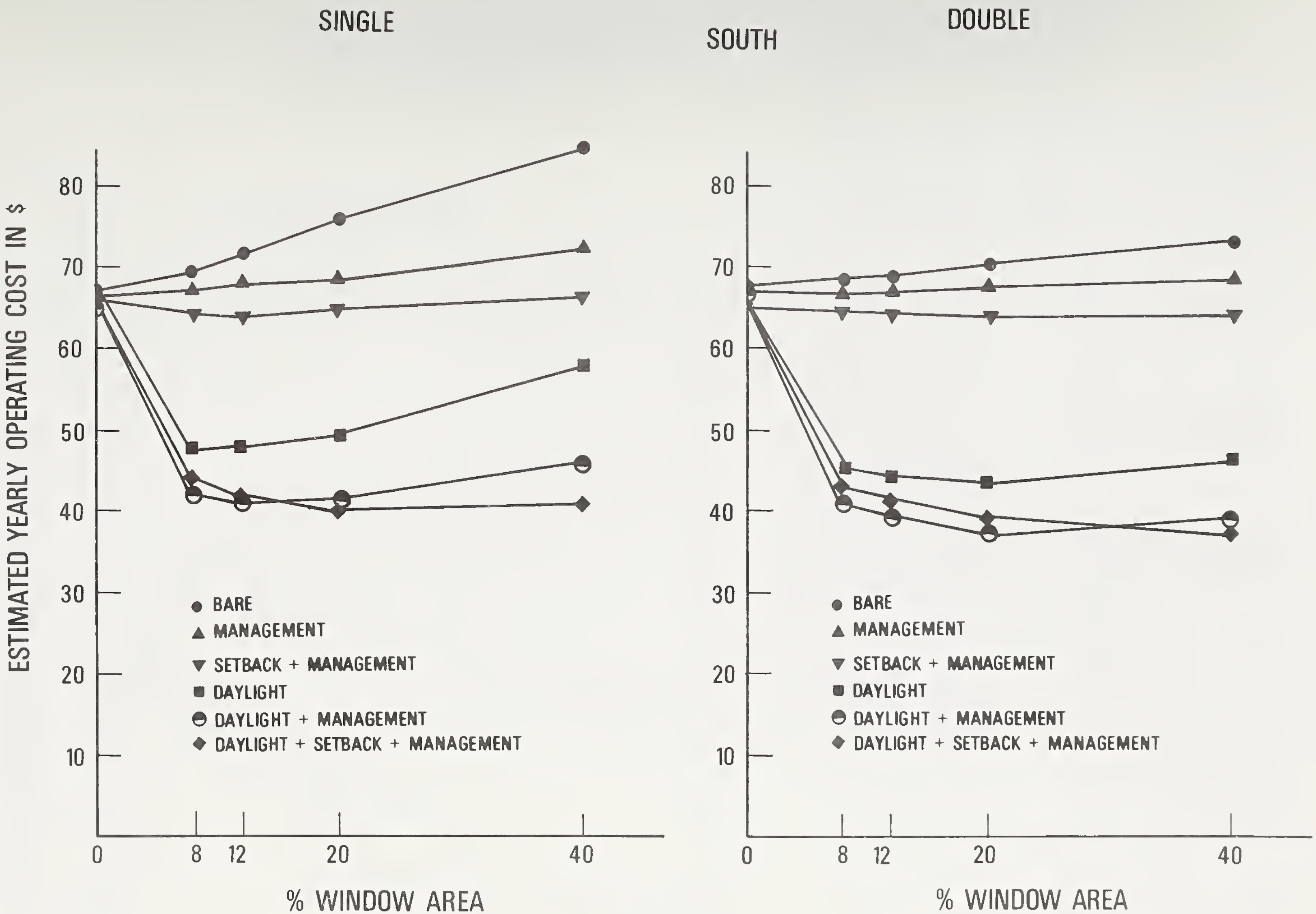


Figure 17. Comparison of estimated yearly operating costs for a south-facing window in a residential module with a wall U value of 0.07, load factor of 0.1, and shading coefficient of 1.0.

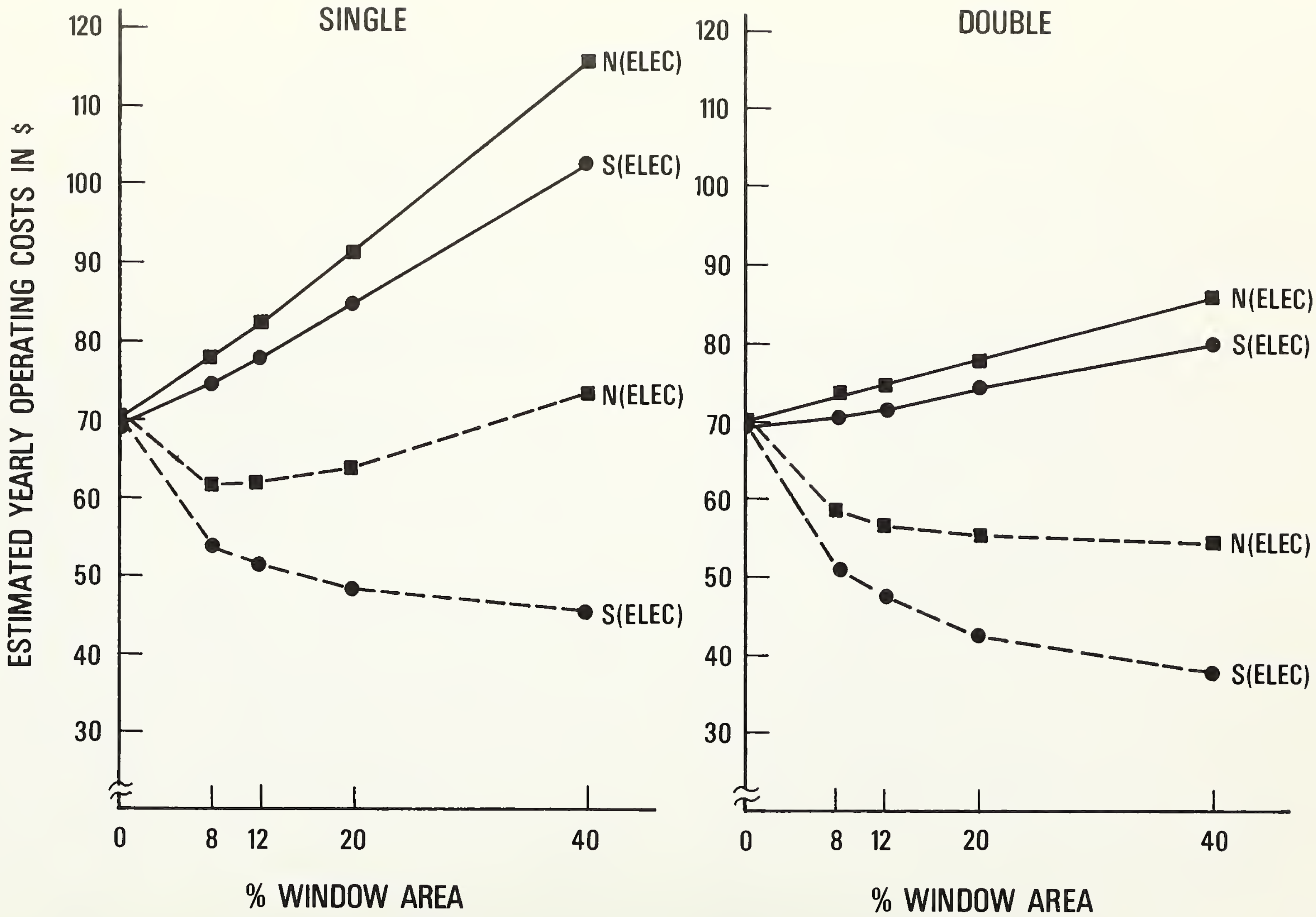


Figure 18. Estimated yearly operating costs for a residential module using electric heating and cooling. The two upper curves represent a bare window (Mode II Case 1). The two lower curves represent a window in which daylight, management, and setback are used. Wall U value = 0.07, load factor = 0.1.

When operating costs are considered for a window with management, daylight utilization, and temperature setback, Figure 18 demonstrates that a single-glazed window results in lower yearly operating costs than an insulated wall system of equal size for all areas except the largest north-facing window. When double glazing is used, even with electric heat, windows of all sizes do better than a comparable wall. Costs are reduced most, of course, with a south-facing window and gas heat. Nevertheless, the combined use of daylight, window management, temperature setback, and double glazing reduces residential energy use and operating costs substantially.

In summary, the energy balance at the window in a residence is affected both by fixed design parameters, and by actual operating practices. The results are similar to those for the office situation, except that the lowest operating costs are obtained with smaller areas of glazing. Although questions remain about the ways in which both daylighting and window management are actually used in homes, these results suggest some ways in which energy resources can be conserved through careful attention to the design and operation of windows.

6. GENERAL CONCLUSIONS

The results from the thermal and lighting calculations demonstrate that a properly designed and operated window system can reduce overall operating costs below those for a solid wall for the two types of rooms simulated in the metropolitan Washington, D.C. area. The reduction is greatest for managed south-facing, double-glazed windows in which daylight replaces or supplements artificial light. In all cases, however, reducing operating costs for windows requires careful consideration of orientation, the balance between annual heat gains and losses, use of daylight whenever sufficient, and good management practices including off-hour temperature setback.

The single option that has the most impact is the use of daylight rather than artificial light. Its use appears to reduce all window operating costs relative to the baseline conditions, for the assumptions outlined in this report.

The findings from the computer analysis should be treated cautiously. They are based upon computer simulation, not actual case studies. Further experimental verification by data collection on window performance and use in existing buildings is necessary. Furthermore, not all the parameters that affect window performance in real situations are modeled. The major omission involves air exchange around and through the window in the form of natural ventilation and infiltration. In addition, the effects of the building HVAC system response upon window performance were not assessed.

Nevertheless, the findings presented in this paper indicate clearly that annual operating costs can be lowered through the use of window management and/or daylight. The use of a thermal barrier on winter nights combined with shading on summer days will cut undesirable heat loss and gain noticeably, while the combination of these devices with the use of natural light improves window performance beyond that of a solid wall. An effective HVAC system which increases the utilization of excess daytime heat gain or storage load factor for the heating season and decreases it for the cooling season should also improve the overall performance of windows. Unless window management and daylight are used, however, windows will increase heating and cooling requirements when compared to an equivalent wall area. These requirements can be reduced somewhat through the use of double glazing, fixed shading, and proper orientation of the window. Nevertheless, the best performance results are obtained when all the options for reduction of heat loss and gain are utilized and daylight is substituted for electric light, whenever practicable.

The results indicate further that there may be a range of window areas which maximizes daylighting and beneficial solar heat gain and minimizes undesirable heat gains and losses. This range appears to be centered between 12% and 20% of the window wall for the residential module and around 50% of the window wall for the office module, if daylighting, setback, and management are used according to the design conditions, and if orientation and double glazing are chosen carefully. The differences in the range of areas between the two modules indicate the importance of the assumptions made about the internal loads inside the two modules. Thus, the external loads, daylight availability, thermal performance of management devices, orientation, and glazing resistance remain the same for both situations. In the office situation, however, the internal loads are much greater due to higher occupancy, higher lighting levels, and higher equipment loads. It is in the latter situation that daylighting is particularly energy-effective by reducing loads upon the cooling system and by reducing the use of electricity for lighting.

This report also makes certain assumptions about patterns of use and management. These are: 1) off-hour thermostat setback; 2) dimming or turning-off of electric lights whenever sufficient daylight is available at a given reference point; 3) use of thermal shutters on winter nights; 4) use of venetian blinds on summer days. Although each of these options can be accomplished manually, there is some question as to the extent to which people will avail themselves of these energy-saving possibilities. It is possible, of course, to circumvent human behavior by using automation. Thus, the first possibility, thermostat setback, is readily available as an automatically timed device. The second option can also be automated through the use of photocell-activated switches and dimmers. The Building Research Establishment in Great Britain is currently investigating such devices.[16] It is more difficult to automate the last two devices, although automated venetian blinds have been used infrequently in England.[17] On the other hand, it may not be necessary to resort to automation in all cases. For example, nighttime closing of shutters or draperies often occurs as a routine matter to preserve privacy or to prevent cold draughts in the winter. It may be possible to accomplish some of these options by informing people of the large energy-saving potential associated with them. Nevertheless, the management options discussed in this paper do require either informed human behavior or extensive automated controls in order to realize the predicted energy savings. (Costs of the various management options are not dealt with here.)

7. RECOMMENDATIONS FOR FUTURE RESEARCH

The limited number of computer calculations summarized in this report indicate the possibility that, at least in the Washington, D.C. area, a window can conserve rather than waste energy. The conditions under which energy savings may occur are based upon specific assumptions about the design and use of windows.

Further research is needed to verify the energy savings predicted in this paper in both field and laboratory situations. Perhaps the two most controversial areas dealt with by the model involve the actual utilization of excess heat gain during the winter, and the exact quantification of available daylight under different sky conditions, room configurations, and window designs.

The model also makes some specific assumptions about window management. Although many theories about human behavior have been advanced to deal with the management of such energy-using building components as lights, HVAC systems, shading devices, and windows, very little investigation has been made of typical management behaviors. How do people use lights, windows, draperies, blinds, and/or shutters? What variables affect the use of each of these? Answers to questions such as these are essential for designing effective energy-conservation systems.

Still another area of major concern is the development of valid daylight prediction techniques under a wide variety of conditions. The calculations discussed in this paper need to be extended to more complex situations. The following list summarizes some important items which should be considered in further daylight research.

a) Hourly variation of available outdoor illumination throughout the U.S.A. as affected by the sun's altitude angle, cloud cover, reflected light from the ground and other exterior objects, and the shadows cast by external objects.

b) Hourly solar heat and light gain through the fenestration as functions of the type, size, location, and shape of the windows and their shading devices (both external and internal).

c) Hourly indoor illumination by daylight at a selected point and the minimum additional illumination required by artificial lighting.

d) Hourly cooling load due to the solar heat gain, lighting, equipment, occupancy condition, heat from the exterior envelope, and infiltration.

e) Hourly heat loss through the window as affected by the outdoor temperature, infiltration, and wind speed and direction.

f) Heating effects of artificial light as compared with the solar heat gain through the window during the winter.

g) Quantification of the extent of window heat loss and heat gain and light transmission when controllable shading or shutter devices are used. By these devices, it would be possible to admit maximum daylight during the winter day to assist heating and lighting of the room, and to utilize the options to minimize the heat loss during the night. The shading device would also be used to impede excess amounts of solar heat gain. For example, Rosenfeld and Selkowitz[18/] have described a novel scheme in which direct daylight illumination is beamed by venetian blinds from the top of the window to a highly reflective ceiling. This scheme increases the room illumination without causing undesirable glare at the working level.

h) The psychological needs of occupants for visual communication with the outdoors through the window. This need is stronger in some rooms, such as those occupied by recuperating hospital patients or by factory workers who are engaged in routine and monotonous work.[27]

Extensive and systematic studies of the windows should be part of a general program which includes some of the items mentioned above. The number of experimental studies and observations can be minimized if selected aspects of fenestration design are studied by computer simulation techniques to determine the daylighting effect and heating and cooling energy consumption on an hourly basis.

NBS is currently developing an hourly daylighting simulation computer program using U.S. Weather Bureau tapes. This program will be designed to perform the following calculations pertinent to the daylight analysis:

1. Solar energy incident upon the surface of a given orientation and inclination under clear as well as cloudy sky conditions can be calculated. The radiation data are determined separately for the direct and diffuse components.

2. Solar heat gain through windows is calculated by considering interior shading devices, exterior overhangs, and side fins.

3. Heat loss and gain through the exterior envelope are determined by taking into consideration the comprehensive heat transfer between the interior as well as thermal mass of the structure and room air.

4. Heat emitted by the occupant, lighting fixture, and equipment is included.

With the addition of a daylight computer routine, it is a relatively simple matter to include in the computer program a scheme for switching off or reducing the artificial lighting whenever the daylighting level at a given point in the room exceeds a prescribed set value of illumination for a specified task.

ACKNOWLEDGEMENTS

The authors are grateful to the many persons in the Center for Building Technology who contributed to the preparation of this manuscript. In particular, we wish to thank John Bean and Bob Chapman for their assistance with the computer work, as well as Reece Achenbach, Joe Murdock, Don Quigley, and Art Rubin for their helpful comments and guidance, and Sharon Rippeon and Susan Stitely for their help with typing.

REFERENCES

1. Hastings, S. R. and Crenshaw, R., Window Design Strategies to Conserve Energy. BSS 104, U.S. Department of Commerce, NBS, June 1977.

2. Collins, B. L., Windows and People: A Literature Survey: Psychological Reaction to Environments With and Without Windows. BSS 70, U.S. Department of Commerce, NBS, June 1975.

3. Ruegg, R. T. and Chapman, R., Economic Evaluation of Windows in Buildings. NBS Report in preparation.

4. Kusuda, T., Hill, J. E., Liu, S. T., Barnett, J. P., and Bean, J. W., Pre-Design Analysis of Energy Conservation Options for a Multi-Story Demonstration Office Building, BSS 78, U.S. Dept. of Commerce, NBS, November 1975.

5. Hopkinson, R. G., Supplementing daylight in offices. Light and Lighting, 1961, 54, 296-299.

6. Holton, J. K., Daylighting of Buildings: A Compendium and Study of its Introduction and Control. NBSIR 76-1098, October 1976.

7. Kusuda, T. and K. Ishii, Hourly Solar Radiation for Vertical and Horizontal Surfaces for the Average Day in the United States and Canada, BSS 96, U.S. Dept. of Commerce, NBS, 1977.

8. All Year Energy Savings All Around the House. Pamphlet prepared by PEPCO, Potomac Electric Power Company, 1900 Pennsylvania Avenue, N.W. Washington, D.C. 20068.

9. Liu, B. H. and Jordan, R.C., Availability of Solar Energy on Flat Plate Solar Heat Collectors, ASHRAE Symposium, Bulletin for Low Temperature Energy Applications of Solar Energy, New York, 1967.

10. DiLaura, D. L., and Hauser, G. A., On Calculating the Effect of Daylighting in Internal Spaces, Smith, Hinchman and Grylls Report, June 1977.

11. DiLaura, D. L., LUMEN-II Lighting Analysis System, Smith, Hinchman and Grylls, June 1977.

12. Lynes, J. A., Principles of Natural Lighting, Applied Science Publishers Ltd., London, 1968.

16. Collins, J. B. and Crisp, V. H. C., "Energy Management and the IES Code", Current Paper, Building Research Establishment, Department of the Environment, U.K., 1977.

17. Beckett, H. E. and Godfrey, J. A., Windows - Performance, Design, and Installation, Van Nostrand Reinhold Company, New York, 1974.

18. Rosenfeld, A. H. and Selkowitz, S., Beam Daylighting, Chapter 5 of Report of 1975 Berkeley Summer Study on Efficient Use of Energy in Buildings, LBL 4411, 1976.

19. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Handbook and Product Directory, 1976 Systems, ASHRAE, New York, 1976.

20. Meriwether, R. F., Computer Programs for Energy System Analyses, APEC Journal, July 1971.

21. Kelly, G., Kusuda, T., and Hill, J., Potential for Energy Conservation in Heating, Ventilating, and Air-Conditioning Equipment for Buildings in Energy Conservation through Effective Energy Utilization, NBS Special Publication 403, pp. 163-191, June 1976.

22. International Recommendations for the Calculation of Natural Daylight, Publication CIE No. 16 (E-3.2), 1970.

23. McNamara, A. C., The potential of location within a room in producing ESI, Journal of the IES, April 1976, p. 169-176.

Appendix A

HVAC SYSTEMS AND WINDOW DESIGN

This section is provided to assist architects and illumination engineers toward an understanding of typical building HVAC systems, operation of which significantly affects the energy benefits obtained from careful window design. An inefficient central HVAC system could more than offset the energy conservation provided by carefully designed fenestration. Only a few selected systems are illustrated. Readers who are interested in more details on this subject should refer to ASHRAE Systems Handbook.[19]

SINGLE-DUCT CONSTANT AND VARIABLE VOLUME SYSTEMS

Figure A-1 depicts a schematic of a single-duct single-zone system which could be either constant volume or variable air volume (VAV), depending upon the air outlet unit in the room's ceiling. In order to respond to the changing space load, the constant volume system regulates its heat delivering capacity by changing the supply air temperature. This is accomplished by regulating the heating coil temperature during the heating season or cooling coil temperature during the cooling season. The variable volume or VAV system, on the other hand, maintains a constant coil temperature during each season, but regulates the supply air flow rate to meet the changing load. This can be done by either a damper in the VAV box at the ceiling or by dumping part of the supply air into the ceiling plenum space. The air supplied to the space exchanges heat with the air in the space.

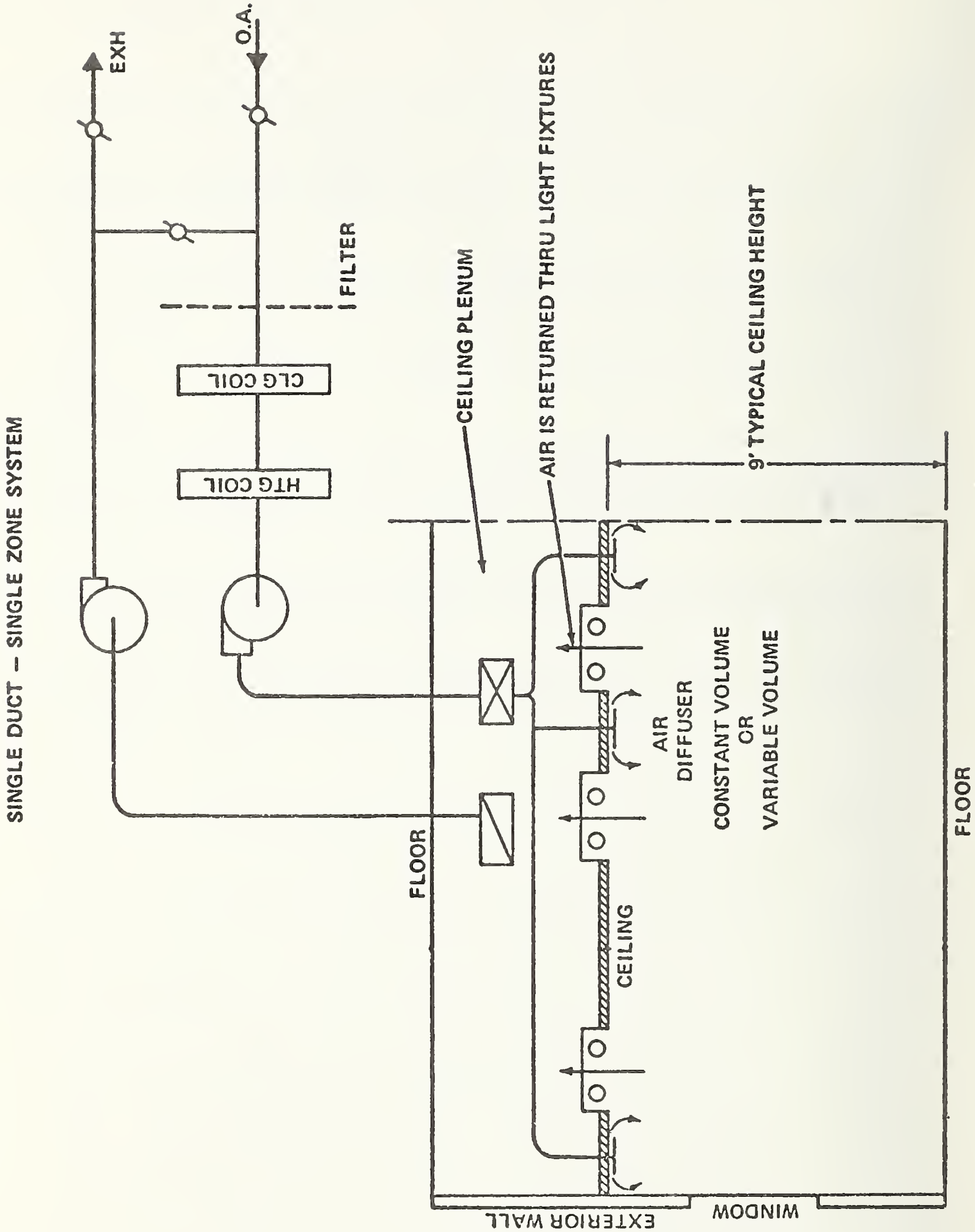


Figure A-1. Single-Duct System

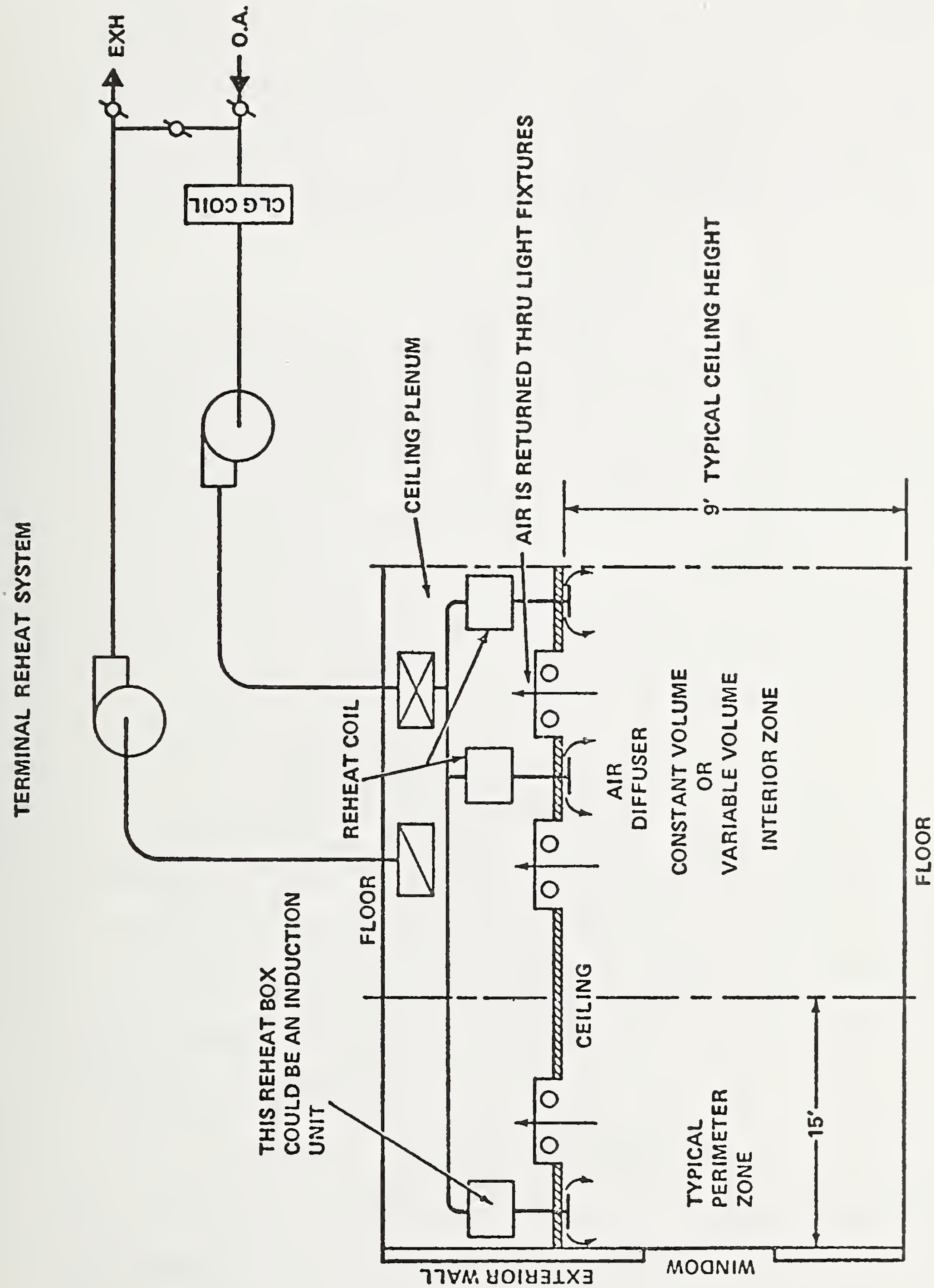


Figure A-2. Terminal Reheat System

The space air is then returned to the central plant through the return air duct. Since the occupants of the space that is being conditioned generate excess carbon dioxide, odor, and smoke, these contaminants are diluted by mixing them with outside air. This is the reason that a part of the return air is exhausted and replaced by make-up outdoor air as indicated in Figure A-1.

On many days during spring and autumn, the space heat loss could be exactly matched by the heat given off by the lights, equipment, and occupants; no net heating or cooling is required. The single VAV duct systems have difficulty in meeting this zero load condition since the supply airflow cannot be made zero. A minimum of supply air must be fed into the space regardless of the thermal load in order to satisfy the space ventilation requirement.

SINGLE DUCT REHEAT SYSTEM

It is not difficult to control the supply air temperature by regulating the heating or cooling coil temperature if a single duct system is connected to a single zone such as shown in Figure A-1. In actual practice however, the system supplies air to more than one space. Particularly during the intermediate seasons, it frequently happens that one space calls for heating while others require cooling. It is impossible to satisfy these different space requirements in the single duct system described above. A common practice employed is to cool the central supply air to the lowest likely required temperature and modulate it up to the desired supply air temperature for the other spaces by the reheat coil such as shown in Figure A-2.

It is obvious that the reheating of the air which is once cooled by refrigeration causes a double expenditure of energy. Obviously, in this type of system, attempts to reduce solar heat gain by shading devices results in the increase of energy use rather than energy saving.

DUAL DUCT SYSTEM

Another commonly used central all-air system is the dual-duct system which is illustrated in Figure A-3. In this system, both heated air and cooled air are provided in two separate supply ducts to all the spaces to be air-conditioned. At the ceiling plenum above the space, mixing boxes are used to yield a desired supply air temperature which meets the heating or cooling load at a specific instant and at a specific location. Although the total air flow of the dual duct system after mixing usually remains constant, it could also be varied by a VAV box. The dual duct system is definitely not energy conserving because it requires mixing of heated air with chilled air to obtain the proper degree of heating or cooling. The office energy requirement of such a system could be reduced, however, if the heating coil were provided with hot water from the chilling machine's condenser or reclaimed heat form the lighting fixtures.

ECONOMIZER CYCLE

When the outdoor temperature and humidity conditions are favorable, it is possible to shut off the cooling plant and use the cool outdoor air to cool the interior zone. This operation is called using an economizer cycle. The dampers indicated in Figures A-1 through A-3 for

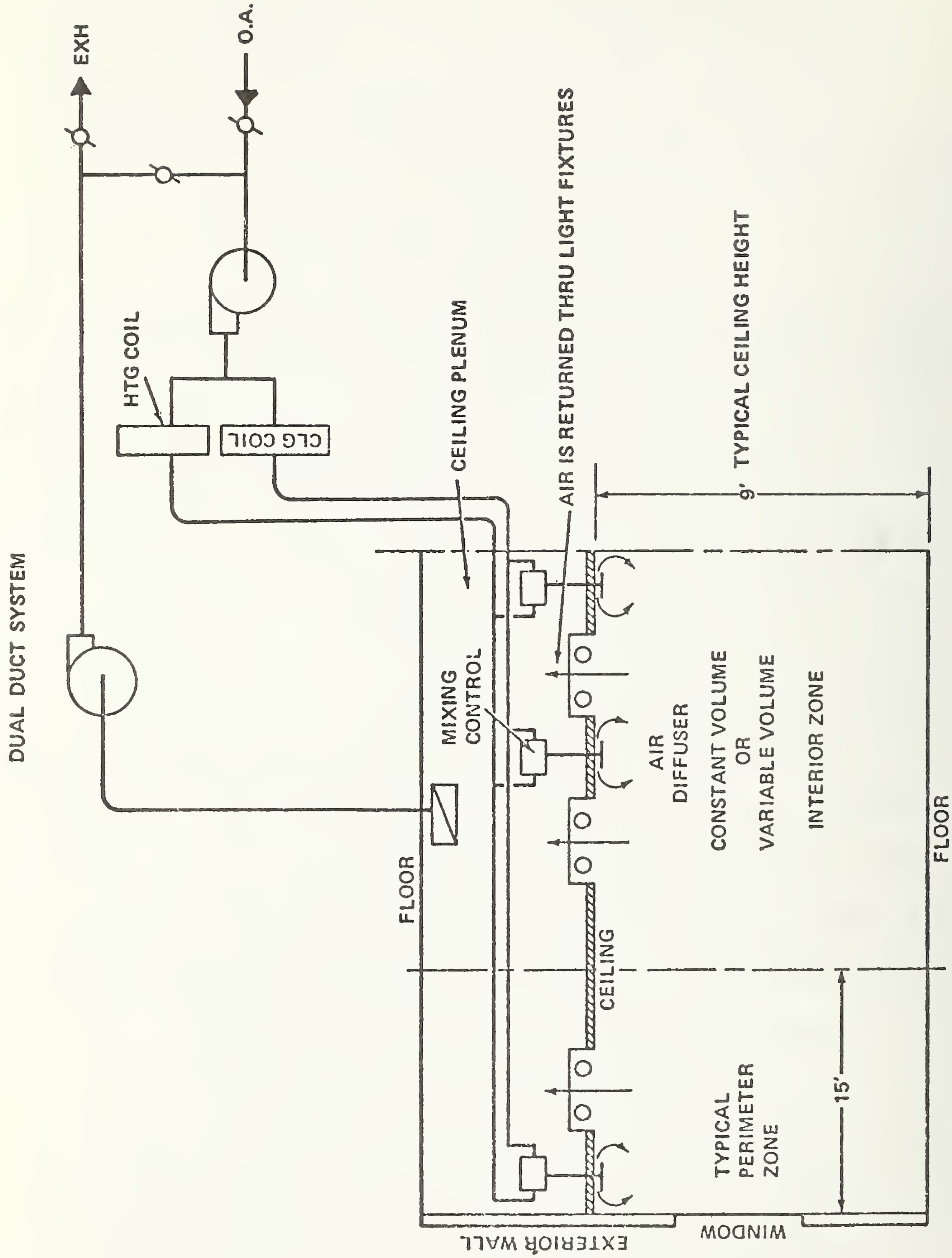


Figure A-3. Dual Duct System

the outdoor air intake, the return air duct and the exhaust air duct are controlled to regulate the mixing rate of outdoor and return air to achieve economizer-cycle operation. The economizer cycle can obviously be a very energy conserving feature of a HVAC system and its use should be very much encouraged. Ross F. Meriwether used a computer simulation[20/] to predict the energy savings by the use of an economizer cycle with a dual duct and VAV system for an office building in San Francisco. The results were as follows:

TABLE 1. PREDICTED ANNUAL COOLING ENERGY CONSUMPTION FOR A SAN FRANCISCO OFFICE BUILDING (TON-HOUR)

	No Economizer Cycle	Economizer Cycle
Dual Duct	2,040,916	825,393
VAV	1,582,240	745,531

As can be seen from this table, the energy savings resulting from employing the economizer cycle are significant indeed. The performance of these HVAC systems actually determines the energy consumption of a building, sometimes independent of the heat gain and heat loss through windows.[21/]

For example, total energy demand expressed on the source energy for various air-side systems with the room heat gain of 10,860 Btu/h may vary depending upon the system, such as follows:

Constant-volume dual duct system: 24,507 Btu/h

Constant-volume terminal reheat system: 38,215 Btu/h

Variable-volume dual duct system: 10,810 Btu/h

In addition to the air-side system variations, there are numerous ways of producing heating and cooling effects at the central plants. For example, there are many ways of attaining heating effects, such as by electric heating, gas or oil furnace or boiler, heat pump system, and waste heat utilization. Similarly for cooling, there are gas/oil absorption chiller, electric centrifugal chiller, electric reciprocating chiller, gas-engine-driven centrifugal chiller, and gas-engine-driven reciprocating chiller. Numerous other possibilites exist which would produce different building energy consumption data even for the same heating and cooling loads imposed on the heating and cooling coils in the central air handling system. Also, it is extremely difficult to determine how much of the daily total heat gain would become the daily total cooling load (storage load factor). What fraction of the daily total heat gain in the winter months would assist in reducing the daily total heat loss also depends upon the heat absorbing characteristics of building thermal mass and building HVAC system.

The important thing to note is that there is no simple way to express the window heat gain/loss in terms of building energy consumption. An approach taken in this report is to discuss the effect of window heat gain in terms of total daily heat gain and heat loss to a given space irrespective of the complexities of heating and cooling systems.

The resulting analysis, therefore, does not purport to answer all the questions about windows and energy conservation. It does, however, seek to quantify and compare some of the energy consequences of variations in window parameters.

Appendix B

DAYLIGHT CALCULATION PROCEDURES

This section describes a procedure for determining the available indoor illumination, when the outdoor illumination is known, by using the Daylight Factor concept. The Daylight Factor is defined as the ratio between the illumination [12,13] on a horizontal plane at a reference point in the room and the illumination on a horizontal plane under the open sky, both without direct sun. While the outdoor illumination is determined by a routine called OUTLIT, the Daylight Factor is determined as the sum of the sky component (SC), external reflection component (ERC), and internal reflection component (IRC), with correction factors applied for the dirtiness of the window and the type of window glazing and framing. In this procedure, however, the daylighting level is calculated by also considering the direct sun illumination reflected by external obstructions when they are exposed to the sun as shown in the routine called DALITE. In order to determine the sky component (SC), external reflection component (ERC), and internal reflection component (IRC), several subroutines are developed, such as SCERC, ERC, EOF, SF, and BSF, which are briefly described as follows:

BCF and BWF: BCF determines a geometric factor which corresponds to the views of the sky from a specific reference point in a room through a rectangular window.[12] BWF is the calculation of a similar factor between the reference point and the bright window. The reference point in this case is a point along the normal to the window through its lower left-hand corner.

SF: This is an extension of BCF and BWF to allow the reference illumination point to be shifted from that along the normal through the lower left-hand corner of the window to that of any other location.

EOF: This algorithm determines the view factor between the room reference point and the external obstruction viewed through the window. The algorithm is so written that the percentage of horizontal obstruction covering the window area is given for the purpose of describing the size of the external obstructions.

IRC: In this routine it is assumed that the room is divided into two parts by a horizontal plane passing through the centroid of the window. It is assumed in this routine that the external obstruction has the horizontal edge parallel to and all the way across the window and its reflection factor is known.

SCERC: This routine simply utilizes the routines SF and EOF to obtain the sky component (SC) and externally reflected component (ERC) of the daylight factors.

DALITE: This routine determines the daylight intensity available at a given point in a given room by utilizing the daylight factors and outdoor illumination value, as well as other pertinent factors such as window dirtiness, glazing and frame construction.

OUTLIT: Available outdoor illumination is calculated by this routine for the typical sky conditions as a function of the sun's altitude angle, a graphic representation of the equation used is shown in Fig. B-1. Fig. B-1 also shows a direct beam illumination for cloudless conditions.

Algorithms for all of the routines mentioned are given in the following sections.

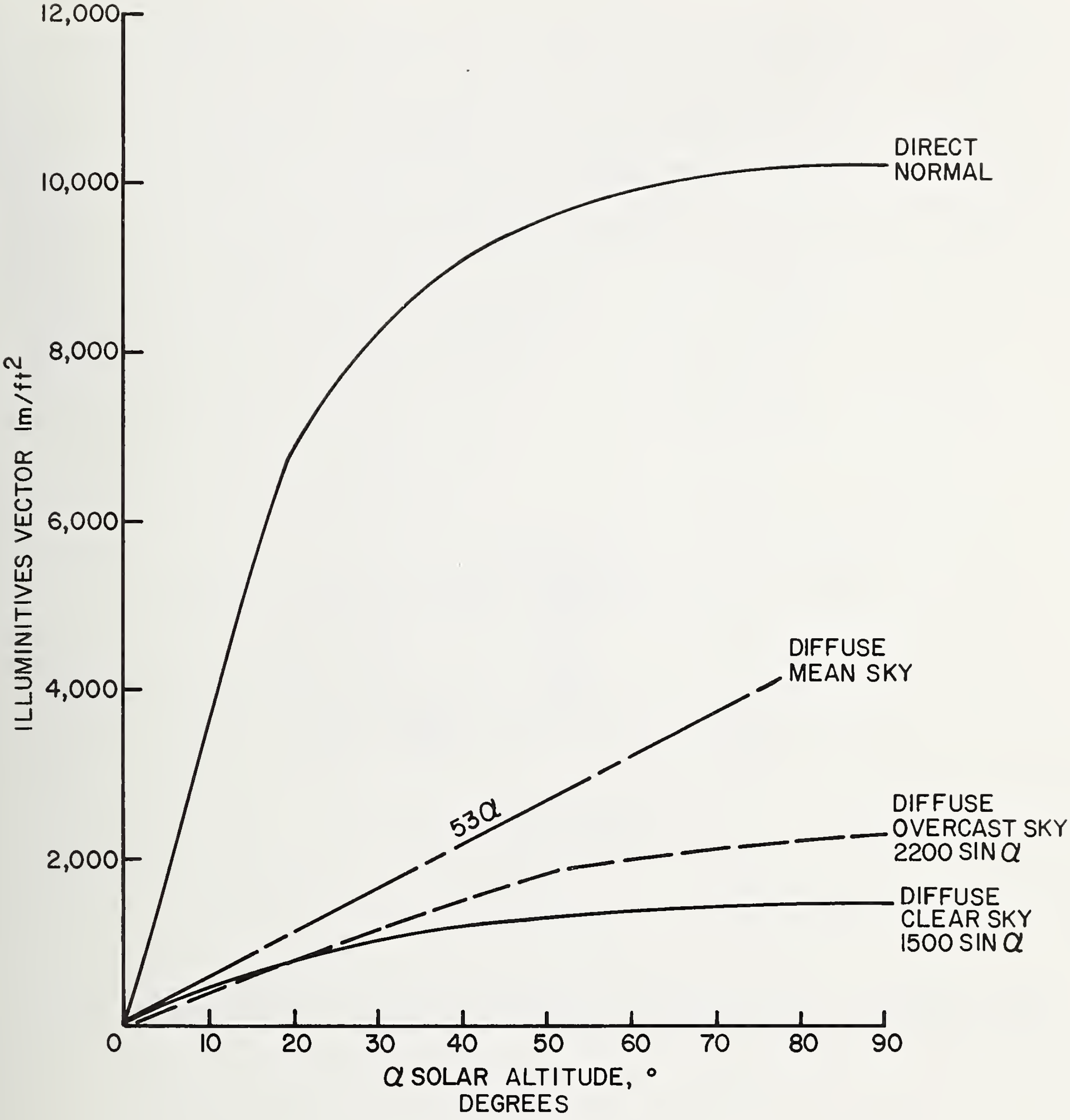

12,000
10,000
8,000
6,000
4,000
2,000
ILLUMINITIVES VECTOR lm/ft2
DIRECT
NORMAL
DIFFUSE
MEAN SKY
53α
DIFFUSE
OVERCAST SKY
2200 SIN α
DIFFUSE
CLEAR SKY
1500 SIN α
0
10
20
30
40
50
60
70
80
90
α SOLAR ALTITUDE, °
DEGREES

Figure B-1.

OUTLIT (ALT, ISKY, SKYLIT, SUNLIT)

SKYLIT: Sky illumination, lm/ft^2

SUNLIT: Direct sun illumination, lm/ft^2

ALT: Altitude angle, degree

ISKY: Type of sky

1. mean sky
2. overcast sky
3. cloudless sky

SKYLIT = 53 * ALT, if ISKY = 1

$$SKYLIT = 2200 * \sin \left(\frac{ALT}{180} * \pi\right), \text{ if } ISKY = 2$$

$$SKYLIT = 1500 * \sin \left(\frac{ALT}{180} * \pi\right), \text{ if } ISKY = 3$$

$$SUN = 12847 * EXP \left(-0.2259/\sin \left(\frac{ALT}{180} * \pi\right)\right)$$

SUNLIT = 0.5 * SUN, if ISKY = 1

SUNLIT = 0 if ISKY = 2

SUNLIT = SUN if ISKY = 3

This algorithm is developed to represent the outdoor illumination curves given in "Principles of Natural Lighting" by Lynes.

DALITE (WAZ, SC, SAZ, ERC, XIRC, SKYLIT,. SUNLIT DLFTR, M, G, B)

DALITE: Indoor illumination

SC: Sky component, percent

ERC: Externally reflected component, percent

XIRC: Internally reflected component, percent

SKYLIT: Sky luminance, lm/ft^2

SUNLIT: Direct sun luminance, lm/ft^2

M: Maintenance factor

Non-industrial area	0.9
Dirty industrial area	0.8

G: Correction factor to be applied for materials other than clear flat glass

Wired cast windows	0.9
Heavily diffusing glass	0.7
Double glazing	0.85

B: Correction factor for glazing bars

Metal windows	0.8
Wooden windows	0.7
Conventional	

DLFTR: Daylight factor %

DLFTR = (SC + ERC + IRC) * M * G * B

$\delta = (SAZ - WAZ) * \pi/180$

IF $\delta \geq 0$, SUNLIT = SKYLIT

DALITE = (SKYLIT * (SC + XIRC) + SUNLIT * (ERC)) * M * G * B/100.

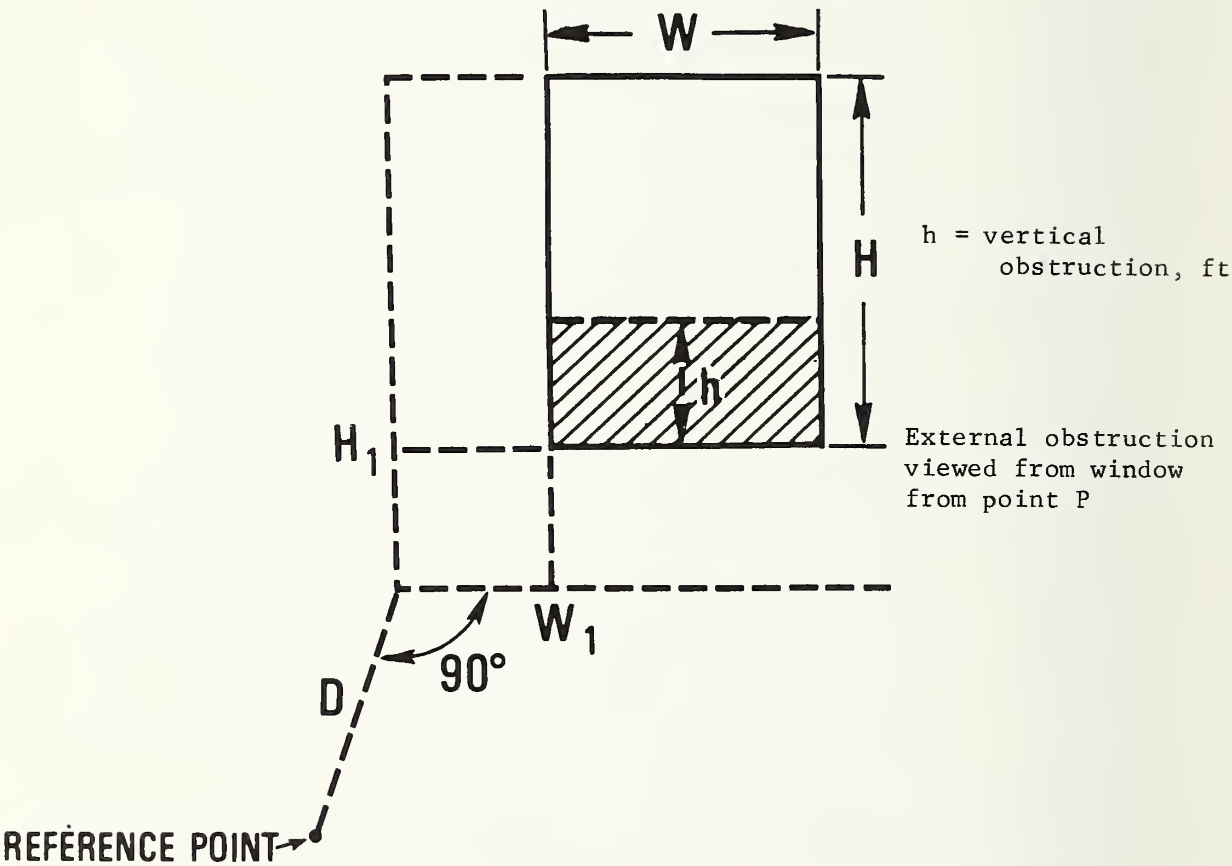
SCERC (W, H, W_1, H_1, D, w, h, τ, RX, SC, ERC)

SC: Sky component, percent

ERC: Externally reflected component, percent

τ: Transmission coefficient of the window

RX: Reflectance coefficient of the external obstruction



$$SC = \tau * SF(W, H, W_1, H_1, h, D) * 100$$

$$ERC = RX * \tau * EOF(W, H, W_1, H_1, h, D) * 100$$

IRC (W, A, ρ, RFW, RCN, RX, α, D, h)

IRC: Internally reflected component, percent

D: Distance of the reference point from the window

W: Window area, ft^2

A: Internal surface area, ft^2

h: Window obstruction height, ft

ρ: Average reflectance of the room

RFW: Average reflectance factor of the floor and of the wall area below the horizontal plane through the window centroid excluding the window wall

RCN: The same as RFW except that above the horizontal plane through the window centroid

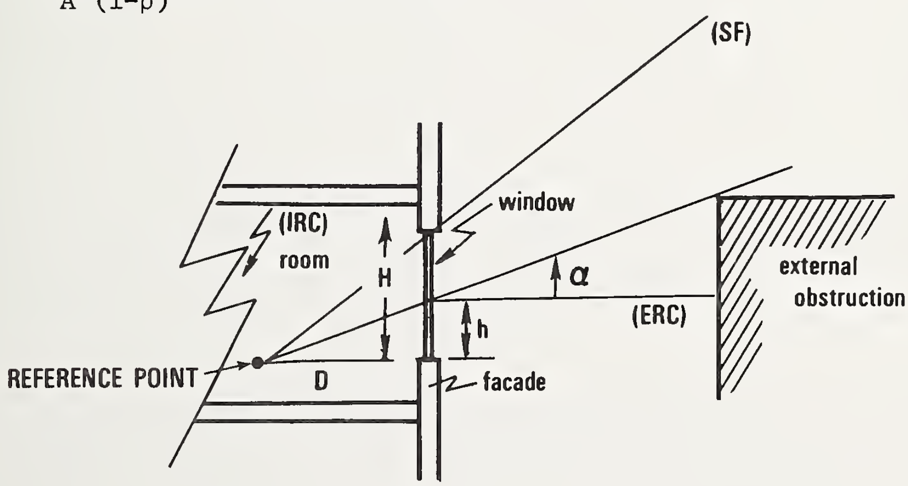
RX: Reflectance factor of external obstruction

α: Angle of obstruction from center of window (degrees above horizontal)

1. Determine window obstruction constant C as a function of α as follows:

α	0	10	20	30	40	50	60	70	80
C	39	35	31	26	20	15	10	7	5

2. $IRC = \frac{0.85W}{A\ (1-\rho)} * [C \cdot RFW + 50.RX \cdot RCN]$



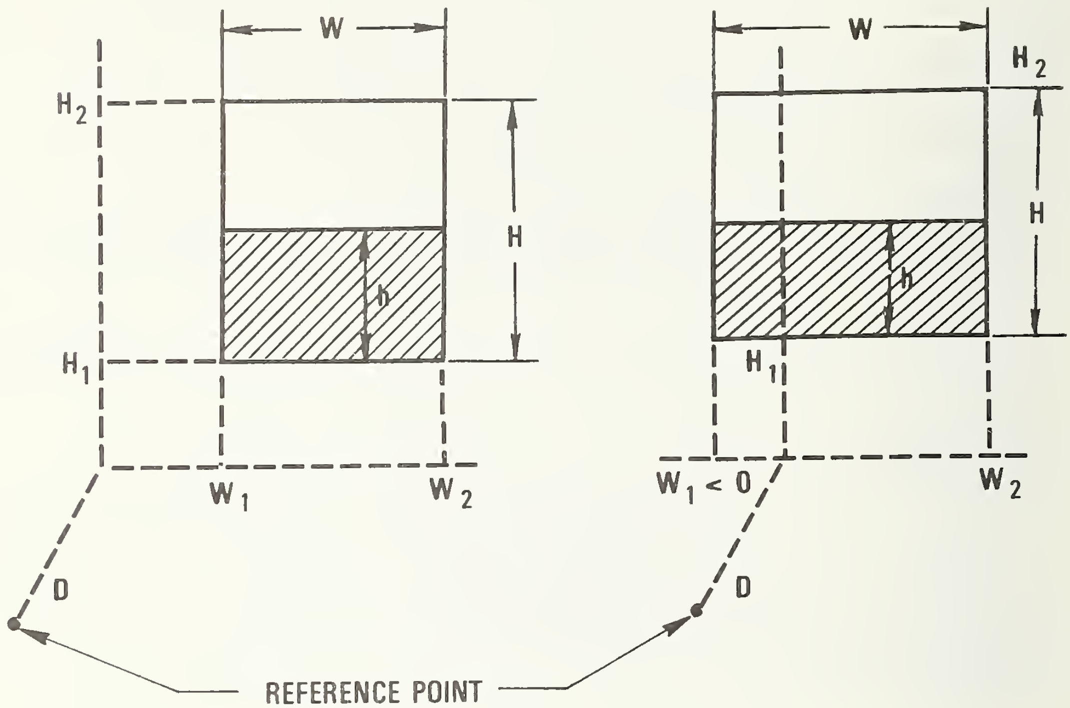
where
$h = D * \tan(\alpha * \pi/180)$

$$SF\ (W,\ H,\ W_1,\ H_1,\ h,\ D)$$

$$\text{and } EOF\ (W,\ H,\ W_1,\ H_1,\ h,\ D)$$

SF: Sky factor for a point P in the room

EOF: External obstruction factor



$H_2 = H_1 + H$

$HH = H_1 + h$

$W_2 = W_1 + W$

IF $(W_1 > 0)$

$SF = BCF\ (W_2,\ H_2,\ D) - BCF\ (W_1,\ H_2,\ D) - BCF\ (W_2,\ HH,\ D) + BCF\ (W_1,\ HH,\ D)$

$EOF = BWF\ (W_2,\ HH,\ D) - BWF\ (W_1,\ HH,\ D) - BWF\ (W_2,\ H_1,\ D) + BWF\ (W_1,\ H_1,\ D)$

IF $W_1 < 0$

$SF = BCF\ (W_2,\ H_2,\ D) + BCF\ (W_1,\ H_2,\ D) - BCF\ (W_2,\ HH,\ D) - BCF\ (W_1,\ HH,\ D)$

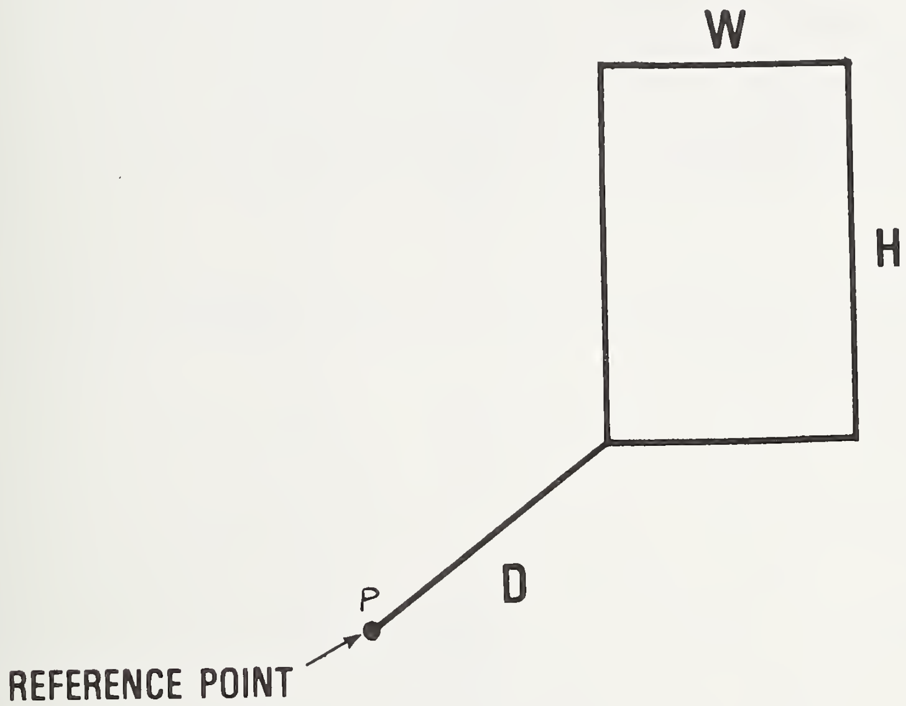
$EOF = BWF\ (W_2,\ HH,\ D) + BWF\ (W_1,\ HH,\ D) - BWF\ (W_2,\ H_1,\ D) - BWF\ (W_1,\ H_1,\ D)$

IF $SF < 0$, $SF = 0$

BCF (W, H, D) and BWF (W, H, D)

BCF: Basic geometric factor between the overcast sky and a point in a room

BWF: Basic geometric factor between the window and a point in a room



Yet $X = W/D$

$Y = H/D$

$A = \sqrt{1 + Y^2}$

$$BCF = \frac{1}{14\pi} [3 (\tan^{-1} X - \frac{1}{A} \tan^{-1} \frac{X}{A}) + 4 (\tan^{-1} \frac{XY}{B} - \frac{XY}{A^2 \cdot B})]$$

$$BWF = \frac{1}{2\pi} [\tan^{-1} X - \frac{1}{A} \tan^{-1} \frac{X}{A}]$$

Table B-1 DAYLIGHT FACTOR DATA SHEET

		SAMPLE DATA			
Altitude, degree	ALT	30			
Azimuth, degree	WAZ	90			
Solar azimuth, degree	SAZ	90			
Distance from window ft.	D	5.	10	15	20
Window width ft.	W	1.5	3.75	7.5	11.25
Window height ft.	H	8			
Horizontal distance of window	W1	-6			
Vertical distance of window	H1	0			
Room width (along the window facade)	RMW	12			
Room length (Normal to the facade)	RML	20			
Room height	RMH	10			
External obstruction %	HL	0	40	80	100
Room distance surface area, ft^2	A	Calculate *			
Window area ft^2	WA	12	30	60	90
Reflection of external obstruction	R	0.3			
Reflection of walls and floor	RFW	0.2	0.4	0.6	
Reflection of ceiling	RCN	0.4	0.6	0.8	
Maintenance factor	M	1			
Glass convection factor	G	1			
Glazing bar factor	B	1			
Sky ID factor	ISKY	2			
Window obstruction angle	ALPHA	0			
Daylight factor	DCFTR				
Internal reflection component	XIRC				
Sky luminance	SKYLIT	Calculate			
Sun's luminance	SUNLTE				
Daylight luminance	DALITE				
Transmission coefficient (glass)	T	0.85			
Sky component	SC				
External reflection component	ERC	Calculate			

*REMARKS ROOM INFORMATION

A = 2 (RM(*RMH + RM (*RMW) + (RMH * RMW
+ (RMH * RMW - W * L)

TK: 462.01: 3/25/76

In the following pages sample daylight-factors for the office module are given as obtained by this program for a point 3 ft above the floor at 15 ft from a window of 8 ft height located 3 ft above the floor. As shown in Table B-1, window area was varied from 10, 25, 50 to 75% of the 120 sq. ft. facade. It is assumed in this sample calculation that a wire cast metal window of transmission factor 0.85 was used. The reflectance factors for the ceiling and floor/wall are also varied as shown in the Daylight Factor data sheet.

The following parameter values are used for the daylight factor calculations:

	Dark	Average	Light
Wall/floor reflectance, RFW	0.2	0.4	0.6
Ceiling reflectance, RCN	0.2	0.4	0.6
External obstruction reflectance		0.1	0.4

Figures B-2 through B-5 are obtained from sample calculations to depict the daylight factors in relation to the percent of window area, window positions, distance of task point from the window, and the external obstructions, respectively.

With the daylight factor increases in near proportion to an increase in window area, it decreases very rapidly as one moves away from the window. Both the window height and the lateral position of the window with respect to the task point have a strong effect on the daylight factor. Figure B-5 shows that the daylight factors are also

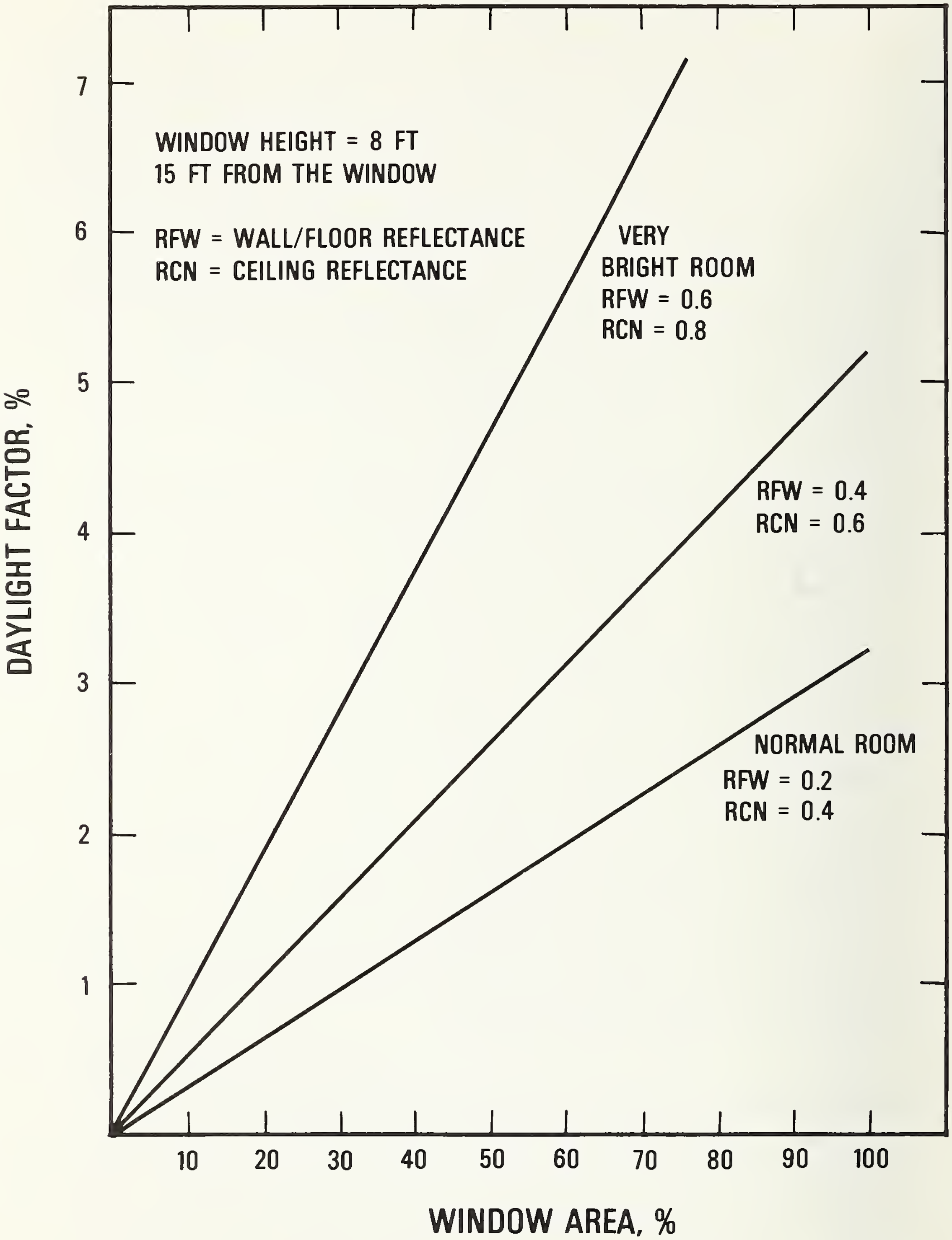


Figure B-2. Daylight factors vs window area % for various wall-ceiling reflectance values

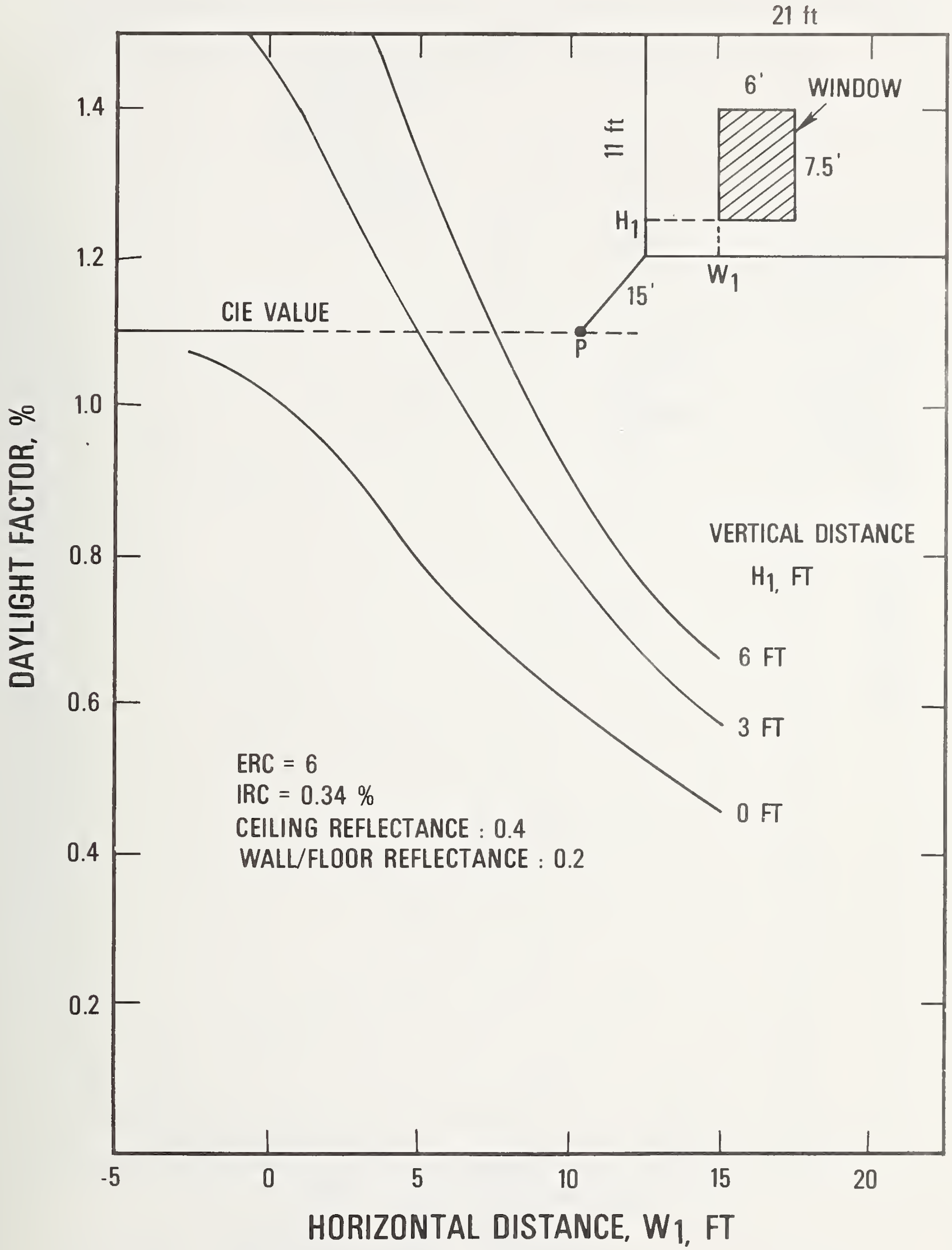


Figure B-3. Daylight factors vs window position.

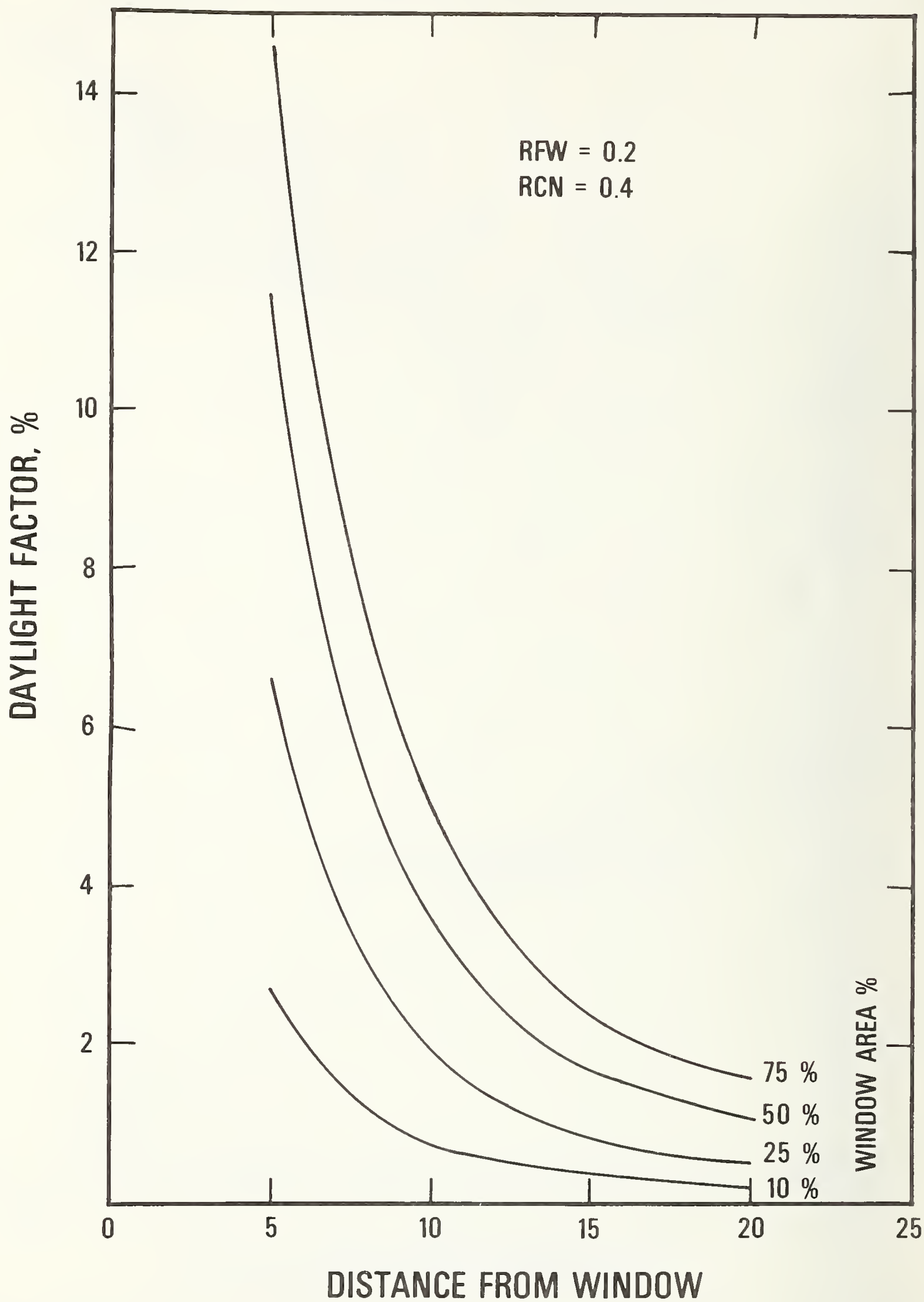


Figure B-4. Daylight factors vs distance of task point from the window.

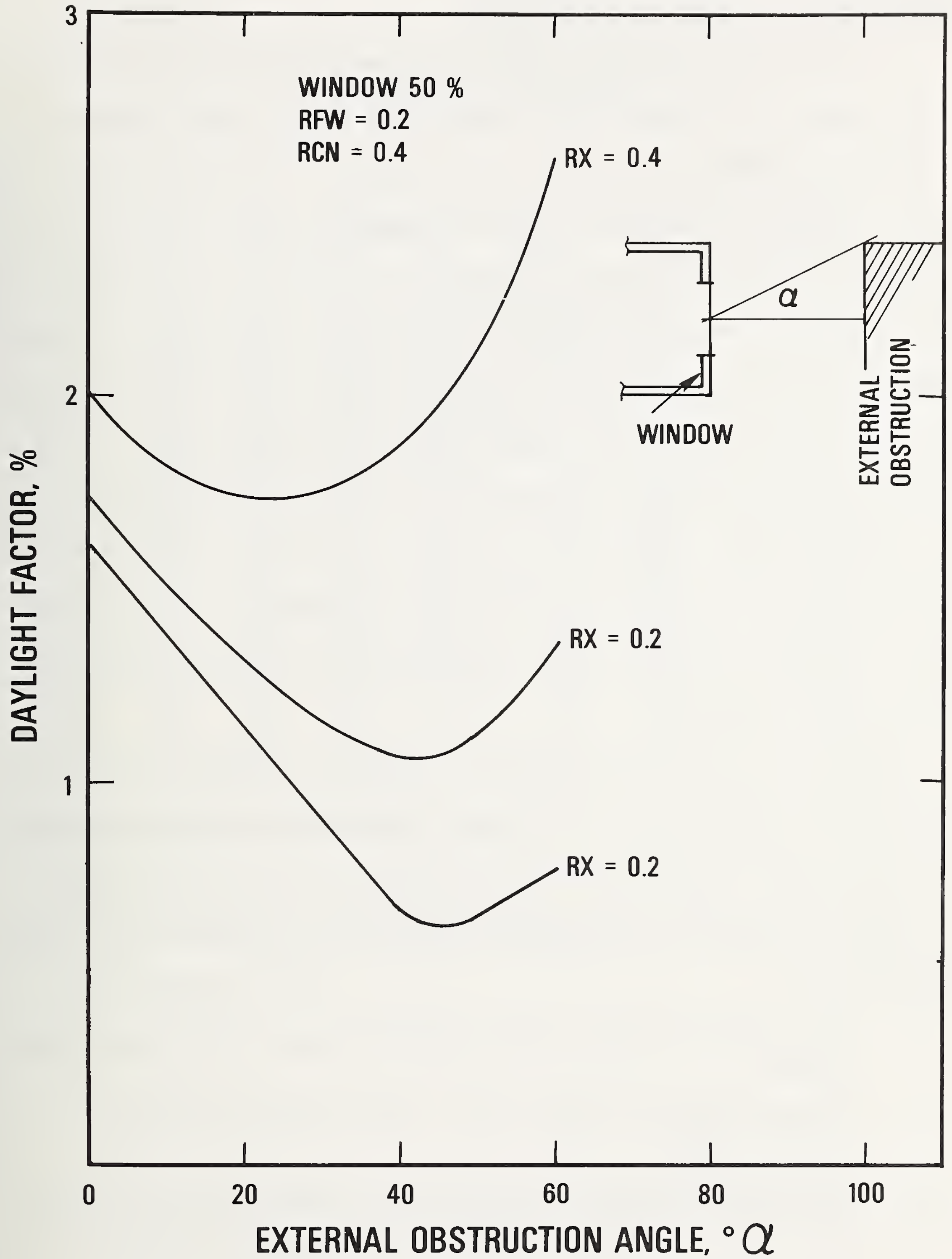


Figure B-5. Daylight factors vs external obstruction angles.

Exact Daylight Calculation Using GLIM

The calculation procedure used in the previous analysis is a simplified version of more exact methods which include the actual simulation of successive inter-reflection by inside surfaces. The exact calculation process starts with initial excitation illumination from outside sources, considers the first "inter-reflection", then the second, and continues the interaction until the luminous values calculated on all intended surfaces converge. One of the computer programs that treats this inter-reflection process is called GLIM "General Lighting Inter-reflection Models" developed by the Applied Research of Cambridge, Ltd. in England. According to D. Archer, author of GLIM, calculation by the inter-reflection factors is accurate to within ±15% of experimental measurements. This GLIM was used to check the daylight factor calculated by the simplified NBS daylight routine "DALITE."

Figure B-6 and Table B-2 provide the physical dimensions for the room and window which were used for the comparison calculation, whereas Table B-3 is the summary of the 306 GLIM daylight factor calculations. The sample room used for the comparison faces north and has the following characteristics:

1. Only one heat/light transfer surface which is the north facing facade.

2. North-facing wall surface area = 12' (3.93^m) wide and 10' (3.05^m) high.

3. Single-glazed regular windows with no fixed shading. However, the window location and size will vary as shown in Table B-1.

4. No external shading.

5. Internal shading has two options: (1) being no shading, and (2) venetian blinds - open position (light colored).

Table B-2

NBS Daylight Calculation Data

Run	Y_1 m	Y_2 m	Z_1 m	Z_2 m	Z_3 m	Window Data Area m^2	Aspect Ratio	%
1	.23	3.46	0	2.77	.28	9.59	.8	80
2	.23	3.46	.80	2.08	.17	7.19	.6	60
3	.87	2.19	.80	2.19	.06	4.79	1.0	40
4	.55	2.83	.80	1.70	.55	4.79	.6	40
5	.23	3.46	.80	1.38	.87	4.79	.4	40
6	1.42	1.09	.80	2.19	.06	2.40	2.0	20
7	1.19	1.55	.80	1.55	.70	2.40	1.0	20
8	.23	3.46	.80	.69	1.56	2.40	.2	20
9	1.69	.55	.80	2.19	.06	1.20	4.0	10
10	1.58	.77	.80	1.55	.70	1.20	2.0	10
11	1.42	1.09	.80	1.09	1.16	1.20	1.0	10
12	1.42	1.09	1.20	1.09	.76	1.20	1.0	10
13	1.42	1.09	1.60	1.09	.36	1.20	1.0	10
14	1.19	1.55	.80	.77	1.48	1.20	.5	10
15	.23	3.46	.80	.35	1.90	1.20	.1	10
16	.23	3.46	1.60	.35	1.10	1.20	.1	10
17	.23	3.46	2.40	.35	.30	1.20	.1	10

Wall width = 3.93 m = $2\ Y_1 + Y_2$

Wall height = 3.05 m = $Z_1 + Z_2 + Z_3$

% = Glass area/wall area x 100 = $[Z_2 \cdot Y_2/(3.93 \times 3.05)] \times 100$

Aspect ratio = Z_2/Y_2

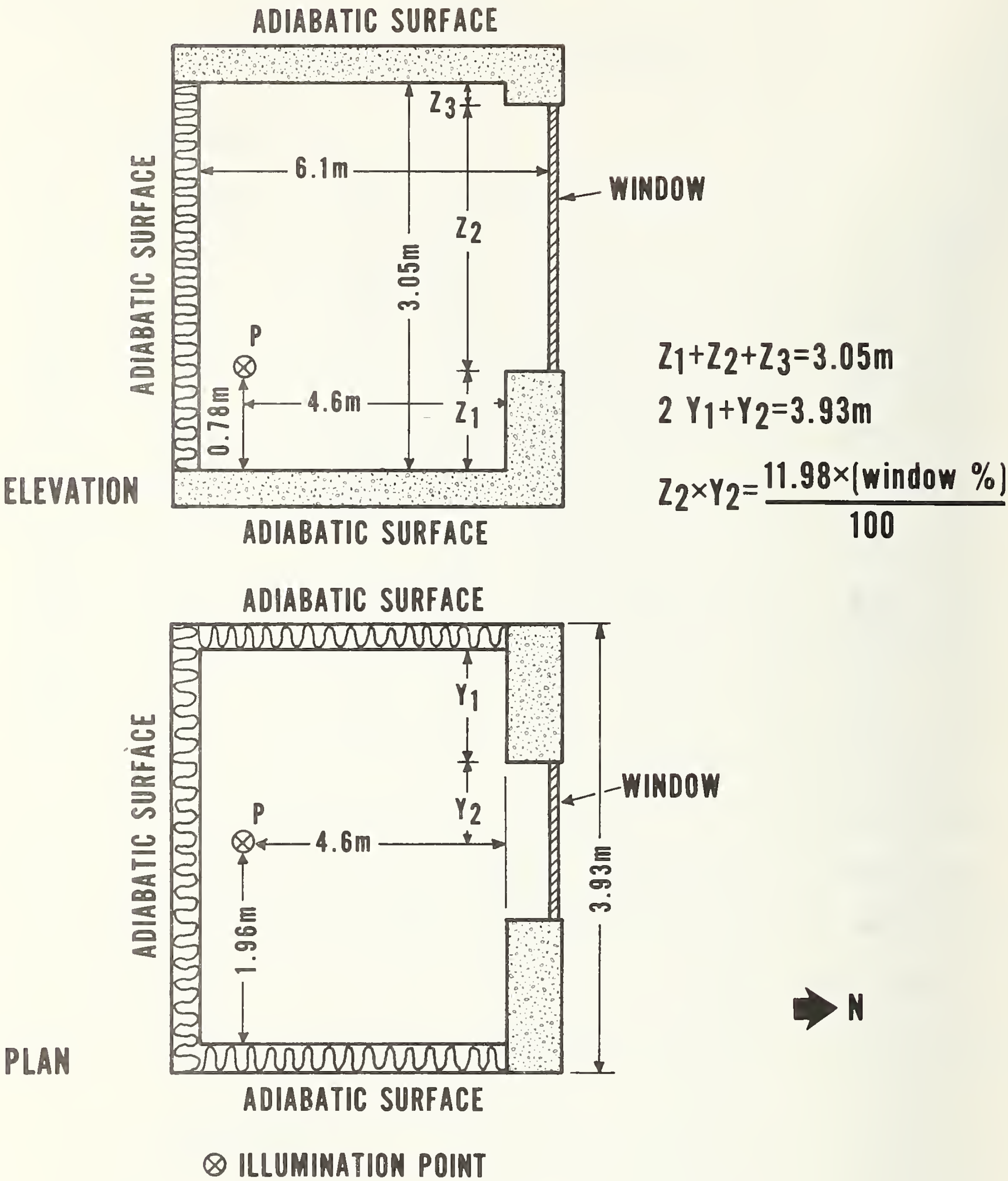

ADIABATIC SURFACE
ADIABATIC SURFACE
6.1m
WINDOW
Z3
Z2
3.05m
P
4.6m
Z1
0.78m
ELEVATION
ADIABATIC SURFACE
Z1+Z2+Z3=3.05m
2 Y1+Y2=3.93m
Z2×Y2= 11.98×(window %) / 100
ADIABATIC SURFACE
ADIABATIC SURFACE
Y1
Y2
P
4.6m
WINDOW
3.93m
1.96m
N
PLAN
ADIABATIC SURFACE
⊗ ILLUMINATION POINT

Figure B-6

TABLE B-3. SUMMARY OF DAYLIGHT FACTOR CALCULATIONS BY GLIM

OFFICE DAYLIGHTING STUDY FOR NATIONAL BUREAU OF STANDARDS WASHINGTON USA

BY APPLIED RESEARCH OF CAMBRIDGE LTD UK

AUGUST 1976

RESULTS: Planar Illuminance Totals (Daylight Factors)

Case	Reflectances Floor/Ceiling/Walls \ Run / Glazing	A 80%	B 60%	C 40%	D 40%	E 40%	F 20%	G 20%	H 20%	I 10%	J 10%	K 10%	L 10%	M 10%	N 10%	O 10%	P 10%	Q 10%
1	.5/.85/.8	10.67	9.77	7.20	6.31	6.34	4.38	3.23	3.42	2.21	1.70	1.64	1.85	2.06	1.71	1.96	1.59	2.68
2	.3/.85/.8	8.45	7.91	5.91	5.04	5.08	3.69	2.60	2.50	1.70	1.36	1.27	1.53	1.67	1.28	1.49	1.26	2.26
3	.1/.85/.8	6.72	6.47	4.91	4.06	4.12	3.16	2.16	1.92	1.41	1.11	1.00	1.29	1.39	0.96	1.13	1.02	1.94
4	.5/.4/.8	5.59	5.29	4.10	3.48	3.53	2.73	1.80	1.60	1.20	0.94	0.84	1.08	1.18	0.82	0.94	0.90	1.55
5	.3/.4/.8	4.83	4.68	3.67	3.01	3.06	2.51	1.60	1.33	1.06	0.83	0.72	0.97	1.05	0.67	0.76	0.79	1.41
6	.1/.4/.8	4.10	4.08	3.26	2.62	2.67	2.30	1.40	1.08	0.95	0.72	0.60	0.88	0.94	0.55	0.62	0.69	1.30
7	.5/.85/.4	4.82	4.26	3.29	2.96	2.96	2.25	1.50	1.25	0.98	0.78	0.64	0.90	0.94	0.64	0.65	0.78	1.14
8	.3/.85/.4	4.18	3.77	2.97	2.60	2.64	2.08	1.34	1.04	0.89	0.70	0.55	0.83	0.86	0.53	0.55	0.70	1.05
9	.1/.85/.4	3.56	3.29	2.66	2.31	2.33	1.94	1.19	0.88	0.80	0.62	0.47	0.76	0.78	0.45	0.45	0.63	0.97
10	.5/.4/.4	3.00	2.79	2.32	2.04	2.07	1.77	1.04	0.75	0.72	0.54	0.40	0.67	0.69	0.39	0.37	0.56	0.84
11	.3/.4/.4	2.72	2.58	2.18	1.88	1.91	1.71	0.97	0.67	0.68	0.50	0.36	0.64	0.66	0.34	0.32	0.53	0.81
12	.1/.4/.4	2.46	2.38	2.05	1.75	1.78	1.64	0.91	0.59	0.64	0.47	0.33	0.61	0.63	0.30	0.28	0.50	0.78
13	.5/.85/.2	3.51	3.03	2.45	2.26	2.29	1.81	1.14	0.88	0.77	0.59	0.44	0.72	0.72	0.44	0.41	0.63	0.81
14	.3/.85/.2	3.11	2.73	2.26	2.07	2.09	1.72	1.05	0.76	0.71	0.54	0.39	0.68	0.68	0.39	0.35	0.58	0.77
15	.1/.85/.2	2.72	2.44	2.07	1.88	1.91	1.63	0.96	0.66	0.66	0.49	0.34	0.64	0.63	0.33	0.30	0.54	0.73
16	.5/.4/.2	2.32	2.11	1.86	1.69	1.71	1.53	0.86	0.57	0.60	0.44	0.30	0.57	0.58	0.29	0.24	0.49	0.65
17	.3/.4/.2	2.13	1.98	1.77	1.60	1.61	1.48	0.81	0.52	0.58	0.42	0.27	0.55	0.56	0.27	0.22	0.47	0.63
18	.1/.4/.2	1.96	1.85	1.69	1.51	1.53	1.44	0.77	0.48	0.56	0.39	0.25	0.53	0.54	0.24	0.19	0.45	0.62
										*	*					*	*	*

* these runs required greater sky subdivision due to small narrow windows

Table B-4

Inner Surface Reflectance Floor-wall/ceiling		Window Opening % for 120 ft^2 Facade			
		75%	50%	25%	10%
.4/.80	DALITE	6.0	4.0	2.0	0.8
	GLIM	4.4	3.5	2.4	0.9
.4/.4	DALITE	4.4	2.8	1.4	0.6
	GLIM	2.8	2.5	1.9	0.7
.2/.8	DALITE	4.1	2.7	1.4	0.5
	GLIM	2.8	2.4	1.8	0.7
.2/.4	DALITE	3.0	2.0	1.1	0.4
	GLIM	2.0	1.8	1.5	0.6

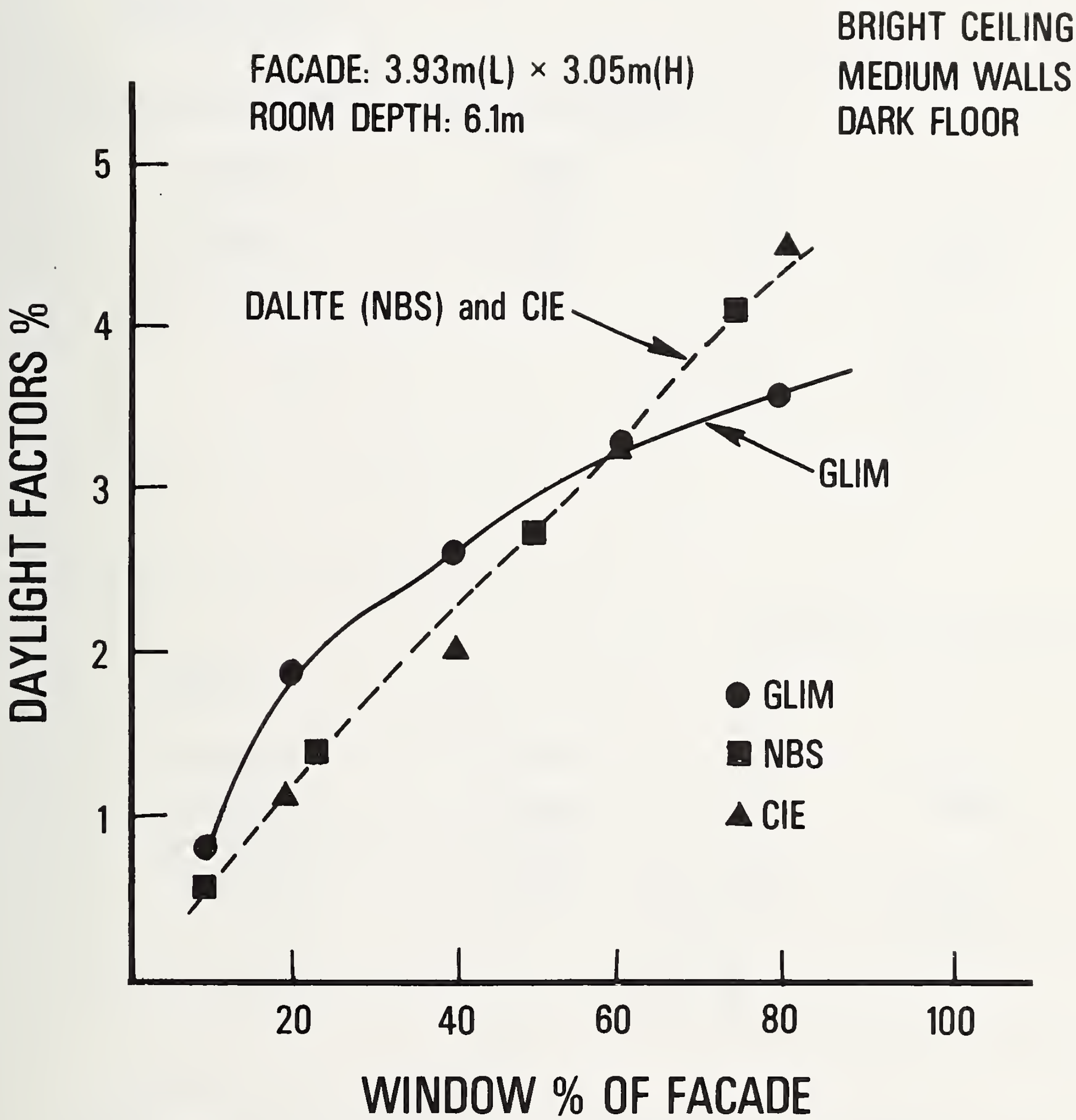
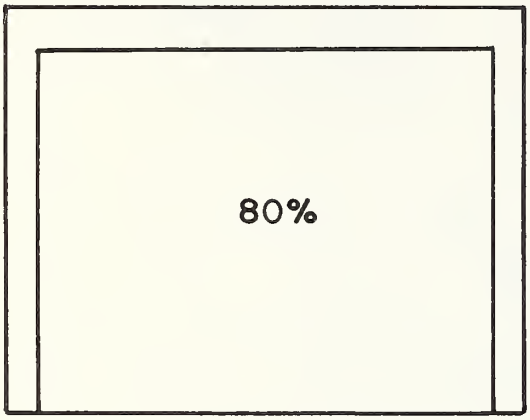
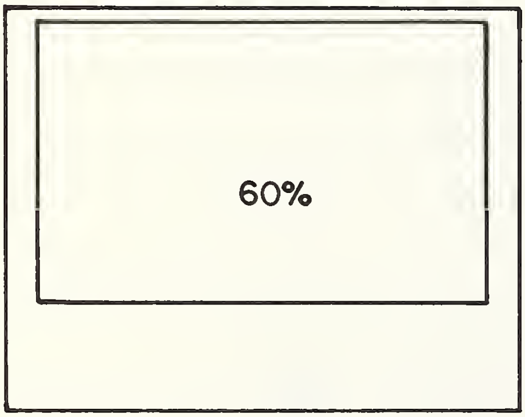

BRIGHT CEILING
MEDIUM WALLS
DARK FLOOR
FACADE: 3.93m(L) × 3.05m(H)
ROOM DEPTH: 6.1m
DALITE (NBS) and CIE
GLIM
GLIM
NBS
CIE
DAYLIGHT FACTORS %
1
2
3
4
5
20
40
60
80
100
WINDOW % OF FACADE

Figure B-7

REFLECTANCE

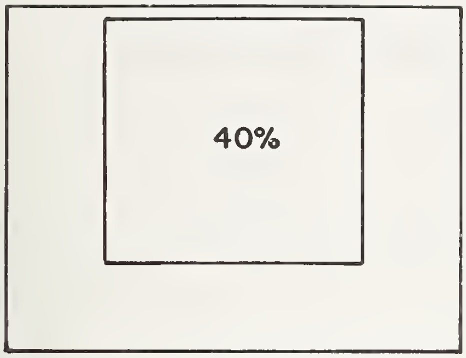


DAYLIGHT FACTORS	FLOOR/CEILING/WALL
10.65	.5/.85/.8
3.56	.1/.85/.4
1.96	.1/.4 /.2

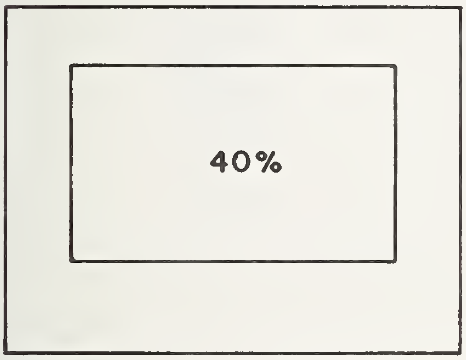


	F/C /W
9.77	.5/.85/.8
3.29	.1/.85/.4
1.85	.1/.4 /.2

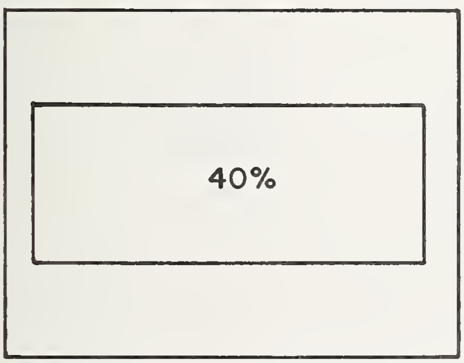
Figure B-8. Effects of Varying Window Size and Room Reflectances Upon Daylight Factors.



DAYLIGHT FACTORS	REFLECTANCE FLOOR/CEILING/WALL
7.20	.5/.85/.8
2.66	.1/.85/.4
1.69	.1/.4/.2

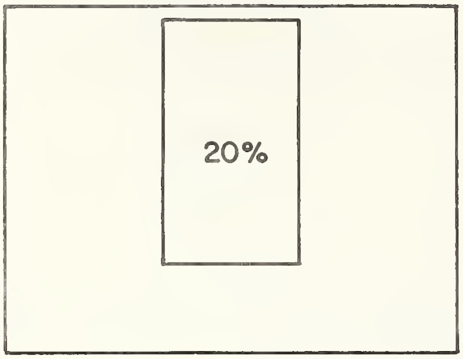


	F/C/W
6.31	.5/.85/.8
2.31	.1/.85/.4
1.51	.1/.4/.2

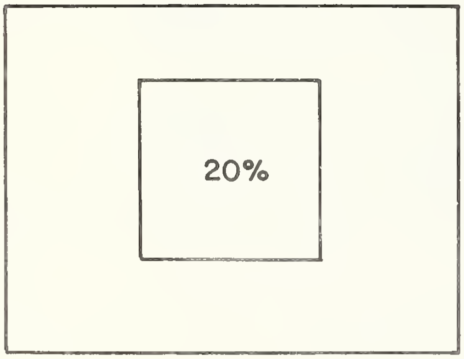


	F/C/W
6.34	.5/.85/.8
2.33	.1/.85/.4
1.53	.1/.4/.2

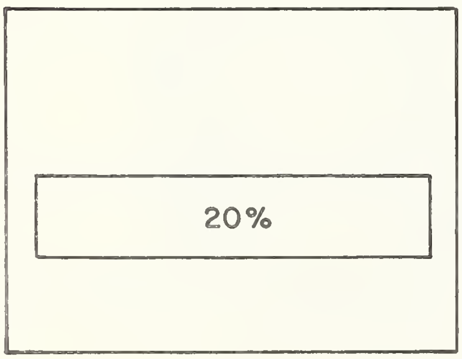
Figure B-9. Effect of Varying Window Location and Internal Reflectances Upon Daylight Factor.



DAYLIGHT FACTORS	REFLECTANCE FLOOR/CEILING/WALL
4.38	.5/.85/.8
1.94	.1/.85/.4
1.44	.1/.4/.2

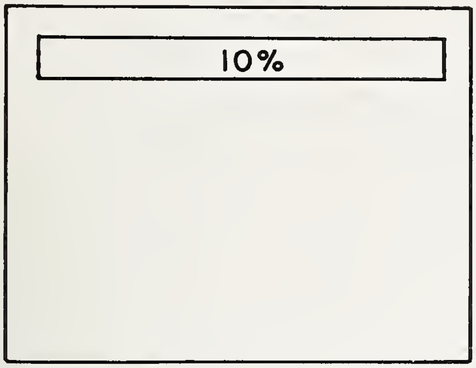


	F/C/W
3.23	.5/.85/.8
1.19	.1/.85/.4
0.77	.1/.4/.2

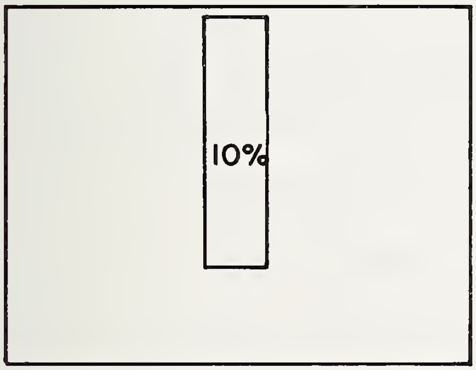


	F/C/W
3.42	.5/.85/.8
0.88	.1/.85/.4
0.48	.1/.4/.2

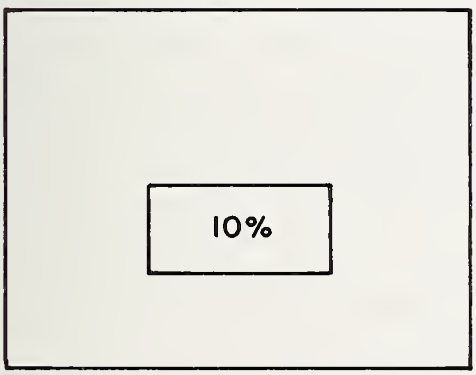
Figure B-10. Varying Window Location.



DAYLIGHT FACTORS	REFLECTANCE FLOOR/CEILING/WALL
2.68	.5/.85/.8
0.97	.1/.85/.4
0.62	.1/.4/.2



	F/C/W
2.21	.5/.85/.8
0.80	.1/.85/.4
0.56	.1/.4/.2



	F/C/W
1.71	.5/.85/.8
0.45	.1/.85/.4
0.24	.1/.4/.2

Figure B-11. Varying Window Location.

strongly affected by the exterior obstruction angle when the reflectance of the obstruction is high.

6. Reflectance of interior surfaces:

ceiling	0.85, 0.4
wall	0.8, 0.4, 0.2
floor	0.1, 0.3, 0.5

Table B-3 clearly shows that the daylight factors (at 15 feet from the window) are strongly affected by the reflectance of the room surfaces, with the same window percentage and with the same inner surface reflectances. The daylight factor could vary as much as a factor of 2 depending upon the shape and location of the window in relation to given room dimensions. Table B-4 and Figure B-7 compare the daylight factors computed by the NBS routine DALITE against those determined by GLIM for several window sizes and inner surfaces reflectance combinations. Except for the largest window area (75% of the window wall), the agreements between these two calculations are reasonably good.

Figure B-7 also indicates the daylight factors calculated by the CIE (International Commission on Illumination) procedure described in their publication No. 16 (E3.2), 1970.

Figures B-8 through B-11 are daylight factors as determined by the GLIM program, shown together with the relative size, shape and location of windows. The purpose of these figures is to demonstrate the effectiveness of the window design in terms of natural lighting.

It is clear, for example, from Figure B-8 through B-11 that the location and shape of the window have a greater effect upon the daylight factor for a small window area than for a larger area. The daylight factors for 40% window area, shown in Figure B-9, are relatively unaffected by the location and shape of the window while the opposite is true for a 10% window area (Fig. B-11).

EQUIVALENT SPHERE ILLUMINATION

The daylight calculation presented in the previous pages deals only with the total illumination available on the horizontal plane at 15 ft from the window over a task 3' above the floor. These daylight factors do not indicate the quality of the illumination, however. The quality of the illumination is usually affected by contrast, brightness of the task, size of the task, time of viewing, reflected glare, and veiling reflection and position of the viewer. The only meaningful overall index which incorporates all or part of these parameters is the Equivalent Sphere Illumination (ESI). The calculation of the ESI involves describing the visual performance potential of a real environment of known actual illumination in terms of the illumination under the reference conditions of a photometric sphere providing equivalent performance potential. According to McNamara,[23/] ESI can be calculated by an equation such as illustrated in Figure B-12.

Since GLIM is able to determine the illumination from various sources in the room, with a slight modification, it would be possible to calculate ESI by providing required task reflectance and contrast in sphere, and view angle for the given task. This would add some assessment of the quality of illumination provided by daylight to the thermal analysis presented here.

$$CRF = \frac{\tilde{C}_e}{\tilde{C}}$$

$\tilde{C}_e$ = Effective contrast

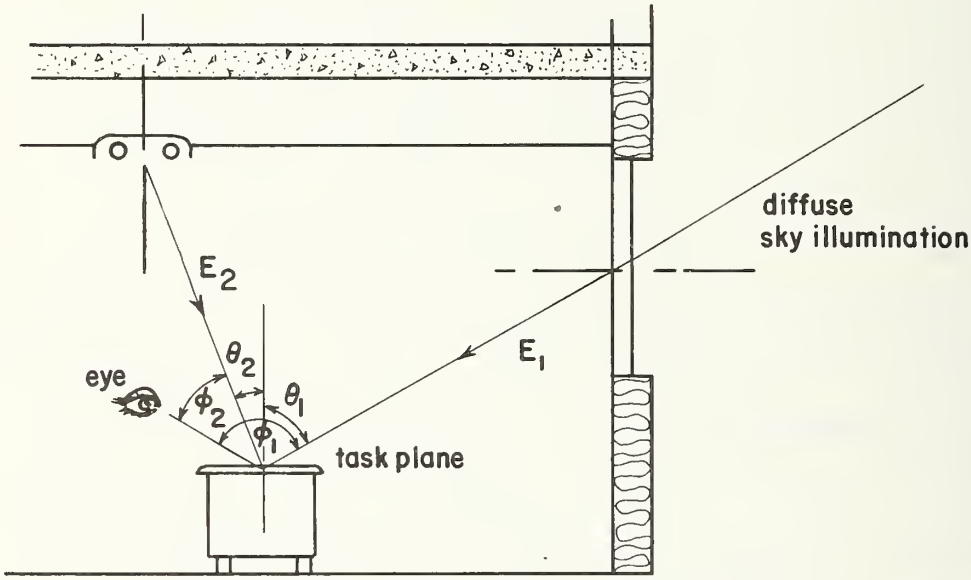
$\tilde{C}$ = Equivalent contrast

$$\boxed{ESI = \rho^{-1} L_r (CRF)^{-6.54}}$$

ρ = the reflectance of the task in the sphere

L_r = luminance of task in the real world

CRF = Contrast rendition factor



$$\boxed{ESI = \rho^{-1} C_0^{-6.54} \left(\sum_{i=1}^{M} E_i \Delta_i \right)^{6.54} \left(\sum_{i=1}^{M} E_i \beta_{Bi} \right)^{-5.54}}$$

C_0 = task contrast in sphere

E_i = foot candles from source i

$\Delta_i = \beta_{Bi} - \beta_T$

β_{Bi} = background luminance factor for $\theta = \theta_i$ and $\phi = \phi_i$

β_T = the reflectance of the task in the real world

M = number of sources

Figure B-12

EXPERIMENTAL VALIDATION OF DAYLIGHT CALCULATIONS

In order to validate the daylighting calculation procedure described in the previous sections, daylight intensity over a horizontal surface in one of the north-facing office modules at the National Bureau of Standards was measured and compared against the calculated values. The measurement was made by a calibrated recording photometer placed at 15' from the window on the surface 30" above the floor, on March 4-8, 1977, which included clear sky, partially clear sky and completely overcast sky conditions as shown in Figure B-13. In the calculation, it was assumed that the reflectance of the wall, ceiling, and floor was 0.6, 0.7, and 0.2, respectively. The calculated daylight illumination under the clear sky condition agrees fairly well with the observed value except at the low sun's altitude angles. More studies of this nature are needed to improve the daylight calculation methodology, particularly in terms of its effect on the total building energy consumption.

It is suggested that a comprehensive research program be carried out to obtain the following information:

1. Available outdoor daylight and skylight data under clear, partially clear, and overcast sky conditions in relation to the solar insolation data
2. Simultaneous measurement of indoor and outdoor illumination to cover the following variables:
    a. Window dimensions
    b. Window shading
    c. Window orientation

d. Sun's altitude

e. Interior surface reflectance

f. Exterior obstructions

3. Precise measurement of indoor surface reflectances and outdoor obstruction reflectances.

4. Energy consumption measurement of daylight utilization system vs. conventional system for heating and cooling of the office as well as residential buildings

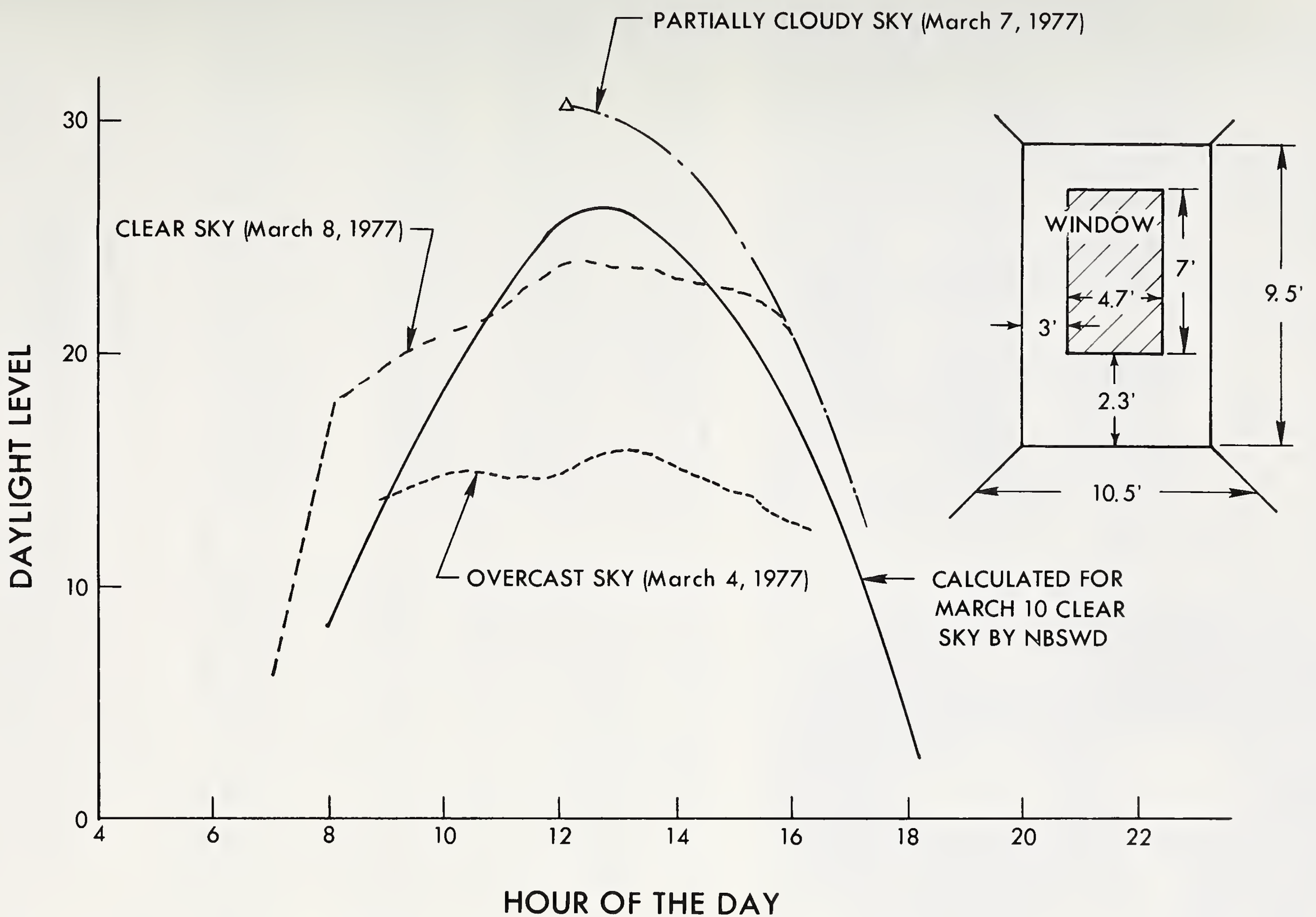


Figure B-13. Comparison of Measured and Observed Daylight in an NBS Office.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS BSS 109	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies

5. Publication Date

February 1978

6. Performing Organization Code

7. AUTHOR(S)

Tamani Kusuda and Belinda Lowenhaupt Collins

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Energy Research and Development Administration
Washington, D.C. 20545; and

U.S. Department of Housing and Urban Development
Washington, D.C. 20410

13. Type of Report & Period Covered

Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 77-600071

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

Results of a simplified analysis for annual heating, cooling, and lighting requirements associated with windows are presented. The analysis includes the effects of window size, heat transfer, solar shading, and compass orientation for typical commercial and residential modules located in a climate typical of Washington, D.C. Three different modes of operation with respect to heating and cooling requirements through windows were assessed: external loads only; external and internal; and external, internal, and daylight. In addition, the effects of selective fenestration heat-transfer management, such as planned employment of thermal shutters and shading devices, and off-hour temperature setback were considered. This analysis assumed that daylight could replace or supplement artificial light whenever it could supply a specified minimum level of illumination. The use of daylight was found to offer the greatest potential for reducing energy costs, particularly when combined with selective fenestration management.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Daylighting; energy conservation; fenestration design; solar heat gain; window management.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[XX] Unlimited [ ] For Official Distribution. Do Not Release to NTIS	UNCLASSIFIED	113
[XX] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 .29/2:109 [ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price $2.75

USCOMM-DC 29042-P74

Waste Heat Management Guidebook

A typical plant can save about 20 percent of its fuel—just by installing waste heat recovery equipment. But with so much equipment on the market, how do you decide what's right for you?

Find the answers to your problems in the *Waste Heat Management Guidebook*, a new handbook from the Commerce Department's National Bureau of Standards and the Federal Energy Administration.

The *Waste Heat Management Guidebook* is designed to help you, the cost-conscious engineer or manager, learn how to capture and recycle heat that is normally lost to the environment during industrial and commercial processes.

The heart of the guidebook is 14 case studies of companies that have recently installed waste heat recovery systems and profited. One of these applications may be right for you, but even if it doesn't fit exactly, you'll find helpful approaches to solving many waste heat recovery problems.

In addition to case studies, the guidebook contains information on:

- sources and uses of waste heat
- determining waste heat requirements
- economics of waste heat recovery
- commercial options in waste heat recovery equipment
- instrumentation
- engineering data for waste heat recovery
- assistance for designing and installing waste heat systems

To order your copy of the *Waste Heat Management Guidebook*, send $2.75 per copy (check or money order) to Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. A discount of 25 percent is given on orders of 100 copies or more mailed to one address.

The *Waste Heat Management Guidebook* is part of the EPIC industrial energy management program aimed at helping industry and commerce adjust to the increased cost and shortage of energy.

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards
FEDERAL ENERGY ADMINISTRATION/Energy Conservation and Environment

*U.S. GOVERNMENT PRINTING OFFICE : 1978 O-261-238/13

(cut here)

Announcement of New Publications
of the
National Bureau of Standards

Superintendent of Documents,
Government Printing Office,
Washington, D. C. 20402

Dear Sir:

Please add my name to the announcement list of new publications as issued by the National Bureau of Standards.

Name..

Company...

Address...

City...................................State.........................Zip Code...............................

(Notification Key N519)

229-317 O - 77 - 47

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology, and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent NBS publications in NBS and non-NBS media. Issued six times a year. Annual subscription: domestic $17.00; foreign $21.25. Single copy, $3.00 domestic; $3.75 foreign.

Note: The Journal was formerly published in two sections: Section A "Physics and Chemistry" and Section B "Mathematical Sciences."

DIMENSIONS/NBS

This monthly magazine is published to inform scientists, engineers, businessmen, industry, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on the work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing.

Annual subscription: Domestic, $12.50; Foreign $15.65.

NONPERIODICALS

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a world-wide program coordinated by NBS. Program under authority of National Standard Data Act (Public Law 90-396).

NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N.W., Wash., D.C. 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The purpose of the standards is to establish nationally recognized requirements for products, and to provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order **above** *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.*

Order **following** *NBS publications—NBSIR's and FIPS from the National Technical Information Services, Springfield, Va. 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Services (Springfield, Va. 22161) in paper copy or microfiche form.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service. A literature survey issued biweekly. Annual subscription: Domestic, $25.00; Foreign, $30.00.

Liquified Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $30.00. Send subscription orders and remittances for the preceding bibliographic services to National Bureau of Standards, Cryogenic Data Center (275.02) Boulder, Colorado 80302.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

U.S.MAIL

SPECIAL FOURTH-CLASS RATE
BOOK