NBS BUILDING SCIENCE SERIES 119

Economic Evaluation of Windows in Buildings: Methodology

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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 in part 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), in conjunction with the Building Energy Performance Standards Program.

COVER: *Windows in houses and in offices can have important effects on their life-time costs and benefits.*

ACKNOWLEDGEMENTS

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Economic Evaluation of Windows in Buildings: Methodology

by

Rosalie T. Ruegg and Robert E. Chapman

Abstract

This study, which is one part of a National Bureau of Standards interdisciplinary project on windows, is aimed at improving the cost-effectiveness of window selection and use in buildings. It develops and illustrates a life-cycle costing evaluation model and computer program for assessing for alternative window systems the net dollar impact of acquisition, maintenance and repair, heating and cooling energy gains and losses, and artificial lighting and daylighting trade-offs. The method is applicable to the evaluation of many different window sizes, designs, accessories, and uses, both for new and existing residential and commercial buildings. Two step-by-step examples of evaluating selected window alternatives in a residence and in an office building in Washington, D.C. serve to illustrate the application of the method.

A companion report, A Regional Economic Assessment of Selected Window Systems, presents the results of eight additional residential case studies and eight additional commercial case studies. While the emphasis of this report is on the method of evaluation, the companion report focuses on summarizing the results of a regional analysis in a form that will be convenient for use by building owners, operators, designers, financiers, and builders, those whose interest centers on the actual implementation of research results.

Key Words: Building economics; daylighting; economic analysis; energy conservation; engineering economics; life-cycle costs; solar heat gain; thermal efficiency; window; window management

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SI CONVERSION

In view of the presently accepted practice of the building industry in the United States, common U.S. units of measurement are used throughout this paper. Because the United States is a signatory to the Eleventh General Conference on Weights and Measures, which defined and gave official status to the Metric SI system, the following conversion factors are given to assist users of SI units.

Length 1 in = 0.0254* meter

1 ft = 0.3048* meter

Area $1\ in^2 = 6.4516^* \times 10^{-4}\ meter^2$

$1\ ft^2 = 0.0929\ meter^2$

Volume $1\ in^3 = 1.638 \times 10^{-5}\ meter^3$

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

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

Energy $1\ Btu\ (International\ Table) = 1.055 \times 10^3\ joule$

Power 1 Btu/hr = 0.2930 watt

Temperature $^oC = \frac{5}{9}\ (^oF - 32)$

Illumination 1 ft candle (fc) = 10.76 lux

* Exactly

Facing page: *Exterior shading devices and interior draperies are two strategies for reducing the energy costs of windows.*

1. INTRODUCTION

1.1 Background

This report is concerned with the impact of window selection and use on the life-cycle costs of office and residential buildings. Particular attention is given to the effect of windows on heating, cooling and lighting costs and to the cost effectiveness of alternative energy conserving strategies. Not all window strategies for conserving energy are necessarily cost effective when their life-cycle costs, including purchase, installation, and maintenance costs, are taken into account. The emphasis here is on a method of identifying energy conserving window strategies that are also cost effective.

As shown in Table 1.1, nearly 27 million windows costing more than $1 billion are estimated to be installed yearly in new residential units alone. It is estimated that these 27 million windows will subsequently

TABLE 1.1

Estimated Number and Cost of Windows Used in New Residential Construction in a "Typical" Year

Type of Housing Unit	Average Number of Windows Per Unit[a]	Total Number of Windows Installed Per Year (Millions)[b]	Total Area of Prime Windows Installed Per Year (Millions ft^2)[c]	Total Cost of Windows Installed (Millions 1977 $)[d]	Total Yearly Cleaning Cost (Millions 1977 $)[e]	Total Average Yearly Repair Cost[f] (Millions 1977 $)	Impact on Yearly Energy Cost[g]
1 & 2 Family Houses	16	17.9	179	777	17.9	53.7	May Increase
Apartments	6	4.6	46	200	4.6	13.8	or
Mobile Homes	10	4.3	43	187	4.3	12.9	Reduce
All Residential		26.8	268	1,164	26.8	80.4	Costs

[a] Pittsburgh Plate Glass Marketing Research Department, Pittsburgh, PA.

[b] The figures for 1 and 2 family houses and apartments are derived as yearly averages of total windows of all materials used in new construction during the period 1970 to 1974, as reported in Architectural Aluminum Industry Statistical Review, Architectural Aluminum Manufacturers Association, Publication No. AAMA-MIR-1-1975, 1975, p. 17. The figure for mobile homes is estimated by multiplying the average number of windows per mobile homes times the average number of mobile home shipments per year during the period 1970 to 1975, as reported in National Association of Homebuilders, "Economic News Notes," Housing Starts Bulletin, Vol. XXIII, No. 1, January 20, 1977.

[c] This is a conservative estimate based on an average window size of 10 ft^2.

[d] This estimate is based on an average cost of $4.34 per ft^2 of window area.

[e] This estimate is based on an average cost of cleaning of $.10 per ft^2 of window area.

[f] This estimate is based on an average cost for recaulking, scraping, and repainting of $1.50 per ft^2 of window area once every five years, or an approximate average of $.30 per ft^2 every year.

[g] This conclusion is based on the changes in yearly energy costs observed in applying the model developed in this report to 18 case studies for nine cities in different regions of the U.S. The case studies looked at a range of window systems and uses, ranging from the use of single glazed windows without shading or insulating devices and without utilization of their potential for daylighting to the use of double glazed windows with shading and insulating devices and provision of daylight. [See Rosalie T. Ruegg and Robert E. Chapman, A Regional Economic Assessment of Selected Window Systems, National Bureau of Standards, NBSIR (In Press).]

require an expenditure of almost $27 million each year for maintenance (cleaning), about $80 million on the average for yearly repair costs. According to the results of this study, these windows may substantially raise or lower the energy costs of the buildings in which they are installed, depending on how they are designed, sized, located, fitted, and used.[1]

Table 1.1 illustrates the potential costs of windows in new residential buildings only. If the total United States stock of residential and nonresidential buildings were considered, the yearly costs of acquisition, replacement, maintenance and repair, and energy would total many billions of dollars. According to an ERDA-sponsored window research program at the Lawrence Berkeley Laboratory in California, about 5 percent of the total national energy consumption is due to windows.[2] This loss amounts to about one-fourth of the total energy used for heating and cooling buildings in the U.S. each year, the equivalent of 1.7 million barrels of oil per day averaged over the year.[3] According to another recent article, the "development of more efficient windows (is) a high priority on ERDA's (DoE's) energy conservation checklist."[4]

While the costs associated with windows can be greatly affected by their selection and use, architects, builders, and building owners often find it difficult to know what is the cost-effective choice regarding windows. The cost-effective choice is often obscured by the multitude and diversity of effects from windows, by the difficulty of measuring certain effects, and also by the fact that there are many available alternative window designs, sizes, and accessories (hereafter referred to collectively as "window systems") which may differ significantly in their costs and benefits. In many cases neither intuition nor attention

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1 For example, results of applying the model developed in this study in a number of case studies showed the yearly energy costs for a typical single family residence to rise or fall by 25 percent by having a window as compared to not having a window, depending on how the window was sized, oriented, and used. [See Rosalie T. Ruegg and Robert E. Chapman, A Regional Economic Assessment of Selected Window Systems, National Bureau of Standards, NBSIR (In press).

2 S. M. Berman and S. D. Silverstein, "Energy Conservation and Window Systems," Efficient Use of Energy; The APS Studies on the Technical Aspects of the More Efficient Use of Energy, Part III, LC 75-18227, 1975.

3 "Science and the Citizen," Scientific American, April 1977, p. 58.

4 Engineering News-Record, April 21, 1977, p. 12.

to single attributes of windows, such as U values,[1] is adequate to answer the following kinds of questions: (1) Which window system and size will be most cost-effective? (2) How much will it cost to enjoy the benefits of a good view? (3) How will window orientation affect costs? (4) How much should be spent to up-grade the thermal characteristics of windows? and (5) What window accessories will it pay to add? A better method than subjective judgment is needed to evaluate the diverse effects associated with different window strategies in order to arrive at economically sound decisions.

Economic analysis offers a logical approach to bringing together and summarizing, using common measures, the architectural, thermal, and, to a lesser extent, the psychological consequences of alternative window strategies. Although complete quantification may not be possible, measurement of even part of the different kinds of benefits and costs in common dollar terms should substantially improve the ability of the building community to make informed decisions regarding windows.

1.2 Purpose

The broad purpose of this study is to promote cost-effective energy conservation in buildings through improved window selection and use. The specific purposes are (1) to provide a conceptual model for determining the impact of alternative window systems on life-cycle capital, maintenance, and energy costs; (2) to provide a computer program that can be used by the building community to exercise the method of evaluation; (3) to illustrate the use of the method by applying it in two selected case studies; and finally (4) in carrying out the above tasks, to lay the analytical groundwork for the future preparation of a comprehensive set of general guidelines for window selection and use. It develops and illustrates the economic evaluation method that is subsequently applied in a companion report for 18 regional case studies.[2]

1.3 Scope and Approach

A focus of this report is on determining the impact of alternative window systems on the energy costs of a building. The main focus, however, is on determining the total life-cycle costs of providing alternative window systems. The inclusion of capital, maintenance, and repair costs enlarges the scope of the report from energy-efficient windows to cost-effective windows. By measuring the cost effects of alternative

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[1] U = coefficient of thermal transmission. See "Design Heat Transmission Coefficients," ASHRAE Handbook of Fundamentals (New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1972) pp. 347-371.

[2] Rosalie T. Ruegg and Robert E. Chapman, A Regional Economic Assessment of Selected Window Systems.

window systems, sizes, orientations, accessories, and management for different scenarios, the model can provide cost information which will be of interest to designers of new buildings who are relatively free to select complete window systems, as well as to owners of existing buildings who are constrained to making their existing windows more economically efficient.

To provide a broader perspective of window performance than previous studies, the window research at the National Bureau of Standards was undertaken as an inter-disciplinary effort. In addition to the economists, the research team included architects, a thermal engineer, and a research psychologist. This economic evaluation of windows draws upon the results of the companion architectural, thermal, and psychological studies for its technical underpinning in these other areas. In the following description of the approach, the particular contributions from the other disciplines are noted.[1]

1.3.1 Delineation of Costs and Benefits Treated

The first task in the economics study was to define the kinds of costs and benefits that may arise from windows. These are listed in Table 1.2. This list provided a basis from which to select the items for economic analysis.

"Costs" and "benefits" as listed in Table 1.2 are defined broadly to ecompass any sacrifice or gain, respectively, from windows, in terms of money, goods, leisure time, safety, prestige, comfort, or pleasure. Costs of windows arise from the purchase and installation of the windows, their maintenance and repair, their heat loss during the heating season and heat gain during the cooling season, and from undesirable effects on users such as privacy loss, noise, hazards, visual distractions, and reductions in usable interior wall space. Benefits of windows arise from passive solar heat gains during the heating season, the availability of natural ventilation when needed, beneficial daylight, and other desirable features, such as view out and contact with the outside world, enhancement of the appearance of the interior and exterior of the building, and improvement of the morale of building users. An indication of the importance of some of these costs and benefits to users of buildings was provided by a recent literature survey of user reactions to windows made by the psychologist member of the NBS window research team.[2]

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[1] For an overview of the inter-disciplinary project, see Belinda L. Collins, Rosalie T. Ruegg, et. al., A New Look at Windows, National Bureau of Standards, NBSIR 77-1388, January 1978.

[2] Belinda L. Collins, Windows and People, National Bureau of Standards, Building Science Series 70, June 1975.

TABLE 1.2

Costs and Benefits of Windows

Costs	Benefits
Purchase and Installation	Passive Solar Heat Gain
Maintenance and Repair Costs	Daylight
Undesirable Heat Loss and Gain	Natural Ventilation
Safety Hazard	Higher User Productivity
Noise and Visual Distractions Which Reduce User Comfort or Productivity	User Sense of Well-Being View Out
Undesirable Light, Glare, and Contrast	Enhanced Interior and Exterior Appearance
Loss of Privacy	User Source of Information
Inflexibility in Interior Space Arrangement	Safety Aid for Emergency Entrance and Egress
Undesired Air Infiltration	

It is assumed that the owners of buildings will desire to maximize their net benefits (i.e., benefits minus costs) from the combination of glazed and opaque surfaces in their exterior walls. Ideally, an economic analysis would look for the solutions which maximize net benefits. However, this would require the assigning of dollar measures to each of the items listed in Table 1.2. While there is some precedence for developing dollar measures for safety and psychological factors in other areas, it is difficult to develop dollar measures for windows which are broadly applicable.

For this reason, the focus here is on those costs and benefits whose effects can be measured in dollars with a relatively high degree of confidence. These include the purchase and installation costs, thermal gains and losses,[1] energy savings through daylighting, and repair and maintenance costs. These are the first three cost items and the first two benefit items listed in Table 1.2. In addition, insurance and tax effects for window systems in commercial buildings are treated.

This focus on owning and operating costs does not mean that the equally important, but difficult to measure, psychological effects are totally ignored. The net dollar costs or savings provided by the life-cycle cost approach can be regarded as measures against which decision makers can compare their estimates of the value of these other effects. While a large element of judgment remains in the decision, the decision maker need not rely completely on subjective choice. The development of economic measures for those types of window effects not presently covered in the economic evaluation model would further guide the selection of cost-effective windows.

1.3.2 Choices in Design and Use

There are numerous choices available in the selection, location, and use of windows.[2] Many of these choices will affect the energy usage and life-cycle costs of buildings. In their recent report, Window Design Strategies to Conserve Energy,[3] the architects working on the NBS interdisciplinary window project catalogued the following six broad areas of opportunities for making windows more energy efficient: (1) site selection; (2) use of exterior appendages; (3) choice and treatment of frame; (4) choice of glazing material; (5) use of interior accessories; and (6) treatment of the building interior.

Within these six groups, thirty-three specific "strategies" for making windows more energy efficient are explained. These include, for example, the reduction of winter heat loss through the use of multiple glazing,

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[1] Although the economic evaluation model is capable of incorporating the cost effects of natural ventilation, these effects are not included in the case illustrations of the model because at the time of this report the NBS thermal analysis model, which was used to obtain the thermal data needed for the economic model, did not treat natural ventilation.

[2] A general reference to the different types of window design; the available materials for glazing, frames, and weatherstripping; the various kinds of fittings; the features of design and construction which affect the performance of windows; their costs; and available window accessories is provided by H. E. Beckett and J. A. Godfrey, Windows: Performance, Design, and Installation (New York: Van Nostrand Reinhold Company, 1974).

[3] Robert Hastings and Richard Crenshaw, Window Design Strategies to Conserve Energy, National Bureau of Standards, Building Science Series 104, June 1977.

storm sashes, edge-sealed transparent roll shades, and windbreaks; the reduction of night-time heat loss through the use of tight-fitting draperies, opaque roll shades, and insulating shutters; and the reduction of solar heat gain in summer by the use of heat-absorbing and reflective glass, shade tress, and exterior appendages such as sun screens and awnings. Their report describes each strategy; explains the physical phenomena that account for the effect of the strategy; gives the energy and non-energy advantages and disadvantages of the strategy; discusses aesthetic factors to consider in adopting the strategy; indicates the approximate acquisition cost of the strategy; and provides results of applicable laboratory studies, illustrative examples, and references to relevant literature.

The economic evaluation model presented in Section 2 is suitable for analyzing the cost effectiveness of most of the strategies detailed in the NBS report on window design strategies.[1] Similarly, the economic evaluation model is capable of receiving energy data based on comprehensive analysis of the impact of the strategies on the thermal and lighting characteristics of a building. The model's main limitation in this regard is the difficulty in obtaining comprehensive energy data.

In the case illustrations presented in Sections 3 and 4 of this report and in the regional analyses presented in the companion report, a limited number of window strategies are examined. These include choice of window size; choice of orientation; choice of single, double, or triple glazing; use of two interior accessories--venetian blinds and insulating shutters; and use of windows for daylighting.

1.3.3 Method of Treatment

The economic evaluation model--a life-cycle cost model--provides a means of assessing the dollar consequences of choosing alternative options for windows. The model enables us to include relevant costs or savings occurring in the past, present, and future, and to take into account changing prices over time. It brings together the costs of purchasing, installing, maintaining and repairing, and operating a specified window system in a given type of building with a specified orientation, geographical location, and mode of use.

The data required for the model are the purchase and installation costs of the window systems under consideration and of the wall system which would be used in lieu of the windows; the sizes of the windows under consideration; the current maintenance and repair costs per unit size; the different quantities of energy used in the building space for

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[1] The only strategies which the model is not capable of handling are those which affect the energy performance of the other elements of the building. An example would be the addition of a fence as a wind barrier. The model cannot apportion capital costs between the window and the other affected building elements.

each of the alternative window options and cases of use; the current price of energy and the expected rate of future price escalation; the technical efficiency of the mechanical heating, cooling, and lighting systems; the interests rate(s) which indicates the opportunity cost of money; and the life expectancy of the window.

For the purpose of the case illustrations in this report and the regional studies in the companion report, purchase, installation, maintenance, and repair costs of the previously listed window options were estimated by consulting manufacturers, builders, and written sources. The operating (energy) costs were obtained by applying a thermal evaluation model developed as part of the NBS inter-disciplinary study of windows.[1] Realistic values for energy costs, system efficiency, interest rates, and expected life were assumed.

A computer program, written in BASIC,[2] is used to apply the life-cycle cost model. The program calculates life-time energy costs for the interior space with the designated window system, the life-time additional costs of the envelope with the designated window system (as compared with having no window), and the life-time costs of any designated accessories used with the window system, and then sums the results. These calculations are reiterated for specified sizes of the designated window system and for specified orientations. For each orientation, the least-cost window system and size are then identified from among those alternatives for which data are entered into the program. For each least-cost window system, the program computes the net present value of costs and savings, the years to discounted payback (i.e., the elasped time until cumulative savings offset the purchase and installation costs of the window system),[3] and the break-even rate of future fuel price escalation (i.e., the fuel price escalation rate for which the combined costs of accessories, energy, and the windows for the least-cost window system are identical to the corresponding costs associated with having no window).

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[1] For a description of the model and case results see, Tamami Kusuda and Belinda L. Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, National Bureau of Standards, Building Science Series 109, February 1978.

[2] "BASIC" is an acronym for Beginners All-purpose Symbolic Instructions Code. For a description of the use of BASIC, see BASIC LANGUAGE, Honeywell Software Series 400, Honeywell Information Systems, Inc., August 1971.

[3] The payback calculation can be made only if the life-cycle cost of the least-cost window is less than that associated with having no window.

1.4 Organization

The report is organized in five major sections and has a supporting appendix. Section 2 presents the methodology. It provides an overview of life-cycle costing, presents the economic evaluation mode for windows, and formulates a computer program to implement the model. (The computer program is described in the text and is listed in detail in Appendix A.)

In Section 3, the method is applied step-by-step in a case study for a residence in Washington, D.C. In Section 4, the method is again applied step-by-step in a case study for an office building in Washington, D.C. Four measures of life-cycle costs are provided, based on four different levels of thermal analysis.

The final part, Section 5, gives a summary, conclusions and suggestions for further research.

Facing page: *The interactive computer program described here can be used to evaluate the life-cycle costs associated with windows in new and existing residential and commercial buildings.*

2. LIFE-CYCLE COST METHODOLOGY

2.1 General Description of the Life-Cycle Cost Method

Life-cycle cost analysis is an economic evaluation technique which is used to measure costs over the life of a system. The technique can be applied to alternative systems (investment choices) in order to compare them on an equivalent basis and select the most cost-effective system. The technique involves four main steps: (1) the identification of the relevant cost items for each alternative, (2) the determination of the amounts and timing of cash flows, (3) the conversion of cash flows to a common point in time, and (4) the calculation of net life-cycle costs by summing the discounted cash flows.

In the evaluation of windows, the time adjustment of cash flows, step three, is necessary because windows give rise to cash flows that are spread over time. While purchase and installation costs, i.e., "first costs", are incurred at the outset, other effects, such as maintenance and repair and heat losses and gains, are usually more-or-less continuous over the life of the window. Given that the life of the window generally corresponds rather closely to the life of the building in which it is located, the cash flows associated with a window may extend over a period of 20 to 100 years.[1]

There are two factors in the time adjustment: (1) possible changes in prices and (2) the time value of money. With respect to price changes, it is necessary to ensure that all costs and benefits are stated in terms of comparable prices. This requires that past and future prices be adjusted for purely inflationary or deflationary price changes. One way of adjusting "current" (inflated or deflated) dollar amounts to "constant" (level purchasing power) dollars is to apply a price index[2] to the current dollar amount. For example, based on the 1975 annual average wholesale price index for industrial commodities (1975 = 171.5, where 1967 = 100), a window component that cost $100 in 1967 would cost roughly $172 in 1975.[3]

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[1] Assumptions as to the useful life of a building vary greatly. For example, a recent study of educational facilities assumes a life of 40 years for a school. [Educational Facilities Laboratories, The Economy of Energy Conservation in Educational Facilities, (New York: Education Facilities Laboratories, Inc., November 1973), p. 10.] A recent report on public buildings suggests the assumption of a 50 year life for purposes of analysis, but acknowledges that some buildings will have a shorter economic life because replacement will become cost effective and that some buildings will have substantially longer lives than 50 years. [Booz-Allen and Hamilton, Inc., Life-Cycle Costing in the Public Building Service, Volume 1, (A Report Prepared for the General Services Administration, Public Building Service), undated, pp. I-2 and IV-2.] A recent study of university buildings in Canada uses a 60 year cost horizon. [Report on Building Life Costs, (a report prepared by the Council of Ontario Universities), Toronto, Ontario, November 1973, p. 1.14.] Because of the uncertainty associated with future energy prices, as well as with intended use of the building, the period of the analysis is often set substantially less than the expected physical life of the building. As is explained in the discussion of assumptions in Section 3.1, for example, the "period of analysis" for purpose of the case illustrations in this report is defined as 25 years.

[2] A price index is a statistical measure of the average change in prices over time for a given item or "market basket" of items.

[3] U.S. Department of Labor, Bureau of Labor Statistics, Monthly Labor Review, Volume 99, Number 2, February 1976, p. 93.

It is also necessary to take into account changes in prices of particular goods or services relative to general price changes. Altered supply and demand factors can cause some prices, such as for energy, to rise more sharply than is warranted by changes in the purchasing power of the dollar in general. A life-cycle cost analysis needs to take into account any "real" price changes that occur over time.

With respect to the second factor, the time value of money, it is necessary to adjust cash flows to incorporate the opportunity cost which is incurred by using resources for the purpose at hand rather than for the best alternative purpose (i.e., the foregone earnings on alternative investments). The concept of opportunity cost applies regardless of whether there is inflation or deflation and regardless of whether borrowed or equity funds are used, as long as alternative productive investments are possible. If there is a positive opportunity cost, an individual investor or firm will prefer to delay expenditures (costs) and hasten receipts (benefits). The opportunity cost is generally stated as a compound interest rate referred to as the "discount rate." For example, if our opportunity cost were indicated by a discount rate of 10%, compounded annually, we would just break even if we spent $385.54 today to save $1,000 ten years from now. (That is, $385.54 invested at 10% for ten years = $1000). Similarly, we would be indifferent, other things being equal, between paying $564.47 now and paying $1000, six years from now.

Interest formulas, which are listed and explained in most engineering economics textbooks, can be used to discount cash flows to a common time for comparison.[1] Interest factors derived from the interest formulas, and also contained in most engineering economics textbooks, can be used to simplify the discounting calculations.[2]

2.2 Development of the Model

Table 2.1 lists the main elements in the life-cycle cost model for windows. The impact of windows on energy consumption is the most difficult item of information to estimate. The NBS thermal model,[3] used to estimate energy consumption for use in the life-cycle cost model, takes into account climate; thermal resistance of glazed and unglazed portions of exterior wall; window size, directional orientation of the windows; the effects on energy usage of window accessories, internal heat loads such as equipment, people, and lights; and operational factors including

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[1] See, for example, Gerald W. Smith, Engineering Economy: Analysis of Capital Expenditures, 2nd Ed. (Ames, Iowa: The Iowa State University Press, 1973) pp. 47 and 50.

[2] Ibid., pp. 575-621.

[3] Tamami Kusuda and Belinda Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, National Bureau of Standards BSS 109, February 1978.

TABLE 2.1

Elements in the Life-Cycle Cost
Model for Windows

Type of Cost	Type of Information Required
Energy	Energy Sources Quantities Used Unit Prices Tax Rates and Rules
Acquisition	Purchase Price of Windows, Walls, and Accessories Installation Price of Windows, Walls, and Accessories Tax Rates and Rules
Maintenance, Repair, and Replacement	Cleaning Cost per Unit Area Painting Cost per Unit Area Window Size Insurance Costs Insurance Reimbursables Nonreimbursable Repair Costs Tax Rates and Rules

changing the thermostat and utilizing daylight. The thermal model, however only applies to a single room in a larger structure and does not take into account natural ventilation effects of operable windows.

An algebraic statement of the life-cycle cost model is given below.[1] The model is designed to assess the life-cycle cost implications of

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[1] The model as stated in equation 2.1 is deterministic. As such, it assumes that the timing and values of all cash flows are known. In the event that the timing or values of future cash flows are nondeterministic but governed by a probability distribution (i.e., the timing and values of cash flows are random variables) it is necessary to use probabilistic methods to calculate the present value of the window system cost. [See A. Reisman and A. Rao, "Stochastic Cash Flow Formulae Under Conditions of Inflation," The Engineering Economist, Vol. 18, No. 1, Fall 1972, pp. 49-69; and Young, D. and Contreras, L., "Expected Present Worths of Cash Flows Under Uncertain Timing," The Engineering Economist, Vol. 20, No. 4, Summer 1975, pp. 257-268.]

windows in either residential or commercial buildings. It enables the determination of the least-cost window system and its savings relative to alternative window systems and relative to the wall with no windows. The model also enables the calculation of time to payback and the performance of sensitivity analysis. Assessing sensitivity to fuel prices is particularly important because of the uncertainty attached to present forecasts of long-term increases in fuel prices. The model is also able to assess the impact that different tax structures and depreciation allowances have on the cost-effectiveness of window systems for commercial buildings.

Present Value Costs = ENERGY COSTS

$$PV = [E_H \times C_H + E_C \times C_C + E_{LE} \times C_{LE}] \times R(1) \times T(1)$$

+

PURCHASE AND INSTALLATION

$$+ [PW + IW - A \times CW + ACC \times [PB_A + IB_A + PS_A + IS_A]] \times T(2)$$

+

MAINTENANCE, REPAIR, AND REPLACEMENT

$$+ [M_A \times R(2) + M_{BA} \times R(3) + INS_A \times R(2)] \times T(1) \qquad 2.1$$

where,

PV = the present value of the acquisition, maintenance and repair costs for the window and its accessories, plus the energy costs for the interior space with the designated window system.

E_H, E_C, E_{LE} = the quantities of energy required for heating, cooling, and lighting and equipment. These quantities incorporate values for the efficiency of heating, cooling and lighting systems.

C_H, C_C, C_{LE} = the current prices per unit of the energy sources used for heating, cooling, and lighting and equipment.

R(1) = the uniform present value factor for a series of end-of-period sums changing by a constant rate, FPE, per period. It adjusts fuel prices for future escalation and sums the per unit expenditure over the expected life. It is defined algebraically as

$$R(1) = \sum_{t=1}^{L} \left(\frac{1+FPE}{1+DIS}\right)^t$$

where, FPE = the rate of fuel price escalation,
DIS = the discount rate, and
L = the expected system life in years.

T(1) = the proportion of operating expenses remaining after taxes. For residential case applications T(1)=1.

PW = the purchase price of the window.[1]

IW = the framing and installation costs associated with the window.

A = the area of the window in square feet.

CW = the cost per square foot for the windowless exterior wall.

ACC = 1 if management accessories are used; 0 otherwise.

PB_A = the purchase price of venetian blinds of area A.

IB_A = the installation price of venetian blinds of area A.

PS_A = the purchase price of a thermal shutter of area A.

IS_A = the installation price of a thermal shutter of area A.

T(2) = a factor which adjusts for the present value of capital depreciation allowances in computing taxable income.

M_A = the cleaning cost in the base year for a window of area A.

R(2) = the uniform present worth factor, used to calculate the present value of constant yearly recurring costs, i.e., cleaning and insurance expenditures. It is defined as

$$R(2) = \sum_{t=1}^{L} \frac{1}{(1 + DIS)^t} .$$

M_{BA} = the repainting and recaulking costs for a window area A assumed to occur in the fifth year, but evaluated in base year dollars. (M_{BA} is equal to 0 in the commercial case application).

R(3) = the uniform present worth factor used to find the present value of constant future expenditures that occur periodically but not yearly, i.e., repainting and recaulking every fifth year. It is defined algebraically as

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[1] Prices would reflect taxes, contractor discounts and contractor markup for overhead and profit.

$$R(3) = \sum_{t=1}^{L/5} \frac{1}{(1 + DIS)^{5t}} .$$

INS_A = the annual insurance cost in the base year for a window of area A. (If yearly recurring repair and replacement costs are not available, insurance premium costs can be used as a proxy for these costs. If the data are available, insurance costs should be expressed inclusive of nonreimbursable expenses and exclusive of reimbursable expenses.)

(Note: R(2) and R(3) are based on M_A, M_{BA}, and INS_A being given in constant dollars and DIS representing a "real" discount rate ajusted to exclude inflation. If, however, the analysis is performed in current dollars, using "nominal rates that include inflation, it would be necessary to include a price inflation escalation rate in R(2) and R(3), similar to R(1).)

2.3 Flowcharting of the Computer Program

To perform a comparative evaluation of alternative window systems, window sizes, and orientations, and to perform sensitivity analysis, equation 2.1 must be applied a number of times. To facilitate these calculations a computer program was developed. The program, written in BASIC computer language, is designed to provide users flexibility in specifying the values of the critical variables upon which analysis is based. This approach was taken in order to satisfy the dual objectives in developing the evaluation model: to provide a method which others can apply to their particular problem of window selection, and to provide a method for performing the case studies of this and the companion report.

Figure 2.1 shows a detailed flowchart of the computer program. At the beginning of the program the operator is called upon to enter the values of the rate of fuel price escalation (FPE) over the specified life cycle and the discount rate (DIS), and to indicate the types of glazing and building that will be considered. The program automatically assesses the life-cycle cost impacts of single and double glazing; if triple glazing is to be considered 1 is entered; otherwise 0 is entered. To specify whether the building type is residential or commercial, the variable CO is assigned a value of 0 or 1, respectively. If a commercial application is specified, the program will request that an income tax rate be entered.[1]

[1] If greater flexibility on the part of the user is desired, additional variables now given in the program may be changed to input variables. For example, expected life is given in the program as 25 years, but the program could easily be modified to allow the life to be entered by the user.

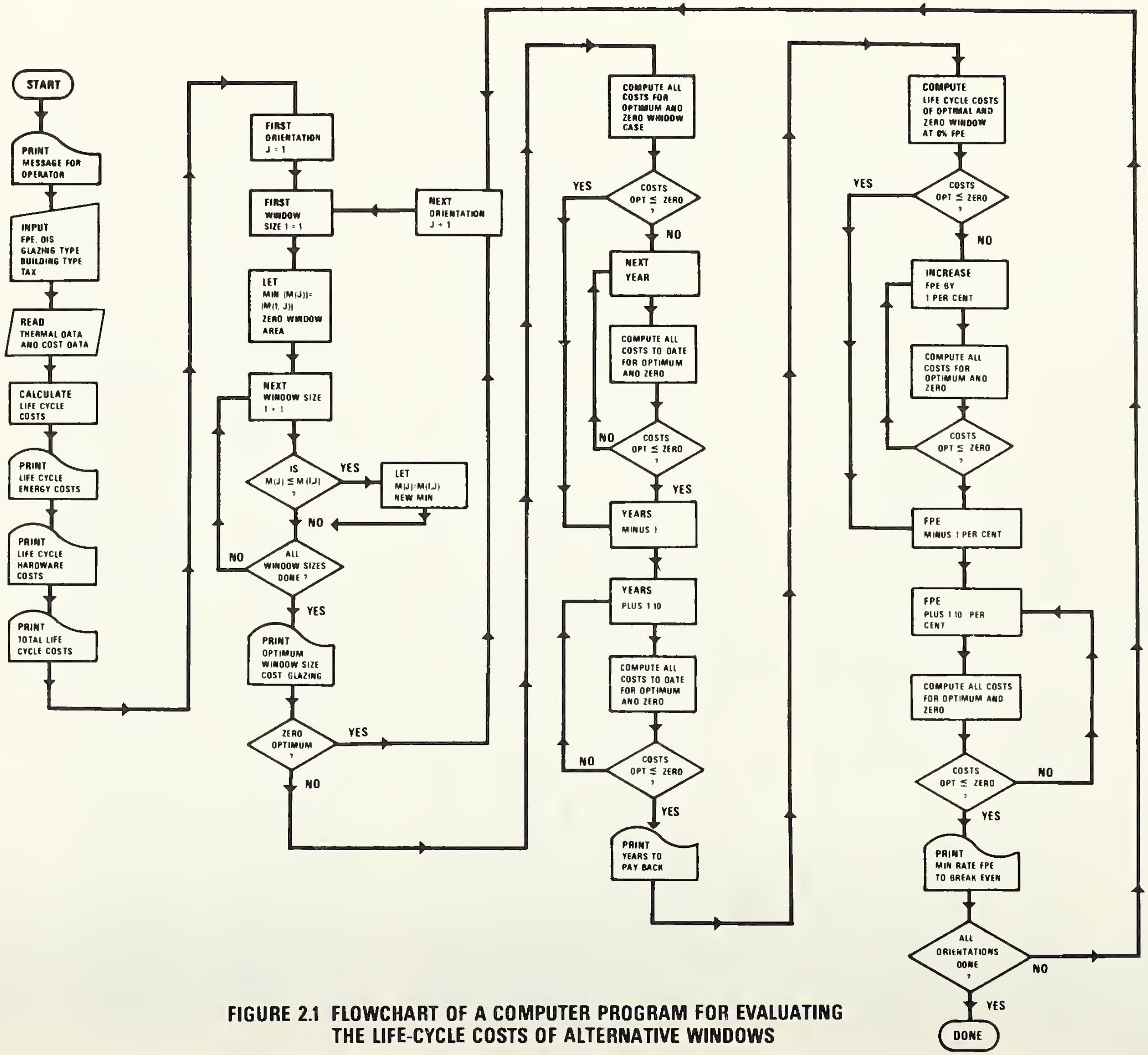

FIGURE 2.1 FLOWCHART OF A COMPUTER PROGRAM FOR EVALUATING THE LIFE-CYCLE COSTS OF ALTERNATIVE WINDOWS

After the values for the key variables have been entered, the computer reads thermal and cost information from its data bank. The data bank is entered at the outset by the user and consists of three sets of thermal data:[1] (1) the heating requirement in therms, (2) the cooling requirement in therms, and (3) the number of kilowatt hours required for lights and equipment; and four sets of cost data: (1) the cost per unit of energy for heating and cooling and of electricity for lighting, (2) the purchase and installation cost of the window less the cost of a comparable wall system, (3) the costs of maintaining, repairing, and replacing the window system, e.g., cleaning, painting, caulking, and insuring, and (4) the cost of window accessories.[2] Using these data and the values of the variables entered by the user, the computer program calculates and prints three sets of life-cycle cost values for each window size, glazing type, and orientation: one set for life-cycle energy costs; one set for life-cycle purchase, installation, maintenance, repair and replacement (insurance) costs (referred to hereafter as "envelope costs"); and one set for total life-cycle costs (the sum of the first and second sets).

A sample printout of the life-cycle cost tables is shown in Table 2.2. The first two sections of the table give the life-cycle energy costs for single and double glazing, respectively, for designated window sizes and orientations. The third section of the table gives the life-cycle envelope costs. The fourth and fifth sections of the table give total life-cycle costs, again for first single and then double glazing.

Table 2.3 shows the additional outputs of the computer program: (1) the identification of the window system which minimizes life-cycle building costs for each orientation,[3] (2) the total life-cycle costs and cost savings resulting from the least-cost window system, (3) the years required for the least-cost system to pay back, and (4) the rate of future fuel price escalation required for the least-cost system to break even.

To derive the above outputs, first the life-cycle costs are examined for the first orientation in the computer program, which is south (J=1),

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[1] As the window life-cycle costing program becomes more widely used, thermal and cost data files on selected cities could be established for referencing directly by the user, by inputting only a city file ID. This step would greatly simplify usage of the program and reduce error.

[2] This thermal and cost data should fit the particular case of window use being examined.

[3] The routine for this computation is contained within the second column of blocks in Figure 2.1.

TABLE 2.2

Sample Computer Printout From Window
Life-Cycle Costing Computer Program:
Energy Costs, Envelope Costs, and Total Costs in Dollars

LIFE-CYCLE ENERGY COSTS FOR SINGLE GLAZING

Designated Size of Windows (ft.^{2})	SOUTH	SOUTHWEST SOUTHEAST	EAST/WEST	NORTHWEST/ NORTHEAST	NORTH
0	1628.31	1635.64	1639.23	1631.77	1622.22
12	1109.27	1122.91	1137.07	1157.49	1152.82
18	1060.78	1075.76	1094.20	1128.09	1125.18
30	1023.55	1043.92	1068.20	1124.00	1123.32
60	1037.02	1066.58	1105.46	1219.62	1227.69

LIFE-CYCLE ENERGY COSTS FOR DOUBLE GLAZING

Designated Size of Windows (ft.^{2})	SOUTH	SOUTHWEST/ SOUTHEAST	EAST/WEST	NORTHWEST/ NORTHEAST	NORTH
0	1635.64	1639.23	1631.77	1631.77	1622.22
12	1096.44	1110.19	1123.55	1125.33	118.93
18	1041.58	1056.12	1071.56	1074.96	1068.82
30	982.99	1000.05	1021.92	1031.23	1026.51
60	940.89	967.31	1000.57	1017.81	1015.80

LIFE-CYCLE ENVELOPE COSTS

Designated Size of Windows (ft.^{2})	SINGLE-GLAZED WINDOW	DOUBLE-GLAZED WINDOW	MAINTENANCE, REPAIR AND REPLACEMENT	WINDOW ACCESSORIES
0	0.00	0.00	0.00	0.00
12	18.48	48.08	42.93	71.00
18	20.12	58.78	64.40	84.00
30	38.25	108.31	107.33	155.00
60	76.50	216.53	214.67	320.00

TOTAL LIFE-CYCLE COSTS FOR SINGLE GLAZING

Designated Size of Windows (ft.^{2})	SOUTH	SOUTHWEST/ SOUTHEAST	EAST/WEST	NORTHWEST/ NORTHEAST	NORTH
0	1628.31	1635.64	1639.23	1631.77	1622.22
12	1241.68	1255.32	1269.48	1289.90	1285.23
18	1229.30	1244.28	1262.72	1296.61	1293.70
30	1344.13	1344.50	1368.78	1424.58	1423.90
60	1658.18	1677.74	1716.62	1830.78	1838.86

TOTAL LIFE-CYCLE COSTS FOR DOUBLE GLAZING

Designated Size of Windows (ft.^{2})	SOUTH	SOUTHWEST/ SOUTHEAST	EAST/WEST	NORTHWEST/ NORTHEAST	NORTH
0	1635.64	1639.23	1631.77	1631.77	1622.22
12	1258.45	1272.20	1285.56	1287.34	1280.94
18	1248.76	1263.30	1278.74	1282.14	1276.00
30	1353.64	1370.69	1392.56	1401.87	1397.15
60	1692.09	1718.51	1751.77	1769.01	1767.09

TABLE 2.3

Sample Printout of Life-Cycle Cost Optimization, Payback, and Fuel Price Sensitivity Routines: Minimization of Life-Cycle Costs

Orientation	1[a]	Area in Sq Ft	18	Single Glazing
Total Cost	1229.30	Total Savings	399.01	
Years to Payback	5.4			
Percent FPE	-1[b]			

[a] South orientation (J = 1).

[b] A negative value indicates that the window system would break even relative to the life-cycle costs of a windowless section of wall even if fuel prices declines by 1 percent per annum. A positive value means that the system would break even even if fuel prices increased by the designated percentage rate per annum.

and for the first window size, which is 0 (I=1).[1] These are defined initially as the minimum life-cycle costs. That is, the least-cost window system for orientation J, M(J), is taken to be the zero window case for orientation J; hence, initially M(J) = M(1,J). The next window size (I=2) is then compared with the prior least-cost window. The comparison is performed by testing whether the life-cycle costs of the new window system are less than the life-cycle costs of the preceding window system. If the life-cycle costs of the new window system are less, then a new least-cost window system is designated. The process is repeated for each glazing type and window size until the ones which minimize the window system's life-cycle costs are identified. The computer then prints the following information for the least-cost window system for the given orientation, J: (1) the orientation, (2) the window area, (3) the glazing type, (4) the total life-cycle cost, and (5) the life-cycle savings over the zero window case. If the least-cost window system costs less than an unwindowed section of wall in terms of total life-cycle costs, the program enters the payback routine.[2] The time to payback is calculated to the nearest tenth of a year. The program then

[1] Throughout this discussion J refers to the orientation of the window and I refers to the size of the window.

[2] This routine is contained within the third column of blocks in Figure 2.1

enters the sensitivity routine which assesses the effect of the rate of fuel price escalation (FPE) on the cost of the least-cost window.[1]

2.4 Graphical Representations

The relationship that exists between life-time energy costs and envelope costs determines the size of the least-cost window. Figure 2.2, parts a through c, illustrates three of the relationships that may exist between these two components of costs. On the vertical axes, life-cycle costs are measured; on the horizontal axes, window area as a percentage of total wall area is measured. The curves labeled "E" represent energy costs; the curves labeled "C", envelope costs for a window minus the cost of a wall of equal size; and the curves "TC," combined energy and envelope costs. The slopes of the curves indicate the impact on costs of changing the window size.[2]

If the window costs more to purchase, install, maintain, repair, and accessorize than an unglazed portion of the wall of equal size, and also raises the building's energy consumption as its size increases, the least-cost window is no window. This relationship is demonstrated in Figure 2.2a which shows the area of least-cost window, designated A', to be zero.

If the window costs less than an equal area of unglazed wall to purchase, install, maintain, repair, and accessorize, and also reduces energy consumption, the least-cost approach is to glaze the entire wall area. This relationship is illustrated by Figure 2.2b, which shows the least-cost window, A', to be 100 percent of the wall area.

A third possible relationship is for the window to cost more to purchase, install, maintain, repair, and accessorize than an equal area of unglazed wall, but to reduce energy consumption. In this case, the the energy savings potential of the window may be sufficient to more than offset the extra investment costs of the window, and life-cycle building costs may be minimized by having a window larger than zero, but smaller than the entire wall area. This relationship is illustrated by Figure 2.2.c.[3]

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[1] This routine is contained within the fourth column of blocks in Figure 2.1.

[2] The least-cost window size may be defined in terms of incremental (marginal) costs as that window size for which the last dollar investment in a larger window area produces a dollar in life-cycle energy savings.

[3] Other possible relationships between window envelope and energy costs include the following: (1) rising envelope (energy) costs might more than offset falling energy (envelope) costs as window size is increased such that the least-cost window is zero; (2) falling energy (envelope)
(continued on page 24)

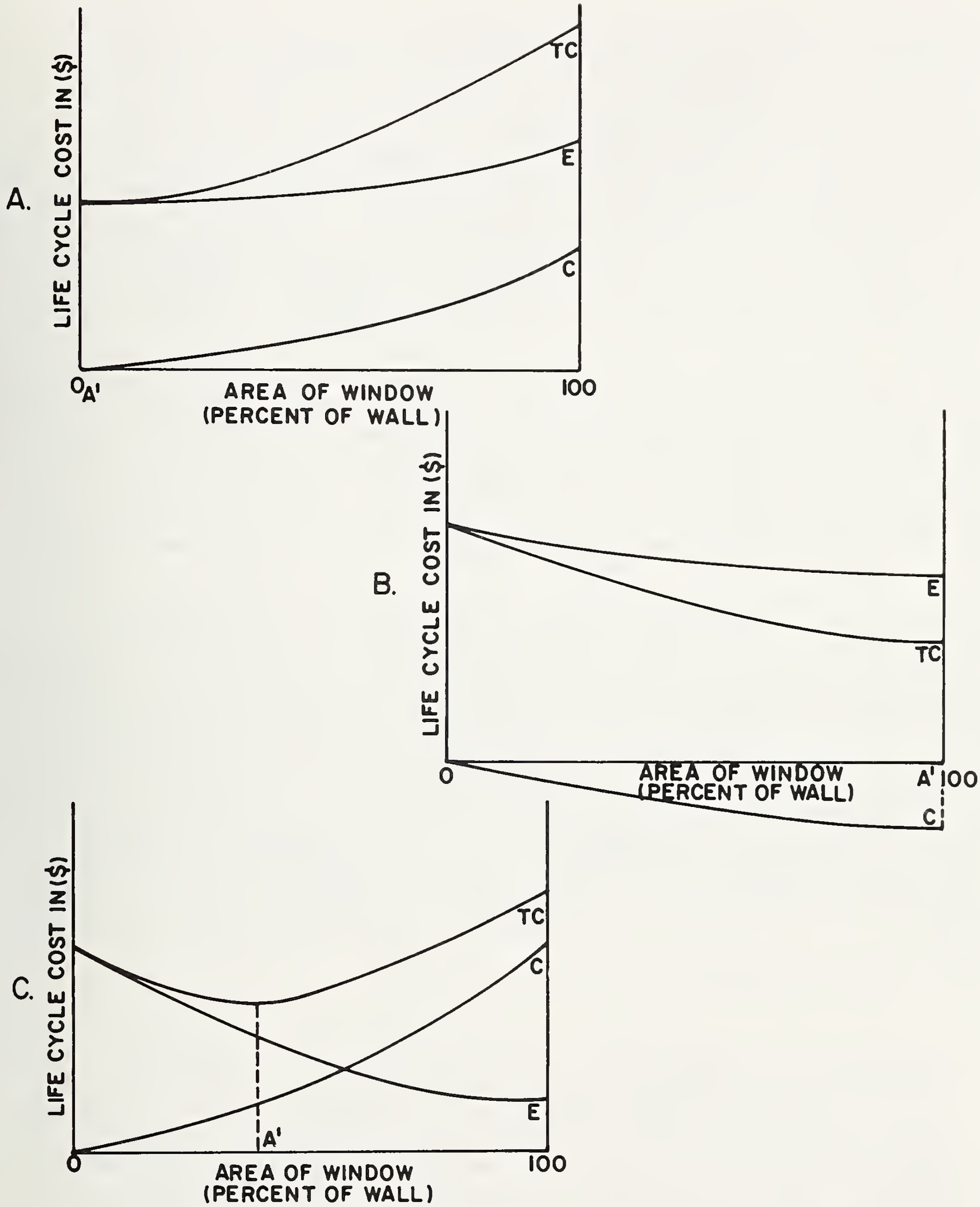

Figure 2.2 Alternative Relationships Between Window Envelope and Energy Costs

Notation: E = Energy costs of the interior space with a window of designated size,
C = Envelope costs attributable to a window of designated size,
TC = Combined energy and envelope costs.

Life-cycle costs may also be represented graphically as a function of window orientation. The results convey considerable information simply and compactly. The graphs shown in Figures 2.3a through c use polar coordinates to represent the different orientations. For example, the top vertical line may be designated as north and the bottom vertical line as south, as is shown in the graphs. The curves that are equally distant from the center of the graph are designated as equal-cost, or isocost, curves. For example, on Figure 2.3a, the first curve from the center indicates life-cycle costs of $250, the second indicates $500, the third $750, and the fourth, $1000. To complete the diagram, a series of curves can be drawn that plot life-cycle costs against orientation for each window size.

To differentiate these curves from the isocost curves, they are referred to as equal-window area, or "isoarea", curves. On Figure 2.3a, the curve designated "0" is the isoarea curve for a window of size zero. It shows the life-cycle costs associated with the windowless case for the alternative orientations. The case with no window is shown because the cost effectiveness of alternative window systems can be measured by comparing their life-cycle costs with those of the alternative wall investment.[1]

Figure 2.3b shows, in addition to the isoarea curve for the case with no window, two isoarea curves designated "A_1" and "A_2" that represent a single-glazed window system and a double-glazed window system, respectively, both of size A. With these three curves overlaid, it is possible to construct a least-cost envelope, and to see which of these window areas and glazing types are least costly with respect to orientation. The envelope is constructed by making a fourth curve which consists of the innermost segments of the three existing curves. This envelope, illustrated in Figure 2.3c by a heavy solid line, shows for each orientation how large the window should be and whether single or double glazing should be used in order to achieve the lowest life-cycle cost. In this illustration, for example, when facing north, a windowless wall results in lowest costs; when facing south, a single-glazed window of

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(Continued from page 22)

costs might more than offset rising envelope (energy) costs such that the least-cost window size is 100 percent of the wall area; (3) the fall in envelope (energy) costs might just offset the rise in energy (envelope) costs such that there is indifference from a cost standpoint between having and not having windows. The possibility of non-monotonic energy and envelope costs means that more than one minimum may occur for certain cases.

[1] It may be noted that any positive window area could be used as a standard for comparison. However, using the case of no window as the standard has the following advantages: (1) it explicitly allows for the option of having no windows, and (2) it does not favor any particular minimal window size.

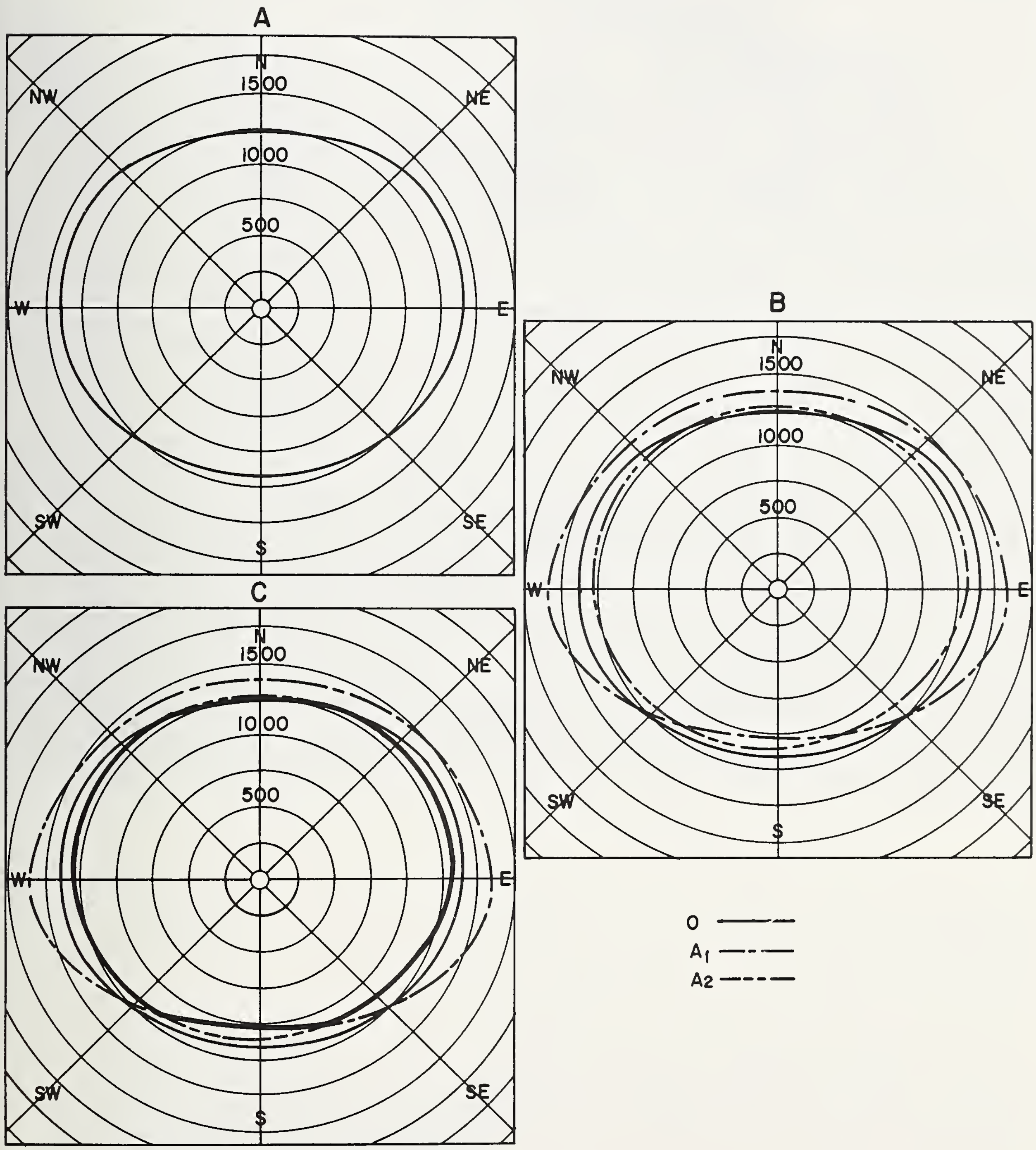

Figure 2.3 Window Life-Cycle Costs in Relationship to Window Area and Orientation

area A; and on the east and west, a double-glazed window of area A. By comparing the least-cost envelope with the other curves, 0, A_1, and A_2, the extra costs may be seen of using the same size and type of window system for all orientations.

2.5 Limitations of the Model

In interpreting the results obtained from the life-cycle cost model, the potential importance of factors omitted from the model should not be overlooked. Factors such as the influence of windows on the physical and psychological comfort of occupants, the internal and external appearance of the building, and safety may cause the optimal window to differ from the least-cost window as defined in the model.

Furthermore, the results of the model apply only to the particular situation described by the data and assumptions used. It should be recognized, for example, that the NBS thermal model used here to generate thermal data for the life-cycle cost model is itself based on many assumptions about thermal loads, climate, functional properties of windows, and user operational behavior. In addition, it omits certain factors such as natural ventilation, and there is uncertainty about other factors such as its daylight, artificial light trade-off routine.

The life-cycle cost model nevertheless serves to reduce uncertainty about the energy costs and economic efficiencies of alternative window choices, although it does not provide a truly comprehensive measure of all benefits and costs. The life-cycle costs of alternative window systems can be viewed as measures against which decision makers can compare the importance of other factors.

Facing page: *Nearly 27 million windows costing more than $1 billion are estimated to be installed in new residential units each year.*

3. ILLUSTRATION OF THE METHODOLOGY: RESIDENTIAL CASE STUDY

The following is a detailed illustration of the method of evaluation developed in Section 2 of this report. The illustration is for selected window systems in a room of a residence assumed to be located in Washington, D.C. (The room is referred to hereafter as the "residential module.")

The primary purpose of the illustration is to demonstrate the evaluation approach in sufficient detail to guide others in using the model with their own data. A secondary purpose is to derive results which are useful to the building community in selecting, accessorizing, and using windows. Because the primary objective is that of illustration, a detailed, step-by-step approach is provided.

3.1 Basic Assumptions

The residential module is assumed to be a kitchen/family room in a one story ranch-style house with a full basement. The overall dimensions of the house are 28 feet wide by 50 feet 6 inches long, and the total floor area is 1414 square feet. The layout of the house including the location of windows and doors is shown in the floorplan in Figure 3.1. The kitchen/family room shown shaded in the floorplan, is used for the purposes of both the thermal and the economic analysis of the alternative window systems. The dimensions of the room are 15 feet wide by 18 feet long by 8 feet high.

The exterior wall of the house has 4" brick veneer over 8" cinder block, and contains 3-1/2" of blown-in insulation (cellulose). The U value of the wall is 0.07.

The windows used in the economic analysis are wooden and double hung. Both single and double glazing are examined for window sizes ranging from 0 to 60 square feet. Figure 3.2 shows the four window sizes examined in relationship to the size of the exterior wall. Additional assumptions, such as lighting requirements, heating and cooling system efficiencies, and occupancy patterns are given in Table 3.1.

The NBS thermal model which is used to provide input to the economic model assumes that all heat flows entering or leaving the room are through the exterior wall which contains the window. It is therefore explicitly assumed that no heat flows occur between the room under examination and the basement, attic, or adjacent rooms. (Such a system is usually referred to as adiabatic.)

Furthermore, the thermal model does not take into account the inter-dependencies between building components that may result in a change in one factor affecting the thermal performance of other factors. To account for all possible heat flows and thermal interdependencies would require a considerably more sophisticated thermal model than that which was used in the case studies.

The simplifying assumptions employed in the thermal model result in specific limitations for the life-cycle cost measures produced by the economic model for the case study. One limitation is that the life-cycle costs of the windows for the single room cannot be multiplied by a constant, say, 6 or 8 depending upon the size of the house, in order to get the life-cycle window costs for the entire house. One reason is that the computer program assumes that there is only one exterior wall in the room. Since all residences have some corner rooms which have two or more exterior walls, the assumption that there are no heat flows through these walls is overly strict. Another reason is that most houses do not have basements and attics with regulated temperature. The fact that the thermal model makes no allowance for the effects of natural ventilation on energy usage further limits the reliability of the life-cycle cost measures produced by the case study. But the most tenuous aspect of

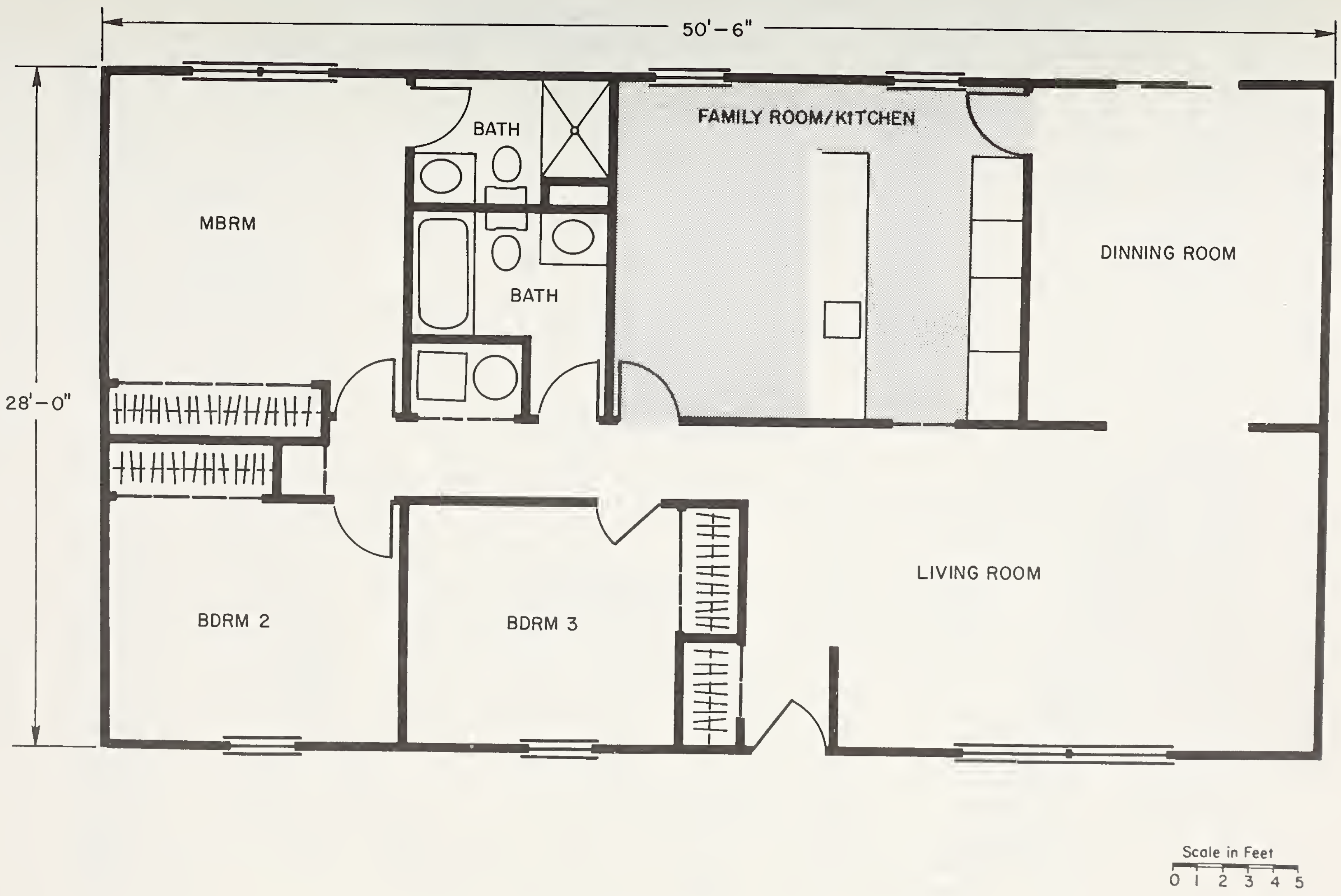

Figure 3.1 Plan of House Used in the Case Study

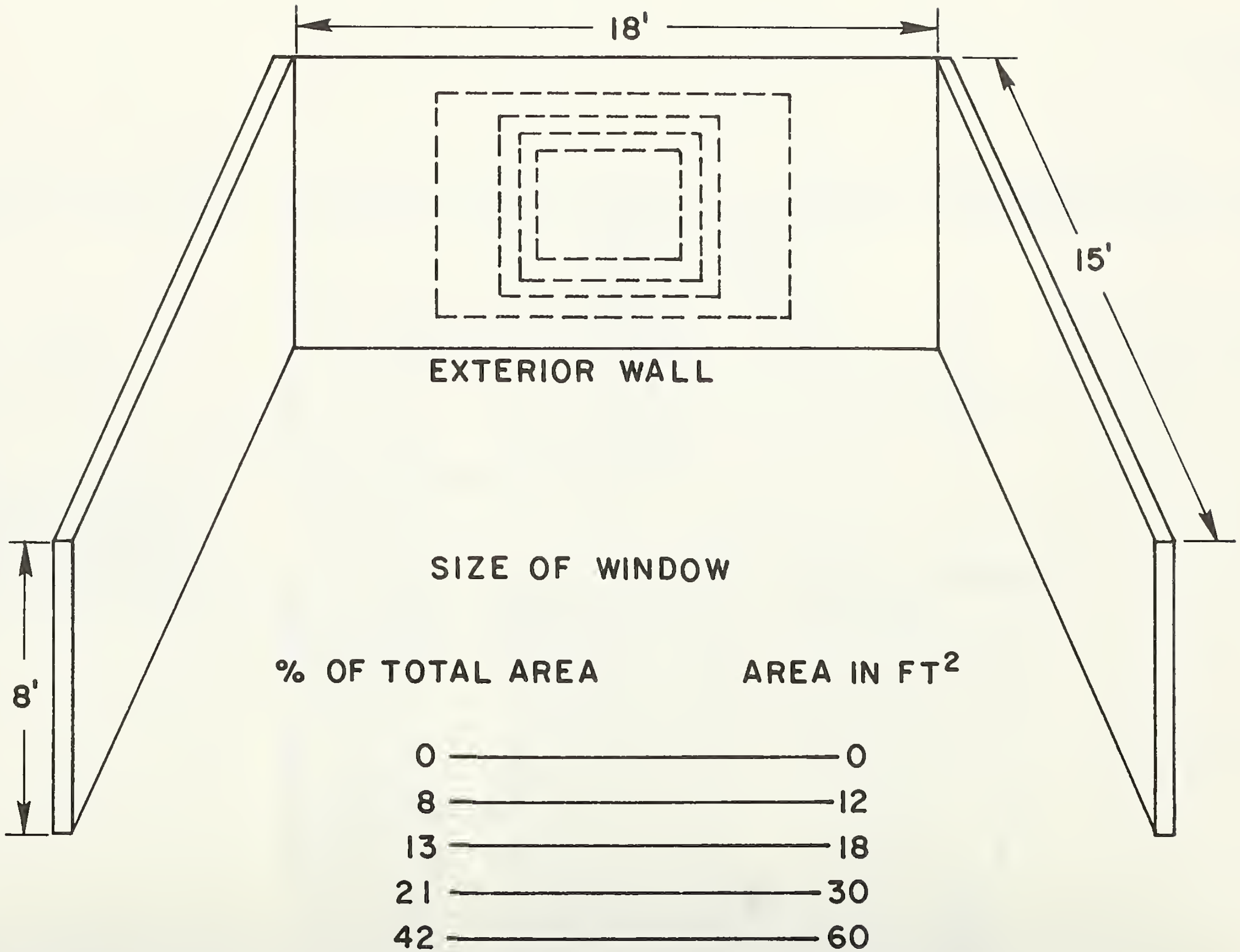

Figure 3.2 Window Sizes in Relationship to the Size of the Exterior Wall of the House

TABLE 3.1 Assumptions for Residential Case Study[a]

Building Specifications	Assumptions
Dimensions of Module[a]	15' wide x 18' long x 8' high
Type of Construction	Block with brick veneer; 3-1/2" cellulose insulation; U = 0.07
Exterior Wall Area	144 ft^2
Window Size	0, 12, 18, 30, 60 ft^2
Window Construction	Wood; double hung; weatherstripped
Internal Loads[b]	
Lights	0.65 $watts/ft^2$
Equipment	0.52 $watts/ft^2$
Air Leakage	0.5 air changes/hour
Occupancy	0.5 persons
Heat Load/person	260 But/hour/person
System Efficiency	**Specifications**
Furnace Efficiency	0.65
Cooling COP[c]	2.0
Electric Heating	1.0
Fuel Type	**Costs**
Electricity	$0.03 per kWh
Gas	$0.30 per therm
Operation	**Conditions**
Thermostat Adjustment	72° to 62° F winter nights 78° to 84° F summer nights
Window Management	**Times**
Thermal Shutters	Winter nights
Venetian Blinds	Summer days

[a] Due to the difficulty of modeling the thermal exchange between rooms, only a single room was modeled. The model assumes no heat transfer to adjacent surfaces such as walls, floors, or ceilings. Study of windows within a single room of a house may not necessarily reflect the performance of windows in the house in general.

[b] All loads are averaged over the 16 hour period from 7:00 AM to 11:00 PM. The assumptions underlying the thermal calculations are described in greater detail in Tamami Kusuda and Belinda Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, February 1978, pp. 10-20.

[c] COP = Coefficient of Performance.

the case study is the assumption made in the thermal model concern daylighting. Although the amount of daylight predicted by the daylight computer subroutine has now been validated against two other considerably different computer programs,[1] available amounts of daylight and the concomitant savings in electric energy for lighting and cooling have not been adequately validated by laboratory and field testing.[2]

In addition, there are questions about people's actual use of daylighting to supplement or replace electric lighting. Typical lighting levels and duration of use in residences are not well established, nor is the human response to available daylight well determined.

A further limitation of the case study is that it compares daylighting only with general lighting of the room by incandescent bulbs; for other solutions, such as task lighting, daylighting might have less value.

3.2 Envelope Costs

In general, purchasing and installing windowed areas in a home is more expensive than providing windowless walls. However, because windows displace portions of the wall, they raise initial building costs by substantially less than their full purchase and installation costs. To estimate their additional acquisition costs, window costs are compared with wall costs in Table 3.2. This table shows that purchase and installation of good quality wood windows are estimated to add between \$18 and \$76 to initial building costs for single-glazed windows and from \$48 to \$216 for double-glazed windows, depending on their size. Window prices are distributor-quoted for the Washington, D.C. area. The wall costs are the estimates of a builder of homes in the Washington, D.C. area.

If management devices are used, additional acquisition costs are incurred. Costs of venetian blinds and wooden shutters based upon averages of currently quoted prices in the Washington, D.C. area are given in Table 3.3.

Window areas also usually require somewhat more maintenance than windowless wall areas. Estimates of window cleaning costs, based on a current cost of \$0.10/ft^2, are shown in the first row of Table 3.4. Estimates of maintenance and repair costs based on scraping, recaulking, and repainting once every five years at a current cost of \$1.50/ft^2, are shown in the second row of Table 3.4.

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[1] The other computer programs are LUMEN II and GLIM, two more complex programs used for lighting calculations in the United States and in Great Britain.

[2] A research program is currently underway at NBS to validate both the predicted daylight amounts and the energy savings.

TABLE 3.2

Residential Case Study:

Acquisition Costs of a Window in Excess of the Cost of a Windowless Wall

Component	Dollar Cost By Size of Window			
	$12\ ft^2$	$18\ ft^2$	$30\ ft^2$	$60\ ft^2$
Windows[a]				
Single Glazed	52.20	70.70	122.55	245.10
Double Glazed	81.80	109.36	192.61	385.23
Wall[b]	33.72	50.58	84.30	168.60
Window Cost Less Wall Cost[c]				
Single Glazed	18.48	20.12	38.25	76.50
Double Glazed	48.08	58.78	108.31	216.63

[a] Purchase prices are list retail prices, reduced 10 percent to reflect a typical builder's discount, for good quality wood double-hung windows, provided by a distributor in the Washington, D.C. area. A typical contractor markup of 25 percent for overhead and profit is then applied to the purchase price. Prices are for single and multiple units of windows of a size which comes close to providing the designated areas of the exterior wall in glazing. The $12\ ft^2$ area is provided by a 3' x 3'11" window; the $18\ ft^2$ area, by a 3' x 6' window; the 30 ft area by two 3' x 5' windows, and the $60\ ft^2$ area, by four 3' x 5' windows. An installation cost of $5.00 per window or pair of window is used, based on an estimate given by a home builder in the Washington, D.C. area. The installation cost and the purchase cost are then added together to get the acquisition cost.

[b] Costs of non-windowed wall areas corresponding in size to the windowed areas are based on a price of $2.81/ft² as estimated by a home builder in the Washington, D.C. area. The wall section is assumed to be face brick veneer over 8" cinder block with building paper sheathing, 3 1/2" of cellulose insulation, and 1/2" of painted interior drywall.

[c] The additional costs incurred for windows are calculated by taking the difference between the costs of windows and the costs of a comparably sized wall area.

TABLE 3.3

Residential Case Study:
Cost of Window Accessories

Type of Accessory	Dollar Cost by Size of Window			
	12 ft^2	18 ft^2	30 ft^2	60 ft^2
Venetian Blinds[a]	17.00	20.00	36.00	72.00
Wood Thermal Shutters[b]	42.00	51.00	96.00	192.00

[a] Prices shown are average of several quoted prices. Installation is assumed to be done by the homeowner at negligible costs.

[b] Estimates are those of a Washington area building contractor for building, installing, and finishing solid, tight-fitting wooden shutters. (Prices quoted by custom drapery shops in the area were considerably higher.)

TABLE 3.4

Residential Case Study:
Maintenance and Repair Costs

Type of Maintenance and Repair	Current Dollar Cost by Size of Window			
	12 ft^2	18 ft^2	30 ft^2	60 ft^2
	(Yearly Cost)			
Annual Cleaning at \$0.10/ft^2	1.20	1.80	3.00	6.00
	(Recurring 5th Year Cost)			
Scraping, Recaulking, Repainting[a] every 5th Year at \$1.50/ft^2	18.00	27.00	45.00	90.00

[a] Costs are based on a large sample of data collected in conjunction with a lead paint abatement program at NBS (R. Chapman, Economic Analysis of Experimental Lead Paint Abatement Methods: Phase I, National Bureau of Standards, Technical Note 922, September 1976.)

3.3 Energy Costs

Due to the uncertainty about future energy prices, energy costs of the windows are evaluated first based on no future escalation in energy prices and then on a relatively rapid rate of increase of 12 percent compounded annually, to establish a range of possible costs. In addition, energy costs are assessed for both natural gas, a currently less expensive energy source, and electric resistance energy, a more expensive energy source. (The room is assumed to be electrically cooled regardless of whether heating is by natural gas or electric resistance energy.)

In order to take into account the fact that windows are used in diverse building situations, their energy effects are evaluated for four different cases.

In the first case (referred to hereafter as the "unmanaged window, not used for daylighting" case), it is assumed that no energy conserving devices such as shutters and blinds (hereafter, referred to as "management devices") are installed in the window. The thermal calculations are based on traditional ASHRAE methods.[1] Included in the calculations is the heat generated by the people occupying the room and by lights and equipment (e.g., televisions, dishwashers, stoves, garbage disposals), as well as climate-determined heat gains or losses.[2] The climatological data are monthly mean daily temperature and solar radiation figures published by Kusuda and Ishii.[3]

The second and third evaluation cases are extensions of the first case. The second case (referred to as the "managed window not used for daylighting" case) assumes that management devices are used and that the desired room temperature is changed between day and night by adjusting the thermostat. Venetian blinds are used during the summer day to reduce excessive solar heat gain. Thermal shutters are used during winter nights to cut heat losses. It is assumed that the thermal shutters are custom fitted into the window opening. The combination of single glazing and the shutters result in a U value of 0.5; the combination of double glazing and the shutters result in a U value of 0.2. The resetting of the thermostat at night permits both heating and cooling costs to be reduced regardless of whether the room is windowless or has windows. During the heating season the thermostat is reset from 72°F to 62°F, and during the cooling season the thermostat is reset from 78°F to 84°F.

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[1] ASHRAE, Handbook of Fundamentals, 1972.

[2] In this study a base temperature of 65°F is used for heating degree day calculations (See ASHRAE Handbook of Fundamentals, 1972); a base temperatrue of 80° is used for cooling calculations.

[3] Kusuda, T. and Ishii, K., Hourly Solar Radiation Data for Vertical and Horizontal Surfaces on Average Days in the United States and Canada, National Bureau of Standards, BSS 96, April 1977.

In all other ways, the analysis for the second case of window use is identical to that of the first.

The third case of window use (referred to as the "unmanaged window used for daylighting" case) assumes that daylighting is substituted for electric lighting when the quantity of daylight available exceeds 6.7 fc (72.1 lux) measured at a reference point 15 ft (4.2 m) from the window and 3 ft (0.9 m) from the floor. This case further assumes that no management devices have been installed and that the thermostat is not reset at night. Hence, the third case is identical to the first with the exception of the trade-off between natural and artifical lighting.

In the fourth case of window use (referred to as the "managed window used for daylighting" case), daylighting is substituted for electric lighting, window management is practiced, and the thermostat is reset at night. Thus the fourth case brings together all of the elements of the first three cases. It is the case that would be expected to have the greatest potential for energy conservation.

As was indicated above, the third and fourth modes of operation--those which utilize daylighting--are unfortunately subject to more uncertainty than those which do not use daylighting. As was explained earlier, this is because the computer program which calculates the natural/artificial light trade-off has not yet been adequately validated.

3.3.1 Energy Costs for Unmanaged Windows Not Used for Daylighting

First the energy costs for different window sizes and glazing types are analyzed based on a bare, unmanaged window, not used for daylighting. Figure 3.3 shows base-year energy costs for single glazing in Part A and for double glazing in Part B, for two orientations. On the vertical axis of both graphs the estimated base-year energy expenditure is given in 1977 dollars. On the horizontal axis the window area in square feet is given.[1]

Parts A and B of Figure 3.3 show that base-year energy costs rise rapidly as window area is increased whether it is single or double glazed, although the rise is more rapid with single glazing. In the base-year, energy costs of the room heated by natural gas range from \$66 for a windowless wall with a southern orientation, to \$83 for a 60 ft^2 single-glazed window with a southern orientation. On the north side, costs range from \$66 to \$90.

If the room is heated by electricity, the base-year energy costs range from \$70 for a windowless wall on the south side, to \$102 for a 60 ft^2 single-glazed window on the south side. For a northern orientation,

[1] The format used in Figure 3.3 will be followed throughout the chapter. Recall that these energy costs are for the room indicated on Figure 3.1 and not for the entire house.

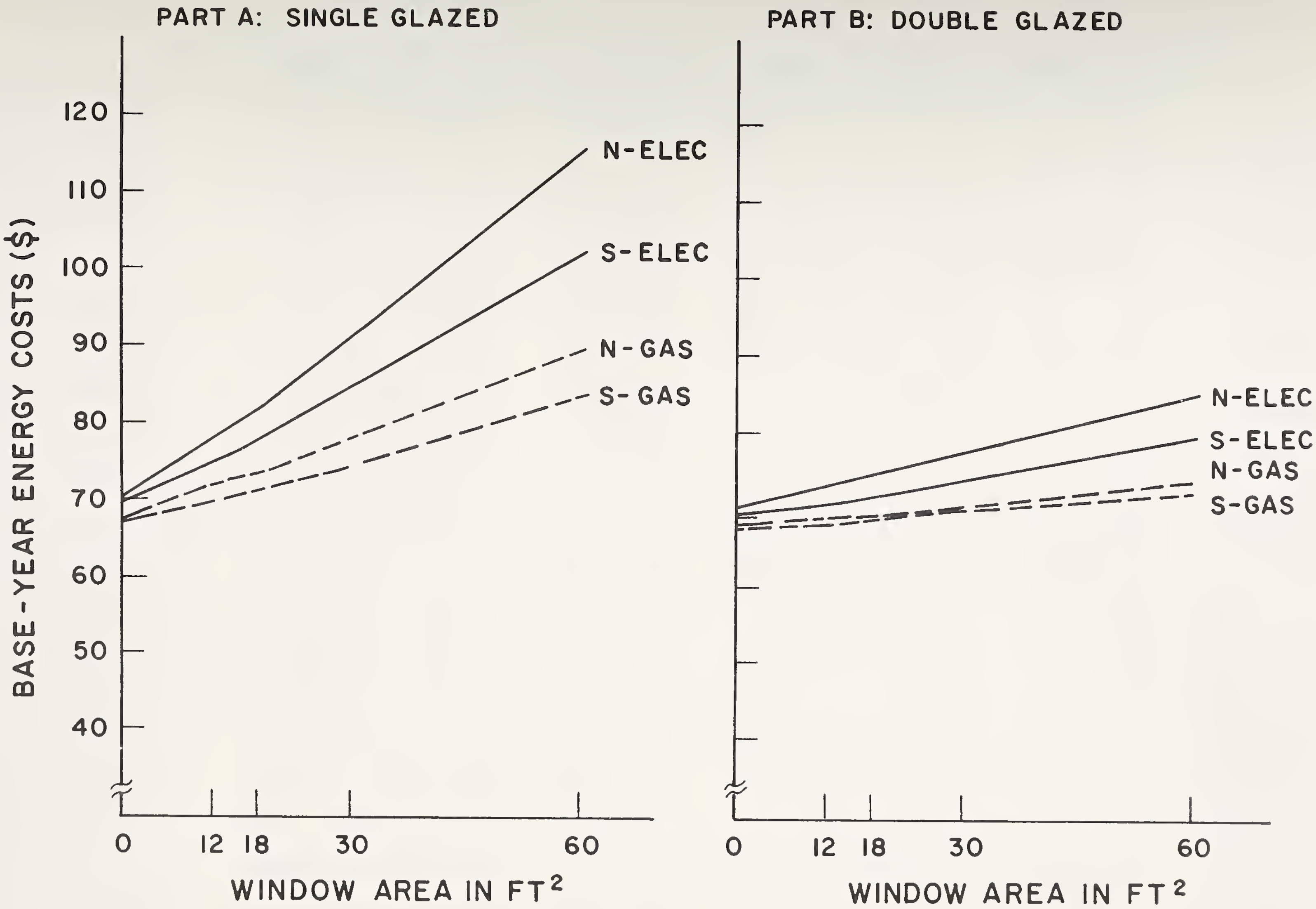

Figure 3.3 Base-Year Energy Costs for the Residential Module for North (N) and South (S) Facing Unmanaged Windows Not Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

costs range from $70 to $118. Thus, room energy costs in the base year are increased as much as $24 by a large single-glazed window when gas heating is used and as much as $48 when electric heating is used. This means that the additional energy costs attributable to windows will be substantial over the life-cycle.

Part B of Figure 3.3 shows that double glazing reduces the additional energy costs from a maximum yearly amount of $24 to $9 when gas heating is used, and from $48 to $14 when electric heating is used.[1] Although double glazing reduces the base-year energy costs of the window, it does not altogether eliminate the negative effects of increasing window size.[2]

Figure 3.4 shows the annual energy costs of Figure 3.3 converted to a life-cycle basis, assuming no change in future energy prices. Part A shows that when gas heating is used, even at fixed energy prices, a 60 ft^2 single-glazed window can raise life-cycle energy costs for the room by about $175 (from $720 to $895) for southern orientations, and by about $250 (from $720 to $970) for northern orientations. Life-cycle energy costs are raised even higher when electric heating is used, ranging from an increase of about $350 (from $740 to $1090) for southern orientations, to about $500 (from $745 to $1245) for northern orientations. Part B of Figure 3.4 shows that the increases in life-cycle energy costs are significantly reduced by the use of double glazing.

The assumption that energy costs will not rise is very conservative in light of the current energy crisis. With escalating energy prices, the the energy costs attributable to bare, unmanaged windows could be considerably higher than shown in Figure 3.4. For example, Figure 3.5 indicates the impact on life-cycle costs of energy prices rising at a rate of 12 percent compounded annually.

The reference point (i.e., the room's life-cycle energy costs when it has no windows) increases from $720 with gas heat fixed in price, to $2800 with gas heat escalating in price at a 12 percent rate. With large, single-glazed windows on the north side, the life-cycle energy costs for the room may now exceed $3700 for gas heating and $4800 for electric heating. This means that the windows would raise life-cycle energy costs by between $1,000 and $2,000, depending on the type of energy used. Part B of Figure 3.5 indicates that the savings potential of double glazing becomes more important the higher the rate of energy price escalation.

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[1] Similar reductions would result if storm windows are installed initially or later retrofitted over single-glazed windows.

[2] It was found that annual energy costs increased for all orientations and for both glazing types as window area increased whenever the case of window use was assumed to be a bare unmanaged window.

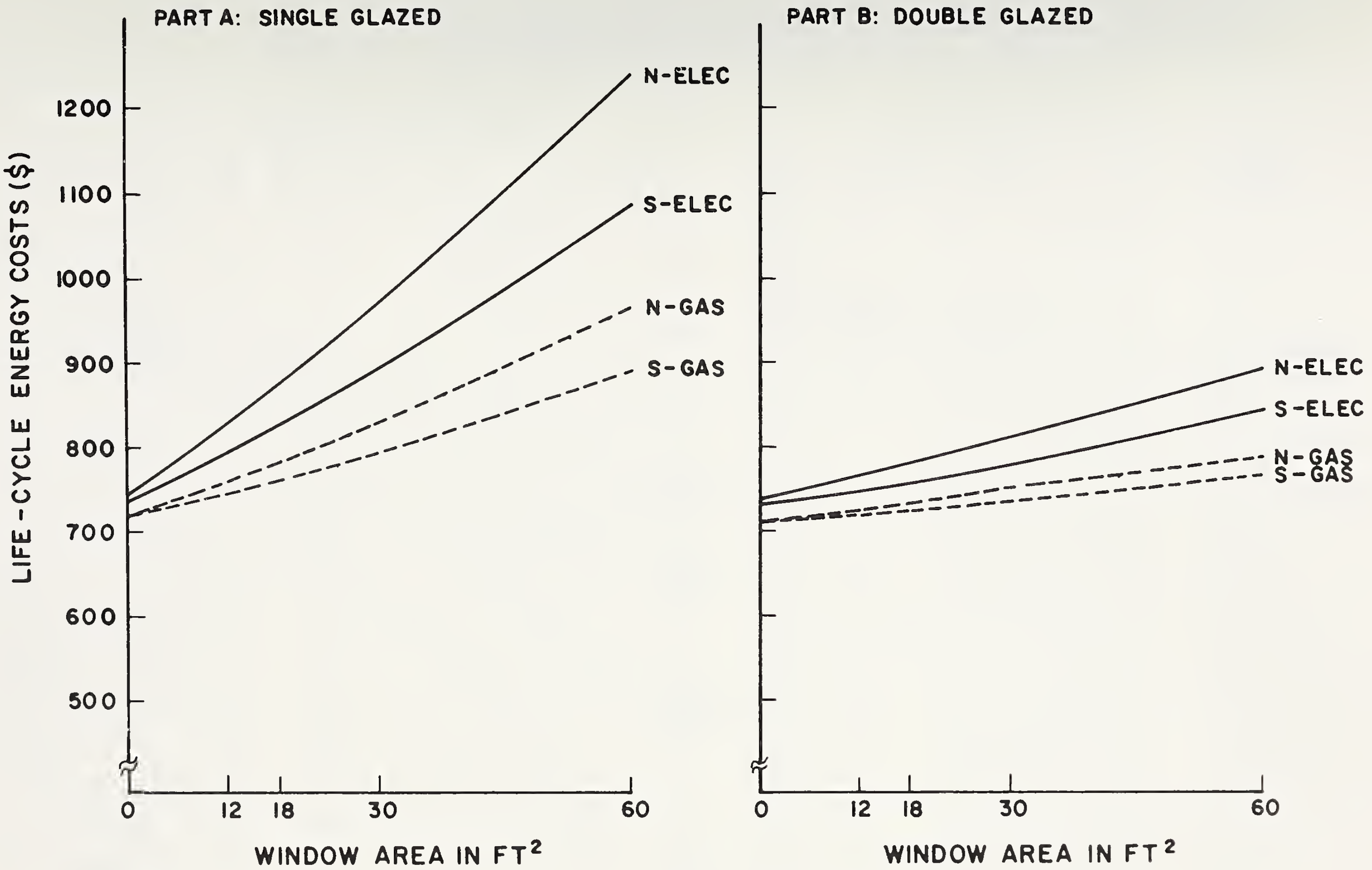

Figure 3.4 Life-Cycle Energy Costs at Constant Energy Prices for the Residential Module for North (N) and South (S) Facing Unmanaged Windows Not Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

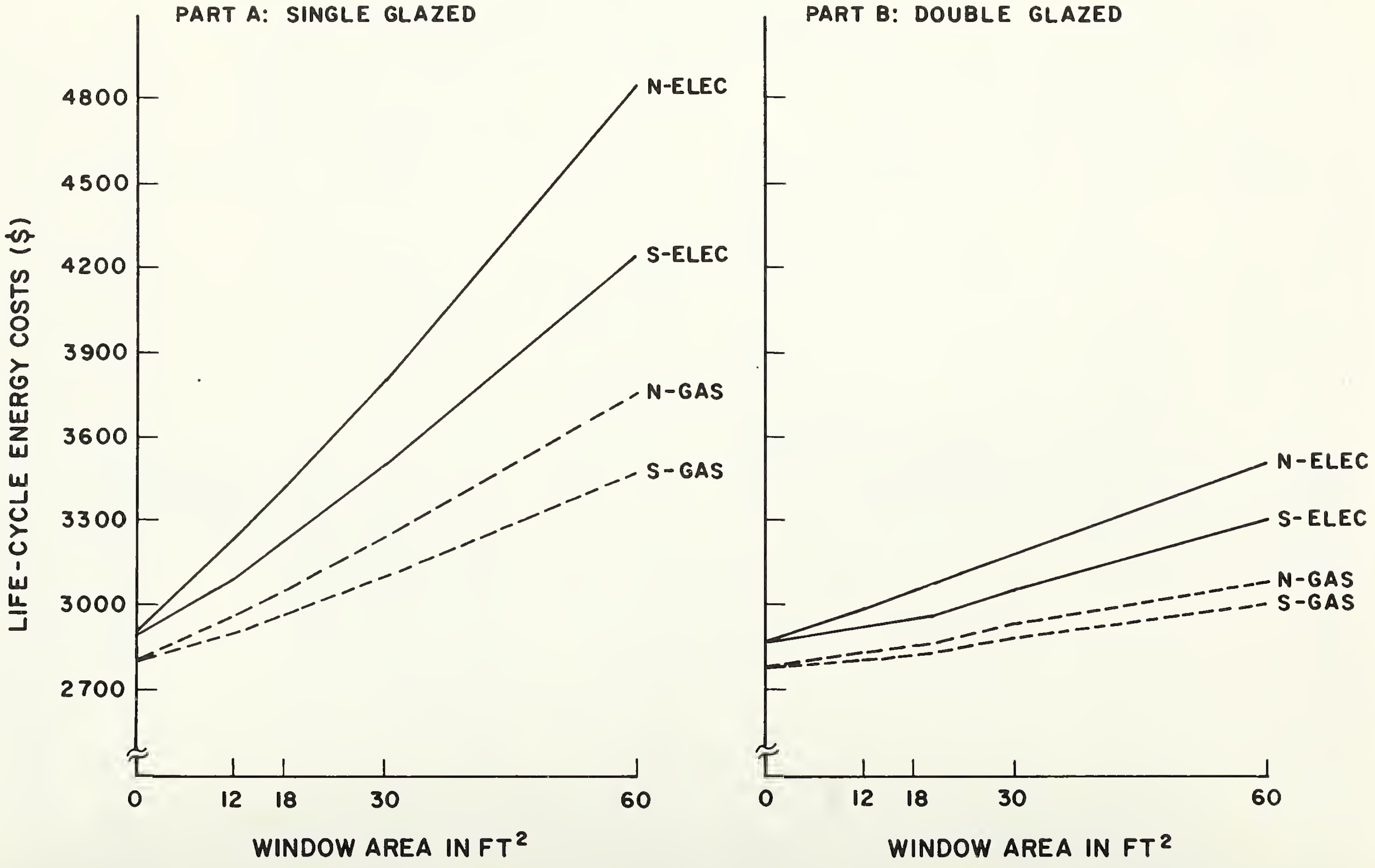

Figure 3.5 Life-Cycle Energy Costs at 12% Escalation for the Residential Module for North (N) and South (S) Facing Unmanaged Windows Not Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

3.3.2 Energy costs for Managed Windows Not Used for Daylighting

Let us now see how the second case of window use, the addition of window management devices complimented by a nighttime temperature adjustment, affects energy costs. The evaluation procedure follows that of the first case.

Figure 3.6 plots the base-year energy costs for single glazing in Part A and for double glazing in Part B. In both Parts A and B of Figure 3.6, the energy cost curves remain approximately horizontal as the window area is increased, with the exception of single-glazed windows facing north. This means that the energy costs of the room are not substantially different whether it is windowless or has windows, even large ones, provided they are not single-glazed windows facing north. The use of management devices and adjustment of the thermostat have reduced dramatically the energy costs below those found in the first case.

With no escalation in fuel prices, the life-cycle costs follow about the same trend as the base-year costs, and there is little difference in the life-cycle energy costs of the room with and without windows. The exception is for single-glazed windows facing north, and even those differences are not large.

When energy prices rise at a rate of 12 percent per year, life-cycle energy costs are about quadrupled. The windowless room now requires an expenditure of $2700, as shown by Figure 3.7, Parts A and B.

The energy costs attributable to the windows, however, continue to be considerably lower than those for the first case. Double glazing, though still important as a means of reducing energy use, does not result in as large a savings when blinds and shutters are used and the thermostat is adjusted at night, as when the windows are bare. The higher the rate of fuel price escalation, the more important double glazing becomes.

3.3.3 Energy Costs for Unmanaged Windows Used for Daylighting

Let us now examine the third case which includes the utilization of daylight as an alternative to electric lighting, but excludes the use of window management and thermostat adjustment.

Figure 3.8 shows base-year energy costs for the residential module to range from $68 with no windows, to as high as $98 with a large, single-glazed window facing north and with electric heat, to as low as $44 with a moderate size, double-glazed window facing south and with gas heat. In both Parts A and B of Figure 3.8, energy costs fall off quickly as window area is increased. However, as window area is increased further, energy costs begin to rise. This pattern of initially falling and then rising energy prices reflects the fact that once the level of daylight is sufficient to turn off the electric lights the model ceases

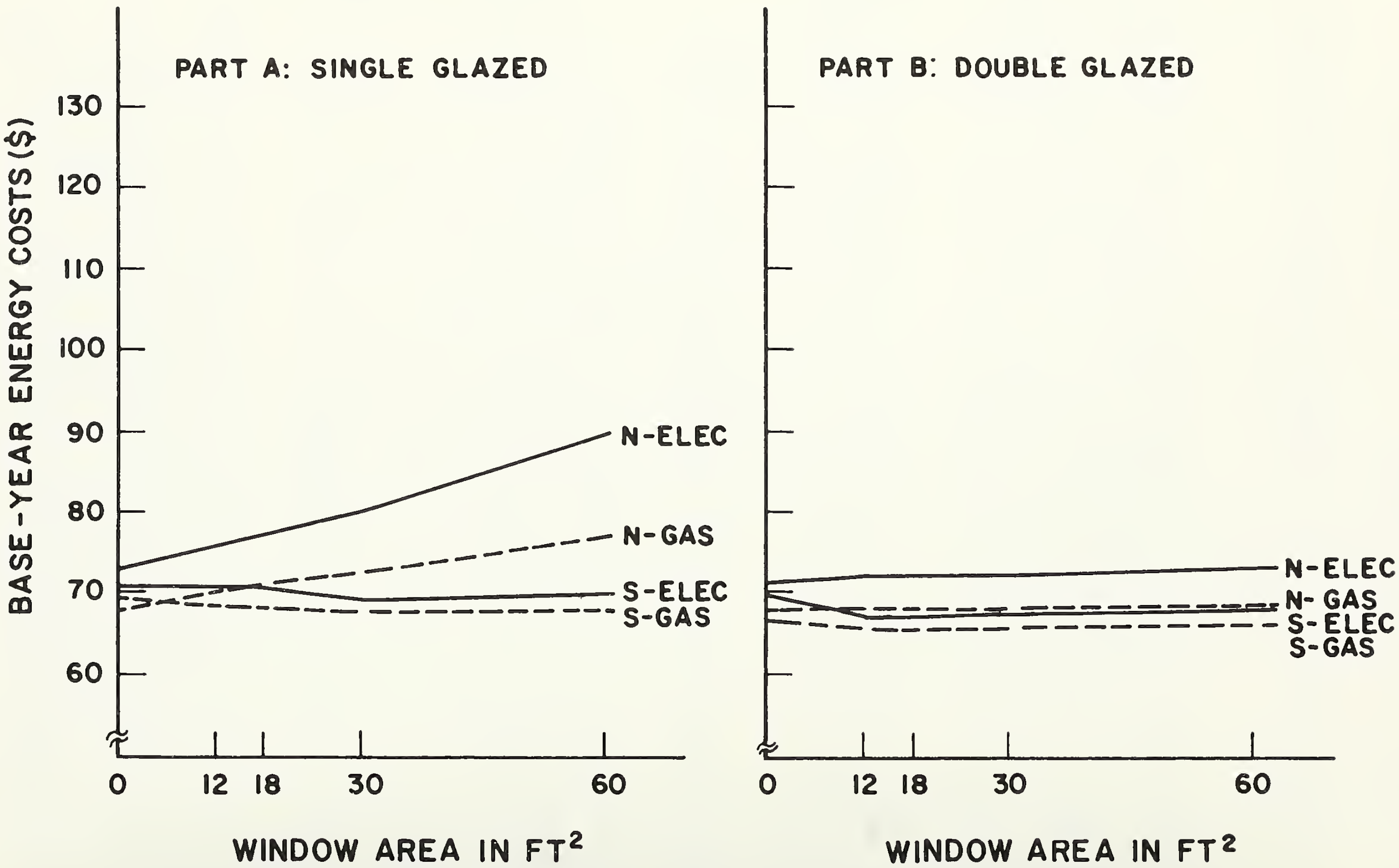

Figure 3.6 Base-Year Energy Costs for the Residential Module for North (N) and South (S) Facing Managed Windows Not Used for Daylighting
(Gas and Electric (Elec) Heating and Electric Cooling)

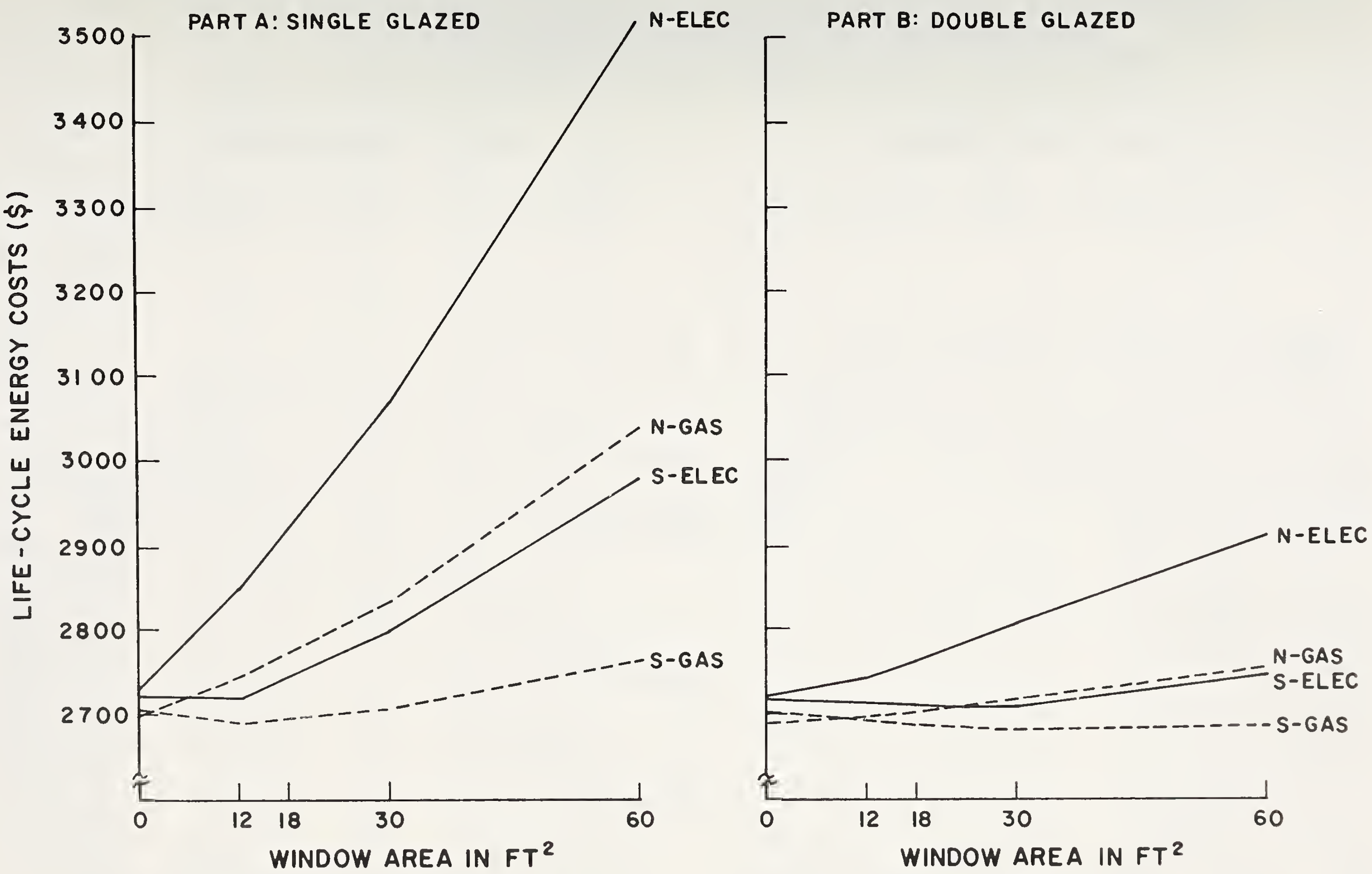

Figure 3.7 Life-Cycle Energy Costs at 12% Escalation for the Residential Module for North (N) or South (S) Facing Managed Windows Not Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

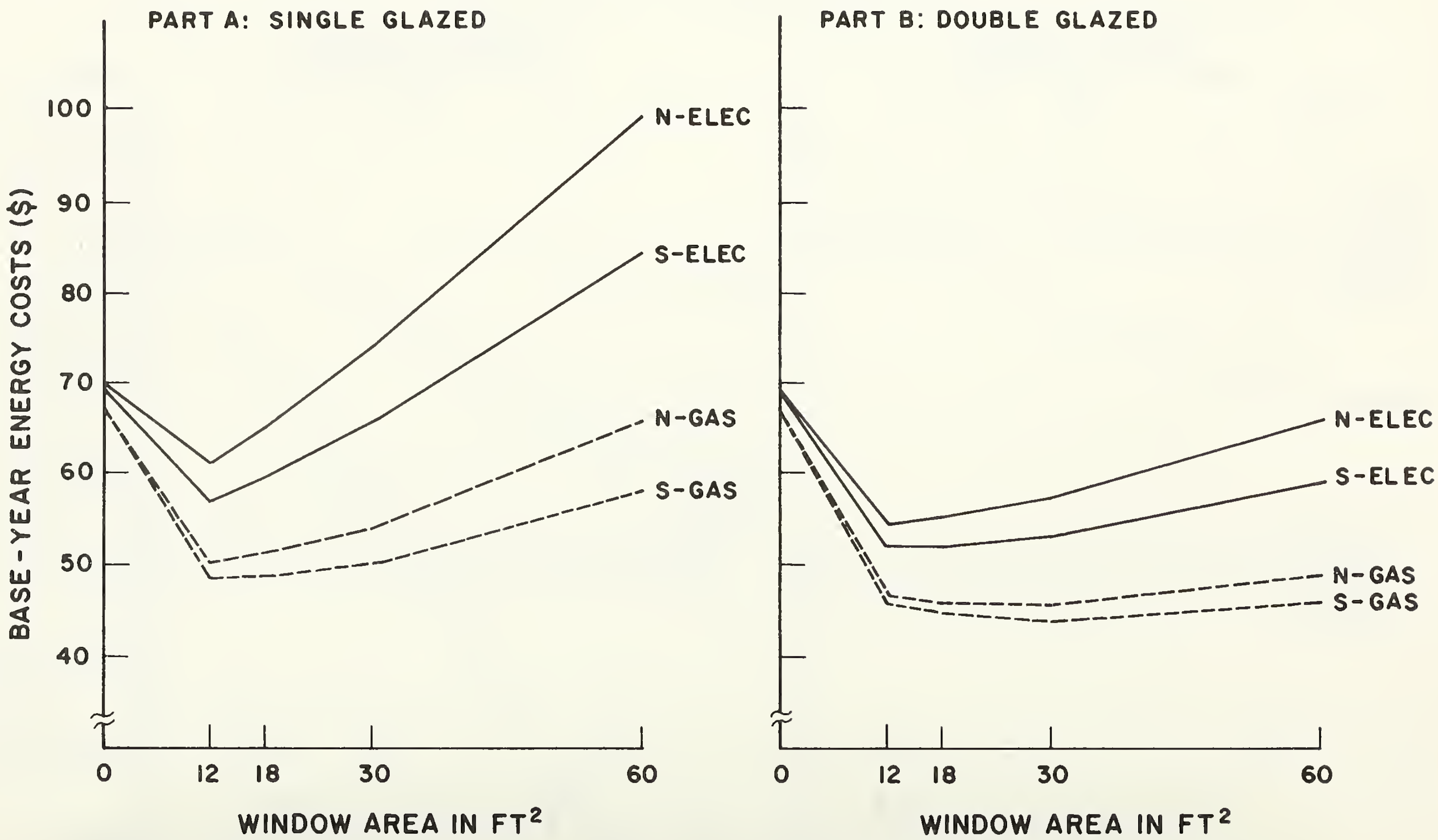

Figure 3.8 Base-Year Energy Costs for the Residential Module for North (N) or South Facing Unmanaged Windows Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

to attribute energy savings to daylighting.[1] Undesirable heat flows, on the other hand, tend to increase as window area increases, offsetting beyond a certain window size the potential gains from daylighting.

The life-cycle energy costs for the third case are particularly interesting because a large potential for savings exists. For example, with constant energy prices, gas heating and no windows, life-cycle energy costs for the room amount to \$720. Adding a 12 ft^2 single-glazed, south-facing window causes energy costs to fall to \$510. Increasing its size to 60 ft^2 raises energy costs to \$610, still significantly below the room's energy cost with no windows.

The utilization of daylight becomes more attractive the higher the rise in the cost of electric lighting. (The heating and cooling costs associated with windows, however, continue to rise, the higher the energy costs.) Figure 3.9, which assumes that all energy prices increase at the rate of 12 percent per year, shows the life-cycle costs for the windowless room to be about \$2800. It further shows that, with the use of daylighting, double-glazed windows facing north side may save as much as \$900 when gas heating and electric lighting is used, and \$630 when electric heating and electric lighting is used. By comparing Figure 3.9 with Figure 3.5 (the first case), we can see the considerable potential of daylighting for conserving scarce energy resources and for reducing the homeowner's utility bills.

3.3.4 Energy Costs for Managed Windows Used for Daylighting

In the fourth case, we examine the effects on energy costs of combining window management with daylighting. Figure 3.10 shows that the management devices and thermostat adjustment keep undesirable heat flows substantially in check, thereby reducing the costs for large windows that were observed in the preceding case when only daylighting was considered. The mitigating effect of management devices on winter nighttime heat losses and summer heat gains, plus the beneficial effects of daylighting result in a significant potential for windows to save energy.

Only with relatively large single-glazed windows on the north side of the electrically heated room do life-cycle energy costs with windows exceed the energy costs without windows.

Should a 12 percent rate of energy price escalation prevail over the next 25 years, the windowless room would require a life-cycle energy expenditure of \$2700. This is almost four times the required energy costs of the same room if constant prices were to prevail. As is shown

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[1] In the trade-off analysis, supplementary electric lighting is assumed to be added whenever room illumination supplied by daylighting falls below 6.7 fc at a distance 15 ft. from the window within the room, such that a minimum illumination level of 6.7 fc is maintained.

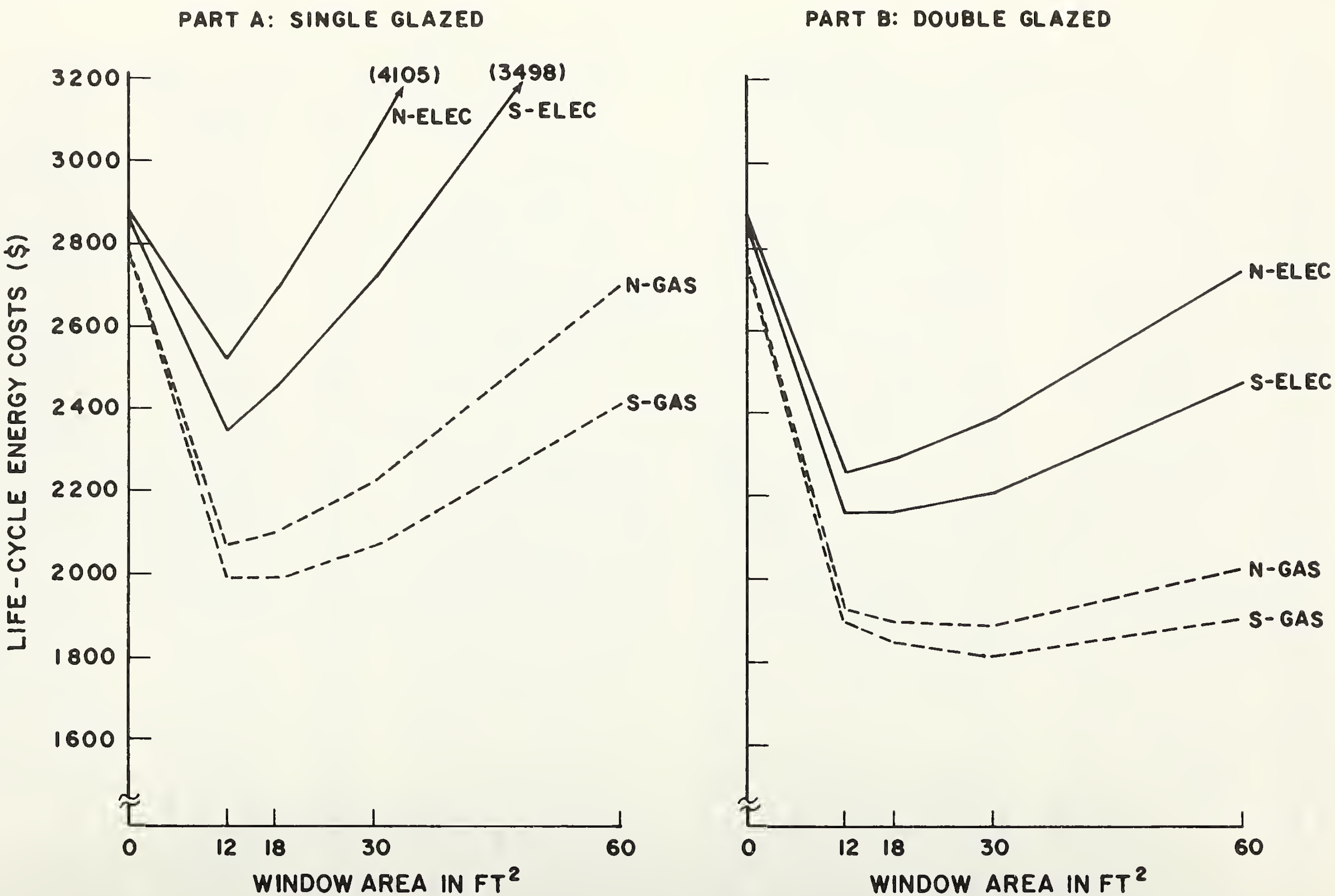

Figure 3.9 Life-Cycle Energy Costs at 12% Escalation for the Residential Module for North (N) and South (S) Facing Unmanaged Windows Used for Daylighting (Gas and Electric Heating and Electric Cooling)

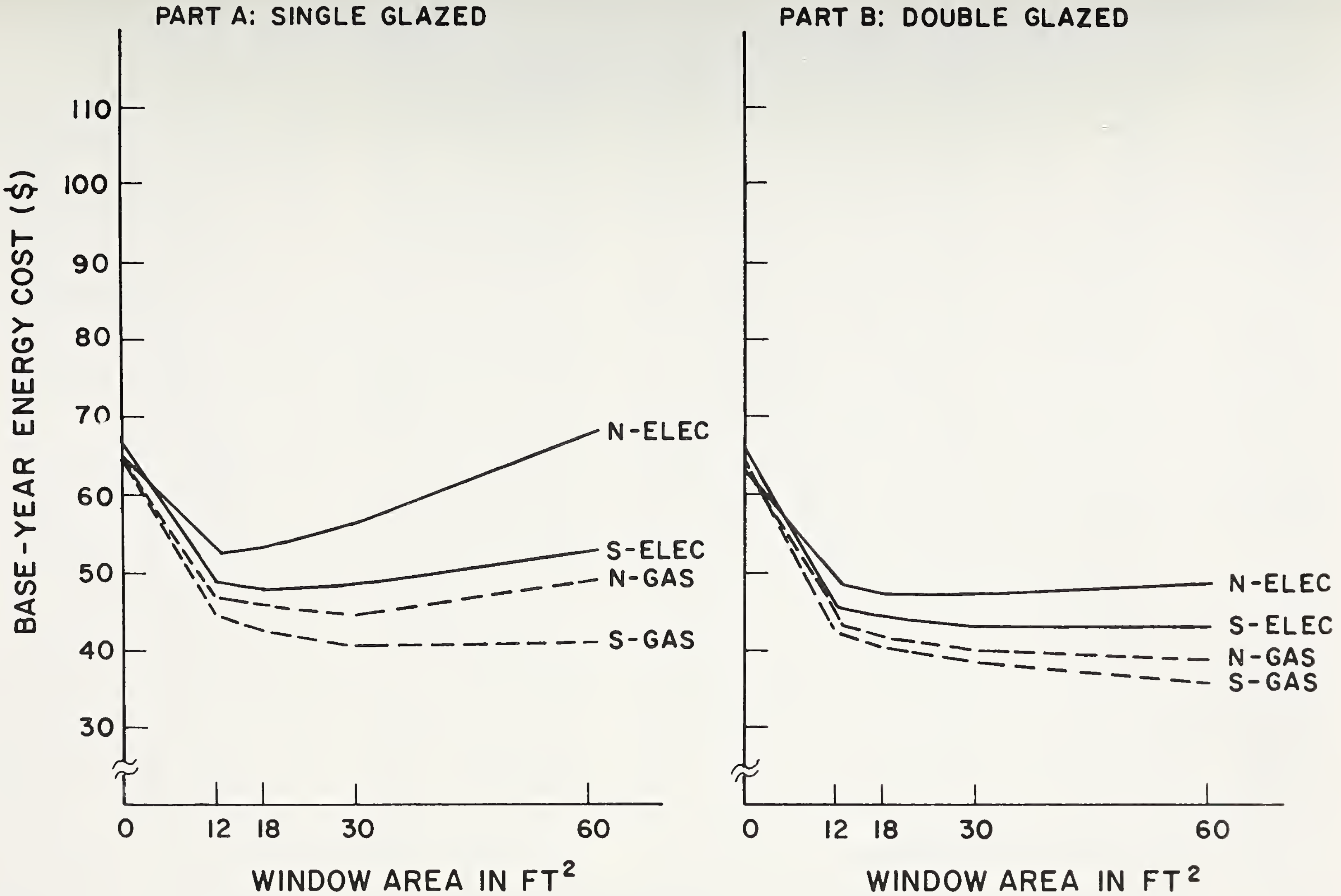

Figure 3.10 Base-Year Energy Costs for the Residential Module for North (N) and South (S) Facing Managed Windows Used for Daylighting. (Gas and Electric (Elec) Heating and Electric Cooling)

in Figure 3.11, life-cycle energy savings increase as single-glazed windows up to about 30 ft^2 in size are added if gas heat is used. Life-cycle energy savings may be as high as $1140 when 60 ft^2 double-glazed windows are used facing south if gas heat is used.

3.4 Life-Cycle Costs[1]

Let us now see how combining life-cycle energy costs with life-cycle envelope costs will affect overall life-cycle building costs. We do this for each of the preceding four cases of window use.

3.4.1 Life-Cycle Costs for Unmanaged Windows Not Used for Daylighting

Table 3.5 shows that combined life-cycle costs, for five orientations, for unmanaged windows not used for daylighting, both when energy prices are fixed and when they are escalating at a rate of 12 percent. It can be seen that in every case, life-cycle costs increase as window area increases. Although double glazing was shown to be effective in reducing energy costs, when the extra acquisition costs are also considered, the two almost exactly offset one another when energy prices are constant, and the overall life-cycle costs for single and double glazing are nearly equal. However, with rapid energy price escalation, double glazing becomes more cost effective than single glazing for all window sizes and orientations, but particularly for large, north-facing windows. At the same time, the table indicates that life-cycle costs are not raised substantially by adding small windows, particularly small, south-facing windows.

A comparison of the upper and lower portions of Table 3.5 demonstrates the increased weight which would need to be given to window investment decisions for this case of window use as the price of energy increases. As the table shows, the life-cycle costs for a south-facing, double-glazed window of 12 ft^2 increases from about $820 at constant energy prices to about $2,924 when energy prices rise at 12 percent. The entire increase of more than $2,000 is due to changing energy prices. The appropriate design practice for cost control would be to size windows as small as possible and use double glazing on all windowed areas.

3.4.2 Life-Cycle Costs for Managed Windows Not Used for Daylighting

The upper portion of Table 3.6 shows the total life-cycle costs, including envelope and energy costs, when energy prices remain constant over the 25 year period. It can be seen that life-cycle costs are increased by windows of all sizes, regardless of orientation and glazing type when they are managed but not used for daylighting. It can also be seen that

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1 "Life-Cycle Costs for Windows" refers to the combination of life-cycle envelope costs given in Section 3.2 and life-cycle energy costs for the residential module with alternative window systems given in Section 3.3.

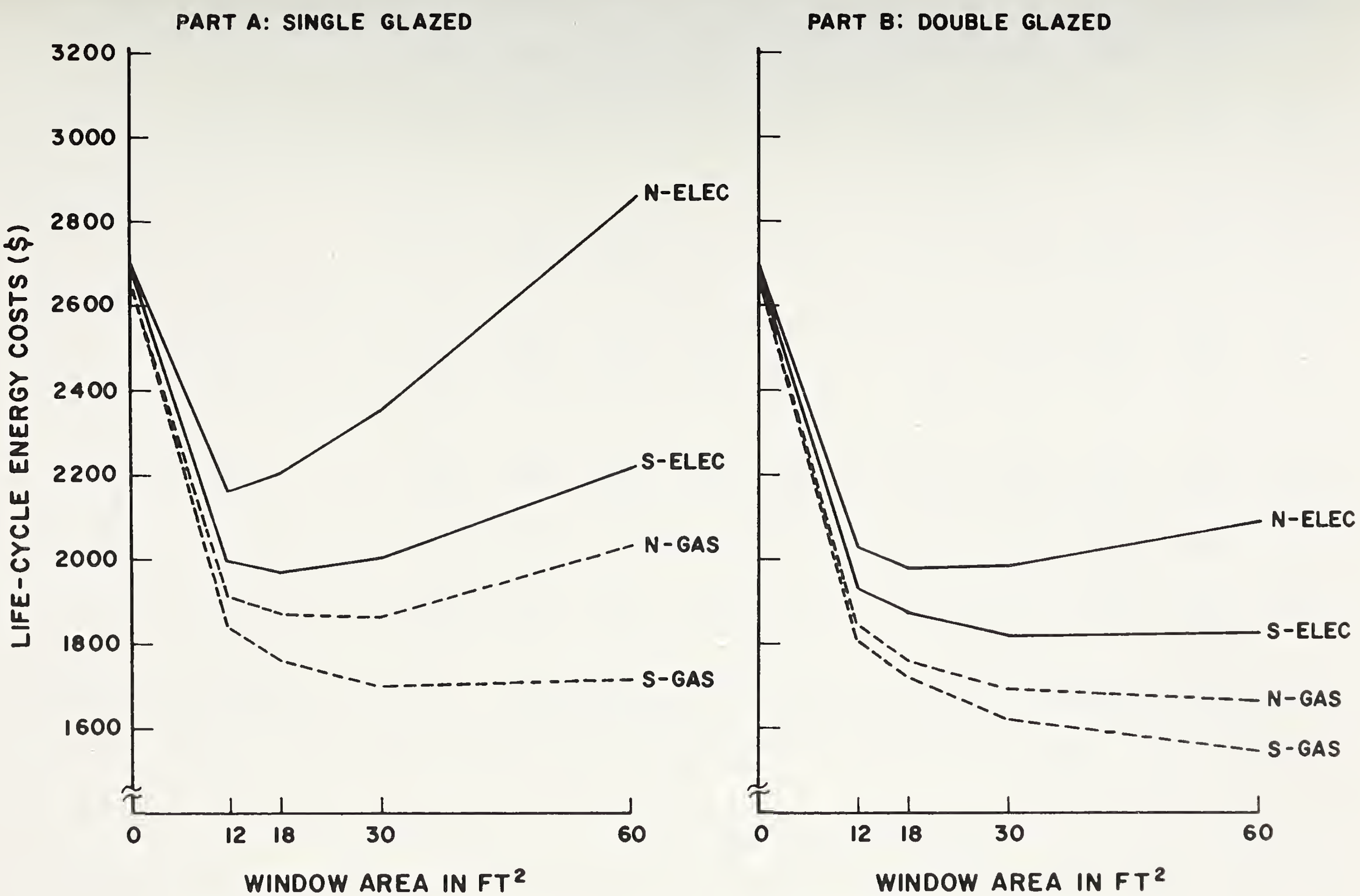

Figure 3.11 Life-Cycle Energy Costs at 12% Escalation for the Residential Module for North (N) and South (S) Facing Managed Windows Used for Daylighting (Gas and Electric (Elec) Heating and Electric Cooling)

TABLE 3.5

Life-Cycle Costs When Windows Are Unmanaged
and Not Used for Daylighting
(Gas Heating and Electric Cooling)

		Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
		Orientation					Orientation				
	Window Area (FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	719	723	725	722	718	719	723	725	722	718
	12	808	815	821	827	824	820	825	830	829	824
	18	849	856	863	873	870	857	864	870	870	865
	30	944	945	963	981	980	963	972	980	980	975
	60	1187	1202	1219	1219	1260	1214	1227	1239	1240	1234
12% Energy Price Escalation	0	2794	2810	2819	2809	2793	2794	2810	2819	2809	2793
	12	2965	2991	3014	3039	3025	2924	2945	2963	2959	2942
	18	3055	3085	3112	3151	3138	2976	3002	3028	3026	3008
	30	3251	3288	3322	3395	3388	3121	3156	3188	3187	3167
	60	3774	3832	3897	4059	4058	3474	3524	3572	3576	3550

TABLE 3.6

Life-Cycle Costs When Windows Are Managed
and Not Used for Daylighting
(Gas Heating and Electric Cooling)

	Window Area (FT^2)	Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
		Orientation					Orientation				
		S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	695	698	700	697	693	695	698	700	697	693
	12	824	829	834	841	838	855	859	862	860	856
	18	861	868	874	884	881	899	904	908	907	903
	30	997	1004	1012	1031	1029	1061	1068	1075	1075	1071
	60	1322	1333	1346	1391	1393	1444	1454	1464	1466	1462
12% Energy Price Escalation	0	2703	2715	2721	2709	2693	2703	2715	2721	2709	2693
	12	2820	2842	2862	2887	2874	2857	2873	2884	2876	2860
	18	2861	2887	2910	2952	2940	2899	2916	2932	2929	2914
	30	3007	3037	3065	3141	3133	3056	3082	3109	3109	3093
	60	3376	3416	3469	3643	3651	3444	3483	3523	3529	3514

when equipped with venetian blinds and thermal shutters, single glazing is more cost effective than double glazing except when facing north with rapidly escalating energy prices.

By comparing Table 3.6 with Table 3.5, it can be seen that the energy savings from the blinds and shutters are not sufficient to offset their extra capital costs when energy prices are constant, but more than pay for themselves when energy prices escalate rapidly.

3.4.3 Life-Cycle Costs for Unmanaged Windows Used for Daylighting

In both the upper portion of Table 3.7 which assumes constant energy prices and the lower portion which assumes 12 percent energy price escalation, life-cycle costs are shown first to decline and then to increase as window size is increased. With rapid price escalation, however, even the large window area is shown to result in lower costs than the windowless wall. The initial decline in costs reflects the electric energy savings from daylighting. The rise in costs as the window area is expanded past 12 ft^2 reflects the loss in the value attributed by the model to daylighting once the target illumination level of 6.7 fc is reached, together with the strong negative effects on heating and cooling costs of larger unmanaged windows. The life-cycle savings due to daylighting are greater at a high rate of energy price escalation because the cost of the electricity for lighting is greater.

While there is little difference in the life-cycle costs of single and double-glazed windows at constant energy prices, double glazing is cost effective when energy prices rise rapidly. Double glazing is shown to be more important in this case where windows are unmanaged than in the previous case where thermal shutters functioned in large measure as a substitute for double glazing.

Table 3.8 indicates: (1) the least-cost window size; (2) the life-cycle energy costs of the room combined with the differential costs of the least-cost window system; (3) the savings that result from having the window as compared with having a windowless room; (4) the years required for the energy savings of the window to pay back its added cost to purchase, maintain, and repair; and (5) the minimum rate of fuel price escalation for which the window will continue to pay back. With constant energy prices, the least-cost window is shown by the upper portion of the table to be 12 ft^2 and single glazed, except for northerly exposures where it is 12 ft^2 and double glazed. These windows can pay for themselves in 1.1 to 2.7 years depending on the orientation. The last column of Table 3.8 shows that these windows could pay for themselves even if energy prices were falling.[1]

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[1] This information on least-cost window, savings, and payback was not presented for the preceding cases because the least-cost window was no window.

TABLE 3.7

Life-Cycle Costs When Windows Are Unmanaged
and Used for Daylighting
(Gas Heating and Electric Cooling)

		Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
	Window Area	Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	719	723	725	722	718	719	723	725	722	718
	12	573	580	587	596	593	580	586	592	592	589
	18	598	606	615	627	625	600	605	614	616	613
	30	678	688	699	720	718	684	694	704	707	703
	60	914	928	945	986	989	926	937	955	960	956
12% Energy Price Escalation	0	2794	2810	2819	2809	2793	2794	2810	2819	2809	2793
	12	2052	2077	2105	2138	2130	1991	2015	2039	2039	2027
	18	2080	2111	2145	2195	2187	1976	1998	2033	2040	2027
	30	2215	2254	2297	2379	2373	2037	2074	2114	2126	2112
	60	2711	2766	2831	2994	3005	2353	2399	2467	2488	2471

TABLE 3.8

Least-Cost Window Systems When Windows Are Unmanaged and Used for Daylighting (Gas Heating and Electric Cooling)

	Orientation	Least-Cost Window System					
		Size (ft^2)	Glazing Type	Total Life Cycle Cost ($)	Total Life Cycle Saving ($)	Years to Payback	Minimum FPE (%)
Constant Energy Prices	S	12	Single	573	145	1.1	< 0
	SW-SE	12	Single	580	143	1.1	< 0
	E-W	12	Single	587	138	1.1	< 0
	NW-NE	12	Double	592	130	2.7	< 0
	N	12	Double	589	129	2.7	< 0
12% Energy Price Escalation	S	18	Double	1976	818	2.5	< 0
	SW-SE	18	Double	1998	811	2.5	< 0
	E-W	18	Double	2033	787	2.6	< 0
	NW-NE	12	Double	2039	770	2.2	< 0
	N	12 or 18	Double	2027	766	2.3	< 0

With rising energy prices, the least-cost window systems are shown by the lower portion of Table 3.8 to be in all cases double glazed. For all except northerly orientations, the least-cost window size is 18 ft^2; for northerly orientations, 12 ft^2 is the least-cost size. The additional acquisition, maintenance, and repair costs of the least-cost windows can be recovered through energy savings in 2.2 to 2.6 years. As in the previous case, the windows can pay for themselves in the 25 year period even if energy prices fall.

3.4.4 Life-Cycle Costs for Managed Windows Used for Daylighting

Table 3.9 shows the combined life-cycle envelope and energy costs. The upper portion of the table indicates that when energy prices are constant, single-glazed windows are slightly more economical than double-glazed windows. Second, it indicates that both single- and double-glazed windows are more economical than a windowless wall as long as their area does not exceed about 18 ft^2, but that large windows can raise life-cycle costs substantially. A comparison of the upper portions of Tables 3.9 and 3.7 show life-cycle costs to be greater with the management devices than without them; that is, when energy prices remain constant, the added costs of the management devices are not offset by the resultant energy savings.

The lower portion of Table 3.9 indicates that if energy prices were to increase at a rate of 12 percent per year, windows of all sizes and orientations tend to reduce life-cycle building costs compared to a windowless wall, provided they are managed and used for daylighting.

With constant energy prices, the least-cost window system is indicated by Table 3.10 to be 12 ft^2 and single glazed. This window system can pay for itself in 6.6 to 7.5 years depending on its orientation. Savings of between $70 and $90 can result over the 25 year period by having this least-cost window system as opposed to having no window. With 12% price escalation, the least-cost window size is shown in Table 3.10 to be 18 ft^2. For southerly orientations there is little difference in the potential savings of single- and double-glazed windows, although single glazing is slightly more cost effective. For northerly orientations double glazing is more cost effective. The least-cost windows can pay for themselves in 4.9 to 6.4 years depending on the orientation.

The polar coordinate graphing technique introduced in Section 2.4 is used here to compare the life-cycle costs associated with the single- and double-glazed 18 ft^2 windows and the windowless room.

In Figure 3.12, it can be seen that the curve labeled "A", indicating the life-cycle costs associated with the windowless room, is well outside of the curves "B" and "C" which give the costs associated with single- and double-glazed 18 ft^2 window. By closer inspection, it can also be seen that curve B (single glazed) lies slightly inside curve C (double glazed) for the southerly coordinates and slightly outside curve C for the

TABLE 3.9

Life-Cycle Costs When Windows Are Managed and Used for Daylighting (Gas Heating and Electric Cooling)

		Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
	Window Area	Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	695	698	700	697	693	695	698	700	697	693
	12	606	612	618	627	625	630	636	642	643	640
	18	621	628	636	650	649	652	658	665	666	664
	30	738	746	757	781	780	790	798	807	811	809
	60	1054	1067	1083	1132	1135	1153	1164	1179	1186	1185
12% Energy Price Escalation	0	2703	2715	2721	2709	2693	2703	2715	2721	2709	2693
	12	1974	1997	2020	2054	2046	1982	2005	2027	2030	2020
	18	1930	1955	1985	2041	2037	1936	1961	1986	1992	1982
	30	2000	2034	2074	2167	2166	2003	2031	2067	2083	2075
	60	2333[a]	2382	2446	2636	2649	2313[a]	2357	2412	2441	2438

[a] By comparing this table with Table 3.6, it may be seen that double glazing is more cost effective than single glazing when windows are both managed and used for daylighting. Double glazing becomes the cost-effective choice as a result of the net effect of increased heating loads and decreased cooling loads due to daylighting.

TABLE 3.10

Least-Cost Window Systems When Windows Are Managed and Used for Daylighting (Gas Heating and Electric Cooling)

Orientation	Least-Cost Window System					
	Size (ft^2)	Glazing Type	Total Life Cycle Cost ($)	Total Life Cycle Saving ($)	Years to Payback	Minimum FPE (%)
S	12	Single	606	89	6.6	< 0
SW-SE	12	Single	612	87	6.7	< 0
E-W	12	Single	618	82	6.8	< 0
NW-NE	12	Single	627	70	7.4	< 0
N	12	Single	625	68	7.5	< 0
S	18	Single	1930	774	4.9	< 0
SW-SE	18	Single	1955	761	5.0	< 0
E-W	18	Single	1985	736	5.1	< 0
NW-NE	18	Double	1992	717	6.4	< 0
N	18	Double	1982	712	6.4	< 0

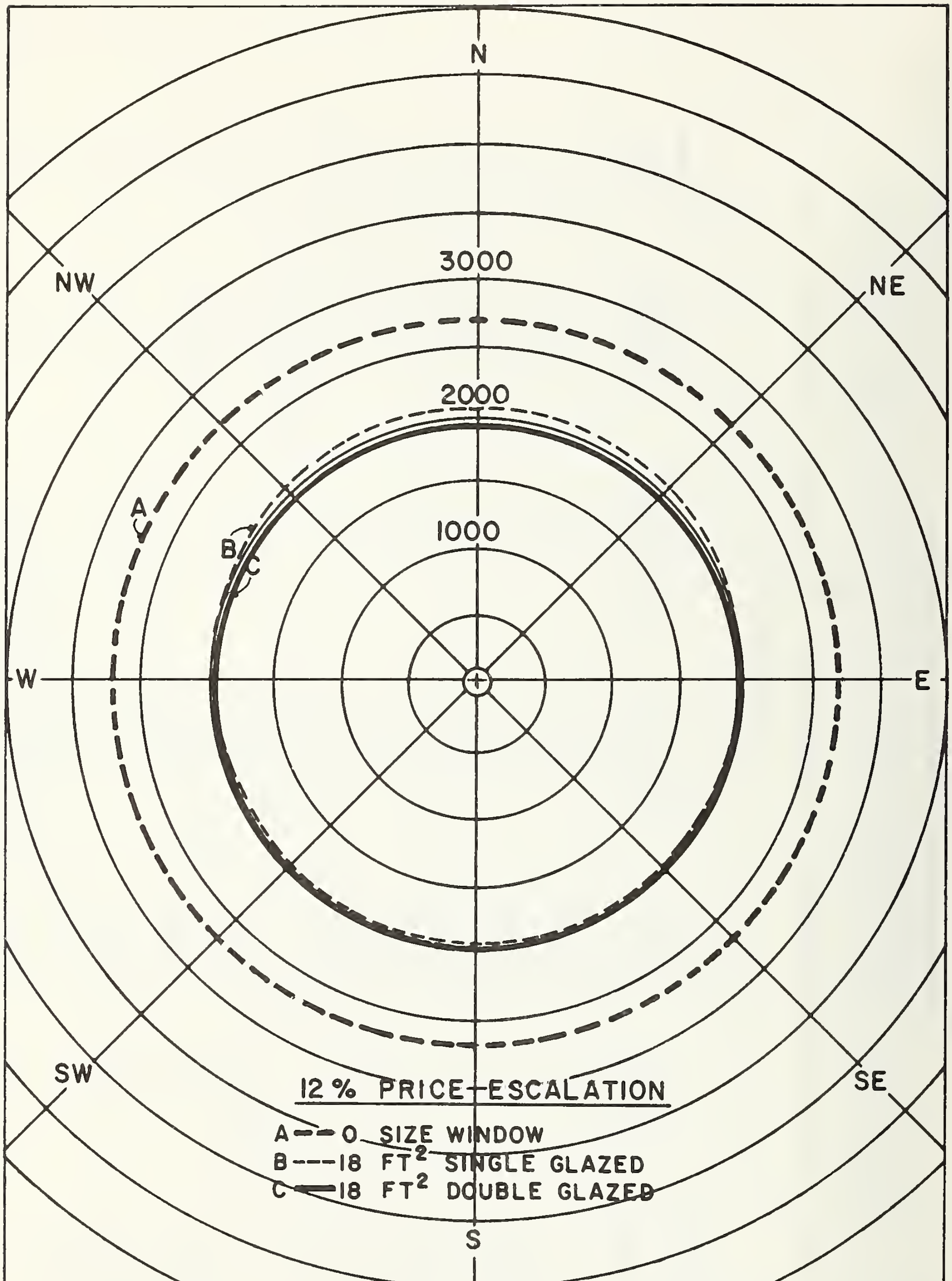


Figure 3.12 Graphical Determination of Least-Cost Window System for the Residential Module

northerly coordinates, thus indicating slightly lower costs by using single glazing for southerly exposures and double glazing for northerly exposures. Costs of single and double glazing are essentially equal for easterly and northerly applications.

3.5 Implications of Results

The preceding Section 3.4 presented the life-cycle costs of the alternative window systems used in a single room of a house, which in turn reflects the life cycle costs of the building, for four different cases of window use. This section summarizes conclusions drawn from the four cases. These conclusions are first listed below in some detail for each case, the results of the four cases are then compared, and, finally, the principal findings are summarized in Figure 3.13.

When Windows Are Unmanaged and Not Used for Daylighting

1. The larger the window, the larger its life-cycle cost as well as the life-cycle cost of the building.

2. If windows are used, their costs are lowest when facing south and highest when facing north.

3. Rising fuel prices raise window costs.

4. If fuel prices escalate rapidly, double glazing is economical for all window sizes examined and for all orientations.

5. If fuel prices remain about constant, it makes little difference from a cost standpoint whether the window is single or double glazed.

When Windows Are Managed But Not Used For Daylighting

1. The larger the window, the larger its life-cycle costs.

2. If windows are used, their costs are lowest if they face south and highest if they face north.

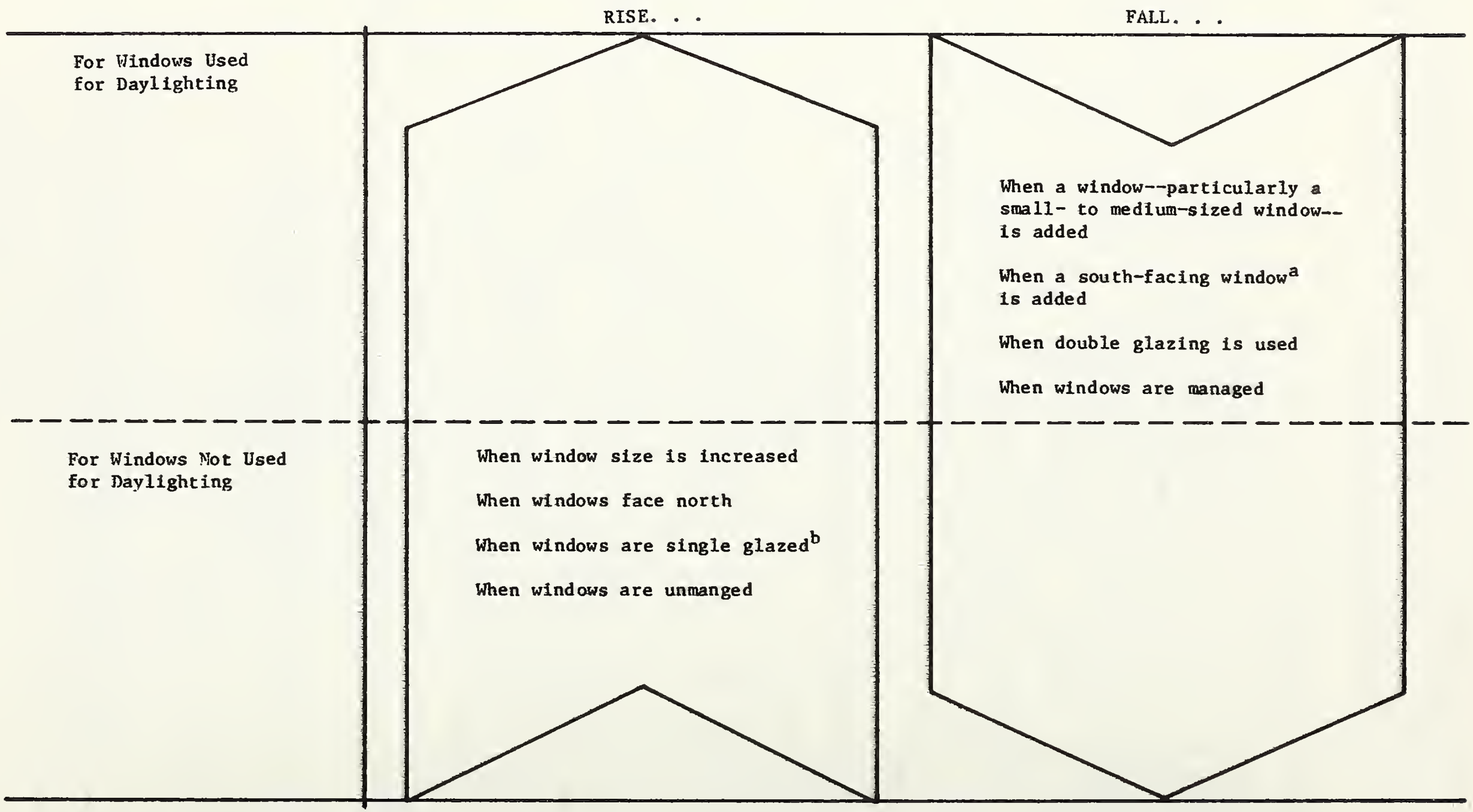
3. Window management greatly dampens the negative impact of energy price escalation on window costs.

4. Life-cycle building costs are not raised greatly by adding small windows.

5. Double glazing, used in addition to window management, tends not to be economical except for northerly orientations when energy prices are rising rapidly.

Figure 3.13 KEY RESULTS

LIFE CYCLE COSTS (With rapid Energy Price Escalation) WILL



[a] An exception is that double glazing was not shown to be cost effective for small-to-medium windows on the south, even with rapidly escalating energy prices.

[b] An exception is that single glazing tends to be more cost effective than double glazing for southerly orientations when management is not used.

When Windows Are Unmanaged But Used For Daylighting

1. The life-cycle cost of the building can be reduced by adding a window if care is taken in its sizing or orientation.

2. If fuel prices remain about constant, life-cycle building costs are lowest if a small, single-glazed window facing south is added.

3. If fuel prices rise rapidly, life-cycle building costs are lowest if a small to medium, double-glazed window facing south is added.

4. It generally pays to use double glazing for all unmanaged windows if energy prices are expected to increase rapidly.

5. Rising energy costs, by increasing the savings of electricity for lighting, tend to improve the cost effectiveness of a window despite the concomitant rising costs of heating and cooling.

6. When energy prices rise rapidly, even large windows may be had at a lower life-time cost than a windowless wall area, provided that the windows are either facing south or are double-glazed.

7. The net energy savings from installing a window used for daylighting can pay back the additional costs for window acquisition, maintenance, and repair in just several years.

When Windows are Both Managed and Used for Daylighting

1. The life-cycle cost of the building can be reduced by adding a window, particularly if energy prices rise rapidly.

2. Whether fuel prices remain about constant or rise rapidly, life-cycle building costs are lowest if a relatively small, single-glazed window facing south is added.

3. Double glazing tends not to pay even on the north side if energy prices remain about constant, but if they escalate sharply, double glazing tends to pay for all window sizes and orientations examined, except for south-facing, small-to-medium sized windows.

4. The net energy savings from installing a window that is managed and used for daylighting can pay back the additional costs of window acquisition, maintenance, and repair in about six to seven years.

When Energy Prices Are Constant (All Four Cases of Use Considered)

1. Life-cycle building costs can be minimized by adding a small (12 ft^2), single-glazed window facing south and utilizing it for daylight, but not equipping it with venetian blinds or thermal shutters.[1]

2. Regardless of window size, orientation, and glazing type, the least-cost mode of window use is the third case examined, i.e., using the window for daylighting but not investing in accessories. In descending order of cost effectiveness, the other cases rank as follows: the fourth, i.e., using the window for daylight and accessorizing it; the first, i.e., neither using the window for daylight nor accessorizing it; and, lastly, the second, i.e., accessorizing the window but not using it for daylight.

3. When venetian blinds and thermal shutters are used, it does not appear to pay to invest additionally in double glazing, and vice-versa.

4. Even when venetian blinds and thermal shutters are not used, double glazing appears to be cost effective only for window areas with northern exposures, and even then it is only slightly preferable to single glazing.

5. Small windows appear to be less costly than large windows; very large windows tend to raise life-cycle building costs even with the most favorable method of window use.

When Energy Prices Rise Rapidly at 12 Percent, Compounded Annually (All Four Cases of Use Considered)

1. Life-cycle building costs are minimized by adding a medium-sized (18 ft^2), single-glazed window facing south, by equipping it with venetian blinds and thermal shutters, and by using it for daylighting.

2. Regardless of window size, orientation, and glazing type, the least-cost case of window use is the fourth examined, i.e., using the window for daylighting and managing it. In descending order of cost effectiveness, the other cases rank as follows: the third, i.e., using the window for daylight but not investing in accessories; the second,

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[1] Here specific reference is made to the accessories as opposed to the more general term "window management" because "window management" includes thermostat adjustment, an action which generally is cost effective since it can save energy at little or no cost.

i.e., using accessories but not daylight; and lastly, the first, i.e., neither using the window for daylight nor accessorizing it.

3. Double glazing pays for all of the window sizes and orientations examined whenever they are not accessorized.

4. For most window sizes, single glazing is more cost effective on southerly exposures and double glazing is more cost effective on northerly exposures, if the windows are accessorized.

5. Double glazing and the use of venetian blinds and thermal shutters appear to have closely comparable impacts on the life-cycle costs of windows even though double glazing has the advantage, accounted for in the evaluation model, of not requiring daily attention for effective use.

6. Small- to moderate-sized windows tend to be less costly than large ones in all cases examined.

7. If used for daylighting and managed for energy conservation, even a relatively large window (60 ft^2) will tend to reduce life-cycle building costs below what they would be without a window.

8. If neither managed nor utilized for daylighting, large windows can greatly increase life-cycle building costs.

The key results that can be drawn from this case study are summarized in Figure 3.13 for the condition of rapidly rising energy prices. One major finding is that life-cycle costs of the room, thus the building, tend to be raised by the windows examined if they are not used for daylighting, particularly if they are large in size, oriented to the north, single glazed,[1] and unmanaged. A second major finding is that life-cycle costs tend to be lowered by the windows examined if they <u>are</u> used for daylighting, particularly if they are small to medium in size, oriented to the south, double glazed,[2] and managed. The negative cost impact of windows not used for daylighting can be lessened by reducing their size as much as possible, orienting them to the south, and managing them. (As was indicated by the more detailed listing of conclusions, the cost-effective rules for double glazing and window management become somewhat more complex when the uncertainty in energy price escalation is taken into account.)

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[1] Note the exceptions in footnote b of Figure 3.13.

[2] Note the exceptions in footnote a of Figure 3.13.

Apart from the consideration of psychological or other factors, these conclusions suggest that a homeowner, builder, or designer in the Washington, D.C. area could reduce life-cycle building costs by keeping window areas as small as possible in those rooms which are not used much during the day or for which for some other reason cannot be used substantially to reduce electric lighting requirements. But if a large savings potential from daylighting exists and is to be utilized,[1] it is better from a life-cycle cost standpoint to have windows -- even relatively large ones, but preferably small- to moderate-sized ones -- than to have a windowless exterior wall.

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[1] It should be recognized that an individual occupant's use of windows may not closely fit any of the four cases of use described here. In fact, individual use will likely shift over time. If this is the case, a homeowner may seek to minimize the maximum losses that could be expected from windows. This behavior, which can be explained in part by game theory, would lead to the choice of smaller windows even though the potential for significant savings might exist from larger windows. Such an unstable equilibrium might persist for some time if the public were not made aware of the potential that daylight utilization has for permitting homeowners to achieve significant dollar savings in lifetime building costs.

Facing page: *Two major challenges in using windows more efficiently in office buildings is ensuring proper management of interior shading devices and integrating the use of daylighting and artificial lighting.*

4. ILLUSTRATION OF THE METHODOLOGY: COMMERCIAL CASE STUDY

The application of the life-cycle cost model in this section is different from the preceding residential case study in two ways: (1) it includes income tax considerations and depreciation allowances which are currently accorded commercial structures; and (2) it is based on a different set of data and assumptions.

4.1 Basic Assumptions

The wall construction of the office building used in the case study is representative of curtain wall construction which has become increasingly important in recent years. The office building under consideration is assumed to be between 5 and 10 stories in height. However, for purposes of the economic analysis, we shall focus on one room, an office module, to evaluate the alternative window systems. The floor area of the office module is 180 square feet and the volume of the module is 1800 cubic feet. It is assumed that two people are assigned to the office during the normal working hours of 9:00 AM to 5:00 PM. Their occupancy is averaged over the day and the resultant figure of 1.8 persons is used in the computer model to calculate heat loads generated by the occupants. The calculation of expected heat gains also takes into account the effects of office equipment, such as typewriters, electric adding machines/desk calculators, and computer time-sharing terminals as well as lighting.

The exterior wall of the office building consists of a dark glass spandrel panel with 1 inch of rigid fiberglass insulation applied with a mastic. The mullions which hold the spandrel panels are dark anodized aluminum with a thermal break. The interior surface of the exterior wall is cut out and installed. The size of the cutouts is determined by the size and type of glazing. The U value of the non-windowed wall is approximately 0.15.

The windows used in the economic analysis are fixed. The framing is dark anodized aluminum with a thermal break. No tints or low emissivity coatings are assumed to be used. All glazing is erected from the inside of the building as a stick wall; elastomeric gaskets[1] (dryset) are used on all windowed areas. Both single and double glazing are examined. Window sizes range from 0 to 90 square feet. Figure 4.1 illustrates the shape of the office module and the window sizes in relationship to the size of the exterior wall. Additional assuptions, such as lighting requirements, heating and cooling system efficiencies, and occupancy patterns are given in Table 4.1.

As in the residential case studies, the thermal model[2] which is used to provide input to the economic model assumes that all heat flows entering or leaving the office module are through the exterior wall which contains the window. It is therefore explicitly assumed that no heat flows occur between the office module under examination and adjacent office modules. (Such a system is usually referred to as adiabatic.)

Furthermore, the thermal model does not account for the interdependencies between building components whereby a change in one factor affects the thermal performance of other factors. To account for all possible heat flows and thermal interdependencies would require a considerably more sophisticated thermal model than that which was used in the case studies.

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[1] The use of elastomeric gaskets reduces the likelihood of repairs which would probably result from chemical sealants applied at the site. The elastomeric gaskets are assumed to perform satisfactorily throughout the 25 year life cycle.

[2] Tamani Kusuda and Belinda L. Collins, Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies, February 1978.

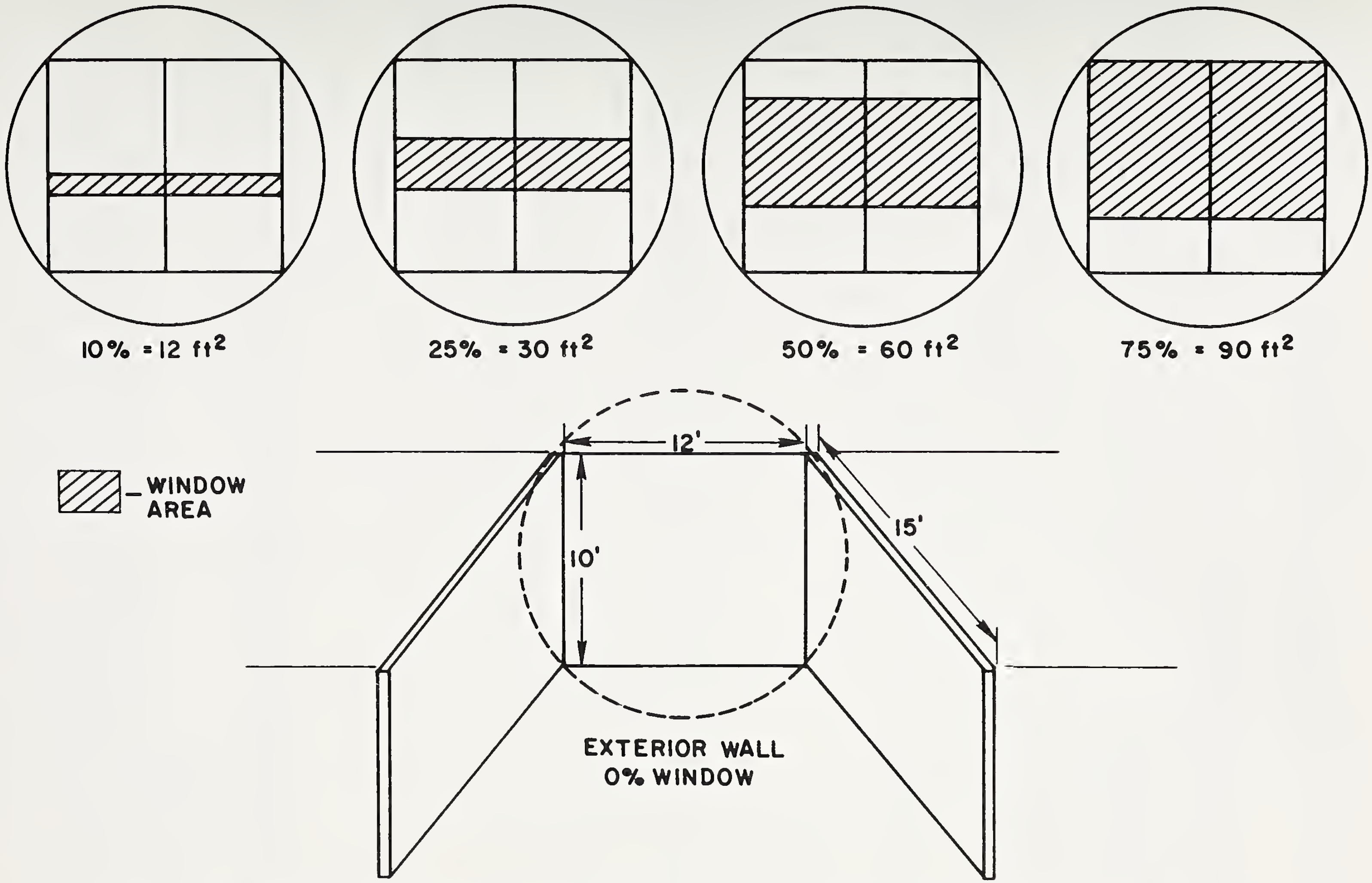

Figure 4.1 Window Sizes in Relationship to the Size of the Exterior Wall of the Office Module

TABLE 4.1

Assumptions for Commercial Case Study[a]

Building Specifications	Assumptions
Dimensions of Module	12' wide x 15' long x 10' high
Floor Area	180 ft^2
Volume of Module	1800 ft^3
Type of Construction	Curtain Wall
Exterior Wall Area	120 ft^2
Window Size	0, 12, 30, 60, 90 ft^2
Window Construction	Anodized aluminum with thermal break
Internal Loads	
Lights	3.25 watts/sq. ft.
Equipment	0.50 watts/sq. ft.
Air Leakage	0.25 air changes/hour
Occupancy	1.8 persons
Heat Load/Person	260 Btu/hour/person
System Efficiency	**Specifications**
Gas Furnace Efficiency	0.65
Cooling COP[b]	3.0
Electric Heating (Heat Pump)	2.0
Fuel Type	**Cost**
Electricity	\$0.03 per kWh
Gas	\$0.30 per therm
Operation	**Conditions**
Thermostat Adjustment	72° to 62° F winter nights 78° to 84° F summer nights
Window Management	**Times**
Thermal Shutters	Winter nights
Venetian Blinds	Summer days

[a] The model assumes no heat transfer to adjacent surfaces such as walls, floors, or ceilings.

[b] COP = Coefficient of Performance.

As was the case for the residential case example, the simplifying assumptions employed in the thermal model result in specific limitations for the life-cycle cost measures produced by the economic model.

The thermal model's limitations, however, are less serious for the commercial case than they were for the residential case. Since most office buildings have a large number of office modules which have only one exterior wall, the majority of these office modules are surrounded mostly by other modules which are maintained at approximately the same temperature such that an adiabatic system is probably typical in most cases.[1]

Again the thermal model's assumptions about daylighting are tenuous. However, the problem is somewhat less severe in the commercial case study than in the residential case study. For the office module the assumption of a fixed level of illumination appears more reasonable than for the residential module. (We have followed the GSA guidelines and used 50 fc as the reference level.) The fixed level of illumination could be maintained by the use of automated controls, a much more feasible approach for the office module than for the residential module. (The cost of automated controls is, however, not included in this life-cycle cost analysis.)

The method of presentation of this case study is similar to the preceding residential case study. First, the life-cycle envelope costs, including the costs of purchasing and installing the windows, equipping them with management devices and maintaining and repairing them, are presented. Second, the life-cycle energy costs of the office module with alternative window sizes, orientations, and glazing types are presented based on four different cases of window use: (1) unmanaged windows[2] not used for daylighting; (2) managed windows not used for daylighting; (3) unmanaged windows used for daylighting; and (4) managed windows used for daylighting. Third, the total life-cycle costs are presented, again for each of the four different cases of window use. Conclusions and the implications of these conclusions for the building community are then summarized.

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[1] There would, of course, be some office modules which are not adiabatic even though they have only one exterior wall. For example, offices adjacent to unconditioned areas (e.g., equipment rooms and/or garages) would generally not be adiabatic.

[2] As explained earlier, "unmanaged windows" means those windows that are used bare; "managed windows" means those windows that are equipped, in this case study, with venetian blinds and thermal shutters which are used to reduce undesired daytime heat gain in the summer and nighttime heat loss in the winter, and, in addition are used in a room in which nighttime adjustment of the thermostat is practiced for energy conservation.

4.2 Envelope Costs

In commercial buildings, unlike private residences, the cost of windowed areas may either increase or decrease initial construction costs, that is, a wall with windows may cost more or less to purchase and install than a windowless wall. For this reason the costs presented in Table 4.2 are the acquisition costs of the 10' x 12' exterior wall (bay) and not the net costs of the windowed area above or below those of the exterior wall. These costs include the purchase and installation prices for all glazing (spandrel panel and window), mullions, and the interior curtain wall. A 25 percent markup for contractor overhead and profit is included.

TABLE 4.2

Commercial Case Study:

Acquisition Costs[a]

	Dollar Cost by Size of Window				
Glazing Type	0 ft^2	12 ft^2	30 ft^2	60 ft^2	90 ft^2
Single	1238	1229	1204	1257	1009
Double	1238	1301	1323	1446	1255

[a] Cost figures are for the entire exterior wall (bay) and include materials, installation, and markup costs. The cost differential associated with a given window size/type is thus equal to the difference between the cost of the bay with that window size/type and the windowless bay. The area of the exterior wall is 120 square feet. Variations in cost among window sizes are due both to differences in framing costs and to the costs of glazing. Lower framing costs are particularly evident in the case where the window area is 90 square feet.

Source: A leading manufacturer and distributor of building materials provided the cost estimates.

The exterior wall used in the case studies was chosen for two reasons. First, it is typical of those currently used in commerical buildings. Second, it is relatively less expensive than the alternative exterior walls which are sometimes used in commercial buildings. The lower cost reflects the factory fabrication and the design for inside glazing and stick wall erection. The building envelope used in the economic analysis is on the low end of the cost range for envelopes currently being used in commercial applications. The costs of the glazed portions of the envelope, unlike the rest of the envelope, should remain about constant even if more expensive opaque portions of the envelope are substituted for those used in the economic analysis. Consequently, if the window system is found to be economically viable (cost effective) in this case it will also be cost effective for those cases where more expensive exterior walls are used, other things being equal.

If management devices are used, additional acquisition costs are incurred. Costs of venetian blinds and insulated thermal shutters based upon large volume sales are given in Table 4.3. All costs reflect purchase, installation, and contractor markup. If management devices are used it is assumed that their costs are added to the capital costs of the exterior wall system and then depreciated along with the rest of the exterior wall system.

TABLE 4.3

Commercial Case Study:

Cost of Window Accessories

	Dollar Cost By Size of Window			
Type of Accessory	12 ft^2	30 ft^2	60 ft^2	90 ft^2
Venetian Blinds	47	47	64	95
Thermal Shutter	232	412	750	1050

Source: A leading manufacturer and distributor of building materials provided the cost estimates.

Most commercial buildings usually have a schedule for window washing which may be done by contract. The cost-of-cleaning data presented in Table 4.4 reflect estimated contract prices for annual washing of all windows of a specified size in the building. The annual insurance premium is used as a proxy for repair/replacement costs. These figures are quoted in Table 4.4 as a function of the size of the window and the glazing type.

TABLE 4.4

Commercial Case Study:

Cleaning and Insurance[a] Costs

	Current Dollar Cost By Size of Window			
Type of Cost	12 ft^2	30 ft^2	60 ft^2	90 ft^2
Annual Cleaning	3.10	4.10	5.80	7.50
Annual Insurance Premium[b]				
Single	0.60	1.70	4.10	5.90
Double	3.80	10.40	24.50	35.60

Source: Insurance costs were provided by a major insurance company, based on company rate manuals.

[a] Insurance costs are used as a proxy for repair and replacement costs.

[b] Premiums are unadjusted for regional rate differentials.

4.3 Energy Costs

4.3.1 Energy Costs for Unmanaged Windows Not Used for Daylighting

Base-year energy costs for the office module heated by natural gas start at $53 for a windowless wall and go as high as $70 for a 90 ft^2 single-glazed window with a southern orientation, with energy costs rising steadily in relationship to window size. For a northern orientation, costs range from $53 to $91. With heating by electricity, base-year energy costs range from $52 for the windowless module, to $70 for the module equipped with a 90 ft^2 single-glazed window facing south. For a northern orientation, costs range from $52 to $89. Base-year energy costs are increased by as much as $18 by a large, south-facing, single-glazed window when either gas or electric resistance heating is used.[1]

Figure 4.2 shows the base-year energy costs converted to a life-cycle basis, both for constant future energy prices and for 12 percent escalation. The lower portion of Figure 4.2, Part A, shows that even at fixed energy prices, life-cycle energy costs for the office module may be raised by about $160 (from $480 to $640) by using 90 ft^2 single-glazed windows for southern orientations, and by about $350 (from $480 to $830) for northern orientations. Part B of Figure 4.2 shows that the increases in life-cycle energy costs are limited to between $70 and $110 by the use of double glazing.

The upper portion of Figure 4.2 shows that with energy prices escalating at a rate of 12 percent, the energy costs for the reference point (i.e., the windowless office module) are $1670, as compared with $480 with constant energy prices. With large, single-glazed windows facing north, the life-cycle energy costs for the office module now approach $2900, indicating an increase in life-cycle energy costs of approximately $1200 attributable to the windows. Part B of Table 4.2 indicates that the savings potential of double glazing becomes more important the higher the rate of energy price escalation (net losses attributable to windows are now limited to $400).

4.3.2 Energy Costs for Managed Windows Not Used for Daylighting

The addition of window management causes base-year energy costs to remain approximately level as the window area is increased, with the exception of single-glazed windows on the north side. Energy costs are reduced dramatically below those found in the preceding case.

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[1] The coefficient of performance (COP) for electric heating is 2.0; therefore the equivalent energy cost per therm is

$$\frac{(100{,}000\ \text{Btu}) \times \$/\text{kwh}}{(3413\ \text{Btu/kwh}) \times \text{COP}} = \$0.44 .$$

The equivalent energy cost per therm for gas heating is $0.46. Thus electric resistance heating is, in this case, less expensive than gas heating by virtue of the relatively high coefficient of performance for electric heating. Since the energy costs are nearly equal, all future references in the text to the figures plotting energy costs will refer only to the orientations and glazing type and ignore energy type.

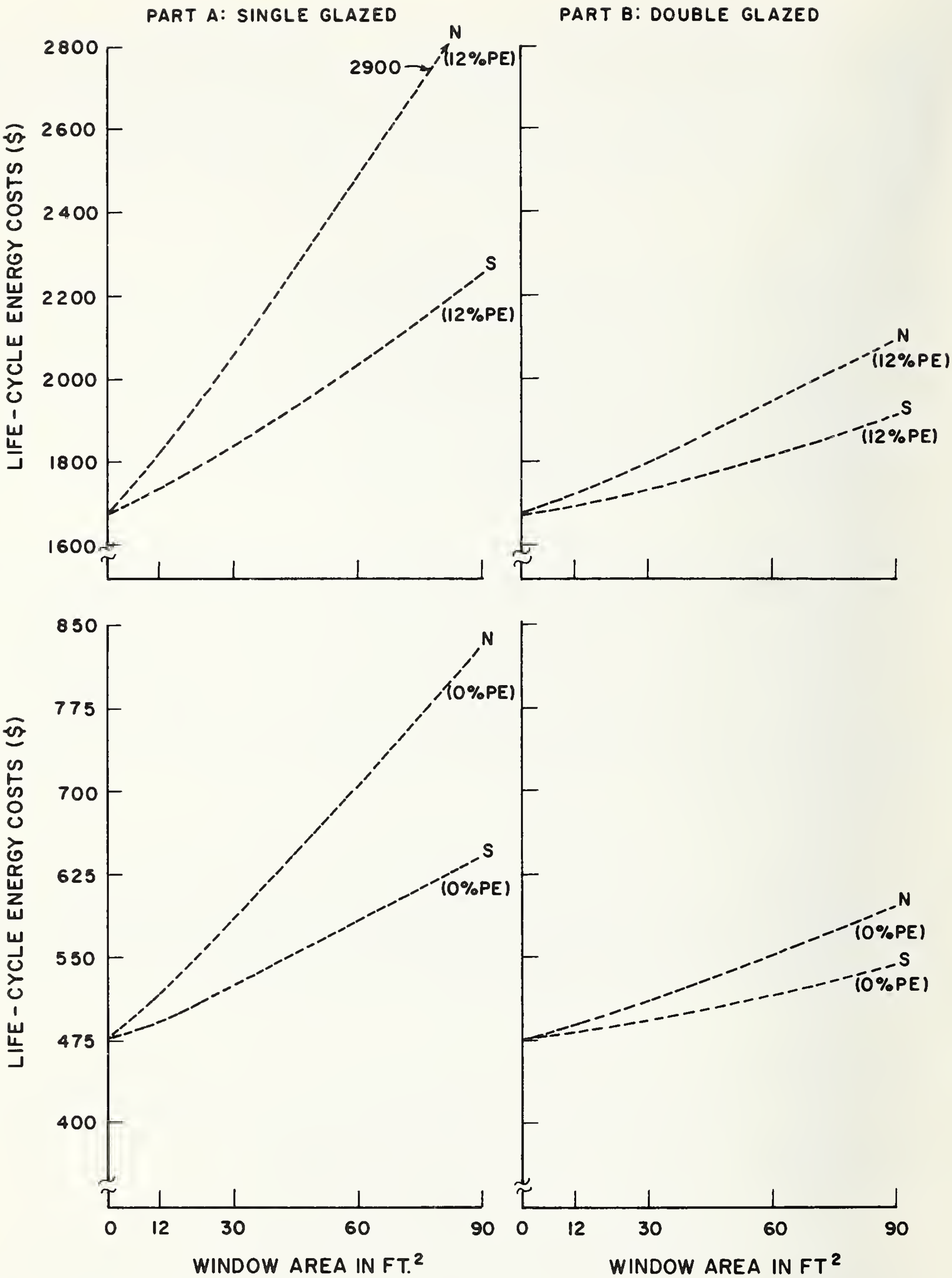

Figure 4.2 Life-Cycle Energy Costs for the Office Module for North (N) and South (S) Facing Unmanaged Windows Not Used for Daylighting
(Gas Heating and Electric Cooling Evaluated for both 0 and 12% Price Escalation)

With constant fuel prices, there is, therefore, little difference in the life-cycle energy costs of the room with and without windows. The exception is for north-facing, single-glazed windows which raise costs by about $120.

When energy prices rise at a rate of 12 percent per year, life-cycle energy costs are about quadrupled. The windowless office module now requires an energy expenditure of $1,620, as shown by Figure 4.3A, and the office with a single-glazed 90 ft^2 window facing north now has an energy cost of about $2,050. Part B of Figure 4.3 shows that double glazing used in conjunction with management tends to reduce energy consumption, but not by as much as in the preceding case when the windows were unmanaged. (By comparing Figure 4.3 with Figure 4.2, it may be seen that the nighttime temperature adjustment reduces life-cycle costs by approximately $50.)

4.3.3 Energy Costs for Unmanaged Windows Used for Daylighting

When the use of daylight is considered, but window management is not, base-year energy costs start at $53 and decline as window area is initially increased. However, as window area is increased past 30 ft^2 with single glazing or past 60 ft^2 with double glazing, energy costs begin to rise. As in the residential case, this pattern of initially falling and then rising energy prices reflects the fact that once the reference illumination level of 50 fc is met, additional daylight provided by increasing window size is not treated as energy savings in the evaluation model, while undesirable heat flows that tend to increase as window area increases continues to be treated as costs.

The life-cycle energy costs for this third mode of operation are particularly interesting since a large potential for savings exists. With constant energy prices, the life-cycle energy costs of the windowless office module are approximately $480. Even with a 90 ft^2 window area, costs remain below the initial energy cost provided the window area is either facing south or double glazed.

The utilization of daylight becomes even more important with a rise in energy costs. This relationship is demonstrated by Figure 4.4 which assumes that energy prices increase at the rate of 12 percent per year. The energy costs for the windowless room are now about $1670. (They are about $50 more than in the preceding case because there is no thermostat adjustment in this case.) If used for daylighting, south-facing, single-glazed windows may reduce energy costs to as low as $965, and south-facing, double-glazed windows to as low as $625. By comparing Figure 4.4 with Figure 4.2 (the first case), we can see the considerable potential that daylight utilization has to conserve scarce energy resources.

By comparing Parts A and B of Figure 4.4, the large potential savings for double glazing may be seen. For example, the energy costs associated with a 90 ft^2 double-glazed window facing north are nearly $900 less

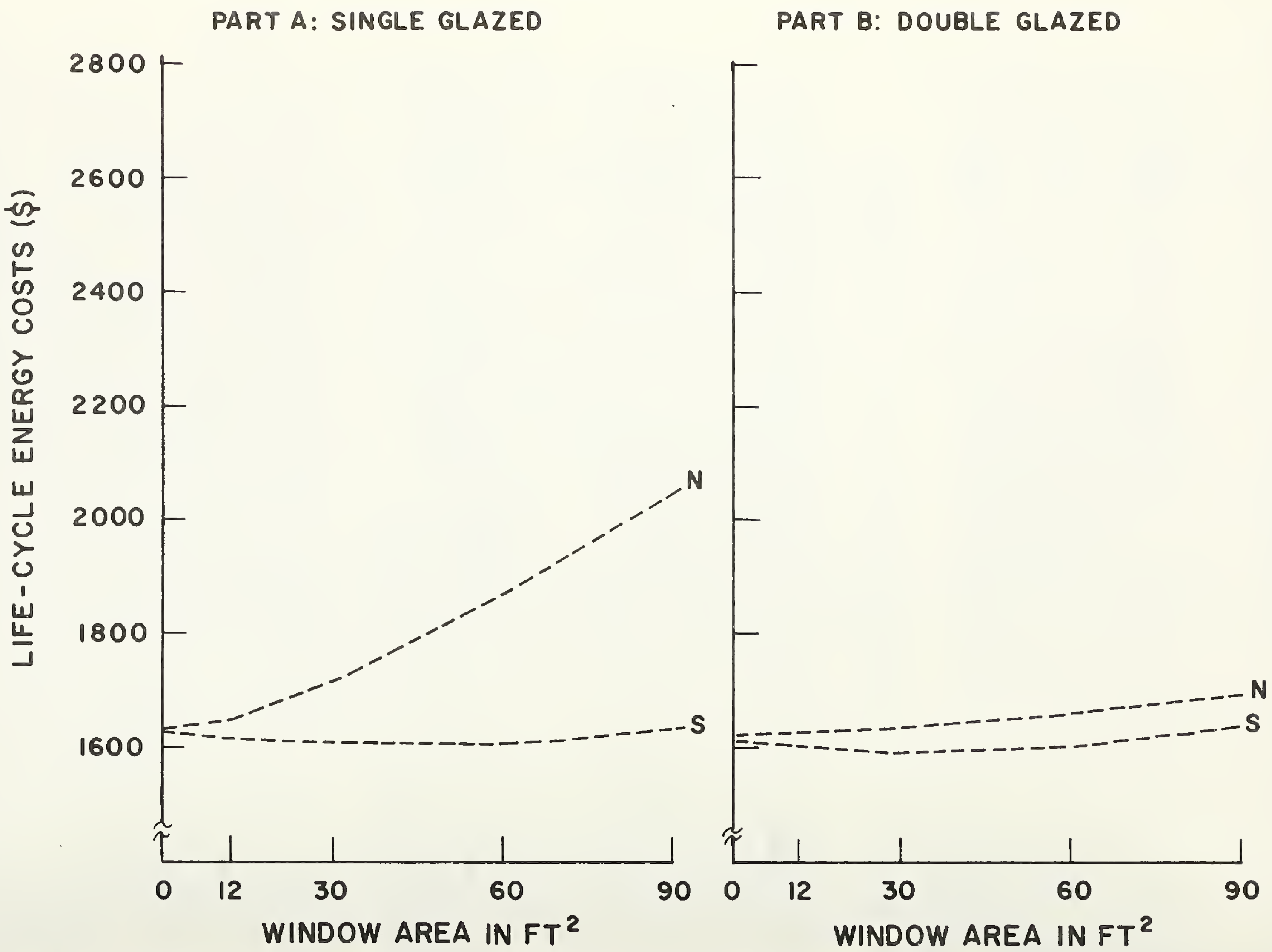

Figure 4.3 Life-Cycle Energy Costs for the Office Module for North (N) and South (S) Facing Managed Windows Not Used for Daylighting (Gas Heating and Electric Cooling Evaluated for 12% Price Escalation)

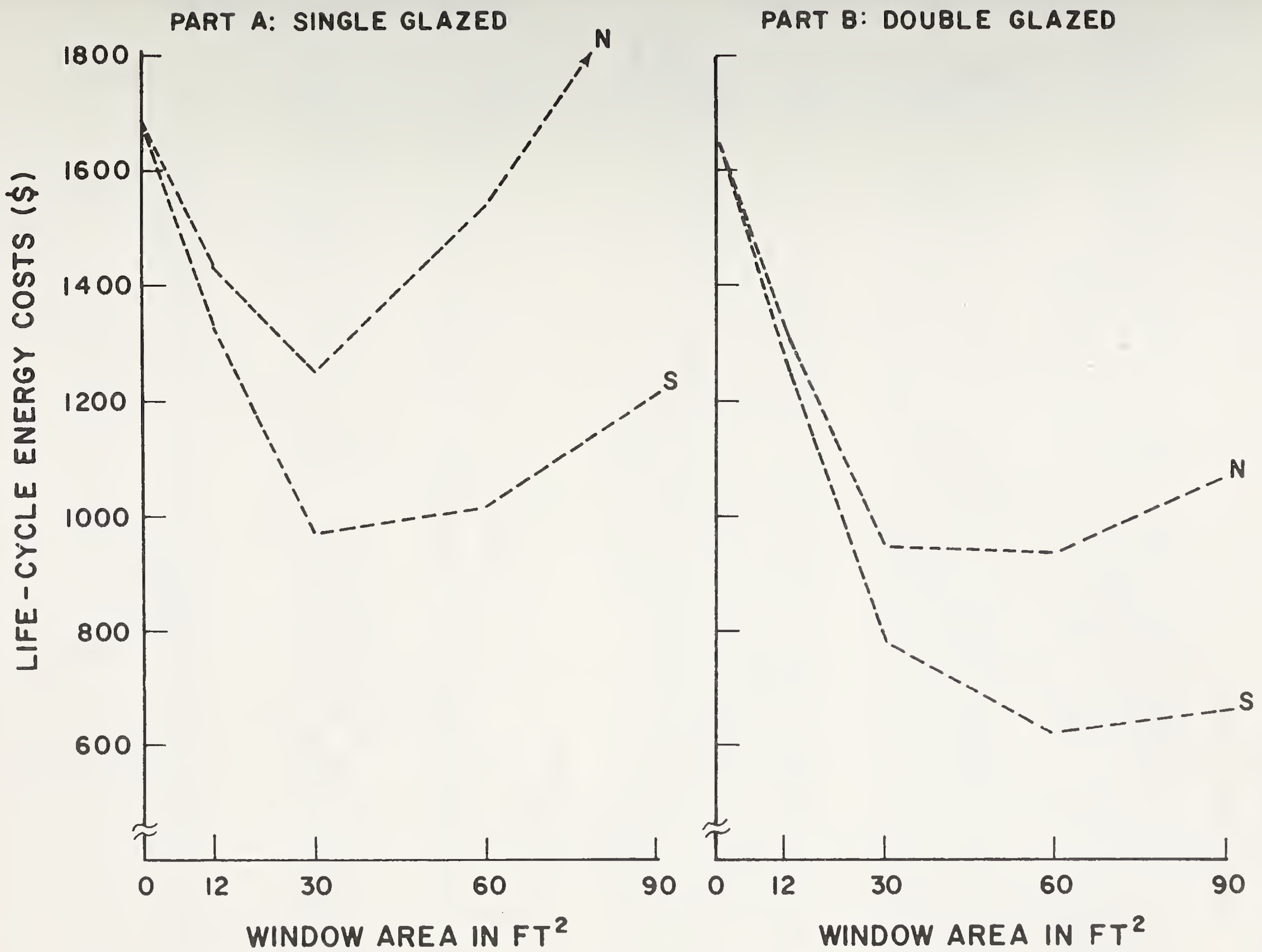

Figure 4.4 Life-Cycle Energy Costs for the Office Module for North (N) or South (S) Facing Unmanaged Windows Used for Daylighting (Gas Heating and Electric Cooling Evaluated for 12% Price Escalation

than the energy costs associated with a single-glazed window of the same size also facing north.

4.3.4 Energy Costs for Managed Windows Used for Daylighting

When both window management and daylighting are practiced, base-year energy costs for the module with either single or double glazing are lower than in the preceding case. Except for single-glazed windows facing north, costs now continue to decline for window sizes up to 90 ft^2. However, the decline in costs slows down as window size is enlarged.

With constant energy prices, energy requirements over the 25 year period for the windowless room are approximately \$460, \$20 less with the thermostat adjustment than without it. For southern exposures, the life-cycle costs fall to \$250 when a single-glazed window of 40 ft^2 is added, and fall further to \$150 when the window area is expanded to 60 ft^2. Life-cycle energy savings may range as high as \$340 by having a window.

With energy price escalation at 12 percent, the life-cycle costs of the windowless module again almost quadruple, and the potential energy benefit from using windows becomes quite large. As is shown by Figure 4.5, energy costs for the module decline for all the sizes of single- and double-glazed windows facing south, as well as for double-glazed windows facing north. Costs are shown to increase if single-glazed windows larger than 60 ft^2 are used facing north. Using a combination of daylighting and window management results in a potential (before tax) savings from windows as high as \$1,200.

4.4 Life-Cycle Costs

4.4.1 Life-Cycle Costs for Unmanaged Windows Not Used for Daylighting

Let us now examine the effects of combining life-cycle energy costs for the office module with life-cycle envelope costs for the window.[1]

Table 4.5 shows the combined life-cycle costs associated with unmanaged windows not used for daylighting. For all cases, life-cycle costs are higher with windows than without, although single-glazed windows add relatively little to total costs if energy prices are constant. In every

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[1] For the life-cycle cost calculations, the deductibility from taxable income of energy costs and depreciation for capital investment costs are taken into account in the model.

The depreciation allowance D(n) in year n is given as

$$D(n) = \frac{1.5}{N} \times BV(n-1)$$

(continued on page 81)

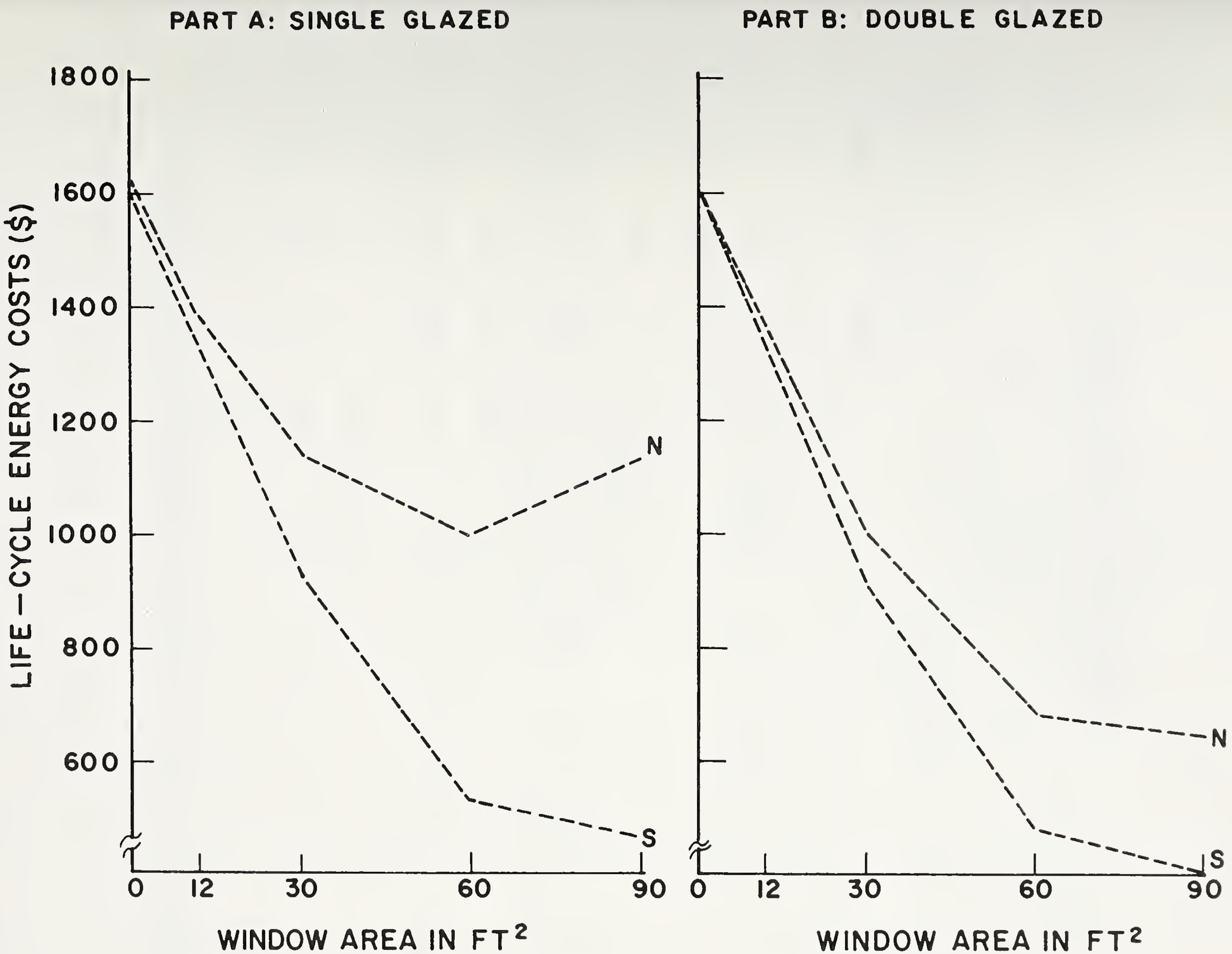

Figure 4.5 Life-Cycle Energy Costs for the Office Module for North (N) and South (S) Facing Managed Windows Used for Daylighting (Gas Heating and Electric Cooling Evaluated for 12% Price Escalation)

TABLE 4.5

Life-Cycle Costs When the Window System is Unmanaged and Not Used for Daylighting (Gas Heating and Electric Cooling)

	Window Area (FT^2)	Single Glazed: S	SW/SE	E/W	NW/NE	N	Doubled Glazed: S	SW/SE	E/W	NW/NE	N
		Life-Cycle Costs in Dollars									
		Orientation					Orientation				
Constant Energy Prices	0	1248	1250	1252	1251	1249	1248	1250	1252	1251	1249
	12	1270	1276	1282	1284	1282	1364	1368	1371	1370	1368
	30	1284	1295	1308	1317	1313	1473	1479	1486	1487	1482
	60	1392	1412	1439	1458	1452	1767	1777	1789	1793	1785
	90[a]	1249	1279	1320	1349	1343	1769	1783	1800	1806	1795
12% Energy Price Escalation	0	1846	1853	1857	1854	1848	1846	1853	1857	1854	1848
	12	1887	1905	1927	1936	1927	1970	1983	1993	1992	1983
	30	1939	1979	2024	2055	2043	2093	2115	2138	2143	2126
	60	2119	2189	2283	2351	2331	2415	2453	2494	2506	2478
	90[a]	2049	2153	2296	2398	2377	2450	2500	2560	2580	2541

[a] Life-cycle costs are lower for 90 ft^2 of single-glazing than 60 ft^2 due to reductions in framing costs.

case, the fuel savings of double glazing are more than offset by its extra acquisition and repair[1] costs, causing overall life-cycle costs for double glazing to be significantly higher than for single glazing.

4.4.2 Life-Cycle Costs for Managed Windows Not Used for Daylighting

Table 4.6 shows that the total life-cycle costs are higher with windows that are managed but not used for daylighting than with no windows, regardless of window size, orientation, glazing type, and energy price escalation. It can also be seen that single glazing is more cost effective than double glazing for all sizes and orientations examined.

By comparing Table 4.6 with Table 4.5, it can be seen that the energy savings from the blinds and shutters are not sufficient to offset their extra capital costs,[2] especially for the larger window areas. Life-cycle

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(continued from page 78)

where N is the period over which the capital asset is depreciated and BV(n-1) is the book value of the capital asset in the previous period. BV(0) is assumed to be the acquistion cost of the system. The present value, $P_tV(n)$, of the depreciation allowance in year n is then given as

$$P_tV(n) = \frac{D(n)}{(1 + \text{DISCOUNT RATE})^n} .$$

The present value, PV(n), of the reduction in income taxes due to the depreciation allowance is then given as

$$PV(n) = P_tV(n)(1-\text{TAX RATE}) .$$

The present value of all tax reductions due to depreciation allowances PV is given as

$$PV = \sum_{n=1}^{N} PV(n) .$$

[1] Recall that insurance costs are used in this case study as a proxy for repair costs.

[2] At this time there do not appear to be any commercially available insulated shutters that would be appropriate for office buildings. Those used in the case study are custom and have an acquisition cost of approximately $13 per square foot on the average. This figure is thought to be prohibitively expensive. However, in the fourth case of window use, two separate analyses are conducted. The first uses the custom made shutter and the second assumes an in place cost of $5 per square foot. Although the $5 per square foot figure is an assumed value, price reduction through competition may result if building owners demand insulated shutters.

TABLE 4.6

Life-Cycle Costs When the Window System is
Managed and Not Used for Daylighting
(Gas Heating and Electric Cooling)

	Window Area	Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
		Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	1241	1242	1244	1243	1242	1241	1242	1244	1243	1242
	12	1482	1486	1489	1488	1487	1579	1583	1585	1585	1583
	30	1626	1631	1638	1643	1642	1828	1833	1838	1838	1835
	60	1995	2006	2018	2035	2033	2402	2407	2414	2414	2410
	90	2099	2111	2131	2157	2158	2667	2673	2680	2681	2675
12% Energy Price Escalation	0	1818	1825	1829	1827	1822	1818	1825	1829	1827	1822
	12	2058	2070	2080	2080	2074	2153	2165	2175	2173	2166
	30	2200	2219	2240	2260	2254	2399	2416	2433	2433	2433
	60	2568	2606	2649	2709	2701	2977	2996	3021	3021	3006
	90	2683	2728	2797	2890	2891	3254	3276	3229	3305	3284

costs are actually higher for the second case than for the first, despite the beneficial results of thermostat adjustment in the second case. However, management does become relatively more worthwhile with the escalation in energy prices.

4.4.3 Life-Cycle Costs for Unmanaged Windows Used for Daylighting

Perhaps the most striking result of Table 4.7, which shows the life-cycle costs when the window system is unmanaged but used for daylighting, is that double glazing is in all cases uneconomical. Nevertheless, daylighting, as in the residential case, is sufficiently beneficial to cause the life-cycle costs with a window system, whether double or single glazed, to be less than the costs without a window system despite the fact that winter heat losses and summer heat gains are not being mitigated by window management. However, this does not hold for all combinations of window sizes, glazing types, and orientations.

When energy prices are assumed to remain constant, the least-cost window, for all cases except northerly exposures, is 90 ft^2 and single glazed. This condition is shown in Table 4.8. Notice also from Table 4.8 that due to reduced capital costs, the use of this window system results in an immediate payback indicated by an "I" entry in the column "Years to Payback."

Single glazing is also indicated as the least-cost glazing when energy prices escalate at 12 percent. The least-cost window size is smaller (30 ft^2) with price escalation. Through energy savings and reduced capital costs the use of these windows again results in an immediate payback. They can pay for themselves within the 25 year period even if energy prices fall somewhat.

4.4.4 Life-Cycle Costs for Managed Windows Used for Daylighting

Table 4.9 gives total life-cycle costs for the fourth case when windows are both managed and used for daylighting. Several facts are apparent from this table. First, the single-glazed windows are more economical over the life-cycle than the double-glazed windows for all window sizes and orientations, and for both constant and escalating energy prices. Second, the large savings that were found in the residential example when windows were both managed and used for daylighting do not materialize in this example; neither single- nor double-glazed windows are more economical than the windowless wall. In fact, large windows raise life-cycle costs between \$700 and \$1,300, depending on orientation and glazing type. The fact that real reductions in life-cycle costs resulted in the third case when daylight alone was used indicates that daylighting is very beneficial. The increase in costs in the fourth case indicates that the added costs of the management devices are not offset by energy savings through reduced window heat loss and summer heat gain.

Figure 4.6 uses the polar coordinate chart to compare the life-cycle costs of the 30 ft^2 single-glazed, managed window used for daylighting

TABLE 4.7

Life-Cycle Costs When the Window System is Unmanaged and Used for Daylighting (Gas Heating and Electric Cooling)

	Window Area	Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
		Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	1248	1250	1251	1251	1249	1248	1250	1251	1251	1249
	12	1215	1221	1227	1231	1229	1306	1310	1315	1316	1313
	30	1160	1173	1189	1201	1200	1339	1348	1360	1365	1362
	60	1247	1268	1299	1324	1322	1599	1616	1638	1648	1643
	90	1103	1134	1177	1214	1211	1593	1617	1646	1659	1651
12% Energy Price Escalation	0	1846	1852	1857	1854	1848	1846	1852	1857	1854	1848
	12	1692	1713	1735	1749	1742	1765	1779	1798	1800	1791
	30	1505	1550	1607	1650	1645	1620	1652	1695	1713	1702
	60	1609	1684	1792	1881	1872	1825	1886	1963	1998	1981
	90	1535	1642	1795	1926	1915	1833	1915	2017	2065	2036

TABLE 4.8

Least-Cost Window Systems When Windows Are Evaluated Without Window Management But With Daylighting

	Orientation	Size (ft^2)	Glazing Type	Total Life Cycle Cost	Total Cycle Saving ($)	Years to[a] Payback	Minimum FPE (%)
Constant Energy Price	S	90	Single	1103	145	I	< 0
	SW-SE	90	Single	1134	117	I	< 0
	E-W	90	Single	1177	74	I	< 0
	NW-NE	30	Single	1201	50	I	< 0
	N	30	Single	1200	49	I	< 0
12% Energy Price Escalation	S	30	Single	1505	340	I	< 0
	SW-SE	30	Single	1550	302	I	< 0
	E-W	30	Single	1607	250	I	< 0
	NW-NE	30	Single	1650	204	I	< 0
	N	30	Single	1645	203	I	< 0

[a] "I" indicates an immediate payback reflecting the initial reduction in capital costs when the 90 ft^2 window system is used.

TABLE 4.9

Life-Cycle Costs When the Window System is Managed and Used for Daylighting (Gas Heating and Electric Cooling)

	Window Area	Life-Cycle Costs in Dollars									
		Single Glazed					Double Glazed				
		Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	1240	1242	1244	1243	1241	1240	1242	1244	1243	1241
	12	1444	1447	1450	1451	1450	1541	1544	1547	1546	1544
	30	1529	1536	1548	1560	1560	1732	1737	1742	1746	1744
	60	1841	1855	1881	1906	1908	2241	2246	2261	2271	2270
	90	1933	1948	1986	2023	2027	2491	2499	2514	2528	2526
12% Energy Price Escalation	0	1818	1824	1829	1826	1821	1818	1824	1829	1826	1821
	12	1923	1935	1945	1949	1944	2018	2030	2040	2038	2031
	30	1861	1884	1927	1967	1968	2060	2077	2096	2110	2103
	60	2029	2079	2167	2256	2265	2413	2432	2484	2517	2516
	90	2102	2156	2287	2419	2432	2639	2663	2719	2767	2761

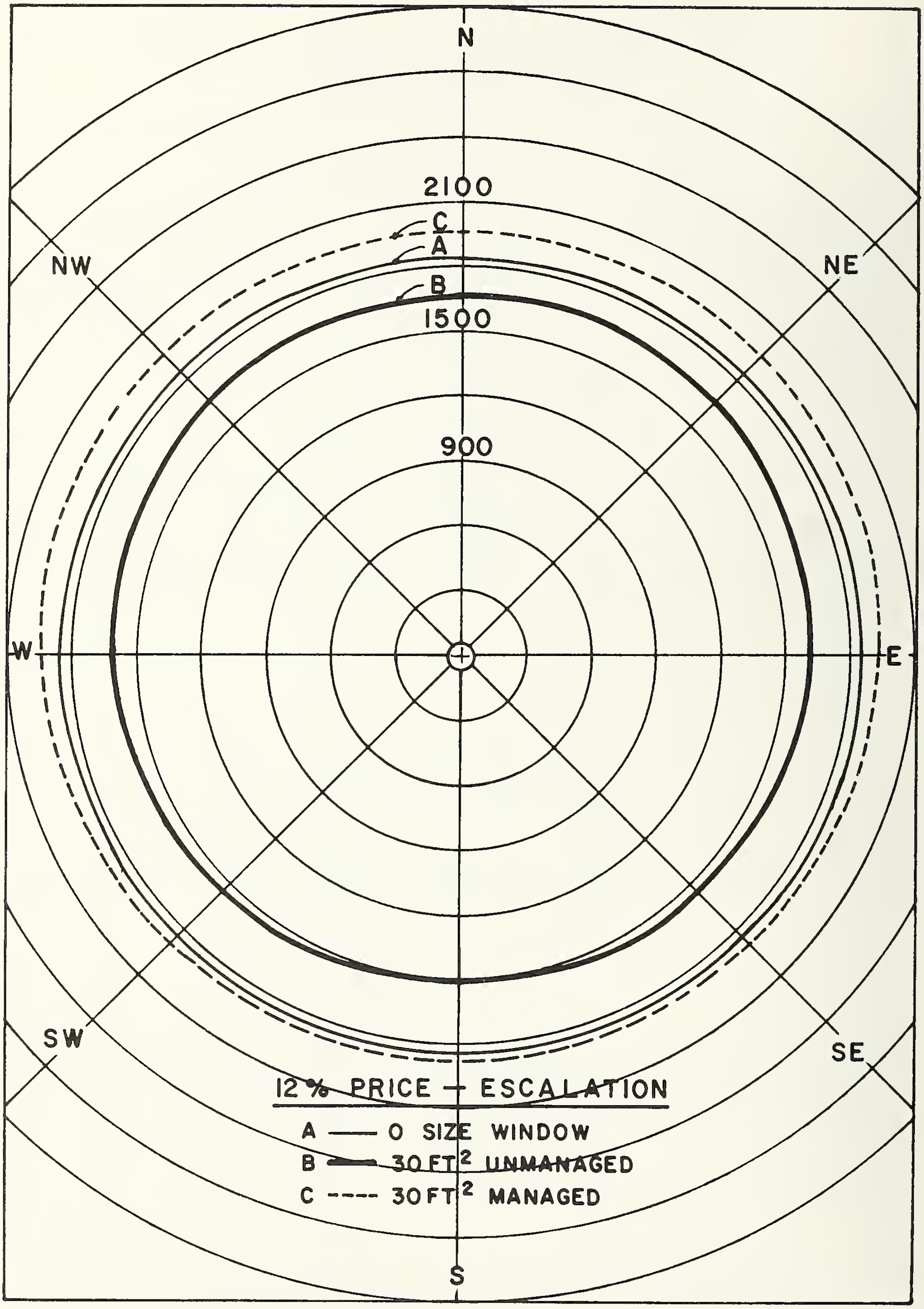

Figure 4.6 Graphical Determination of Least-Cost Window System for the Commercial Office Module

(the curve labeled "C") with two alternatives: (1) the windowless wall (labeled "A"), and (2) the 30 ft^2 single-glazed, unmanaged window used for daylighting (labeled "B"). The fact that curves A and B lie everywhere on a lower cost line than curve C indicates that the 30 ft^2 single-glazed, managed window used for daylighting is not the most economical of the three choices.

It was noted earlier that the cost figures for the thermal shutter used in the commercial case study were quite high due to its small market size at present. In order to test the cost impact of a lower price for the shutter, the analysis was repeated using a price of \$5 per ft^2 rather than \$13 per ft^2 that was based in all of the preceding commercial window management calculations. The results are shown in Table 4.10.

The thermal performance of the shutter is assumed to remain constant. Because the \$5/ft^2 cost is purely hypothetical, the results presented in Table 4.10 should be viewed as an illustration of sensitivity analysis rather than as a guide for window sizing.

With the lower priced shutters, the life-cycle costs associated with the windowed wall that is both managed and used for daylighting are lower than for the non-windowed wall, provided energy prices escalate rapidly, and the windows are single glazed and kept to 30 ft^2 when used for northerly exposures. However, by comparing Table 4.10 with Table 4.7, the third case, we can see that the unmanaged windowed wall used for daylighting continues to be more cost effective than the managed windowed wall used for daylighting.

4.5 Implications of Results

This section summarizes the major conclusions that can be drawn from the analyses of the life-cycle costs of the alternative window systems in the office module. The two cases of window operation which do not make use of daylighting are grouped together.

When Windows Are Not Used for Daylighting

1. In all situations examined, life-cycle costs were higher with windows than without windows.

2. If management devices are used, the larger the window, the larger the life-cycle cost of the office module.

3. If windows are used, their costs are lowest if they are located with southern exposures, and highest if located with northern exposures.

4. Rising fuel prices raise the costs of having windows of all sizes as compared to the windowless wall.

TABLE 4.10

Life-Cycle Costs When the Window System is Managed and Used for Daylighting; Testing the Sensitivity to $5/ft^2 Shutter Cost (Gas Heating and Electric Cooling)

	Window Area	Single Glazed					Double Glazed				
		Orientation					Orientation				
	(FT^2)	S	SW/SE	E/W	NW/NE	N	S	SW/SE	E/W	NW/NE	N
Constant Energy Prices	0	1240	1242	1244	1243	1241	1240	1242	1244	1243	1241
	12	1303	1306	1309	1310	1309	1400	1403	1406	1406	1404
	30	1315	1322	1334	1345	1346	1517	1522	1528	1532	1530
	60	1474	1488	1513	1539	1541	1874	1879	1894	1903	1903
	90	1443	1459	1496	1533	1537	2002	2009	2024	2038	2036
12% Energy Price Escalation	0	1818	1824	1829	1826	1821	1818	1824	1829	1826	1821
	12	1782	1794	1804	1808	1803	1877	1889	1899	1897	1890
	30	1646	1669	1713	1752	1754	1846	1862	1882	1896	1888
	60	1662	1711	1800	1889	1898	2045	2065	2117	2149	2149
	90	1612	1666	1797	1928	1942	2149	2174	2229	2277	2271

Life-Cycle Costs in Dollars

5. Even if fuel prices escalate rapidly, double glazing, due to its higher capital and insurance costs, is less economical than single glazing regardless of window size and orientation.

When Windows Are Unmanaged, But Used for Daylighting

1. The life-cycle cost of the office can be reduced by adding a window if care is taken in its sizing and orientation.

2. For some window areas, there may be savings relative to the windowless wall, as well as energy savings from using the window for daylighting.

3. When the value of trading daylight for electric lighting is considered, rising energy costs tend to improve the cost effectiveness of the window.

4. If fuel prices remain about constant, life-cycle costs of the office are lowest if a large, single-glazed, south-facing window is added.

5. If fuel prices rise rapidly, life-cycle costs of the office are lowest if a medium-to-large, single-glazed, south-facing window is added.

6. Even if energy prices are expected to increase rapidly, single glazing is more cost effective than double glazing.

When Windows Are Both Managed and Used for Daylighting

1. At the current market price for the thermal shutter examined, none of the window systems examined was found to reduce life-cycle costs below those for the windowless module.

2. Double glazing was less cost effective than single glazing for all window sizes and orientations examined.

3. Even at a moderate cost of $5 per square foot for the thermal shutter, the managed window is not as cost effective as the unmanaged window.

4. If a thermal shutter could be purchased and installed for a cost of $5 per square foot and fuel prices rise rapidly, life-cycle costs of the office module can be lowered by adding a window, particularly a large, single-glazed window facing south.

When Energy Prices Are Constant

1. Life-cycle building costs are minimized by adding a large (90 ft^2), single-glazed window facing south and utilizing it for daylight, but not equipping it with management devices.[1]

2. Regardless of window size, orientation, and glazing type, the least-cost case of window use is the third examined, i.e., using the window for daylighting but not investing in management devices. In descending order of cost effectiveness, the other cases rank as follows: the first case, i.e., neither using the window for daylight nor using management devices; the fourth case, i.e., using the window for daylight and using management devices; and, lastly, the second case, i.e., using management devices with the window but not using it for daylight.

3. Regardless of whether or not window management is practiced, it does not appear to pay to invest additionally in double glazing.

4. Small areas are preferred if management devices are used, whereas large window areas are preferred if management devices are not used.

When Energy Prices Escalate at a Rate of 12 Percent

1. Life-cycle costs are minimized by placing a medium-sized (30 ft^2), single-glazed window facing south and using it bare for daylighting.

2. Regardless of window size, orientation, and glazing type, the least-cost case of window use is the third examined, i.e., using the window for daylighting but not investing in management devices. In descending order of cost effectiveness, the other cases rank as follows: the first, i.e., neither using the window for daylight nor using management devices; the fourth, i.e., using the window with management devices for daylight; and lastly, the second, i.e., equipping the window with management devices but not using it for daylight.

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[1] Recall that the term window management includes not only the use of selective management devices such as thermal shutters and venetian blinds but also nighttime thermostat adjustments. Although selective management devices may not be cost effective, a nighttime thermostat adjustment would generally be cost effective since it produced energy savings at little or no cost.

3. Single glazing is preferred for all of the window sizes and orientations examined.

4. The thermal shutter is not cost effective due to its high current market price.

5. If the thermal shutter examined could be installed at a cost of $5 per square foot and large windows were used, it would be more cost effective to use the shutter than double glazing, but it would be still more cost effective to use neither.

Apart from the consideration of psychological or other factors, these results suggest that a building owner, builder, or designer in the Washington, D.C. area could reduce life-cycle costs by keeping window areas as small as possible or eliminating them altogether in those office modules which are not used much during the day or which for some other reason cannot be used substantially to reduce electric lighting requirements. The results, however, suggest that it is better from a life-cycle cost standpoint to have windows -- even relatively large ones -- than to have a windowless exterior wall if the windows can be used successfully to reduce electric lighting requirements.

If energy prices continue to rise rapidly, some consideration might be given to the use of either window accessories like those described or double glazing but not both. However, in all cases, even for northern exposures, single glazing should be given precedence.

The results further suggest that double glazing is generally not cost effective for the type of office module examined, nor is the use of management devices unless the thermal shutters examined could be acquired at very low cost or unless energy prices rise much more rapidly than the 12 percent rate examined here.

Facing page: *The provision of a view through windows can be an important factor in window design but is difficult to assess in dollar terms.*

5. SUMMARY, CONCLUSIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

This report has developed a life-cycle costing model and computer program for evaluating the dollar costs of acquisition, maintenance, and repair for windows of alternative design, size, orientation, geographical location, and with various accessories and modes of use, as well as the energy costs for the interior space with the alternative windows. It has described the importance of windows to energy costs, delineated the costs and benefits of windows, presented the economic evalution model verbally, algebraically, and in BASIC computer language, provided step-by-step illustrations of the application of the model to the windows in a residence and in an office building, and has drawn tentative conclusions based on the illustrations.

The results of the illustrations have indicated that window size, orientation, thermal resistance, accessories, and use--particularly the substituting of daylight for electric lighting--can affect significantly the energy consumption and life-cycle costs of windows. By examining the impact of windows on the life-cycle costs for four different levels of thermal analysis, the illustrations have shown how energy and overall building costs are influenced by the use of selected window accessories, thermostat adjustment, and daylighting. By examining energy and other costs separately and in combination, the approach has demonstrated the relationship between the energy efficiency and the cost effectiveness of different window designs. If energy costs can be reduced with little or no additional investment cost, as by changing window orientations, the least-cost energy decision is also the least-cost building decision. However, if capital and labor costs are increased by choosing one window design or accessory over another, it is important to weigh these costs against the value of energy savings to determine the cost-effective decision.

Considerable work remains to be done in the economic evaluation of windows. One task is to apply this or other evaluation models to develop guidelines for cost-effective window decisions for many types of window features, buildings, geographical locations, and uses. The companion to this report[1] takes a step in this direction by analyzing selected window features for two types of buildings in nine locations under alternative conditions. Much remains to be done, however, to develop a comprehensive set of guidelines for the nation.

Another important task is to extend and improve the thermal model to incorporate important effects now omitted. The inclusion in the model of the effects of natural ventilation from operable windows is a prime example of a needed improvement. An additional critical task is to raise the quality and reliability of the data with which the model must be used. For example, there is notable uncertainty about the utilization of excess heat gain in the winter and the available daylight under various sky conditions, room configurations, and window designs. Further research in both the laboratory and in the field is needed to provide reliable estimates of the energy impacts of windows.

With these suggested improvements in the evaluation model and in the input data to the model, a high payoff could be expected from the intensive application of the model to window alternatives and the analysis of the results. Development of easy-to-use, reliable guides to energy efficient and cost-effective windows could result in better decisions by the building community and in energy and dollar savings to the nation.

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[1] Rosalie T. Ruegg and Robert E. Chapman, Regional Economic Assessment of Selected Window Systems.

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Appendix - Computer Program for Life-Cycle Cost Evaluation of Windows (BASIC Language)

```
100 DIM R(5,5), S(5,5), T(5,5)
110 DIM U(5,5), V(5,5), W(5,5)
120 DIM X(5,5), Y(5,5), Z(5,5)
130 DIM C(5,3), F(5,3), H(5,3)
140 DIM A(5), B(5), D(5), E(5), G(5), I(5), J(5)
150 DIM K(5), L(5), M(5), N(5), O(5), P(5), Q(5)
160 PRINT "F1  FUEL PRICE","ESCALATION RATE"
170 PRINT "D1  DISCOUNT R","ATE"
180 INPUT F1,D1
190 READ C1,C2,C3
200 READ L9
210 PRINT "COMMERCIAL","NO 0   YES 1"
220 INPUT CO
230 IF CO=0THEN 290
240 PRINT "TAX FACTOR"
250 INPUT FO
260 REM -------------------------------------------------------------
270 REM - calculate annual energy costs for each glazing type      -
280 REM -------------------------------------------------------------
290 MAT READ R
300 MAT READ S
310 MAT READ T
320 MAT R=(C1)*R
330 MAT S=(C2)*S
340 MAT T=(C3)*T
350 MAT U=R+S
360 MAT U=U+T
370 MAT R=ZER
380 MAT S=ZER
390 PRINT "TRIPLE GLAZING","NO 0   YES 1"
400 INPUT TO
410 MAT READ R
420 MAT READ S
430 MAT R=(C1)*R
440 MAT S=(C2)*S
450 MAT V=R+S
460 MAT V=V+T
470 IF CO=0 THEN 500
480 PRINT "CALCULATIONS","BASED ON TAX","RATE OF",FO
490 LET FO=1-FO
500 MAT R=U
510 MAT U=TRN(R)
520 MAT S=V
530 MAT V=TRN(S)
540 REM -------------------------------------------------------------
550 REM - calculate life cycle energy costs for each glazing type  -
560 REM -------------------------------------------------------------
570 IF F1=D1 THEN 620
580 LET A1=((1+F1)/(D1-F1))*(1-((1+F1)/(1+D1))^L9)
590 MAT X=(A1)*U
```

```
600 MAT Y=(A1)*V
610 GO TO 640
620 MAT X=(L9)*U
630 MAT Y=(L9)*V
640 PRINT "LIFE CYCLE ENE","RGY COSTS FOR","SINGLE GLAZING"
650 IF C0=0 THEN 680
660 MAT X=(F0)*X
670 MAT Y=(F0)*Y
680 MAT PRINT X
690 IF C0=0 THEN 720
700 MAT U=(F0)*U
710 MAT V=(F0)*V
720 PRINT "LIFE CYCLE ENE","RGY COSTS FOR","DOUBLE GLAZING"
730 MAT PRINT Y
740 IF T0=0 THEN 960
750 MAT READ R
760 MAT READ S
770 MAT R=(C1)*R
780 MAT S=(C2)*S
790 MAT W=R+S
800 MAT W=W+T
810 MAT T=W
820 MAT W=TRN(T)
830 IF F1=D1 THEN 860
840 MAT Z=(A1)*W
850 GO TO 870
860 MAT Z=(L9)*W
870 PRINT "LIFE CYCLE ENE","RGY COSTS FOR","TRIPLE GLAZING"
880 IF C0=0 THEN 910
890 MAT W=(F0)*W
900 MAT Z=(F0)*Z
910 MAT PRINT Z
920 FOR I=1 TO 5
930 READ O(I)
940 NEXT I
950 REM -----------------------------------------------------------
960 REM - life cycle hardware costs                                -
970 REM -----------------------------------------------------------
980 FOR I=1 TO 5
990 READ A(I),B(I),D(I),E(I)
1000 IF C0=0 THEN 1020
1010 LET D(I)=F0*D(I)
1020 NEXT I
1030 MAT READ C
1040 IF C0=0 THEN 1060
1050 MAT C=(F0)*C
1060 LET D2=(1/D1)*(1-(1/(1+D1))^L9)
1070 IF C0=0 THEN 1170
1080 LET E0=0
1090 LET E9=1
1100 FOR K=1 TO L9
1110 LET E8=(1.5/L9)*E9
1120 LET E9=E9-E8
1130 LET E1=E8/(1+D1)^K
1140 LET E0=E1*F0+E0
1150 NEXT K
1160 LET E0=1-E0
1170 LET Q=L9/5
```

```
1180 MAT F=(D2)*C
1190 FOR I=1 TO 5
1200 LET D3=0
1210 LET K=1
1220 LET M=5*K
1230 LET D3=D3+(1/(1+D1)^M)
1240 LET K=K+1
1250 IF K<=Q THEN 1220
1260 LET G(I)=(D3)*D(I)
1270 FOR J=1 TO 3
1280 LET H(I,J)=F(I,J)+G(I)
1290 NEXT J
1300 IF CO=0 THEN 1410
1310 LET R(1,I)=A(I)
1320 LET R(2,I)=B(I)
1330 LET R(3,I)=E(I)
1340 IF TO=0 THEN 1360
1350 LET R(4,I)=O(I)
1360 LET A(I)=EO*R(1,I)
1370 LET B(I)=EO*R(2,I)
1380 LET E(I)=EO*R(3,I)
1390 IF TO=0 THEN 1410
1400 LET O(I)=EO*R(4,I)
1410 LET K(I)=B(I)+E(I)+H(I,2)
1420 LET J(I)=A(I)+E(I)+H(I,1)
1430 IF TO=0 THEN 1450
1440 LET P(I)=O(I)+E(I)+H(I,3)
1450 NEXT I
1460 PRINT "LIFE CYCLE","HARDWARE COSTS"
1470 IF TO=0 THEN 1610
1480 PRINT "SINGLE","DOUBLE","TRIPLE","ACCESSORIES"
1490 FOR I=1 TO 5
1500 PRINT A(I),B(I),O(I),E(I)
1510 NEXT I
1520 PRINT "MAINTENANCE","COSTS"
1530 PRINT "SINGLE","DOUBLE","TRIPLE"
1540 MAT PRINT H
1550 FOR I=1 TO 5
1560 FOR J=1 TO 5
1570 LET Z(I,J)=Z(I,J)+P(I)
1580 NEXT J
1590 NEXT I
1600 GO TO 1650
1610 PRINT "SINGLE","DOUBLE","ACCESSORIES","MAINT SING","MAINT DOUB"
1620 FOR I=1 TO 5
1630 PRINT A(I),B(I),E(I),H(I,1),H(I,2)
1640 NEXT I
1650 FOR I=1 TO 5
1660 FOR J=1 TO 5
1670 LET X(I,J)=X(I,J)+J(I)
1680 LET Y(I,J)=Y(I,J)+K(I)
1690 NEXT J
1700 NEXT I
1710 PRINT
```

```
1720 PRINT "TOTAL COSTS","SINGLE GLAZING"
1730 MAT PRINT X
1740 PRINT "TOTAL COSTS","DOUBLE GLAZING"
1750 MAT PRINT Y
1760 IF TO=0 THEN 1950
1770 PRINT  TOTAL COSTS","TRIPLE GLAZING"
1780 MAT PRINT Z
1790 GO TO 1950
1800 LET Q(J)=Z(1,J)
1810 FOR L=1 TO 5
1820 IF Q(J)<Z(L,J) THEN 1870
1830 LET Q(J)=Z(L.J)
1840 LET S4=L
1850 NEXT L
1860 REM ---------------------------------------------------------------
1870 REM - minimization of life cycle costs                           -
1880 REM ---------------------------------------------------------------
1890 GO TO 2200
1900 IF M(J)<Q(J) THEN 2280
1910 LET S=S4
1920 LET Z=3
1930 LET N(J)=Q(J)
1940 GO TO 2310
1950 PRINT "MINIMIZATION","OF LIFE CYCLE" "COSTS"
1960 REM ---------------------------------------------------------------
1970 REM - identify least cost window system for each orientation    -
1980 REM - j correspondes to the orientation as follows:             -
1990 REM -                   j=1  implies south                      -
2000 REM -                   j=2  implies southeast/southwest        -
2010 REM -                   j=3  implies east/west                  -
2020 REM -                   j=4  implies northeast/northwest        -
2030 REM -                   j=5  implies north                      -
2040 REM ---------------------------------------------------------------
2050 FOR J=1 TO 5
2060 LET Z=0
2070 LET L(J)=X(1,J)
2080 FOR I=1 TO 5
2090 IF L(J)<X(I,J) THEN 2120
2100 LET L(J)=X(I,J)
2110 LET S1=I
2120 NEXT I
2130 LET M(J)=Y(1,J)
2140 FOR K=1 TO 5
2150 IF M(J)<Y(K,J) THEN 2180
2160 LET M(J)=Y(K,J)
2170 LET S2=K
2180 NEXT K
2190 IF TO=1 THEN 1800
2200 IF M(J)<=L(J) THEN 2270
2210 IF TO=0 THEN 2230
2220 IF Q(J)<=L(J) THEN 1910
2230 LET N(J)=L(J)
2240 LET S=S1
2250 LET Z=1
```

```
2260 GO TO 2310
2270 IF TO=1 THEN 1900
2280 LET N(J)=M(J)
2290 LET S=S2
2300 LET Z=2
2310 LET I(J)=X(1,J)-N(J)
2320 IF S=1 THEN 2370
2330 IF S=2 THEN 2390
2340 IF S=3 THEN 2410
2350 IF S=4 THEN 2430
2360 GO TO 2450
2370 LET S=0
2380 GO TO 2460
2390 LET S=12
2400 GO TO 2460
2410 LET S=30
2420 GO TO 2460
2430 LET S=60
2440 GO TO 2460
2450 LET S=90
2460 IF Z=2 THEN 2500
2470 IF Z=3 THEN 2520
2480 PRINT "ORIENTATION",J,"AREA IN SQ FT",S,"SINGLE GLAZING"
2490 GO TO 2530
2500 PRINT "ORIENTATION",J,"AREA IN SQ FT",S,"DOUBLE GLAZING"
2510 GO TO 2530
2520 PRINT "ORIENTATION",J,"AREA IN SQ FT",S,"TRIPLE GLAZING"
2530 PRINT "TOTAL COST",N(J),"TOTAL SAVINGS",I(J)
2540 IF CO=0 THEN 2620
2550 FOR I=1 TO 5
2560 LET A(I)=R(1,I)
2570 LET B(I)=R(2,I)
2580 LET E(I)=R(3,I)
2590 IF TO=0 THEN 2610
2600 LET O(I)=R(4,I)
2610 NEXT I
2620 IF S=0 THEN 3860
2630 LET E9=1
2640 LET E2=0
2650 LET E0=0
2660 IF Z=1 THEN 2710
2670 LET X1=B(S2)+E(S2)
2680 LET H(J,Z)=V(S2,J)
2690 LET S3=S2
2700 GO TO 2750
2710 IF Z=3 THEN 2760
2720 LET X1=A(S1)+E(S1)
2730 LET H(J,Z)=U(S1,J)
2740 LET S3=S1
2750 GO TO 2790
2760 LET X1=O(S4)+E(S4)
```

```
2770 LET H(J,Z)=W(S4,J)
2780 LET S3=S4
2790 LET D9=0
2800 LET X4=A(1)
2810 REM ---------------------------------------------------------------
2820 REM - calculate payback period on least cost window system        -
2830 REM ---------------------------------------------------------------
2840 LET P=5
2850 LET M=1
2860 LET L=1
2870 IF D1=F1 THEN 3100
2880 LET D4=((1+F1)/(D1-F1))*(1-((1+F1)/(1+D1))^M)
2890 LET D6=(1/(1+D1))*(1-(1/(1+D1))^M)
2900 IF C0=0 THEN 3010
2910 LET X0=D4*U(1,J)
2920 LET X5=X4
2930 LET X9=X1
2940 LET E8=(1.5/L9)*E9
2950 LET E9=E9-E8
2960 LET E1=E8/(1+D1)^M
2970 LET E2=E1*F0+E2
2980 LET E0=1-E2
2990 LET X1=X1*E0
3000 LET X4=X4*E0
3010 LET X2=X1+D4*H(J,Z)+D6*C(S3,Z)
3020 LET X0=D4*U(1,J)+X4
3030 IF M=P THEN 3140
3040 LET X3=X2+D9*D(S3)
3050 IF X3<=X0 THEN 3170
3060 LET M=M+1
3070 LET L=L+1
3080 IF L>L9 THEN 3120
3090 GO TO 2870
3100 LET D4=M
3110 GO TO 2890
3120 PRINT "PAYBACK OVER",L9
3130 GO TO 3420
3140 LET D9=D9+1/(1+D1)^P
3150 LET P=P+5
3160 GO TO 3040
3170 IF M=P THEN 3350
3180 LET Y=M-1
3190 IF C0=0 THEN 3210
3200 LET E0=E0+E1*F0
3210 LET N=1
3220 IF D1=F1 THEN 3380
3230 LET D5=((1+F1)/(D1-F1))*(1-((1+F1)/(1+D1))^Y)
3240 LET D6=(1/(1+D1))*(1-(1/(1+D1))^Y)
3250 IF C0=0 THEN 3280
3260 LET X1=E0*X9
3270 LET X4=E0*X5
3280 LET X3=X1+D5*H(J,Z)+D9*D(S3)+D6*C(S3,Z)
3290 LET X0=D5*U(1,J)+X4
3300 IF X3<=X0 THEN 3410
3310 LET Y=Y+0.1
3320 LET N=N+1
3330 IF N>10 THEN 3410
3340 GO TO 3220
```

```
3350 IF X3=X0 THEN 3400
3360 LET D9=D9-1/(1+D1)^P
3370 GO TO 3180
3380 LET D5=Y
3390 GO TO 3240
3400 LET Y=M
3410 PRINT "YRS TO PAYBACK",Y
3420 REM -------------------------------------------------------------
3430 REM - calculate the minimum rate of fuel price escalation at   -
3440 REM - which least cost window system can still pay for itself  -
3450 REM - duing the study period.                                  -
3460 REM -------------------------------------------------------------
3470 IF510
3480 LET G(J)=K(S2)
3490 LET H(J,1)=V(S2,J)
3500 GO TO 3570
3510 IF Z=3 THEN 3550
3520 LET G(J)=J(S1)
3530 LET H(J,1)=U(S,J)
3540 GO TO 3570
3550 LET G(J)=P(S4)
3560 LET H(J,1)=W(S4,J)
3570 LET F2=0
3580 IF F2=D1 THEN 3660
3590 LET D7=((1+F2)/(D1-F2))*(1-((1+F2)/(1+D1))^L9)
3600 LET B0=(D7)*U(1,J)+J(1)
3610 LET B1=G(J)+(D7)*H(J,1)
3620 IF B1<=B0 THEN 3680
3630 LET F2=F2+0.01
3640 IF F2>F1 THEN 3840
3650 GO TO 3580
3660 LET D7=L9
3670 GO TO 3600
3680 LET F2=F2-0.01
3690 LET P=1
3700 IF F2=D1 THEN 3790
3710 LET D8=((1+F2)/(D1-F2))*(1-((1+F2)/(1+D1))^L9)
3720 LET B0=(D8)*U(1,J)+J(1)
3730 LET B1=G(J)+(D8)*H(J,1)
3740 IF B1<=B0 THEN 3810
3750 LET F2=F2+0.001
3760 LET P=P+1
3770 IF P>10 THEN 3810
3780 GO TO 3700
3790 LET D8=L9
3800 GO TO 3720
3810 LET F2=F2*100
3820 PRINT "PER CENT FPE",F2
3830 GO TO 3860
3840 LET F2=F1
3850 GO TO 3820
3860 NEXT J
3870 REM -------------------------------------------------------------
3880 REM - repeat for next orientation (j)                          -
3890 REM -------------------------------------------------------------
3900 REM ----------------------- data section -----------------------
3910 REM - itemize inputs as follows:                               -
3920 REM - input data for cost per 100,000 btu delivered to the     -
3930 REM - condition space for heating, for cooling, and the cost   -
3940 REM - per kilowatt hour of electricity as line 3950.           -
3950 REM data --, --, --
```

```
3960 REM - input data for length of study period in years as line 3970 -
3970 REM data --
3980 REM ----- data for heating loads with single glazing -----------
3990 REM - for each orientation input the number of therms of heating-
4000 REM - energy for each of five window sizes.  begin each line   -
4010 REM - with the number of therms associated with a windowless wall
4020 REM - and orientation of: line 4040 for south; 4050 southeast/southwest;
4030 REM - 4060 east/west; 4070 northwest/northeast; 4080 north.    -
4040 REM - data --, --, --, --, --                                  -
4050 REM - data [-, --, --, --, --                                  -
4060 REM - data --, --, --, --, --                                  -
4070 REM - data --, --, --, --, --                                  -
4080 REM - data --, --, --, --, --                                  -
4090 REM ----- data for cooling loads with single glazing -----------
4100 REM - orientation key is the same as that used for heating     -
4110 REM - using lines 4140  4150, 4160, 4170, and 4180 for the     -
4120 REM - corresponding orientation:  south, southeast/southwest,  -
4130 REM - east/west, northeast/northwest, and north.               -
4140 REM - data --, --, --, --, --                                  -
4150 REM - data --, --, --, --, --                                  -
4160 REM - data --, --, --, --, --                                  -
4170 REM - data --, --, --, --, --                                  -
4180 REM - data --, --, --, --, --                                  -
4190 REM ----- data for illumination requirements in kilowatt hours -
4200 REM - (note - this data is assumed the same for double and triple -
4210 REM - glazing also) for each orientation input the number of   -
4220 REM - kilowatt hours for lighting for each of five window sizes-
4230 REM - if daylight is not used as a light source, this figure   -
4240 REM - should remain constant for all window sizes.  begin      -
4250 REM - with the number of kilowatt hours associated with a      -
4260 REM - windowless wall.  orientation key is same order as before-
4270 REM - using lines 4280, 4290, 4300, 4310, and 4320.            -
4280 REM - data --, --, --, --, --                                  -
4290 REM - data --, --, --, --, --                                  -
4300 REM - data --, --, --, --, --                                  -
4310 REM - data --, --, --, --, --                                  -
4320 REM - data --, --, --, --, --                                  -
4330 REM - data for heating loads with double glazing --------------
4340 REM - input data will follow the same format and the same key  -
4350 REM - as that of single glazing.  use lines 4370, 4380, 4390   -
4360 REM - 4400, and 4410 for data.                                 -
4370 REM - data --, --, --, --, --                                  -
4380 REM - data --, --, --, --, --                                  -
4390 REM - data --, --, --, --, --                                  -
4400 REM - data --, --, --, --, --                                  -
4410 REM - data --, --, --, --, --                                   -
4420 REM - data for cooling loads with double glazing --------------
4430 REM - input data will follow the same format and the same key  -
4440 REM - as that of single glazing.  use lines 4460, 4470, 4480,  -
4450 REM - 4490, and 4500.                                          -
4460 REM - data --, --, --, --, --                                  -
4470 REM - data --, --, --, --, --                                  -
```

```
4480 REM - data --, --, --, --, --                                          -
4490 REM - data --, --, --, --, --                                          -
4500 REM - data --, --, --, --, --                                          -
4510 REM - data for heating loads with triple glazing - if used -----
4520 REM - input data will follow the same format and the same key  -
4530 REM - as that of single and double glazing   use lines 4550,   -
4540 REM - 4560, 4570, 4580, and 4590 if needed.                    -
4550 REM - data --, --, --, --, --                                  -
4560 REM - data --, --, --, --, --                                  -
4570 REM - data --, --, --, --, --                                  -
4580 REM - data --, --, --, --, --                                  -
4590 REM - data --, --, --, --, --                                  -
4600 REM - data for cooling loads with triple glazing - if used -----
4610 REM - input data will follow the same format and the same key  -
4620 REM - as that of single and double glazing.  use lines 4640,   -
4630 REM - 4650, 4660, 4670, and 4680 if needed.                    -
4640 REM - data --, --, --, --, --                                  -
4650 REM - data --, --, --, --, --                                  -
4660 REM - data --, --, --, --, --                                  -
4670 REM - data --, --, --, --, --                                  -
4680 REM - data --, --, --, --, --                                  -
4690 REM - input the cost of single glazing, cost of double glazing -
4700 REM - five year painting cost, cost of window accessories as a -
4710 REM - function of window size.  statement 4750 should correspond -
4720 REM - to the smallest window size, statement 4790 should       -
4730 REM - correspond  to the largest window size examined and 4760 -
4740 REM - through 4770 represent intermediate sizes.               -
4750 REM - data --, --, --, --                                      -
4760 REM - data --, --, --, --                                      -
4770 REM - data --, --, --, --                                      -
4780 REM - data --, --, --, --                                      -
4790 REM - the first column of data in statements 4890 through      -
4800 REM - statement 4930 correspondS to the annual cleaning and    -
4810 REM - insurance costs of a single glazed window. statement 4890-
4820 REM - is the smallest window size, statement 4930 is the largest-
4830 REM - window size examined.  the second column of statements   -
4840 REM - 4890 through 4930 corresponds  to the annual cleaning and-
4850 REM - insurance costs of a double glazed window.  the third    -
4860 REM - column of statements 4890 through 4930 correspondS  to   -
4870 REM - the annual cleaning and insurance costs of a triple glazed-
4880 REM - window.                                                  -
4890 REM - data --, --, --                                          -
4900 REM - data --, --, --                                          -
4910 REM - data --, --, --                                          -
4920 REM - data --, --, --                                          -
4930 REM - data --, --, --                                          -
4940 END
```

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

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.)*

This study, which is one part of a National Bureau of Standards interdisciplinary project on windows, is aimed at improving the cost-effectiveness of window selection and use in buildings. It develops and illustrates a life-cycle costing evaluation model and computer program for assessing for alternative window systems the net dollar impact of acquisition, maintenance and repair, heating and cooling energy gains and losses, and artificial lighting and daylighting tradeoffs. The method is applicable to the evaluation of many different window sizes, designs, accessories, and uses, both for new and existing residential and commercial buildings. Two step-by-step examples of evaluating selected window alternatives in a residence and in an office building in Washington, D.C. serve to illustrate the application of the method.

A companion report, A Regional Economic Assessment of Selected Window Systems, presents the results of eight additional residential case studies and eight additional commercial case studies. While the emphasis of this report is on the method of evaluation, the companion report focuses on summarizing the results of a regional analysis in a form that will be convenient for use by building owners, operators, designers, financiers, and builders, those whose interest centers on the actual implementation of research results.

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)*

Building economics; daylighting; economic analysis; energy conservation; engineering economics; life-cycle costs; solar heat gain; thermal efficiency; window; window management.

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