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Proceedings of a Working Conference

Committee on Solar Energy in the Heating and Cooling of Buildings
Building Research Advisory Board
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National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1976

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

The growing disparity between our nation's demand for energy and the supply of nonrenewable fuels is a generally accepted fact. The significant proportion of this demand directly attributable to buildings is another generally accepted fact. Given these facts, there is a clear need to approach all building construction and remodeling activities with the unwavering goal of conserving energy and maximizing the use of renewable sources of energy such as that obtained from the sun. To this end, several federal agencies are undertaking and supporting programs and activities that will help make solar energy technology a viable alternative method for heating and cooling buildings, and the Building Research Advisory Board is privileged to be participating in these efforts.

The Board gratefully acknowledges the work of the Committee on Solar Energy in the Heating and Cooling of Buildings responsible for compiling this report and sincerely appreciates the contribution of the steering group that organized the April 1975 Working Conference on Solar Effects on Building Design, the individuals who presented papers at the conference, the participants in that conference, and the authors of the other papers incorporated in this report.

Walter R. Hibbard, Jr.
Chairman, Building Research Advisory Board

PREFACE

As part of its Research Applied to National Needs (RANN) program, the National Science Foundation (NSF) initiated, in fiscal year 1971, a major activity focusing on the application of solar energy in the heating and cooling of buildings. The plan for this activity called for the support of research and development efforts aimed at testing and proving new concepts, and its ultimate goal was to complete and disseminate the results of proof-of-concept demonstration projects.

When the NSF initiated its program, certain segments of the private sector of the building community already had begun and were continuing to independently develop the technology needed to harness solar energy for heating and cooling buildings. By the end of fiscal year 1973, participation by the building community in the RANN program was increasing, but evidence indicated that building community independent efforts also were increasing in number and scope. Thus, in the early part of fiscal year 1974, the NSF requested that the National Academy of Sciences (NAS) assist it in effecting a linkage between the RANN program and the independent efforts of the private sector of the building community. Specifically, the NAS was to:

1. Bring up to date the 1963 publication of the Building Research Institute, *Solar Effects on Building Design*.
2. Identify solar energy research, development, and applications programs being undertaken by the private sector and the nonproprietary research needs of the private sector that should be considered for inclusion in the RANN program.
3. Recommend a cost-effective information dissemination system for communicating the results of RANN-supported solar energy research to those in the best position to use it.

In response to this request, the NAS entered into a contract with the NSF and charged the Building Research Advisory Board (BRAB) with administration of the program. A project committee, the BRAB Committee on Solar Energy in the Heating and Cooling of Buildings, was appointed to participate in and guide the process whereby information needed for the study would be developed by the BRAB staff and its consultants, to render the judgments--conclusions and recommendations--that would constitute the essence of the study, and to participate in and guide the preparation of the reports conveying its judgments.

In the early part of fiscal year 1975, the NSF additionally requested that the NAS assist it in characterizing the segments of the building community involved in solar energy projects. Following the creation of the Energy Research and Development Administration (ERDA) in the latter part of fiscal year 1975 and the transference to ERDA of portions of the RANN solar energy activities, responsibility for administering the contract between the NAS and the NSF was transferred to ERDA. The NAS then entered into an additional contract with ERDA and charged the BRAB with the task of characterizing the involvement of the building community in solar energy projects.

PURPOSE OF THIS REPORT

This report* was prepared by the Committee in response to that portion of the NSF contract related to the updating of the 1963 publication of the Building Research Institute, *Solar Effects on Building Design,* which is now out of print. This report contains 15 individually authored papers that focus on various aspects of the problem of planning and designing buildings, irrespective of their energy sources for heating and cooling, that use the natural and man-made environment and materials of construction to advantage in conserving energy.

CONDUCT OF THE STUDY

To complete its task involving updating the 1963 Building Research Institute publication, *Solar Effects on Building Design,* the BRAB Committee on Solar Energy in the Heating and Cooling of Buildings organized a six-member steering group under the direction of one of its members.† To gather the material it needed, this group convened a limited-invitation working conference of 64 individuals on April 8-9, 1975, in Washington, D.C. Eleven prepared papers on topics covered in the 1963 publication, as well as on new topics identified as important by the steering group,

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*Two additional Committee reports, "Solar Heating/Cooling of Buildings: Activities of the Private Sector of the Building Community and Its Perceived Needs Relative to Increased Activity" and "Solar Heating/Cooling of Buildings: An Information Dissemination Process," respond to the other tasks posed by the NSF and ERDA contracts.

†Under the chairmanship of Committee member William G. Wagner, the steering group comprised: Joseph Demkin, Program Director, Professional Practice, American Institute of Architects, Washington, D.C.; James W. Griffith, Partner, K-G Associates, Dallas, Texas; William C. Louie, Vice President, Smith, Hinchman and Grylls Associates, Inc., Detroit, Michigan; Robert McKinley, Manager, Technical Services, Glass Division, PPG Industries, Pittsburgh, Pennsylvania; and Lee Stephen Windheim, Senior Vice President--Systems, Leo A. Daly Company, San Francisco, California. A list of the conference participants is presented at the end of this volume.

were presented and discussed at the conference and then were revised by the authors to reflect the discussion as they deemed desirable. In addition, since several aspects of architectural design considered relevant could not be covered in the limited time available at the conference, two papers from the 1963 publication were updated by their authors (i.e., "Design of Windows" by J. W. Griffith and "Design of Skylights" by B. H. Evans) and one general paper on solar design was prepared by D. C. Bullen for inclusion in this report. At the request of the parent Committee, one paper from the 1963 publication (i.e., "Selection of Glass and Solar Shading to Reduce Cooling Demand" by A. L. Jaros, Jr.), which is still deemed to be pertinent, has been reprinted here.

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THE GREATEST WASTE OF ALL

Lee Stephen Windheim

We are all fellow travelers on the spaceship *Earth*. Our ship receives its energy from the star sun. This energy from the sun, combined with the natural processes of our spaceship, provides us with: (1) a limited store of low-entropy, high-energy fuels and (2) an abundance of higher entropy, but continuing, current energies.

Early man, whose power to reason was limited, developed use of the current and relatively unconcentrated energies. He used them largely in the place he found them. Recent man discovered that he could dig up--literally, scoop up--the longtime highly concentrated deposits. So "spoon-fed," he has, in a very short time by universal standards, expanded himself and his power to reason.

Now modern man is faced with a crisis. This crisis first manifested itself in terms of pollution--pollution generally brought about by the exponential uses of the earth's concentrated buried energies in too short a time and in too limited locations. Thus, the question becomes whether man will use his expanded ability to reason or whether he will continue his dangerous present line of development.

As Kenneth Boulding has said: "It takes a terribly long time to think of the simplest things." Often when systems cease to function well, conventional wisdom prescribes patching up the old system in hopes of improved performance. Sadly, however, the worst parts of the old system are often retained, while the planners and engineers tinker with the remaining components. The most ill-conceived systems of all result when the best parts of the old system are eliminated and the remaining malfunctioning parts are combined with another, even worse, subsystem.

Today, we have a highly interactive synergistic problem set. In somewhat simpler terms, we can identify three foci: (1) supply diminishment, (2) pollution increment, and (3) financial exhaustion. But beyond this identification there is yet little evidence that we understand the second-level effects. For example:

1. It takes energy to get energy. The true value of energy to society is not the gross amount that exists in the world. The true value is the net energy--the amount remaining after you subtract the energy costs of getting and concentrating that energy.
2. Pollution is potentially the result of every energy exchange.
3. Energy policy that does not take net energy into consideration

will bring about increasing economic instability. The more successful the United States is in maintaining or increasing its total energy consumption under conditions of declining net energy, the more rapidly inflation, unemployment, and general economic instability will increase. The disruptive effects of an inappropriate energy policy will be seen in terms of an "economic crisis" rather than an "energy crisis."

But what does this have to do with designers, developers, and constructors of the built environment (cities and buildings) and our theme, "Solar Effects on Building Design"?

Cities and buildings--the products of our thinking, our design, our manufacturing processes, and our construction prowess--use lots of energy, create lots of pollution, and, increasingly, cost more than we can afford. Today's urban dweller consumes and exhausts enormous amounts of the low-entropy, high-energy, stored fuels. This process involves an exchange that now poses a threat to both the environment and man's own survival. The air and water of many urban areas are contaminated, and pollution seems likely to continue. Clearly there is a limit to the amount of waste the environment can handle, and clearly man has not recognized this limit--either in the magnitude of his endeavors or in the rate at which they are undertaken. Thus, modern man is faced with the situation of having to pay ever greater costs to sustain an environment that is becoming ever more unstable.

Still, as Boulding says, "It takes a long time to think of the simplest things." And in considering our theme, "Solar Effects on Building Design," we are going to have a chance to think of some of the "simplest" things--for example, in the United States the sun provides an average amount of energy equal to 16+ watts per square foot for each of the 24 hours in a day. With some simple applications of common sense and perhaps some very simple push-pull devices, this energy can be captured for use in the very building that it is impinging upon.

As an architect, I believe that the use of some common sense about fitting buildings into their environment and configuring buildings to accept multiple activities will be more rewarding than increased mathematical analysis of conventional building forms and components. Mathematical analysis, unfortunately, has become the handmaiden of mechanical systems. Because push-pull mechanical systems give the appearance of surety and efficiency and because they can be calculated, the reverse is also true. Only those components that are immediately calculable can be used. It would be a great error to fall into the trap of black and white, either/or. Of course, devices should be considered, but one should start with the simple and keep them simple!

Energetics is a new tool for evaluating the worth of any project from an energy viewpoint. It is an accounting procedure for use in determining the net energy contributed to or consumed by the project. For example, its application to a solar heating system would require the determination of the total amount of energy used in producing, processing, assembling, and operating the components of the system. This total then would be subtracted from the energy collected by the system to give the net energy. One criterion for the worth of the system would be the length of time needed to offset the production energy with solar energy collected.

And yet, with all this attention to energy conservation, we may still have "the greatest waste of all." Buildings are for people--to play in, to rest in, to work in, to pray in, to learn in. A building must help people. It has a prime task. If that task is not done well, all the insulation in the world will not help. What I am saying is that function, beauty, and economy can go down the drain along with energy if we are tied to prescription codes. And this is a loss we do not have to suffer because of the energy crisis.

To better utilize energy, we need to work with principles--to work with the principles of a natural process. To work toward reasonable solutions to our multiple problems of supply diminishment, pollution increment, and financial exhaustion, it seems to me that we should design with the following in mind:

- Keep it simple.
- Rely on traditional architectural intuitive senses; do not become overwhelmed by "calculable certainties."
- Use the concepts of net energy and the principles of energetics (as identified by Howard Odum in *Toward a General Theory of Planning Design*) to valuate our choices of location, form, and material.
- Heed Ralph Knowles' admonition: "...questions of urban settlement must be couched in terms of the energy balances between man's arrangements and the natural work where change is fundamental."
- And last, but certainly not least, let us not forget that *buildings are for people*. To gain all else but this would be the greatest waste of all!

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I

Urban Development

SOLAR ENERGY AND URBAN FORM

Ralph L. Knowles

In his classic work, *A Tale of Two Cities*, Charles Dickens described the year 1775 as "the best of times . . . the worst of times." Dickens was writing about political and industrial change and he depicted two cities, London and Paris, as illustrations of such change. Were he writing today, he would find U.S. cities to be equally sensitive indicators of change and would quite possibly employ Los Angeles, which has expanded dramatically during the 30 years since the end of World War II, as his example.

The war years almost completely diverted the nation's energy and resources abroad, so that by 1945 there was a backlog of building need. The population was increasing, it had shifted from the farms to the cities, and much of the building stock needed to be replaced. The result was a postwar period of exuberant urban expansion. Because we could depend upon the automobile for highly personalized transportation, we could and did build outward onto our agricultural land and the raw land beyond.

It was "the best of times"! There was the GI loan, which typically converted into the new kitchen, two bathrooms, and three bedrooms that comprised everybody's dream of a ranch house. Attached to the ranch was the barn, which typically contained 320 horses, 160 under each hood! None of it, of course, would have been possible without those hoods and horses. Los Angeles became an offspring of 2 × 160 horses × 1 million families--and a very awesome offspring it has become. Large, brash, unsettled, malleable, and mobile--always mobile--for without motion it cannot survive. This city is comprised of vast and segregated areas of housing, commerce, and industry, and people are constantly on the move conducting their daily transactions among these three. For their mobility, they have depended almost exclusively upon the private automobile.

The expansionary growth of the past 30 years now seems to be ending. Whether this also means an end to "the best of times" remains to be seen. Certainly we can expect a period of transition. For three decades we have expanded across relatively flat land easy to develop. We have exploited that land extravagantly and have reached the natural geographic limits of mountain and sea. If we expand much farther using our accustomed mode, we will be faced with the exorbitant proposition of flattening mountains and filling in the oceans.

The second limit upon expansionary growth has very much to do with water, though of a potable sort. If we are going to continue to expand upward, we shall need greater water resources than we now have. At present, 80 percent of Los Angeles' water comes from the Owens Valley of California. The Owens Valley aqueduct was built just after the beginning of this century, when settlement in the valley was minimal. We have apparently reached the natural limit of that resource and can go no further without tampering with the ecology by tapping the precious water table. If we tap other resources, we deprive other regions of their settlement options, an action not viewed kindly in many quarters. Canada, for example, views its water and other natural resources with increasing pride of ownership.

Besides being limited by water resources, further expansionary growth may be limited by our inability to generate additional electric power by the traditional methods--damming rivers, burning fossil fuels, and sustaining low-level nuclear reductions--without committing irreparable harm to the natural environment.

A final resource-related limit on expansionary growth is that of transportation. The automobile provides individual freedom of movement, but it has the concomitant disadvantage of consuming an irreplaceable energy resource. Most limits upon growth are energy-related. For example, one-third of the national energy bill goes for transportation and much of that obviously for personal mobility within cities. Another one-third of the national energy bill goes to regulate the climate of the buildings that comprise those cities. Most of the buildings have been erected in the past 30 years, and in Los Angeles such buildings were intentionally energy-dependent. At a time when energy sources were thought inexhaustible, old climate-sensitive, indigenous styles were abandoned in favor of modern residential, commercial, and industrial types that required energy. The final one-third of the national energy bill maintains industry of all kinds. While this is a rough breakdown, it makes clear that 30 years of expansionary growth have generated cities that consume huge amounts of energy. The impact of this high maintenance bill is of international proportion. It affects foreign policy; it affects domestic policies at the federal, state, and local levels; it even affects military preparedness! It has warped the economy. It has brought us, if not to "the worst of times," certainly to a time when we must consider alternatives.

Two vital questions then are pertinent at this critical time. First, if expansionary growth ends, will urban growth change or cease entirely? Second, if it changes to a new mode, can we give greater consideration to the purposes of growth?

In general, I would agree with those who make the policy, with those who make the designs, and with those who take a direct hand in the physical development of our cities when they prophesy a changed growth mode in the future rather than a cessation of growth. What some term "recycling," I call "transformation." Whichever term is used, the process involves rebuilding and reorganizing the existing city rather than continuing its expansion. Such transformational growth not only provides an array of developmental options, but also contains the potential cure for some of the current crop of energy-related ills.

In such cities as Los Angeles, somewhere between 80 and 90 percent of the building stock is original--nothing stood before. Attempts to produce an instant city resulted in overbuilt areas, and the subsequent exodus of urban populations to the suburbs has left vast portions of the city poorly maintained. Much of it needs rebuilding.

Rebuilding offers a chance to take two major steps toward curing energy ills. The first is to design buildings according to principles of energy conservation, not merely to ape building types such as the pueblo and the early California ranch house, which were both in their own ways well adapted to the local climate, but to devise new urban types with forms that correlate with the natural variations of the region and reduce their dependency upon mechanical support systems. The second major step will be to generate designs that will reduce the absolute need for transportation by increasing diversification on a smaller urban scale.

The Los Angeles City Planning Department, under the direction of Calvin Hamilton, has already taken steps in this direction by identifying actual and potential centers distributed throughout the region. If these centers were to be strengthened by increasing the diversity of housing, commerce, and industry within them, a choice would be provided, as well as an alternative to driving as much as 20 or 30 miles across town to work, shop, bank, see the doctor, and so on. Sense of community increases proportionately within such well-balanced centers, since the scale of daily transactions is reduced to levels comprehensible to the individual. The University of Southern California (USC) School of Architecture has concerned itself with these two vital steps for nearly a decade. The work actually began in 1962 at Auburn University, in Alabama. I worked there with other faculty and students in the development of building prototypes designed to reduce the impact of solar radiation during critical times of the day and year and to minimize the need for expensive air conditioning equipment. Results were encouraging and led to conjecture on my part that further study of the building shape, as well as its surface structure, held great potential for future development.

Consequently, in 1967, with support from the National Endowment for the Arts in Washington, D.C., the School of Architecture at USC began studying the pueblos of the Southwest to discover how their shapes, as well as their structure, aided in mitigating the effects of daily and yearly thermal variations. We discovered some very sophisticated adaptations to climate from which we have been able to derive useful principles that correlate form with natural variation and apply to an urban context.

The pueblos of the Southwest employed techniques involving building shape and orientation, materials, and the spacing between buildings to ensure maximum heat gain in the winter and minimum heat gain in the summer. These techniques, adapted, augured an energy-conserving prototype as a model for the transformation of our existing cities (Figure 1).

In the same year faculty and students in the School of Architecture designed large-scale frameworks for potential development that would be cheaper to maintain. The shapes of these frameworks related to the dynamic geometry of the earth and sun (Figure 2). They were unique and as exciting within a modern context as the study of the historical pueblos had been. In the beginning, these studies generated pure shapes with prescribed properties in relation to solar energy. Our thought was that, with today's massive earth-moving equipment, whole sites might be altered to demonstrate energy consciousness. Alternatively, we could build large structures with desirable shapes and orientation that might contain whole communities and a diversity of functions. In any case, we found that a range of building scales and proper design were keys to energy conservation.

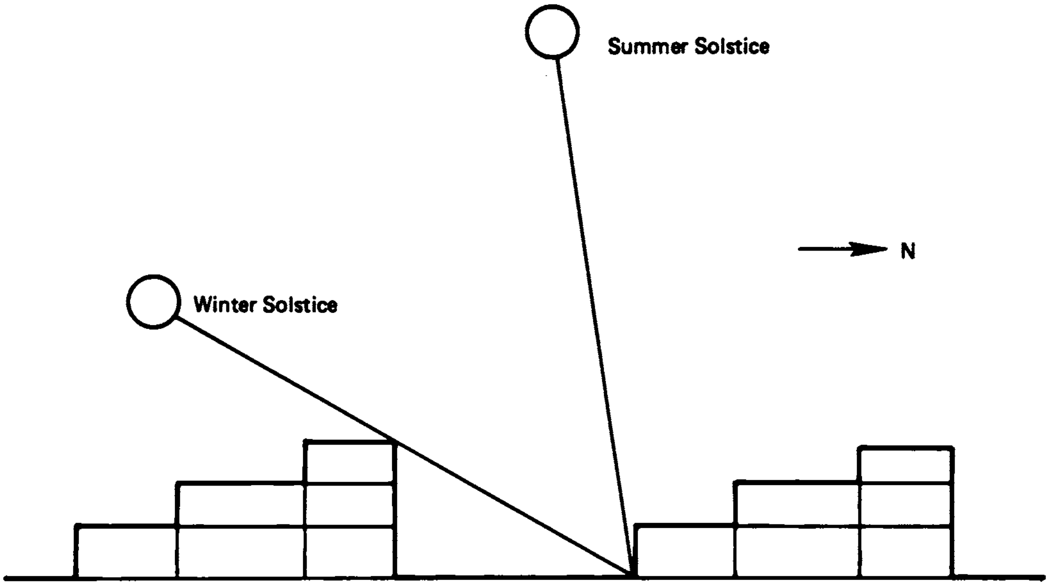

FIGURE 1 Acoma Pueblo, New Mexico. A typical section shows the critical spacing between rows of houses to ensure the "sun rights" of neighbors. Vertical surfaces of masonry with a high heat transmission coefficient and a high heat storage capacity receive solar energy most directly in winter. Horizontals of timber, reeds or cactus fiber, grasses, and clay with insulating properties receive solar energy most directly in summer. The combination of shape and orientation, materials, and spacing mitigates the effects of natural thermal variation.

The second step in our research identified those centers within Los Angeles that could be transformed. The forces that shape cities change with time. The tightly compacted and walled cities of medieval Europe derived their form from the need for defense, whereas the cities of the early industrial revolution clustered around mills and mines for easy access by road and, later, railroad. The modern city of this country consists of a quickly expanding grid laid over the irregular diagonals of traditional paths and riverways, which in turn have become concrete freeways designed to facilities our mobility.

In Los Angeles the urban form is clearly a diagram of transporation forces. Originally, the limits of its development were established by the extent of the Pacific Electric Rail System, which served the many settlements that later expanded and merged to become greater Los Angeles. The special character of these settlements derived partly from their regional roles and partly from their separation by farmland, especially orange groves. At the end of World War II, rapid development very soon filled in the spaces and the orange groves disappeared. Even so, the studies at USC have discerned that settlements are still identifiable and, if strengthened by diversified development, would provide a variety of urban centers distributed throughout the Los Angeles region.

Self-sufficiency would offer an alternative to traveling long distances to perform necessary daily transactions by developing commerce, housing, and industry in close proximity and on a smaller community scale. This transformation would not rule out the need for a regional transport

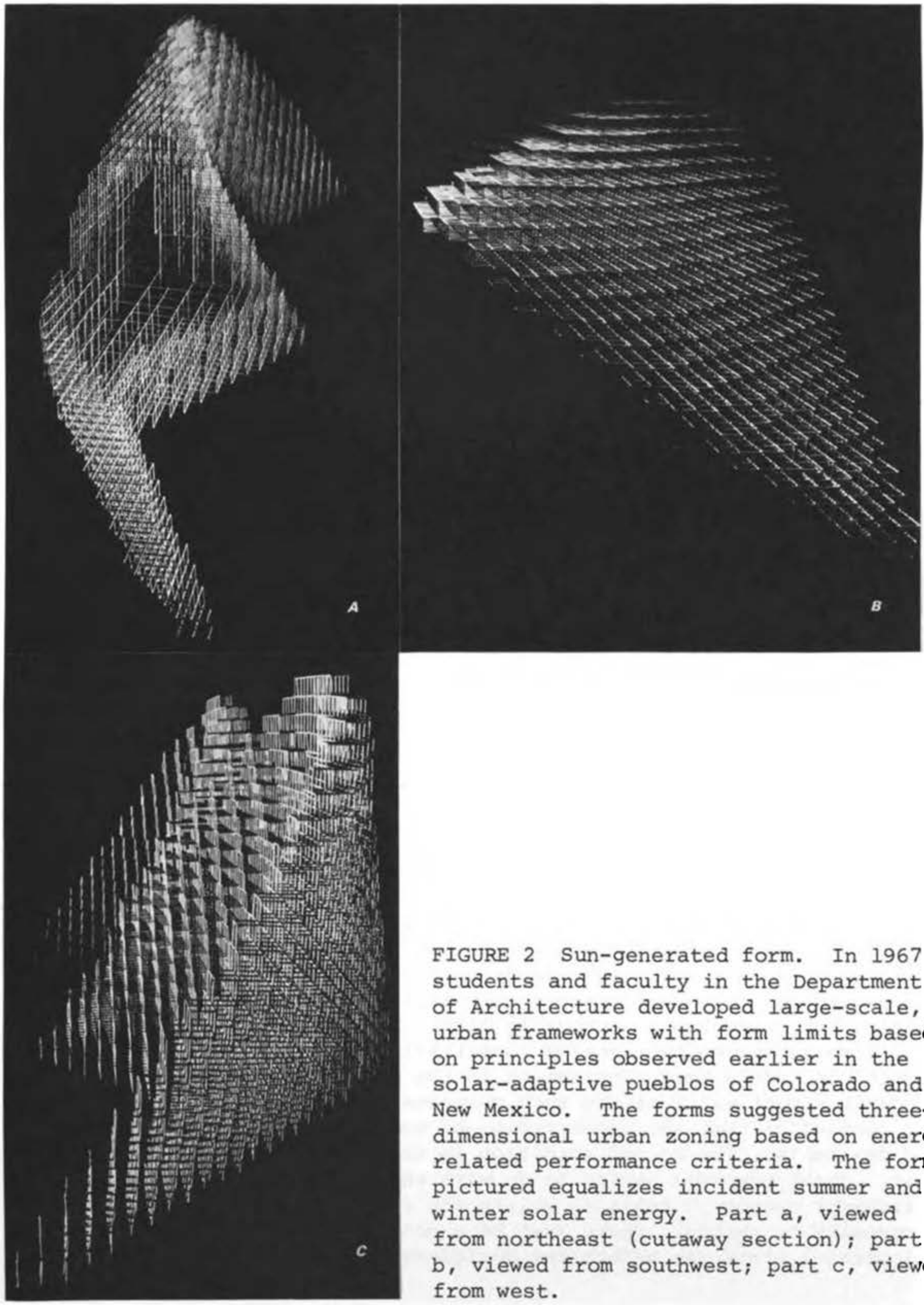

FIGURE 2 Sun-generated form. In 1967 students and faculty in the Department of Architecture developed large-scale, urban frameworks with form limits based on principles observed earlier in the solar-adaptive pueblos of Colorado and New Mexico. The forms suggested three-dimensional urban zoning based on energy-related performance criteria. The form pictured equalizes incident summer and winter solar energy. Part a, viewed from northeast (cutaway section); part b, viewed from southwest; part c, viewed from west.

system. We need that to allow us to take advantage of the rich resources that the region provides and to satisfy those who prefer to commute long distances. On a smoggy day in September or October, it is easy to believe that our survival may depend upon such decentralization. The resulting reduction in load upon the regional freeway system would permit an improved regional bus system to serve our needs more quickly and certainly at less expense than most of the public rapid transit systems presently being discussed.

The work at USC concerned with building and urban design for purposes of energy conservation has been undertaken for three reasons. First, our growth mode will change from one of simple expansion to one of transformation, with the possibility that new purposes can be assigned to this more complex form of urban growth. Such transformation is beginning to take place already in Los Angeles. The question is whether we will take advantage of the possibilities offered by transformation in order to realize some new purposes for growth through urban design.

Second, those purposes must have something to do with energy conservation. As far as we can tell, the scarcity of world resources is fast becoming the main governing factor affecting our policies and our designs. It must affect the development of any new urban arrangements. Conservation of resources, rather than their extravagant consumption, must govern our life-style, and such conservation does not necessarily translate into a poorer way of life. To the contrary, it may well be that energy-conserving urban design will provide greater diversity and greater choice than we enjoy at present.

Third, the building that through shape and structure distinguishes between north, south, east, and west for purposes of energy conservation will exhibit variety that translates directly into human choice. The housing development that recognizes in house design and spacing the differences between north and south slopes and east and west slopes, to take advantage of solar radiation for purposes of energy conservation, will provide a variety of housing and siting that translates into further human choice. The community that by means of design places housing, commerce, and industry into sufficiently close proximity that long-distance traveling may be avoided provides high-contact diversity and, therefore, the broadest human choice in daily life. Once it is unnecessary to spend time traveling each day, such time becomes available for recreation, cultural enrichment, or just getting to know the people next door! A living arrangement made in the light of principles of energy conservation will exhibit diversity on a comprehensible scale and will therefore contribute to a richer, more humane community life.

I firmly believe that energy conservation as a governing policy for growth can induce vast improvement in the quality of life. However, two conditions must exist before such purposes can be realized. The first is the conviction that the conservation of world resources is both necessary and desirable. The second condition is that urban change must be imminent. Fresh purposes having to do with energy conservation and community enrichment cannot be realized unless the city or parts of the city have a propensity to change. There must be a convergence of political and developmental pressures before the designers' work can bear fruit.

One very interesting result of a regional transportation study conducted in the School of Architecture between fall of 1971 and spring of 1973 suggests that USC lies in a part of the city with a unique willingness and propensity for change. This in turn indicates that the university is right in the middle of a vital working laboratory where change can be observed, quantified, and studied on a case-by-case basis. But there are further implications beyond education and research. If change is imminent in our part of the city, can purposes be assigned by intent? Can policies be agreed to? Can designs be generated, and can future urban development take place that would serve as a model for transformational growth throughout the region? Could we, for example, focus political, design, and economic resources on the problem of energy-conserving urban growth because, first, it would be the best thing to do for our city and, second, it would act as a guide to instruct national growth policies? I do not think such things are impossible.

We live in a time of ever-increasing public awareness. More and more we are conscious of how much our traditional attitudes toward growth are now costing us. Urban development, especially the kind that we have seen in the past 30 years, has benefited a small and private sector of the economy. We have created our urban arrangements cheaply. Over time the cost of maintaining these arrangements, to heat and cool them and to link them together with transportation, has cost a staggering two-thirds of the total national energy bill. This cost of maintenance has been borne by the public sector of the economy. This grow cheap/maintain expensive/private profit/public expense syndrome is what we are presently calling an energy crisis. What is required for the future is clear distinction between short-term and long-term costs. Initial development will have to be better designed or highly controlled and will have to cost more. The benefits will accrue over the long term with reduced maintenance costs. If further evidence is needed before we develop fresh purposes and transform our cities, I would emphasize that energy conservation can usher in a demonstrably better quality of life.

ACCESS TO SUNLIGHT

William Thomas

A sizable percentage of the popular literature on solar energy concerns solar rights, and the American Bar Foundation has received many inquiries concerning these rights. Often questions are asked by people who recently have heard something about a mysterious concept known as the "Doctrine of Ancient Lights" or about other deep, dark, and intriguing matters. The reason for their concern is a logical one--if you do not have access to sunlight, you are not going to have a very efficient solar energy system.

It is often necessary in legal discussions to place the issue in historical perspective. I will go back only about 700 years, to the year 1250, by which time the Latin maxim, *Cujus est solum, ejus est usque ad coleum et ad inferos,* had been incorporated in French, German, Roman, and Jewish law. The origin of the maxim is lost in antiquity; however, it means that "He who owns the soil also owns to the heavens and to the depths." The owner of the surface was considered to own all the way to the core of the earth and all the way to the heavens.

In 1586, a man named Bury in England lived in a house built near the property line between him and his neighbor and received light through the window on the neighbor's side of his house. His neighbor, who was named Pope, decided to build a house, also near the property line, that would prevent light from entering Bury's window. Bury went to court claiming that Pope should not be allowed to do that because Bury needed the light. The judge, in a very short decision, said that Bury had been foolish to build his house that near the property line and then cited the Latin maxim stated above. Ever since then it has been part of Anglo-American law.

Under this maxim, a person who fires a bullet across someone else's backyard is a trespasser. A long string of cases dating back through the centuries deal with overhanging tree branches, overhanging roof eaves, and this sort of thing, all holding that they constituted a trespass. In one case, a man having an altercation with his neighbor struck him across the fence between their properties and was charged not only with assault and battery, but also with trespass because his fist had penetrated the airspace over his neighbor's land.

It does not take much imagination to see that this is not at all compatible with aviation, and during the first half of this century the maxim was gradually weakened to provide for this new technology. Referring to the maxim, Mr. Justice Douglas, in the *Causby* opinion in 1946, explained: "But that doctrine has no place in the modern world. The air is a public highway, as Congress has declared. Were that not true, every transcontinental flight would subject the operator to countless trespass suits." Thus, the doctrine expressed by the maxim was by necessity modified so that the landowner has control upward only as far as is necessary for reasonable use and enjoyment of the surface as adjudged on a case-by-case basis.

Over the centuries, English judges developed another doctrine on a case-by-case basis known as the Doctrine of Ancient Lights. It is frequently mentioned in discussions on solar energy, but it is not the law in the United States. In summary, the doctrine states that the owner of the property is entitled to light across his neighbor's land up to the amount he needs for reasonable use and enjoyment of his own land if he has received that light for a specified period of time. In early common law this time period was only specified as "from the time when the memory of man runneth not to the contrary" or, as stated by another judge, "the time before which no man has memory," which merely means that light had been received for a very long time and that no one can remember anyone having blocked it. If the landowner had received light for that period of time, his neighbor would not be allowed to block it unreasonably. Evidently Bury could not prove that he had received light over this period and therefore could not prevent Pope from blocking it.

This standard was very vague indeed, and eventually the Limitation Act of 1923 established the time period at 20 years. It was extended to 27 years by the Right to Light Act of 1959.

The question remains, of course, of how to define unreasonable obstruction. Obviously, this must be decided on a case-by-case basis. English law cases now speak of "substantial deprivation" and point out that what matters is not the amount of light that is blocked, but the amount of light that is left. It's not difficult to visualize a circumstance where blockage of 20 percent of the light entering a window--a fenestration in early cases--would not really make a lot of difference and other circumstances where a 20 percent blockage would be unreasonable indeed. The problems associated with this doctrine are evident, particularly when one considers redevelopment of a complex urban area.

The British devised an ingenious aid in these cases that is called the "grumble line." The grumble line is the position in a room at which an ordinary person reading ordinary print grumbles and turns on the artificial light. A rule of thumb seems to be that if at least half of the room is between the grumble line and the window, there is a reasonable amount of light entering it. Engineers have come up with an empirical standard for the position of the grumble line that is equivalent to 1 footcandle on top of a desk 2 feet 9 inches tall. In conjunction with the 50-50 rule, if over half of the room at 2 feet 9 inches above the floor receives 1 footcandle, the room is considered to receive an adequate amount of light from the window to satisfy the Doctrine of Ancient Lights. A problem exists, of course, in that architectural styles change, as does the concept of reasonableness, causing all sorts of conflicts.

How could the British accommodate this doctrine with the increased utilization of solar energy for heating and cooling? Well, it has been suggested that they could modify the doctrine in several ways. One suggestion is that installation of a solar energy device creates a presumption at law that it has been there for 27 years, and thus its owner is assured continuous light across his neighbor's land. Another one, which is a little more reasonable, would be to require public notice, or actual notice given to all neighbors within a certain distance, of the plan to install a solar energy device. If no one files a complaint with the office handling this registration within a specific time period, a presumption is created that the solar energy device when installed has been receiving light across neighboring property for 27 years. The former suggestion seems a bit harsh, and the latter one apparently also would raise problems. I doubt that many people would fail to complain because of the substantial reduction in property values in urban areas where they would have to forego the right to build.

In the United States, some of our early colonial courts did accept the Doctrine of Ancient Lights because we brought the English common law across the ocean with us, but it was very shortly repudiated in New England as being inconsistent with a growing and dynamic country. The key American case on this point concerns two well-known resort hotels in Miami Beach, Florida. The Fountainbleau Hotel was constructed in 1954, and the following year saw the construction of the Eden Roc immediately north and adjacent to the Fountainbleau. Several years after construction, the owners of the Fountainbleau decided to add 14 stories on the northern portion of their property. Doing this would cast a shadow during winter for most of the afternoon over the swimming pool, sunbathing area, and cabana of the Eden Roc. Not surprisingly, the Eden Roc sued, claiming that they had a right to continue receiving the light across the Fountainbleau property and that the Fountainbleau should not be allowed to proceed with its plans because it was doing so with malice. A lower court actually enjoined the Fountainbleau on the principle that a property owner could not use that property to the injury of another, but an appellate court held otherwise. In essence, the judge said that although one person is not allowed to use his property in violation of the rights of an adjacent property owner, the Eden Roc had no rights that were being violated because the Doctrine of Ancient Lights is not law in the United States and no cause of action existed "regardless of the fact that the structure may have been erected partly for spite."

So the law in the United States now is well established that the surface owner has a right to receive light from that area of the sky directly above his property, but not to receive it across the land of his neighbors. This means that the adjacent landowner can construct a building, plant trees, put up fences, do anything he wants to even though it blocks the light that otherwise would impinge on his neighbor's land. There apparently is some question about the legality of fences built purely out of malice, i.e., spite fences, but different jurisdictions have different ideas about this.

Well, what can a property owner do to ensure lateral light? Rather than consider those legal aspects of a public nature (i.e., those that require ordinances or statutory authority), I will only very briefly mention here the subject of easement, which is defined as a right that one person has to use the land of another for a specific purpose.

An easement is a property right that has all the formal characteristics of any other legally recognized interest in real property. It is not just occasional permission to do something, or license, which can be revoked at will. For example, if you have a right-of-way across my land and I sell my land, the buyer takes it subject to your right-of-way. Similarly, should you sell your land, it includes the easement across mine.

The relationship between the two parties in an easement frequently is spoken of as a dominant estate and a servient estate. The former has control over the land of the latter. An affirmative easement is exemplified by a right-of-way that allows one party to cross or do something on the land of another. In a negative easement, one property owner precludes another from doing something on his own land that he would be allowed to do if it were not for the easement. For example, if I have an easement for light across your property, I cannot come on your property, but I can keep you from building above a certain height or from allowing your trees to grow to a certain height so that I will get light across your property, depending upon the terms of the easement. Affirmative easements can be created by prescription, which means, for example, that if one party has been crossing the land of another for a number of years, normally 20 years in most jurisdictions, and the landowner has not complained, then a right-of-way by prescription is established. The judges create what is called a "lost grant" to do this. Even though the trespasser cannot prove that he has an easement, the judges assume, for simplicity, that if he has been doing it for 20 years and the landowner acquiesced for 20 years, there must have been a grant at some time. It is similar to adverse possession, but it is adverse use. Light easements, however, are negative easements, and these cannot be acquired by prescription. They must be created expressly. This means that after constructing a solar energy device, the landowner cannot surprise his neighbors by claiming a negative easement because he has actually been using the light for other purposes for 20 years.

It might be economically feasible to purchase negative easements from adjacent landowners in rural areas, where the main use of the land now is agriculture and for the foreseeable future will be limited to that or other limited purposes such as single-story houses. But, for example, in downtown Manhattan a light easement would come very dear indeed, because it would be such a restriction on the possible use of that property that the owner would probably prefer to convey his entire interest in it. It might be possible, of course, to purchase an easement only at such a height above ground that it would become economically attractive.

There are several other aspects to this issue of acquiring lateral light. It would be preferable for the taxing authorities to assess land on its income-producing value rather than on what it could produce under what is sometimes called its highest and best use. Some states (e.g., Michigan) have attempted to preserve open spaces in this manner by taxing agricultural land in suburban areas at its actual income-producing value rather than at the value it would produce if developed. It might also be possible to place solar devices on a building at the north end of a north-south-oriented lot and then deed the south end of the lot to the public authority for a park, perhaps with an incentive of receiving in return a tax write-off somewhat in excess of the actual market value of the land.

Other legal issues that influence access to light are the law of weather modification and various laws concerning air pollution. An increase in air pollution, especially of particulate matter, would decrease solar insolation, and any relaxation in air pollution standards would decrease the overall contribution of solar energy devices. Changes in weather modification, such as increased precipitation patterns over long periods, would have the same effect. Also, we must keep in mind that the next step will be solar farms, and we will have to consider other laws, such as the National Environmental Policy Act of 1969 and the Multiple Use and Sustained Yield Act of 1960, that restrict land use either substantively or procedurally. When we get to that stage, we also will have to be more concerned with public utility and transmission laws.

In summary, I would only note that several centuries ago the chief reason for securing a right to light across a neighbor's land was for interior lighting. With the advent of inexpensive electricity, concern shifted from interior lighting to preservation of scenic vistas and other esthetic considerations. We now are refocusing our concern once again on light for interior lighting, heating, and other utilitarian purposes. I know there's a fine moral there somewhere.

II

Human Satisfaction

DESIGNING FOR SUNSHINING

Calvin W. Taylor

In the Architectural Psychology Program at the University of Utah, we continually seek realistic problems or, more accurately, challenging opportunities to engage our students in thinking, research, and training experiences.[1] "Designing for People," the name of my human engineering course, has essentially been the theme of all our work in architectural psychology and education at the university, as well as in our work with other organizations, in which we help to identify, cultivate, and utilize creativity and multiple talents.

We are starting our fifteenth year of path-creating work in architectural psychology and find that in recent years many others are entering into the field to work at it in their own ways. By the end of next year, we foresee that we will have produced 23 graduate degrees, including nearly a dozen doctoral degrees and well over 15 other research articles and products. We have taken as broad a perspective in performing our task as possible. In fact, in the individual selection and development of each graduate student, we believe strongly in strength through diversity.

MacKinnon's work shows that architecture represents a combination of the arts and the sciences, with most emphasis in the past being on the natural (especially the physical) sciences rather than on the human sciences.[2] In "Designing for People," we, of course, always try to add the human emphasis. This point is well illustrated by Eric Hoffer. By contrasting Mother Nature with human nature, he calls for greater emphasis on people in the designing of environments.[3]

Some writers recently have challenged present practices by describing them as "designing without people" (which is the form in which blueprints finally appear, i.e., without people). Another has talked about "designing for non-persons." We believe that the design processes should occur with man directly and primarily in mind rather than with man involved indirectly and removed one or more steps from the direct focus. In the latter case, a building might actually be designed "independently of man" or might even prove to be ill-designed for man.

My task also calls for a combination of arts and sciences. The problem with both sunlight and daylight is to draw upon what is known and to deal as effectively as possible with the unknowns. In all of my university classes, I assign my students the task of thinking about and talking about the unknowns in whatever human science field is being studied. In reading both the thoughts and the selected literature provided to me by my students, I sense that the topic of human satisfaction is far more full of unknowns than of knowns. They have uncovered far too much material on sunshine and daylight to be treated in this paper, let alone a consideration of other environmental variables.

Therefore, to give a simple nontechnical presentation that is sound and meaningful, my compromise is to point to some summary articles, such as two by D. Geoffrey Hayward,[4] and to encourage the reader to become aware of the topic and give more attention and effort to the challenges in it.

THE SUN SERVES MAN IN MANY WAYS

"Every child should have a place in the sun" is a way of saying that each person is precious. Perhaps a more complete title herein would have been "Designing Sunshining for People." A similar title, "The Sun in the Service of Mankind," was the topic of a UNESCO International Conference held in Paris in July 1973 (a brief report of this conference is given by Peter G. Burgess[5]).

The sun is valuable to man in numerous ways. By its shadows it serves as a clock for the time of day. It helps tell the day, the month, and the time of year by its location, angles, and extreme arcs and by its reflected sunlight from the moon.

The importance of sunshine in the lives of people is displayed in many different forms, such as in figures of speech, in other familiar quotations, in poems, and in lyrics to songs. Numerous examples will come to mind with just a few moments' thoughts. The composer Leroy Robertson often commented that music (either live or piped in) can be sunshine to people and that to him it provided the nearest thing to heaven on earth. Sunshine and darkness are contrasted many times and in many ways in literature. All humans, not only with their eyes, but also in psychological and figurative ways, experience daylight and darkness.

Some exciting, rare events of nature include occasional sunshine during rain and, more rarely, moments when rays of sunshine emerge briefly during a snowstorm. Colorful rainbows created by the sun have always delighted mankind. The most fascinating ones to me have been those that I have seen twice when looking down from an airplane in which full rainbow circles appeared (in fact, they consisted of two concentric rainbow circles around a third solid rainbow ball in the center). In seeking variety in colors and lighting within buildings, I have pondered whether appropriate designing might turn the sun's rays into rainbow rays with varying color effects throughout the indoors while the sun changes its angle of entrance.

Often at night man yearns for sunlight, whether it be the reflected sunlight from the moon, starlight from another more distant sun, or the next rising of the sun. Reflected sunlight from snow, from white clouds, from lakes, from buildings, and from the moon at night provides intriguing variations in sunlight experiences. Many claim that Lake Louise in the Canadian Rockies is the most beautiful sight on earth, especially when the mountainous west wall is reflected back onto the lake's surface at sunrise.

Historically, whenever a culture believed in multiple gods, the sun was usually one of them. In the Christian tradition, the Messiah is sometimes described as the "Light of the World." Easter usually connotes a bright sunny day with flowers blossoming from the sunshine of spring. The hope of Easter, concerning both life here and hereafter, is often celebrated at the dawning of the day with sunrise ceremonies in pleasant natural settings.

People of all ages seek sunshine in a variety of ways. Many visit beaches and sunny lands where they can soak up sunshine. J. Paul Getty, perhaps the wealthiest man alive, once announced that he was going to move from England to Southern California to obtain what money cannot buy--namely, sunshine and good weather, which are not characteristic of the long, inclement English winters. For people in confinement, such as in prison, access to sunlight can be highly important, since it may be their only view and contact with the world outside. There and elsewhere, a ray of sunshine may symbolize a ray of hope.

Most people find comfort by lying in the sun's rays. They can be energized by the sun, which represents a power and warmth source. Sunroofs on the tops of buildings, porches, and backyards enable people to relax and enjoy sunbathing.

SUNLIGHT AND HUMAN FUNCTIONING

There are many changes in sunlight, daily and yearly, that create great variety for people--the break of dawn and sunrise, the sun appearing in and behind clouds, shafts of light with different angles, rainbows that might occur across the day from sunrise to sunset, sunsets, twilights, eclipses, and various combinations of the above, together with weather and storm changes. With windowless buildings, these daily changes are largely "designed out" of the experience of those remaining indoors most of the day.

Some architects use the phrase "designing for visual release." Physiologically, the eye muscles relax if one is looking at a long-distant view, possibly leading to a more relaxed total state of the person. Visual release may provide a physiological release or relaxation of the eye muscles, together with a mental release that can free the mind to think. Consequently, if one is hemmed in by walls or trees or such, he may not easily or naturally obtain this released visual and psychological condition.

John Ott has expressed some unorthodox and controversial, but provocative ideas concerning sunshine.[6] He talks about how improper lighting (i.e., the lack of ultraviolet, blue, and red rays) stimulates hyperactivity, about antiseptic and antijaundice features of sunlight, about effects of sunlight upon temperature cycles and other human biological rhythms, about the sun's contribution to the manufacturing and absorption of vitamin D in the body, and about how short ultraviolet light apparently can trigger skin cancer. He also suggests that there are at least some small lighting effects on growth, reproduction, aggression, mood, school performance, and even sex determination. He notes that anything that filters out ultraviolet light provides a condition less beneficial for plant growth than would exist with unfiltered light and reports that in either natural sunlight or fluorescent plus long ultraviolet light male rats, mice, and rabbits tended to be docile, friendly, and motherly, whereas under standard fluorescent lights they tended to become irritable and cannibalize their young. He also claims that improved light led to better dental health and comments that "black" lights (consisting of long ultraviolet rays) were satisfactory to performance and wellness; that different light and different light compositions might affect glands, hormones, and enzymes; and that deprivation of ultraviolet light is antihealth and anti-well-being.

Louis Kahn, the famous architect, who died in 1974, was concerned with the way his designs interacted with light, and buildings can be designed to be great in absorbing, reflecting, and dispersing sunshine and daylight while being effectively displayed by sunlight.

The sun can have even greater effects when it falls upon people. This is especially true when all its positive effects occur both within and through people as absorbers, reflectors, and spreaders of sunshine and brightness. As a result of changes in sunshine and temperature, certain changes in the blood flow within individuals can create warmth and relaxing effects, which could spread to other individuals. To paraphrase some advice of the past, people shouldn't hide their daylight and sunshine under a bushel, and, therefore, designers should function so that these "people effects" can occur inside buildings as well as outside.

Sunlight can be a completely constant thing for many hours, as on a summer day, or can be highly variable with changing effects on man throughout some, if not most, days. Consequently, if inside lighting is to somewhat parallel outside lighting, it should not be continually static, but should have changing effects as in the lighting outdoors. Some of this will automatically occur if the building is designed to use the changing outdoor daylighting as part of the total indoor lighting system.

Various artificial lights may be potentially dangerous (although this knowledge is quite tentative). The suggestion is that the nearer artificial light approaches natural light, the better for man, and, conversely, the farther it varies from the character of natural light, the greater the potential dangers.

Daylight seems to be preferred over artificial light. It also is indirect and does not cast such clear shadows as does direct sunshine. Further, it tends to create a more relaxed, informal, natural situation than does artificial light. In the deep interior of houses, skylights or other unusual designs can bring more daylight illumination inside than can more typical designs.

THE NEED TO DESIGN OUT POTENTIAL NEGATIVE FEATURES

A question that may be raised is whether the natural environment and existing man-made environments are friends or foes to man. The challenge is whether it is possible to design and construct future man-made environments that are almost entirely friendly to man by minimizing or eliminating any features that are his foes.

One viewpoint is to design so that the natural processes (both psychological and physiological) of people grow and function naturally. An international conference has stated that when the sun is no longer of concern to life, then there is no living. The task is to design so that sunshining is central to living and so that its positive effects on people are maximized and its negative effects are reduced as much as possible.

A building is a special container that can be designed to shield persons from undesirable stresses of the raw natural environment. Buildings also can support and free man to focus his energies on his own productive work.

No doubt there are times when sunshine is welcome and other times when it is unwelcome, when shading from the sun is welcome or unwelcome, and when nighttime is welcome or unwelcome. In Fairbanks, Alaska, a flexible building could be designed to receive maximum exposure to winter sun and to be enclosed and shielded from too much exposure to a combination of dreary sunless days and a cold friendless outside environment by artificially producing a sunny, cheerful indoor environment.

Glass windows, while giving protection from the outdoors, should allow sunlight to enter into the lives of people indoors. Over the long range, the aesthetic and humanistic features can overshadow costs for the type of windows that will best serve this purpose. Glass windows also can provide needed insulation when properly designed. With appropriate types of window glass, windows can allow the favorable aspects of sunlight to be part of living indoors.

Natural lighting can create a feeling of informality in a space instead of a feeling of formality that does not quite permit people to relax. One feeling many people would like, although indoors, is to sense that they are near nature and close to earth.

People generally like sunshine, including the light, the brightness, the warmth, and how it can spur activities, health, and hope. They would like these same experiences inside buildings. However, they want to avoid thermal and visual discomfort. Too much light directly into the eye can be bouncing, glaring, tiring, and painful, as in cases of snow blindness. Nonetheless, in some cases the warmth or brightness of the sunlight can be more important to people than any visual or thermal discomfort. These situations argue for maximum sunshine inside buildings with adequate shading available (i.e., for whatever is needed in order to maximize the comfort and also to maximize the variability effects of the persons in buildings).

One effective approach through top-notch planning of a building site and layout is to capitalize on capturing daylight, but not direct sunlight, in order to minimize heating, lighting, comfort, and glare problems. At the same time one could still get all the best views possible through all windows that let in the daylight.

Architectural and engineering designers can and do study the arcs and angles of the sun from summer through winter and consider the site and building orientation in order to maximally capture and utilize sunlight and daylight in the interior of buildings. My class recently visited a house that caught the maximum lighting effects and maximum picturesque views through 270 degrees without direct sunshine causing an undue problem. (It also should be noted that light can be a bacterial agent for hygiene in the interior of buildings.) There are, however, potential dangers of direct sunlight and of daylight, including the sunburn (erythemal) effect from too much sunshine.

Lighting can reduce or increase the complexity and ambiguity of a situation, depending on the effects desired for people. For example, Henry Dreyfuss stated that the lighting for an evening party should be so designed that matrons look and feel like young debutantes.[7]

It is likely that some variety and complexity in lighting may be more stimulating than completely standardized lighting. Some use of the natural daytime lighting inside buildings with some variation to parallel outdoor daylight might be totally better for workers psychologically than continually uniform indoor lighting.

With a belief that the mood of a person can be affected by the presence or absence of sunlight and daylight, we have imagined putting a house on a pivot so it could be rotated, permitting different rooms to be in the sunlight as the tenants desired. This has led to the concept of a "room of moods" in which a person could modify the room (by controls or otherwise) to exaggerate a given mood or, alternatively, to bring about a change in mood. The room would be designed to increase the options and the freedom of choice by the user. Sunlight, daylight, rainbows, and other color changes could be very important variables in this room of moods. In this way a person could be master of his mood by being master of his environment, adjusting the environment so that it would be best for him and for his desired mood at that time. Such a manipulable environment is a direct contrast to the present built environment, which is usually designed by others and not under control of the users, so that the users have to adjust themselves to their environment (rather than being able to adjust their environment to themselves).

When our law school building was new, certain faculty members had first choice of the office they wanted--either an outside office with windows or a windowless inside office. All the first choices went to outside offices; yet after a while, all the shades and drapes had been drawn closed and were kept closed by those occupying outside offices--and who definitely still did not want to have a windowless inside office. If those in inside offices could have traded for an outside office, we wonder if they would also have fallen into the same rigid habit pattern of closing the drapes and leaving them that way.

An inadvertent event led to a unique design in our office building. After a truck accident wiped out the corner of the building, the walls were replaced with picture windows that let in the sun's warmth. This room has proven to be good for both humans and plants. Upon checking on the shortest day of the year when the sun was at its lowest arc, we found that its rays through these picture windows went clear across the room to a belt-high level on the opposite wall. For our office staff this provides an ideal sunshine room.

Building interiors should be designed to avoid overbrightness, glare of all kinds, and overreflection and overheating from sunlight and daylight. The inside lighting depends upon the daylight, the walls and windows, the outside weather, the temperature, the time of day, certain space conditions, and the comfort of the viewers. The latter depends upon whether the area in focus is brighter than the surrounding area by at least three times. Thus, the effectiveness of the lighting depends upon the illumination level, the brightness contrast, the sparkle of the sunlight, the reflections, the specific qualities of the lighting, the room luminance, the specific glare, and other distribution of lights.

Boyce has found that the appreciation of sunshine by building occupants is greatly dependent upon their activity.[8] Different types of lighting may be needed for visual production work, for thinking and meditation, for leisure activities, and for special purposes (like reverence in church). In a study of office occupants and their environments, he found that the overwhelming majority preferred daylight as their light source. Exposure to unchanging stimuli, especially in windowless buildings, has been shown to induce satiation and boredom.[9] I remember reading about a chemist who had worked for 15 years at a large chemical corporation. He recalled that he had done his best chemistry not when in his lab or when working at his desk, but rather when he had turned away from his desk, put his feet on the windowsill, and was gazing outside through his window.

Throughout history man has marvelously survived and functioned in different regions and climates. Nonetheless, I suspect that he has been most fruitful in the middle latitudes where the four seasons are most noticeable and, oddly enough, where the climate and the sunshine effects are more widely variable than in either the equatorial region or the extreme polar region.

A complicating factor is that the pleasantness of an experience may be associated psychologically with the day having been a good one. New Englanders who went to the beach for an enjoyable outing later recalled that it was a nice sunny day, even though the official weather report indicated that it had rained and generally had not been good weather.

SOME GENERAL COMPLEXITIES AND CONSIDERATIONS IN DESIGNING

I am persuaded that the design field is a multidimensional one, with each of the vast number of relevant variables being complex and complicated to us at our present level of insight. First, in the primary dependent variables of human performance and also human satisfaction, we find multidimensions. Second, there are a great number of complex independent variables with which the designer can be directly concerned as he tries to bring about the desired results in human performance and human satisfaction. To further complicate matters, there are individual differences between persons and also differences within a person as time and conditions change. As a consequence, one cannot solely design for the typical person under typical conditions.

Thinking geometrically or vectorially, the designer is involved in a many-dimensional mathematical space of variables. At times in such problems, the designer may have to plan and design using approaches more crude and less precise than he ideally might wish. Perhaps the optimum for performance is not a point or even a very narrow range but rather is a wide region in this total space. From this perspective the task is to locate this region and then to design so that the whole optimal region becomes available through daily natural changes of sunlight and daylight, as well as through the changes under the manipulable controls of the ultimate users of the building.

We have learned from hospital adminstration that the building is a small part of the long-range cost of an organization (i.e., the operating of a hospital for 3 years will approximately equal the building costs; furthermore, the personnel costs in operating the hospital will equal the cost of the building in less than 5 years). The building, although quite an expensive item in itself, can, if properly designed, be a most important tool in the hands of the personnel running the organization to facilitate the organization's doing the best work possible. On the other hand, it may present barriers that hinder human performance. Cost factors may too often predominate, whereas if one takes the larger view of considering a long period of time, then aesthetic, humanistic, and performance factors, including designing for sunshine and daylight, often should overshadow initial costs in importance.

SOME FINAL SUNSHINING SPECULATIONS

As a closing point, let me tell about my imagination soaring on sunlight. There is plenty of sunshine any morning or afternoon if you go high enough directly upward. The challenge is somehow to capture the unlimited sunlight (which in daytime is always there high above the clouds and smog) and somehow transmit it into our buildings, regardless of the natural and man-made barriers that must be pierced. In this way we could extend the daily influence of the sun by lengthening the daylight period as well as the sunny seasons, even in the polar regions in the winter. Someone should somehow do something analogous to what we can now do with radio and television (i.e., we reflect waves from outer-space vehicles back to earth--they can be piped into any place on earth, outdoors or inside any building, and the initial sound and picture are effectively transmitted so that they approximate the full experience at the original source). We need to find ways to pierce the barriers that prevent daily sunlight, daylight, and solar energy from reaching people on earth, both outside and inside buildings.

After these many speculations, my last thought is how sorely we need a greater feel of the total phenomena of sunshine and daylight and their effect on man. We need to know much if we are to design buildings to be best for people as far as utilizing and managing sunshine and daylight are concerned.[10]

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WINDOWS AND HUMAN SATISFACTION

Belinda Lowenhaupt Collins

The current energy crisis has forced us to realize that many buildings waste a considerable amount of energy. Although unnecessary heat gain and loss can occur at many locations throughout a building, one architectural feature that has come under specific attack is the window. The criticism is particularly strong because, with the trend toward sealed buildings having mechanical ventilation and artificial illumination, windows sometimes appear to be an unnecessary frill. Various analyses of energy consumption by "typical" buildings suggest that these structures would function much more efficiently if they were windowless.

In all these calculations, human requirements or desires have been virtually ignored. Yet, the suspicion arises that people do not find a windowless structure to be the most desirable building design. It is possible that windows are not a mere "architectural frill" and that they continue to fulfill some human need beyond the provision of light and fresh air. In order to deal with questions about possible human requirements for building fenestration, a review of the literature on human reaction to windows was undertaken by the National Bureau of Standards, and I shall present some of the findings from this review, along with some implications for further research.

Perhaps the best place to begin a study of human reaction to windows is with an evaluation of the response to spaces without windows. In this way one can determine if windows are considered desirable by those who do not have them. Although totally windowless buildings are somewhat rare, windowless interior rooms within otherwise windowed buildings are quite common. As a result a great many people spend a considerable amount of time in windowless places. What is their reaction to these?

The research on psychological reaction to the windowless environment has generally dealt with one building type at a time, such as schools, offices, and hospital wards. As yet, there has been no study employing the same research methodology to a variety of windowless situations.

The windowless school, originally constructed for safety in the event of nuclear attack, is considered to have the following advantages: (1) the elimination of outside distractions for the children, (2) greater wall space for bookcases and blackboards, (3) easier maintenance of heating and cooling, and (4) reduced vandalism and window breakage.[1] Opponents of the windowless school counter these arguments with statements about possible psychological damage from confinement in a "windowless box," away from the educational experiences of the outside world.[2]

Numerous studies were undertaken to evaluate the impact of the windowless school upon learning performance and general attitudes. Two studies, conducted in the early 1960's in California[3] and Michigan,[4] found no significant difference between the performance of students in classrooms with windows and in classrooms without windows. The findings about attitudes toward the windowless classroom were less clear-cut. In the California study, the teachers reported that the children in the windowless classroom appeared more passive and withdrawn, but about half the pupils stated that they liked the windowless classroom. In the Michigan study, perhaps the most significant findings were an increase in absences by kindergartners in windowless classrooms and a marked increase in preference for the windowless situation by the teachers (who had expected to dislike it). A third survey of a number of schools in California revealed much stronger preference for windows in classrooms. In all cases, though, once the windowless classroom had been experienced, both teachers and students found it to be less adverse than expected. However, only the teachers in one of the studies expressed any real enthusiasm for the windowless classroom.

Although windowless interior offices (in buildings with windows) are so common as to be unremarkable, there has been very little investigation of the attitudes toward them. A general feeling is that people do not particularly care for them, but little formal research into this question has been done. One detailed study of more than 100 office personnel was conducted in Seattle.[5] The subjects in this study were all female clerical personnel who worked in small offices by themselves or with only one other person. Each subject was given a questionnaire about her reaction to her office and working environment.

The results of the questionnaire revealed that, although the subjects expressed general satisfaction with their working conditions, 90 percent were dissatisfied with the lack of windows and almost 50 percent thought that this affected them or their work adversely. When the subjects were asked what they disliked most about their offices, 35 percent responded spontaneously, "The absence of windows." The subjects volunteered the following reasons: (1) no daylight, (2) poor ventilation, (3) a desire to know the weather conditions, (4) a desire for a view out, (5) feelings of claustrophobia and confinement, and (6) feelings of depression and tension.

While most investigators have assessed reaction to windowless spaces simply by asking people (by means of questionnaires), a physician in Arkansas examined differences in the behavior of two groups of patients, one in an intensive-care ward with windows and the other in one without windows.[6] Aware that some patients can experience a very brief psychotic episode known as postoperative delirium following surgery, this physician had both groups of patients examined for symptoms of this disorder.

Although both groups of 50 patients were similar in age, sex, general physical condition, type of surgery, and treatment, more than twice as many of the patients in the windowless intensive-care unit developed postoperative delirium. Furthermore, a greater number of patients in this ward developed postoperative depression and similar adverse psychological reactions. As a result, it was concluded that the absence of windows appeared to exert an excessive amount of stress upon an already stressed patient.

The reaction to windowless buildings is not always unfavorable, however. Windowless museums, theaters, restaurants, and department stores are only a few of the numerous building types in which the absence of windows is rarely criticized or even noticed.[7] The activities of individuals utilizing these structures are usually sufficiently demanding and absorbing that windows do not seem to be required for escape or additional stimulation. On the other hand, small single-person offices and hospital wards seem to require windows to relieve the monotony of the situation. These observations suggest that the kind of activity, the size of a space, the opportunity for personal interaction, and the number of occupants may determine the reaction to the absence of windows in a room. Of course, personality differences also can influence the reaction. It appears that the smaller and more restricted a windowless space is, the more repetitive and monotonous the task is, and the more reduced the freedom of movement and interaction its inhabitants have, the more unpleasant and oppressive it will be. Such static and confined situations appear to require the stimulation of windows for momentary escape and excitement.

Although some windowless situations are much more oppressive than others, people are rarely enthusiastic about them. Tolerance or dislike appears to be the rule rather than the exception. It is clear that the needs of the users, as well as the nature of the task, ought to be carefully evaluated before a building is designed windowless. Despite their convenience, windowless buildings should not be considered as the only design solution for energy conservation.

In the preceding portions of this paper, I have discussed the general desirability of windows for people in buildings. Examination of the reaction to windowless buildings only hints at the benefits provided by windows, however. There is still a need to answer questions such as: Why do people continue to want windows? What benefits do they provide? Are some functions of windows more desirable than others?

Researchers of these and other questions have tended to pick one aspect of a window that they consider important and study it in detail. As a result, there are almost no investigations into the overall impact of a window, but numerous studies of selected aspects. I shall deal with three of these: view, daylight, and sunshine.

In all the investigations of attitudes about windows, one aspect that consistently emerges as important is that of view. Further studies have attempted to define the factors that characterize a good view and the relative importance of view itself.

The importance of view is generally not found to be the most important characteristic of a pleasant office environment.[8] Yet, on the other hand, only a very small percentage of subjects claim that "a good view out" is unimportant or unnecessary. The importance of view probably becomes greater if one does not have one.

Although the presence of any view, even one of a nearby wall, may be preferable to none at all, there must be certain elements that characterize a "good" view. People seem to desire dynamic information as well as static beauty. An English study of the importance of view to office workers revealed that a good view (according to these subjects) should contain information about the sky, the horizon, and the nearby ground.[9]

It also should supply information about a variety of different, changing events. Furthermore, it should contain both man-made and natural objects. Similar results were obtained in another British study that asked subjects to rate numerous slides seen through a simulated window as good or bad.[10] Again, the complexity of the scene, the balance between natural and urban elements, and the possibility of dynamic action emerged as desirable. Slides containing variations in color, brightness, shape, texture, and sky quality were rated as highly desirable. The results from this study suggested, however, that some views can be too complex--too exciting. There may be an optimal level of stimulation beyond which a scene becomes annoying rather than pleasant. In addition, view appears to be essential in determining preferred window size and shape.[11]

In addition to view, windows also provide illumination in the form of both sunshine and daylight. Each of these appears to have a unique psychological impact upon people in buildings. Daylight, of course, is still used as an illuminant in some cases. This is perhaps more true in England, where elaborate systems for integrating both artificial and natural daylight have been developed.[12] The usefulness of daylight as the sole illuminant appears to be limited by the depth of a room. Yet, daylight through windows can still contribute to the quality of the overall illumination.

The few surveys that have been done on lighting preferences have revealed a widespread belief that daylight is a better light source than artificial light.[13] Furthermore, the majority of subjects state a definite preference for daylight in their offices. A frequent complaint about windowless offices is the lack of daylight and the total reliance upon artificial lighting.

In addition to providing illumination, daylight also introduces a certain element of change into an office. The lighting becomes dynamic; it has variety during the course of a day.

Another element of illumination provided by a window, which also introduces change within a room, is sunshine. More variable than daylight, sunshine appears to be highly valued by many people in a manner different from daylight.

As with daylight, almost all the research into attitudes toward sunshine has been done in England and Northern Europe. As a result, the findings should be viewed with some caution because they may not be strictly applicable to all areas in the United States. Three surveys of housewives in England, Holland, and Switzerland revealed that 75 to 90 percent of those questioned expressed a desire for sunshine in their homes.[14] The Dutch subjects even said that they would sacrifice a good view out for sunshine. In other studies, however, view emerges as more desirable than sunshine.

The desire for sunshine appears to be strongest in the home. A survey of the occupants of four building types revealed that sunshine was desired by 90 percent of those in homes and hospitals, by 70 percent of those in offices, and by only 40 percent of those in schools. Furthermore, sunshine was considered to be a nuisance by 60 percent of the hospital staff, 50 percent of the school occupants, and 25 percent of the office personnel, but by only 4 percent of those in homes.[15] The investigators suggested that the differing reactions to sunshine were due to an individual's ability to use shading devices to control the heat and glare from the sun. Furthermore, annoyance due to the sun also may be related to a person's activity and freedom to move about and escape the thermal disadvantages of the sun. Evidently, the more confined a person's activity, the more severe the adverse effects of the sun. The desire for sunshine in a room, then, appears to be balanced against a desire for thermal comfort. It is possible that a view of sunshine outdoors would satisfy the desire for sunshine, particularly in working environments, but little research has been done in this area.

Although the relative importance of sunshine, view, and daylight may vary with both climate and culture, there appears to be no question that people in buildings continue to find windows highly desirable. Windows provide a view out, allowing a person within a building to have both information about external events and momentary emotional release from internal happenings. The changes in both sunshine and daylight during the course of a day can add a dynamic, vital quality to the internal environment of an office. In summary, while there can be disadvantages to windows, such as undesirable heat gain and loss, glare, and lack of privacy, the advantages of view, sunshine, daylight, and spaciousness appear to outweigh them substantially. As a result, other options in building design for reducing energy consumption, such as double or triple glazing, external and internal shading devices, special solar glass, or reduced window size, should be investigated.

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III

Available Solar Data

AVAILABLE SOURCES OF INSOLATION DATA

John I. Yellott

When the Building Research Institute (BRI) held its 1962 conference to consider solar effects on building design, only four basic sources of solar radiation data were available:

1. The fundamental studies of the solar constant and the solar spectrum that had been carried out by the Smithsonian Institution for half a century under the direction of the late Dr. C. G. Abbot.[1]
2. The standard solar radiation curves published by Professor Parry Moon in 1940.[2]
3. Papers in the *Transactions* of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), formerly the American Society of Heating and Ventilating Engineers (ASHVE) and the American Society of Heating and Air-Conditioning Engineers (ASHAE), and in the ASHRAE *Journal*, by Professors Jordan, Liu, and Threlkeld of the University of Minnesota.[3]
4. Hour-by-hour values for direct and diffuse radiation on August 1 at 40° north latitude derived from Moon's data and from actual measurements by the ASHVE staff, then located in Pittsburgh, for "clean" and "industrial" atmospheres.[4]

The proceedings of the 1962 BRI conference presented a valuable summary by Professors Jordan and Liu of more comprehensive information, including an illustration showing that the average atmospheric transmission coefficient for the continental United States was approximately 0.55.[5] Jordan and Liu based their estimate upon the solar constant in use at that time, Johnson's value of 442.4 Btu/h/ft^2 (1,395 W/m^2)[6] and would probably now raise the coefficient to approximately 0.57.

Before publication of the *ASHRAE Guide and Data Book* in 1963, the ASHRAE Technical Committee on Fenestration (currently designated TC 4.5) concluded that the data then available for estimating solar heat gains through fenestration were inadequate and that procedures were not sufficiently precise to cope with the reflective glazing materials then becoming available.[7] Donald J. Vild had evolved an entirely new procedure that tremendously simplified the problem of estimating the solar and total heat gain through fenestration and his procedure was incorporated into the 1963 *ASHRAE Guide and Data Book*.[8] Vild's procedure involved the use of a solar heat gain factor (SHGF) that is actually the solar heat gain (due to transmission and inward flow of absorbed radiation) for any given date, latitude, time, and orientation through unshaded, clear, double-strength window glass, expressed in Btu/h/ft^2. (To convert SHGF to Sl units, W/m^2, multiply the U.S. units by 3.1524; to convert SHGF to total insolation, including 20 percent ground reflection for vertical surfaces, multiply the SHGF[9] by 1.15, which is the ratio of the actual insolation to the radiant energy admitted through the reference glass by transmission and inward flow of the absorbed radiation.)

The 1963 *ASHRAE Guide and Data Book* contained SHGF data only for the months of July through December and for latitudes from 24° to 48° N by 8° intervals. The data were compiled by Mr. Vild and his staff using Moon's values of direct normal insolation versus solar altitude. For the 1965 revision of the *Guide,* which became the first edition of what is now the *ASHRAE Handbook of Fundamentals,* a new procedure was adopted, which is described below.

EVOLUTION OF THE 1967 AND 1972 ASHRAE INSOLATION DATA

There are two principal methods of predicting clear-day insolation at the earth's surface for any given latitude, date, time of day, and surface orientation. The first involves working downward from the extraterrestrial insolation, I_o, based upon the best available value of the solar constant, I_{sc}, and the variations in the earth-sun distance that occur due to the earth's elliptical orbit (Table 1), where the distance is expressed in astronomical units (AU) of 92.956 • 10^6 miles or 1.496 • 10^8 km.

TABLE 1 I_o, I_{sc}, and Earth-Sun Distances Throughout the Year

Dates	I_o (Btu/h/ft^2)	I_{sc} (W/m^2)	Distance (AU)
January 1	443.79	1,399	0.9834
January 4[a]	444.11	1,400	0.9831
February 1	442.20	1,394	0.9852
March 1	437.13	1,378	0.9909
April 4[b]	429.20	1,353	1.0000
May 1	422.86	1,333	1.0075
June 1	417.56	1,316	1.0138
July 1	415.24	1,309	1.0167
July 5[c]	415.24	1,309	1.0167
August 1	416.51	1,313	1.0151
September 1	421.27	1,328	1.0094
October 5[b]	429.10	1,353	1.0000
November 1	435.54	1,373	0.9927
December 1	441.56	1,392	0.9859

[a] Perihelion: earth-sun distance is at its minimum.
[b] Earth-sun distance is 1.0000 AU; $I_o = I_{sc}$.
[c] Aphelion: earth-sun distance is at its maximum.

The second method of estimating the rate of insolation involves the use of actual measured values on the earth's surface and endeavoring to correlate them with the variations in moisture and dust content that are largely responsible for the monthly changes in atmospheric transmission reported earlier by Threlkeld and Jordan.[10]

In either case, it is necessary to determine the altitude (β) of the sun above the local horizon and the solar azimuth (ϕ), reckoned from the south in ASHRAE tabulations rather than from the north as in navigation tables. These angles can be calculated readily using the following equations related to the time of day (solar, not daylight saving or local standard time), the date (which gives the solar declination), and the local latitude:

$$\begin{aligned}\text{sin altitude} = {} & \text{cos latitude} \cdot \text{cos hour angle} \cdot \text{cos declination} \\ & + \text{sin latitude} \cdot \text{sin declination},\end{aligned} \tag{1}$$

and

$$\text{sin azimuth} = \text{cos declination} \cdot \text{sin hour angle/cos altitude}, \tag{2}$$

where hour angle = 0.25 • number of minutes from solar noon.

The ASHRAE publications give values of altitude, azimuth, and direct normal insolation for the 21st day of each month--a date that has particular significance in December and June (the winter and summer solstices) and March and September (the spring and fall equinoxes). Since there seemed to be no good reason for using other dates for other months, the 21st now has been adopted throughout the year. The declination varies slightly from year to year, but this variation is small and the values given in Tables 2 and 3 may be used with confidence.[11]

Solar time must be used in these calculations (rather than local standard time), and the almost universal use of daylight saving time in summer presents a hazard that must be considered in finding apparent solar time (AST) from the following equation:

$$\begin{aligned}\text{AST} = {} & \text{local standard time} + \text{equation of time} \\ & + 4 \cdot \text{number of degrees of longitude east or} \\ & - 4 \cdot \text{number of degrees of longitude west} \\ & \text{of the local standard time meridian of longitude},\end{aligned} \tag{3}$$

where the equation of time = the number of minutes that solar time is faster (+) or slower (-) than civil or mean time as told by a clock that runs at a uniform rate. The longitudes of the six standard time meridians that affect the United States are: eastern, 75°; central, 90°; mountain, 105°; Pacific, 120°; Yukon, 135°; and Alaska-Hawaii, 150°. Table 2 presents the declinations and the values of the equation of time for the 21st day of each month.

Table 3 gives the parameters that are used in the ASHRAE method of estimating clear-day insolation for the 21st day of each month. This procedure is based on the fact that the intensity of the direct solar beam, on a surface normal to the beam, depends upon the clarity of the

TABLE 2 Solar Data Pertaining to the 21st Day of Each Month

Month	Year Day	Declination Degree	Equation of Time (min)	Solar Noon
January	21	-19.9	-11.2	Late
February	52	-10.6	-13.9	Late
March	80	0.0	-7.5	Late
April	111	+11.9	+1.1	Early
May	141	+20.3	+3.3	Early
June	173	+23.5	-1.4	Late
July	202	+20.5	-6.2	Late
August	233	+12.1	-2.4	Late
September	265	0.0	+7.5	Early
October	294	-10.7	+15.4	Early
November	325	-19.9	+13.8	Early
December	355	-23.5	+1.6	Early

NOTE: Data from *ASHRAE Handbook of Applications* (New York: ASHRAE, 1974), chap. 59, p. 59.3.

TABLE 3 Parameters Used to Estimate Solar Radiation Intensity

		Parameter			
		A		*B*	*C*
Date	Declination[a]	Btu/h/ft^2	W/m^2	Air Mass^{-1}	Dimensionless
January 21	-20.0	390	1,230	0.142	0.058
February 21	-10.8	385	1,215	0.144	0.060
March 21	0.0	376	1,186	0.156	0.071
April 21	+11.6	360	1,136	0.180	0.097
May 21	+20.0	350	1,104	0.196	0.121
June 21	+23.45	345	1,088	0.205	0.134
July 21	+20.6	344	1,085	0.207	0.136
August 21	+12.3	351	1,107	0.201	0.122
September 21	0.0	365	1,151	0.177	0.092
October 21	-10.5	378	1,192	0.160	0.073
November 21	-19.8	387	1,221	0.149	0.063
December 21	-23.45	391	1,233	0.142	0.057

NOTE: Data adapted from D. G. Stephenson, *Tables of Solar Altitudes, Azimuth, Intensity, and Heat Gain Factors for Latitudes from 43 to 55 Degrees North*, Division of Building Research Technical Paper 243, NRC 9528 (Ottawa: National Research Council of Canada, 1967).

[a] The declination for a given date varies slightly from year to year; therefore, the values given above do not agree precisely with those used in Table 2. These small differences do not produce any significant errors in the values found by using Eq. (4).

atmosphere and the length of the solar beam's path through that atmosphere. The major absorbing components of the atmosphere are water vapor, ozone, CO_2, and dust particles. The variations in the earth-sun distance, given in Table 1 in terms of astronomical units (the average earth-sun distance), also are significant since the actual extraterrestrial intensity varies inversely as the square of the earth-sun distance.

The length of the solar path generally is expressed in terms of the air mass, m, which is the dimensionless ratio of the actual mass of atmosphere through which the beam must pass to the shortest possible path at the given location. This would occur if the sun were directly overhead. For solar altitudes greater than about 15°, $m = 1/\sin$ altitude. The air mass also is affected by the elevation of the location in question, and, for elevations significantly above sea level, $m = 1/\sin$ altitude $\cdot$ local barometric pressure/barometric pressure at sea level. Beyond the earth's atmosphere, $m = 0.0$ since there is obviously no more atmosphere to impede the passage of the sun's rays.

More than a century ago, the French astronomer Bouguer concluded that the intensity of the direct solar beam could be expressed by the equation:

$$I_{DN} = A/e^{B/\sin \text{ altitude}}, \qquad (4)$$

where A = apparent direct normal intensity for the given month and date, beyond the earth's atmosphere (Figure 1); B = atmospheric extinction coefficient, which varies seasonally as the amount of moisture changes; and e = base of natural logarithms = 2.71828.

Using U.S. Weather Bureau data for horizontal insolation at the earth's surface in some 70 locations through the United States and southern Canada, values of A and B were calculated for each month[12]

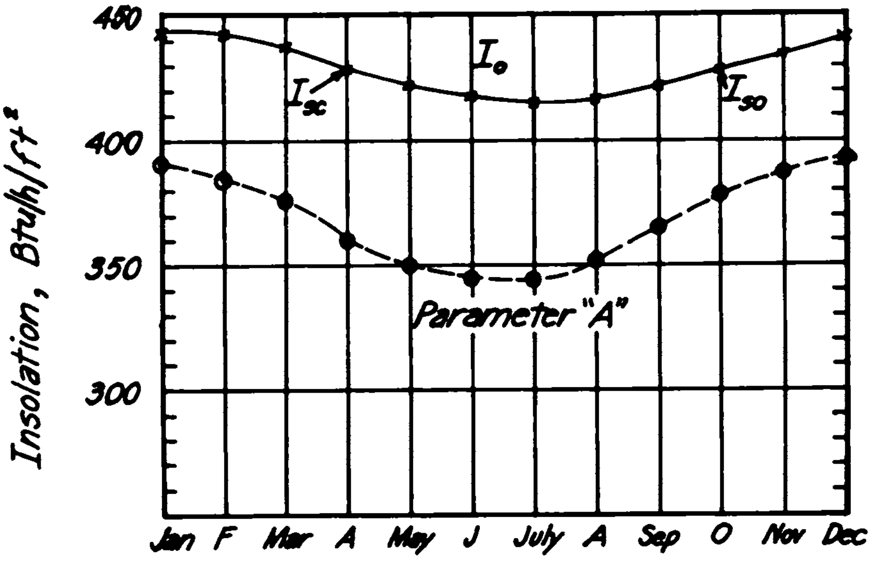

FIGURE 1 Annual variation of extraterrestrial insolation and parameter A (I_o and I_{sc} are adapted from Thekaekara[6]; parameter A is adapted from Stephenson)[12].

and were in good agreement with the actual data. Table 3 presents these values, with a third parameter, *C*, which is the ratio of the diffuse radiation falling on a horizontal surface on a clear day to the direct normal insolation at the same time and place.

In the Threlkeld and Jordan procedure for estimating insolation,[13] from which the ASHRAE values were derived, a basic atmosphere at sea level is defined as containing 2.5 mm of ozone, 200 dust particles per cm^3 (a relatively clear air condition), and an amount of precipitable water vapor which varied month by month approximately as shown in Table 4 and Figure 2. These humidity values are averages for the entire continental United States; the very high humidities experienced in midsummer are primarily responsible for the fact that, for the same solar altitude, the direct normal insolation is much higher in winter than in summer.

TABLE 4 Variations in Average Atmospheric Precipitable Moisture Content

Month	Inches	Millimeters
January	0.32	8.13
February	0.32	8.13
March	0.35	8.89
April	0.50	12.7
May	0.75	19.1
June	0.97	24.6
July	1.10	27.9
August	1.09	27.7
September	0.93	23.6
October	0.61	15.5
November	0.45	11.4
December	0.35	8.9

NOTE: Data from U.S. Weather Bureau, *Climatic Atlas of the United States* (Washington, D.C.: U.S. Government Printing Office, 1968).

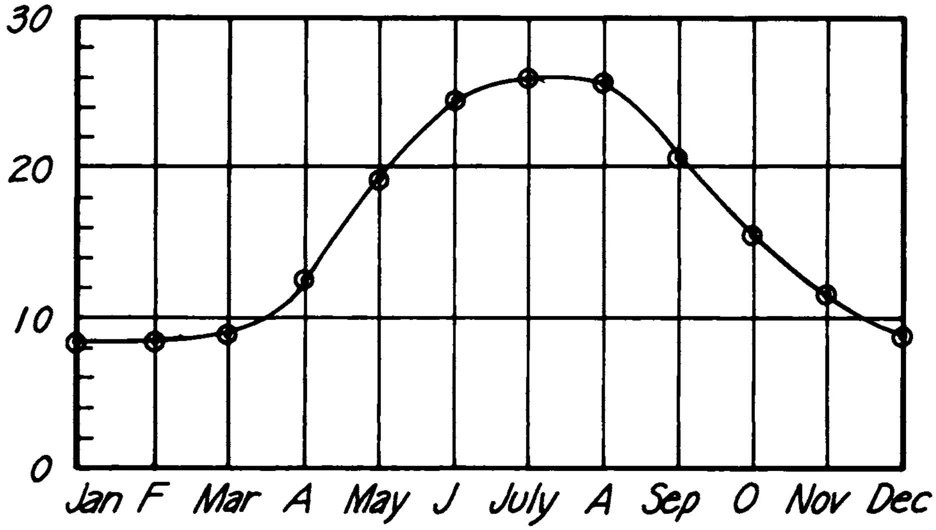

FIGURE 2 Variation of precipitable moisture in average U.S. atmosphere throughout the year (adapted from Threlkeld).

ASHRAE STANDARD VALUES FOR SOLAR ANGLES AND DIRECT NORMAL INSOLATION

Using Eq. (1) and Eq. (2) to find the solar angles for the average declinations corresponding to the 21st day of each month, computer programs for finding the direct normal insolation for each hour of the day have been developed at the National Research Council of Canada's Division of Building Research[12] and the University of Florida. The parameters *A* and *B*, given in Table 3 for each month, are averages, and the resulting values of I_{DN} require some correcting to account for the higher-than-average humidity along the Gulf Coast and the much lower-than-average amount of moisture in the atmosphere above the high and dry mountain states. These variations are accommodated to a satisfactory extent by the use of "clearness numbers" (Figure 3) derived by Threlkeld and Jordan.[15]

The 1967 and 1972 editions of the *ASHRAE Handbook of Fundamentals* gave values of the solar altitude, β, and the azimuth, ϕ (Figure 4), and the direct normal irradiation at sea level, I_{DN}, at latitudes from 24° to 56° N, by 8° intervals, for the 21st day of each month. The Canadian publication by Stephenson[12] gives the same information for latitudes from 43° to 55° N by 2-degree increments, and it also includes values of I_{DM} in SI units, watts per square meter (W/m^2).[16] The 1974 *ASHRAE Handbook of Applications*[17] gives the same information, as well as total insolation, direct plus diffuse, for south-facing surfaces tilted at the following angles for each latitude, L; 0° (horizontal); L - 10°; L°; L + 10° and L + 20°; 90° (vertical).[17] These will be particularly valuable to the

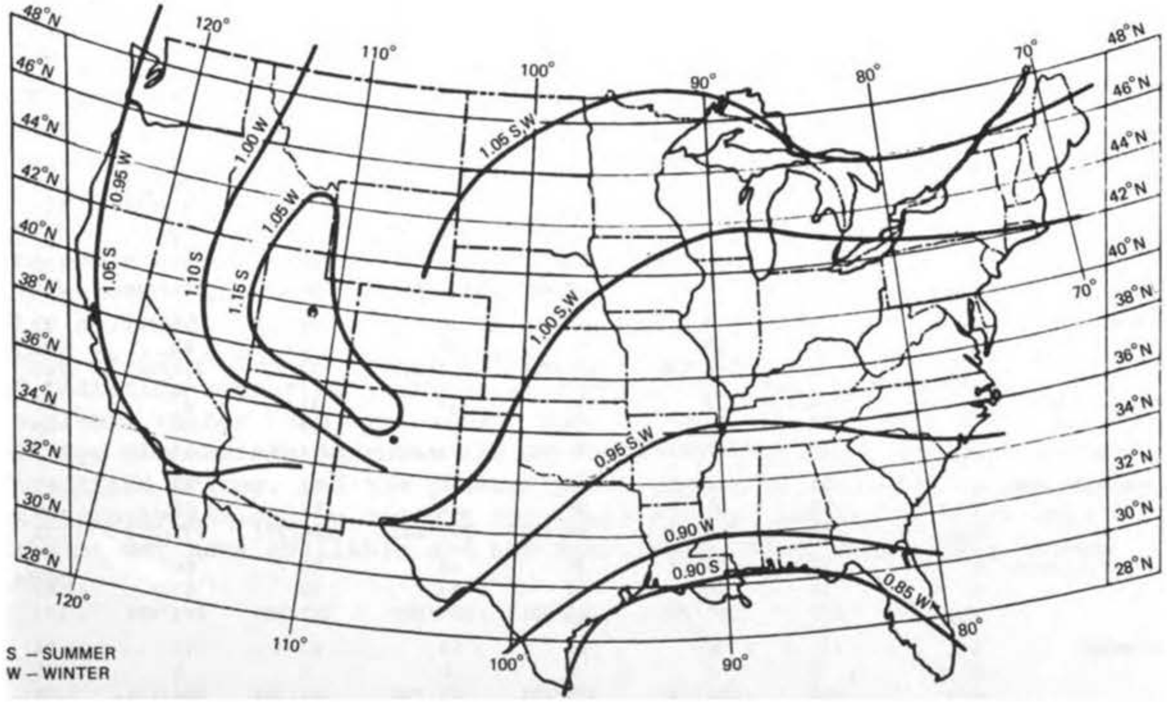

FIGURE 3 Estimated atmospheric clearness numbers in the United States for nonindustrial localities (reprinted with permission from Threlkeld and Jordan)[3].

designers of flat-plate solar energy collectors. Table 5 shows how the solar angles vary throughout the year for a particular latitude (40° N) and how the direct normal irradiation varies due to the changing moisture content of the atmosphere.

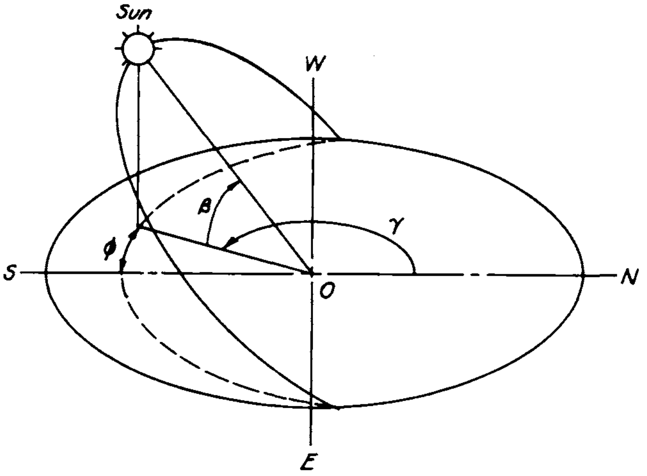

FIGURE 4 Diurnal path of sun illustrating solar altitude and azimuth angles.

TABLE 5 Solar Angles (Declination, δ; Altitude, β; Azimuth, ϕ) and I_{DN} for 40 Degrees North Latitude, 6 a.m. to 6 p.m.

		Months (data apply to the 21st day of each month)						
Time	Angles/ Intensity	Dec.	Jan./Nov.	Feb./Oct.	Mar./Sept.	Apr./Aug.	May/July	June
Declination	δ	-23.45	-19.9	-10.6	0.0	+12.0	+20.4	+23.45
6 a.m./6 p.m.	β	[a]	[a]	[a]	[a]	7	13	15
	ϕ	[a]	[a]	[a]	[a]	99	106	108
	I_{DN}	[a]	[a]	[a]	[a]	89/81	144/138	155
7 a.m./5 p.m.	β	[a]	[a]	5	11	19	24	26
	ϕ	[a]	[a]	73	80	90	97	100
	I_{DN}	[a]	[a]	69/48	171/149	206/208	216/208	216
8 a.m./4 p.m.	β	6	8	15	23	30	35	37
	ϕ	53	55	62	70	79	87	91
	I_{DN}	88	142/136	224/204	250/230	252/237	250/241	246
9 a.m./3 p.m.	β	14	17	25	33	41	47	49
	ϕ	42	44	50	57	67	76	80
	I_{DN}	217	239/232	274/257	282/263	274/260	267/259	263
10 a.m./2 p.m.	β	21	24	33	42	51	58	60
	ϕ	29	31	36	42	51	61	66
	I_{DN}	261	274/261	295/280	297/280	286/272	277/269	272
11 a.m./1 p.m.	β	25	28	38	48	59	66	69
	ϕ	15	16	19	23	30	37	42
	I_{DN}	279	289/280	305/291	305/287	292/278	283/275	277
12 noon	β	27	30	40	50	62	70	74
	ϕ	0	0	0	0	0	0	0
	I_{DN}	284	294/285	308/294	307/290	293/280	284/276	279

NOTE: Data from *ASHRAE Handbook of Applications* (New York: ASHRAE, 1974), chap. 59, Table 2, p. 59.4,5.

[a] Before sunrise or after sunset.

ASHRAE VALUES OF SOLAR HEAT GAIN FACTORS FOR VERTICAL SURFACES

The solar heat gain factors that appear in the *ASHRAE Handbook of Fundamentals* enable the designer of an air conditioning system to estimate the solar and total heat gains through any fenestration system if he knows the shading coefficient and thermal conductance factor, *U*, for the system and the location (latitude and longitude) and orientation of the building. The diffuse radiation from the sky plays an important part in these calculations, and reflected radiation from the foreground also can be significant.

The manner in which the diffuse and reflected insolation are included in the total solar irradiation of vertical surfaces is explained clearly in Stephenson's paper.[18] The insolation values given in the *ASHRAE Handbook of Applications* for tilted south-facing surfaces do not include any allowance for reflected radiation since they are intended to be conservative estimates; therefore, it should be remembered that highly reflective foregrounds (e.g., water, clean snow and ice, white roof surfaces) can cause significant increases in the total insolation of tilted surfaces.[19]

Tables for solar heat gain factors in the *ASHRAE Handbook of Fundamentals* contain data for surfaces oriented towards the north, northeast, east, southeast, south, southwest, west, and northwest. Data for horizontal surfaces such as flat roofs also are included.[20] To convert these to total insolation in Btu/h/ft^2, it is only necessary to multiply the tabulated values for each orientation by 1.15.

CONCLUSIONS

The information presented above deals only with clear-day data, and there is no simple manner in which one can provide precise estimates of the effect of such unpredictable phenomena as cloud cover. Figure 5 shows one of the many versions of the annual horizontal insolation over the continental United States. The isopleths showing lines of constant insolation are necessarily drawn with a tremendous degree of judgment on the part of the meteorologist and the draftsman. Local climatological conditions play a vitally important part in the insolation that is actually experienced by any specific locality and, unfortunately, the national network of radiation-measuring stations is contracting, due to instrumentation problems, rather than expanding. Data on daily hours of sunshine or percentage of possible sunshine are available for far more stations across the United States, and the prospective designer of sun-related apparatus is strongly advised to consult his local weather bureau to learn what data it may have available and how many years of data have been accumulated.

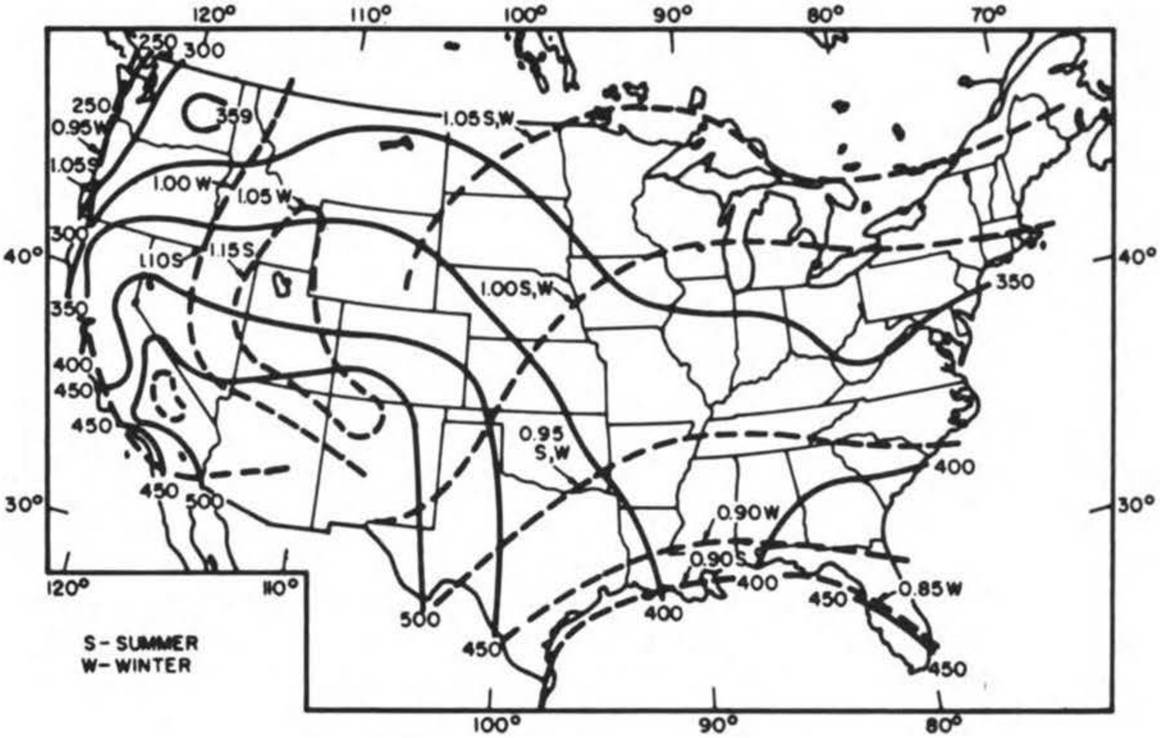

FIGURE 5 Clearness numbers (dashed lines) for winter and summer in the United States and approximate average annual insolation (solid lines) (in langleys per day). Reprinted with permission of ASHRAE from *1974 Applications*.

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SOLAR RADIATION DATA FOR BUILDING DESIGN

R. B. Lollar and A. J. Kemp

The availability of accurate solar radiation data and other meteorological parameters is an important factor in building design. Since these parameters vary widely as a function of climatological region, knowledge of this variability and the corresponding effects within a building are required for adequate building design. This paper describes a system, presently being built by IBM under contract to the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center, that measures solar irradiance and the response of solar conversion materials to solar energy. This device, called a sunfall monitor (Figure 1), uses tracking and non-tracking sensors to measure direct and total energy received from the sun. Total energy received can be measured in reference to any preset plane corresponding to a roof angle on which solar energy thermal collectors may be mounted.

The sensors that provide data concerning the "available" solar energy include a pyrheliometer on the tracking surface and two pyranometers, one on the tracking surface and the other on the tiltable surface. The pyrheliometer measures the solar energy coming directly from the solar disc, while the pyranometers measure the total solar energy coming directly from the solar disc plus the diffuse component from the sky that is reflected off of clouds and other surfaces within the hemisphere seen by the pyranometer sensor.

Solar cells and thermal absorber test samples are mounted in both the tiltable and tracking surfaces. The concentrating test sample is mounted at 45° to the tracking surface in order to reflect solar energy into a second pyrheliometer mounted inside the tracking assembly. The efficiency of the concentration sample can be obtained by comparing the reflected energy against the total direct energy received.

Figures 2 and 3 illustrate sensor-data utilization. For instance, Block 1 in Figure 2 provides the available energy from the direct solar component. In Block 2 the direct energy from a reflective surface is read by a second pyrheliometer. The reflective surface could be a material test sample being evaluated for a concentrator system. The difference between the two readings represents the energy loss by the reflective surface, thus enabling one to determine the efficiency of the concentrator test sample. The same approach is utilized for Blocks 6 and 7 in Figure 3 to determine efficiencies of thermal absorber samples. The total available energy shown in Block 6 may be taken on any angle corresponding to a

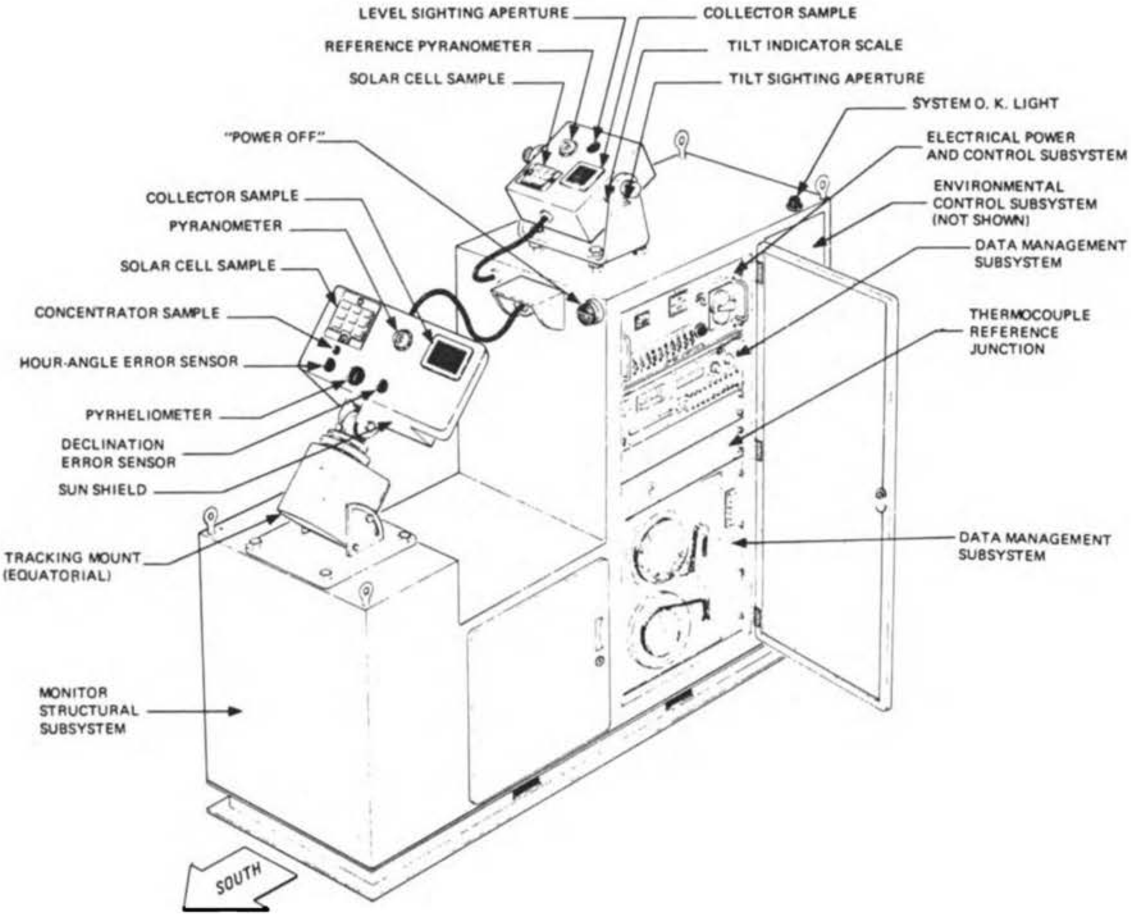


FIGURE 1 Sunfall monitor.

selected house or building roofline. The data are then integrated and a statistical analysis is performed to provide probabilities of average daily radiation by month to determine thermal collector sizing for a particular geographical location.

The unit is designed to record data in a computer-compatible format for 30 days in extreme outside environmental conditions ranging from -40° F to +125° F. To provide the user with complete flexibility through his host computer software, the data and channel assignment shown in Figure 4 has been implemented. These data may then be reduced by user computer programs to provide the typical information outputs shown.

While no individual sensor or subsystem is in itself unique, the integration of these elements:

1. Eliminates tedious manual integration of radiation plots (system software provides wide flexibility of engineering units, period of integration, and computations; nine-track tape provides compact storage and easy retrieval of data).
2. Permits recording of both *direct component* and *total radiation* for tracking systems and total radiation collected *at any tilt* angle for non-tracking systems.

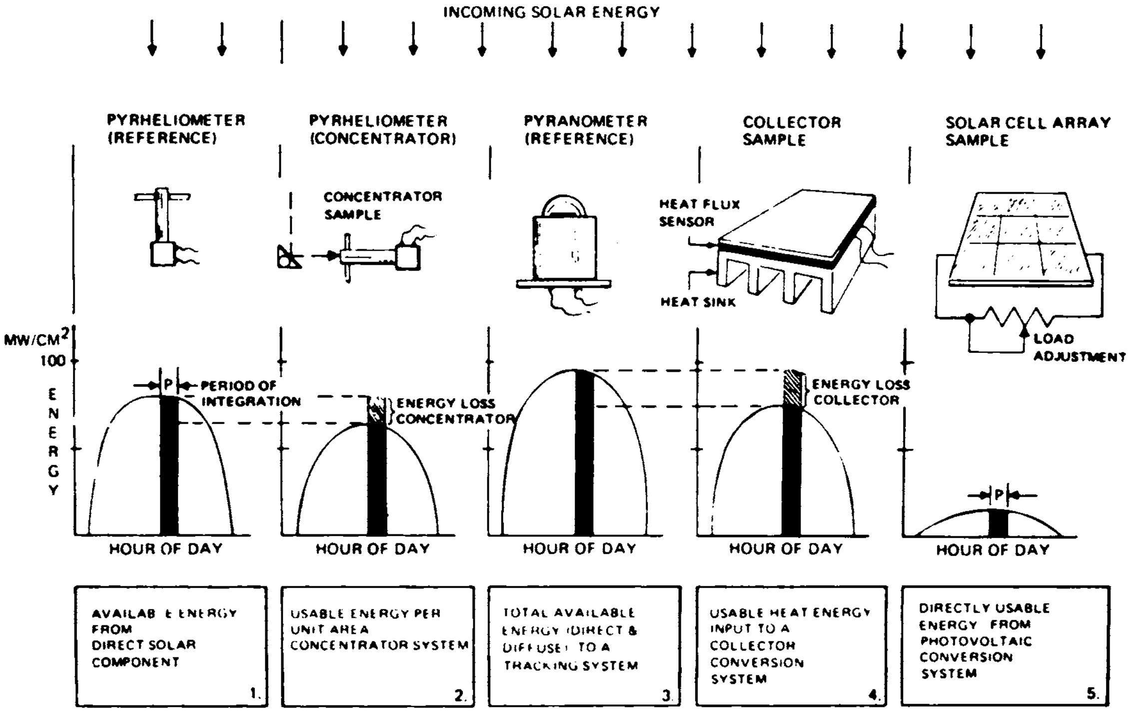


FIGURE 2 Data utilization--tracker-mounted sensors. (Reprinted from *Solar Energy* 5:73-80, with permission of the Pergamon Press.)

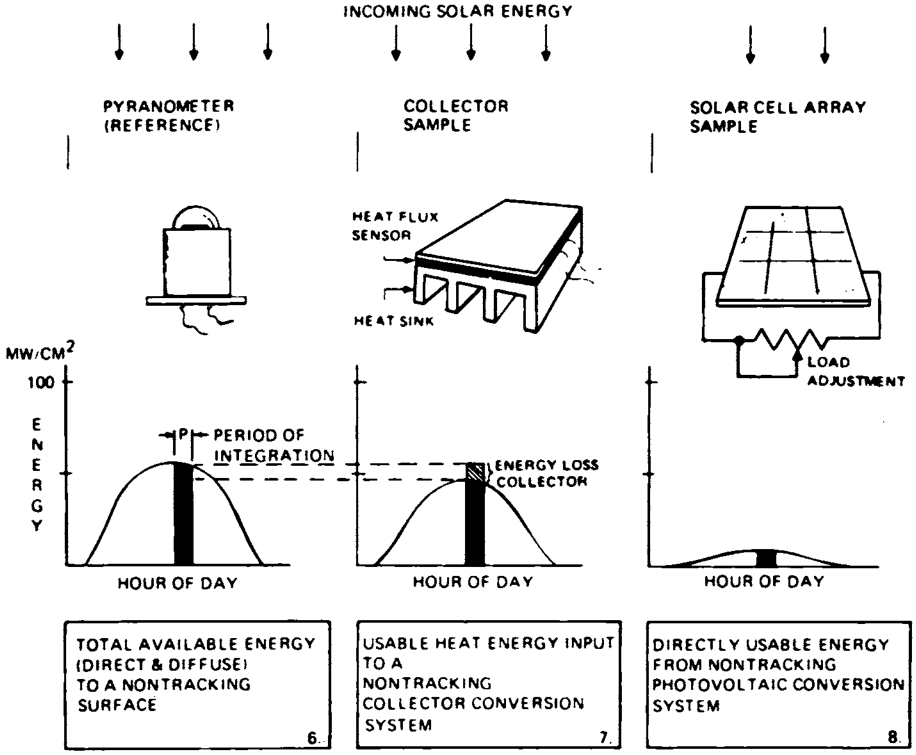


FIGURE 3 Data utilization--nontracking sensors. (Reprinted from *Solar Energy* 5:73-80, with permission of the Pergamon Press.)

SIGNAL SOURCE	CHANNEL NUMBER	DATA
TRACKER ASSEMBLY		
PYRHELIOMETER	1	AVAILABLE DIRECT SOLAR ENERGY
PYRANOMETER	2	AVAILABLE TOTAL SOLAR ENERGY
PYRHELIOMETER (CONCEN.)	3	REFLECTED VALUE-DIRECT COMPONENT
ABSORBER TEST MODULE	4	USABLE ENERGY TRACKING ABSORBER
ABSORBER THERMOCOUPLE	5	ABSORBER OPERATING TEMPERATURE
SOLAR CELL T.M. SHUNT RES.	6	MODULE OUTPUT VOLTAGE
SOLAR CELL T.M. LOAD RES.	7	MODULE OUTPUT CURRENT
NON-TRACKING ASSEMBLY		
PYRANOMETER	8	AVAILABLE TOTAL ENERGY - NON-TRACKING SYSTEM
ABSORBER TEST MODULE	9	USABLE ENERGY - NON-TRACKING ABSORBER
ABSORBER THERMOCOUPLE	10	ABSORBER OPERATION TEMPERATURE
SOLAR CELL T.M. SHUNT RES.	11	MODULE OUTPUT VOLTAGE
SOLAR CELL T.M. LOAD RES.	12	MODULE OUTPUT CURRENT
ENVIRONMENTAL DATA		
THERMOCOUPLE	13	AMBIENT AIR TEMPERATURE
THERMOCOUPLE	14	ELECTRONICS COMPARTMENT TEMPERATURE
TRACKER		
PHOTOCELL ASSY. NO. 1	15	(+) TRACKING ERROR HOUR ANGLE AXIS
PHOTOCELL ASSY. NO. 1	16	(–) TRACKING ERROR HOUR ANGLE AXIS
PHOTOCELL ASSY. NO. 2	17	(+) TRACKING ERROR-DECLINATION AXIS
PHOTOCELL ASSY. NO. 2	18	(–) TRACKING ERROR-DECLINATION AXIS
DATA MANAGEMENT SUBSYS.		
CALIBRATION CIRCUIT	19	CALIBRATION SIGNAL

USER SOFTWARE

- DIRECT AND TOTAL SOLAR RADIATION DATA INTEGRATED WITH TIME
- STATISTICAL PROBABILITIES OF DAILY, MONTHLY, OR YEARLY RADIATION
- TEST SAMPLE EFFICIENCIES
- TEST SAMPLE LONG TERM DEGRADATION ANALYSIS
- TEST SAMPLE ENERGY OUTPUT IN ENGINEERING UNITS FOR ELECTRICAL AND THERMAL ENGINEERS
- CORRELATION OF SOLAR RADIATION DATA AND CLIMATIC DATA
- VARIOUS TREND ANALYSIS STUDIES OF THE RECORDED DATA

FIGURE 4 Data channel allocations and utilization.

- MEASURES:
  - TOTAL INSOLATION AS SEEN ON ANY SELECTED PLANE
  - DIRECT INSOLATION
  - REFLECTED ENERGY FROM MATERIAL SAMPLE
- ACCURACY: SOURCE TO TAPE –5 PERCENT
- TEST SAMPLE EVALUATION MODULES FOR
  - SOLAR CELLS
  - COLLECTORS
  - CONCENTRATORS
- TRACKER
  - SEMI-AUTOMATIC EQUATORIAL MOUNT
    - CLOCK DRIVEN
    - MANUAL SETTING OF HOUR ANGLE AND DECLINATION.
- SENSORS

  TRACKER MOUNTED

  - DIRECT INCIDENCE PYRHELIOMETER
  - REFLECTED INCIDENCE PYRHELIOMETER
  - PYRANOMETER
  - HOUR ANGLE AND DECLINATION ERROR SENSORS

  STATIONARY

  - PYRANOMETER
- DATA MANAGEMENT
  - 20 CHANNELS, PREWIRED FOR EXPANSION TO 100 CHANNELS
  - 9 TRACK/800 BITS/INCH/TRACK
  - 30-DAY TAPE CAPACITY
  - LOW LEVEL INPUTS (1MV, 10MV or 100MV)
- WEATHER PROTECTION FOR OUTDOOR ENVIRONMENT
  - DESIGNED TO MAINTAIN INTERNAL CABINET 32°F TO 104°F WITH AMBIENT OF -40°F TO 125°F
- STATUS LIGHTS
  - OUTSIDE BLUE "A-OK" LONG RANGE VISIBILITY
  - MAIN CB ON–OFF
  - POWER FAILURE ALARM (MAINTAINED)
  - ECS OVERTEMPERATURE ALARM (MAINTAINED)
- POWER SAFETY
  - REAR CABINET DOORS INTERLOCKED
  - OUTSIDE INSTANT POWER OFF SWITCH
- LIFTING EYES/FORKLIFT CHANNELS
- PHYSICAL

WEIGHT	–	850 POUNDS
POWER	–	1600 VOLT-AMPERES
COLOR	–	WHITE

FIGURE 5 General characteristics of the sunfall monitor.

3. Provides for comparison of *collected* solar energy with *available* solar energy at location of interest via test samples and precision instruments.

4. Permits long-term data collection with minimum manual intervention. The general features of the unit are summarized in Figure 5.

PRESENT SOLAR RADIATION DATA

Solar radiation data for the United States are presently available from the National Climatic Center (NCC) in Asheville, North Carolina. These data are in the form of hourly and daily totals and are in units of langleys (gram-calories per square centimeter). Sixty-seven sites in the United States provide daily radiation totals and 29 provide both hourly and daily radiation totals.[1] A map of the 1973 solar radiation is shown in Figure 6.[2]

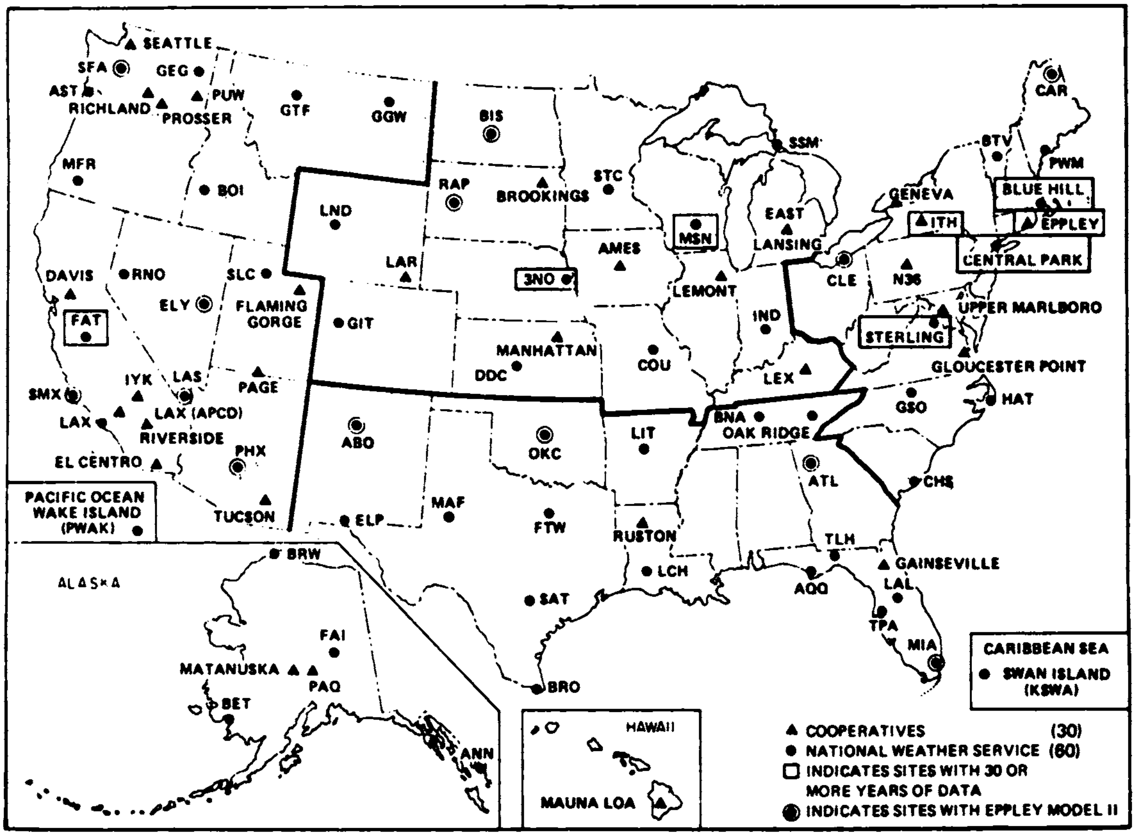


FIGURE 6 1973 solar radiation network. From Edward Jessup, "A Brief History of the Solar Radiation Program," in *Solar Energy Data Workshop*, Report NSF-RA-N-74-062 (Washington, D.C.: National Science Foundation, 1974).

Due to the disperse locations recording hourly and daily totals of solar radiation via pyranometers, another network that records the duration of sunshine via sunshine switches presently exists to allow estimates of solar radiation to be made in areas without pyranometers. The network of sunshine switches existing in 1973 is shown in Figure 7. Correlation between solar radiation and sunshine at the same site ranges from 0.82 to 0.92. Perfect correlation was not expected, since sunshine measurements are dependent on duration while only radiation measurements include sunshine intensity as well as duration.[3]

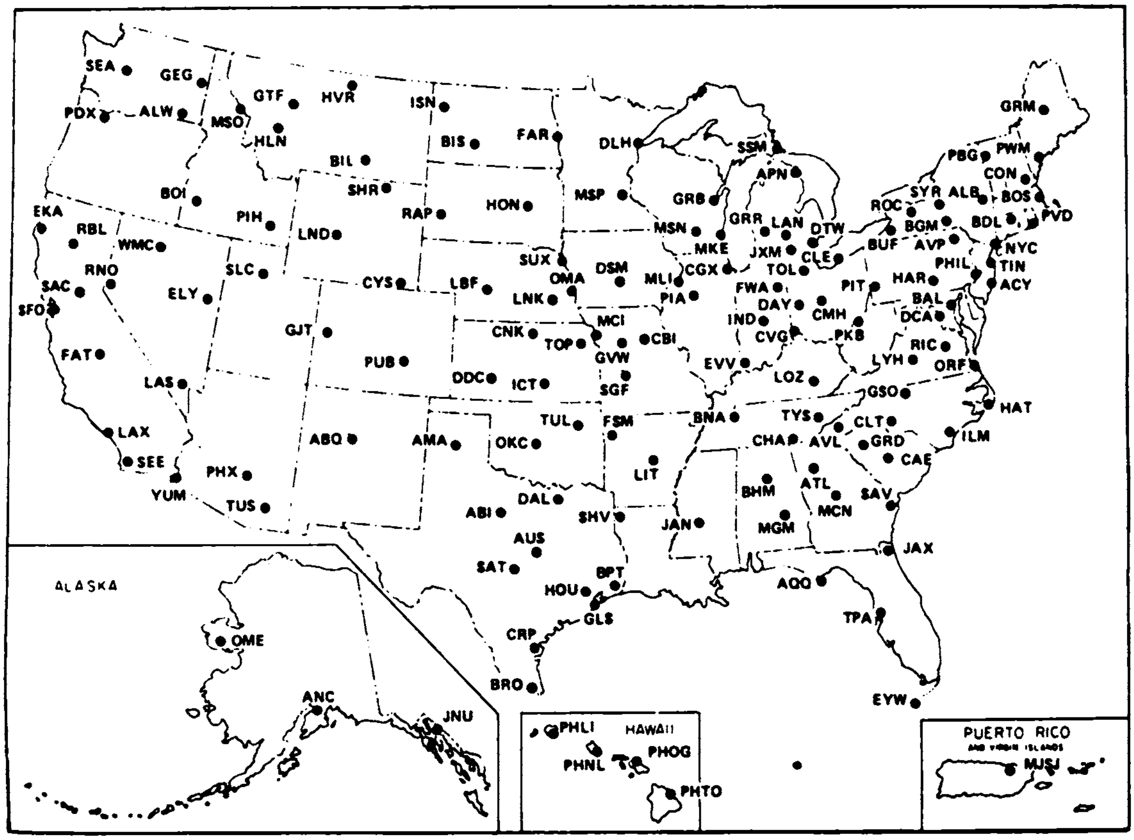


FIGURE 7 National Weather Service sunshine network 1973. From Edward Jessup, "A Brief History of the Solar Radiation Program," in *Solar Energy Data Workshop,* Report NSF-RA-N-74-062 (Washington, D.C.: National Science Foundation, 1974).

Tables 1 and 2 are examples of hourly and daily radiation values plus sunshine data. Copies of the computer printouts of these standard types of listing are available from the NCC and can be obtained in tape or card format depending on the user's need. The daily data are taped from July 1952 to within 3 months of NCC's current processing. These data are on five magnetic tape reels. The hourly data are taped from January 1967 only and consist of four reels. Hourly data for the period July 1952 through December 1966 are on FOSDIC microfilm. Solar radiation for the period prior to July 1952 is in keyed form on FOSDIC microfilm.[4]

TABLE 1 Tabulation of Hourly Hemispheric Radiation

	Hour											
Day	7 a.m.	8 a.m.	9 a.m.	10 a.m.	11 a.m.	Noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.	6 p.m.
1	1.0	13.5	29.8	42.0	51.7	46.0	37.4	37.9	35.7	26.5	9.9	0.6
2	0.8	11.5	27.5	40.7	41.6	53.7	58.3	51.4	42.1	26.2	9.3	0.6
3	0.6	10.2	22.0	31.8	41.9	42.2	29.9	27.9	35.6	21.8	5.7	0.5
4	0.2	4.6	8.2	23.8	23.2	27.6	32.4	43.6	19.4	4.9	2.0	0.3
5	0.0	0.0	0.1	5.2	27.7	31.1	9.4	5.2	4.4	2.9	1.1	0.1
6	0.1	2.6	9.0	27.6	36.4	48.4	47.5	18.4	14.9	7.0	2.3	0.5
7	0.2	5.9	21.6	31.8	30.9	41.0	16.5	13.8	8.1	16.4	8.6	0.5
8	0.3	1.8	12.6	19.1	27.7	37.0	36.0	39.9	37.7	22.0	8.3	0.5
9	0.2	4.5	17.2	15.4	9.4	20.7	7.6	5.0	10.0	9.0	2.0	0.0
10	0.4	11.1	26.6	40.2	51.0	56.6	56.6	51.0	40.0	25.0	9.0	0.0
11	0.4	10.1	25.8	39.9	50.2	55.5	55.3	49.5	38.0	24.0	8.0	0.0
12	0.4	10.4	25.5	38.2	48.2	53.6	54.3	49.3	38.0	23.0	8.0	0.0
13	0.3	8.7	23.4	36.8	46.8	54.3	49.7	31.2	26.0	12.0	8.0	0.0
14	0.1	6.9	21.7	35.9	42.0	34.7	36.9	35.5	35.0	16.0	9.0	0.0
15	0.4	9.1	20.5	30.4	42.2	48.0	51.5	48.5	35.0	17.0	6.0	0.0
16	0.3	9.9	25.3	38.9	49.1	54.4	54.1	48.4	37.0	22.0	8.0	0.0
17	0.2	8.6	22.3	35.3	45.0	50.8	50.9	32.2	32.0	20.0	7.0	0.0
18	0.2	4.6	19.8	26.9	43.1	49.0	52.2	43.0	34.0	21.0	6.0	0.0
19	0.1	2.9	8.9	14.0	25.9	31.0	52.5	35.5	24.0	14.0	5.0	0.0
20	0.2	5.2	9.9	29.8	38.2	17.4	7.0	7.7	6.0	9.0	2.0	0.0
21	0.1	8.4	22.5	36.4	46.5	51.8	51.8	47.0	36.0	22.0	7.0	0.0
22	0.1	4.0	11.5	20.1	37.0	35.2	31.8	24.6	22.0	20.0	4.0	0.0
23	0.1	3.6	9.9	15.9	30.8	40.6	45.4	33.3	20.0	10.0	3.0	0.0
24	0.1	6.3	18.5	31.9	38.0	48.8	48.2	36.6	31.0	18.0	4.0	0.0
25	0.1	5.7	19.7	31.6	41.1	46.9	42.9	32.0	29.4	18.3	5.0	0.1
26	0.1	3.4	5.9	8.9	14.8	34.5	44.1	20.1	17.8	10.0	3.9	0.1
27	0.1	1.6	3.9	6.8	22.4	37.0	32.0	18.0	8.4	6.5	1.8	0.1
28	0.1	7.1	22.4	36.7	47.0	52.0	51.5	46.3	35.4	20.9	6.0	0.1
29	0.1	7.5	21.5	35.4	45.4	50.8	50.1	44.4	33.8	19.5	5.5	0.1
30	0.1	6.0	20.5	34.3	44.7	49.9	50.0	45.2	35.5	21.2	6.4	0.1

NOTE: Data obtained from November 1973 Sample Hourly and Daily Radiation Listing (Tabulation 610C, Station 03937, Lake Charles, Louisiana) provided April 11, 1974, by R. E. Himberger, National Climatic Center, Asheville, North Carolina.

TABLE 2 Tabulation of Daily Hemispheric Radiation and Sunshine

Day	Daily Radiation	ETR	Minutes Sunshine	% Poss. Sun	Avg. Sky Cover	% Poss. Rad.
1	205.3	479	242	38	7	43
2	73.8	474	176	28	7	16
3	268.9	469	579	93	4	57
4	177.0	464	240	39	6	38
5	299.4	459	520	84	2	65
6	279.8	454	504	81	5	62
7	220.3	449	161	26	9	49
8	99.0	445	0	0	10	22
9	288.3	440	499	81	3	66
10	292.9	430	319	52	4	67
11	283.8	432	384	63	5	66
12	136.3	427	0	0	10	32
13	156.1	423	2	0	10	37
14	119.9	419	0	0	10	29
15	87.0	415	44	7	8	21
16	219.7	411	316	53	5	53
17	214.7	407	227	38	6	53
18	121.5	403	0	0	9	30
19	66.8	399	0	0	10	17
20	97.1	396	0	0	10	25
21	92.6	392	195	33	7	24
22	213.4	389	328	57	6	55
23	101.8	386	0	0	10	26
24	32.9	382	0	0	10	9
25	93.0	379	17	3	10	25
26	60.0	376	0	0	10	16
27	48.6	373	0	0	10	13
28	103.9	370	151	26	7	28
29	216.9	367	398	69	4	59
30	234.0	365	477	83	6	64

NOTE: Data obtained from November 1973 Sample Hourly and Daily Radiation Listings (Tabulation 610D, Station 93819, Indianapolis, Indiana) provided April 11, 1974, by R. E. Himberger, National Climatic Center, Asheville, North Carolina. Standard printout also gives totals and means.

Due to insufficient resources available for the solar radiation network, routine maintenance and station inspection are inadequate, data monitoring and quality control are limited, and equipment is deteriorating. This has resulted in the publication of data so poor that the National Weather Service (NWS) requested the NCC to stop publishing data in September 1972. Estimated data errors range from ±5 percent to ±30 percent.[5]

FUTURE SOLAR RADIATION DATA

In order to provide accurate solar radiation data, the National Oceanic and Atmospheric Administration (NOAA) has proposed to the National Science Foundation (NSF) that a new solar radiation network be established.[6] This new network would initially consist of 35 stations as shown in Figure 8 and Table 3.[7] All stations would be equipped with new pyranometers and cassette recording equipment to sample data every minute. In addition, 10 of these stations would have a second pyranometer with a shading ring attached to obtain diffused radiation. Also 5 of the 35 stations would have a pyrheliometer to obtain direct solar radiation data. After installation of the initial 35 stations, an expansion of 2 to 5 stations per year is proposed.[8] Data recorded on the cassette tapes would be processed at the NCC, and the proposal recommends that the data be published in metric units of milliwatts per square centimeter instead of the present langleys.[9]

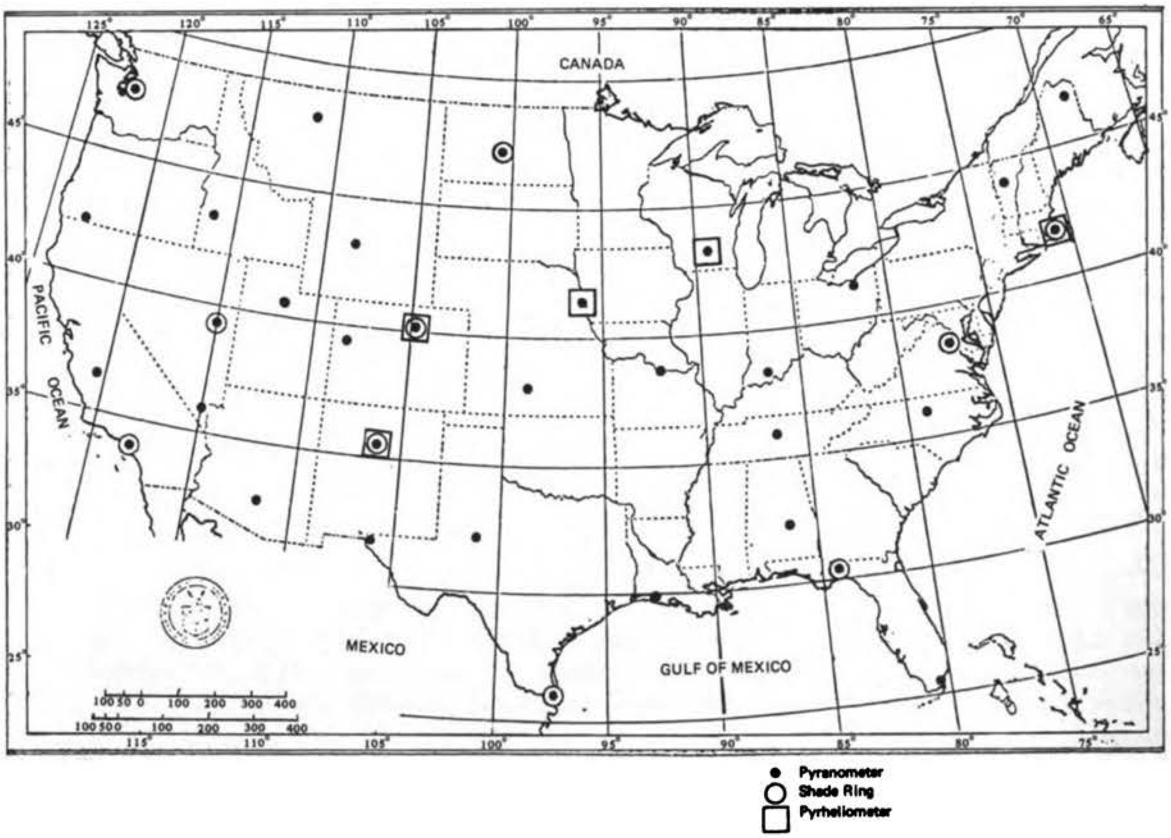


FIGURE 8 Recommended solar radiation network. From R. E. Himberger, National Climatic Center, Asheville, North Carolina, letter to R. B. Lollar, February 25, 1975.

TABLE 3 Recommended Solar Radiation Network

1. Fairbanks, Alaska
2. Montgomery, Alabama
3. Phoenix, Arizona
4. Fresno, California
5. Los Angeles, California
6. Boulder, Colorado
7. Grand Junction, Colorado
8. Miami, Florida
9. Tallahassee, Florida
10. Boise, Idaho
11. Indianapolis, Indiana
12. Dodge City, Kansas
13. Lake Charles, Louisiana
14. Blue Hill, Massachusetts[a]
15. Caribou, Maine
16. Columbia, Missouri
17. Great Falls, Montana
18. Omaha, Nebraska[a]
19. Greensboro, North Carolina
20. Bismarck, North Dakota
21. Albuquerque, New Mexico[a]
22. Ely, Nevada
23. Las Vegas, Nevada
24. Cleveland, Ohio
25. Medford, Oregon
26. Nashville, Tennessee
27. Brownsville, Texas
28. El Paso, Texas
29. Midland, Texas
30. Salt Lake City, Utah
31. Sterling, Virginia
32. Burlington, Vermont
33. Seattle, Washington
34. Madison, Wisconsin[a]
35. Lander, Wyoming

NOTE: Data from Edward Jessup, "A Brief History of the Solar Radiation Program," in *Solar Energy Data Workshop*, Report NSF-RA-N-74-062 (Washington, D.C.: National Science Foundation, 1974).

[a] Existing pyrheliometric sites.

SOLAR RADIATION DATA FOR BUILDING RESEARCH

In order to study accurately the effects of solar radiation on a building design, a modified sunfall monitor, such as shown in Figure 9, could be utilized to collect and record on magnetic tape the necessary data for this type of research. The modification consists primarily of a reconfiguration of the sensor heads to provide total irradiance measurements for the north, east, south, west, and horizontal hemispheres. The pyrheliometer would remain on the tracking head to provide the direct component, and all other sensors and the provisions for testing material samples would be removed. Advantage would be taken of the present unit's built-in flexibility to expand its data management system capability to 200 measurements. The system normally would be installed on top of a building (Figure 10). If the building to be studied is very large and the recording of more than 200 parameters would be required, an approach utilizing a computer (Figure 11) could be implemented to obtain the necessary information. This approach could also provide for effective power management of the building power system and simultaneous control of the solar heating and cooling system. An installation such as this in each of the major climatological zones[10] (Figure 12) would provide valuable insight of the relationship of solar energy on optimization of energy-efficient building designs.

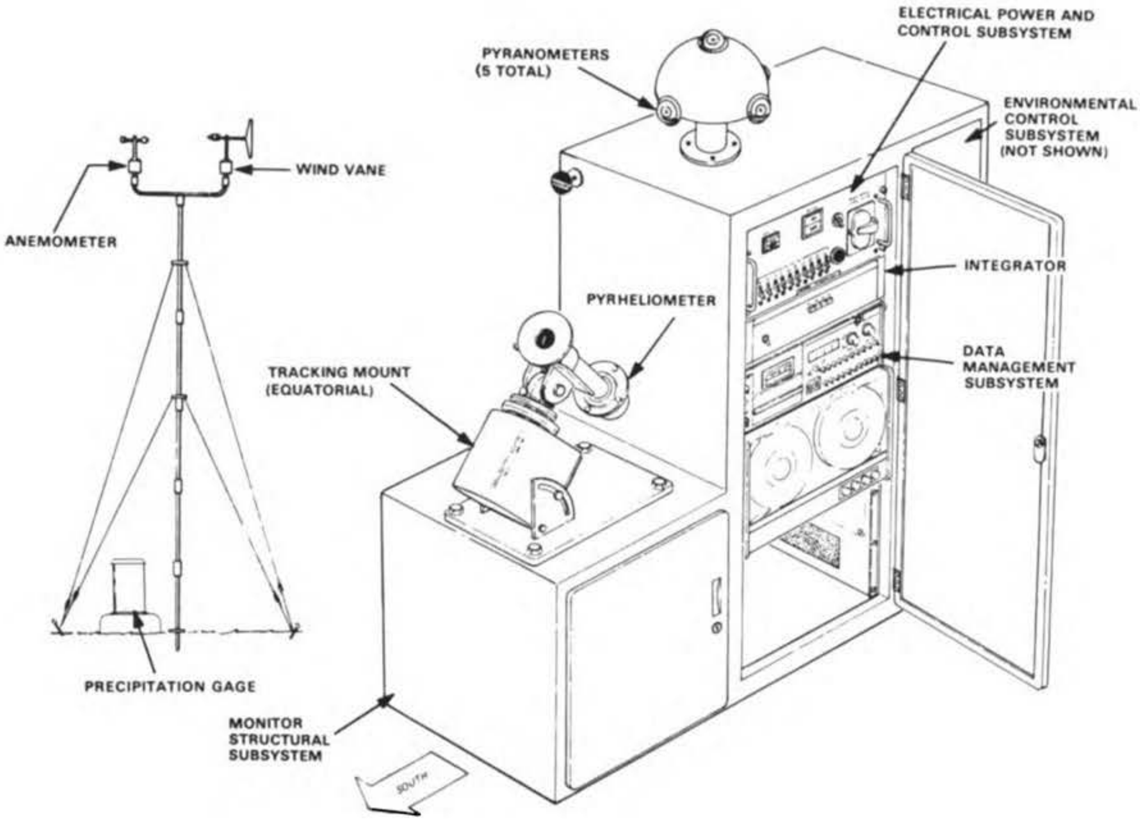


FIGURE 9 Building research data recording system.

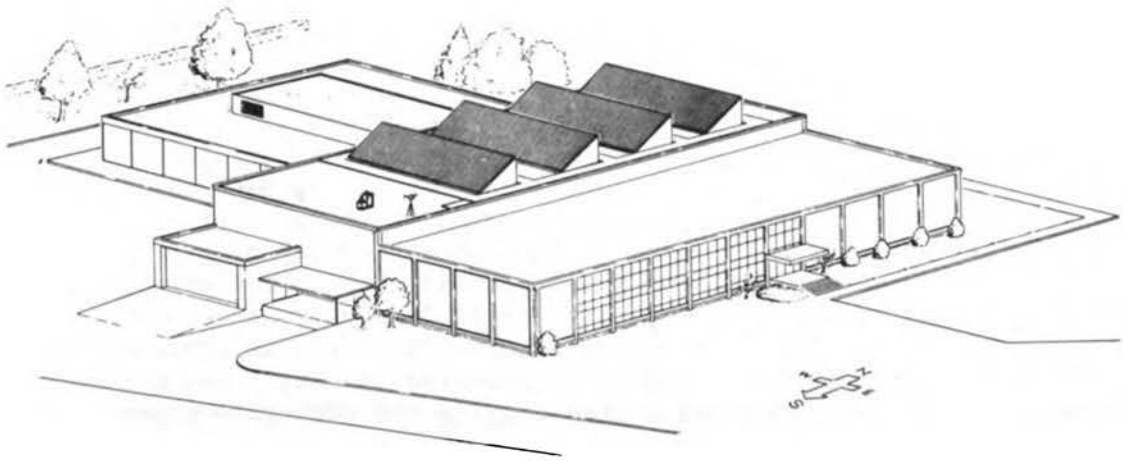


FIGURE 10 Typical location of data recording system.

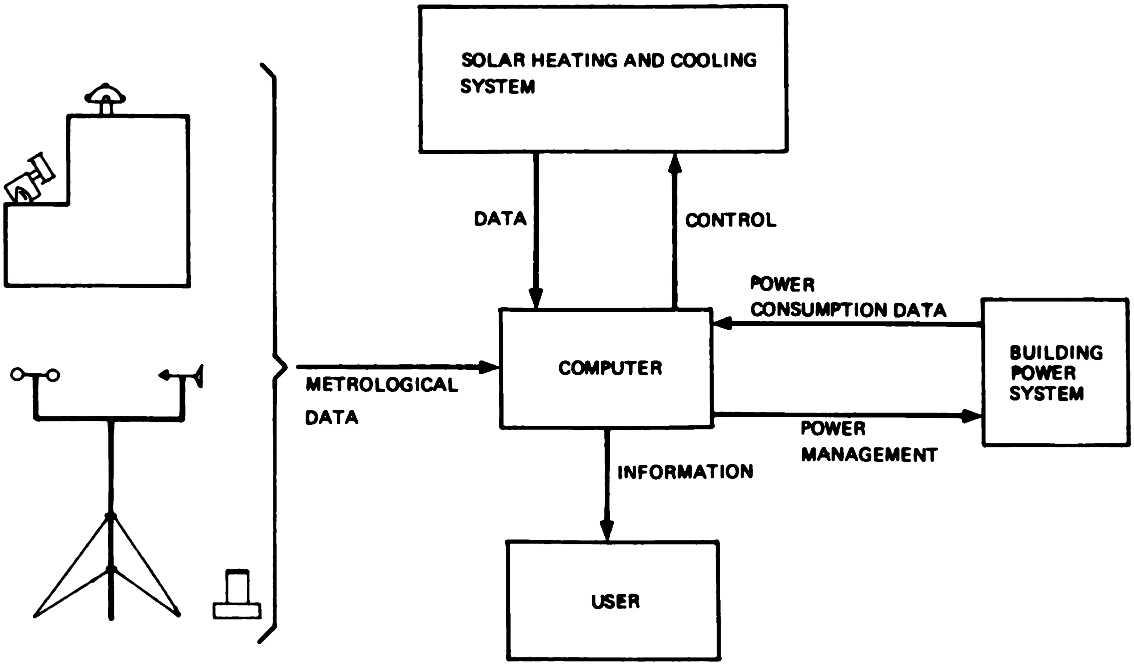
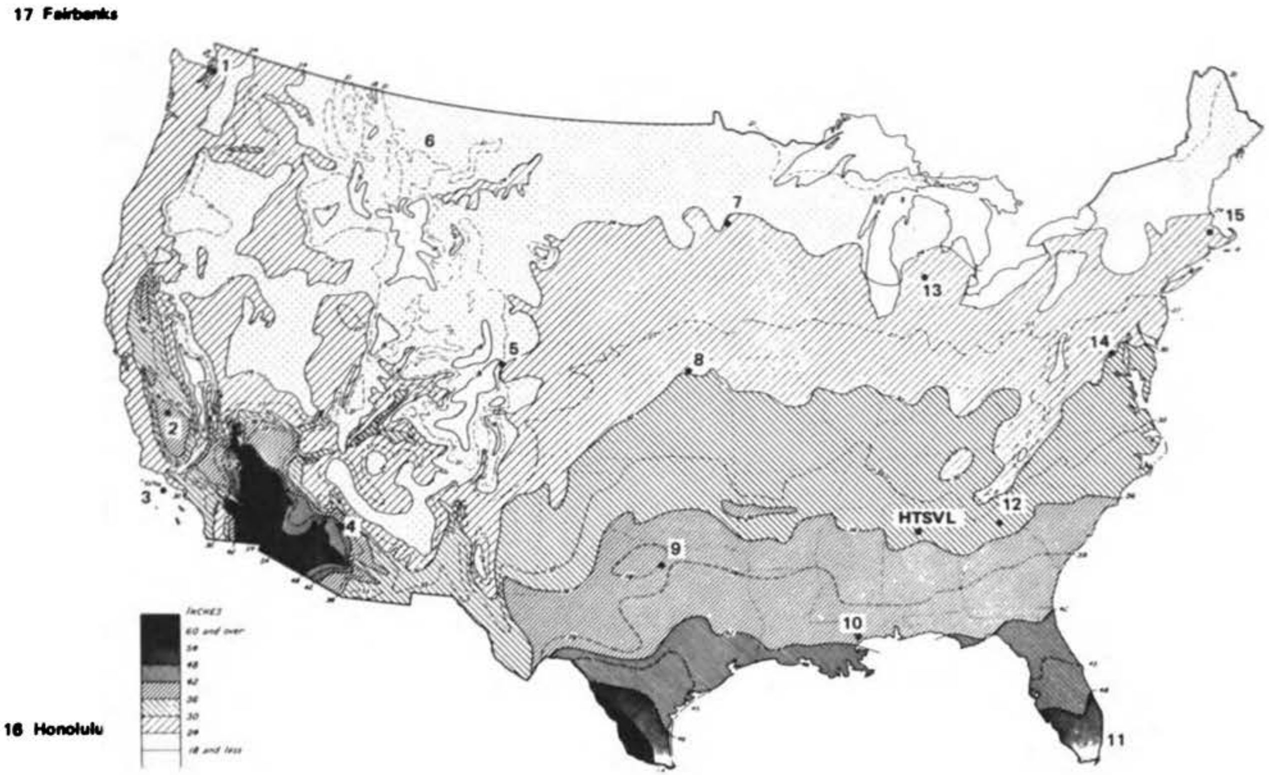


FIGURE 11 Solar effects analysis of large buildings.



Climatic Types:

I. Wet and Dry Tropics
  11. Miami
  16. Honolulu
II. Tropical Arid
  3. La Jolla
  4. Phoenix
III. Tropical Semiarid
  9. Fort Worth
IV. Dry Summer Subtropics
  2. Fresno
V. Humid Subtropics
  10. New Orleans
  12. Atlanta
VI. Marine
  1. Seattle
VII. Mid-Latitude Semiarid
  5. Boulder
VIII. Humid Continental Warm Summer
  8. Omaha
  13. East Lansing
  14. Washington, D.C.
IX. Humid Continental Cool Summer
  7. St. Cloud
  15. Boston
X. Highland
  6. Great Falls
XI. Taiga
  17. Fairbanks

FIGURE 12 Possible sites to evaluate solar radiation effects upon buildings as a function of climates. From C. W. Thornthwaite, "An Approach toward a Rational Classification of Climate," *Geographical Review* 38:64.

REFERENCES

1. R. E. Himberger, "Access to Solar Radiation Data," in *Solar Energy Data,* NSF-RA-N-74-062 (Washington, D.C.: National Science Foundation, 1974), pp. 21-27.
2. Edward Jessup, "A Brief History of the Solar Radiation Program," in *Solar Energy Data,* pp. 13-20.
3. *Ibid.*
4. Himberger, "Access to Solar Radiation Data."
5. Jessup, "A Brief History."
6. Mike Riches, NOAA, Silver Spring, Md., telephone conversation with R. B. Lollar, March 12, 1975.
7. R. E. Himberger, NCC, Asheville, N.C., letter to R. B. Lollar, February 25, 1975.
8. Riches, telephone conversation.
9. R. E. Himberger, NCC, Asheville, N.C., telephone conversation with R. B. Lollar, March 12, 1975.
10. C. W. Thornthwaite, "An Approach toward a Rational Classification of Climate," *Geographical Review* 38(January 1948):55-90.

IV

Building Costs

RESOURCE OPTIMIZATION USING LIFE-CYCLE COST-BENEFIT ANALYSIS

James W. Griffith

The utilization of solar energy as daylight and heat transmitted through windows is one of the oldest and most common uses of a natural resource. In fact, it is so prevalent that many people fail to recognize the true significance of windows in energy conservation.

When properly evaluated, the direct component of daylight and reflected daylight from windows may be many times more effective than equal levels of illumination from conventional overhead electric lighting. When a footcandle of daylight replaces a footcandle of electric light, the savings in basic energy at the generating plant may be as much as three times the electric energy it took to produce the footcandle of electric lighting. This advantage in illumination effectiveness results from reducing overall generating and distribution losses.

Daylight footcandles from windows, if properly utilized on typical office, school, residential, and industrial reading tasks, have been shown to be three to four times as effective in increasing visual performance as equal footcandles from conventional electric lighting. When the daylight source is a window and the daylight strikes a reading task from the side rather than from overhead, the veiling reflection caused by the mirrored reflections of overhead light sources can be eliminated and increase the contrast of the task. With proper layout of work places (daylight from the side), 20 to 30 footcandles of daylight can permit better visual performance than 70 to 100 footcandles of traditional overhead lighting.

Proper design and evaluation of the total effect of windows on the life of a building will conserve irreplaceable energy in most buildings. Unfortunately, however, buildings are usually designed by bringing together a group of subsystems with little analysis of the interactive effects on the total system. Heating/ventilating/air conditioning (HVAC) designers consider windows as a heat loss in the winter and a heat gain in the summer when sizing HVAC equipment, and rarely do they recognize the solar heat gain in the winter and the cooling through the windows at night in the summer in their design analysis of window sizes, orientation, and glazing material.

The illuminating engineer usually designs the electric lighting system to operate with no daylight, and proper evaluation of energy saved through daylight utilization is almost never provided to the architect as an alternative. If it were not for the desirability of having large window areas, the architect, in reviewing the HVAC design with the illumination design, could erroneously conclude that windows waste rather than conserve energy and reduce or eliminate them. This method of "conserving" by limiting maximum connected power loads of various subsystems is comparable to reducing the pollutants in the lungs by breathing less air.

What the building design profession needs is a "thermavision engineer" who would design the HVAC and illumination equipment as an integrated system based on interior equipment needs and the effect of the shell of the building on the total building over its annual cycle. This would allow the architect and the owner to compare alternative designs to best utilize all available resources based on their costs and their benefits over their life cycle.

Resource optimization in building design must be based on the total system over its expected useful life. Obviously, complete and accurate analysis can be done only after the fact, but estimates of future facts of the system must be forecast for design purposes. Systems analysis is any orderly analytic study that enables the designer to identify and establish preferred alternative designs to satisfy one or more goals. In general, buildings are designed to house people and equipment to perform some specific functions. The designer, with the sanction of the owner or occupant, establishes a set of objectives he wishes to accomplish within some finite limits of time and resources.

Viable alternative environmental systems, composed of a multiplicity of subsystems, must be evaluated in terms of resource costs and goal effectiveness. This is done by collecting data and constructing models synthesizing real life cause-and-effect relations pertinent to the total expected life of the systems. The cost (resources that will not be available for other projects) then is evaluated in terms of objective satisfaction.

Design is not a simple process, since the alternatives do not completely satisfy all objectives, which may in themselves be conflicting and uncertain. Thus, the design process is an iterative one with the designer questioning each assumption and how sensitive his decision is to it, reexamining objectives and formulating new ones, and developing new alternatives until time, creativity, or resources dictate a decision.

A key factor in this process of analysis is a criterion for evaluating cost against effectiveness. The structured approach in building design traditionally has been to minimize the cost of each subsystem to provide some minimum standard. A more effective approach, and one that must be used in resource conservation, is one using cost-benefit models for analysis based on some common index for estimating costs (inputs) and benefits (outputs). The most common index and the easiest to use is the dollar index, in which all costs and, when practical, all benefits are expressed in dollar values. The time at which these values occur in the total life cycle of the building are also estimated, since all resources have a greater value when properly invested.

In energy utilization no expenditure of resources should be made if the investment does not return benefits equal to total cost plus some additional return to account for the use of the resource for the proposed project rather than for other available purposes. This extra return may be expressed as an interest rate where interest is a percentage of the investment.

Equivalent economic models of alternative systems and subsystems can then be developed to aid the architectural and engineering designers in evaluating each on a common basis. This information is then referred to the owner or user for reevaluation of the goals and objectives, since these greatly affect the total energy utilization. For example, if the owner or the user insists that the building be designed so that all tasks, regardless of their frequency, accuracy, and difficulty, can be performed at any time and location, the cost will be excessive and energy waste is most likely. The use of models permits and encourages reevaluation and trade-offs in costs and benefits to better utilize resources.

There are two basic types of equivalent model that can be used for evaluation of alternatives. The simplest and easiest to understand is the annual-cost model, in which all practical costs and benefits expected throughout the life cycle of a building are transformed into an equivalent uniform annual cost-benefit model. The other type of equivalent model is one that transforms all practical costs and benefits to a present value for each alternative over an equal time frame. This may necessitate many renewals of the alternative systems and their subsystems to produce equivalency.

There are relatively good data banks on costs, but little has been done on benefit valuation. The use of cost analysis for like subsystems in building design, using equivalent economic analysis, has therefore prevailed, even though it does not allow trade-off analysis between unlike systems or subsystems.

Some costs and benefits may not be considered in the model because they are too difficult to reduce to a dollar value or their effect on the design is not worth the cost of reduction. These irreducibles are noted and used in the final decision if two or more alternatives are relatively close in annual or present worth costs.

The usual approach to cost analysis is to compare alternatives that meet a set of minimum requirements using a life-cycle model. This is accomplished by forecasting the costs and when they will occur, along with the obvious benefits such as salvage values and tax write-offs. Two or more alternatives then are compared using some minimum rate of return applied to the model.

To simplify cost analysis, tables of the six factors relating the five variables--interest (i), years (y), present worth or principal (P), a future worth in y years from the present (F), and a uniform annual series of costs (A) for y years--have been developed and are explained below with a common example of their use (based on J. W. Griffith and B. J. Keely, *Life-Cycle Cost-Benefit Analysis*, in press).

1. The Single Present Worth (SPW). Used to find the present worth (P) of a future sum of money (F) in y years from now using an interest of i. For example, if you wanted to know the present worth of a $1,000 renewal cost in 10 years at 10 percent interest, you would use the

following model (given F to find P) and find the 10-year SPW in the 10 percent table:

$$P = F(\mathrm{SPW})$$

2. The Single Compound Amount (SCA). Used to find the value *(F)* in y years from now of a present sum of money with an interest rate of i. For example, if you invest or spend $1,000 today, you could determine what it would be worth at any interest rate any time in the future using the following model (given P to find F):

$$F = P(\mathrm{SCA}).$$

3. The Uniform Capital Recovery (UCR). Used to recover a present sum of money *(P)* in uniform annual increments *(A)* in a given number of years *(y)* with an interest rate of i. This is the factor used to recover capital with interest, such as a mortgage payment. It accounts for first costs on an annual basis and is calculated using the following model (given P to find A):

$$A = P(\mathrm{UCR}).$$

4. The Uniform Present Worth (UPW). Used to find the present worth of uniform costs, taking into account the effect of interest. This factor would be used to find out how much you would have to pay without penalty if you wanted to pay off a note or to find the present worth of uniform annual operation and maintenance costs or benefits. The appropriate model is (given A to find P):

$$P = A(\mathrm{UPW}).$$

5. The Uniform Compound Amount (UCA). Used to find the future worth *(F)* of a series of uniform annual end-of-year costs *(A)* with interest. This factor is used to find the future worth of uniform-annual costs or benefits. It is also used in the financial field to determine the value of sinking funds at a future date. The appropriate model is (given A to find F):

$$F = A(\mathrm{UCA}).$$

6. The Uniform Sinking Fund (USF). Used to establish a uniform annual payment *(A)* that will produce a future sum of money *(F)* in given number of years *(y)* with interest. It is used to put salvage values into a uniform annual benefit. The four annual-cost factors also are used to simplify model construction. The appropriate model is:

$$A = F(\mathrm{USF}).$$

A simple illustration of this type of cost analysis is shown in Table 1 using the forecasted costs and expected benefits shown in Table 2 for two subsystems that will satisfactorily fulfill one of the building objectives using an arbitrary 10 percent rate of return to justify the investment of the valued resources.

TABLE 1 Annual Cost Comparison with Interest at 10 Percent

Cost Item	Subsystem 1	Subsystem 2
Life of system	5 years	8 years
First cost (UCR)	\$25,000 (0.2638) = \$6,595	\$30,000 (0.1874) = \$5,622
Annual operation and maintenance	\$6,000	\$4,000
Annual property tax and insurance	\$1,500	\$1,800
Income tax allowance	-\$5,750	-\$4,400
Salvage (USF)	\$5,000 (0.1638) = -\$819	\$6,000 (0.0874) = -\$524
Annual Cost	\$7,526	\$6,498

TABLE 2 Forecasted Costs and Expected Benefits

Factor	Subsystem 1	Subsystem 2
Useful life	5 years	8 years
First cost	\$25,000	\$30,000
Annual operation and maintenance costs	\$6,000	\$4,000
Annual property tax and insurance costs at 6% of first cost	\$1,500	\$1,800
Income tax depreciation at 5% tax rate using straight line depreciation	\$4,000	\$3,000
Salvage	\$5,000	\$6,000

The capital recovery of the first cost is computed for each system using the capital recovery factor for 10 percent at 5 and 8 years. Operation and maintenance costs along with the property taxes, if applicable, and insurance risk are itemized since they are already in annual cost form. The income tax allowance, if applicable, is computed for each system by adding the deductible costs and multiplying by the tax rate. This is a negative cost, since that amount will not have to be paid out in taxes as a result of selecting one of the alternatives. The salvage value is also a negative cost, and the annual value of it is computed by multiplying the salvage value by the sinking fund factor for 5 and 8 years, respectively.

Had a present-worth comparison of these two systems been made, a life cycle of 40 years would have been used with seven renewals of the 5-year life and four renewals of the 8-year life alternatives. These values can be obtained easily by multiplying the annual costs of each system by the uniform present-worth factor, UPW, for 40 years at 10 percent interest:

(\$7,526)(9.779) = \$73,597 for the 5-year system

and

(\$6,498)(9.779) = \$63,544 for the 8-year system.

In both the annual-cost and present-worth models, the 8-year life alternative is more desirable at 10 percent return on the investment. However, the architect would like to know whether he should recommend the 8-year life subsystem to his client or not, since the 10 percent rate of return may not represent a fair return when compared with other subsystems performing other objectives satisfactorily. To make this decision he needs to know what rate of return the extra investment of $5,000 will produce so he can invest available resources to provide the greatest productivity.

The problem of establishing the rate of return on the extra investment of one alternative over another is simply a mathematical exercise, since all of the cost and obvious benefit data have already been gathered. The technique is to put two annual-cost or present-worth comparisons into mathematical models or equations with the interest factors being the unknowns and equate them. The rate of return on the extra investment is determined by substituting the interest rate factors from a range of interest rate tables until those from one table make the two models equal. It is unlikely that a rate of return will be an exact table rate; therefore, by trial and error the two closest interest rates that cause the value to shift from one side of the equation to the other are found to bracket the rate that is somewhere in between the two. By interpolation or the use of larger interest tables a closer estimate can be determined.

To illustrate, the two annual-cost equations for the previous example are constructed and set equal:

$$\begin{aligned} &\$25{,}000(\mathrm{UCR};5\ \mathrm{yr}) + \$6{,}000 + \$1{,}500 - \$5{,}750 - \$5{,}000(\mathrm{USF};5\ \mathrm{yr}) \\ &= \$30{,}000(\mathrm{UCR};8\ \mathrm{yr}) + \$4{,}000 + \$1{,}800 - \$4{,}400 - \$6{,}000(\mathrm{USF};8\ \mathrm{yr}). \end{aligned}$$

Then by trial and error the two are almost equal if factors from the 30 percent table are substituted:

$$\begin{aligned} &\$25{,}000(0.4106) + \$6{,}000 + \$1{,}500 - \$5{,}750 - \$5{,}000(0.1106) \\ &= \$30{,}000(0.3419) + \$4{,}000 + \$1{,}800 - \$4{,}400 - \$6{,}000(0.0419) \\ &\qquad \$11{,}462 \neq \$11{,}406. \end{aligned}$$

Thus the expected rate of return on the extra investment of $5,000 for the 8-year alternative is approximately 30 percent over and above the 5-year one. The architect can now ask his client if he wishes to invest $5,000 with a 30 percent return on the investment. If he has a fixed design budget, he can look at other subsystems where similar analysis of the various satisfactory alternatives has been established and decide where to invest his available resources to produce the greatest benefit for his client.

By using the rate-of-return analysis, the architect can design with input-output utilization (IOU) with only cost data and obvious benefit data. Using this design tool will not only provide for better utilization of energy and other resources, but will also show the advantages of basing design decisions on the effective output for optimum input. This will then amplify the need for research to develop good data banks on benefits of buildings.

Good cost-benefit data banks would allow the overall optimization of resources. If the benefit of the subsystem in the example were estimated to be an annual savings or income of $7,500, the rate of return on each investment could be determined by writing a cost-benefit equation for each. The return on each investment would be determined by setting the costs equal to the benefits and substituting interest factors for various rates until they are equal.

In the example, the 5-year system will yield a return of approximately 10 percent, as shown in the model using 10 percent factors:

$$\$25{,}000(0.2638) + \$6{,}000 + \$1{,}500 \neq \$7{,}500 + \$5{,}750 + \$5{,}000(0.1638)$$
$$\$14{,}095 \neq \$14{,}069.$$

If money actually were costing 10 percent, this investment would be marginal and probably would not be taken.

The 8-year life system yields a return of approximately 15 percent on the investment, as seen in the model using factors from a 15 percent interest table:

$$\$30{,}000(0.2229) + \$4{,}000 + \$1{,}800 \neq \$7{,}500 + \$4{,}400 + \$6{,}000(0.0729)$$
$$\$12{,}487 \neq \$12{,}338.$$

By comparing the model using 12 percent factors and straight-line interpolation, the rate of return on the system is 14.4 percent.

Using rate of return on the investment based on IOU would allow overall resource optimization not only within subsystems but also between subsystems and, conceivably, between systems. Someday the building designer might even be in a position of convincing his client that he would get greater productivity out of his resources if he did not build a building.

Once cost-benefit analysis models are constructed, they can be used for other decisions, such as how long a subsystem must last to make it desirable. This is done by comparing two models with the break-even time to make them equal at some opportunity rate. If the opportunity rate were 10 percent, the break-even life for the first alternative in the example would be between 6 and 7 years, as shown by setting the first equation with unknown factors equal to the second equation having a known value of $6,498:

$$\$25{,}000(\mathrm{UCR}{:}y{:}10\%) - \$5{,}000(\mathrm{USF}{:}y{:}10\%) - \$1{,}750 = \$6{,}498.$$

For 6 years,

$$\$25{,}000(0.2296) - \$5{,}000\ (0.1296) + \$1{,}750 = \$6{,}842,$$

and for 7 years,

$$\$25{,}000(0.2054) - \$5{,}000\ (0.1054) + \$1{,}750 = \$6{,}358.$$

Since $6,498 is between the two determined values, the break-even life for the first alternative to equal the second is 6.7 years if the opportunity rate is 10 percent. This 10 percent opportunity rate was used for illustration, since the sample table is 10 percent; however, it is a very low opportunity rate and is the minimum recommended by the Office of Management and Budget for most federal economic decisions.

Economic models also can be used to determine the sensitivity of various alternatives to any one variable. This is done by substituting various values for one variable in the model and seeing how sensitive the result is to these changes. Since it is quite likely that energy costs will increase at a greater rate than normal inflation, the effect of various rate changes at different times can be inserted into a model to see how sensitive the design decision is to this factor. If the decision is very sensitive to a factor, it may warrant more research on the forecasting technique to be used for inclusion in the analysis.

Using life-cycle, cost-benefit models to compare alternative building designs based on the expected cost during the annual operating cycle (daily, monthly, or quarterly as required) will enable architects and engineers to design the best buildings utilizing their clients' available resources. It will allow trade-offs of costs versus benefits in the various subsystems as well as between alternative designs. The final choice will be an energy-conserving alternative, since energy will continue to be a significant part of the annual operation cost of buildings.

The techniques for evaluating models of systems and subsystems are relatively simple to use. The big problem is in forecasting. Since forecasts must be made and since values are placed on benefits, whether recognized or not (when a decision to proceed with an alternative is made, those resources cannot be used for other investments), the use of life-cycle, cost-benefit analysis is one more valuable tool for resource optimization. It is not a simple computer readout; rather it requires the full use of the designer's ability and creative design potential to produce the best input-output utilization.

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SOLAR ENERGY CONSERVATION CASE STUDY

Willard A. Oberdick

The major problem in assessing solar impact on any component or building configuration is that of predicting quantitatively the component's or building's performance and relationship to the whole. The problem is complicated not only by many interrelationships, but also by the stochastic nature of the microsolar climate environment of the structure and the nature of its occupancy.

Using a case study, this paper will illustrate the use of two methods of quantifying the energy factors in buildings--i.e., solar climatic simulation and the statistical analysis of an appropriate energy-related historic data base. The paper is not intended to offer prescriptive answers or specific conclusions on building situations; indeed, at this time even the qualitative assessment of solar impact can only be based on fundamental principles, not "rules of thumb." The intuitive approach implicitly includes a strong experience factor, and the feedback of energy performance has been minimal at best. Hopefully, the methods advanced can be used to reinforce the experience factor in the decision-making process.

TENSIONS IN AN ENERGY-CONSCIOUS ENVIRONMENT

National awareness of the limitation of energy and material resources has resulted in many tensions for the architectural designer. After years of dependence on the use of mechanical equipment to obtain "design" independence from the influence of microclimate, such now must be considered. Subjects such as natural ventilation and natural lighting are discussed openly, but the designer cannot be sure if such options really save energy. If this dilemma is considered in the context of high expectations of predictable performance in thermal, luminous, and acoustic control, the question is raised: Must we change our performance requirements to meet our energy expectations? After years of technological development and research in increasing the efficiency of artificial lighting, as well as in maintaining higher light levels, it is a "shock" to walk in a dark corridor or see a building owner remove half of the light bulbs in a new building.

The answer to these implied concerns is life-cycle costing, a term that is rapidly coming into use by professionals, government officials, and building owners. If an analysis of a project indicates that significant energy can be saved by an initial higher cost, a test of commitment to life-cycle costing for all concerned will be evident. This is especially true if the payback period is greater than 3 years.

The major tension for the designer lies in the information gap. He may wish to carry out a life-cycle analysis for a project but probably cannot even obtain information on long-term costs for a piece of mechanical equipment or the annual "coefficient of energy" performance of, for example, an air-to-air heat pump. The problem is even more fundamental since, after all these years of sophisticated research, some have suggested that it is not possible to identify in a predictive sense the microclimate or even the macrosolar insolation. Thus, the approach in this paper is to use what are judged to be satisfactory methods based on available information and to check them by independent methods.

COMPARATIVE STUDY: DRAFTING STUDIO AT THE UNIVERSITY OF MICHIGAN

The dilemmas noted above were much in evidence for both the students and staff of the University of Michigan on the occasion of their occupancy of the new Art and Architecture Building. The building,[1] designed before the energy crisis, has been recognized as an efficient, well-designed structure with a low initial cost. Using 1974 life-cycle criteria, many were surprised to find no individual wall switches and a large percentage of single-glass and fixed glazing throughout. Further, within a 4-month period, the university had implemented an energy-conservation program[2] in which light bulbs were removed with the objective of reducing the lighting load by 50 percent. In addition, ventilation fans were placed on time clocks to reduce hours of operation and the associated loads.

Within this situation, many have had the "intuitive" reaction that the building would be one of the largest energy consumers on campus. However, based on projection of electrical and gas-metered data as recorded to date, we could assume that the consumption per square foot will be below the campus average for air conditioned buildings. We have used the large drafting room (Figure 1) of this building for the comparative computer study and the entire building (Figure 2) as a base of projection using the model developed with the analysis of the historic data base.

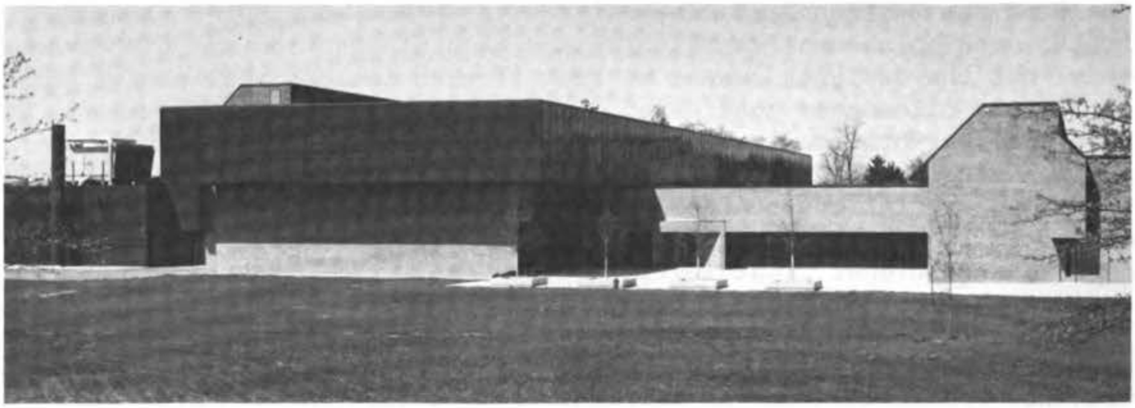

FIGURE 1 Northeast view of drafting studio (100 ft by 360 ft).

FIGURE 2 Southeast view of Art and Architecture Building.

Solar Climate Data Base

The information on solar climatic extremes is perhaps sufficient if one is concerned with peak heating loads, but only marginally adequate for cooling-load estimates. Where the building response is such, daily estimates of energy consumption may be adequate; however, where solar performance is crucial, as in a solar collector, hour-by-hour analyses may be required.

Assessment of solar impact requires data on or a method of predicting the insolation on any surface at any time. A major point that certainly involves consideration is cloud cover. One might not be concerned with this factor if long-term, recorded, solar-insolation (direct and indirect radiation) data are available, but in Michigan only one recording station exists in the Lower Peninsula, and it is limited to daily totals. Further, researchers have questioned the quality of the National Oceanic and Atmospheric Administration (NOAA) recorded data, indicating a possible 30 percent error. The computer simulation used for this study is based on U.S. Weather Bureau records relating recorded cloud cover to atmospheric turbidity and utilizing this in the prediction of direct and indirect radiation. The reader may question this approach, since the method of identifying cloud cover is qualitative in nature; however, one must consider this in relation to the alternatives.

A statistical comparison of 5 years of climatic data is included in Appendix A-1 to this paper. Cloud cover is taken from the NOAA weather station in Lansing and the corresponding daily total insolation data from the Michigan State University NOAA cooperating station in East Lansing. The histogram plot is of recorded solar radiation on a horizontal surface in Btu/ft^2/day. The regression model points out the major significance of the declination of the earth (days from the equinox) and sky clearness (i.e., inverse of cloudiness).

The simulation computer data base consists of 3 prototypical days for each month. Each day consists of climatic data interpolated for 10 2-hour periods with a.m. and p.m. sky clearness. All values are averages for appropriate days of that month taken from a selected year. The 3 days correspond in high-, average-, and low-temperature days.

In addition to the correlation studies of weather data, a macro comparison has been made between the simulation of a large building for a specific year and the metered energy consumption.

Method of Computer Simulation

Presently there is a proliferation of computer programs on building-energy analysis, although one can anticipate standardization efforts in the near future. The programs used in this study have been under development and in use by the Department of Architecture since 1966. The early versions were used for the life-cycle comparative analysis of exterior wall and roof components. The present version incorporates air conditioning psychometrics and partial-load energy summaries.

The simulation consists of computations for 36 days of 10 2-hour periods with intermediate information stored in 36-by-10 arrays. Five program steps are involved: (1) identification of building data, materials, dimensions, and thermal organization; (2) identification of system and design parameters; (3) analysis of walls; (4) analysis of systems; and (5) analysis of partial-load energy requirements. Selected output is included in Appendixes B-1 and B-2 of this paper. As suggested above, solar radiation is computed considering cloud cover. Heat-transfer computations involve thermal lag of opaque materials as well as the angle of incidence on a transparent surface. Exterior shading is accomplished on a point-by-point check during periods of direct sunlight on the panel.

The comparisons included in this paper were implemented by editing the file noted as BLDG (Appendix B-1). For example, to rotate Room 310 180 degrees, it was necessary only to change Wall 10 to Wall 30 and Wall 30 to Wall 10. To explore the option of "no sun," it was necessary only to zero the absorptivity (0.70) for each of the walls and the transmission (0.47) for the glass. The latter situation did require repeating step 3 on wall analysis. To change the user pattern for lights (MYSYS) or occupants (ACTI), one needs to change the 1.00 (MSYS) to, for example, 15.00 as used for the alternative strategy.

Solar Impact Comparisons

The studies are presented in two forms. First a comparison (Table 1) is made of the relative importance of the several factors in terms of design loads and projected energy consumption. All values are for the 36,670-ft^2 drafting studio as built (see Figures 1 and 2).

The slight increase in heating load due to the impact of the sun results from night cooling on clear, cold nights. The passive solar impact in heating is negated by a substantial gain in cooling (14 percent) of gas energy. The reduction of cooling energy due to ventilation varies with the actual cooling load at the time. The low value (-9,680) applies to the hypothetical operation with only internal loads. The total at-source equivalent for the information shown is 213,600 Btu/ft^2/yr. The solar impact of this north-oriented room of light construction is very minimal, assuming full use of artificial lighting.

TABLE 1 Functional Distribution of Loads and Energy for Drafting Studio

	Thermal Factor					
Load/Energy	Internal Lights and Occupants	Ventilation (assumed 10%)	Walls and Roof (air to air)	Walls and Roof (solar)	Auxiliary Motors	Total
Heating load	0	9.7	22.7	0.4	--	32.8
Cooling load	10.6	1.4	2.4	7.2	--	21.6
Heating energy (gas)	0	16,900.0	51,600.0	-4,500.0	--	64,000.0
Cooling energy (gas)	47,900.0	-22,900.0 -9,680.0	6,600.0	20,000.0	--	51,800.0
Electrical energy (energy)	26,700.0	--	--	--	5,700	32,400.0

NOTE: All values in Btu/ft^2 of floor area. Loads as capacity and energy on per annum basis. Negative values indicate a reduction in energy consumption for the particular factor.

TABLE 2 Comparison of Solar Impact for Alternative Solutions for Drafting Studio

Building cond.	As built	As built	180° rot.	Modified	Modified	Modified and 180° rot.	Modified and 180° rot.
Environ. cond.	Normal	No sun	Normal	Normal	No sun	Normal	Normal
Glazing	Single	Single	Single	Double	Double	Double	Double with shade
Heating load	32.7	32.4	35.3	25.3	24.8	25.3	25.3
Cooling load	21.5	14.3	21.6	18.9	13.3	37.5	23.0
Heating energy (gas)	64,000	68,500	57,600	46,800	52,000	41,300	41,300
Cooling energy (gas)	51,800	31,600	72,600	50,600	32,600	70,500	66,400
Total energy (gas)	115,800	100,100	130,200	97,400	84,600	111,800	107,700

NOTE: All values in Btu/ft^2 of floor area. Loads as capacity and energy on a per annum basis. For the studio each 1,000 Btu of energy/ft^2 is the equivalent of 185 barrels of oil or 266 ft^3 of gas over the next 40 years.

Table 2 includes comparisons only for heating and cooling, omitting the electrical energy factor (the first column corresponds to Table 1). A comparative examination of the charts permits one to identify principles relating to both initial costs (loads) and/or energy consumption. The large scale of the room reduces the solar impact on a unit floor area comparison.

Conclusions: An Alternative Strategy

From the strategies compared in the above, it is quite apparent that a major solar impact can be achieved only if direct use is made of natural lighting (Table 3). Changes would include reorienting the direction of fluorescent lights to parallel the glass wall, reswitching, placing the north and south glass in the most effective location (i.e., not at the floor), introducing shading on the south, and changing the glass to double clear plate. Note that the present situation includes the bulb-removal energy reduction strategy.

TABLE 3 Comparison of an Alternative Design Strategy for the Drafting Studio

Conditions	Present Situation	Alternative Strategy
Floor area	36,700 ft^2	36,700 ft^2
Volume	587,000 ft^3	587,000 ft^3
North wall	100% glass	30% glass
South wall	100% of 25% length	30% of 25% length
West wall	No glass	No glass
East wall	No glass	No glass
Wall materials	Insulated panel; single height absorb. plate	Insulated panel; double clear plate with shading
Lighting type	Fluorescent 2 W/ft^2	Fluorescent 2 W/ft^2
Lighting use	2,940 h/yr	650 h/yr
Ventilation min	3,700 ft^3/min	3,700 ft^3/min
Heating load	1,200 thousand Btu	700 thousand Btu
Cooling load	790 thousand Btu	430 thousand Btu
Heating fuel	2,350 million Btu/yr	1,600 million Btu/yr
Cooling fuel	1,900 million Btu/yr	800 million Btu/yr
Lighting electricity	980 million Btu/hr	290 million Btu/yr
Total at-source energy	196 thousand Btu/ft^2/yr	90 thousand Btu/ft^2/yr

The alternative strategy (Table 3) utilizes the same 2 W/ft^2 at a reduced-use factor. The computer simulation utilizes the user pattern designated as 15.00 in Appendix B-2. A net reduction of 106,000 Btu/ft^2 is significant and is a major solar factor. Luminous and thermal performance are inextricably linked and must be so considered in decision making.

HISTORIC ENERGY DATA

During the fall of 1973 the Architectural Research Laboratory developed a trial data base as part of a feasibility study of a state computer-based building information system for life-cycle costing.[3] This trial data file was adapted as an energy data base to run on MIDAS, a university-supported statistical computer software system.[4] The objectives in this study were to explore the use of historic building and energy data in forecasting energy consumption and/or total owning costs and to explore the use of the method for identifying significant parameters that need to be considered in effective forecasting and/or control. The predictions from regression models identified in this study are compared to the current year's metered data for the Art and Architecture Building.

Scope of Data Base and Analyses

The original data base consisted of 25 public buildings located in Lansing, East Lansing, and Ann Arbor, Michigan, operated by four public agencies. Five buildings were removed from the set because no building-based metered energy data were available. The present building energy data base consists of 90 variables, 11 of which are categorical. The analytical variables consist of building descriptors: initial, janitorial, and maintenance costs and unit and total energy costs. The descriptors were selected on what were assumed to be logical determinants of energy consumption and long-term costs.

The group of 20 buildings has a wide range of physical characteristics varying in area from 25,000 ft^2 for an elementary school of 370,000 ft^2 for an office-laboratory-classroom complex. Further, there is a corresponding variation in the complexity of the mechanical system and design environmental criteria. Although this variation may be a desirable feature, the small number of cases (buildings) limited the options in subsetting. The metered energy noted is based on condensate (steam) or gas-oil and electric meter readings interpreted to equivalent Btu. No adjustment was made between the efficiency of steam and that of gas and oil except that the type of heat source is one of the categorical variables. The term "Total Energy" in contrast to "Fuel" and "Electricity" refers to at-source energy and is interpreted to be the sum of fuel energy equivalents and of three times the electrical energy. It is used as a transformed dependent variable in the regression studies. In each case the values used are the averages for the fiscal years 1971 and 1972. Refer to Table 4 for a comparison of the air conditioned buildings.

TABLE 4 Comparison of Subset of Buildings Used in Regression Models

Building No.	Use	Floor Area (ft^2)	Surface[a] Dec.%	Glass[b] Dec.%	Source Energy (million Btu/ft^2/yr 1971	1972
149	Office	79,100	0.65	0.06	504	592
2543	Office	242,000	0.47	0.29	360	434
2544	Office	253,500	0.51	0.37	333	313
2547	Office	157,500	0.87	0.28	700	676
2546	Office	280,000	0.51	0.13	648	628
2545	Office	212,000	0.48	0.30	650	630
145	Office	81,600	0.54	0.04	734	734
162	Classroom, office, and lab	307,200	1.27	0.02	504	505
207	Classroom and office	127,400	0.50	0.42	387	536
440	Classroom	110,000	0.89	0.16	388	423
234	Lab and office	169,600	0.51	0.19	596	590
Mean		183,600	0.65	0.21	527	551
Art and Archi-tecture	Classroom and lab	210,000	0.94	0.38	--	388

[a] Surface percent = roof area and wall area/floor area.
[b] Glass percent = glass area/wall area.

The selection of acceptable least squares regression models was based on the following criteria: (1) the particular equation should account for more than 90 percent of the variation; (2) the standard error of the estimate should be less than 5 percent of the mean amount of the dependent variable; (3) the statistical uncertainty for treating any apparent difference as real should be slight, a level of 1 percent; and (4) the residuals should be such that any differences related to particular categories are explained.

Dummy variables are introduced to account for differences assumed to be associated with certain of the categorical variables. These were related to air conditioning, location, heat source, and air handling. Because of complexities, air handling was identified by two variables. The specific variables referenced in the models are noted in Appendix C-1.

Analysis of Energy Consumption--Total Energy

The entire set of 20 buildings was studied for total energy consumption. The independent variables, volume, glass area, and unit watts, together with dummy variables for air conditioning and location, were found to be the most significant. The resulting Regression Model A and comparisons are included in Appendix C-1. The model accounts for 98 percent (R-squared statistic) of the variation of total energy in the set of 20 buildings. The ratio of standard error to mean is 12 percent for the entire set; however, if the set is restricted to the air conditioned buildings using absorption refrigeration, this is reduced to 9 percent. An analysis of the variance of the errors (i.e., difference between the predicted value and actual value, referred to as residuals) indicates that the model does explain difference accounted for by agency, percentages of glass, and size.

Each of the independent variables used in this model can be considered as logical determinants of total energy consumption in this particular set of public buildings. If the group of buildings were restricted further, as indicated in Table 4, to only air conditioned buildings using absorption refrigeration, the particular differences of the set would result in different variables. Models developed for this set resulted in volume, roof area, the number of mechanical zones, and the dummy variable for the type of air handling as being the more significant variables. In the latter situation Building 2550 had been removed as it was the only building using electrically powered refrigeration in unitary roof-mounted units. This set was used for the models for fuel and electric consumption. Comparison of the variables for the 12 buildings are included in Appendix C-1.

The Art and Architecture Building was excluded from each of these sets. Predictions using Model A results in an energy consumption prediction of 355 thousand Btu/ft^2/yr. This is an 11 percent underestimate from the metered consumption in the past year.

Analysis of Energy Consumption--Fuel and Electricity

A regression model based on the energy equivalent of average fuel consumption for 1971 and 1972 was developed with the set of 12 buildings, Model B in Appendix C-2. The model was obtained using wall area, the construction date, and electrical consumption as variables. The ratio of standard error to mean of 12 percent is excessive and does indicate the need for further study. Projections for the Art and Architecture Building of 243 thousand Btu in this case do compare favorably to the metered value of 233 thousand Btu, an overestimate of 4 percent.

The same set of 12 buildings was used as a base for developing a regression model for the electrical "at-building" energy consumption for 1971 and 1972, Model C in Appendix C-2. The variables, volume, glass area, unit watts, and the dummy variable for location were the significant parameters in the model. The model statistically should account for 99 percent of the variation in the set with the ratio of standard error to the mean of 8 percent. The estimate for the Art and Architecture Building was 49 thousand Btu as compared to the current years of total of 56 thousand Btu, a 12 percent underestimate.

Using the regression models for fuel and electricity one would obtain an estimate of 390 thousand Btu/ft^2 as compared to the metered 401 thousand Btu. Both of these can be compared to the results from Total Energy Model A of 355 thousand Btu.

Although the estimates in this case may be satisfactory, one cannot conclude that the factors would be the most significant in other cases. The small number of cases and resulting limitations in statistical significance preclude any such observations. The examples presented appeared to be the best illustrations of the use of the data base then available.

Solar Impact--Principles

In the discussion of the regression models, significant parameters were identified in each case. Although in each case the particular parameters are intuitively logical, one must note the relation in each case between the unique characteristics and differences of the selected set of buildings. One particular concern has been the relationship between the quantity of glass and total energy consumption. Examination of the models for total energy and electricity indicate a strong negative impact of the glass area (i.e., those buildings in the set which have large glass areas also use relatively less electrical energy). One cannot, on the basis of this study, assume a direct causal relationship, although statistical checks indicate that the models account for differences in relation to the ratios of glass areas to floor areas. The several parameters in the multiple regression cannot be taken out of context, particularly in relation to their negative or positive influence in the equation. Rather one can only say that in the set of 12 office-classroom buildings in southeastern Michigan using electricity primarily for lighting and air handling, the buildings with less glass used more electrical energy in 1971 and 1972.

CONCLUSIONS

We have attempted to identify two methods, namely computer simulation and the statistical study of historic data in the study of solar effects on buildings. Both methods require considerable resources for implementation. Based on our experience, we suggest that consortia of practitioners and academicians could logically prepare these research instruments (i.e., assemble energy-related data sets for study and use by the participants). Perhaps, in that way, the "intuitive approach" in predicting solar effects can be examined without adding more energy "guzzlers" to our environment.

NOTES

1. The Art and Architecture Building, North Campus, University of Michigan at Ann Arbor--Swanson Associates, Architects and Engineers, Birmingham, Mich.; Hoyem Associates, Electrical Engineers, Birmingham, Mich.; Spence Brothers, General Contractors, Toledo, Ohio. Construction period--September 1972 to September 1974.
2. Program under the direction of Donald F. Wendel, Director of Plant Operations, University of Michigan.
3. Research was jointly supported by the Bureau of Facilities, Department of Management and Budget, State of Michigan, and the Institute of Science and Technology, University of Michigan.

4. MIDAS--Michigan Interactive Data Analysis System, supported by the Statistical Research Laboratory, University of Michigan.

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#$RUN STAT:MIDAS
#EXECUTION BEGINS

 M I D A S
 STATISTICAL RESEARCH LABORATORY
 UNIVERSITY OF MICHIGAN
 00:01:11
 APR  3, 1975


 READ OBSERVATIONS
 VARIABLES BY CASE

   2191 CASES READ FOR   19 VARIABLES
 MISSING DATA SUMMARY

 INDEX VARIABLE    #MISSING #LEVELS        VARIABLE LIST

       1 YEAR                  70
       2 MONTH                 12
       3 DAY                   31
       4 EQUIN                           Days from Equinox
       5 DRYBUL          21              *Degree Fahrenheit (Dry bulb)
       6 HUMRAT          21              *Grains/10 lbs. of Dry Air (Humidity Ratio )
       7 WINDSP          21              *Miles per hour(Wind Speed)
       8 WINDDIR         21              *Wind direction  (Degrees from North)
       9 VISIB           21              *Visibility in tenth of a mile
      10 SKYCLEAR        21              **Percent of sky clearness (0 - 100)
      11 CALCRAD         21              BTUs/sq.ft. of horizon/day calculated
      12 12NRAD          21                "      "      "       "      "
      13 CLEARAD         21              "      "      "       "      "
      14 12NCLRAD        21              "      "      "       "      "
      15 RAIN            21              Hours per day
      16 SNOW            21                "    "   "
      17 DAILYRAD       146              BTUs/sq.ft. of horizon/day recorded
      18 ETR            146
      19 PERCTR         146

 TOTAL MISSING          690             *Average for 24 hour period
 TOTAL # CASES         2191            **   "      for daylight hours
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DISTRIBUTION OF RECORDED DAILY RADIATION - 1965 - 1971

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 HISTOGRAM/FREQUENCIES

 MIDPOINT    COUNT FOR DAILYRAD     (EACH X =9)

  2.0000      107 +XXXXXXXXXXXX
  327.70      358 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  653.40      323 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  979.10      285 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  1304.8      223 +XXXXXXXXXXXXXXXXXXXXXXXXX
  1630.5      206 +XXXXXXXXXXXXXXXXXXXXXXX
  1956.2      189 +XXXXXXXXXXXXXXXXXXXXX
  2281.9      214 +XXXXXXXXXXXXXXXXXXXXXXXX
  2607.6      122 +XXXXXXXXXXXXXX
  2933.3       17 +XX
  3259.0        1 +X

  MISSING     146
  TOTAL      2191  ( 325.70    = INTERVAL WIDTH)
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 DESCRIPTIVE MEASURES          STRATUM = 65

 VARIABLE        N    MEAN       STD DEV   SE OF MEAN   MINIMUM     MAXIMUM

 DRYBUL         360   47.153     19.612     1.0337      1.0000      84.000
 HUMRAT         360   445.20     272.64     14.370      44.000      1177.0
 WINDSP         360   9.5444     4.1407     .21824      2.0000      30.000
 SKYCLEAR       360   44.067     27.203     1.4337     -1.0000      100.00
 DAILYRAD       358   1181.1     789.41     41.721      2.0000      2833.0


 DESCRIPTIVE MEASURES          STRATUM = 66

 DRYBUL         362   46.787     20.255     1.0646     -1.0000      85.000
 HUMRAT         362   389.00     246.50     12.956      41.000      1068.0
 WINDSP         362   8.4116     4.2517     .22346      1.0000      21.000
 SKYCLEAR       362   46.964     29.219     1.5357     -1.0000      100.00
 DAILYRAD       357   1211.4     783.03     41.442      39.000      2781.0


 DESCRIPTIVE MEASURES          STRATUM = 67

 DRYBUL         362   46.575     19.441     1.0218      0.          83.000
 HUMRAT         362   392.85     240.84     12.658      41.000      1033.0
 WINDSP         362   9.1050     3.8890     .20440      2.0000      20.000
 SKYCLEAR       362   45.110     28.416     1.4935     -1.0000      100.00
 DAILYRAD       339   1242.3     759.01     41.224      76.000      2813.0


 DESCRIPTIVE MEASURES          STRATUM = 68

 DRYBUL         363   47.074     19.943     1.0467      1.0000      84.000
 HUMRAT         363   407.68     276.70     14.523      47.000      1228.0
 WINDSP         363   8.8671     4.2939     .22537      1.0000      27.000
 SKYCLEAR       363   48.317     28.899     1.5168     -1.0000      100.00
 DAILYRAD       320   1202.8     754.67     42.187      32.000      2829.0


 DESCRIPTIVE MEASURES          STRATUM = 69

 DRYBUL         364   47.453     19.692     1.0322      5.0000      82.000
 HUMRAT         364   432.87     291.59     15.283      58.000      1214.0
 WINDSP         364   8.8269     3.6372     .19064      2.0000      22.000
 SKYCLEAR       364   46.923     29.546     1.5486     -1.0000      100.00
 DAILYRAD       322   1182.6     754.65     42.055      64.000      3259.0


 DESCRIPTIVE MEASURES          STRATUM = 70

 DRYBUL         359   46.905     20.368     1.0750      2.0000      82.000
 HUMRAT         359   434.40     295.72     15.608      49.000      1259.0
 WINDSP         359   9.3816     3.9525     .20860      1.0000      21.000
 SKYCLEAR       359   45.178     28.131     1.4847     -1.0000      100.00
 DAILYRAD       349   1240.9     798.42     42.739      41.000      3059.0
```

DESCRIPTION OF VARIABLES BY YEAR 1965 - 1970

APPENDIX A-1 Solar-climatic simulation: Lansing-East Lansing, Michigan.

APPENDIX A-2
Solar-Climatic Data Analysis:
East Lansing-Lansing, Michigan.

```
COMMAND
?SELECT V=17,4-10,15,16 OPTION=FORWARD LEVELS=.05,.1
MAXIMUM NUMBER OF STEPS
?8


SELECTION OF REGRESSION


ANALYSIS OF VARIANCE OF DAILYRAD           N= 2024       EQN= 4

SOURCE                  DF    SUM OF SQRS   MEAN SQUARE   F-STATISTIC SIGNIF

REGRESSION               4    .10090+10     .25224 +9     2528.0      0.
ERROR                 2019    .20145 +9     99779.
TOTAL                 2023    .12104+10

MULTIPLE R= .91300   R-SQR= .83357    SE= 315.88


VARIABLE            PARTIAL    COEFFICIENT    STD ERROR    T-STATISTIC SIGNIF

CONSTANT                       455.53         19.513       23.345      0.
EQUIN               .80850     8.6210         .13966       61.730      0.
VISIB               .06858     .60544         .19602       3.0887       .0020
SKYCLEAR            .74632     14.919         .29611       50.384      0.
SNOW                .16227     43.861         5.9357       7.3895       .0000

REMAINING           PARTIAL    SIGNIF

DRYBUL              .04118     .0643
HUMRAT             -.03944     .0763
WINDSP              .01905     .3921
WINDDIR             .02435     .2740
RAIN               -.02704     .2245


REGRESSION OF DAILYRAD                FORWARD  SELECTION

EQN   R-SQR   STD ERR   # VAR       VARIABLE          PARTIAL   T-STAT     SIGNIF

1     .54957 519.27         1 IN    EQUIN             .74133    49.669     0.
2     .82867 320.34         2 IN    SKYCLEAR          .78716    57.378     0.
3     .83278 316.54         3 IN    SNOW              .15497    7.0503      .0000
4     .83357 315.88         4 IN    VISIB             .06858    3.0887      .0020
```

SELECTION OF REGRESSIONAL MODEL WITH RECORDED DAILY RADIATION AS THE DEPENDENT VARIABLE

Refer to A-1 for identification of variables

APPENDIX B-1

Computer Simulation--Sample Output: Drafting Studio, University of Michigan.

```
 C BLDG
>MATE    2 PANEL WALLS
>          17.22  URETHANE/BDINSULAT/2IN/         11110000000010001
>            2.00    2.00    0.15    0.29    0.0     3.00
>          35.10  GLASS/PLHTABS/                  00001110000010001
>            0.47    0.70    1.06    1.00    3.00
>          TRANS.  SHGF.   "U"
>MATE    4 ROOF
>          23.10  ASPHALT/BUILTUPROOF/            11110000000010001
>            0.37   70.00    1.11    0.35    0.0     3.00
>          17.40  FIBERGLAS/BDINSULAT/2IN/        11110000000010001
>            2.00    7.00    0.25    0.19    0.0     3.00
>          13.12  CONCRETF/POURFDSLAB/4IN/        11110000000010001
>            4.00  145.00   12.00    0.16    0.0     3.00
>          THIC.  DENSITY  COND.   SPEC.H T.
>WALL   10 NORTH
>            2    90.00     0.00     0.70    0    0
>          MATE ELEV.     AZIM     ABSORBTIVITY
>WALL   20  EAST
>            2    90.00    90.00     0.70    0    0
>
>WALL   30  SOUTH
>            2    90.00   180.00     0.70    0    0
>
>WALL   40 WEST
>            2    90.00   270.00     0.70    0    0
>
>WALL   50 ROOF
>            4     0.0      0.0      0.90    0    0
>
>WALL   60 SLOPED SKYLIGHT
>            2    60.00     0.0      0.70    0    0
>
>ACTI   10  GENERAL
>         70.60  SEMINAR/COLLEGE/                 00000000000010111
>           9.00 250.00 200.00   3.00
>                SENSIBLE LATENT?OCCUPANT.
>MSYS   10 GENERAL LIGHTING
>         50.10  LIGHTING/FLUOR/SURFACE/          00000000000220222
>           1.00000   8.00000   0.0         4.08000   3.00000
>         % H T. TO SPACE.                   BTUs/NOM. WATT.
>
>ROOM 310DRAFTING ---NORTH ORIENTATION
>        WALL   10   361.20WID16.00 HT 1.00 % GLASS
>        WALL   20   101.50     16.00     0.0
>        WALL   40   101.50     16.00     0.0
>        WALL   30    89.70     16.00     1.00
>        WALL   5035516.00      1.00     0.0
>        WALL   60 1150.00      1.00     1.00
>        MSYS   1036670.00AREA2.00WATT4.00CAV.1.00 USER PATTERN
>        ACTI   10   300.00     2.00          DEPTH
>                    NO.OCCUP.USER PATTERN
>
>ZONE 100
>        ROOM 310
>
```

FILE BLDG. - DESCRIPTIVE BUILDING INFORMATION FOR THE DRAFTING STUDIO

```
                                                        USER PATTERNS
 C USEPATR(31,43)
>USEP    1   4   6   8 10 12 14 16 18 20  22DAYS/MONTH    ( )/10* 100 = Percent of
>            0   0 10 10 10 10 10 10  2   2 23      JAN    use at a specific hour
>            0   0 10 10 10 10 10 10  2   2 22      FEB
>            0   0 10 10 10 10 10 10  2   2 23      MAR
>            0   0 10 10 10 10 10 10  2   2 22      APR
>            0   0 10 10 10 10 10 10  2   2 23      MAY
>            0   0  7  7  7  7  7  7  2   2 22      JUN
>            0   0  7  7  7  7  7  7  2   2 23      JUL
>            0   0  7  7  7  7  7  7  2   2 23      AUG
>            0   0 10 10 10 10 10 10  2   2 22      SEP
>            0   0 10 10 10 10 10 10  2   2 23      OCT
>            0   0 10 10 10 10 10 10  2   2 22      NOV
>            0   0 10 10 10 10 10 10  2   2 23      DEC
#

 C USEPATR(213)
>USEP   15   4   6   8 10 12 14 16 18 20  22DAYS/MONTH
>            0   0   0   0  4  4  4  0  2   2 23      JAN
>            0   0   0   0  4  4  4  0  2   2 22      FEB
>            0   0   0   0  4. 4  4  0  2   2 23      MAR
>            0   0   0   0  4  4  4  0  2   2 22      APR
>            0   0   0   0  4  4  4  0  2   2 23      MAY
>            0   0   3   3  3  3  3  0  2   2 22      JUN
>            0   0   3   3  3  3  3  0  2   2 23      JUL
>            0   0   3   3  3  3  3  0  2   2 23      AUG
>            0   0   0   0  4  4  4  0  2   2 22      SEP
>            0   0   0   0  4  4  4  0  2   2 23      OCT
>            0   0   0   0  4  4  4  0  2   2 22      NOV
>            0   0   0   0  4  4  4  0  2   2 23      DEC
#SRUN ARCH:WANALM# 3=THER 7=BLDG 5=ARCH:CLIMASIMU 1=-WALL *=*SOURCE*  *=
#EXECUTION BEGINS
 NAME OF CITY-YEAR?
 DECL
 WALL SUMMARY--BTUS/SQ.FT./HR.                                  WALL SUMMARY
           TRANSPAREN       OPAQUE   SHAD
            MAX    MIN    MAX    MIN   PERC
 WALL  20 139.0 -74.1    2.1   -4.6    0.0
    HOUR      8      4      8      4      0
    MONT      8      2      7      2      0
 WALL  40 146.0 -74.2    2.7   -4.6    0.0
    HOUR     16      8     16      4      0
    MONT      8      2      7      2      0
 WALL  10  35.0 -74.2    1.0   -4.6    0.0
    HOUR     18      8     14      4      0
    MONT      6      2      8      2      0
 WALL  50   0.0    0.0   3.9   -7.6    0.0
    HOUR      0      0     18      8      0
    MONT      0      0      5      2      0
 WALL  60  54.0 -74.2    1.4   -4.6    0.0
    HOUR     16      8     16      4      0
    MONT      6      2      7      2      0
 WALL  30 144.0 -74.1    2.1   -4.6    0.0
    HOUR     12      4     12      4      0
    MONT     10      2      9      2      0
 WALL  30 144.0 -74.1    2.1   -4.6    0.0
    HOUR     12      4     12      4      0
    MONT     10      2      9      2      0

  STOP      0
#EXECUTION TERMINATED                                         SYSTEM SUMMARY
#SOU BTECH(4,4)
#SRUN ARCH:AIRSYST# 0=-ROOM 1=-WALL 2=-SYST 3=THER 4=ARCH:USFPATP *=ARCH
#EXECUTION BEGINS
          MAXIMUM MO HR  MINIMUM MO HR   CFM   RSHR
 ROOM 310  703641  5 18 -868043  2  4 31983  0.92  MAX & MIN...BTUs/HR
  SYST 100 APR.DP= 58.00 SHR=  0.92 PLEN.DB= 78.00
 SYST 100  789434  8 14-1202097  2  6 31983
```

```
#SOU BTECH(5,5)+*SOURCE*
#SRUN N959:SECTENER# 0=-SYST 5=ARCH:CLIMASIMU
#EXECUTION BEGINS
  ENTER NAME OF CITY YEAR...? DECL
  ENTER MAX. COOLING LOAD FORSECT  0 ...? 789434.
  ENTER COPS FOR 100/75/50/25 %S...? .54,.58,.59,.54
 SUMMARY ENERGY USAGE--FOR  SECT  0
 TOTALS FOR PROTYPICAL DAYS IN THE MONTH--SUBTOTALS FOR THE MONTH
 ALL ENERGY VALUES AND LOADS ARE IN MBTUS I.E.X1000 BTUS
  MONTH  HTFUEL COOFUEL  HTLOAD COOLOAD     DAYS  WINDSP AMSKYCL PMSKYCL
 HIGH 1  -12270       0   -9819       0        3       8      99      99
 AVER. 1 -15446       0  -12360       0       24      12      28      3*
 LOW. 1  -21584       0  -17270       0        4      10      **      20
 SUBTOT -493850       0 -395177       0
      2  -11809       0   -9449       0        3      11      99      99
      2  -13394       0  -10718       0       23      13      18      29
      2  -20581       0  -16466       0        2      14      70      80
 SUBTOT -384651       0 -307793       0
      3   -6187       0   -4951       0        2      16      99      99
      3  -10789       0   -8633       0       28      14      30      30
      3  -12689       0  -10153       0        1      12       *      1*
 SUBTOT -327155       0 -261779       0
      4   -3307    7282   -2647    3934        2      17      99      99
      4   -6357    2504   -5087    13*4       25      14      2*      22
      4   -7064    2580   -5654    1394        3       6      53      *3
 SUBTOT -186731   84904 -149431   45900
      5   -1730   14507   -1384    7835        1       9      99      99
      5   -1646    9893   -1318    5344       26      10      26      17
      5   -5377    3671   -4303    1984        4      10      30      31
 SUBTOT  -66034  286409  -52864  154715
      6    -472   14007    -378    7567        4      10      99      99
      6    -577   11269    -462    6087       22       9      31      26
      6   -2687    7816   -2151    4222        4       8      67      42
 SUBTOT  -25330  335210  -20280  181070
      7    -127   15287    -102    8257        2       9      99      99
      7    -382   12295    -306    6642       26       8      38      27
      7   -1378   10888   -1103    5882        3       6      75      31
 SUBTOT  -14320  382908  -11469  206852
      8       0   17060       0    9215        2      11      99      99
      8       0   12971       0    7007       27       9      30      24
      8   -1875    9216   -1500    4978        2       9      *5      62
 SUBTOT   -3750  402769   -3000  217575
      9    -803   14439    -643    7799        5      10      99      99
      9   -1525    9563   -1221    5166       23      10      27      32
      9   -5812    4453   -4651    2406        2       8      60      5*
 SUBTOT  -50714  301050  -40600  162625
     10   -1032   12653    -826    6835        1      13      99      99
     10   -4724    3579   -3780    1934       25       9      29      26
     10   -7581     858   -6067     464        5      10      34      47
 SUBTOT -157037  106418 -125661   57505
     11   -2955       0   -2365       0        1      16      99      99
     11   -9582       0   -7668       0       27      12      30      23
     11  -17168       0  -13737       0        2      19       ?      27
 SUBTOT -296005       0 -236875       0
 HIGH 12  -8900       0   -7121       0        1      12      99      99
 AVER. 12 -10880      0   -8706       0       29      10      27      24
 LOW 12  -17443       0  -13958       0        1       6       0      10
 SUBTOT -341863       0 -273553       0      SOLAR CLIMATIC DATA

 HEATING FUEL ENERGY PER YEAR= -2347440 MBTUS
 COOLING FUEL ENERGY PER YEAR=  1899668 MBTUS
```

APPENDIX B-2 Computer Simulation--Sample Output: Drafting Studio, University of Michigan.

MODEL A TOTAL AT - SOURCE ENERGY
TOTAL SET - 20 BUILDINGS

LEAST SQUARES REGRESSION CASES=CASE#:1-20

ANALYSIS OF VARIANCE OF 108.AVENER N= 20 OUT OF 20

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
REGRESSION	5	.49039+11	.98078+10	148.82	.0000
ERROR	14	.92263 +9	.65902 +8		
TOTAL	19	.49961+11			

MULT R= .99072 R-SQR= .98153 SE= 8118.0

VARIABLE	PARTIAL	COEFF	STD ERROR	T-STAT	SIGNIF
CONSTANT		-18590.	5304.4	-3.5046	.0035
16.VOLUME	.95383	.28654 -1	.24115 -2	11.882	.0000
20.GLAS.ARE	-.89178	-2.0406	.27671	-7.3746	.0000
24.WATT.UNI	.79382	9819.0	2010.4	4.8840	.0002
100.DUMAC	.83499	26834.	4726.2	5.6778	.0001
104.DUMLOCAT	.74215	24688.	5958.7	4.1431	.0010

COMPARISON OF MODEL A
TOTAL SET - 20 BUILDINGS

DESCRIPTIVE MEASURES CASES=CASE#:1-20

VARIABLE	N	MINIMUM	MAXIMUM	MEAN	STD DEV
108.AVENER	20	4949.0	.17872 +6	66964.	51279.
332.PRED.ENE	20	2046.2	.18112 +6	66964.	50803.
112.UNENER	20	136.30	883.13	427.52	219.96
334.ENER.PRE	20	78.380	885.47	420.08	230.66
335.ENER.ERR	20	-.46469	.66900	.20701 -1	.28077

COMPARISON OF MODEL A.
SET WITH ABSORPTION STEAM - REFRIGERATION.

DESCRIPTIVE MEASURES STRAT=REFR.TYP:4 CASES=CASE#:1-20

VARIABLE	N	MINIMUM	MAXIMUM	MEAN	STD DEV
108.AVENER	12	43387.	.17872 +6	92557.	45358.
332.PRED.ENE	12	45627.	.18112 +6	92534.	43907.
112.UNENER	12	323.18	734.49	524.99	135.92
334.ENER.PRE	12	351.87	680.99	527.97	126.82
335.ENER.ERR	12	-.25619	.98767 -1	-.14348 -1	.10696

PARAMETERS - FOR BUILDING SET USING.
ABSORPTION STEAM REFRIGERATION.

DESCRIPTIVE MEASURES STRAT=REFR.TYP:4 CASES=CASE#:1-20

VARIABLE		N	MINIMUM	MAXIMUM	MEAN	STD DEV
15.FLO.AREA	sq.ft.	12	79107.	.30716 +6	.17913 +6	78105.
16.VOLUME	cu.ft.	12	.10699 +7	.42467 +7	.25944 +7	.12339 +7
18.ROOFAREA	sq.ft.	12	9689.0	70000.	33929.	19370.
19.WALLAREA	sq.ft.	12	34722.	.32654 +6	86765.	79266.
20.GLAS.ARE	sq.ft.	12	1448.0	37500.	14212.	11162.
21.FLOO.NUM	No.	12	3.0000	10.000	6.5000	2.1106
23.MECH.ZON	No.	11	35.000	276.00	170.73	76.802
24.WATT.UNI	watts/ft^2	12	1.4300	4.9000	2.9192	1.2967
100.DUMAC	0 or 1	12	1.0000	1.0000	1.0000	
102.DUMAH.1	0 or 1	12	0.	1.0000	.75000	.45227
104.DUMLOCAT	0 or 1	12	0.	1.0000	.41667	.51493
106.AVFUEL	MM BTUs/yr.	12	22544.	76748.	44191.	16610.
207.AVELEC	"	12	4304.3	37502.	16122.	10568.
108.AVENER	"	12	43387.	.17872 +6	92557.	45358.
110.UNFUEL	M BTUs/sqft/yr.	12	88.933	423.81	272.05	91.137
211.UNELEC	"	12	39.076	133.93	84.311	31.564
112.UNENER	"	12	323.18	734.49	524.99	135.92

KEY:

AVENER	METERED AT SOURCE°ENERGY MM BTUs/YR. AVERAGE 1971 - 1972
PRED.ENE	MODEL - PREDITIONS MM BTUs/YR.
UNENER	UNIT METERED M BTUs/sqft/YR.
ENER.PRE	UNIT PREDICTED M BTUs/sqft/YR.
ENER.ERR	RESIDUAL/METERED (dec.%)
DUMAC	DUMMY VARIABLE - AIR CONDITIONING.
DUMAH.1	DUMMY VARIABLE - AIRHANDLING TYPE
DUM LOCAT	DUMMY VARIABLE - LOCATION

APPENDIX C-1 Historic Data Base--Energy: Analysis of Data.

MODEL B **FUEL ENERGY**

SET WITH STEAM ABSORPTION REFRIGERATION.

```
LEAST SQUARES REGRESSION  STRAT=REFR.TYP:4  CASES=CASE#:1-20

ANALYSIS OF VARIANCE OF 106.AVFUEL  N= 12 OUT OF 12

       SOURCE              DF  SUM SQRS   MEAN SQR   F-STAT    SIGNIF

       REGRESSION           3  .27645+10  .92149 +9  27.272     .0001
       ERROR                8  .27031 +9  .33788 +8
       TOTAL               11  .30348+10

       MULT R= .95443  R-SQR= .91093 SE= 5812.8

       VARIABLE     PARTIAL    COEFF     STD ERROR   T-STAT    SIGNIF

       CONSTANT              -.25955 +7  .56661 +6 -4.5808     .0018
    19.VALLAREA     .76504   .81556 -1   .24272 -1  3.3601     .0099
    26.CONS.DAT     .85289   1333.5      288.61     4.6205     .0017
   207.AVELEC       .87408   .92685      .18211     5.0894     .0009
```

COMPARISON OF MODEL B

```
DESCRIPTIVE MEASURES  STRAT=REFR.TYP:4  CASES=CASE#:1-20

     VARIABLE          N  MINIMUM      MAXIMUM      MEAN         STD DEV

 106.AVFUEL           12  22544.       76748.       44191.       16610.

 400.PRED.FUE         12  29649.       77051.       44191.       15853.

 110.UNFUEL           12  88.933       423.81       272.05       91.137

 402.FUEL.PRE         12  124.22       423.72       273.35       93.104

 403.FUEL.ERR         12 -.45701       .25300      -.21205 -1    .16590
```

MODEL C **ELECTRICAL ENERGY**

SET WITH STEAM ABSORPTION REFRIGERATION

```
LEAST SQUARES REGRESSION  <1> REFR.TYP:4  CASES=CASE#:1-20

ANALYSIS OF VARIANCE OF 207.AVELEC  N= 12 OUT OF 12

       SOURCE              DF  SUM SQRS   MEAN SQR   F-STAT    SIGNIF

       REGRESSION           4  .12162+10  .30406 +9  172.50     .0000
       ERROR                7  .12339 +8  .17626 +7
       TOTAL               11  .12286+10

       MULT R= .99497  R-SQR= .98996 SE= 1327.6

       VARIABLE     PARTIAL    COEFF     STD ERROR   T-STAT    SIGNIF

       CONSTANT              -2518.1     1245.8     -2.0213     .0830
    16.VOLUME       .98193   .65412 -2   .47643 -3  13.730      .0000
    20.GLAS.ARE    -.95342  -.44694      .53448 -1  -8.3621     .0001
    24.WATT.UNI     .83087   1425.9      360.95     3.9505      .0055
   104.DUMLOCAT     .93494   9261.7      1328.5     6.9715      .0002
```

COMPARISON OF MODEL C

```
DESCRIPTIVE MEASURES  <1> REFR.TYP:4  CASES=CASE#:1-20

     VARIABLE          N  MINIMUM      MAXIMUM      MEAN         STD DEV

 207.AVELEC           12  4304.3       37502.       16122.       10568.

 316.PR.ELEC          12  4521.8       36913.       16122.       10515.

 211.UNELEC           12  39.076       133.93       84.311       31.564

 318.ELEC.PRE         12  34.872       131.83       84.327       30.622

 319.ELEC.ERR         12 -.29699       .20915      -.13144 -1    .15664
```

KEY:

REFR.TYP:4	ABSORPTION STEAM REFRIGERATION.
CASE # 1 - 20	SET OF BUILDINGS EXCLUDING ART & ARCHITECTURE
CONST.DAT	YEAR OF START OF CONSTRUCTION
AVFUEL	METERED FUEL (STEAM) MM BTUs/YR.
AVELEC	METERED ELECTRICITY MM BTUs/YR.
UNFUEL	METERED FUEL M BTUs/sqft/YR.
FUEL.PRE	PREDICTED FUEL M BTUs/sqft/YR.

APPENDIX C-2 Historic Data Base--Energy: Analysis of Data.

MODEL COMPARISONS **METERED VS. PREDICTION AND RESIDUALS**

BUILDING SET (ABSORPTION REFRIGERATION)

```
WRITE OBSERVATIONS  STRAT=REFR.TYP:4
VARIABLES BY CASE

             14.        211.       318.       319.                110.      402.       403.              112.      334.       335.
             BLDG.NUM   UNELEC     ELEC.PRE   ELEC.ERR            UNFUEL    FUEL.PRE   FUEL.ERR          UNENER    ENER.PRE   ENER.ERR

              149.00    54.411     70.570     -.29699             385.23    423.72     -.99909 -1        548.46    617.75     -.12633
              162.00    85.174     85.783     -.71538 -2          249.87    250.85     -.39455 -2        505.39    469.34      .71319 -1
              145.00    103.56     81.901      .20915             423.81    418.65      .12171 -1        734.49    680.99      .72841 -1
              207.00    57.703     46.806      .18886             286.39    313.22     -.93693 -1        459.50    419.10      .67907 -1
              440.00    47.668     61.510     -.29039             263.07    269.54     -.24586 -1        406.07    510.10     -.25619
              165.00    39.076     34.872      .10760             247.89    231.82      .64806 -1        365.11    351.87      .36263 -1
              234.00    90.343     94.550     -.46567 -1          322.33    292.54      .92412 -1        593.36    625.06     -.53426 -1
              2543.0    77.093     80.593     -.45398 -1          166.30    124.22      .25300           397.58    380.24      .43605 -1
              2544.0    78.081     74.528      .45503 -1          88.933    129.58     -.45701           323.18    358.61     -.10965
              2547.0    114.78     119.69     -.42821 -1          344.04    328.97      .43801 -1        688.37    620.38      .98767 -1
              2546.0    133.93     131.83      .15697 -1          236.50    238.78     -.96501 -2        638.30    646.85     -.13396 -1
              2545.0    129.91     129.29      .47730 -2          250.30    258.27     -.31858 -1        640.03    655.32     -.23882 -1
ARCH & ARCH   990.00    56.110     49.091      .12566             233.20    243.12     -.42535 -1        401.50    355.64      .11454
```

MODEL C **ELECTRICAL ENERGY** **MODEL B** **FUEL (STEAM) ENERGY** **MODEL A** **TOTAL AT – SOURCE ENERGY (FUEL + 3 x ELECTRICAL)**

KEY:

UNELEC	**METERED UNIT ELECTRICITY M BTUs/sqft/year**
ELEC.PRE	**PREDICTED UNIT ELECTRICITY**
ELEC.ERR	**(-) MODEL OVERESTIMATE** **+ MODEL UNDERSTIMATE** **0.46467 - 1 = 0.046 of 4.6%**

APPENDIX C-3 Historic Data Base: Analysis of Data.

V

Architectural Design for Optimum Solar Effects

SOLAR DESIGN

David Charles Bullen

There can be no question about the fact that architectural and engineering design is a complex task that must successfully combine many diverse elements. What is becoming more apparent, however, is the fact that one of the most important elements in terms of relevant future design will be solar energy. Two beneficial ingredients of solar energy, light and heat, must be considered in any design solution. How well these two elements are used can determine how successfully the final product will fulfill the users' needs.

Solar radiation reaches a building by direct rays, by rays reflected from adjacent buildings or the ground, or by rays diffused by clouds and atmosphere (Figure 1). In each case the energy can be helpful or detrimental, depending on how well the building responds to the conditions imposed by the climate and the site. The angles of the sun related to a specific site can be accurately determined for any time of day throughout the year. Although climatic conditions can be predicted statistically on an annual basis, day-to-day variance is great. When climatic elements are defined on an annual basis and combined with solar radiation data, the architect/engineer has the basic information needed to effectively design with solar energy.

Climate consists of the combined effects of temperature, humidity, precipitation, wind, and solar radiation. Years ago Mark Twain emphasized that these elements are constantly changing by saying, "If you don't like the weather, just wait a few minutes." Thus, it is the general pattern, repeated annually over a period of years, that determines the climate of any given region.

Although climates of the world vary greatly, most have temperature patterns that require heating of buildings during the winter and cooling during the summer. In addition, there are some periods when both heating and cooling can be required during the same day.

Successful integration of solar design into any building or building complex requires that the architect/engineer thoroughly understand all relevant elements. In addition to the basic solar ingredients of light and heat, these elements include the building form, envelope, mechanical systems, orientation, solar radiation controls, materials, and shading.

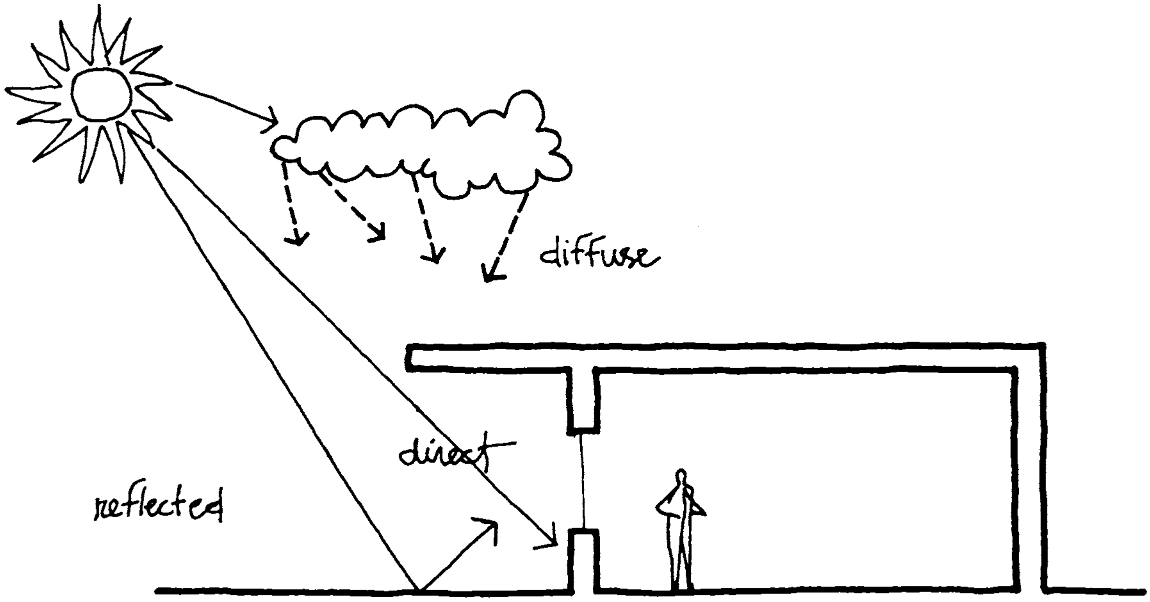


FIGURE 1 Solar radiation can impact on a building in three ways: (a) rays may be received directly, (b) they may be reflected from adjacent surfaces, or (c) they may be diffused by clouds and atmosphere.

BUILDING FORM

Buildings are shaped by many forces that must be considered to meet the owners' and users' needs. One of the major needs emerging today for both owners and users involves energy conservation. The very shape of a building or arrangement of building components in relation to the sun can assist in reducing the heating and cooling loads.

Opaque building elements, for example, can be arranged to shield the sun from the more transparent materials such as glass (Figure 2). The architects who designed the science building shown in Figure 3 located all major plumbing chases on the exterior wall. Windows were deeply recessed to penetrate this exterior space and, therefore, were protected from direct rays of the sun. A variation of this shading method is to use the upper floors to provide shade for lower glass or opaque walls by designing these floors as a projection or overhang; this method of sun control is shown in Figure 4.

Any present-day building is a system that combines an exterior envelope with the necessary mechanical elements to create comfortable interior conditions. In one sense, a building envelope can be a passive element that, because of careful selection and arrangement of materials, components and subsystems, requires little or no assistance from mechanical elements to maintain the occupants' selected comfort level. Most buildings, however, require significant assistance from mechanical, or active, elements and must be considered as a combination of passive and active elements. The percentage of active or passive elements varies from project to project and is illustrated in Figure 5.

FIGURE 2 This building at a college in Southern California is a good example of the stepback method used to control the sun. The upper floors serve as overhangs to shade the lower floors. The soffit must be well insulated to ensure against heat transfer.

FIGURE 3 Windows of the Olin Hall of Science, Colorado College, in Colorado Springs, were deeply recessed and were protected from the direct rays of the sun. ▼

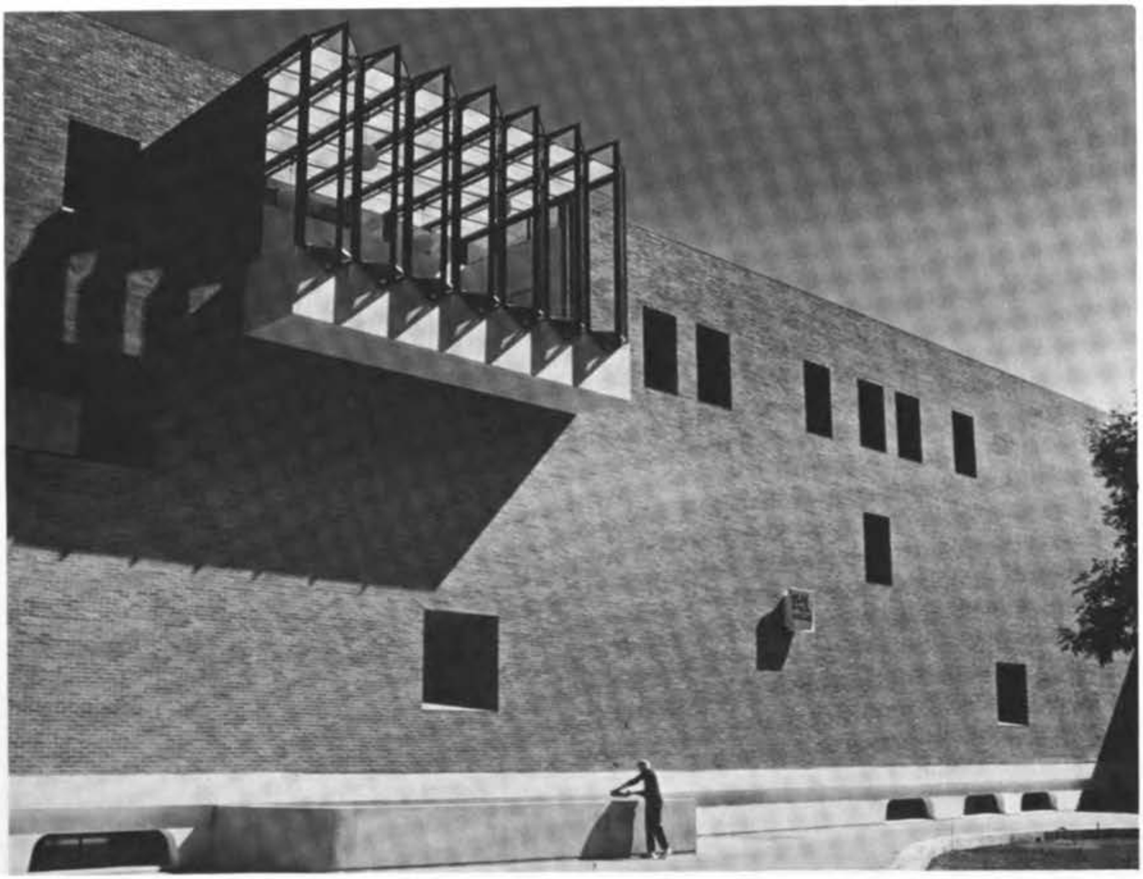


FIGURE 4 The Fine Arts Center of the University of Houston, Texas, has a breezeway entrance that provides a movement of air and ventilates the interior court.

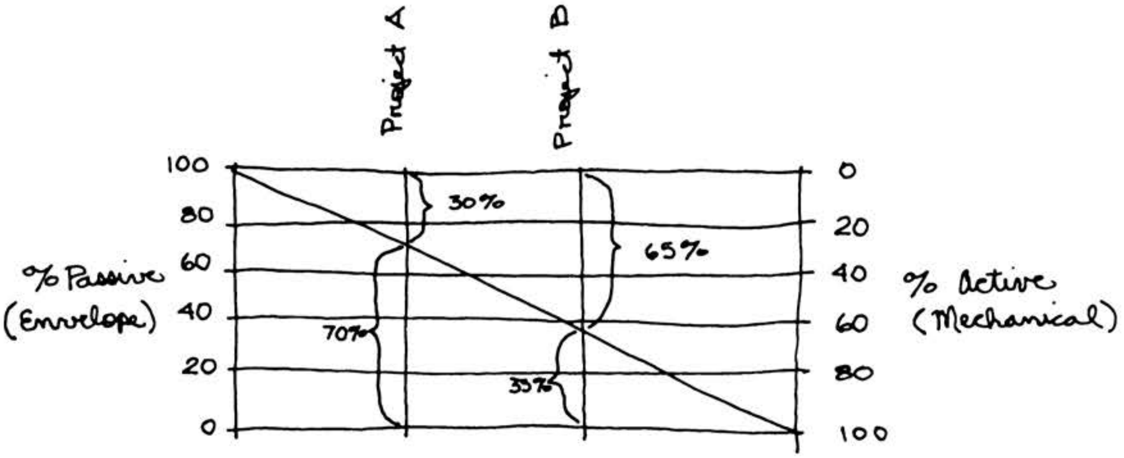


FIGURE 5 Every project adapts to its environment with varying degrees of passive and active elements. A well-designed building envelope, for example, will require smaller mechanical systems to maintain the required level of comfort.

ORIENTATION

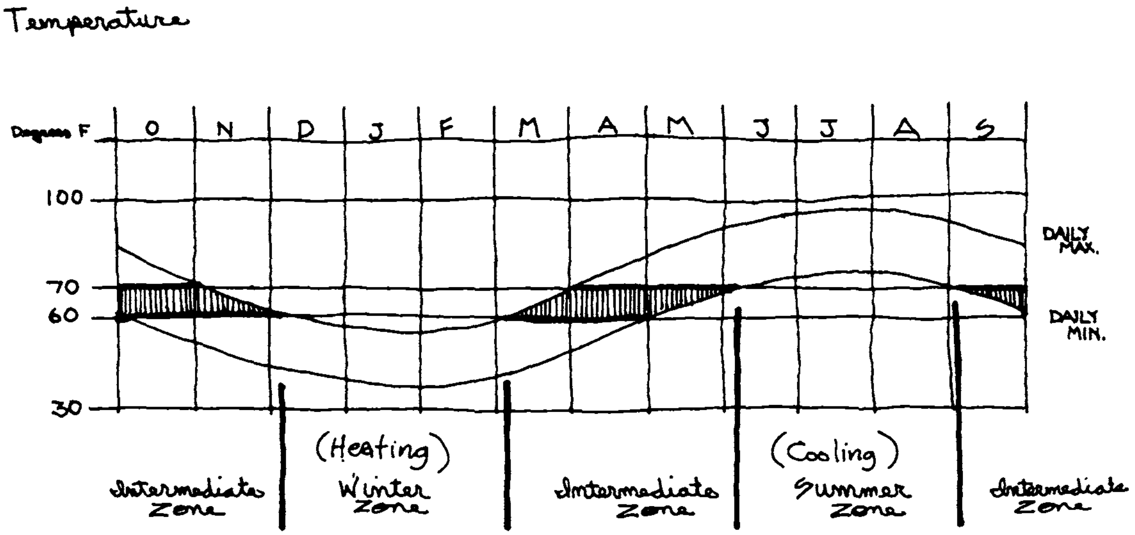
Orientation in terms of solar design refers to the position of a building or building complex in relation to the sun's rays. Although the direction of the sun is changing constantly, the angle of the sun's rays is predictable for any surface of the building for any hour of the day throughout the year. It is possible to estimate maximum solar heat gains for various orientations and make judgments regarding the optimum relationships with other factors affecting energy consumption. For example, it was found that a 20 percent reduction in the solar heat load on a combination office/bank building in Galveston, Texas, was possible if the main facade was oriented toward the south rather than the west (Figure 6).

FIGURE 6 Orientation of blank walls and glass window elements is important in determining the energy consumption of a building.

SOLAR HEAT AND SOLAR RADIATION CONTROL

The heat from the sun can be a desirable commodity in most regions of the world and can be used in a variety of ways. The most common uses are for space heating and cooling and domestic water heating and, in some areas, for swimming pool heating. Most areas of the world have periods of the year when either space heating or cooling is required throughout the day and night and other intermediate periods of the year when the daily temperature fluctuations require space heating at night and cooling during the day (Figure 7).

Controlling solar radiation is one of the best ways the architect/engineer team can reduce energy consumption in a building or group of buildings. Basically this control consists of maximizing solar energy during periods requiring heating (winter) and reducing to a minimum the solar energy entering the building during cooling periods (summer). Solar heat should not be permitted to enter occupied spaces during the summer; it can, however, be collected and used with absorption chillers to air condition interior spaces (Figure 8). During the intermediate periods, solar radiation can be collected and stored daily so excessive heat received during the day can be released to the interior at night.



▲
FIGURE 7 Seasonal temperature variations must be understood to optimize year-round energy consumption.

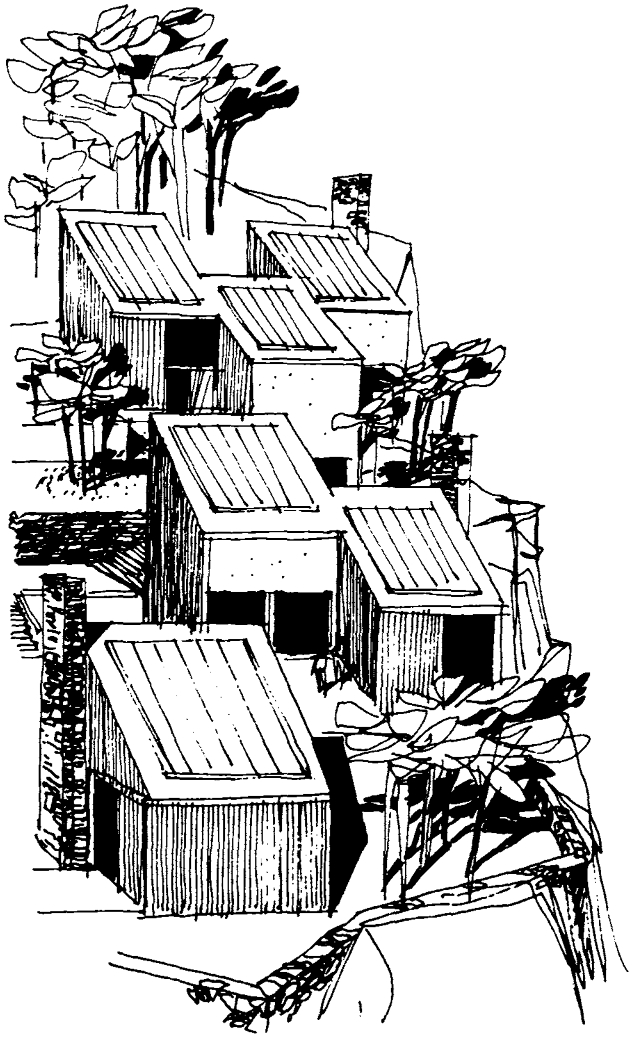


FIGURE 8 Solar collectors▶ enhance this housing project visually as well as reduce its fuel consumption.

MATERIALS

Material selection has a definite effect on how a building uses or misuses the heat received from solar radiation. The architect/engineer is concerned with two types of materials: opaque and transparent. Heat from solar radiation enters a building by conduction through opaque walls and roofs or by direct radiation through transparent materials such as window walls or skylights.

While opaque materials such as brick, concrete, wood, and aluminum prevent the passage of light, their thermal characteristics vary considerably because of different degrees of mass, color, and surface reflectivity. With current construction methods, opaque walls and roofs usually are combinations of several materials and the architect/engineer can therefore combine various elements to achieve the most advantageous overall performance.

The importance of insulation has been clearly demonstrated by a National Bureau of Standards study in which the heat loss of an uninsulated building was compared with that of the same building with insulation added. The study found that 55 percent of the energy originally required was saved after the building received insulation. The percentage of loss through each building element both before and after insulation is shown in Figure 9. While the value of insulation has been proven, we also know that the location of the insulating material within the exterior wall can change the thermal characteristics of that wall.

Two major properties of opaque walls that help determine their thermal performance are color and reflectivity. Dark colors absorb solar radiation and add heat to the building. By contrast, light colors reflect a larger portion of sunlight and reduce the cooling load. Careful consideration should be given to the selection of opaque walls with the proper mass, insulation, color, and reflectivity. Figure 10 shows a school that successfully utilizes light-colored, reflective walls to reduce solar heat gain.

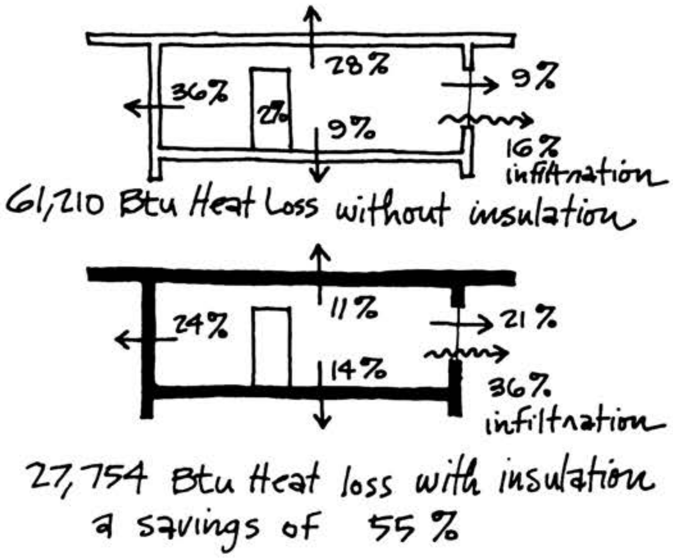


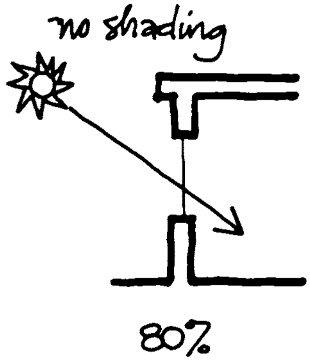
FIGURE 9 The use of insulation in walls and roof can greatly change the heat-loss patterns of any building.

FIGURE 10 This school in Alabama does have considerable glass, but it is in areas offering protection from hot-month sun and cold wintry winds.

Transparent materials, such as clear glass, admit up to 80 percent of all radiant solar energy that strikes the surface (Figure 11). This can be beneficial during periods of the year when space heating is required, since it reduces the amount of heat that must be supplied by fossil fuel or electricity (Figure 12).

Transparent materials that admit solar energy also allow heat within the building to escape by conduction. Heat loss through glass is an important factor during both cooling and heating periods, but it is particularly critical in colder climates where the temperature variation between indoor and outdoor environment is greater. Combining two or three sheets of glass with air spaces or vacuums in between can reduce heat transfer 40 to 60 percent over that experienced with a single sheet of glass (Figure 13).

Glass types also have been developed that reduce solar heat gain. Heat-absorbing plate-glass, for example, is used frequently in air conditioned buildings today. Reflective glass, used either in single sheets or combined with double glazing, also reduces solar heat gain. This type of glass is particularly effective in reducing summer heat gains and, thus, allows a reduction in the size of the air conditioning system, which, in turn, reduces energy consumption (Figure 14).



▲
FIGURE 11 Clear glass admits up to 80 percent of the radiant solar energy.

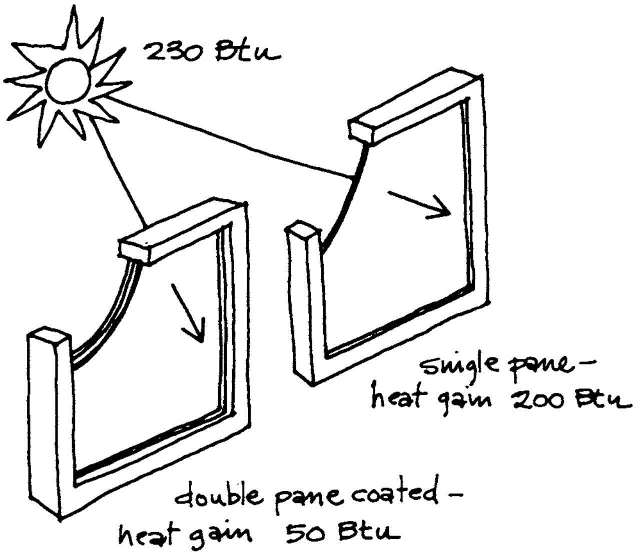
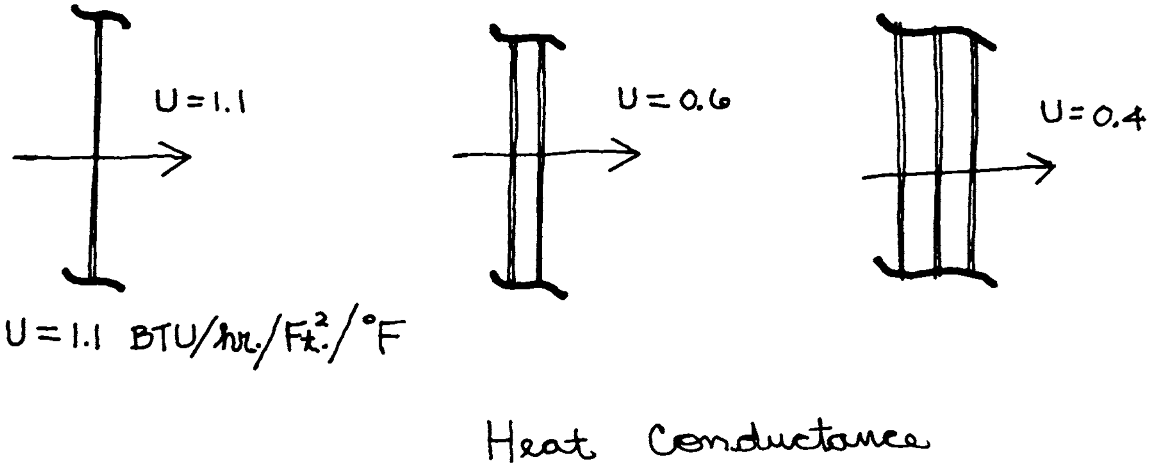
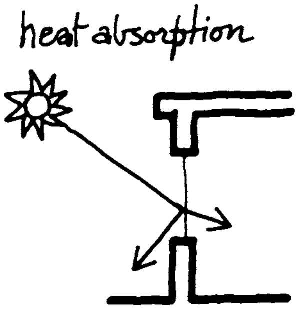


FIGURE 12 This use of special glass coatings and double glazing can greatly reduce heat loss. ▶



▲
FIGURE 13 Double or triple glazing is an effective method for reducing heat transfer by conduction.



◀
FIGURE 14 Special glass types are available that reflect and absorb various portions of solar radiation.

SHADING

Shading is the most effective method of reducing heat gain through transparent materials, and, ideally, a good shading device should keep sunlight in during the winter. Internal shading can reduce the amount of heat dispersed within a space, but it is not as effective as external shading, since much of the radiant heat that enters the space is trapped inside the space at the exterior wall. The most common internal shading devices are venetian blinds, vertical blinds, shades, and draperies, and these devices can reject up to 65 percent of the solar radiation that strikes the glass directly (Figure 15).

External shading is most effective against overall heat gain, since it can block out up to 95 percent of the solar radiation that otherwise would enter the building (Figure 16). Many devices are available for exterior shading. Horizontal overhangs, using both fixed and movable elements, are very effective in south elevations, because the solar angles are highest as they approach due south during midday. The sun also is higher in summer than in winter, and the overhang can be proportioned to screen out the sun in summer but admit it in winter (Figure 17). On east or west elevations, however, the sun's angle is too low to be blocked out by horizontal overhangs, and properly oriented vertical louvers have proven more beneficial on these elevations (Figure 18). If the louvers are movable, the user can control them to provide a better view or greater diffusion of light at times when the sun is located on the opposite face of the building.

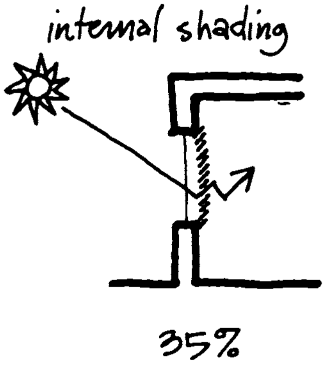


FIGURE 15 Internal shading devices can reject up to 65 percent of the solar radiation.

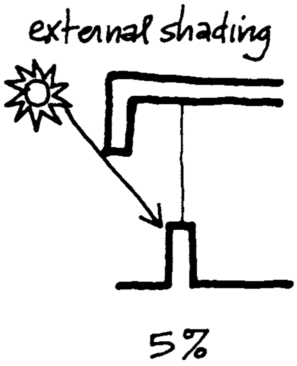


FIGURE 16 External shading devices usually are the most effective method of preventing solar radiation from entering a building.

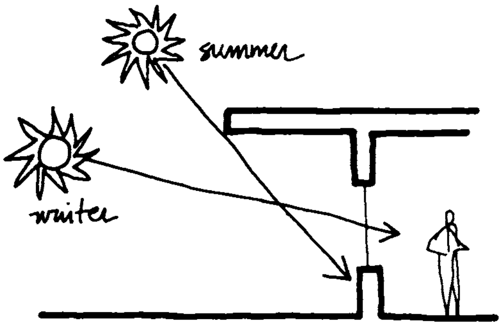
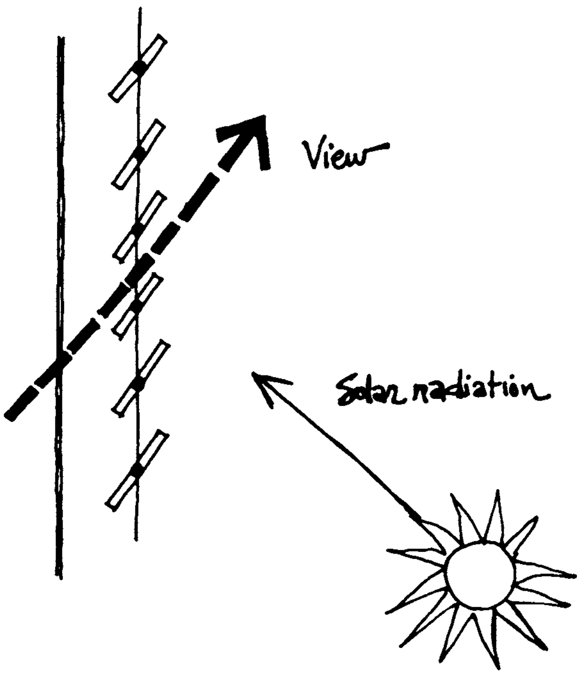


FIGURE 17 A horizontal roof overhang along the south wall is the most effective method of rejecting summer heat when the sun angle is high while permitting winter heat to enter when the sun angle is low.

FIGURE 18 Louvers permit views while rejecting direct solar radiation for walls facing west or east. ▶



Combinations of vertical and horizontal elements can be used effectively to control solar radiation if the proportions are carefully related to sun angles during the critical times of the day. The low sun angles of early morning and late afternoon may be blocked by interior shading devices if the building is occupied during these hours (Figure 19).

If glass must be used on a west or east wall, the low sun angles can be blocked by using a sawtooth wall as shown in Figure 20; direct sunlight is totally eliminated from the building's interior, although, as Figure 21 demonstrates, both natural daylight and views are possible. If little or no glass is required on the east and west walls, the most effective solar control is a simple horizontal overhang along the southern exposure. This blocks the direct sun rays during the summer months when the sun's angle is highest, but allows the sun's rays to penetrate during the winter when the angle is lowest. This classic principle, which allows heat to be rejected in summer when it is not needed and received in winter when it is most needed, is illustrated by the building shown in Figure 22.

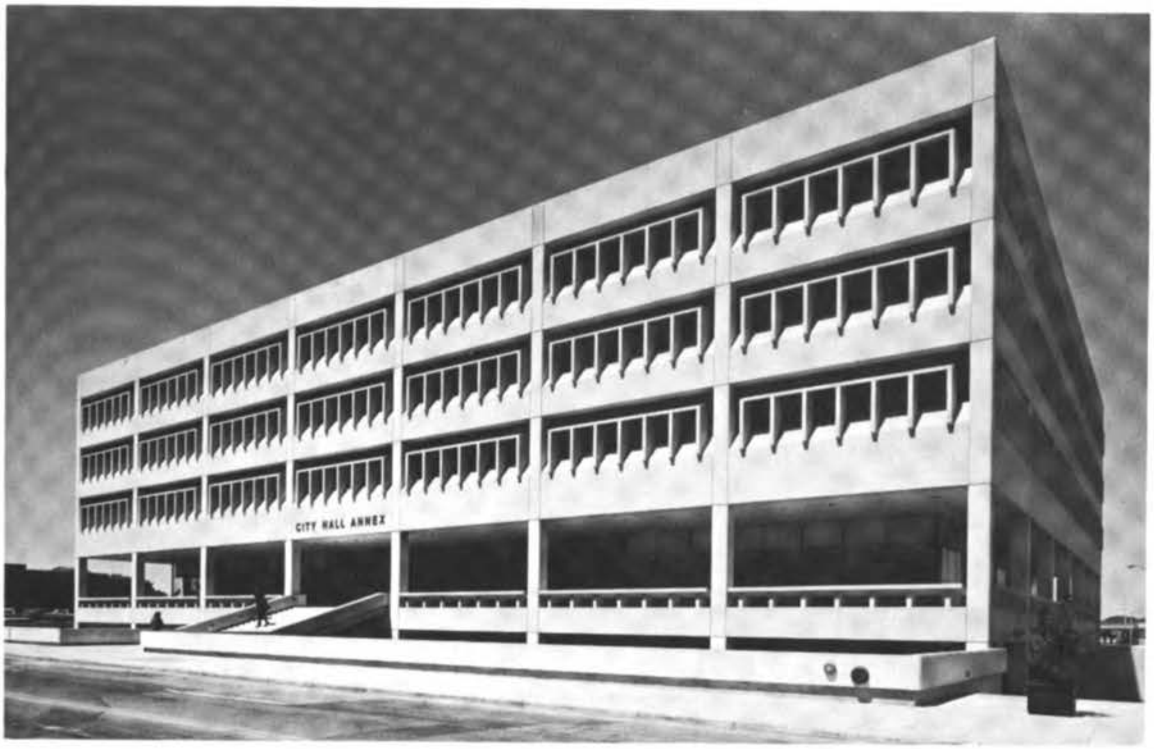


FIGURE 19 Shading devices that consist of both horizontal and vertical elements can be effective for controlling solar radiation.

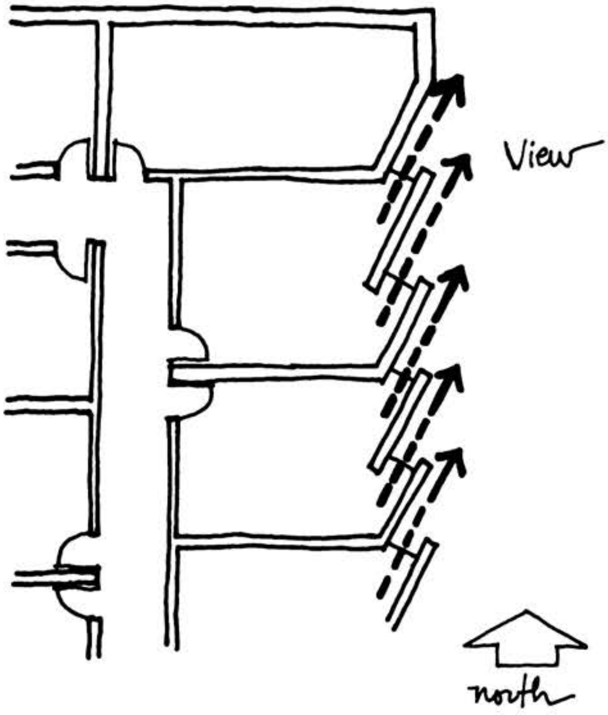


FIGURE 20 Sawtooth walls consisting of transparent and opaque elements are a good method of allowing views and rejecting unwanted solar radiation.

FIGURE 21 Fine Arts Center, University of Houston, Texas. Direct sunlight is totally eliminated from this building's interior, yet the sawtooth effect does permit natural daylight to enter.

FIGURE 22 This Mississippi research building is a classic example of the simple horizontal overhang principle.

When properly proportioned and located, a roof can provide excellent sun protection during the most critical times of day and remains the most common shading device used for both transparent and opaque wall surfaces. This principle was used for the schools pictured in Figures 23-26 and was extended in the design of the elementary school shown in Figure 27, where a lightweight upper roof was placed over compact, but separate, classroom groups to allow natural ventilation of the space above the lower classroom roofs. A portion of the upper roof was glazed with transparent plastic panels to allow diffused light to enter the classrooms through skylights in the lower roof (Figure 27).

Solar radiation also can be reduced by locating a portion of the building underground or by using earth berms against ground-level walls (Figures 28-30).

FIGURE 23 The umbrella type roof on the Carlsbad High School, in Carlsbad, New Mexico, permits the use of exterior corridors while protecting the students from direct solar radiation.

FIGURE 24 Sunlight is too intense for prolonged outdoor activities in Laredo, Texas, on the Mexican border, but this permanent roof blocks the direct sunlight while permitting natural daylight to filter through.

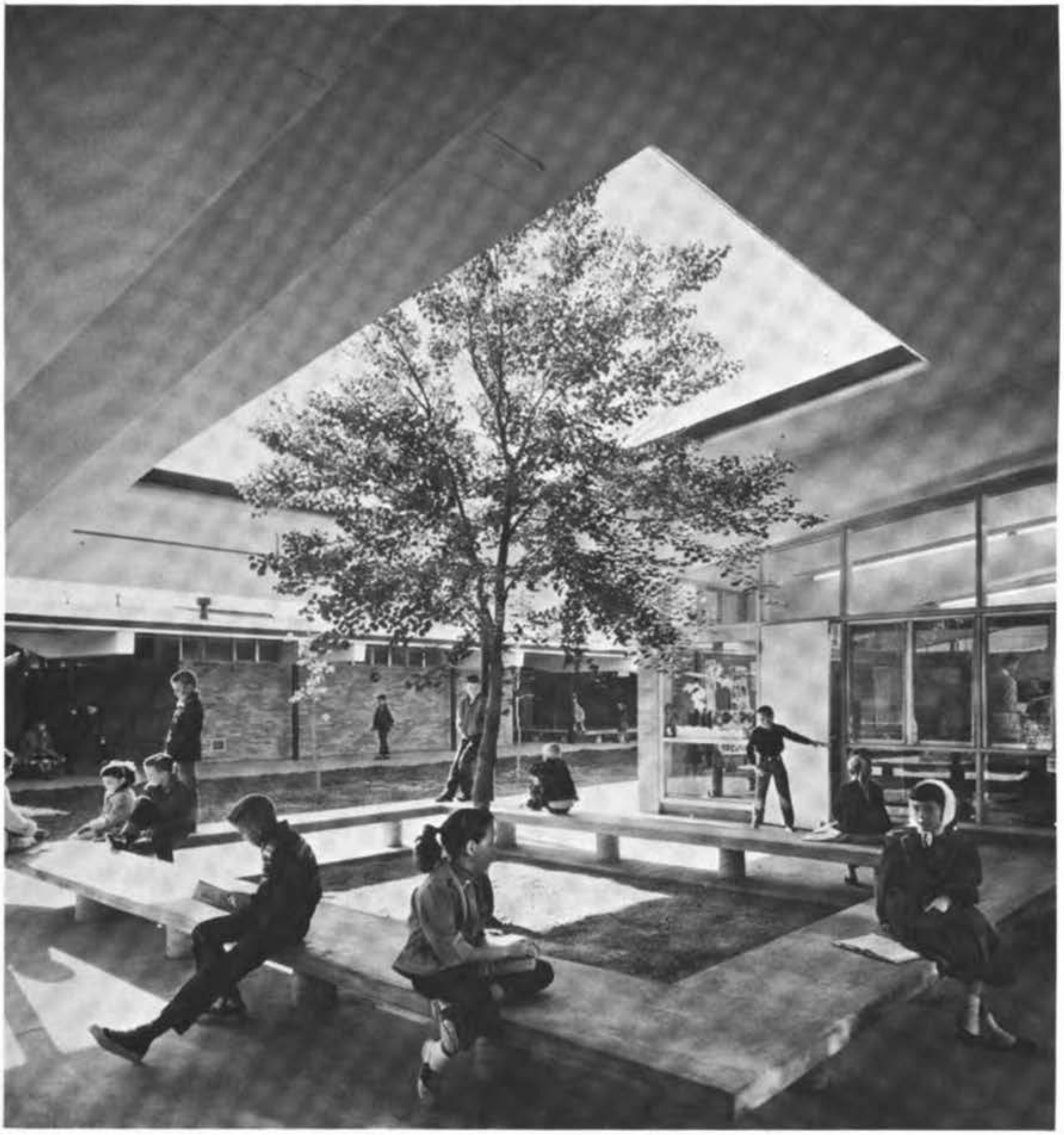


FIGURE 25 This partial roof provides needed sun protection for the students in this school while admitting enough daylight and direct solar radiation to maintain greenery.

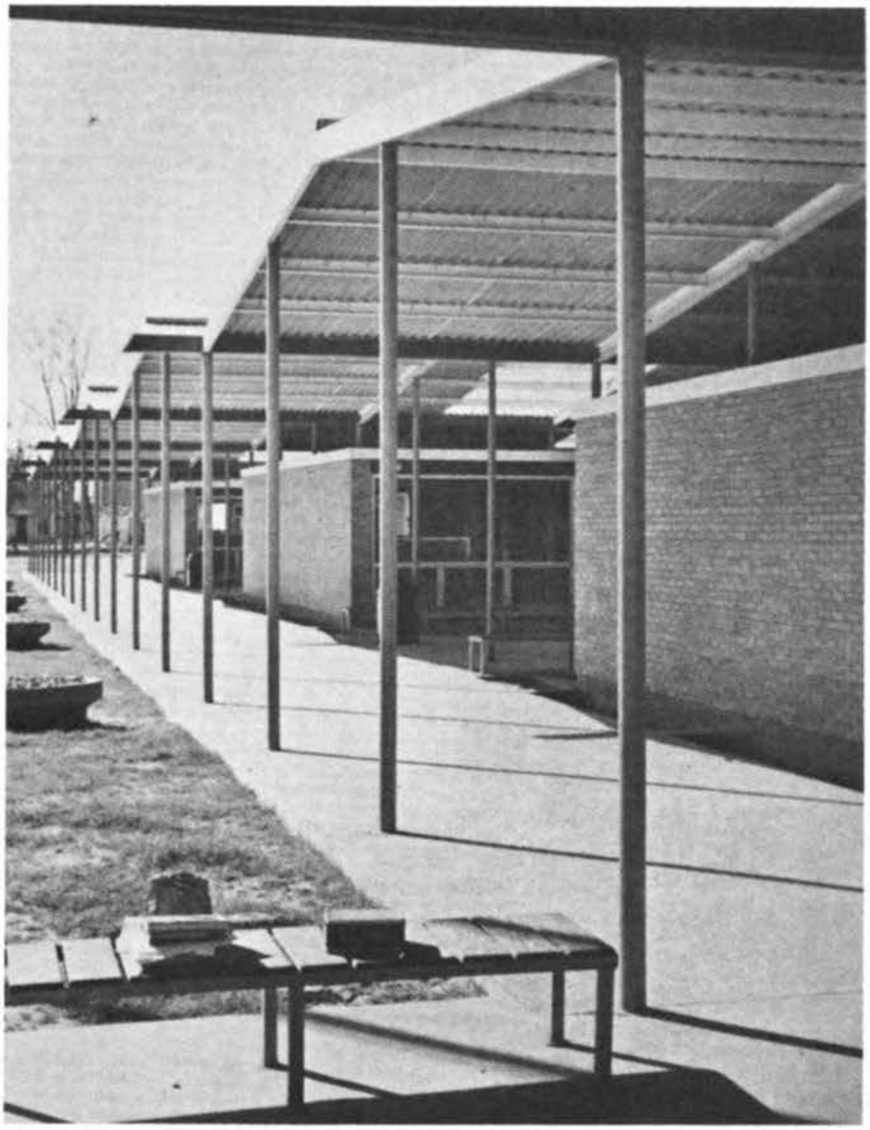


FIGURE 26 The upper floor on this Gulf Coast school is in effect an umbrella that protects both the building and the students from rain and hot sun.

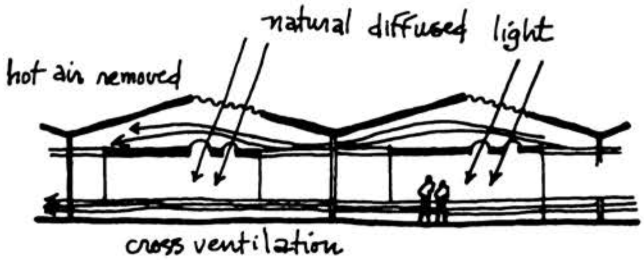


FIGURE 27 The breeze flowing between two roofs removes hot air. Direct sunlight rarely reaches the walls and never reaches the second floor, although natural diffused light is admitted into the rooms below.

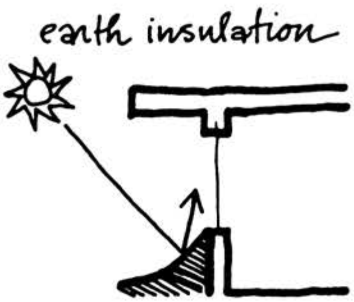


FIGURE 28 Earth berms are good insulation since they significantly reduce heat loss through walls.

FIGURE 29 This technical school in Phoenix, Arizona, illustrates the application of earth berms to reduce heat loss by conduction.

FIGURE 30 Insulation and scale were the primary reasons for using earth berms in the Mission Viejo Elementary School, Aurora, Colorado.

NATURAL LIGHTING

Natural light is desirable in any climatic area of the world. Properly controlled, natural light can reduce the amount of artificial lighting required and, therefore, save energy. The design problem is to transform the direct rays, which usually cause glare and excessive footcandle levels, into a softer, less bright, more useful light that can be used for total illumination or as a supplement to artificial light.

People, plants, and domestic animals all respond favorably to moderate amounts of natural light (Figure 31), and, while many people and animals

FIGURE 31 People and plants, particularly, respond to natural light as is evidenced in this employees' facility in a light industrial plant near Austin, Texas.

and some types of plants could exist in an artificially illuminated environment, this use of electricity (energy) is not efficient if natural light can be made available. In addition, if plants and animals are considered a valid part of the indoor environment, one must remember that natural sunlight best meets their needs; when natural light is available, the variety of plants available for indoor use also is greatly increased.

People, of course, constitute the major design determinant in any built environment. Changes in lighting that occur naturally throughout the day create a more interesting environment. Most people are delighted by and obtain a sense of well-being from sunlight, whether received as direct rays or as diffused light. The ongoing energy crisis has caused a renewed interest in natural light. If one examines the sketches presented in Figure 32, one can see how natural light responds to form.

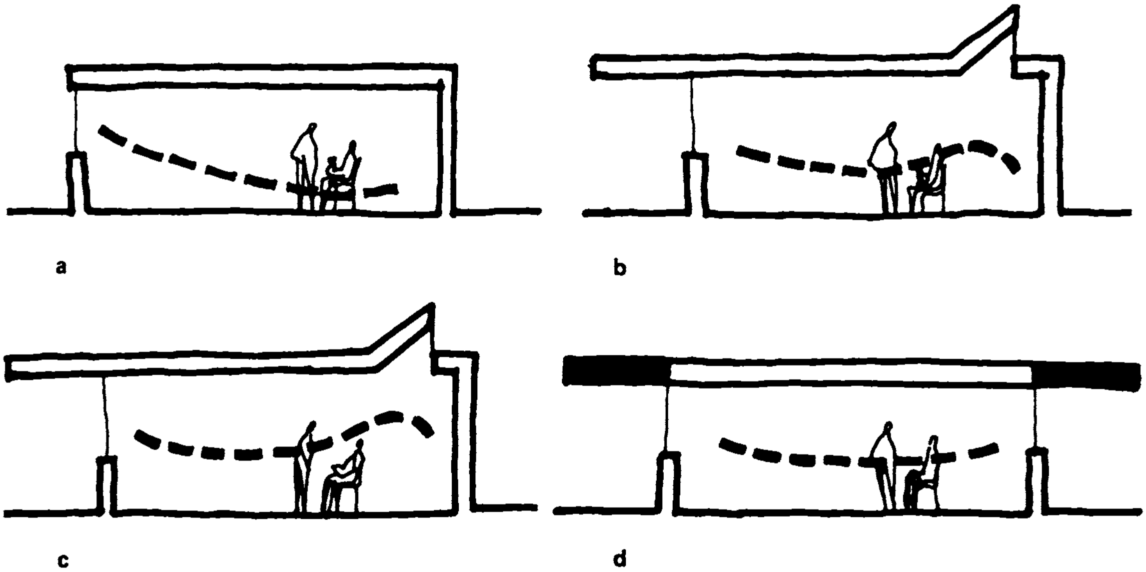


FIGURE 32 The space (a) is unilaterally lighted (a window on one side only) with light near the window and not much near the opposite wall. An overhang and skylight have been added in (b); the light curve reveals that, although light intensity is lowered somewhat near the window, the distribution is more even and considerably better. By increasing the ground reflection in (c), light bounces to the ceiling, and the illumination near the overhang is increased. The skylight is eliminated and a second window and overhang are added in (d); an excellent bilaterally lighted space with a nearly straight line-distribution curve is achieved.

If one is able to use natural light, the light should be brought in high. A mere 2-foot slit at the connection of a wall and ceiling does a great job of lighting the spaces. The school pictured in Figure 33 has a clerestory arrangement in the student lounge that provides lighting for the large, interior space.

FIGURE 33 The clerestory arrangement in the student lounge at the Ohio Institute of Technology, in Columbus, provides the necessary natural light.

Architects have designed spaces so one cannot tell where daylight stops and electric lighting begins. In the school hallway pictured in Figure 34, the lights are rarely turned on during the day. In another school (Figures 35 and 36), the classrooms are lighted using a plenum that mixes and integrates natural and electric light. This light is directed through an aggregate ceiling that is required to prevent glare and provide quality lighting.

FIGURE 34 The artificial lighting system is seldom used during the day in the hallway of this school, in Miami, Oklahoma.

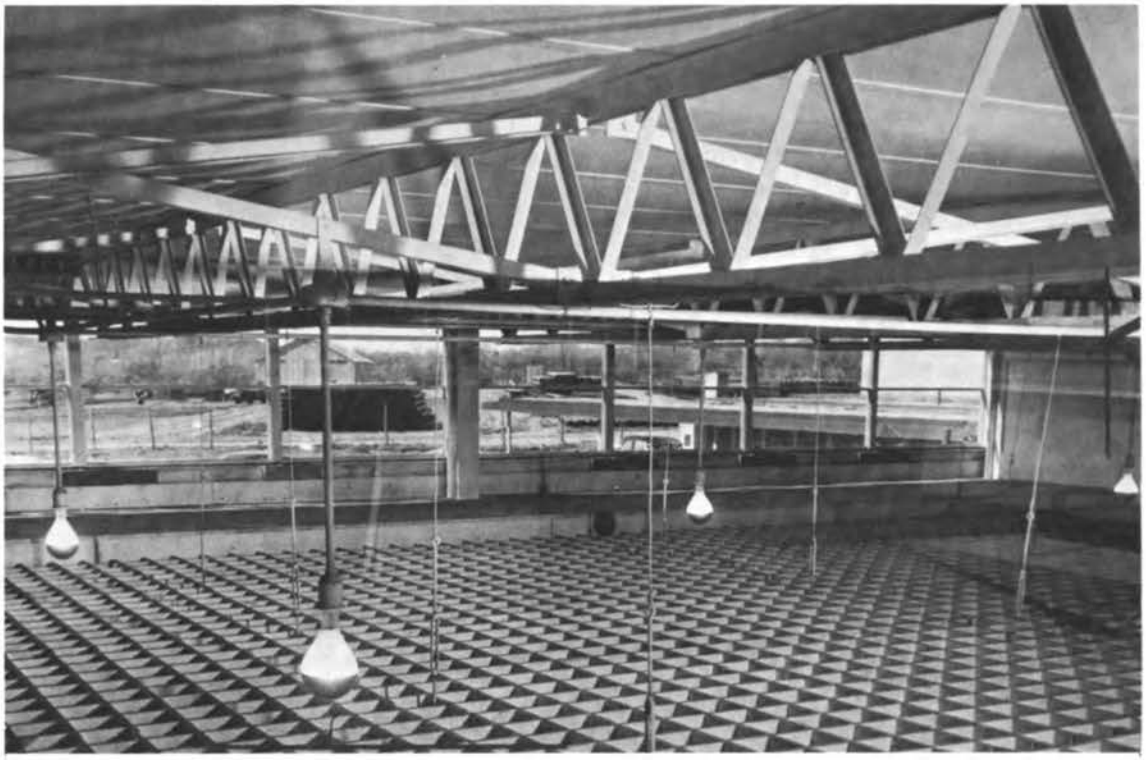


FIGURE 35 Classrooms in this school are lighted using a plenum that mixes and integrates natural and electric light.

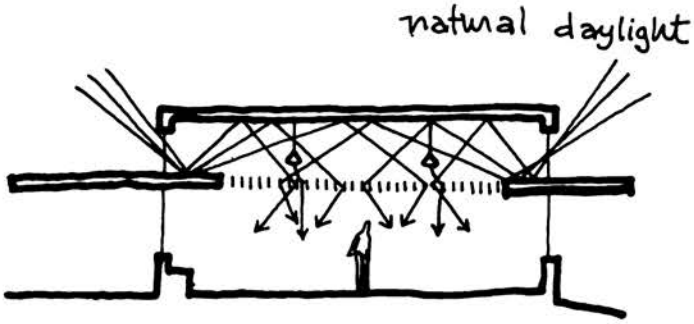
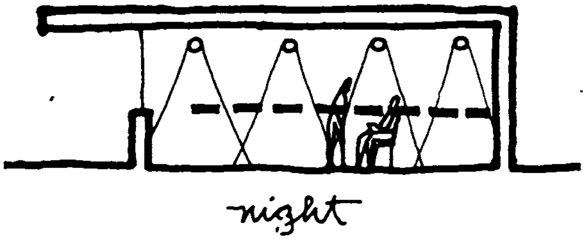
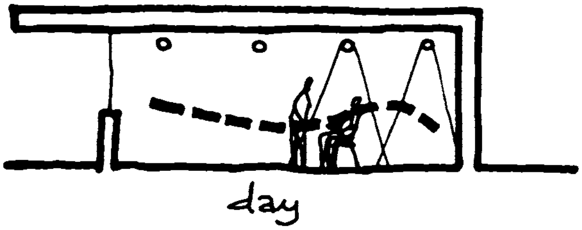


FIGURE 36 Plenum lighting is combined with an aggregate ceiling to prevent glare and provide quality lighting.

Uniform lighting, which may be required at night, can easily be provided by using rows of parallel lights (Figure 37). Energy savings are possible if these lights are switched to allow use of interior and perimeter zones. Daylight can replace the artificial lights in the perimeter zone for much of the day, and lighting levels can be controlled to a uniform level (Figure 38).

FIGURE 37 Rows of parallel lights easily provide the uniform type of illumination needed at night. ▶

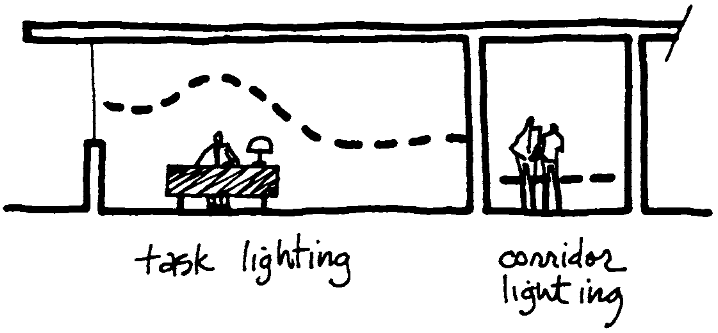




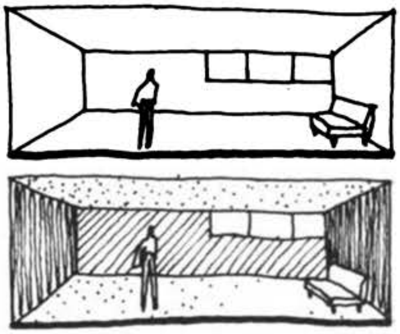
◀ FIGURE 38 Daylight can replace the perimeter artificial lights for much of the day, yet uniform lighting levels still can be maintained.

Natural lighting also can provide a good background level that can be supplemented by individual-task artificial lighting (Figure 39). Specific-task lighting, which provides only what is needed for each task, can save energy when it is properly designed, since it results in equal or greater visibility with less watts of power than would be required by a higher overall level of illumination. Reducing artificial lighting also reduces the load on the air conditioning systems (in some commercial buildings, heat from the lights is one-half the cooling load).

FIGURE 39 Low general lighting with specific high-intensity light at work stations can reduce electric demand by 20 to 50 percent.



Proper use of color can make both natural and artificial light more effective. Lighter, reflective colors on walls, ceiling, floor, and furnishings can increase illumination by 30 footcandles without a change in lighting, as shown in Figure 40.



lighter surfaces
give more
illumination
with same
light sources.

FIGURE 40 Lighter, reflective colors on walls, ceiling, floor, and furnishings can increase illumination without a change in lighting.

FUTURE OF SOLAR DESIGN

The future of solar energy is very exciting. Solar energy hardware is undergoing extensive research and development in programs funded both by private industry and the federal government, and early demonstrations appear most promising. (For example, the National Bureau of Standards estimates that a 40-by-14-foot solar collector panel combined with a 150,000 Btu heat storage water tank can save 40 percent of the energy required to heat an average residence in the Washington, D.C., area.)

Many architects and engineers believe that there will be an evolution of new forms to reflect the new energy-conservation ethic. Leading designers are particularly excited about the fact that solar energy sources will bring new forms to architecture. Housing, schools, hospitals, and other building types will begin to take on different silhouettes. The great designers will be inspired by the possibilities of honestly expressing the solar collectors and will find ways to include them as elements that help create exciting architecture.

Solar power, on a more centralized basis, will be even more prevalent in the future. The often-predicted "solar farms" in deserts to convert solar energy into electrical energy will become a reality. We will have new types of high-technology power plants to run our cities.

The design profession is capable of meeting the challenge of the energy crisis with the help of solar energy. Challenges have been faced before and overcome in ways that have improved both our communities and our profession. Likewise, this challenge will be accepted, and we will produce better, more meaningful, and more appreciated buildings in the process.

PLANTING FOR ENERGY CONSERVATION

William Flemer III

Few, if any, events have had a more sudden and profound effect upon the accustomed way of doing things in this country than the Arab oil embargo in 1973 and the subsequent catastrophic rise in oil prices. Despite the major and painful adjustments with which the Western world is still struggling, the oil crisis will be looked on as a blessing by future generations. So long as abundant and cheap oil was flowing from the Arab nations, virtually nobody in the two spheres of real influence, government and business, could muster the courage to examine the unthinkable--that the amount of oil on this globe is finite, that in a historical time frame it will be gone tomorrow, and that there will never be any more. Today, even with its many troubles, will be considered a time of tranquil prosperity compared with the turmoil in the not too distant future when the oil finally runs out, if we continue our present course of dangerous dependence on this one predominant energy source.

It helps little to dwell on the rueful knowledge that the West, particularly the United States, has been profligate in the squandering of the global oil reserves. The use of oil to generate electricity, the American automobile, and the dominant position of plastics in our "prepackaged" way of life are outstanding examples of our economy of waste, and many more come readily to mind. It is equally pointless to look for someone to blame (such as those in advertising, the automobile industry, or government) for we are all to blame. A much more fruitful course is to see what can be done at present and to make plans for a future that will certainly be an era with very little oil and with inexorably diminishing coal and other fossil fuels.

In this reexamination of our future course, and in planning timely remedial measures, the architect has a crucial role. The heating, lighting, and cooling of houses, offices, and factories vies with transportation for first place in the consumption of oil and enormously exceeds transportation in the consumption of coal. Judging by the design of all kinds of edifices in the past 25 years, efficiency in the use of energy has been among the last of all the design criteria considered.

Next to a corncrib, a greenhouse must be the least efficient building of all to heat in winter and to cool in summer. The modern office building, with its facade of enormous sheets of glass, shares with the greenhouse this matchless inefficiency in energy use. Even given the cheap and abundant fuel of the immediate past, it has been incredibly costly to heat in winter and to cool in summer. While by no means as profligate in energy consumption as the modern office building, the modern home is no paragon of efficiency in either heating or cooling. The amount of energy consumed by office and commercial buildings is enormous, but even this is dwarfed by the demands of the millions upon millions of single-family homes in North America. Only the vaguest of estimates have been attempted in the determination of how much oil and electricity they consume each year for temperature modification, but the amount is stupendous.

Improved construction, the use of thermopane glass, and better insulation can make great strides in improving the efficiency of the home. Still further improvement can be attained by proper siting and the proper use of plants for energy conservation.

In cities, the orientation or alignment of a building is determined by that of the lot available for construction, and there is little or no room for variation. In suburban or more rural areas, the greater size of the site makes it possible to align the building in order to minimize the consumption of energy. As in so many other fields, building alignment for greater comfort and efficiency has already been successfully accomplished in the natural world. One of the marvels that early caught the attention of explorers in South Africa was the so-called compass termitaria; these enormous slablike constructions are the dwellings of a species of termite that, unlike our North American species, lives above ground. These termitaria are often 15 feet tall, 12 or more feet long, but only a foot or so in width, and they are invariably and precisely oriented on a north-south axis, with the narrow side to the north. Termites do not have wings that can be used for forced-air cooling during the heat of summer, as bees do in their hives, but the alignment of the mound reduces to a minimum the effect of the blazing tropical sun during the middle of the day. Incidentally, these termitaria, in relation to the size of the tiny insects that build them, are far larger than any skyscrapers built by man! The use of exactly the same orientation for buildings in the hot areas of this country can save very significant amounts of air conditioning electricity in summer.

In the cold parts of the country, proper orientation of the long axis of a building can conserve considerable amounts of heat in winter. Here the long axis should be along the lines of the prevailing winter winds. The winds are, of course, not invariable, but careful observation will show that there is a prevailing pattern, particularly during outbursts of especially cold weather. Presenting the narrow side of a long building to these winds does reduce fuel consumption compared with an orientation that opposes the long side to the wind.

Changes in construction and orientation are the only useful measures that can be used to reduce the energy requirements of skyscrapers and other large buildings. However, proper planting can do wonders in reducing the energy consumption and improving the efficiency of smaller commercial buildings and individual houses. Fortunately, much of the necessary basic research has already been done in the Plains states--some at the Agricultural Experiment Station at Kansas State University in Manhattan and some at other locations.

We know that shelter plantings have a remarkable effect in reducing wind velocity and heat loss from homes. On the lee side of shelter plantings, even those composed of deciduous species, daily temperatures are 4° higher than those in exposed areas. Evergreen plantings have, of course, a much more dramatic effect.

In South Dakota, the fuel consumption of identical experimental houses was 25 percent less in a house located on the lee side of a tall windbreak than in an exposed house. If the house was sheltered on three sides, but exposed on the south side, the wind reduction was 71 percent and fuel consumption was reduced by 40 percent--a truly remarkable saving. Other experiments have shown comparable effects.

In small experimental houses warmed by electric heaters, which can give very precise records of fuel consumption, the fully exposed house required 442.6 kWh to heat it to 70° for the month of January 17 to February 17. Its identical counterpart, which was sheltered by a windbreak, required only 270 kWh to be held at the same temperature during the same 30-day period. The difference in the average fuel consumption for the entire winter was 33.92 percent.

FUEL SAVINGS

One would expect such remarkable effects in the windswept Plains country. In the more sheltered eastern states, which are not subject to such constant fierce winds in winter, the energy savings are less dramatic. In one eastern calculation, which compared the fuel consumption in the same house before and after an evergreen windbreak reached the height of the house, a saving of 10 percent per winter over the former exposed condition was recorded.

In terms of national fuel consumption, the eastern experience is much more significant, since there are thousands of houses in the East for every one on the Great Plains. Even a 5 percent reduction of fuel consumption on the eastern seaboard would save much more fuel than the total consumption of all the Plains states combined, because so many millions of houses are involved.

For the homeowner, the dollar savings of even minor reductions of fuel consumption are highly significant. The price of fuel oil has already doubled in many areas, and it is likely to continue to increase. Crude oil, which previously sold for $2.90 a barrel in the Middle East, now costs $14 a barrel from other sources. There may well be some future downward readjustments in the cost of crude oil, but, in the final analysis, these huge price increases have to be borne by the consumer. Modest investments in evergreen windbreak plantings will give the homeowner many decades of increasingly important fuel savings in the years ahead.

The location of a windbreak is, of course, the key to its effectiveness. Most of our cold winter winds throughout the nation come from the north or the west. Therefore, windbreaks should be located on these sides, with an extension on the eastern side wherever space permits. The south side should be left open to permit the sun to enter. The sun lies low in the southern sky in winter, but an open southern exposure permits the yard and house to absorb the heat. It has been shown with anemometers that the maximum wind reduction appears at a distance of from four to six times the height of a windbreak; so plantings should be established at this distance from the house. Rapid-growing species should be chosen, ones that reach from 1 to 1½ times the height of the house at maturity. A 20-foot house would benefit most from a hedge of tall evergreens located 80 to 120 feet from the north side of the house. A single row of evergreens is effective, but a double or triple row is even more beneficial.

SOLID WALLS

At first thought, a tall, solid wall of masonry or wood would appear to be even more effective in reducing heat loss than a hedge of plant material through which some wind does pass, especially when the velocity is high; however, plant material has proved to be much more effective. The solid barrier lifts the wind up over itself and creates great turbulence on the lee side, while a hedge or barrier planting permits enough wind to pass through so that what are called "spoiling currents" in aerodynamics are formed, and their effect is to dampen and cancel the force of the downdraft. The final result is a maximum wind reduction. This has been clearly proved in Great Britain.

For generations, the Isles of Scilly, off the southeastern coast of England, have had a specialized agriculture, capitalizing on mild temperatures to produce early flowers and vegetables for mainland markets. The great obstacle to horticulture on these islands has been the severe gales that blow in from the open sea. The early solution to these problems was the planting of densely sheared hedges to shelter the flower fields. Without this protection, flower culture was hopeless, even though the overall temperature was not severe.

During the first part of this century, some growers on the Isles decided that they could save much space, as well as the cost of maintaining the hedges, by substituting solid wooden fences. Severe storms, however, often blew down or broke up these fences. But, even where they held firm, they created such turbulence behind them that flowers and delicate vegetables, like lettuce, were rendered unsalable. When the hedges were reestablished, the problem was solved. In the United States today, plant barriers are far cheaper to install than any other kind of fence, and, if appropriate plants are used, future maintenance is negligible. For once, the least-expensive material is the best for the purpose--a rare occurence around the home!

MODERN DESIGN

Winter and summer are the two peak periods of energy consumption in both homes and commercial buildings. In winter, heating consumes energy; in summer, air conditioning also makes enormous inroads on the capacity of our power-generating facilities.

The contemporary trend of modern office design has made the problem still worse. Most modern office buildings comprise fashionable cubes of glass, whose huge transparent walls create a greenhouse effect. The resulting accumulation of heat makes the interiors intolerable in summer unless they are air conditioned. To compound the problem, most of these buildings have hermetically sealed windows that cannot be opened, no matter how hot it becomes. Fortunately, properly sited shade trees can improve the situation, at least for buildings up to 60 feet or so in height.

Trees are, after all, nature's air conditioners, and they have been doing the job well for countless years. A woodland on any hot summer day shows, without any elaborate instruments to prove it, the job trees do.

Deciduous shade trees come into leaf in late spring when the daily temperature begins to climb. All summer long, they absorb the sun's heat and, at the same time, transpire cooling water. In the fall, when the temperature drops, the leaves shed automatically, and the sun can fall on house or office walls, adding its heat to that produced by the furnaces inside.

Properly shaded houses have little need for costly air conditioning. Even when air conditioners are installed, they need to work only half as much to do their job in a shaded house as compared to one on which the sun beats down unimpeded on walls and roof. Differences of 8° have been recorded between shaded and unshaded outdoor surfaces.

LOCATION OF PLANTS

Obviously, shade trees should be planted on the south and west sides of a building to do the best job of cooling. In very cold climates, those species with compound leaves are especially effective, because they have fewer and coarser twigs than those with simple foliage. Ashes, honey locusts, and Kentucky coffee trees are examples of trees with large leaves and relatively few twigs. Ashes have the added advantage of being among the last trees to leaf out and the first to defoliate, a beneficial factor in cold areas.

In addition to trees, deciduous vines have a tremendous effect in cooling walls in summer. For masonry walls, clinging species like Boston ivy *(Parthenocissus tricuspidata)* and Virginia creeper *(P. quinquefolia)* are excellent cooling devices. Their leaves are borne in an orderly shingle pattern on 4-inch to 6-inch petioles. The leaf blades intercept and absorb the rays of sunlight while, behind them, a convection current carries the warm air up and away from the wall. Deciduous vines are most effective on southern and western walls, which receive the full heat of the sun in summer. Evergreen species, like English ivy *(Hedera helix)*, are effective on sunless north surfaces, where their persistent foliage deflects wind in winter and their stems have an insulating function.

Clinging vines are not good for wooden walls, because their stems and tendrils hold moisture and cause the wood to deteriorate. However, the same cooling effect can be obtained by training twining vines, like wisteria or climbing roses, on trellises. The trellises can be detached and swung away from wooden walls when they need painting and then pulled up in place again. Since the vines do not touch the wooden surface, they do not hold moisture against it and, indeed, slow down the deleterious effect of summer sun on paint surfaces.

In tropical areas, where cooling is desirable throughout the year, evergreen clinging or twining vines are useful on all walls exposed to direct sunlight. Climbing fig *(Ficus pumila)* and the many other permanently evergreen species work well in cooling exposed walls.

PARKING LOT USE

Screen plantings of tall conifers can work wonders in reducing the cost of plowing out parking lots when blizzards strike, particularly if the parking areas are sunken and accumulate deep drifts. Screens must be set back far enough so that the drifts that form behind them accumulate on the bordering banks or grass areas rather than on the pavement itself. Not only do such screens deposit the snow where it does not require machine removal, but they also act as sun traps when clear weather returns and hasten melting and runoff on the paved areas.

Not all parking lots are so located as to capitalize on the benefits of snow control by judicious planting, and, of course, there are countless ones in southern areas where snow is not a problem. However, the benefits are so striking where the terrain and climate are appropriate that site planners would do well to keep this method in mind.

Proper and skillful planting is no panacea for the nation's energy problems, both present and future, and it would be a gross exaggeration to make such a claim. However, besides its many other benefits to spirit and body alike, planting can make long-lasting contributions to the conservation of energy.

REDUCING BUILDING SOLAR HEAT GAIN

Ian Grad

The most significant new development in building design, construction, and operation is expressed by the catch phrase "energy conservation," which embodies an energy crisis of a dual nature, one being the dwindling supply from available energy sources and the other being the sudden leap in energy costs by as much as five times over those of just a few years ago. Presently, it is the energy-cost crisis that is having the greater impact on building design, construction, and operation rather than the reduced availability of the energy supply. Since energy conservation is also money conservation, building owners are naturally very aware of the potential for reducing building operating costs by reducing energy consumption.

One of the ways frequently suggested to reduce building operating costs is to use solar energy in place of the conventional energy supply of oil, gas, or electricity. Although the use of solar energy has its place in the approach to energy conservation, let us explore the possibilities of reducing building energy consumption by the opposite procedure, the nonuse or rejection of the solar energy that normally impinges on a building. For this purpose, we will consider only the negative aspect of the sun's energy--the building solar heat gain during periods of warm weather conditions. During certain seasons of the year, the radiant heat of the sun striking a building will result in an objectionable net heat gain to the interior of the building. Under these circumstances, energy will be consumed in cooling the building to maintain the internal environmental conditions in equilibrium. Unfortunately, solar heat is mostly available in the summer, when we need it least, causing excessive energy consumption for cooling in a building that has inadequate means of deflecting or rejecting solar radiation.

Since ordinary, single-thickness, clear glass is transparent to solar radiation, it is the windows that have the greatest impact on the solar heat gain to the interior of a building. The solar heat gain through a square foot of ordinary window glass could be more than 40 times as much as the solar heat gain through a square foot of conventional wall or roof construction. Because a building's windows can have such an adverse effect on the magnitude of the solar heat gain to its interior, we will devote most of our attention to the methods that are available for reducing the solar heat gain through the windows.

In the days of energy abundance and low energy costs, from 1950 to 1970, we saw the design of many energy-wasteful buildings with all-glass exteriors. Although some of them may be aesthetically pleasing, most of them are large energy consumers and are very expensive to operate. They are at the high extreme of the energy-use spectrum in relation to building solar heat gain. We could easily solve the solar heat gain problem and virtually reduce it to zero by simply going to the opposite extreme of making all buildings sealed boxes with no windows. However, such a simplistic solution would be unacceptable architecturally, functionally, and psychologically, creating a tasteless, monotonous landscape.

Having looked at both extremes of building solar heat gain, now we can look at the possibilities of reaching compromises that will provide acceptable building designs with low solar heat gain and low energy consumption.

METHODS OF REDUCING BUILDING SOLAR HEAT GAIN

How can building solar heat gain be reduced? What methods are available for use in achieving this objective? Although there are no simple solutions or "magic formulas" to accomplish this, we are fortunate to have available a very large assortment of approaches that can be used. The techniques are varied--some are subtle, some are obvious, and some are accomplished by working with nature instead of against it. Others are accomplished by using manufactured hardware or brute-force methods. We can choose one or a combination of methods for reducing building solar heat gain by considering the following ways to reject or deflect the surrounding solar energy: (1) building configuration; (2) building orientation; (3) window shading techniques and devices; (4) construction materials for windows, walls, and roof; (5) absorption; (6) reflection; and (7) thermal insulation.

BUILDING CONFIGURATION

The general arrangement, shape, size, and height of a building all have an impact on the solar heat gain to its interior. Each has a varying degree of sensitivity to solar radiation and each can be examined and adjusted to provide an optimum combination to minimize the overall building solar heat gain.

Suppose we consider the design of a new building, located at 40° north latitude, on a flat, open site of unlimited area that is unshaded by adjacent structures or the surrounding terrain. Starting with the functional program requirements that define the total floor area of the building, we then have an almost unlimited number of possible building arrangements or configurations to choose from.

The entire building could be below grade, above grade, or some combination of both. It could be a low one-story structure, a multifloor highrise building, or somewhere in between. It could be square, rectangular, round, long and narrow, short and wide, *U*-shaped, *S*-shaped, *Y*-shaped, or some other shape. It could be one building or more than one and could have an interior court or a compact arrangement with no interior opening to the outdoors.

In a real building situation, instead of a theoretical one, the choices will be considerably narrowed by: (1) constraints of the building site location, size, and shape; (2) zoning regulations; (3) functional requirements; (4) architectural design considerations; (5) the construction budget; and (6) other conditions peculiar to the particular building project. In spite of all these restrictions, there are still some optimum building arrangements, sizes, and shapes to minimize solar heat gain.

Assuming that the building in our example will have a uniform ratio of window area to exterior wall area on all exposures, the optimum shape and orientation for minimum solar heat gain will be square or rectangular, with the long dimension ranging from 1 to 1½ times the short dimension and with the long axis in an east-west direction. For a rectangular building, as the ratio of the lengths of the east-west axis versus the north-south axis decreases below 1 or increases above 1½, the cooling season solar heat gain will increase. The solar heat gain also will be greater during the cooling season for a round building and for a square building with its axis in a northeast-southwest or southeast-northwest direction.

If the ratio of window area to exterior wall area can be varied to maintain a reasonable level of solar heat gain, the largest glass area should be on the north side of the building, with the smallest glass areas on the east, south, and west sides. Although the south exposure will receive the largest total solar radiation for the year, compared with the north, east, and west exposures, only 36 percent of the total occurs from April through September, which is 20 percent less than is received by the east and west exposures during the same period. Since most of the solar radiation on the south exposure occurs during the fall and winter months, less heating will have to be supplied to the south side of the building during cold weather when the sun is shining.

A building with windows facing an interior court that is open to the sky will have a higher solar heat gain than a similar building without a court. But, if the court area is less than the total combined area of the windows facing the court on the east, south, and west exposures, the solar heat gain can be reduced by covering the court with a skylight.

SHADING TECHNIQUES AND DEVICES

Building solar heat gain through glass can be reduced to any desired level by employing some type of shading at the glass areas. An extensive number of different shading methods, techniques, and devices are available from which to select one or more possibilities for a specific building design. The different types of shading arrangement fall into two general categories--external, or outdoor, types and internal, or indoor, types. Also, both of these categories can be further subdivided into fixed shading methods and adjustable shading devices with the latter either manually operated or motorized. The motorized types can be both manually operated from a switch or pushbutton or automatically controlled by a time clock, heat sensor, or some type of photosensitive controller that detects the sun's radiation and adjusts the shading device to intercept and deflect the radiant heat.

External Shading

External shading is more efficient than internal shading because it can provide a greater degree of heat rejection coincident with maintaining a higher level of natural lighting. Besides, preventing the radiant heat from entering the building is more efficient than trying to block it out after it has passed through the glass into the building.

External shading can be achieved by the configuration and arrangement of the building structure itself using functional overhangs such as terraces, balconies, outside corridors, and cantilevers. Nonfunctional horizontal projections, such as solid eyebrows, open louvers, awnings, and canopies, also are effective for shading glass areas on the exterior of the building. There are also many types of vertical outdoor shading devices that can be used as part of the building structure or as added projections. The structural methods consist of reveals, wing walls, recesses, and indentations in the face of the building.

Vertical shading devices to be added externally include louvers and screens. Louvers are available with either horizontal or vertical slats, and screens are made in unlimited variations of appearance, ranging from very narrow, closely spaced openings in a thin vertical plane only a fraction of an inch in thickness to a pattern of large openings in a vertical plane several inches thick. Louvers and screens also are made from many different materials, such as wood, metal, and concrete.

External shading methods and devices can be used to develop any type of architectural treatment desired while reducing the building solar heat gain from the east, south, and west exposures of the building to a level as low as that received from the north exposure, a 75 percent reduction in the heat gain transmitted through unshaded, clear glass.

Internal Shading

Internal shading devices, although less efficient than external types, are still used extensively and effectively to reduce solar heat gain to the building. They can be used when the building designer has established a uniformly flat exterior to the building and does not want to use external projections.

Internal shading devices are less efficient, because some of the radiant heat is trapped in by the glass and becomes a heat gain to the inside of the building by reradiation and convection from the indoor surface of the glass.

Again, the building designer can select from an extensive array of available devices, such as blinds, roller shades, screens, and draperies. Just as external louvers, internal blinds are made in several varieties, with either horizontal slats that can be raised and lowered or vertical slats that can be moved horizontally across the face of the glass area. The slats on both types are adjustable and can be pivoted from a fully open to a completely closed position, varying the amount of shading and solar heat rejection. The more closed the position of the blades, the greater the reduction in solar heat gain.

Blinds are made in a wide range of colors from light to dark and of various materials such as wood, metal, plastic, and woven fabric. Blinds are most effective in reducing solar heat gain when they are used in combination with clear glass. For example, a light-colored venetian blind set at a 45-degree angle will reduce the solar heat gain through clear glass by 45 percent but will provide only a 23 percent reduction in solar heat gain through glass with a highly reflective coating.

Roller shades also are very effective in reducing solar heat gain through clear glass but have the disadvantage of eliminating outward vision when drawn. A white, opaque roller shade will reduce solar heat gain through clear glass by 75 percent. The main advantage of roller shades is that they are relatively inexpensive compared to other types of shading devices and are available in many different materials and colors.

Draperies are another possibility to be considered in selecting an internal shading device. They also are available in a very large assortment of materials, colors, and styles. The ability of draperies to reduce building solar heat gain depends on both the texture of the weave and the reflective properties of the materials from which they are woven. Light-colored draperies made from a tightly woven fabric will reduce the solar heat gain through clear glass by 63 percent, whereas dark-colored draperies with an open weave will provide only a 16 percent reduction in the solar heat gain through clear glass. Draperies have the same disadvantage as roller shades in obscuring outward vision (i.e., the more efficient draperies are in reducing solar radiant heat, the more they restrict outward vision and interior illumination from daylight).

Still another group of internal shading devices consists of screens of many varied configurations, materials, textures, and colors, which essentially do the same job as shades and draperies. Screens also can be fixed or movable in either a horizontal or vertical direction.

Since any of the internal shading devices discussed can be used to reduce the building solar heat gain to some desired level, the specific choice for any given application will be based more on cost and interior design considerations than on technical criteria.

BUILDING CONSTRUCTION MATERIALS

Thus far we have looked at many ways of reducing the solar heat gain of a building and have said very little about the construction of the building shell itself--the walls, windows, and roof. There are still to be considered many more approaches to blocking out the solar radiation falling on the building shell (i.e., by constructing the shell of materials that will screen out and reduce some of the radiant heat entering the building).

Glass

Starting with windows of 1/8-in.-thick clear glass, which, as stated above, is transparent to the sun's radiated heat, let us focus on how to reduce the building solar heat gain by varying the materials used for the glass areas. Before resorting to the obvious methods of reducing the area of the glass or eliminating it entirely from those parts of the building that are exposed to direct solar radiation, what other choices do we have to consider?

The use of a heavier single thickness of clear glass will reduce radiant heat little, only 10 percent for 3/8-in.-thick glass. The next choice is to use some type of tinted, heat-absorbing glass that is capable of cutting down the radiant heat still further. The best that can be achieved by this approach, using 1/2-in.-thick, heat-absorbing glass, is a 50 percent reduction in the amount of radiant heat reaching the interior of the building. A light-colored venetian blind on the interior side of 1/8-in.-thick clear glass will reduce radiant heat gain by 45 percent. Thus, the extra 5 percent is not very impressive, particularly since it is obtained at a considerably higher cost than that of the clear glass/venetian blind combination.

Another method of reducing radiant heat while still using single-thickness glass is to use reflective or, as it is commonly called, mirrored glass. A 3/8-in.-thick glass with a tinted, reflective coating can reduce the building solar heat gain by 63 percent. To achieve substantially greater reductions in the radiant heat gain, but not with single glazing, one can employ sealed, double-glazed units, commonly called insulating glass. Insulating glass consists of two panes of glass with a hermetically sealed dry air space between them and is available in a large number of combinations of glass types and thicknesses, in conjunction with various thicknesses of the sealed air space.

Starting at the low end of the range, relative to radiant-heat-rejection capabilities, insulating glass with two panes of 1/8-in.-thick clear glass will provide a 10 percent reduction in solar heat gain. But, at the high end of the range, insulating glass with two 1/4-in.-thick panes, a reflective coating on the exterior side and clear glass on the interior side, will provide a 93 percent reduction in solar heat gain. Additionally, with insulating glass the heat transfer rate, or U factor, is approximately half the U factor of single glass, providing the benefit of a 50 percent reduction in transmitted heat gain from a higher outdoor temperature to a lower indoor temperature. Between the two extremes of insulating glass units, there is a large selection of combinations to choose from to reduce the effects of solar radiation to a desired level for a specific building project.

Still another possibility that is available with insulating glass is a combination unit with an integral venetian blind in the air space between the two panes of glass. This arrangement has the radiant-heat-reduction benefits of both insulating glass and a shading device in a single package. The particular advantage of this combination is that the venetian blind is much more effective in reducing the radiant heat gain in this position, where it approaches the characteristics of an external shading device, than it is when located inside the room. An insulating glass unit with two panes of 1/8-in.-thick clear glass and an integral, light-colored venetian blind will reduce the radiant heat gain by 67 percent.

Glass block is yet another form of glass that can be used to reduce the influx of radiant heat into the building. It does so, however, at the sacrifice of outward visibility. Glass block is available in a number of variations in color and in combinations with other materials. It can be obtained to reduce radiant heat in a range from 35 to 75 percent.

Walls

As previously mentioned, the solar heat gain through the walls is very small compared to the amount transmitted through the windows. But, if the building designer intends to use small glass areas that are less than 50 percent of the gross wall area, consideration should be given to providing thermal insulation as part of the wall construction. This will reduce the heat gain from the solar radiation absorbed by the exterior wall surface. Normally, exterior building walls are only insulated when some type of metal or glass panel construction is used for the building skin. This is done to provide the same heat transmission rate, or *U* factor, as normally obtained with heavier masonry wall construction. If 2-in.-thick thermal insulation is added to a standard medium-weight masonry wall, which consists of 4-in.-thick face brick and 4-in.-thick light-weight concrete block weighing 62 lb/ft^2, and having an uninsulated *U* factor of 0.33, the new *U* factor with the insulation would be down to 0.10, or a 67 percent reduction in the heat-transfer rate through the wall. Consequently, the heat gain from solar radiation on the exterior surface of the wall also would be reduced by 67 percent.

The general range of variation in *U* factors for masonry wall construction is from a high of 0.48 for a 4-in.-thick concrete wall with a 1-in.-thick stucco finish on one side to a low of 0.2 for a cavity wall consisting of a 4-in. thickness of brick, a 2-in.-wide air space, a 4-in.-thick concrete block, and an interior finish of 1/2-in.-thick gypsum board on furring stripes. It is obvious that the solar heat gain through the walls can be minimized by building them with materials that in combination will provide a *U* factor at the low end of this general range.

If a further reduction below the minimum level is necessary, thermal insulation will have to be incorporated in the wall construction to achieve it. Adding 1-in.-thick insulation to the wall construction at the low end of the heat transfer range will reduce the *U* factor from 0.2 to 0.1, a 50 percent reduction in solar heat gain through the wall. If 2-in.-thick insulation is used, the *U* factor will drop to 0.08, a 60 percent reduction in solar heat gain. If a 3-in.-thick insulation is used, the *U* factor will be reduced to 0.06, a 70 percent reduction in solar heat gain.

Roof

The roof of a building, although exposed to continuous solar radiation throughout the day, has only a very small impact on the total solar heat gain of a building. The percentage of the total solar heat gain that the roof contributes to a building is proportional to the ratio of the roof area to the glass area of the building. Comparing two buildings with the same total floor area, and equal ratios of glass area to gross wall area, the solar heat gain transmitted through the roof will have a greater impact on the total solar heat gain for a one-story building than it will for a 10-story building.

Because normal roof construction materials, such as metal decking, precast concrete planks, and poured concrete, have a high heat-transfer rate, thermal insulation of some type will always be required as part of the roof structure to provide a *U* factor that is equivalent to or lower than that of the wall construction. The *U* factor for conventional types of roof construction with thermal insulation will vary from 0.2 for 1-in.-thick insulation to 0.12 for 2-in.-thick insulation. If it is necessary to reduce the solar heat gain transmitted through the roof, additional insulation will be required (e.g., the addition of 1 in. of extra insulation to a roof with a 0.12 *U* factor will reduce the *U* factor to 0.07, affecting a 42 percent reduction in solar heat gain through the roof).

Reflection

Because radiant heat from the sun is partially reflected by light-colored surfaces and absorbed by dark-colored surfaces, the radiant solar heat gain through the walls and roof can be minimized by using light-colored materials for their construction. The solar heat gain through light-colored walls and roofs will be between 30 and 50 percent less than that through dark-colored walls and roofs of the same respective construction.

Evaporation

Still another possibility for reducing the solar heat gain through roof areas is to cover the roof with a layer of water or to provide a roof spray system similar to a lawn sprinkler system. With such cooling arrangements removing the sun's radiant heat by evaporating the water, the roof solar heat gain can be reduced by 50 to 95 percent from the heat transmitted through a dry, dark-colored roof. The actual amount of heat reduced will vary with the time of day, the thickness of the layer of water on the roof, and the dew-point temperature of the ambient outdoor air.

COSTS

As stated earlier, the selection of appropriate methods, techniques, and devices for reducing the heat gain from solar radiation for a specific building project is not a simple matter. We have established some general guidelines that can be used in formulating an approach to minimize the solar heat gain for a building. However, to meet the needs of an individual set of circumstances, the building designer will have to make a detailed analysis of the conditions peculiar to his particular project to determine the method or combination of methods that will produce the optimum level of building solar heat gain relative to both cost and energy usage. Specifically, an economic study or life-cycle cost analysis must be made to evaluate each device or method being considered for reducing solar heat gain for an individual project to select the most cost-effective alternative. Each method examined will have its own particular impact on the construction cost, the operating cost, and the energy consumption of the building. The effects that each alternate method has on each of these three variables will have to be compared to arrive at the optimum choice.

Some years ago, a lot of tedious, time-consuming, hand calculations were involved in making a rigorous detailed analysis to be able to select the best available alternative method for optimizing the building solar heat gain. But today, with computerized calculation programs available for determining building solar heat gain and building energy consumption and for performing life-cycle cost analysis, an evaluation of this type is not only greatly simplified, but can be done in a relatively short time. The use of computer programs further permits consideration of many more alternate schemes for reducing solar heat gain than could be attempted by using hand calculations.

Because of the very broad range of methods discussed, as well as the almost infinite number of variations in the details of the design from one individual building to another, it is not possible to present any meaningful guidelines regarding construction or operating costs for the different methods identified for reducing building energy use by reducing building solar heat gain during "cooling season" operation. The building designer will have to consult with manufacturers and contractors to determine realistic construction costs for all of those items that will be affected by the various methods being evaluated.

DESIGN OF WINDOWS

James W. Griffith

The design of windows involves more than mere technical data on transmittance, size, and location. All too often the designer thinks of windows only as a heat and light source rather than as a complex design tool that can add beauty, quality, and variability to the environment. This paper presents some of the effects of window design on the human environment.

QUANTITY OF HEAT AND LIGHT TRANSMISSION

In quantitative analysis of window design, the amount of heat and light transmittance may vary from 0 to 100 percent transmittance, as in the case of a clear opening. In general, the total amount of light or heat transmitted through any one type of material will be approximately proportional to the size of the window. The usability and the desirability of this light or heat can be made to vary considerably, depending upon the type of control. The effects of heat transmission through windows with and without controls can be obtained from the *ASHRAE Handbook of Fundamentals*.[1]

Unfortunately, there is no one guide giving the transmittance and effects of light distribution through various types of windows and controls. Most of the research work on daylighting in the United States, notably on effects of controls for windows employing flat glass and effects of transmission and light distribution with glass-block fenestration, has been reported in *Illuminating Engineering* magazine.[2]

The window near the top of the wall contributes more direct illumination to the interior of the room than the lower portion, which usually contributes more indirect illumination. To obtain the best utilization of daylight, the window area should be wall to wall and from the ceiling down to the floor. Some interior designs require a sill, which should be held at a minimum height.

In designing windows, air conditioning is sometimes out of the question, and natural ventilation must be relied on. The heat load or loss through windows and its control contribute considerably to the thermal environment and are also affected by the natural ventilation.[3]

Heat and light distribution through windows from outdoors to indoors is directly dependent upon the availability of daylight and solar radiation. Solar radiation data is readily available from U.S. Weather Bureau reports, but data on the availability of daylighting is rather limited (see the *IES Lighting Handbook* and the "IES Recommended Practice for Daylighting"[4]). Extensive surveys have been made on the availability of daylight in Port Allegheny, Pennsylvania, and Ann Arbor, Michigan,[5] but many more such studies are needed.

QUALITY OF HEAT AND LIGHT TRANSMISSION

An even more interesting aspect of solar transmission through windows is the effect on quality of heat and light transmission.

Double-glazed windows permit the utilization of daylighting within the room without uncomfortable drafts. If the ideal environment in cold climates is economically desirable, some form of double glazing must be used. In extremely cold climates, relative humidities higher than 12 to 13 percent are impractical with single glazing. With double glazing the relative humidity can be maintained in the range of 30 to 40 percent under similar conditions. An additional benefit with double glazing is the reduction of condensation on the inside surface.

The luminous effect of windows on the quality of the visual environment may be even more beneficial. This is particularly true where the completely controlled environment is not practical. It is easily demonstrated by the effect of sidewall lighting on veiling reflection.

Illumination from windows is both direct and indirect. Indirect lighting reduces the veiling reflections caused by specular reflectance. Daylight from the side or behind the task will greatly reduce the loss of contrast caused by specular reflectance. Blackwell has shown that for each 1 percent loss in contrast owing to reflected glare, an increase of 10 to 15 percent in the illumination level must be obtained to give equal performance on a typical task of black pencil on white paper if the illumination level is to be near that recommended by the Illuminating Engineering Society for this task.[6] Chorlton and Davidson have shown that a 13 percent contrast reduction can often occur in classrooms owing to veiling reflection.[7]

Daylighting coming from large angles of incidence on the task helps overcome the effect of specular reflection when the window is not in the specular angle of view. The daylight illumination from the sidewall is extremely valuable in overcoming disability glare. Even if the window wall is in the specular angle of reflection, the brightness can be controlled by adjustable horizontal louvers.

EFFECT OF VEILING REFLECTIONS

The effect of specular reflection on a task can be evaluated by computing the loss of contrast from veiling reflections caused by the mirrored image of a direct-lighting fixture located above and in front of the normal viewing task. Contrast is numerically defined by the equation:

$$C = \frac{B_1 - B_2}{B_1}, \tag{1}$$

where B_1 = brightness of background and B_2 = brightness of object. When specular illumination and diffuse illumination are present, this formula becomes:

$$C = \frac{(B_{1S} + B_{1D}) - (B_{2S} + B_{2D})}{B_{1S} + B_{1D}}, \tag{2}$$

where B_{1S} = specular brightness of background, B_{1D} = diffuse brightness of background, B_{2S} = specular brightness of object, and B_{2D} = diffuse brightness of object.

For a task involving ordinary black ink having a specular reflectance of 0.9 percent and a diffuse reflectance of 2.7 percent, printed on mat white paper having a specular reflectance of 0.3 percent and a diffuse reflectance of 77 percent, the contrast with diffuse illumination of 70 footcandles would be computed as follows:

$$C = \frac{(0.77)(70) - (0.027)70}{(0.77)(70)} = 0.965 \text{ or } 96.5 \text{ percent.} \tag{3}$$

This might be the diffuse illumination on the work plane coming from a window using venetian blinds or glass with a reflective cooling as a control medium. If, on the other hand, the 70 footcandles of illumination were produced by an overhead fluorescent fixture in which the reflection of the fluorescent tube could be seen if a mirror were placed in the position of the task, the contrast would be computed as follows, taking the brightness of the fluorescent tube as 1,840 footlamberts:

$$\begin{aligned} C &= \frac{[(0.003)(1{,}840) + (0.77)(70)] - [(0.009)(1{,}840) + (0.027)(70)]}{(0.003)(1{,}840) + (0.77)(70)} \\ &= \frac{59.4 - 18.7}{59.4} = 0.685 \text{ or } 68.5 \text{ percent.} \end{aligned} \tag{4}$$

The resultant loss in contrast would be 28 percent. It would take three or four times as much illumination to bring the task in the second example up to the relative visability level of the task in the first example.

Fortunately, the task is not always in the mirrored reflection angle. However, Finch, Chorlton and Davidson, and Blackwell have shown that many tasks have great losses due to specular reflection, even when the task is not in the mirrored angle with the light fixture.[8] Furthermore, when the task involves pencil on white paper, the loss of contrast is even greater owing to the high specular reflectance of the pencil and the indentation it produces on the paper.

The problem of veiling reflection is far more complex than the simple example shown here. Using more complex calculation techniques and measured results, Finch has shown the loss in contrast for ink on paper to be as high as 50 percent when the source of illumination varies from a light coming over the right shoulder to an incandescent lamp at the mirrored visual angle. When a fluorescent lamp in the same glare angle was substituted, he found a loss in contrast of 45 percent. When pencil on paper was substituted in the same conditions, the measured contrast changed from 43 percent to 9 percent and 11 percent, respectively.[9] With a similar task Chorlton and Davidson found a contrast loss of 21.6 percent for direct illumination, 20.2 percent loss for general diffuse illumination, and 10.8 percent loss for luminous direct illumination. The illumination level in this experiment was 30 footcandles provided by a normal lighting layout. The losses were compared to a lighting environment produced with an overhead baffle eliminating most of the brightness in the mirrored reflection angles.[10]

It is apparent that illumination on the task coming from large angles of incidence greatly reduces the disability glare caused by veiling reflections. It is also obvious that indirect lighting or luminous ceilings would also reduce the disability glare caused by veiling reflections. However, one must be careful not to create a direct disability glare when designing a lighting installation. One must also be careful of taking laboratory data and extrapolating it to actual environmental conditions that include many factors left out in the laboratory tests.

ECONOMY OF DAYLIGHTING

Probably the most interesting aspect of window design to the building owner is the economy of daylight utilization. Some of the types of economic cost models available for comparing alternate types of building component are presented in "Resource Optimization Using Life-Cycle Cost-Benefit Analysis" (this volume) and in the proceedings of the BRI Conference on Methods of Building Cost Analysis.[11] O. F. Wenzler gave an economic analysis of integrated lighting at the conference[12] that made obvious the economy of daylighting. From a lighting viewpoint alone, Wenzler's study of the effects on the thermal environment points out that for equal levels of illumination there is less heat per footcandle for daylighting than there is for electric lighting. Unfortunately, not all daylighting installations are properly designed, and many people have experienced a blast of heat from windows with sun on them. When a high amount of heat comes through a window, there is usually far more daylight than is necessary. If proper controls are installed, the heat will be reduced to a desirable level.

A common mistake in comparing the economy of daylight utilization with that of electric lighting is made by many air conditioning people. The person figuring the air conditioning load fails to realize that the equivalent sphere of illumiantion (ESI) obtained with daylighting produces less heat than an equal ESI produced by electric light. The normal procedure is to assume a fixed electric-lighting load and consider any daylighting as an additional heat load. This assumption is erroneous and does not recognize the advantages of daylight utilization.

OTHER FACTORS

There is very little information available on acoustical transmission through various types of building material; however, this is not an important factor in window design except in extremely noisy areas. In most environments background noise is desirable and actually makes the room seem quieter. Too little noise can be quite disagreeable, and in normal areas a tightly closed window gives a satisfactory acoustical environment. Double glazing appears to give an even quieter environment than single glazing.

Some thought also should be given to safety. A window provides a means of entrance for firemen and exit for escape from fire and asphyxiation.

The window area should be properly designed and engineered to produce the most desirable effect at the lowest cost. It should not be just placed on a building for vision out because people feel cooped up and unhappy without it. However, some economic value should be placed on the preference of windows to space without windows. Building progress has taken us out of the cave. Shall we let the misunderstanding of daylight energy trade-offs send us back?

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DESIGN OF SKYLIGHTS

Benjamin H. Evans

Man's development of his technical abilities has far exceeded his wildest dreams of only a few decades ago. Today he has the technological ability to control his environment. He can produce and control his own atmosphere, his surrounding temperatures, his sonic and aesthetic environment, and his visual environment. Technologically speaking, he can produce all the clean air, sound, and light that he wants.

But man still looks to nature for the fulfillment of his greatest desires. He prefers natural breezes to air conditioning and natural light to electric light. Mankind's desire for the qualities of nature, which he cannot entirely reproduce, is always a pertinent factor in building design. Humans feel a kinship to all living things, and there is within them an intense desire to explore and understand all the facets of nature. For this reason, the lighting of indoor environments will and should contain a significant amount of natural lighting.

NATURAL LIGHT

Natural light was, of course, the most important source of building illumination until the Industrial Revolution, and the influence of man's need for natural light is evident throughout recorded history. In the early days of his development, man was completely dependent upon natural light. Early builders always provided a small hole of some kind in their tents or huts to let in light and let out smoke. Even in Egypt, where there was an abundance of light, early architects took great care to provide interior natural light.

In the classic Pantheon temple in Rome, rebuilt in its present form during the reign (76-138 A.D.) of Emperor Hadrian, lighting effects were produced by a 27-ft-diameter hole in the crown of a huge 142-ft dome. At the time of the rebuilding, the dome was the largest in the world, covering approximately 2 million ft^3. This space is most sufficiently and pleasingly lighted by the 27-ft "skylight." The dome opening (or eye) also had a symbolic meaning. The idea was that worship should relate to the heavens and to the "illumination" of mankind by the gods. So natural light has a spiritual quality also.

Artistically and mechanically, nothing could have been better than leaving the "eye" of the dome open, but it was inconvenient whenever precipitation fell. A change, therefore, was brought about in subsequent buildings with the use of four circular holes in the side of the dome just above its springing. Thus, natural-lighting devices were put into the vertical plane before the widespread use of glass in such fenestrations was technologically possible.

Moving farther north, Gothic architecture came into being with natural lighting again playing a substantial role in style and character. With the development of thin structural elements and high arches, coupled with the extensive use of glass, the Gothic cathedral became the epitome of naturally lighted buildings.

USE OF SKYLIGHTS

As the problems involved in designing for natural lighting in modern times have become more familiar and better understood, more and more complicated control devices have been developed for application to building windows. In the late 1950's these became the curse of practical, economic architecture. In revolt against this trend of architectural design and in view of the energy shortage, many architects across the world are going back to the roof for light.

The roof or ceiling of a room is one of the most logical places for sources of general illumination. Skylights can and have been effectively used for lighting interiors for many centuries. However, it is only recently that skylights have been designed and prefabricated for easy, economical, and waterproof installations. Postwar economic stresses on school buildings and a demand for greater quantities of natural light have stimulated this development of skylights.

BRIGHTNESS CONTROL

Quite early in the technological development of good lighting, the problem of controlling the brightness of the skylight material as viewed from within the building arose as a significant factor. Clear materials were objectionable because they allowed direct sunshine to enter, causing eyestrain. Thus, the translucent or "milky" skylight material was developed in order to diffuse the incoming light and eliminate the entrance of sunshine.

The translucent materials, in turn, introduced another problem. When exposed to direct sunshine, they often were excessively bright when viewed from within, again causing eyestrain. Continued demand for quality lighting conditions have brought about the use of very high density materials that do provide low surface brightnesses, even when exposed to direct sun. With such a low-transmittance material, it is usually necessary, however, to use very large skylights to provide sufficient light on the room task. The incoming light should be diffused as much as possible and spread over as large an area as possible to reduce brightness characteristics.

To illustrate the advantage of this principle, consider the following example. Assume a 2-ft^2 skylight with a translucent dome of T transmission factor. Assume conditions that provide a level of illumination below 62 footcandles on the desk top. This produces a certain dome brightness.

If, then, the skylight is enlarged to twice its original size and the transmission factor of the dome is reduced to provide the same footcandle level below, the dome brightness will be considerably less. The illumination level of 62 footcandles is still provided, but the brightness of the ceiling dome is much less since the same amount of incoming light has been spread over a larger area.

Skylight manufacturers are now providing numerous variations of skylight materials, allowing designers to select a material, or a combination of materials, that will produce almost any desired lighting condition.

ILLUMINATION CONTROL

Architects and illuminating engineers, however, must have a simple, accurate method of determining the natural lighting conditions of their buildings while they are still in the design stages, and several methods for predetermination have been developed. Most mathematical illumination-prediction systems are based on the lumen input method as described in the *IES Lighting Handbook*.[1] The system is basically the same as that used for the design of electric-light systems:

$$\text{Total lumens} = \frac{\text{average footcandles} \cdot \text{lighted area}}{\text{interreflectance factor}}.$$

Any given skylight, under a given condition, will produce a given number of lumens to the interior space of the building. The number of these lumens then available on any task area below is based on the size of this area, its distance from the skylight, the shape of the space, and the finish on the surface surrounding the space.

SKYLIGHT DESIGN PROCEDURES

The typical procedures for designing for lighting with skylights involve:

1. Deciding how much light is desirable for the task being performed. The *IES Lighting Handbook* provides recommendations for most tasks, but these should be tempered by common sense.[1]
2. Deciding how much of the room area must be lighted by skylights. Adjacent areas may be lighted by windows or electric lighting. If the supplement is from windows, there are tables that provide an estimation of how much area can be lighted by the window alone.
3. Determining the effects of the room geometry on the skylighting by finding the room index:

$$\text{Room index} = \frac{\text{room height} \cdot (\text{room width} + \text{length})}{2 \cdot \text{room area}}.$$

4. Using the room index, establishing the effects of the various room surfaces on the skylighting by finding the interreflectance factor (see tables in the *IES Lighting Handbook*).

5. Calculating the total number of lumens required to produce the desired results:

$$\text{Total lumens} = \frac{\text{average footcandles} \cdot \text{lighted area}}{2 \cdot \text{room area}}.$$

6. After determining the number of skylights desired,

$$\frac{\text{Total lumens required}}{\text{Number of skylights}} = \text{lumens per skylight},$$

and their spacing, selecting the size of skylight and the skylight material that will supply the required number of lumens. The particular skylight can be selected from a lumen table provided by most reputable skylight manufacturers.

BRIGHTNESS VALUES FOR PLASTIC-DOME MATERIALS

Unfortunately, not enough information is available on that most important factor--brightness. Complete brightness values for various skylight plastic-dome materials are a necessity. Such values have been developed by the Texas Engineering Experiment Station and, while not previously made public, are presented in Figures 1-6. The numbers along the right side of Figures 2-6 designate plastic material transmissions: 100 = 20 percent transmission, translucent; 200 = 35 percent transmission, translucent; 300 = 50 percent transmission, translucent; 400 = 55 percent transmission, translucent; 600 = 30 percent transmission, clear gray; 700 = 50 percent transmission, clear gray; and 800 = 30 percent transmission, clear gray.

It may be argued that skylights can be secured from the direct view of the people involved in performing a task in the room below so that skylight brightness is not a problem, and this may be correct in some circumstances. However, in many instances it may not be practical to avoid direct view of the skylight.

There is a direct relationship between the transmission factor of diffuse plastic and the resulting surface brightness produced by a given light source. These brightness curves are based on the maximum brightness values possible (direct sunshine under a partly cloudy sky) with diffuse materials of various transmissions. This involves viewing the skylight plastic-dome materials from a point directly opposite the light source--the sun. Thus, the design of a skylighting system should take into consideration the potential brightness of the source, just as do systems with electric lighting.

The data presented in Figures 1-5 are based on a footcandle intensity normal (perpendicular) to the sun's rays. Since it is common practice to record light intensities horizontally rather than normal to the sun, Figure 1 provides for conversion from horizontal to normal. (All the graphs can be used for either normal or horizontal readings by conversion through Figure 1.) Figures 2 through 6 provide brightness factors for various combinations of plastic-dome skylight materials based on the transmission factor for each material. The uppermost straight line on each graph indicates the brightness values to be expected under the single plastic dome.

Figure 2 provides an example. Assuming a horizontal illumination level of 10,000 footcandles, a dashed line is drawn vertically until it intersects the diagonal line representing a plastic skylight material of 20 percent transmission (designated 100). A dashed line drawn horizontally to the left column indicates that the maximum brightness of the skylight material will be a little less than 1,900 footlamberts. Other diagonal lines on the graphs indicate brightness values for various combinations of plastic materials, usually one used in an outer position (on the roof) and one in the inner position (near the ceiling).

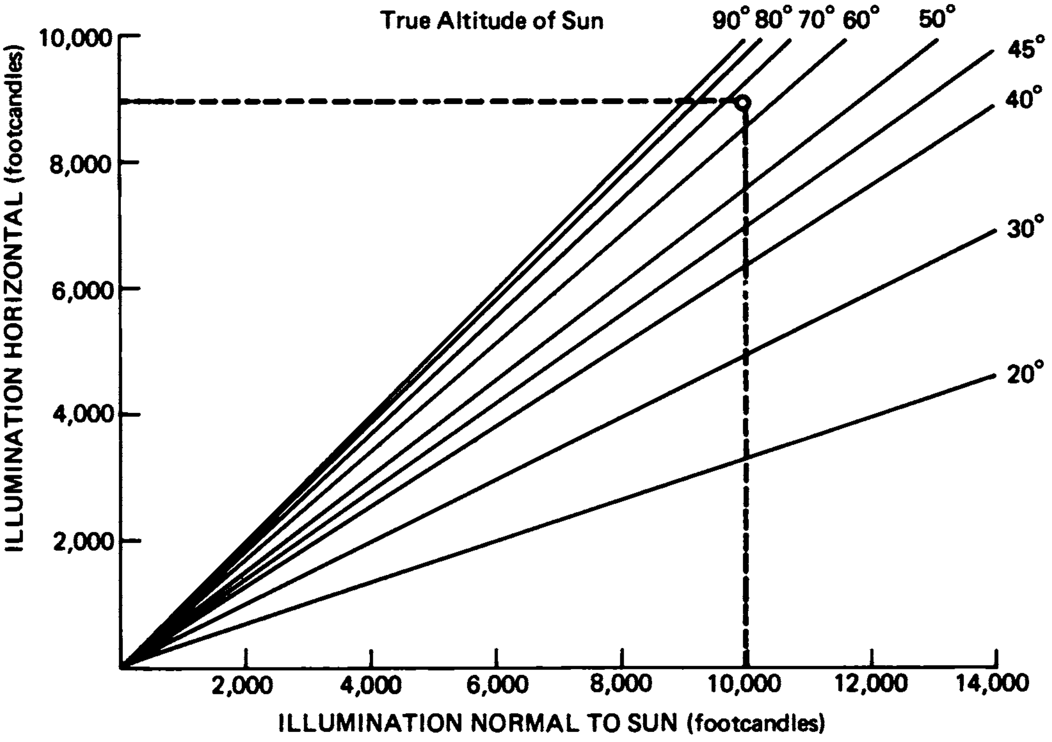

FIGURE 1

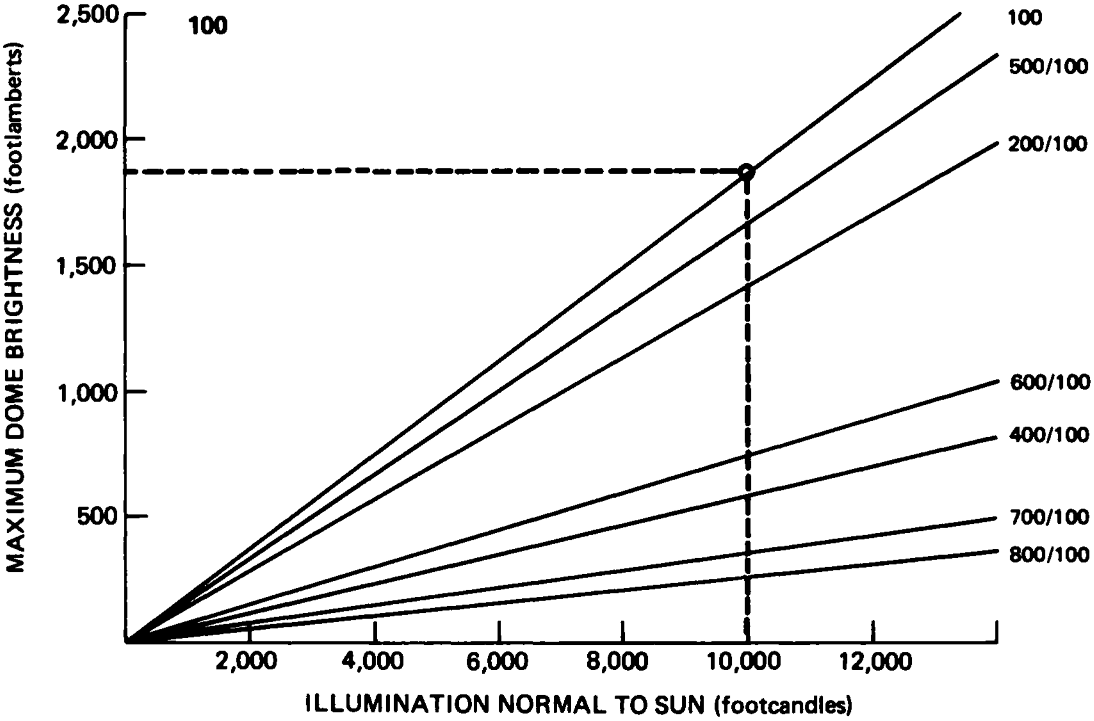

FIGURE 2

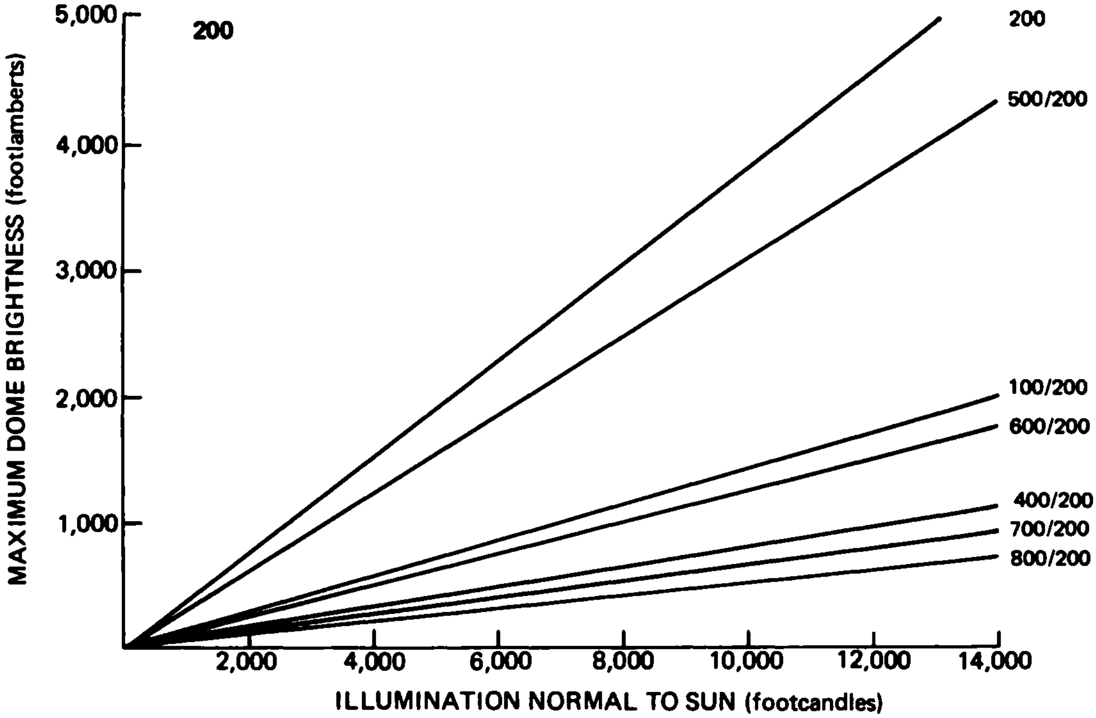

FIGURE 3

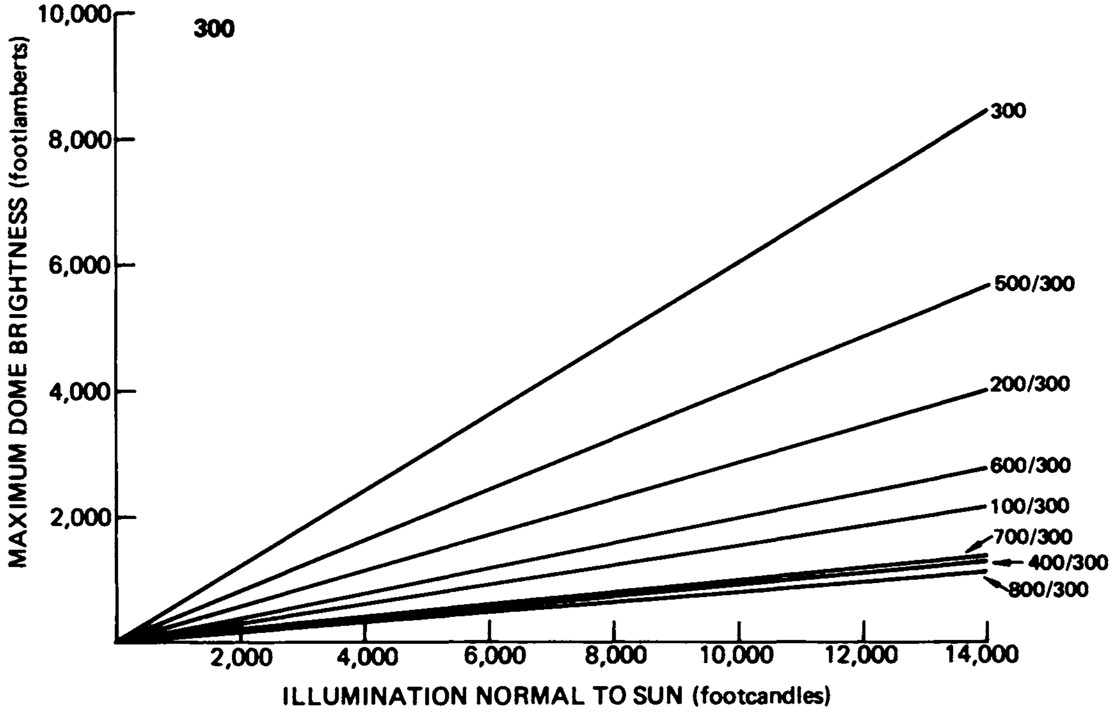

FIGURE 4

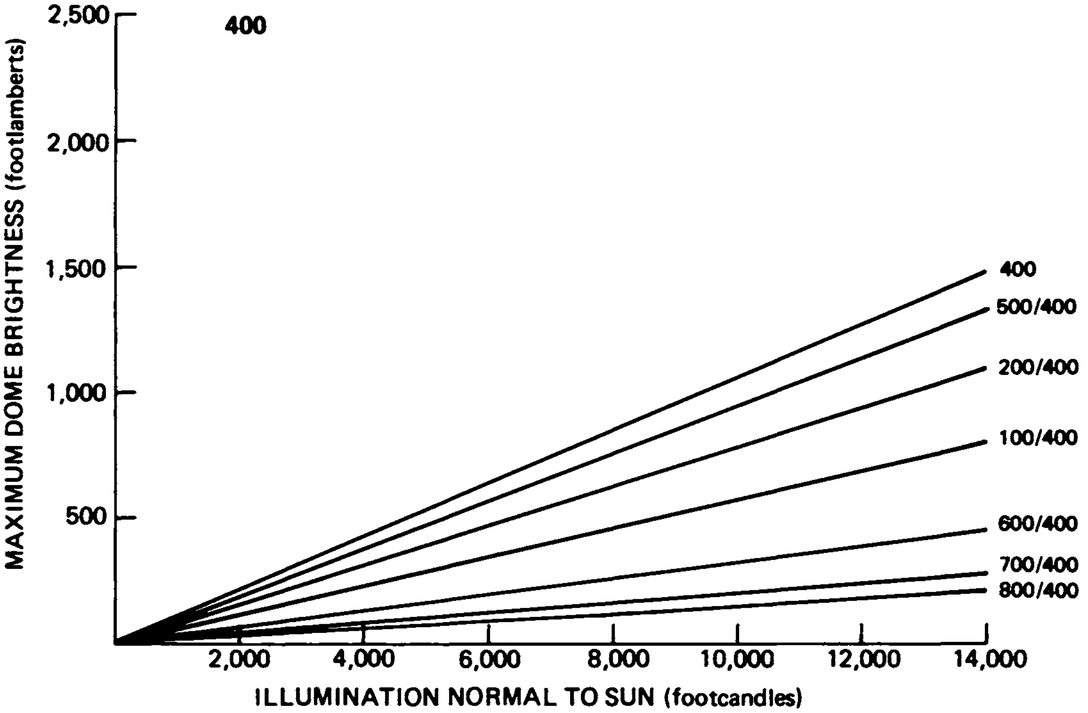

FIGURE 5

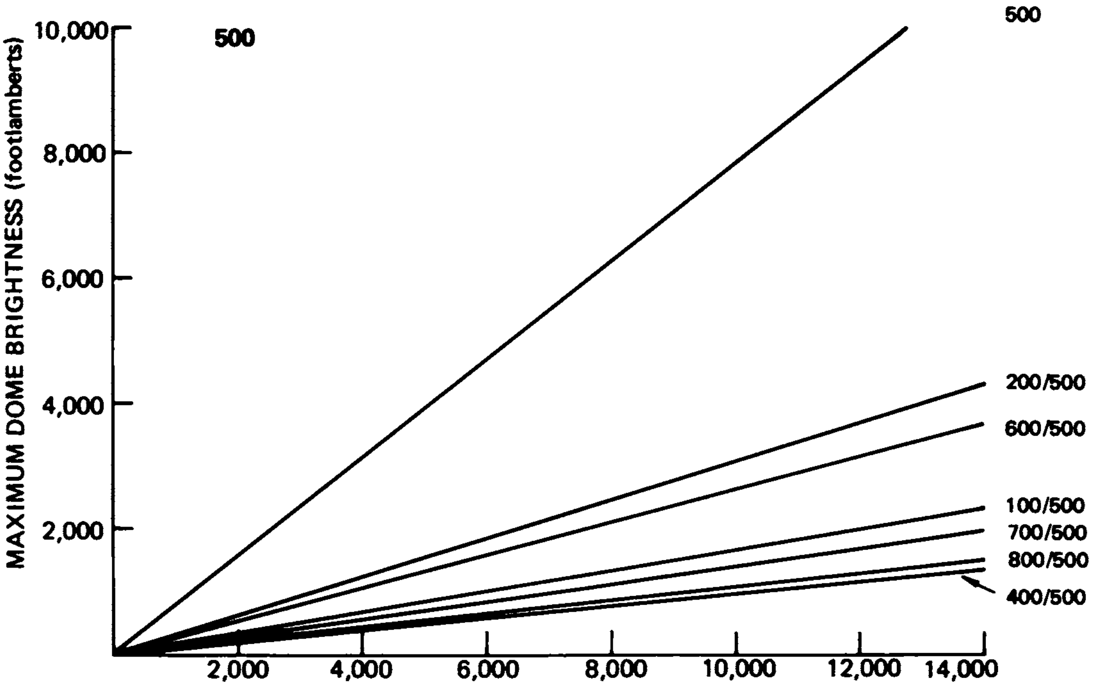

FIGURE 6

SKYLIGHTS AND HEAT

The use of skylights has long been subject to criticism for the quantity of heat transmitted. This criticism is often valid, even if misunderstood. In very general terms, it may be said that light and heat are essentially the same thing, so that where there is light, heat will be there also--almost in direct proportion. (Technologists may criticize this oversimplification.)

It usually, then, comes as a surprise for people to learn that skylights--or daylight--produce less heat per unit of light than most equivalent electric-lighting systems. The figures in Table 1 show that daylighting produces more lumens per watt then electric lighting of the more common varieties and, in terms of air conditioning needs, that daylighting requires less cooling per unit of light, thus indicating that skylights produce better than we often give them credit for. Schutrum and Ozisik indicate the quantities of heat that can be expected from various types of plastic-domed skylight under various sky conditions.[2]

TABLE 1 Efficiency Comparison of Skylights and Electric Lighting

Source of Illumination	Light Output Lumens/ft^2	 Lumens/watt	Air Conditioning Load (tons/100,000 lumens)
Daylight through high-transmission acrylic plastic	5,270	106	0.27
Daylight through medium-transmission acrylic plastic	3,110	106	0.27
Incandescent light	--	20	1.90
Fluorescent light	--	60	0.63

COST COMPARISONS

Last, we must consider the costs for lighting systems whether they are electric or something else. Table 2 presents a typical comparative cost analysis for three different systems of lighting--skylights only (in this case plastic-domed skylights), fluorescent lights only, and skylights and fluorescent lights together. In this analysis we consider all normal expenditures directly related to the various lighting systems. There is the first cost, uniform annual cost of recovering first cost, annual cost of insurance, annual cost for lamps, annual labor costs for cleaning and relamping, and annual power cost. The summation then gives the total annual lighting cost or the annual cost per footcandle. Notice that daylight is the least expensive method of lighting.

Of course there are factors involved other than economics. There is the visual performance level and the general atmosphere being created by the architect, which, in the final analysis, are the primary decision factors. In summary, however, skylights:

1. Can be used economically and effectively for providing high-quality lighting in architectural spaces.
2. Require that surface brightness, if viewable, be kept to a reasonable minimum either by shielding or through the use of a low-transmittance material in the skylight itself.
3. Provide a good quantity of light without unreasonable quantities of heat as compared with other systems.
4. Provide a means as economical as any for providing good-quality daylighting.

TABLE 2 Comparative Costs of Skylights, Fluorescent Lights, and the Two in Combination

	Source of Illumination		
Cost Consideration	Skylights[a]	Fluorescent Light Units[b]	Skylights and Fluorescent Units[c]
First cost of lighting installation (less lamps)	$510.00	$720.00	$950.00
Uniform annual cost of recovering first cost at 4% for an operating period of 25 years	20.40	28.80	38.00
Annual cost for insurance at 1.2% of first cost	6.12	8.64	11.40
Annual cost for lamps[d]	--	18.00	11.00
Annual labor costs for cleaning and relamping[e]	15.00	40.00	39.42
Annual power cost[f]	--	173.88	106.26
Total annual lighting cost	41.52	269.32	206.08
Annual cost per footcandle	0.83	5.43	4.12

NOTE: Costs are based on figures supplied by reputable manufacturers and are believed to be typical. They should be treated, however, as rough approximations only for preliminary comparisons. Consideration should be given to local changes of sky conditions.

[a] Six skylights, 37-by-37-in. inside dimension, double dome of high-transmission acrylic, 10 ft on centers, 9-ft room ceiling, average lighting level under a 5,000-footcandle uniform sky = 50 footcandles.
[b] Eighteen fluorescent units, two 40-W lamps, 45° louvers, 9-ft room ceiling, 30-by-30-ft room, average lighting level = 50 footcandles.
[c] Six skylights and 11 fluorescent units, average lighting level = 50 footcandles.
[d] All lamps replaced once every 3 yr.
[e] Cleaned every 18 months.
[f] Based on $0.035 per kWh, 3,000 h/yr.

REFERENCES

1. Illuminating Engineering Society, *IES Lighting Handbook*, 5th ed. (New York: IES, 1972).
2. L. R. Schutrum and N. Ozisik, "Solar Heat Gains through Domed Skylights," *ASHRAE Journal* (August 1961).

SELECTION OF GLASS AND SOLAR SHADING TO REDUCE COOLING DEMAND

Alfred L. Jaros, Jr.

This paper compares and evaluates the constructions used to reduce the input of heat derived from solar radiation through windows with particular reference to costs of installation, savings in air conditioning load, and consequent net savings in total investment and in evaluated annual costs.[1] For basic data, the selected unit size was 1 ft^2 of glass; for application comparisons, it was 1 horizontal running foot of glass, 6 ft high. Sash, mullions, muntins, and other embellishments were external to these unit sizes. Not all possible shading devices could be considered. Some, such as fixed concrete vertical louvers or vertical screen walls, must be regarded as architectural treatments, and their patterns, proportions, and costs vary so greatly that it was not feasible to evaluate them generally.

METHODS OF ANALYSIS

The following methods seem most practical for evaluating solar radiant heat input and the various devices for controlling it:

1. Determine Btu/h heat input through single plate-glass.
2. Determine the difference in Btu/h transmitted between single plate-glass and the particular solar heat rejecting method for 1 ft^2 of glass.
3. Make comparisons per horizontal linear foot of glass, 6 ft high. Computations have been based on glass running continuously for considerable widths, with suitably spaced narrow mullions; these should apply equally to a row of windows or to a really continuous band. For heights other than 6 ft, one may prorate.
4. Base all computations on net square feet of actual glass. A tentative 15 percent discount may be made in sizing actual air conditioning equipment for that portion of the total window opening that is not glass.
5. Consider the aggregate sensible heat entering through glass. The *ASHRAE Guide* (*Heating, Ventilating, and Air-Conditioning Guide* of the American Society of Heating, Refrigerating and Air Conditioning Engineers) provides basic data for this evaluation. It has been necessary in this paper to extend the ASHRAE data to other types of glass and shading, but these extensions are believed to be as reliable as the data derived from the ASHRAE *Guide*.

6. Determine a reasonable installed cost for the particular solar-heat-rejecting method, assuming that it is to be added to a structurally complete building.

7. Having determined the reduction in heat input resulting from a given type of glass or shading, evaluate the expected saving in installation cost of air conditioning equipment. For the purpose of this paper, it seems reasonable to evaluate such savings at $900/ton of refrigeration or about 65 percent of present-day unit costs of complete installations for typical New York City office buildings of good quality. This figure may be subdivided into $300/ton for the central plant and $600/ton for the distributing systems.

8. Evaluate the probable savings in annual ton-hours of cooling consumption, using data giving the average percentage of sunshine hours and the degree to which the particular glass or shading will exclude sunshine.

9. Consider orientation and configuration. Different orientations produce different figures.

10. Evaluate the annual cooling consumption savings. It seems logical to consider only the costs of electricity, steam, water, and the like, not operating labor nor annual maintenance costs. For this paper, 2.5¢ per ton-hour of refrigeration per season has been used as a working average.

11. Add to the operating savings the savings in fixed charges--interest on the investment, amortization, taxes, and other savings. For this paper, 10 percent has been used.

12. Add to the annual operating saving the fixed charges on the net investment saving resulting from the shading method to get the overall annual saving.

COMPUTATIONS

All computations (except for reflecting glass) have been made in accordance with methods and data given in Chapter 13 of the 1960 ASHRAE *Guide*, pp. 195-201. Data received from one manufacturer of reflecting glass have been used.

Data for 40° north latitude have been used, and the results may be considered sufficiently close for 38° to 43°. Times stated are local sun time.

Solar input figures have been based on very clear weather, which will produce maximum solar heat gain. Reduction because of haze would reduce only the operating savings. Conduction and convection of sensible heat through glass only, owing to difference between indoor and outdoor air temperature, are included in all computations. A maintained indoor dry bulb temperature of 75° F has been used throughout (instead of 80° F as in the ASHRAE *Guide*), as being more typical of future practice. Instead of a uniform 95° F outdoor dry bulb temperature (as in the ASHRAE *Guide*), the following outdoor temperatures have been used as being more typical for a clear summer day:

Time:	0700	0800	0900	1000	1100	1200-1300	1400-1700	1800-1900
Temp.:	85° F	86° F	88° F	90° F	92° F	94° F	95° F	94° F

Since tabulations (see Table 1) are based on net glass area exposed to sunshine, they should not be multiplied by masonry-opening areas without correction. Window frames and sash will conduct in summer only a fraction of what glass would transmit due to direct solar impact. If windows are recessed, the glass directly exposed to sunshine may be reduced to 80 percent or less of the masonry opening. The correction to be applied should be determined to fit each situation. For this paper, such variable factors have been ignored, since they do not materially affect the comparison between types of glass or shading.

Obviously, factors and constants used would change for more southerly latitudes. Any tabulations to be used at 30°, 20°, or even nearer the equator, should be reworked, especially for north and south exposures. Installation savings will decrease (on the side toward the equator only), but operating savings will increase, because there are more annual cooling hours. Figures for Dallas, Texas, have been developed as representing a typical southern U.S. location (see Table 4).

COMPARISON OF TYPES OF GLASS

Figure 1 shows the peak-load values for all orientations for five types of glass: Curve 1--single plate-glass, 1/4 to 3/8 in. thick; Curve 2--double plate-glass, with sealed air space between; Curve 3--single heat-absorbing glass, 1/4 to 3/8 in. thick; Curve 4--heat-retarding plate-glass (double glass with outer layer heat-absorbing); and Curve 5--laminated heat-reflecting glass, with metallized central film.

Heat-retarding plate-glass (Curve 4) has proved troublesome, especially in large panes. In summer, when the sun shines, the outer pane reaches a much higher internal temperature than the inner pane; in cold weather, the reverse may be true. Differential expansion can lead to difficulties in preserving the seal, to spontaneous cracking of the glass, or to damage to the sash.

Another practical difficulty with all types of large double panes is a "hothouse effect." In cold sunny weather, the double pane is quite transparent to high-frequency infrared, but relatively opaque to outward conduction and radiation from the room. This may necessitate using refrigeration for the sunny side of the building, even when the temperature is 25° F or 30° F outdoors.

COMPARISON OF SHADING DEVICES

Only five specific curves for shading devices are shown in Figure 2. Each of these is equivalent thermally to various other shading devices, as noted below. All data relating to effects of shading devices are based only on their use with single plate-glass, since experience has shown that combinations of heat-absorbing and other special glass with shading devices are uneconomical. Shading from nearby buildings, trees, etc., has necessarily been ignored.

The five curves shown are: Curve 6--inside venetian blinds, painted a light color; Curve 7--inside polished-aluminum venetian blinds; Curve 8--

TABLE 1 Solar Heat Conduction of Unshaded Single Plate-Glass[a] on a Typical Business Day (August 1,[b] 40° North Latitude, in Btu/h/ft)

	"True" Orientation (or Solar Azimuth) in Degrees											
Sun Time	0	30	60	90	120	150	180	210	240	270	300	330
0800	11	*45*	170	183	170	82	14	9	9	9	9	9
0900	11	31	141	167	162	120	38	12	10	10	10	10
1000	17	21	62	121	136	132	70	23	20	20	20	19
1100	24	26	30	66	108	111	95	46	26	26	26	24
1200	32	32	32	34	53	96	*108*	94	57	34	32	32
1300	35	35	35	35	35	53	104	127	120	73	40	35
1400	*36*	36	36	36	36	40	87	150	156	140	80	41
1500	35	35	35	35	35	35	61	*156*	185	190	162	55
1600	34	34	34	34	34	34	38	111	*191*	*212*	*198*	85
1700	34	34	29	29	29	29	30	63	181	202	189	100
1800	40	23	22	22	22	22	24	38	113	138	142	*115*
TOTAL	308	352	626	762	820	754	669	829	1072	994	908	525

NOTE: Figures in italics are peak values for those orientations. At certain orientations, higher input for October 1 midday is anticipated: 120° at 1000-165; 150° at 1000-177; 180° at 1400-191; and 240° at 1400-191.

[a] Data throughout for single plate-glass are for thickness of 1/4 to 3/8 in.

[b] August 1 has been selected as a typical time for evaluation of required cooling loads and their comparisons. The only important exception is windows facing in southerly directions (about 135° to 225° true). Maximum demand may occur in October for southward peripheral zones but not for the entire building.

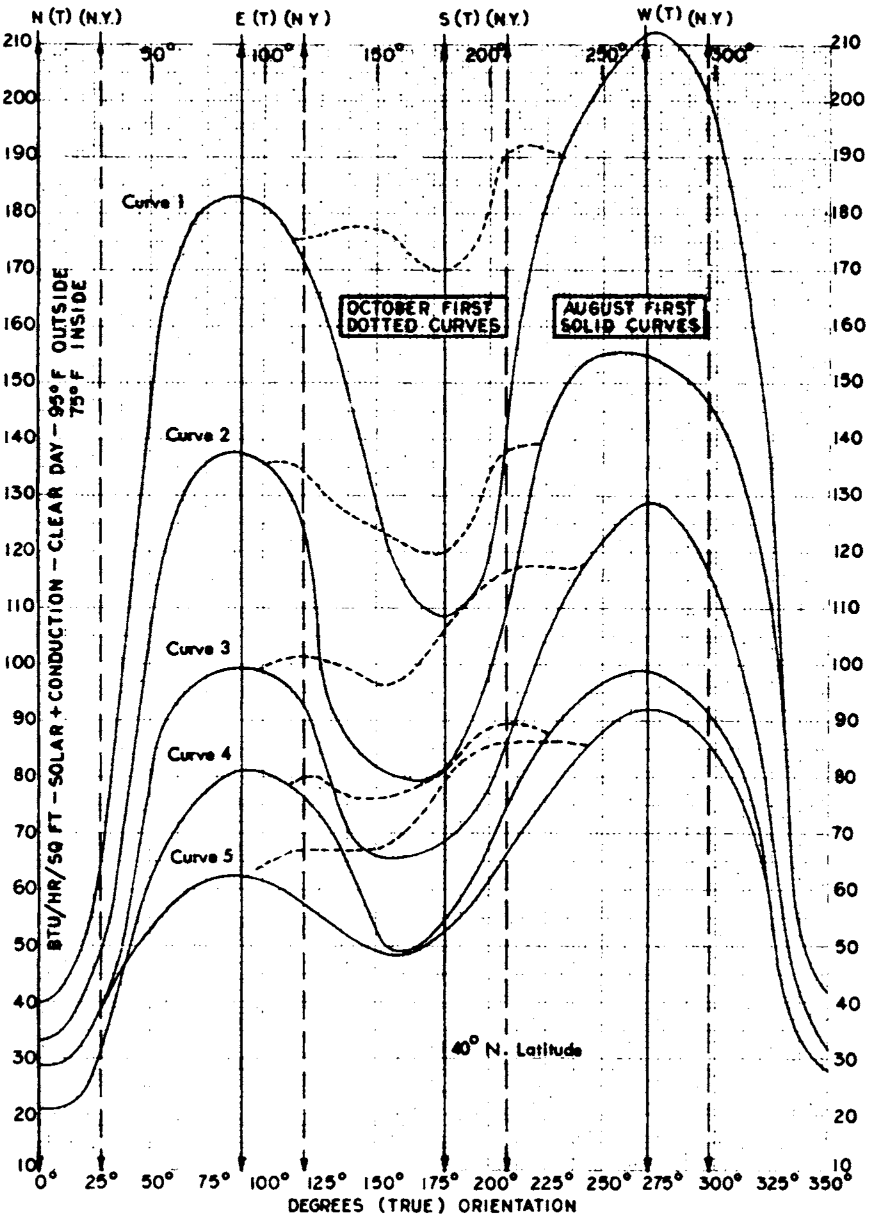

FIGURE 1 Comparison of solar heat conduction through unshaded single plate-glass with solar heat conduction through other types of unshaded glass: Curve 1, single plate-glass; Curve 2, double plate-glass; Curve 3, single heat-absorbing glass; Curve 4, heat-retarding glass (double glass with outer layer heat-absorbing); and Curve 5, laminated heat-reflecting glass.

outside canvas or dark metal awnings with closed sides; Curve 9--outside canvas or dark metal awnings with open sides; Curve 10--outside white aluminum or stainless steel louvers and venetian blinds; or louver-type reflecting insect screens.

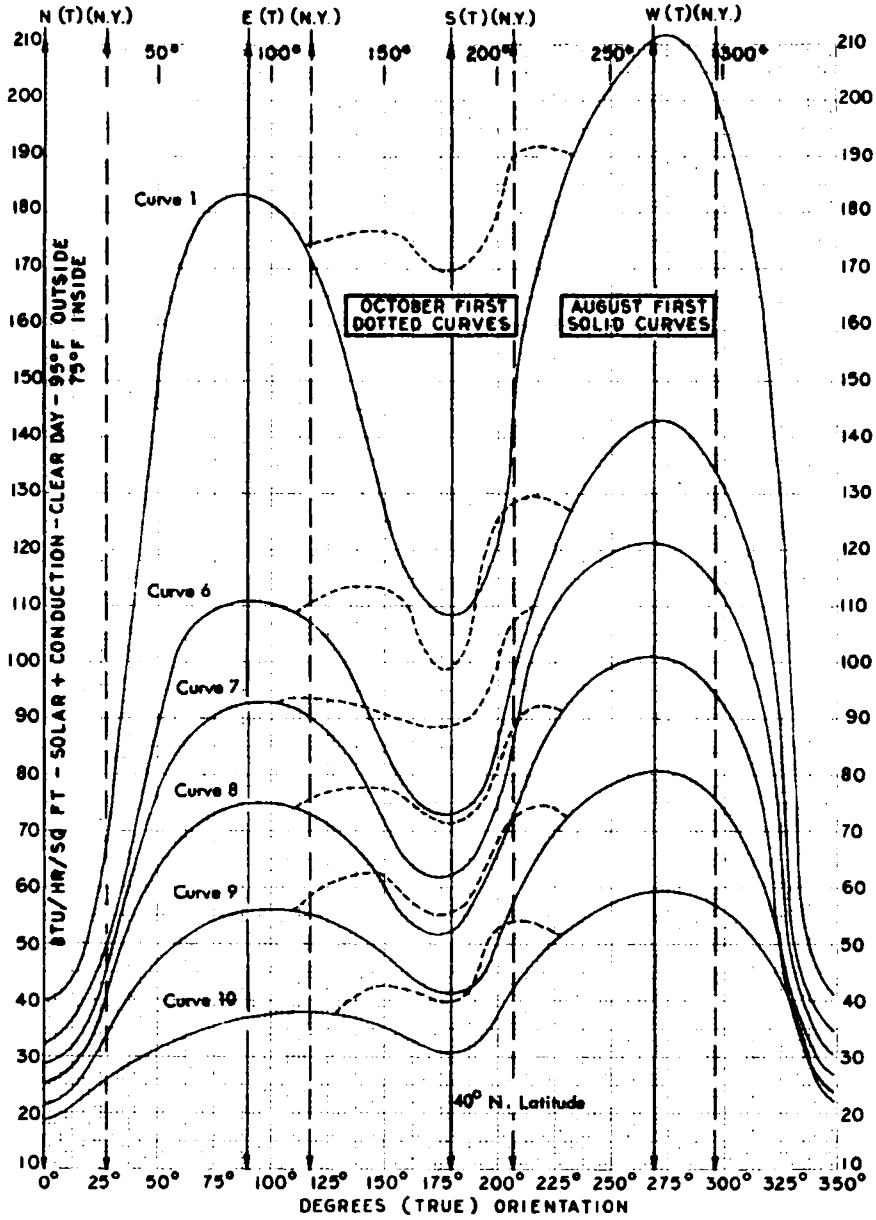

FIGURE 2 Comparison of solar heat conduction through unshaded single plate-glass with solar heat conduction through single plate-glass shaded with the following devices: Curve 6, inside venetian blinds painted a light color; Curve 7, inside polished-aluminum venetian blinds; Curve 8, outside awnings with closed sides; Curve 9, outside awnings with open sides; and Curve 10, outside louvers, venetian blinds, or louver-type shading screens.

For evaluating other types of shading devices, the following comparisons may be useful:

1. Clear white or pale cream-colored drapes are equivalent to cream-colored inside venetian blinds.
2. Certain grades of white glass-fiber or metallic-coated drapes or roller shades can be as effective as aluminum inside venetian blinds.
3. Dark-colored (or dirty) drapes do not reflect much infrared; their effect might be about equal to double plate-glass, unshaded. Really dark drapes or shutters merely convert infrared into sensible heat.
4. The heat-reducing value of outside shading depends largely on its ventilation by air circulation. Light-colored, polished-metals, outside shading is less dependent on air circulation than canvas or dark finishes.
5. Closed awnings with adequate ventilating openings at the top are about equal to open awnings.
6. Projecting solid balconies or cornices are a little better than open awnings, but only to the extent that they actually shade the glass. (See Table 26, p. 205, of the 1960 ASHRAE *Guide* for width of projection.)
7. Outside louvers, well ventilated and properly oriented, are the most efficient shading devices for all-round use. On the south, horizontal louvers are efficient; on east or west, vertical louvers are more effective. In general, louvers should be projected appreciably. With such mounting, louvered shading screens will be as effective as outside louvers when the sun is high, but every 10° by which the sun's altitude is less than 40° (for the 17-bar/in. type) or 25° (for the 23-bar/in. type) will downgrade their protection to about the next higher curve on the graph (Figure 2).
8. Various types of screen walls may be effective for low buildings on the east and west. The screen wall may be combined with a large, cantilevered, roof overhang.
9. An interesting device long used abroad, but relatively new here, is a pivoted sash containing two separate panes of glass, with a venetian blind mounted between. The inner pane is also pivoted and can be swung open. Such windows are competitive in price with standard single-pane windows and inside blinds. They should be effective in reducing transfer of heat and sound, but until adequate data are available evaluation is not feasible.

PRACTICAL LOAD ANALYSIS

Peak cooling demand for the various glass types and shading devices is shown in Figures 1 and 2. The morning peak (August 1) is shown on the line at 90° true, the midday peak (October 1) is shown on the line at 210° true, and the afternoon peak (August 1) is shown on the line at 270° true.

For northeastern U.S. locations, the seasonal consumption of cooling per square foot of unshaded single plate-glass, due only to solar radiant heat, has been evaluated for an office building during business hours in a typical year of 107 business days (Table 2). It is a complex and largely empiric process to evaluate monthly average cooling loads due to glass. One must take into account solar radiant heat input (which varies with

TABLE 2 Average Monthly Cooling Loads for 1 Ft^2 of Unshaded Single Plate-Glass in an Office Building (40° North Latitude)

Orientation	Load Basis	May (14 days)	June (20 days)	July (20 days)	Aug. (21 days)	Sept. (20 days)	Oct. (12 days)	TOTAL (107 days)
0° true	Average Btu/day	150	250	300	280	250	100	--
	Monthly sum	1,300	3,200	3,800	3,700	3,200	800	15,800
60° true	Average Btu/day	300	430	470	450	330	200	--
	Monthly sum	2,600	5,400	5,900	6,000	5,700	1,500	25,600
90°-120° true	Average Btu/day	350	470	520	500	450	350	--
	Monthly sum	3,100	5,900	6,600	6,600	5,700	2,700	30,600
180° true	Average Btu/day	400	520	570	600	600	560	--
	Monthly sum	3,500	5,600	7,200	8,400	7,400	4,200	36,000
240°-270° true	Average Btu/day	620	780	850	850	600	500	--
	Monthly sum	5,500	9,800	10,200	11,400	7,600	3,700	54,200
300° true	Average Btu/day	520	650	700	700	500	400	--
	Monthly sum	4,600	8,200	8,400	9,300	6,300	3,000	39,800

NOTE: Based largely on the writer's judgment and experience. A ratio system can sometimes give results close enough for practical use. Table 3 shows a sample of such an analysis.

each orientation), changing average monthly air temperature, generally rising temperature during the day, and percentage of sunshine (taken at 63 percent in Table 2).

It may be helpful to visualize the proportions of total cooling demand chargeable to different factors. An evaluation may be based on any desired set of assumptions, such as:

Floor area, 100 ft^2/person
Electric heat, 6 W/ft^2
Outside air, 0.4 ft^3/min/ft^2
Outside air conditioning, 40 Btu/h/ft^3/min^2
Glass in facades, 25, 50, and 75 percent (with good inside venetian blinds).

On these assumptions, overall percentages for an entire building can be approximated, as in Table 4. It is assumed that the four facades are more or less equal, that 40 percent of the floor area is interior zone, and that blinds are drawn only on the side exposed to sunshine.

By combining the ratios in Table 3 with estimated cooling loads and assuming equal electric and steam rates, application ratios for Dallas vs. New York City would approximate 3*x* for total operating cost and 2.0*x* to 2.3*x* for window solar operating cost, varying with orientation (Table 5).

TABLE 3 Sample Analysis of Average Cooling Loads, Using Ratio System, in New York and Dallas

Criterion	New York	Dallas	Ratio
Cooling needed, months/ business days	6/107	12/213	2
Cooling needed, total h/h business days	1,400/1,000	5,350/3,700	3.7
Cooling equivalent, full-load business day h	600	1,750	2.8
Average sunshine, summer/ spring-fall	64%/60%	78%/65%	1.22/1.08
Average hours dry bulb temp. over 80°/90° F	597/86	1,861/820	3.15/9.5
Average hours wet bulb temp. over 64°/72° F	1,832/406	2,709/1,791	1.48/4.4
Average noon dry bulb temp. summer/spring-fall	75.8°/56.8°	87.3°/70.6°	+11.5°/+13.8°

TABLE 4 Percentage of Heat Gain for Entire Building

Heat Source	Glass in Facade (%)		
	25	50	75
People, lights, and office equipment	32	24	19
Window heat input (maximum)	32	47	57
Conditioning of outdoor air	20	15	12
Conduction through walls	4	3	2
Miscellaneous allowances	12	11	10
TOTAL	100	100	100

COMPARATIVE COSTS OF UNSHADED GLASSES AND SHADING DEVICES

Figures from manufacturers and experienced builders indicate that estimated installed costs of unshaded glass for large buildings are as shown in Table 6. This cost may be prorated for other heights of glass.

Since direct solar radiation on northern windows is negligible during business hours, comparisons of installed glazing cost vs. air conditioning saving (all per foot of glass perimeter) may logically be based on east and west windows August 1 and south windows October 1.

Costs of inside venetian blinds have been similarly estimated at about \$1.00/ft^2 for horizontal slats of standard metal types manually operated and about \$1.50/ft^2 for vertical slats of metal or fabric with manual operating gear. The choice between horizontal and vertical slats, apart from relative installation costs, is one of esthetics, convenience, and personal preference, since thermal results are equivalent. Vertical inside blinds are more complex, more difficult to maintain, and less apt to be properly used.

Estimated costs for inside light-metal venetian blinds (see Curve 7, Figure 2) per linear foot of 6-ft-high glass perimeter are: horizontal, \$6.00; vertical, \$9.00. They may be prorated for other heights. Because of their lower initial cost, horizontal blinds yield apparent savings of about 30 percent over vertical blinds.

Installation costs have not been estimated for canvas awnings (see Curves 8 and 9, Figure 2), since their use for large modern buildings is rare. For other types of outside shading, data indicate that the costs presented in Tables 7, 8, 9, 10, and 11 may be considered as typical costs per foot of glass perimeter for large buildings. Note that unit costs vary with height of window, so that prorating is not always feasible.

On October 1 at about 41° north latitude, such a balcony, not more than 1 ft above the window, will completely shade a south window 1 ft shorter than the balcony projection (Curve 9, Figure 2). For Dallas, at 33° north latitude, nearly 2 ft less projection would be needed. If balconies are to be used other than for shading, doors and railings would add further cost.

TABLE 5 Annual Ton-Hours per Square Foot of Glass, New York and Dallas

Glass and Shading	0° True		60° True		90°-120° True		180° True		240°-70° True		300° True	
	N.Y.	Dallas	N.Y.	Dallas	N.Y.	Dallas	N.Y.	Dallas	N.Y.	Dallas	N.Y.	Dallas
Single plate, no shading	1.30	3.25	2.20	5.00	2.60	5.60	3.00	6.00	4.50	9.70	3.30	7.60
Double plate, no shading	0.80	2.00	1.70	3.90	2.10	4.50	2.40	4.80	3.25	7.00	2.40	5.50
Single plate heat-absorbent, no shading	1.00	2.50	1.20	2.75	1.45	3.10	1.85	3.70	2.75	5.90	2.00	4.60
Single plate heat-absorbent + single plate, no shading	0.60	1.50	0.95	2.20	1.20	2.60	1.40	2.80	2.10	4.50	1.55	3.50
Single plate heat-reflecting, no shading	0.60	1.50	0.75	1.70	0.95	2.05	1.35	2.70	1.95	4.20	1.45	3.30
Single plate, light inside venetian blinds	1.10	2.75	1.35	3.10	1.60	3.45	2.05	4.10	2.75	5.90	2.00	4.60
Single plate, aluminum inside venetian blinds	1.00	2.50	1.15	2.60	1.40	3.10	1.75	3.50	2.45	5.25	1.75	4.00
Single plate, closed outside awnings	0.60	1.50	0.90	2.05	1.10	2.35	1.40	2.80	1.95	4.20	1.45	3.30
Single plate, open outside awnings	0.60	1.50	0.75	1.60	0.90	1.95	1.15	2.30	1.50	3.20	1.15	2.60
Single plate, aluminum outside louvers, etc.	0.60	1.50	0.45	1.60	0.55	1.20	0.85	1.70	1.25	2.70	0.95	2.20

TABLE 6 Estimated Installed Cost of Unshaded Glass

Type of Glass	Cost per Square Foot Installed ($)	Cost per Foot of Glass Perimeter for 6-Ft Height ($)
1/4-in. single plate-glass (polished)	1.50	9.00
Double plate-glass	3.50	21.00
1/4-in. heat-absorbing glass	2.25	13.50
Double glass, outer layer heat-absorbing	4.29	25.50
Heat-reflecting sheet-glass	3.85	23.10
Heat-reflecting plate-glass	4.85	28.10

TABLE 7 Estimated Costs for Poured-in-Place Reinforced Concrete Shading Balconies[a]

	Cost per Foot of Glass Perimeter ($)		
Projection (ft)	Balcony	Flashing and Drainage	
5	14.00	4.00	18.00
6	17.00	4.00	20.00
7	20.00	4.00	24.00
8	24.00	4.00	28.00
9	30.00	4.00	34.00

[a] With flashing at wall, gutter, and drains but no separate waterproofing, railing, or doors.

TABLE 8 Estimated Costs for Cantilevered Aluminum Horizontal Louvered Canopies[a]

Projection (ft)	Cost per Foot of Glass Perimeter ($)
4	17.00
5	20.00
6	25.00
7	32.00
8	40.00

[a] Cost includes brackets, but not structural changes in building wall.

TABLE 9 Estimated Costs for Continuous Vertical Reinforced Concrete Fins

Window Height (ft)	Approx. Sill Height (ft)	Fin Projection (ft)	Louver Height (ft at each level)	Cost per Foot of Glass Perimeter ($)		
				Concrete	Louvers	Total
4	4	1	5	1.00	18.00	19.00
5	4	2	7	2.00	25.00	27.00
6	3	3	10	3.00	36.00	39.00

TABLE 10 Estimated Costs for Outside Horizontal Aluminum Louvers and Louvered Shading Screens

Window Height (ft)	Horizontal Louvers ($)	Louvered Shading Screens ($)	
		17-bar/in.	23-bar/in.
4 (6-in. vanes)	24.00	18.00	22.00
5 (6-in. vanes)	27.00	22.50	27.50
6 (9-in. vanes)	31.00	27.00	33.00
7 (12-in. vanes)	42.00	31.50	38.50
8 (14-in. vanes)	60.00	36.00	44.00
9 (14-in. vanes)	65.00	40.50	49.50

TABLE 11 Estimated Costs for High-Quality Vertical Louvers

Vane Size (in.)	Type of Control	Height up to (ft)	Cost per Square Foot ($)	Sample Window Height (ft)	Cost per Linear Foot ($)
9	Manual	6	5.50	4 and 6	22 and 33
9	Automatic	6	6.00-6.50	4 and 6	25 and 37
14	Manual	8	5.00	7 and 8	35 and 40
14	Automatic	8	5.40-6.00	7 and 8	39 and 45
20	Manual	10	3.50	9	31.50
20	Automatic	10	3.75-4.00	9	35.00
20	Manual	Over 10	4.50	20 (2-story)	90.00
20	Automatic	Over 10	4.75-5.00	20 (2-story)	97.00

On October 1 at about 41° north latitude, such a canopy, close above the window, will shade an equal height of south window (Curve 10, Figure 2). For Dallas, nearly 2 ft less projection would be needed.

Estimated costs for continuous vertical reinforced concrete fins about 10 to 14 ft apart, supporting interrupted groups of horizontal 6 in. louvers (or wider) set in a vertical plane are shown in Table 9. With 6-ft windows, this device limits outlook considerably; with higher windows, no outlook would remain (Curve 10, Figure 2).

Estimated costs based on foot of glass perimeter for manually adjustable horizontal outside louvers and for louvered shading screens (4 ft to 8 ft wide) are shown in Table 10 (Curve 10, Figure 2).

Costs of louvers are stated only for manual adjustment by individual bays. Horizontal louvers or blinds will be best for south windows; vertical ones, for east and west windows.

Vertical louvers come in many designs. For all but the smallest, automatic operation is much to be preferred. Automatic control costs vary so much that a better approach would be to allow $1,000 to $1,500 beyond estimated costs for manual control for each large group.

Larger and fewer vanes give a cheaper unit cost. The larger vane sizes may also be used efficiently for lower heights than those shown in Table 11, but the increased ratio of mounting and gearing to the vane area would bring unit cost per square foot nearer to that of the next smaller vanes.

None of the unit costs include accessory items such as framing in walls for attachment, extended sills, and scaffolding. These will add a small percentage.

ESTIMATED SAVINGS

Evaluated savings may now be estimated, based on the above costs; some values are tabulated in Table 12, which expresses comparisons for east, south, and west orientations. Relative applicability of these figures depends on the relative proportions of the facades. The saving in air-distributing systems is an integrated average for the four directions. Total operating saving approximates the total of those for all directions.

WET ROOFS

Wetting a roof during sunlit hours is a means of reducing the intake of solar radiant heat into a building, the evaporation of water removing about 1,050 Btu/h as latent heat. Obviously, the possible savings are greater for a low widespread industrial building than for the upper floor of a tall office building.

Data indicate that during mid-afternoon on a clear July-August day the sun may heat the surface of fireproof masonry roofs to 50° F or more above the indoor temperature and that wet roof surfaces will reduce this temperature differential to about 14° F. A cumulative total of the temperature differential between 0800 and 1800 amounts to about 385 degree-hours for a dry roof as against about 85 degree-hours for a wet roof at

TABLE 12 Estimated Saving in Air Conditioning Cost through Use of Different Types of Glass and Shading Devices

6-Foot-High Window/Foot-Wide Type of Glass and Shading	Cost of Scheme ($)		Differential at $900/Ton Refrig.		Net Investment Saving ($)	Est. Ann. Ton-Hours		At 2.5¢/Ton-Hour Annual Operating Saving ($)		Including 10% Charges Annual Total Saving ($)	
	Net	Diff.	Tons	Saving ($)		N.Y.	Dallas	N.Y.	Dallas	N.Y.	Dallas
EAST											
Single plate, no shading	9.00		--			15.6	33.6				
Double plate, no shading	21.00	12.00	0.0235	21.15	9.15	12.6	27.0	0.08	0.17	1.00	1.09
Single plate heat-absorbent, no shading	13.50	4.50	0.0413	37.20	32.70	8.6	18.6	0.18	0.38	3.45	3.65
Single plate heat-absorbent + single plate, no shading	25.50	16.50	0.0510	45.75	29.25	7.2	15.6	0.21	0.45	3.13	3.37
Reflecting sheet, no shading	23.00	14.00	0.0600	54.00	40.00	9.1	19.6	0.26	0.56	4.26	4.56
Reflecting plate, no shading	29.00	20.00	0.0600	54.00	34.00	9.1	19.6	0.26	0.56	3.66	3.96
Single plate, inside horizontal venetian blinds	15.00	6.00	0.0450	40.50	34.50	8.4	18.6	0.18	0.38+	3.63	3.83
Single plate, inside vertical venetian blinds	18.00	9.00	0.0450	40.50	31.50	8.4	18.6	0.18	0.38	3.33	3.53
Single plate, outside vertical automatic louvers	46.00	37.00	0.0720	64.80	27.80	3.3	7.2	0.32	0.64	3.10	3.42
Single plate, 23-bar louvered screen	42.00	33.00	0.0680	61.20	28.20	4.5	9.8	0.28	0.60	3.10	3.42
SOUTH											
Single plate, no shading	9.00	--	--	--	--	18.0	36.0	--	--	--	--
Double plate, no shading	21.00	12.00	0.0266	23.85	11.85	14.4	28.8	0.09	0.18	1.27	1.36
Single plate heat absorbent, no shading	13.50	4.50	0.0368	33.15	28.65	11.1	22.2	0.17	0.35	3.03	3.21
Single plate heat-absorbent + single plate, no shading	25.50	16.50	0.0510	45.75	29.25	8.4	16.8	0.24	0.48	3.16	3.40
Reflecting sheet, no shading	23.00	14.00	0.0530	47.50	33.50	8.7	17.4	0.25	0.50	3.60	3.85
Reflecting plate, no shading	29.00	20.00	0.0530	47.50	27.50	8.7	17.4	0.25	0.50	3.00	3.25
Single plate, inside horizontal venetian blinds	15.00	6.00	0.0403	36.30	30.30	10.5	21.0	0.19	0.38	3.22	3.41

Single plate, inside vertical venetian blinds	18.00	9.00	0.0403	36.30	27.30	10.5	21.0	0.19	0.38	2.92	3.11
Single plate, outside horizontal manual louvers	40.00	31.00	0.0691	62.10	31.10	5.1	10.2	0.32	0.64	3.43	3.75
Single plate, outside vertical fins and fixed louvers	48.00	39.00	0.0691	62.10	23.10	5.1	10.2	0.32	0.64	2.63	2.95
Single plate, outside horizontal balconies	33.00	24.00	0.0590	53.00	29.00	6.9	13.8	0.28	0.56	3.18	4.06
Single plate, outside horizontal balconies (Dallas)	27.00	18.00	0.0590	53.00	35.00	--	--	--	--	--	--
Single plate, outside horizontal louvered canopy	34.00	25.00	0.0691	62.10	37.10	5.1	10.2	0.32	0.64	4.03	5.15
Single plate, outside horizontal louvered canopy (Dallas)	26.00	17.00	0.0691	62.10	45.10	--	--	--	--	--	--
Single plate, 17-bar louvered screen	36.00	27.00	0.0660	59.00	32.00	6.4	12.8	0.31	0.62	3.51	3.82
<u>WEST</u>											
Single plate, no shading	9.00	--	--	--	--	27.0	58.2	--	--	--	--
Double plate, no shading	21.00	12.00	0.0286	26.65	13.65	19.5	42.0	0.19	0.41	1.55	1.77
Single plate heat-absorbent, no shading	13.50	4.50	0.0413	37.20	32.70	16.5	35.4	0.26	0.57	3.53	3.84
Single plate heat-absorbent + single plate, no shading	25.50	16.50	0.0566	51.00	34.50	12.6	27.0	0.37	0.78	3.82	4.23
Reflecting sheet, no shading	23.00	14.00	0.0610	55.00	41.00	13.5	29.0	0.33	0.72	4.43	4.82
Reflecting plate, no shading	29.00	20.00	0.0610	55.00	35.00	13.5	29.0	0.33	0.72	3.83	4.22
Single plate, inside horizontal venetian blinds	15.00	6.00	0.0508	45.60	39.60	14.7	31.5	0.31	0.67	4.27	4.63
Single plate, inside vertical venetian blinds	18.00	9.00	0.0508	45.60	36.60	14.7	31.5	0.31	0.67	3.97	4.33
Single plate, outside vertical automatic louvers	46.00	37.00	0.0878	78.80	41.80	7.5	16.2	0.49	1.05	4.67	5.23
Single plate, 23-bar louvered screen	42.00	33.00	0.0835	74.80	41.80	9.5	20.5	0.44	0.95	4.62	5.13

41° north latitude. On such a basis, possible savings can be approximated as shown in Table 13. A comparable study for the Dallas area indicates that investment savings would be one-third greater and annual operating savings in ton-hours should be about 4.5 times greater in Dallas than the savings shown in Table 13.

From the savings shown in Table 13 must be subtracted the fixed charges on the installation cost of equipment for keeping the roof wet when the sun shines, plus operating and maintenance costs for this equipment, cost of water and possible chemical treatment of the water, and other costs. These figures will vary widely. Reasonable cost criteria derived from some actual installations not requiring any costly treatment of the available water are shown in Table 14. Combining the data in Tables 13 and 14 for a roof with a *U* value of 0.20, for example, results in the figures presented in Table 15.

Large savings may be possible or there may be an actual net loss. Each case must be individually studied. Roof spray equipment may prove

TABLE 13 Estimated Saving in Air Conditioning through Wetting the Roof Surface

	Assumed *U* Value of Complete Roof			
Criterion	0.12	0.16	0.20	0.24
Tons demand/square (100 ft^2), dry	0.0500	0.0667	0.0835	0.100
Tons demand/square (100 ft^2), wet	0.0140	0.0187	0.0235	0.028
Tons demand difference due to wetting	0.036	0.048	0.060	0.072
Air conditioning investment savings at $900/ton (differential)	$32.40	$43.20	$54.00	$64.80
Daily ton-hour saving/square (clear weather)	0.3	0.4	0.5	0.6
Seasonal ton-hour saving/square	20.0	26.0	33.0	40.0
Annual operating saving/square, at 2.5¢/ton-hour	$0.50	$0.67	$0.84	$1.00
10 percent fixed charges on air conditioning investment	3.24	4.32	5.40	6.40
Total annual saving/square, on air conditioning	$3.74	$4.99	$6.34	$7.40

TABLE 14 Comparison of Costs for Roof Spray Systems in New York City and Dallas

Cost Item	Cost of Spray System ($) New York	 Dallas
Spray water annual cost at 3¢/100 gal	0.45/square/season	2.07/square/season
Pumping cost at 1.66¢/kWh	0.05/square/season	0.24/square/season
Investment cost for large installation[a]	15.00/square	17.00/square
Total annual cost[b]	2.10/square	4.21/square

[a] Does not include basic water supply or treatment.

[b] Includes 10 percent fixed charges and 10¢/square maintenance charges for spray system.

TABLE 15 Comparison of Savings Resulting from Use of Roof Spray Systems in New York City and Dallas

Saving Item	Savings ($) per Square for Roof with *U* Value of 0.20 New York	 Dallas
Saving in air conditioning investment minus cost of spray system	39.00	55.00
Air conditioning saving	0.84	3.86
Spray system operating cost	0.60	2.51
Net operating saving	0.25	1.35
10% fixed charge saving	3.90	5.50
Total annual saving	4.14	6.85

easier to operate and maintain than flooding; flooding may be cheaper if frequent rain occurs between sunny periods. Availability of good-quality water as a waste from industrial uses may be a deciding factor in choosing the wet roof operation. Unfortunately desertlike locations where wet roofs can effect the largest air conditioning savings are frequently places where water for such purposes is either unobtainable, too costly, or in need of much chemical treatment to avoid stains from deposits on roofs.

SUMMARY

The material presented here does not cover all possible shading devices and certainly not all locations. In most cases, however, a simple set of correction factors will adapt the graphs and tables to the particular situation.

These definite trends and relationships have been adequately demonstrated:

1. If no shading is provided, some better type of glazing than single plate-glass is economically justified.
2. Thermally, the new heat-reflecting glasses result in greater saving in air conditioning load than any other glass.
3. Theoretically, the combination of outer heat-absorbing glass and inner plate-glass offers somewhat greater savings than heat-absorbing glass alone. However, there are serious mechanical and maintenance objections to this combination, especially for large panes.
4. The overall best choices for unshaded windows appear to be heat-reflecting and single heat-absorbing glasses. At a smaller increase in initial glazing cost, these afford almost as large a reduction in air conditioning demand and operating costs as the combinations, without their practical disadvantages.
5. If shading devices are to be used effectively, single plate-glass will usually offer the most economical combinations. Surprisingly often, a venetian blind (preferably of aluminum, white plastic, or similar finish) is the most commercially efficient shading device. It is simple, low in initial cost, easy to use and maintain, and economical.
6. Vertical inside blinds, especially fabric ones, and drapes can usually be justified only on esthetic grounds. Their cost is high, efficiency is often low, and frequently maintenance is difficult.
7. Outside shading devices, wisely selected and properly used, frequently give the largest thermal saving. However, their cost of installation is so high that the net result is sometimes not as attractive as the thermal aspect would imply. If other use is to be made of outside balconies facing south, the thermal results (therefore not being charged with the full installation costs) would be most attractive.

Study of Table 12 will show that properly used interior horizontal venetian blinds can be expected to earn annually from one-half to three-fourths of their initial cost. Relatively speaking, this is not true of outside devices. If our criterion, instead, is the total building investment, we find that nearly all good outside shading devices will reduce the total investment by at least twice their cost of installation.

Further study of Table 12 indicates that, for office buildings at least:

1. For west windows, single plate-glass with automatically controlled vertical outside louvers offers the largest evaluated annual saving. Louvered shading screens, heat-reflecting glass, vertical inside venetian blinds, and single unshaded heat-absorbing glass follow in that order.

2. For east windows, heat-reflecting glass gives the largest overall annual saving. Horizontal inside venetian blinds, automatic vertical outside louvers, louvered shading screens, vertical inside blinds, and unshaded heat-absorbing glass follow in that order.
3. For south windows, at 41° north latitude, cantilevered louver canopies are best (within their size limits). Then come heat-reflecting glass, horizontal inside blinds, louvered shading screens, outside balconies with projecting fixed louvers, and manual control outside aluminum horizontal louvers. At 33° north latitude, balconies and louvered shading screens take second place.

Still more efficient formulations of heat-reflecting glasses are being developed. Their evaluation must await data on their performance, cost, and durability.

NOTES

1. All values reflect 1962 data.
2. This corresponds to about 75° F outside wet bulb temperature; 77° F and 50 percent relative humidity or 79° F and 45 percent relative humidity inside.

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