Energy Conservation in the Design of Multi-Storey Buildings

edited by
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Papers presented at an International Symposium held at The University of Sydney from 1 to 3 June 1983, sponsored by The University of Sydney, the International Association for Bridge and Structural Engineering, the Council for Tall Buildings and Urban Habitat, and the Institution of Engineers Australia.

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Preface

Since 1954 the Department of Architectural Science of The University of Sydney has organized symposia on subjects of topical interest. The Symposium on Energy Conservation in the Design of Multi-Storey Buildings, held at The University of Sydney from 1 to 3 of June 1983, was co-sponsored by two committees of the Institution of Engineers Australia, the Building Science Panel of Sydney Division and the National Committee on Applied Thermodynamics; and by two international bodies, the International Association for Bridge and Structural Engineering, Zurich and the Council for Tall Buildings and Urban Habitat, Bethlehem, Pennsylvania - a non-governmental member of UNESCO. The most important contributions to this Symposium are reproduced in this volume. Eight of the thirteen chapters are by Australian authors, three come from the United States and two from Singapore.

Part I deals with predictive methods. In the first two chapters Nield, an architect, and Thomas, a mechanical engineer, describe the design of some of their Australian projects where energy was a major issue. In Chapters 3 and 4 Baum and Rao examine energy conservative building design from the standpoints of New York and Singapore.

While Rao's paper includes a discussion of the American BLAST program, Chapters 5 to 8 deal specifically with computers. Brown describes BUNYIP, a new design tool for estimating energy consumption and costs, developed jointly by the Australian Commonwealth Scientific and Industrial Research Organization and Enersonics Pty Ltd. Radford discusses multi-criteria decision methods. Selkowitz details the analysis of the thermal and daylight performance of fenestration with the aid of a new version of the American DOE 2 program and a new daylight illumination program, SUPERLITE. Finally Norman, a mechanical engineering consultant, considers some of the current limitations in the application of computers to the design of the air-conditioning plant.

Part II deals with energy management. Van Ocken and Ellis review surveys of energy management in Australian office buildings and hospitals respectively. Iffland then describes in some detail energy audits in the United States.

Busch discusses currently available methods for the computer control of energy systems. Finally Lim reviews the criteria for thermal comfort in a hot-humid city, such as Singapore, and then describes the reduction of energy consumption made possible by the use of localized cooling and artificial lighting, and by natural ventilation.

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August 1983

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Energy as a Major Architectural Design Issue

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INTRODUCTION

Vitruvius, the father of architecture as a professional dicipline, said around 30 BC,

"Caesar, now we shall proceed aright, if, first we observe in what regions or latitudes of the world or work is placed. For the styles of building ought to be manifestly different in Egypt and Spain, in Pontus and Rome and in countries and regions of various characters. For in one part the earth is oppressed by the sun in its course; in another part the earth is far removed from it; in another it is affected by it at a moderate distance".

He continued, "Your Highness, therefore in the sun's course through the inclination of the zodiac, the relation of the heavens to the earth is arranged by varying effects, it appears that in the like manner the arrangement of buildings should be guided by the kind of locality and the change of climate. Thus we may remedy by art the harm that comes by chance!" (Vitruvius V1.1 Translation F. Granger).

This paper will briefly describe some architectural approaches to reducing energy use. The ideas are the same as those expressed by Vitruvius. Society and the architect's tasks and 'tools' are different. Particular reference will be made to the design of NEWMED 1, a new clinical sciences building for the University of Newcastle, the new general hospital for Albury/Wodonga and the recently completed hospital at Mt Druitt, in the west of Sydney.

CLIMATE AND BUILDING

A University Project

The David Maddison Clinical Sciences Building for the Faculty of Medicine in Newcastle, NSW, was designed by my practice. It is located on a long-thin site with major facades facing east and west.

The goals of flexibility in design and use, as well as the need for a high degree of repetition appropriate to fast construction, resulted in a structure where load-bearing columns were located outside the external wall. This has produced not only a powerfully articulated facade but provided a support structure for external sun-shading. The need for rapid enclosure of the building so that fit-out could proceed at the earliest possible opportunity dictated the use of a lightweight walling system.

The extreme maritime environment of the site, which is exposed to storms and prevailing winds from the south-east, led to the selection of type 316 stainless steel, cold-rolled and brake-pressed to a trapezoidal profile. Supporting structural frames were prefabricated from cold-rolled steel channels in bays of 1.2 metres and these span from floor slab to edge beam above. A sandwich of high thermal performance was built up on this substructure consisting of the following:

- Outer skin of profiled type 316 stainless steel
- Sealed air space 25mm wide
- Vapour barrier of reflective foil
- 100mm of mineral wool insulation
- Vapour barrier of reflective foil
- Sealed air space 25mm wide
- Inner lining of 13mm plaster-board

This relatively simple external wall gives a very low 'U' value of 0.25 W/m^2. deg C. Window frames are fixed into prefabricated stainless steel fabrications and the openings are trimmed internally with two-piece units fabricated from glass reinforced plastic.

The architects' studies showed that the conflicting requirements of view, solar control and daylighting were best satisfied by a horizontal louvre solar control system on the east and west facades. A series of 'manual' technical studies were carried out and finally the CSIRO TEMPER programme was used to simulate the thermal performance of the building.

The sun-shading spans between columns at 4.8m centres and is supported on a stainless steel sub-frame. The system is show in Fig. 1. The louvre blades were constructed from a foam polyurethane sandwich panel with metal skins and a perimeter reinforcing frame of steel.

Low angle sun, which mainly introduces problems of glare rather than solar heat gain very early in the morning or very late in the day, is limited internally by Holland blinds.

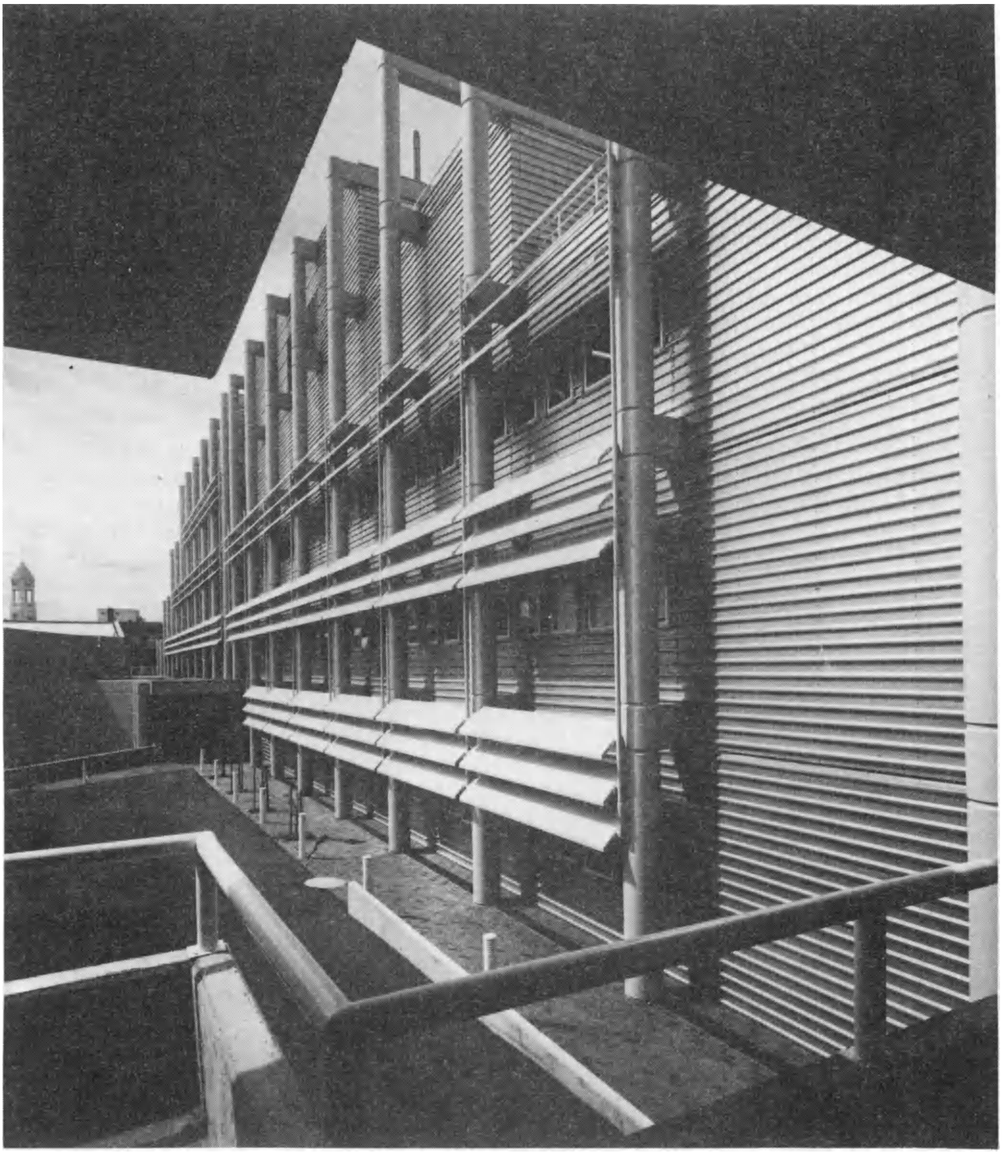

Fig. 1 The David Maddison Clinical Sciences Building at Newcastle, NSW: horizontal solar control system on western elevation developed from thermal performance studies (photo by Max Dupain)

The building is only selectively air-conditioned in that the brief called for natural ventilation except where functional requirements established the need for air-conditioning. In laboratory areas air-conditioning is by the distribution of heated and chilled water to local fan-coil units.

In more detail the TEMPER programme allowed us to predict the following:

- There is no significant benefit from lowering the position of the blades as this will only have an impact late in the working day but will be at the expense of sun penetration over the top of the system earlier in the day.
- The most significant improvement would be the addition of a second blade to the eastern elevation.
- Further studies of cross ventilation were not justified because of unreliability of results, long lead time and negligible possible impact on design ie opening doors and windows are the most practicable methods of controlling cross ventilation.
- Comfort conditions would be satisfactory without air-conditioning.

I suppose one of our conclusions from the work on energy conservation and comfort conditions at the David Maddison Clinical Sciences Building is such that architects getting involved in such calculations and estimations is important for a successful building. The computer analysis of this building took considerable time and without the assistance of the Newcastle University's School of Architecture it would not have been possible. It is important that clients, particularly government clients, realise that energy analysis by architects takes time and money. It cannot be done within the normal fee structure.

ENERGY AND COMPLEX BUILDINGS

Recent Hospital Projects

I want now to move to more current concerns, the design of the large hospitals in Mt. Druitt, a town of 100,000 in the west of Sydney and Albury/Wodonga, the growth centre on the NSW/Victorian border.

Firstly, in connection with the potential effects of architectural design on energy conservation, I think these can be very significant. Obviously the architects have control of the spatial arrangements of activities and the form and fabric of the building envelope. In the continuing series on energy conscious design in the American journal "Progressive Architecture", it has been shown, over a wide range of building types, that energy savings can be made in the order of 20-60%

(Progressive Architecture, Cleveland, April 1981, April 1982, February 1983). Most of these energy design strategies involve form/envelope, lighting and heating/air conditioning considerations. Architects can have a major impact in complex buildings on form/envelope and lighting (use of natural lighting etc). If one made a broad estimate of the architectural design impact as opposed to the engineering design impact on energy conservation I think it would be fair to estimate that architects' actions can be responsible for 50-60% of possible savings, depending on the building type.

My practice, since its commencement in 1975, has been largely working on hospitals, health and university buildings. Hospitals are major energy consumers because of their 24 hour a day operation together with the need for strict environmental, life safety and regulatory requirements. New hospitals in Australia today are almost always air conditioned.

There is a notion that hospitals, because of their deep plan and high levels of mechanical equipment and lighting are "internal load" dominated. Most research shows that this is not the case. In the cold parts of Australia the predominent energy consumption is for heating. Energy consumption would generally not be high in buildings which are internally loaded. In Sydney and warmer parts of Australia the major energy consumer is air conditioning. The extent of the latter has been well documented in Associate Professor Glastonbury's survey work for HOSPLAN, the NSW Hospital Planning Advisory Centre.

Potential effects of architectural design on energy conservation of hospitals are significant. However let us always keep this in context. The annual operating cost of hospitals is enormous. At the Royal Canberra Hospital in 1979 the annual operating cost was $27m and the annual energy cost about $540,000 that is, about 2%. Nevertheless in the 'Progressive Architecture' study, hospitals consumed over 250K Btu per square foot. This study considered 11 hospitals (Progressive Architecture, Cleveland, February 1983). Overall a 40% energy saving was achieved.

As I have said looking at this study, architects, the innovators of form and fabric, can have a potential effect on 50-60% of the 40% possible savings. That is, appropriate awareness by architects of energy conscious design and importantly interactive working with engineers in the design team, can make annual energy savings of 20-25%. Architects control building orientation, the compactness of form, the selection of external wall materials and insulation, the areas and orientation of glass, the shading of glass and the colour of walls and roofs. Together with engineers they control the extent of air conditioning and the extent of acceptable comfort levels. In connection with lighting their interaction with engineers affects lighting levels, use of daylight, 2 level switching, zone switching, extent of open areas, task lighting and the colours of the interior.

The recently opened 200 bed hospital at Mt Druitt shows a design approach embracing energy concerns. This approach is relevant to the central theme of the symposium; the design of multi-storey buildings for physical and environmental performance. This hospital is interesting in that hospitals of this size generally come in 6 to 8 storey configurations. Hospital designers worry most about the association of activities: the generation and zoning of internal movement. Wittingly or

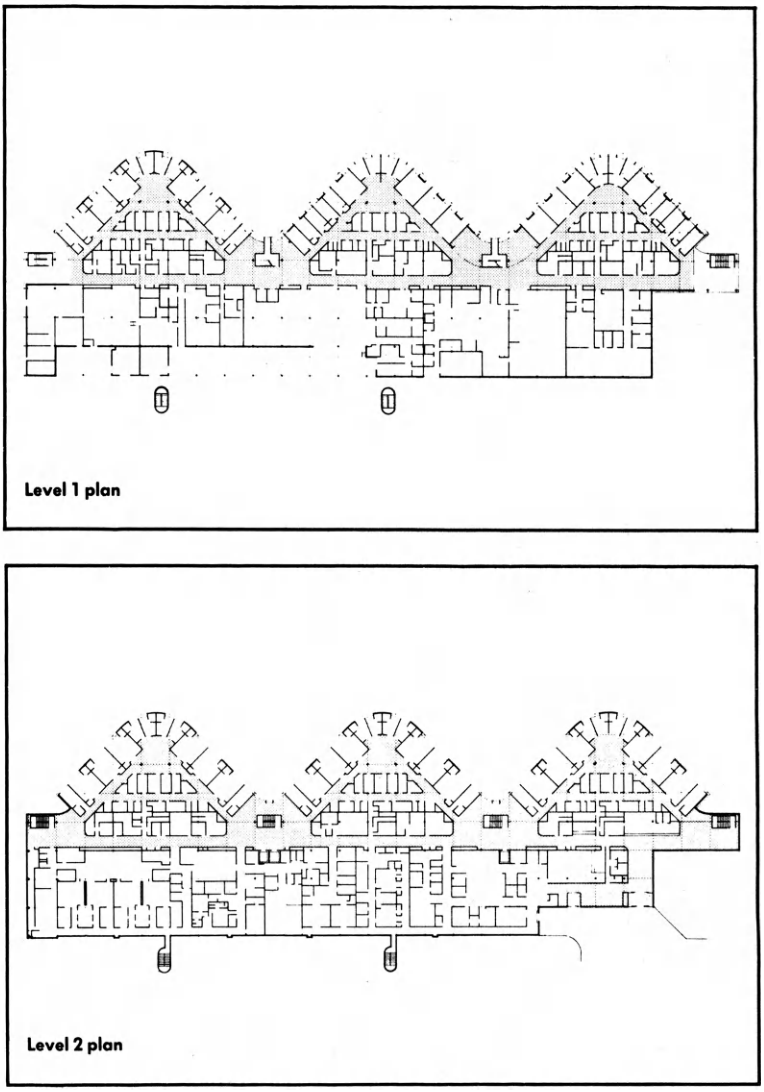

Fig. 2 Mt. Druitt Hospital, NSW, plan

unwittingly the spatial arrangement of activities is the first problem they try and solve. This is often so difficult to do that they retire hurt or exhausted instead of addressing at the same time other important problems such as energy conservation, growth and change or even aesthetics. Lifts are used as a major generator of form.

At Mt Druitt instead of the conventional 6/8 storey block we were able, by analysis of a similar sized hospital (in Lismore, NSW) to construct, with the aid of the CSIRO TOPAZ programme, an 'interaction' simulation model which was able to cost, in terms of total salary spent in staff movement, various possible locations of key hospital activities. The importance of this programme was not simply that it enabled us to picture a convenient layout but we could introduce further considerations such as glass areas and minimum envelope. We could choose solutions that gave us convenient internal movement and an easy-to-build and energy economic form. Our solution was in fact two stories having 30% glazing and an unusually compact plan with ward accommodation on the North East. Fig. 2 shows the plan that was developed.

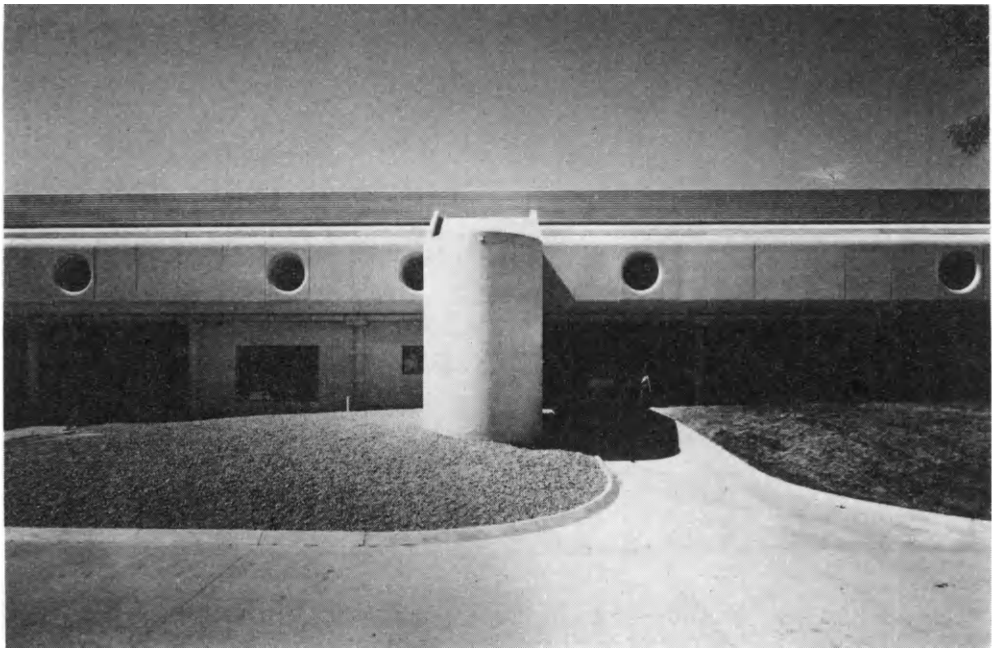

Fig. 3 Mt. Druitt Hospital, NSW: south-west elevation energy conserving windows (photo by Max Dupain)

Other features of this design were in areas where there was no permanent occupation; deeply recessed round windows where used providing good 'visual communication' with the outside world while minimising glass area.

A further aspect of this hospital design is of particular interest and this is the lack of 'robustness' (to say the least!), in future energy cost predictions. Our engineers and ourselves recommend that electrical energy be used on a demand tariff basis to take advantage of the historically low electrical charges in NSW. Electricity generated by the standby generator would operate to reduce peaks and to heat water at night to store energy. This system was designed in 1976 and since then electrical tariffs have exploded. Though the hospital was opened last year it only, in recent weeks, has had all its beds opened. We look forward to an energy audit to give us information on the performance of this new system.

Fig. 4 Mt. Druitt Hospital, NSW: north-east elevation showing horizontal solar control (photo by Max Dupain)

Due to both my practice's concern for energy conscious design together with the policies of the relevant government departments, energy design was one of the 8 key design issues for the Albury/Wodonga hospital. It is important that energy is seen as one of the conflicting demands of the architectural designer. It is an important, but not the only, design issue.

At Albury/Wodonga the 8 key strategies we designated were:

- the location of key facilities in relation to each other
- the multiple address points required by hospitals
- the appropriate segregation of internal traffic
- the convenience of significant staff and patient journies within the hospital
- the capability to handle expected and unexpected growth
- the response to climate and energy efficiency
- the need for a simple repetitive structure with an optimised bay size for ease of construction and extension
- the exploitation of the excellent site

Wodonga District Hospital has 180 beds and a range of clinical and non-clinical support services. The form of the hospital developed as a compact single storey triangular plan for the clinical and 'hotel' services with the patient areas in a north facing three storey block. Again the planning was based on the projected interaction pattern of the new hospital. All glass faces north or south. Because of the high summer temperatures a building of high thermal mass was designed to increase thermal lag. As can be seen in Fig. 5 there was substantial shading of the glass.

There was a close interaction with our mechanical and electrical engineers Norman Disney + Young to ensure that energy conscious design flowed through into the engineering systems. Solar energy was considered in detail but was not economically feasible at this time. The roof is designed to allow future installation of solar panels. Natural gas was chosen as the main fuel.

As the building was on a superb rural site, all the windows in the patient areas are openable and zoning of the air conditioning has been designed to allow for natural ventilation.

In terms of detailed design the building followed the energy standard guidelines of the Victorian Public Works Department, September 1981. This is a useful handbook basing much of its information on ASHRAE, standard 90A (Energy Conservation in New Building Design). This standard considers strategies for building envelope HVAC, domestic hot water, alternative energy, lighting, power distribution systems, automatic systems and energy budgets. Central to the use of this is its energy evaluation worksheets which assist in the working out of U-Value, average ceiling height, area of glazed wall, U-Value of opaque wall, northern glazing, maximum solar factor and actual solar factor. For architects it is useful to go through these work sheets even if this only develops a more interactive relationship with the associated mechanical and electrical engineering consultant.

Hospitals conceptually are not a 'monolith' but a federation of separate states each with quite different functions. In terms of energy there are 5 'separate states' which need to have their own design strategies:

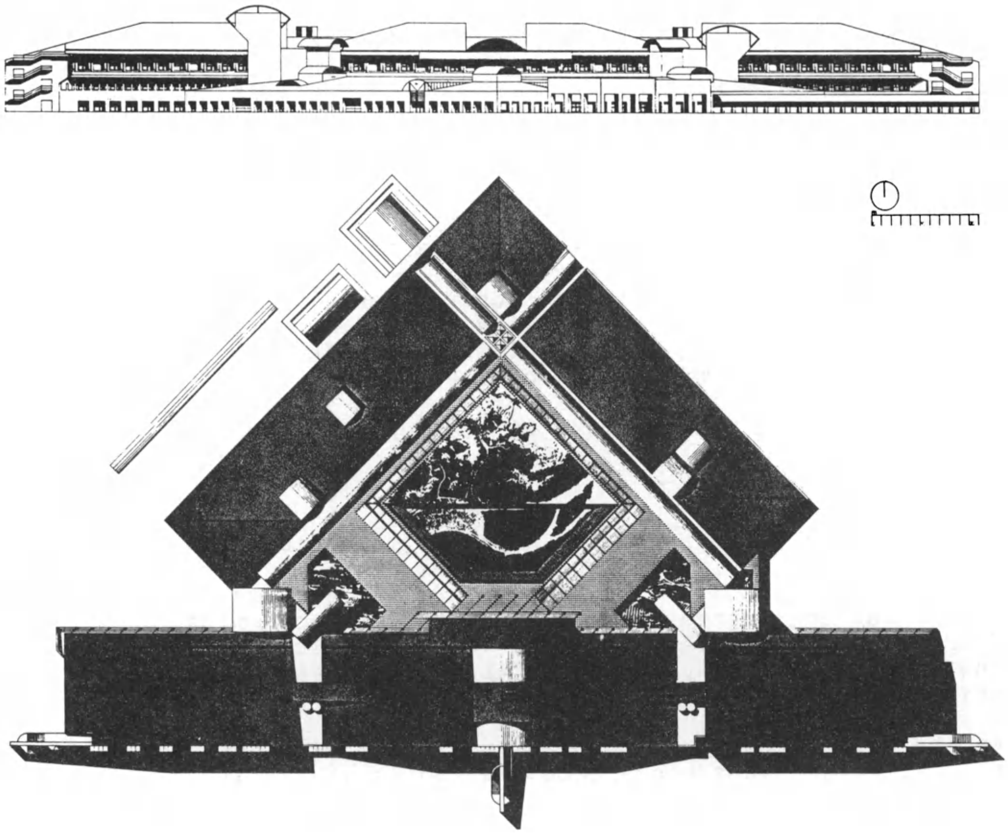

Fig. 5 Wodonga District Hospital, Wodonga, Victoria: north elevation and plan showing single storey clinical and 'hotel' block and three storey patient block

1 Patient rooms, patient areas, wards etc

2 Clinical areas such as operating theatres, X-ray and ICU

3 Administrative areas

4 'Hotel' and stores areas

5 Kitchen, maintenance etc

At Wodonga the energy design approach centred on developing distinct strategies for these 5 areas of the hospital.

As far as we know there are no formal energy budget guidelines in Australia, particular for hospitals, but we think that measures taken at Wodonga should make it energy conservative in terms of ASHRAE 90A and the design team considers it should use about 120KWh/m^2.

ENERGY AND THE CITY

Lastly, and briefly, I want to suggest that in energy design we are dealing with symptoms and not the systemic disease. Our cities and their values and our political systems encourage the excessive consumption of land, of cars (escape vehicles from the city), and for buildings developed for sale rather than for sensible use. CBD office towers are, in a sense, a saleable package as much as a response to a need. Cities no longer represent regional culture. They conform more and more to the international culture, the coca-cola culture of consumerism. Ivan Illich has suggested that as much as 85% of technical progress (cars, planes etc) is in fact counter productive. Not only are they pointless but they cause serious social disadvantage. In "Medical Nemesis" he showed that in fact a large number of diseases in present hospitals are caused by the medical system itself. This is called Iatrogenesis. The medical system is a threat to health! In "Tools for Conviviality" he argued that the mechanical donkey should be introduced, a small mechanical vehicle instead of cars. In education he argues that our present educational infrastructure is counter productive. Its role is similar to religion in pre-science days. He has identified thus, in many areas of our cultures, that "more haste means less speed".

In architecture there are now major groups on both sides of the Atlantic (Christopher Alexander in Berkeley and Morris Culot and Leon Krier in Europe) advocating a return to pre-industrial methods. There is a radical questioning of the city. Buildings are becoming complex pieces of make-work. We pump in heat through lights and have to remove it by air conditioning. Our 'over-dense' and 'under-dense' cities force us to design make-work buildings, force us to have over-dependence on the car and force us to consume more land for bungalows.

Overall our bungalow/high-rise city must consume more energy in terms of buildings and in terms of transportation required than more compact developments. I am continually reminded of this by working in Canberra. Clearly we must go on tinkering with the system but should we perhaps be developing much wider strategies for our ever growing metropolitan environment? It is the city structure that is forcing us into complicated energy management strategies. We should begin finding ways to treat the disease not just the symptoms. If we paraphrase the Vitruvius' quotation with which we commenced we might say "Thus we may remedy by art the harm that comes by the contemporary city".

The Rocks Gateway Project, Sydney
A Study in Integrated Design

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INTRODUCTION

The Rocks Gateway is a major commercial development to be located on a site of some 7200m^2 in area bounded by George, Grosvenor, Harrington & Essex Streets and is envisaged by the Sydney Cove Redevelopment Authority as becoming the gateway to the historic Rocks area of Sydney.

The major development on the site will be an office tower building of 44 occupied levels to provide some 80,000m^2 of lettable floor space. The lettable floor area varies from 1,860m^2 on lower levels to 1,980m^2 on upper levels. These floor areas are substantially in excess of any office tower building in Australia but have been dictated by market research and endorsed by BOMA International in their review of the Project.

A basement of five (5) levels is provided over the major part of the site and accommodates 600 cars and servicing facilities for the office tower and historic buildings, substations and plantrooms.

The development retains the historic buildings fronting Grosvenor Street which comprise in total some 7000m^2 of lettable area for hotel, restaurants, accommodation and offices use.

The plaza level at the address entrance from George Street features an imposing glass enclosed entrance to the office tower, public space, bank, post office, food shops and solarium which provides a link between the office tower and the historic buildings.

The total development has a gross area of approx. 140,000m^2 and a rentable area of approx. 88,000m^2.

The Rocks Gateway project is presented to demonstrate the practical application of an integrated energy design approach to the development of an energy efficient building complex by the incorporation of proven techniques in passive energy design, systems engineering and energy management.

In commercial terms energy efficiency is viewed by the building owner and manager as embracing both energy conservation and energy management aspects.

Energy Conservation is taken to mean a reduction in dependence on utility energy supplies i.e. supplies which are generated from depletable energy sources.

This is not to say that the total energy needs of the building are necessarily reduced - as the reduction in depletable energy demands is often replaced with similar energy input but from natural energy sources e.g. sun, wind, etc., or by waste heat reclaim and recycling.

Energy management relates to the most efficient usage of the residual energy needs of the building having particular regard to consumption versus demand and the cost of energy.

ENERGY TARGETS

The complex nature of the development and the high standards established for system design criteria made difficult a true comparison of the energy demands of the Rocks Gateway Project with any existing developments in Australia.

A conflict exists in establishing an energy target related strictly to maintaining design criteria on the one hand and on the other the potential energy utilisation in actual practice for a well managed building.

It was decided to establish energy targets related strictly to system operation to maintain the high standard design criteria but at the same time to provide system designs which would allow the building owner and manager the facility to operate the various systems and sub-systems to achieve optimum energy performance consistent with tenant satisfaction over a potentially wide range of possible tenancy requirements.

By comparison with currently operating buildings the energy targets established are based on the following design criteria:

- population density of 1 person per $11.0m^2$
- fresh air load of 5.0 l/s per person
- design summer outdoor condition 32°C D.B. 23.5°C W.B.
- design summer indoor condition 22.5°C D.B. ± 1 C. 55% max
- tenancy power usage in general office areas $11.25\ w/m^2$
- tenancy lighting usage $11.00\ w/m^2$
- no duty cycling
- no swing in conditions about design reference
- officer tower occupation: 12 hrs/day, 5 days per week
- commercial use areas: 3000 hrs/pa
- public use areas: 8760 hrs/pa
- car parking area: 3500 hrs/pa
- hotel & accommodation areas: 8760 hrs/pa

The design energy target established for the total development on the above basis was 500 MJ/m^2 nett rentable area per annum excluding tenancy lighting and power in the office tower only. This compared with an estimated 720 $MJ/m^2/pa$ for a similar development of more conventional design and servicing.

In order to relate the development more accurately with the energy utilisation index being developed by BOMA, the target energy index for the development excluding the historic buildings was established at 430 $MJ/m^2/pa$ related to the design conditions stated.

The design development was progressively reviewed and the final designs indicate that the target of 430 MJ will be bettered.

An assessment has also been made of the energy opportunities available to the building owner on completion of the Project for fine tuning and operation of the services to provide an acceptable standard of amenity related to the actual building occupation of high quality office type.

Having regard to the system design criteria on which the energy targets have been based and the increasing acceptance by Tenants of less stringent environmental conditions and the flexibility available for application of energy management techniques the actual energy index in practice will be in the order of 350 $MJ/m^2/pa$ of nett rentable area. Equally important to the Building Owner is the cost of the energy used. The use of the energy storage system will reduce the cost of energy used by approx 40% as compared with the cost of the same energy consumption used on demand.

PASSIVE ENERGY DESIGN

The office tower design recognises the energy implications of orientation and exposure and the conflicting requirements of natural light penetration and exclusion of solar radiation.

The architectural response to these influences has been the development of a building plan form, orientation, solar shading and glazing design in which the optimum energy balance is achieved by passive design, the inherent efficiency of which will be reflected in energy savings in perpetuity.

The facade is double glazed using a solar grey glass from ceiling level to within 300mm of floor level to take advantage of the magnificent views and to maximise natural light penetration.

The mullionless glazing system maintains the high thermal efficiency of the facade under both summer and winter conditions and has special regard to wind effects on surface film co-efficients.

The proposed sunscreens vary in angle of inclination from vertical to horizontal to suit the changing orientation of the building and due to their shading characteristics avoid unduly high surface temperatures being developed on the glazing system and hence eliminate re-radiation problems to the occupied spaces.

The overall shading co-efficient of the integrated glazing system is better than 0.20 and has permitted the effective use of variable air volume air conditioning for both the internal and perimeter areas of the building.

Life cycle cost analysis of the facade treatment demonstrated that the extra over capital cost was justified by the savings in air conditioning capital and operating costs.

ENERGY CONSERVATION FEATURES

The design incorporates a number of energy conservation features which guarantee the long term energy efficiency of the proposed development and place this Project in the forefront of modern energy design technology. It is expected that the building will be a model in energy efficiency and will establish new energy targets for future city high rise commercial developments.

The energy conservation features include:

- the use of recent proven technology in low energy lighting design throughout the development to effect a reduction in lighting energy demand and consumption of approx 60% whilst retaining recommended illumination levels and providing an improved quality lighting installation requiring reduced maintenance
- the location of mechanical plant rooms to optimise air transportation energy costs and to maximise waste heat energy recovery opportunities
- the use of multiple variable air volume air conditioning systems throughout the development with plant designed to cater for varying occupancy and exposure requirements and to provide for low cost after hours tenancy operation
- the use of outdoor air economy cooling cycles for all air handling systems
- the control of car park ventilation systems by contamination detection
- the use of exhaust air waste heat energy reclaim heat exchangers for winter cycle air heating advantage of waste heat resources such as:
    - lift motor room exhaust systems
    - plantroom exhaust systems
    - car park exhaust systems

- the use of the refrigeration heat rejection system for both heat rejection and ambient air heat reclaim as an energy source for winter heat pumping
- the use of 1,000m^2 roof mounted solar collectors to provide all domestic hot water needs for the complex and as a supplementary heat source for winter heat pump operation

The use of low energy lighting is probably the most dramatic energy conservation design feature and introduces the need to carefully consider the implications on internal space zoning flexibility due to the reduction in lighting space load from 25-30 w/m^2 to less than 11 w/m^2.

The heat rejection/heat reclaim feature is a natural development of the 'off peak' energy storage system described later.

While the use of solar collectors has not previously been seriously considered for application in city buildings examination of the average daily insolation in Sydney and the available daily heat production indicated that the use of solar energy could make an economically viable contribution to the heating needs of the complex.

Sydney average daily insolation is:

Nov - Jan	22.5 MJ/m^2
May - July	10.0 MJ/m^2

The mean daily available heat production with standard flat plate collectors is as follows:

Entering Water Temp.	MJ/m^2 Jan	MJ/m^2 June
90°C	2.8	0.5
70°C	5.4	1.7
3-5°C	18.0	9.0

In summer the solar collectors will provide all DHW needs for the complex and HT heating water operating at temperatures of 70 to 90°C to a capacity up to 1500 Kwh/day.

In winter DHW will be provided by 55°C condenser water from the heat pumps and the solar collectors will be operated with an entering water temperature of 3-5°C and reject some 2500 Kwh/day of low grade solar energy to the cold store tank for subsequent heat pumping.

The combination of passive energy design and energy conservation features included in the design of the complex:

- reduces the energy demand of the proposed development by approx 24% as compared with a conventionally serviced building complex and hence reduces the energy demand cost of energy used

- reduces the annual energy consumption of the complex by approx 37% as compared with the normal energy consumption of equivalent commercial developments
- eliminates the need for oil or gas fired boiler heating plant with consequent reduction in pollution
- eliminates water usage for heat rejection cooling towers

ENERGY MANAGEMENT

The instantaneous energy demand profiles for the Rocks Gateway development are similar to that of other city office tower buildings in that a major demand exists for approx 60 hours per week (12 hours per day, 5 days per week) with negligible demand for remaining 108 hours per week.

Considerable operating cost savings are available if the energy load factor can be improved to reduce the proportion of energy accounts which is attributable to demand charges.

$$\text{Load Factor} = \frac{\text{Av. Demand}}{\text{Peak Demand}}$$

In addition to savings in peak demand charges, a reduction in peak demand for this Project would reduce the required installed capacity of stand-by generation plant which is being provided to cater for all normal operations.

The most significant area of control over demand is in the air conditioning plant, in particular the water chillers which provide summer space cooling. This instantaneous demand of the water chilling plant is in the order of 3,000 KWE.

The options available for management of the total project electrical demand are to relocate all or part of the water chiller load to a portion of the day during which lighting, general power and ventilation are at a minimum.

Control of maximum demand which results from the heating operation of the refrigeration equipment is also possible.

A study was made of the potential energy cost savings and the capital cost implications of generating at 'off-peak' times the cooling and heating demands of the development.

The considerations of this study were:

- The reduced capital cost of refrigeration plant.
- The increased capital cost of thermal storage systems.
- The energy cost savings due to reduction in maximum demand charges.
- The reduction in energy use due to operation of refrigeration plant under more favourable ambient conditions.
- The reduction in capital cost of emergency generating plant consequent on the reduction in maximum demand.

- The practical and economic implications of utilising solar energy as a viable energy source.
- The ability of the energy storage system to benefit from waste heat rejected from tenancy computer installations which could be expected to be in the order of 1000 Kw electrical demand.
- The implications of the proposed energy storage systems on 'after hours' tenancy use and continuity of environmental control under conditions of power failure or power restrictions.

The life cycle cost analyses carried out clearly demonstrated that even assuming conservative escalations in energy costs the proposed 'off-peak' energy generation and storage system was economically viable with a pay-back period of less than six years.

The implications of the managed demand loading of the building is to effect:

- a 50% reduction in installed capacity of refrigeration plant
- a reduction in energy demand of approx 52% as compared with a comparable conventional development, thus contributing to the energy efficiency of the State utility supply system in addition to the efficiency of the proposed development
- a reduction of approx 40% in the capacity of emergency generating plant otherwise required for similar type developments.

ENERGY STORAGE

Consideration was given to alternative refrigeration and energy storage systems including water, ice/water and glycol brine solutions. The final design favoured the use of a direct refrigerant ice system for cooling energy storage and water for heating energy storage.

The final design provides for 750,000 kg of ice storage to provide a production capacity of 80,000 Kwh/day of cooling energy storage. 1,000m^3 of storage is proposed for hot water energy needs and is arranged in temperature stages from 35°C to 70°C.

The design allows for the maximum flexibility of operation on a year round basis to take advantage of existing and possible future energy tariffs and optimises the overall C.O.P. having regard to both cooling and heating cycles.

Analysis indicated that daily ice production under 10 hours or the use of suction temperature greater than -10°C will not achieve a full economical use of the ice storage tanks. Lower production time with decreased suction temperature also results in a larger refrigeration capacity requiring more energy input to achieve storage for demand. The KW input per KW refrigeration will also increase if the condensing temperature has to be kept high, because of unfavourable heat-rejection conditions which will be fixed by the equipment selected and the ambient conditions obtaining over the production period.

The ice tanks have been selected with an ice storage capacity 15% greater than the design requirement to allow for tank losses, cooling reserve and for ice to remain on the coils for the next production period.

The refrigeration compressors have been selected with 10% additional capacity to allow for losses due to suction pressure drop caused by insulating value of built up ice.

REFRIGERATION PLANT

The practicability and energy efficiency of using ice storage depends very much on the production time available and the resulting operating conditions of the refrigeration plant.

The refrigeration plant proposed consists of 4 x 1400 kW R22 electrically driven screw compressors operating in cooling mode at -10 to -12°C suction and 35°C condensing for a COP of better than 3:1. Under heat pump mode the compressors will operate at 0°C suction and 55°C condensing. Heating COP is in excess of 4:1.

The selection of screw compressors was founded on the proven reliability of these machines to operate at high compression ratios for long periods over the range of load conditions which will apply to optimise energy demand.

Plate heat exchangers are used for heat transfer between the primary energy storage systems and the secondary reticulation systems. Heat rejection towers incorporate an integrated closed circuit system to operate both in a heat reject mode and as ambient energy heat reclaim units to provide a low grade heat source rejecting to the ice tanks for subsequent heat pumping.

This ambient air heat reclaim facility is made possible due to the flexibility available in the operation of the central refrigeration plant to meet cooling and heating demands.

SYSTEM HEAT BALANCE

The heat balance of the proposed cooling and heating system and the economic use of solar energy as a supplementary heat source is based on the following concepts:

1) Cooling and heating media will be produced in periods of minimal use of office space to provide the benefits of reduced maximum demand energy tariffs, to reduce the capacity of stand-by diesel generation plant and to arrange the rejection of excess summer period heat at the most favourable ambient conditions.
2) Cooling and heating media will be produced concurrently by refrigerative chilling/heat pump apparatus.

3) Summer heating and winter cooling are produced as a necessary by-product of summer cooling and winter heating, respectively. Heating medium produced during the warmer weather will be stored for use to meet daily demands. Conventional systems would require that condenser water (in this case, heating media) be cooled by heat rejection via cooling towers, while a separate boiler attempts to meet light loads by inefficient operation.

4) Winter cooling demands of internal space zones will be used as a basis for heating the building by processing the heat from internal zones via the refrigeration equipment to external zones which lose heat via the facade. The internal processing of heat eliminates the wasteage which occurs by operating chilling plant to reject internal zone heat to atmosphere, while operating boiler plant to heat external zones.

5) Heat reclaim ventilation systems, such as toilet exhaust, lift motor room exhausts, relief air systems, plant room and car park exhaust systems.

6) The use of the heat rejection towers for ambient air heat reclaim to provide a low grade supplementary heat energy source for winter heat pumping.

7) The use of solar collectors to provide all DHW energy needs in summer and between seasons and to provide a supplementary low grade heat energy source for winter heat pumping.

8) The seasonal resetting of cooling and heating media temperatures to match seasonally varying load conditions, and to limit the refrigerant pressure differential across the refrigeration compressors. This limit enables the production of both heating and cooling all year round at high co-efficients of performance.

AIR CONDITIONING AND MECHANICAL SERVICES

The central cooling and heating energy plant will be provided at basement level to serve the office tower, plaza development and historic buildings environmental energy needs.

The air conditioning system designs propose the use of energy efficient high quality performance variable air volume air conditioning systems throughout the development.

The designed thermal performance of the double glazed facade treatment with respect to solar shading and thermal transmission under all external climatic and seasonal conditions is such that the use of all air variable air volume systems is practical to both internal and perimeter areas.

Thirty four independent air handling systems will be located in the tower plant rooms to separately serve internal and perimeter services zones in capacity modules arranged to provide capacity for high quality environmental conditions with flexibility for low energy cost after hours operation. The location of air handling plant minimises air transportation energy needs.

Air distribution to each floor in each wing will be provided by six (6) internal zone and eleven (11) perimeter zone variable air volume terminal units. Each of these units will be capable of individual control of temperature within its served area. Low pressure air supply from the V.A.V. terminal units will be introduced into the served area by flexible ductwork and ceiling mounted linear diffusion equipment integrated with the ceiling grid and lighting/sprinkler layout.

Air return from the wings will be via the ceiling void to eliminate grille noise generation and to minimise acoustic attenuation between sub-divided areas and to further minimise space loads.

All areas of the development will be ventilated to the requirements of AS 1668 for ventilation of toilets, car parking and service areas.

The office tower air handling systems provide for complete smoke exhaust from the building. In the fire mode, supply air systems use 100% fresh ambient air.

All fire stairs are provided with pressurisation fan systems which will be automatically activated under fire conditions to pressureise the stair wells and prevent the entry of smoke. These systems are interlocked with the smoke venting systems and may be controlled from the fire control room.

SOLAR COLLECTORS

Solar collectors will be provided at roof level to provide for all domestic hot water needs of the complex and to provide a heat source independent of the waste heat generated during occupancy of the building and waste heat reclaimed from the "off peak" refrigeration system operation.

As the demand for environmental air heating will be met for a major part of the year by the refrigeration cycle waste heat recovery storage system the solar energy contribution will vary accordingly. The use of tracking type collectors and variation in water supply temperature to the collectors enables the heat production of the collectors and the water supply temperature from the collectors to be varied over a wide range.

In the winter months when the solar irradiation is reduced the daily heat production of the collectors is increased by reducing the supply water temperature to the collectors to $3^{\circ}C$ and storing the solar energy collected by rejecting the heat into the ice storage system for subsequent heat pump operation.

ELECTRICAL SERVICES

Electrical supply for the development will be provided by three independent 11 KV substations located in the basement and at levels 10 and 33 of the tower building.

As a result of the energy conservation features and energy storage proposals the demand of the complex has been reduced from a conventional 10.5MW to 5MW.

Emergency generating plant will be provided adjacent to each sub station and will provide for all normal operating requirements of the complex.

Office areas will be fitted with low energy lighting comprising single tube 26mm fluorescent lamps and super low loss control gear within a low brightness double batwing luminaire. Lighting studies have confirmed that an average illumination level of 500 lux will be achieved at an energy level of 11 watts maximum per m^2. The lighting system will include for a photocell control option and possible use of electronic ballast providing automatic dimming.

The proposed lighting design will achieve a reduction in energy use of not less than 60% as compared with presently used installations. The impact of this load reduction reflects in reduced air conditioning loading as noted previously.

The proposed building provides for the use of satellite communication facilities and special services for security and emergency evacuation and dedicated supplies for tenancy computer installations.

LIFT SERVICES

The lifts and escalator services proposed are designed to provide an outstanding grade of service throughout the development and in the tower building in particular, to cater for the most prestigious type tenancies and possible government or institutional type tenancies in the lower rises.

Particular consideration has been given to the range of occupation densities possible and to the potential downgrading of lift service due to interfloor traffic within large tenancies.

The four (4) rise lift bank with transfer floor configuration proposed to serve the office tower is the optimum configuration having regard to grade of service under all potential tenancy and operating conditions, capital cost, space requirements and energy conditions, capital cost, space requirements and energy efficiency considerations. The lift services proposed will maintain a superior grade of service consistent with the long term prestigious quality of the building.

Goods handling and fire lift operation is provided by a unique arrangement of double deck goods/fire/passenger lift design which will have major benefits during the fitout stage and subsequent servicing of the building and under conditions of fire control.

All machine rooms will be air conditioned to maintain optimum energy efficiency and trouble free performance with waste heat energy released from the lift machine rooms being recovered during the heating season and utilised through energy transfer facilities.

All the lifts are proposed to be equipped with security access facilities which will provide for independent individual floor access security to be available only to authorised persons at any times required.

Emergency power supply will be provided to operate all lifts in the event of power interruption or restriction.

The four (4) rises of lifts and their relationship with mechanical, electrical and fire services plantrooms facilitates the progressive completion of lower rises of the building as construction proceeds on upper levels.

The lift zoning, duty and speed have been selected on the basis of satisfying the most stringent lifts performance criteria for the lower rise lift bank and to provide a superior lift service to upper floors.

Lift provisions are as follows:

Low Rise:	6 lifts x 1600kg x 3.5mps
Medium Low Rise:	6 lifts x 1600kg x 5.0mps
Medium High Rise:	6 lifts x 1600kg x 6.0mps
High Rise:	6 lifts x 1600kg x 7.0mps

The proposed solid state type power control systems for each lift machine enables rapid response to the demands of the control systems and optimum acceleration and deceleration rates commensurate with passenger comfort and consequently minimum floor to floor travelling times.

The group control systems are proposed to be micro-processor based. This equipment will enable extremely rapid calculation of response time for all cars in the group to any particular call and ensure that the response time to any call is always the minimum possible time thereby reducing waiting intervals to a minimum and maximising group handling capacity.

FIRE PROTECTION

Fire protection services have been allowed throughout the development in accordance with the most recent requirements of the Authorities and International Standards for life safety.

In addition to the inherently high standards adopted in construction techniques and materials and fire isolation, the proposed protection systems include:

- automatic wet pipe fire sprinkler installation complete with dual water supply, dual power booster pumps, zoned reticulation system with zoned flow switch indication, master control alarm, indication and communications panel

- automatic wet pipe hydrant/hose reel system complete with zoned storage tanks and dual power booster pumps
- automatic photo-optical and ionization type smoke detectors at each fire stair and in air conditioning and mechanical ventilation ductworks to initiate the operation of smoke venting and fire stair pressurisation cycles and illuminated directional graphics to facilitate fire control and the safe evacuation of all persons from the building complex
- integrated mechanical ventilation systems for smoke venting and stairway pressurisation with uncontaminated fresh air supply available from opposite sides of the building
- automatic smoke venting of all lift shafts.

ENERGY MANAGEMENT

In order to maximise the designed energy benefits of the proposed services installations throughout the operational life of the development, it is proposed to install an optimising computer controlled central monitoring and control system for:

- the operation of all plant to minimise energy consumption and to optimise environmental conditions,
- central monitoring and alarm functions,
- the control of all mechanical and fire protection and evacuation systems under fire mode conditions,
- centralised security control
- the establishment and upkeep of an energy management plant maintenance system to cater for the regular inspection and servicing of all systems and to monitor maintenance problems associated with individual items of equipment.

The system will record data such as electrical energy demand and consumption and progressively process this data to provide a model history against which new data may be compared as part of the energy management programme for the development.

CONCLUSION

The energy conservation and management techniques incorporated in the Rocks Gateway design utilise fully proven technology which has been engineered to match the energy characteristics and conservation opportunities of the development.

The combination of the passive energy architecture and the engineering services energy conservation designs and management techniques results in:

- a 50% reduction in installed capacity of refrigeration plant,

- a reduction in energy demand of approx 52% as compared with a comparable conventional development, thus contributing to the energy efficiency of the State utility supply system in addition to the efficiency of the proposed development,
- a reduction of 37% in annual energy consumption as compared with the estimated energy utilisation for a conventionally serviced similar type development,
- annual savings at current energy costs of 40% on the reduced energy consumption as compared with a conventionally serviced development not incorporating energy storage.
- the elimination of need to provide conventional oil or gas fired heating plant to meet the heating needs of the development,
- a reduction of approx 40% in the capacity of emergency generating plant otherwise required for similar type developments,
- reduced maintenance, improved reliability and increased stand by capacity,
- flexibility to operate the building energy systems to optimise energy costs.

The Rocks Gateway Project incorporates all the ingredients necessary to achieve an optimally energy efficient design, namely:

- a low energy architectural design solution
- the use of energy efficient services designs
- the incorporation of facilities to provide for maximum flexibility and optimisation in energy management.

The design and system concepts incorporated in the Rocks Gateway Project illustrates the potential which is available from the inception of design to achieve commercially viable low energy utilisation targets by the integration of architectural and engineering services designs. The design team involved in the Rocks Gateway Project believes that a new standard has been established by this complex in energy design efficiency which will be a valuable reference for future building designs and hopefully may stimulate some thinking aimed at a more effective 24 hourly utilisation of our reticulated utility supplies with resultant reduction in peak demands on the grid.

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Contemporary Energy Conservation Design Considerations and Methods

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ABSTRACT

Present-day design of energy efficient buildings involves particular attention to 1) the use of an architectural enclosure opaque to solar and temperature effects, 2) the use of lighting systems utilizing footcandle levels not exceeding that required for the purpose intended and utilizing efficient lighting fixtures (which should result in installed electrical power for lighting of less than two watts per square foot for typical general office use), implemented where possible by intelligent daylighting (intelligent in that the daylighting facility should save more energy by minimizing electrical lighting than is expended due to any resultant additional heating and cooling requirement), 3) the use of a minimum quantity of ventilation outside air consistent with health requirements and odor removal, 4) the installation of air conditioning systems minimizing air pressure drops and water pressure drops and minimizing air quantities and water quantities (by the use of maximum temperature differences between maintained room temperature and supply air temperature, consistent with good draftless diffusion, and by utilizing the maximum possible temperature spreads for water systems), 5) the proper zoning and volume control of air and water systems to permit efficient part load and overtime operation, and 6) the use of modern energy management systems to achieve optimum control, except that care should be exercised that capital expenses not be made which cannot be clearly shown to justify themselves in terms of operating cost savings, and that such systems not be so sophisticated as to preclude proper operation and repair and maintenance by the available labor quality.

INTRODUCTION

The purpose of mechanical and electrical systems in commercial office buildings has not changed, in any fundamental sense, over the history of the construction of buildings utilized for such occupancy. Clearly, the primary purpose of these systems is to provide space for the occupants of the building that will permit them to conduct their business in a comfortable and safe atmosphere. What has changed during the past decade, in the United States, is the evolution of energy-conserving building designs that consume significantly less energy than buildings constructed in the period starting in approximately 1950 and ending in 1973. The changes are fully the result of the energy crisis that started in 1973.

The energy crisis has affected the design community in two fundamental ways, both of which have altered designs of buildings. The first change has been the steady increase in the cost of all forms of energy that has permitted the expenditure of more money on energy conservation systems in buildings. In many instances, these systems tend to be capital intensive and the increase in the cost of energy has permitted justifiable expenditure of money for them on a proper business basis.

The second change is in the architectural design of buildings. Architects do not exist in a vacuum. They are subject to the pressure of their clients, who are, if not more knowledgeable about energy consumption in buildings, nevertheless deeply interested in how much energy the building will consume. This interest has affected the architect's design. Moreover, the architect is subject to governmental pressures in the United States in the form of both Codes and suggested goals that fundamentally affect his thinking on what constitutes a proper design. In sum, the second change is altered priorities of the architectural profession as a result of business and governmental pressures, as well as the architect's concerns as a citizen in an energy-conscious world.

A primary impetus to the new energy efficient designs originated with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Standard they have developed — ASHRAE Standard 90-75.

ASHRAE STANDARD 90-75

The development of ASHRAE Standard 90-75 and its successor, Standard 90-80, is the end result of a process that started in the United States in 1973. At that time, the National Conference of States on Building Codes and Standards (NCSBCS) — an organization of 50 members, each appointed by the Governor of one of the 50 United States — through the National Bureau of Standards (NBS), requested ASHRAE to prepare a Standard that could be adopted by various Code writing authorities by referral. The suggested Standard was to address means of conserving energy in new construction. The Standard, finally completed in 1975, was formally entitled 'Energy Conservation in New Building Design'. It has been adopted, in some cases with minor modifications, by more than 45 of the United States and has, in point of fact, become the basis for energy designs in the United States.

The Standard provides performance oriented prescriptive design requirements and evaluation criteria for energy efficient buildings. The prescriptive requirements are directed toward the design of building envelopes with high thermal resistance and with low air leakage. The Standard also establishes practices in the design of improved mechanical and electrical systems which promote the efficient use of energy. The criteria established are flexible to encourage the use of innovative procedures and techniques to achieve efficient utilization of energy and systems.

The effect of the Standard has been to reorient the thinking of the entire design community, not so much by advocating technological advances through the application of new hardware, but rather through effecting the design of buildings that utilized existing hardware in a more energy conserving manner. Its impact on the design of buildings cannot be overemphasized.

BUILDING ENVELOPE DESIGN

In buildings erected in the United States during the 1950's and 1960's, it was not uncommon to see buildings that were designed with floor-to-ceiling glass (approximately 60 to 65 percent of the exterior wall). The glass was almost always single thickness — often clear, sometimes tinted. Exterior walls were minimally insulated with U values of between .12 and .25 Btu/hr.-sq.ft.-°F. (.68 to 1.42 w/m.^{2}-°K.). It is in the detailing of the thermal characteristics of the exterior envelope that some of the most far reaching changes in buildings have occurred in the past decade.

Before proceeding to current envelope design techniques, it will be useful to describe the systems that were finding application in the exterior portion of buildings that, to a substantial degree, resulted from the building envelope design outlined above. The very nature of the architectural scheme for the exterior envelope resulted in thermal loadings that, in a practical sense, required the use of air-water systems, such as the induction system or fan coil system with only enough primary air to handle outside air ventilation requirements and internal dehumidification requirements. The use of all-air systems, particularly in the exterior of high rise buildings, was extremely rare since the quantity of air required would have been so high as to have had such a dramatic effect on the duct sizes (vastly larger) that the resulting floor-to-floor height would have made the use of such systems prohibitively expensive.

The interior portion of buildings constructed in the 1960's was handled by several varying types of system. Almost all were constant volume systems, ranging from reheat systems with reheat coils on each floor or at each point of special usage, such as a conference room, or double-duct systems, or even, in some cases, constant volume systems with only central ability to regulate the temperature control. The systems tended to be simple and, in a practical sense, inexpensive — both in installation cost and in operating cost due to the low cost of energy.

Today there is an early and continuing cooperation between the engineer and the architect in the determination of the building skin structure in order to make it as thermally opaque as possible in order to minimize both heating and cooling loads.

This cooperation is required by the energy codes which, derivative of ASHRAE Standard 90-75 as noted above, require building envelopes with high thermal resistance and low air leakage. These codes, while addressing heat transfer or thermal transmittance values (U values) that are attainable with present day construction methods and materials also are influenced by the weather conditions that exist for the geographic location of the building. This is accomplished by requiring those buildings with cold harsh winters to be more thermally opaque than buildings in milder climates.

The Standard requires that in buildings with annual Fahrenheit heating degree days (65°F. base) of between 2,000 and 10,000, the overall thermal transmittance value for the exterior wall, including glazing, is permitted to vary in a straight line relationship between 0.35 Btu/hr-sq.ft.-°F. and 0.20 Btu/hr-sq.ft.-°F. (The equivalent relationship for annual Celsius heating degree days [18°C. base] is 1000 and 5500, with the permitted straight line relationship in overall thermal transmittance value for the exterior wall, including glazing, varying between 2.0 w/m.^{2}-°K. and 1.1 w/m.^{2}-°K.).

The Standard, in its effort to control the envelope of the building, also addresses the roof and slab areas on grade, as well as the amount of glass and the thermal characteristics of the glass (i.e., both its shading coefficient or reflectivity and its thermal transmittance). Overall, consideration of the envelope and glazing result in drastically reduced energy flow through the building and, in many ways, permit the systemic changes outlined below. It is clearly a major impact upon building design and construction.

No discussion of the building envelope would be appropriate without some discussion of the glass being used in designs and how it is being applied. With glass costs varying between 2.50 U.S. dollars per square foot and 12.00 U.S. dollars per square foot as a function of the type glass, the economics are not always simple to analyze. Moreover, the thermal transmittance values permitted by the code have resulted in the wide application of insulating glazing, particularly in colder climates. In an early reaction to energy concerns, architects utilized dark glazing or reflective glazing with very low shading coefficients (as low as .15 without shading devices). While buildings are still being designed with this type of glass, there has been a reversion to clearer glazing or tinted glass that permits the sun to beneficially brighten exterior spaces.

The reflective glasses have been recognized as a means of reducing heat gain due to solar radiation, but they have two detriments which must be carefully analyzed and addressed in properly analyzing energy savings. First, they not only block out the sun in the summer cooling season but also in the winter months when, in northern climates, the heat gain from the sun is beneficial in offsetting heat loss due to transmission. Second, the light transmittance of reflective glass is less than clear or tinted glass and therefore the number of hours that natural daylight can be used in lieu of or supplemented by artificial light is also reduced. The amount of reduction in both instances is a function of the degree of reflectivity.

LIGHTING SYSTEMS

In buildings designed prior to 1973, footcandle levels for standard office occupancy were approximately 75 to 85 footcandles (750 to 850 lux) and for drafting areas approximately 125 to 150 footcandles (1250 to 1500 lux). Although fluorescent fixtures were extensively used, there was also extensive use of incandescent fixtures. The fluorescent fixtures used were of a lens type which were less efficient and had a lower maintenance factor than today's fixtures. The energy input for lighting in general office areas ranged from 3 to 4 watts per square foot (32 to 44 watts/m.^{2}) and in some cases higher.

ASHRAE Standard 90-75 and 90-80 establish installed wattage criteria as a function of the usage of the space. These criteria usually permit installed wattage of between 2.2 and 2.5 watts per square foot (23 to 28 watts/m.^{2}). Significantly less than traditional designs, but these criteria almost without exception are bettered in actual designs being implemented. In the design of lighting systems today, the accepted goal is to achieve 50 to 60 footcandles (500 to 600 lux) at the task with minimum energy input. The installed wattage to obtain this goal can vary greatly.

In actual present designs, great emphasis is placed upon efficient lighting techniques which break down into two major subcategories — a) The use of highly efficient lighting fixtures and the arrangement of such fixtures to achieve the minimum amount of energy usage, and b) the circuiting of such fixtures to permit turning off lighting in spaces which are not occupied regardless of the time of day or night. In office structures, typical installed wattages range from 1.2 watts per square foot (13 watts/m.^{2}) to 2 watts per square foot (21 watts/m.^{2}) for general office illumination. Moreover, depending upon whether or not fixtures are installed uniformly in a space or located locally only with respect to the task location, installed wattages below these values are being obtained.

With individual room circuiting, lights can be turned off during normal occupancy periods when rooms are vacated or can be turned off during the hours of building cleaning except when the room in question is being cleaned. Hardware is now available (infrared devices, motion detectors, etc.) to automatically achieve this function, but proper training and discipline of building occupants can achieve the same result without the addition of mechanical and electrical hardware which obviously requires additional investment cost and just as obviously needs continuous maintenance and repair.

With regard to the lighting of exterior spaces, the engineer is now, more than ever before, cooperating and coordinating with the architect to achieve what is known in the profession as 'daylighting'. This, in effect, by careful design of the building facade, permits turning off interior illumination in exterior rooms (and even in interior rooms under certain circumstances) when the natural light outside the building can achieve proper internal illumination through suitably sized window areas. It is essential, however, in regard to 'daylighting', that excess glass areas not be installed, or the energy saved by turning off electrical illumination will be exceeded by the additional energy expended to counteract the heating loads and cooling loads imposed by unnecessarily large glass areas.

VENTILATION AIR

The minimum quantity of outside air as a percentage of total air, on a per square foot or square meter basis, or on a per person basis, is a matter that has undergone substantive changes in thinking. In older designs, the amount of outside air used in commercial buildings was very high. For example, in a building with an induction system serving the perimeter areas of the building and with a constant volume terminal reheat system for the interior, the induction system was often 100% outside air and the interior system between 30 and 40 percent. This was an approach that ensured low first cost, but which resulted in increased operating costs.

Greater emphasis is now placed upon the minimum use of the outside air component (as contrasted to the recirculated air component) in air conditioning systems. This is obviously due to the fact that outside air in hot weather constitutes a cooling load and therefore an energy use and in cold weather constitutes a heating load and therefore also an energy use. In brief, the profession is gradually decreasing the use of outside air to the minimum consistent with proper health standards. There is some disagreement as to these standards, but depending upon the authorities having jurisdiction, they now range down to a low of approximately 5 cfm (2.5 l/s) per person for general occupancy use in office buildings and general assembly type occupancy. The American Society of Heating, Refrigerating and Air-Conditioning Engineers in its recently revised Standard, ASHRAE 62-1981, addresses the issue of ventilation and acceptable indoor air quality in considerable detail. While this Standard is not fully accepted within the design community, the argument is often theoretical since the amount of outside air in modern designs usually ranges between 0.10 cfm per square foot (.5 l/s-m.^{2}) and 0.15 cfm per square foot (.08 l/s-m.^{2}) and is primarily determined as a function of balancing the exhaust requirements of the building.

SYSTEM TYPES AND CONFIGURATIONS

In the energy conscious designs of today, reheat systems are rarely used unless, psychrometrically, they are absolutely necessary. Today, induction systems are only being manufactured by one vendor and find virtually no application. The variable air volume (VAV) system, on the other hand, has achieved considerable prominence. The VAV system offers advantages consistent with the goal to conserve energy. These advantages are as follows.

- The total system air is a function of the maximum simultaneous peak of a building and not the sum of the peaks.

- The air capacity and, therefore, the cooling potential is automatically moved to the area of the building where it is needed and the quantity of air into a given space varies in direct proportion to the cooling load in the space.

- With the introduction of variable volume boxes having a low pressure drop, approximately .25 inch H_2O (62 Pa), it is possible to design systems with a total system static pressure in the range of approximately 4-1/2 inch H_2O to 5 inch H_2O (1120 to 1245 Pa).

In addition to alternative system design, the beneficial use of the cool weather of spring and fall has resulted in the design of several alternative free-cooling system features. These features can be incorporated into several types of systems. They all reduce energy consumption. Some examples of these are as follows:

- In all-air systems, the utilization of 100% economizer cycles for free-cooling is common practice.

- In a building utilizing local floor packaged direct expansion condenser water cooled systems, which would operate on minimum outside air at all times, the design can include the introduction of an auxiliary free-cooling coil. This coil would utilize condenser water directly when the outside wet bulb permits water cold enough to cool the air. This is another application of free-cooling.

- In all-air systems, in dry, hot climates, the use of condenser water in lieu of chilled water made by mechanical refrigeration can be utilized when the wet bulb temperature is low enough but the dry bulb is not low enough to permit use of outside air. In this type of climate, there may be also a significant number of hours where the condenser water can be blended with the chilled water to precool it and therefore reduce the load on the refrigeration plant.

- In the retrofitting or upgrading of existing buildings which have an induction perimeter system or a fan coil system, or in new buildings with a fan coil system, condenser water is utilized in lieu of chilled water in cool weather. This can be accomplished by directly injecting condenser water (after proper filtration) into the chilled water circuit, by using a flat plate heat exchanger between chilled water and condenser water circuits or by using the inherent thermal head capability in the refrigeration machine when cold condenser water is pumped through the machine to cool the chilled water being pumped through the machine cooler. In the latter two cases (i.e., where a heat exchanger or the refrigeration machine is used), a certain amount of thermal head is lost and consequent energy savings are reduced.

Extensive literature has been written on the applications of ice storage and chilled water storage systems. Storage systems are an ideal method of dealing with time-of-day utility rates in terms of reducing the cost of utilized energy. In the limited view of a building as an isolated entity in itself, the energy consumed is often greater with a storage system. However, in terms of the long term view of utility company generating capacity, it can be demonstrated that if the existing generating capacity of utilities can be stretched as a result of energy conservation and the reduction of the rate of growth of their peak demand (due to shifting of demand through the use of storage systems), new generating plant capacity would not be required until some time further out into the future than would be required without such measures. The capital required to construct such facilities and the energy consumed in constructing the new plant facilities is a matter of major interest in the United States.

EQUIPMENT

As variable volume systems have blossomed so too has the use of controllable pitch vane-axial fans as the prime mover for such systems. The part load operating characteristic curve for such fans approaches the ideal of a variable speed drive performance curve. The vane axial fan also does not have the inherent losses for example of the inlet vanes on a centrifugal fan which results in higher horsepower and energy used. The turndown ratio of these fans also exceeds that which is available with centrifugal fans.

A feature to be incorporated, if possible, in the design of air handling systems is the use of cooling coil bypass dampers so as to reduce the pressure drop through the system during those times of the year when mechanical cooling is not required. The savings in pressure drop could be realized every hour the fans operate for possibly 5-1/2 to 6-1/2 months of the year in northern climates.

With regard to the design of air handling systems, there is greater emphasis upon increasing the temperature differentials of supply air (for both heating and cooling) in order to circulate the minimum amount of air consistent with occupant comfort. This results in a reduction in fan energy to deliver the air. There is also greater emphasis upon proper selection of filters, cooling coils, heating coils, air terminal units, and air duct sizes in order to minimize air pressure drops, also to minimize fan horsepower.

Similarly, chilled water and hot water systems are now designed to higher temperature spread standards and lower pressure drop standards (consistent with resultant investment costs) in order to reduce pump horsepower.

Also, in the design of air handling systems, greater attention is now given to the ability to have local air handling systems or alternatively with central systems to permit, by means of dampers in the ductwork system working in conjunction with variable speed fans or variable inlet vane controlled fans or fans with variable pitch blades to permit turning off air supplied to spaces not occupied.

Finally, heat recovery systems are now installed whenever economically feasible. Examples of such systems are refrigeration heat pump systems used when cooling is required year round, such as in a computer center, or hot gas reclaim systems (in either boiler flue exhausts or engine generator exhausts) when heating is required (for either building heating or as an energy source for absorption type refrigeration). Such systems, of course, require the expenditure of considerably more initial investment. Their justification is now more frequent only because the saving in operating costs as a result of higher energy costs is so much greater today than it was some years ago. A computer center that years ago may have thrown away its internal heat load today would undoubtedly recover that heat load in the wintertime through the use of heat pump operation and use this recovered heat for building space heating and hot water tempering. This possibility can be drastically altered by the cost of energy.

ENERGY COST IMPACT ON DESIGN

It was stressed earlier that one of the two fundamental ways in which the energy crisis has affected designs for buildings was the steady increase in the cost of energy. This is true but is only a portion of the problem.

Source energy at the building property line in the United States comes from three different sources. These are oil, natural gas or electricity. Each is different from the other. Oil, for a particular grade or type oil (be it No. 2 or No. 4 or No. 6) is, more or less, sold at the same price throughout the United States. Natural gas varies from as low as $.40 per therm to as much as .65 U.S. dollars per therm as a function of location. Still a relatively small variation. Electricity, however, is a completely different matter.

The electrical generation industry in the United States is a large number of generating companies, mostly private but some governmental, that have vastly different cost structures. These rate structures vary as a function of the means of generating electricity and the energy source (e.g., hydropower, nuclear, oil based generator, natural gas generated power, etc.) and according to local State and City tax policy. The cost in the

United States for 10,000 kwh of energy per month with 40 kw demand varies from as little as 350.00 U.S. dollars per month to as high as 1400.00 U.S. dollars per month.

In addition, costs will vary seasonally and as a function of the time of day. Many utilities, as an incentive to foster a higher load factor, have instituted time-of-day and time-of-year rate structures. For example, in New York City, Consolidated Edison, the local utility, has a current rate schedule for commercial buildings whose peak demand exceeds 3,000 kw during May 15th to October 15th of approximately 28.00 U.S. dollars per kw during the hours of 8:00 A.M. to 6:00 P.M., Monday through Friday (on-peak). It steps down to approximately half that from 6:00 P.M. to 10:00 P.M. (on-peak); and from 10:00 P.M. to 8:00 A.M. (off-peak), there is no charge for demand if it is high tension service and approximately 5.00 U.S. dollars if it is low tension. Similarly, there is a different charge for energy on-peak vs. off-peak and summer and winter seasons. Although the differences between on-peak and off-peak may be more dramatic with Consolidated Edison as contrasted to other utilities, nevertheless, the intent and the consequent implications to design of this type of rate structure are clear.

Clearly, these local and national variations can have a tremendous effect upon the types of systems utilized in two identical buildings with identical operating characteristics but with different geography. The cost of an internal sink heat pump may not be appropriate in New York City, but may make considerable sense 50 miles away where a different utility company serves the area. The analysis of designs must be conditioned by these utility rates. The design can only be resolved after a thorough analysis of the use of the building, the utility rates, and alternative system operating costs and initial investment requirements.

ENERGY MANAGEMENT SYSTEMS

No discussion of contemporary energy design considerations would be complete without full reference to the application of computerized systems for controlling a building. Great attention is now being given to the installation of so-called 'energy management systems' which are becoming more and more sophisticated electronic systems using various degrees of computerized control (obviously with the necessary hardware and software) to control building environment and to start and stop mechanical apparatus. The justification for such systems can reasonably extend beyond energy reductions and be made, in part, on increased efficiency of operating labor to the point of staff reductions that may be fully quantifiable.

These systems have been steadily modified in terms of their structure since first introduced. Today, in the United States there are approximately 75 system suppliers. They offer a range of products from a microprocessor, operating as a time clock, timing on and off several pieces of equipment to elaborate systems with multiple processors controlling an entire multi-building facility. To generalize about such a wide range of product offerings may not be fully appropriate. Nevertheless, there are several observations that can be made that may be useful. These are:

- The systems are all rapidly incorporating distributive processing with microprocessors being installed at, or close to, the point of application rather than exercising control at a single central processing unit. The microprocessor has become endemic to the control systems. The systems are becoming more user friendly. Whether they are controlling better is still at issue.

- A distinct development that is still progressing in the commercial control industry is the use of direct digital control (DDC). In this variation, the application or system is directly controlled by electronic sensing to a microprocessor rather than more traditional pneumatic sensing and receiver controllers. The ability to apply proportional-integral and derivative (PID) control algorithms offers the prospect of more precise drift-free control in the future. It must be recognized that the pneumatic valve actuator and damper motor is still the controlling mechanism. Accordingly, in the commercial field with essentially inexpensive instrumentation being used, the alleged benefits with this alternative are still somewhat suspect. This must be contrasted with DDC control in the industrial field. A different market, different solution and, in a true sense, different result.

- Color graphics in CRT's are becoming an end in themselves. Whether there is any virtue in such visual displays is a serious point rarely raised. The color CRT is too intrinsic to the system sizzle to be separated out as a practical question.

- Instrumentation for the commercial applications has never been of sufficient quality to achieve the full capabilities of the computer. Moreover, the maintenance of the instrumentation is an ongoing problem, too often completely ignored when purchasing a system. The difficulty only becomes manifest after the expiration of the manufacturer's warranty.

- Software, particularly the energy conservation or optimization software, is simplistic, in most cases of marginal value and always a concern. The development of software in high level languages (e.g., Pascal or Fortran) and providing to the Owner source deck listings could lead to the development of better project oriented routines. The development of specific project software, though costly, may better realize the capabilities of an automation system. At this time, however, the software, in many instances, due to its general nature, is not fully acceptable.

- The simple direct routines of time clock control, the ability to centrally modify control functions, and the availability of malfunction information are all positive attributes of such systems. The future, however, must enhance their ability to include other claims too often not fully realized.

The inclusion of a computer based automation system in many buildings has become almost de rigueur. It is a standard procedure rather than a cost justified system decision. This should all be suspect. It is our judgment that the key to improving the energy efficiency of any building is the ability of the operating personnel to understand their building and how it should be operated. The strongest, single reason for including an automation system in any building is it becomes a tool that a perceptive staff can use to achieve that end. In a sense, it is no different than the task we engineers face of designing better engineering solutions for buildings. Specifically, we use the computer as an analytical tool, a means to a solution. Similarly, operating personnel have at their disposal, in an automation system, a tool to lower energy consumption. The building staff is the key ingredient in achieving a successful operating computer based control system. This simple conclusion is rarely recognized in the marketing of these systems.

Simulation Studies of Building Energy Performance in Warm and Humid Climates

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ABSTRACT

This paper presents the results of computer simulation studies on energy performance of a typical highrise office building floor module of local design practice at Singapore. BLAST (Building Loads and Systems Thermodynamics) which is a comprehensive computer programme developed by the Construction Engineering Research Laboratory (CERL) of US Army Core of Engineers and TRY weather tape of 1967 for Singapore were used in these simulation studies. Hour by hour cooling load components and system and zone energy consumption on a design day and monthly totals for one full year were calculated. As envelope design will have a considerable impact on a building's energy performance, effect of design parameters such as glass area, aspect ratio and orientation, shading devices, and wall exterior surface solar absorptance, on fabric load has been studied, for a design day. An improved energy efficient envelope was arrived at by a combination of the envelope design elements and computer simulation studies of a design day and annual energy performance are repeated. The results indicate that through envelope design alone it is possible to reduce fabric load by 57 percent. However it would bring about only 16 percent reduction in total energy consumption and 15 percent in peak energy demand. As expected latent load forms a fairly high percentage, (37 to 43%) of the cooling energy demand because of high humidity conditions.

Annual energy budget for the base and improved design buildings are 698 MJ/m^2. Yr and 587 MJ/m^2. Yr respectively. Annual average energy demand is found to be about 72 percent of the peak energy demand for the base building and 71 percent for the improved design. This indicates that envelope design has little influence on the ratio of average to peak energy demand in warm humid climates.

INTRODUCTION

The analysis of energy performance of buildings especially air-conditioned office and commercial buildings is highly complex because of the interactions between the climate and the building, building and air-conditioning system, and user interactions. It is determined by the building fabric design, the air-conditioning and lighting systems design, the occupancy pattern, operating schedules, and the prevailing climatic conditions. For arriving at energy efficient designs, with reference to the climate of a place, effect of various design options on building energy consumption are to be investigated at the conceptual design stage itself. Such an explanatory study is only possible with the use of computers. Several computer programmes for the calculation of cooling and heating loads of buildings are available, (Ref. 1), (Ref. 2), (Ref. 3), (Ref.4) but only a few are capable of simulating Buildings as well as Systems and perform hour by hour energy analysis using design day and or annual weather data. BLAST (Ref. 5) and DOE2 (Ref. 6) are two such comprehensive programmes widely used in United States of America. In recent years results of several computer simulation studies on energy performance of different types of buildings were reported (Ref. 7), (Ref. 8), (Ref. 10). Most of these studies are related to cold or temperate climate. In USA Building Energy Performance Standards (BEPS) are being established and Design Energy Budgets (DEB) for different types of buildings in different parts of the country are being determined. Computer Energy Analysis is accepted for determining Design Energy Consumption (DEC) as a Standard Evaluation Technique (SET) and as a design tool by engineers and architects.

In warm humid climates, especially in the countries of South East Asia region, though the need for evolving energy efficient building designs is often stressed, no systematic studies on energy performance of buildings are made. The authors have initiated computer simulation studies as a joint research project of the University of Illinois, Urbana USA and the National University of Singapore. A high-rise office building floor module of typical local design practice at Singapore is taken as a base case building. BLAST computer programme and Singapore weather tape for 1967 are used in this study.

CHARACTERISTICS OF WARM HUMID CLIMATES

Warm humid climates are found in a belt near Equator extending upto 15°N to 15°S latitudes. In this climate there are very little seasonal variations. The general characteristics of this type of climate are:

Temperature

Both the diurnal and annual ranges of temperatures are quite small. The mean monthly temperatures do not vary by more than a few deg °C from the mean annual value. The average diurnal variation of temperature is 6°C to 8°C. The mean maximum during the day lies between 27°C and 33°C, but occasionally it may exceed the latter value. The mean minimum varies between 22°C and 27°C.

Humidity

High humidity prevails all through the year. The mean Relative Humidity (RH) is greater than 75 percent, but it may vary from 55 to almost 100 percent during the course of the day.

Rainfall

Rainfall is spread throughout the year with some periods of more or less rain. Annual rainfall can vary from 2000 mm to 5000 mm. Wind velocities are low and there are usually one or two dominant directions. Calm periods are frequent.

Sky Condition

Sky conditions are fairly cloudy throughout the year. Cloud cover varies between 70 and 90 percent for most of the time. Clear sky conditions occur rarely.

Solar Radiation

Solar radiation is strong. At noon times, intensities of 900 to 1000 W/m^2 are common. The mean daily totals range from 15 to 21 MJ/m^2. Solar radiation is partly reflected and partly scattered by high cloud blanket and the high water vapour content of the atmosphere. Hence the diffuse radiation is fairly high and forms 40 to 50 percent of the global radiation. Clouds and water vapour also prevent or reduce outgoing long wave radiation from the earth to the sky and hence the nights are warm.

BLAST PROGRAM

A brief description of the BLAST program used in these simulation studies is given below:

The Building Loads Analysis and Systems Thermodynamics (BLAST) program consists of set of comprehensive subprograms for predicting energy consumption and energy systems performance and cost in buildings. It consists of three major subprograms:

The Space Load predicting subprogram - computes, hourly space loads due to solar transmission through windows, heat conduction, internal loads, and room temperature control, in a building zone, based on user input and weather data.

The air distribution system simulation subprogram - uses the computed space loads, weather data, and user inputs describing the building air-handling system to calculate chilled water, hot water steam gas and electric demands, based on space loads and air system performance.

The central plant simulation subprogram - uses results of air distribution system simulation and user input describing the central plant to simulate chillers, boilers, onsite power generating equipment and solar energy system and calculates equipment performance and computes monthly and annual fuel and electrical power consumption. This subprogram also performs life cycle cost analysis based on initial costs, fuel cost and maintenance costs.

A number of Reports are presented by each subprogram. The load subprogram provides hourly and monthly summary of sensible components of the cooling and heating loads of each zone. The latent loads are included in air handling system energy reports on the annual and monthly total energy consumption and peak demands. In the plant subprogram reports equipment use statistics (hours of operation and average part load ratio of each plant component) are included along with the electric power and fuel consumption data.

BASE BUILDING FLOOR MODULE

For the purpose of the present simulation studies a typical intermediate floor of a representative office building tower block of local design practice at Singapore is considered as a reference base. The plan and section of the floor are shown in Fig. 1. The other information on design, construction and the system operation conditions is given in Table 1.

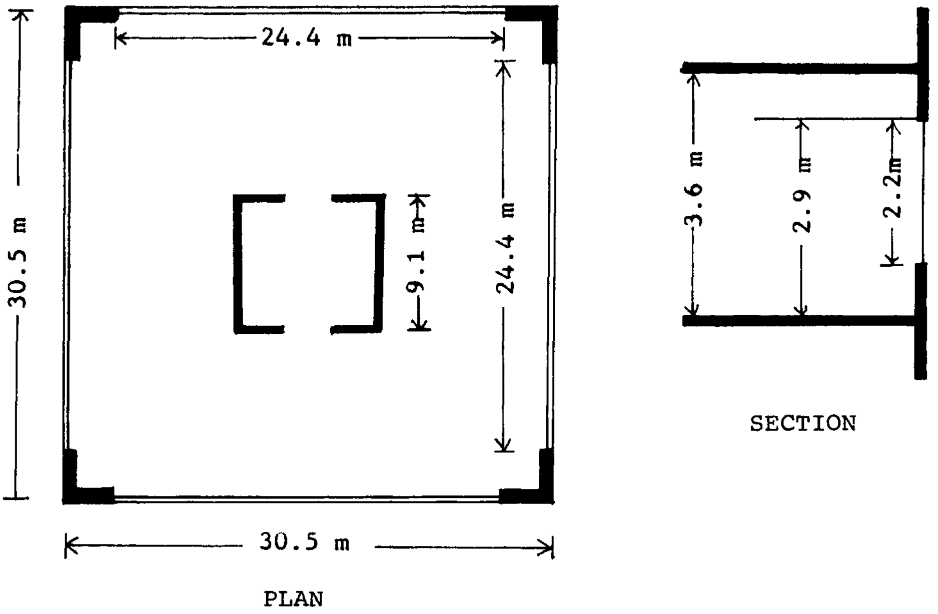

Fig. 1 Plan and section of a typical floor of the building used for simulation studies

TABLE 1 CHARACTERISTICS OF FLOOR MODULE, SYSTEM AND OPERATING CONDITIONS

Characteristics	Base Condition
1. Shape and size	Square Plan 30.5m x 30.5m with 9.15m x 9.15m central service core
2. Ceiling Height	2.93m
3. Floor to Floor height	3.66m
4. External Walls	25.4mm plaster + 101.6mm Hollow Concrete block + 19mm plaster
5. Glass area	48 percent of wall area (in all the four walls)
6. Type of glass	single pane 6mm clear glass
7. Floor	12.7 Acoustic tile, + ceiling air space + 101.6mm dense concrete
8. Ceiling	101.6mm Dense concrete + ceiling air space + 12.7mm Acoustic Ceiling
9. Service Core (partition walls)	19mm plaster + 101.6mm common brick + 19mm plaster
10. People	90
11. Lighting	21.5 W/m^2
12. Electric Equipment	5.4 W/m^2
13. Infiltration rate	40.8 CUM/minute
14. Temperature controls	Dead Band 23°C to 25.5°C
15. System operation	Intermittent (08 to 18 hrs) during week days i.e. Monday to Friday 08 to 13 hrs on Saturday
16. Supply volume air	336 CUM/min (Constant Volume)
17. Chiller plant size	234 kW
18. Average COP of Cooling System	3.0
19. Fan efficiency	70 percent
20. Cold deck fixed temperature	12.8°C
21. Cold deck throttling range	4°C

PARAMETRIC STUDIES

Making multiple runs on the same building while varying only a single design parameter is known as a parametric study. Effect of envelope design parameters on the building fabric load has been studied varying one parameter at a time for a design day. May 15th is taken as design day. This is based on a preliminary year run of weather tape. The building is considered as unoccupied without internal loads and infiltration. Only space loads subprogram is run as fabric loads alone are required for this study.

Glass Area

Glass area expressed as a percentage of the total external wall area in each facade is varied from 0 percent (windowless) to 80 percent and the corresponding fabric loads per unit area per day are calculated and shown in Fig. 2. For the base case the

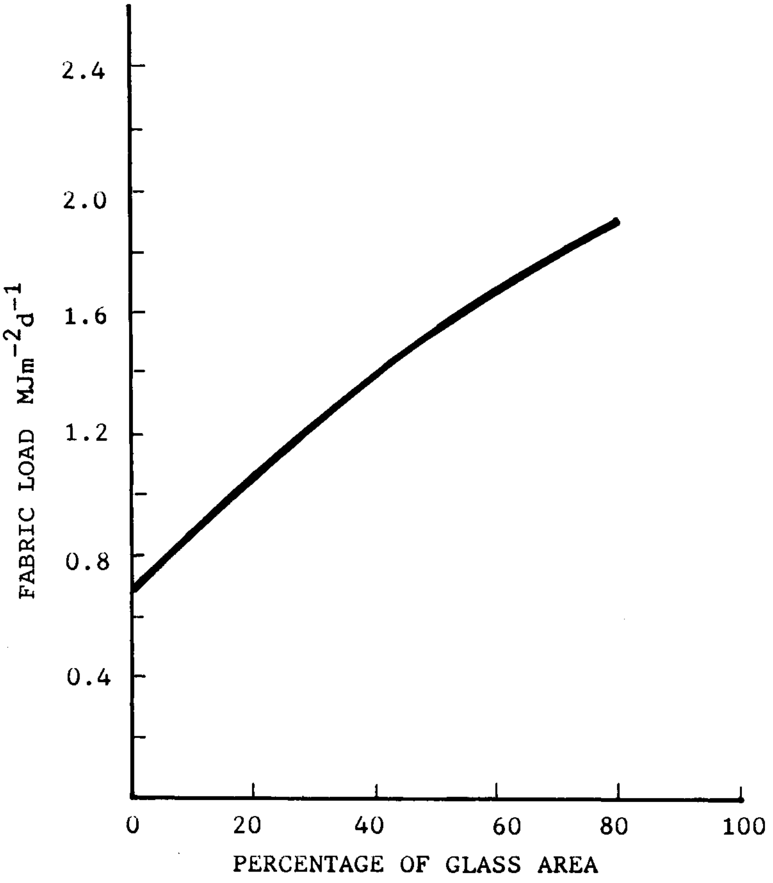

Fig. 2 Effect of Glass Area on Building Fabric Load

fabric load is 1.51 $MJm^{-2}\ d^{-1}$ and this is reduced to 0.68 $MJm^{-2}\ d^{-1}$ (55% reduction) for windowless case and increased to 1.91 $MJm^{-2}\ d^{-1}$ (26.5% increase) when the glass area forms 80 percent of wall area.

Orientation

Effect of orientation of the building on its fabric load depends on the aspect ratio of the buildings. It will have practically no effect on a square plan. For this study two aspect ratios 1:1.5 and 1:2 are taken keeping the same floor area as that of the base building. The orientation axis of the building is changed from 0 to 90 degrees in steps of 15 degrees and the corresponding fabric loads are calculated. The results are shown in Fig. 3. For rectangular shaped buildings orientation has significant effect. For example, for aspect ratio of 1:2 the fabric load for E-W orientation is increased by 31.8 percent as compared to that of N-S orientation.

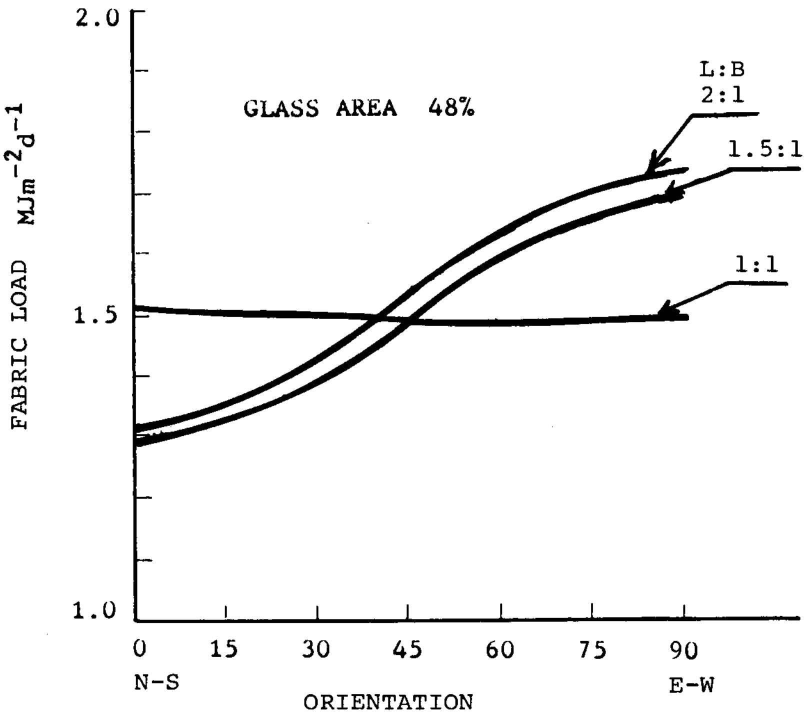

Fig. 3 Effect of Orientation on Building Fabric Load

Wall Surface Solar Absorptance

Surface colour of the external wall affects the percentage of solar radiation absorbed by the external wall and hence the heat conduction load. The overall effect on fabric load depends on the proportion of wall and glass areas of the facade. Hence the solar absorptance of the wall (α) is varied from 0.3 to

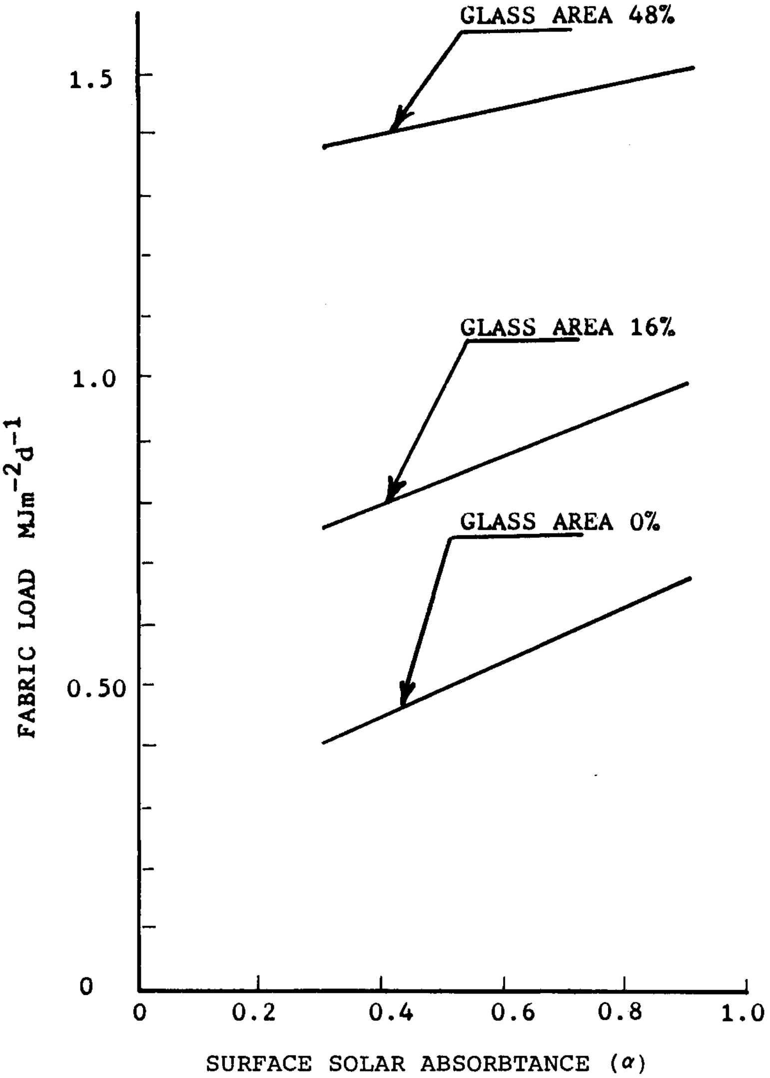

Fig. 4 Effect of Wall Surface Colour on Building Fabric Load

0.9 for 0, 16 and 48 percent glass areas. The results are shown in Fig. 4. It is evident that as the glass area increase the effect of surface colour is less pronounced.

External Fixed Shading (overhangs)

External shading of glass will reduce the direct solar radiation component transmitted and hence will reduce fabric load. Effect of a 1 m overhang projection on all four sides is studied. Fabric load is dropped to 1.12 MJm^{-2} d^{-1} because of shading the glass and a reduction of 23.8 percent in fabric load is achieved.

Internal Shading

It is a common practice to use internal shading devices like venitian blinds, drapes, and rollers shades in buildings. These too would reduce building fabric loads to some extent. Effect of the types of Internal Shading devices are studied. The fabric loads are reduced to 1.37, 1.26 and 1.05 MJm^{-2} d^{-1} for the above three devices respectively. The corresponding percentage reductions in fabric load are 9.3, 16.6 and 30.5

Type of Glazing

Many buildings use special glasses rather than clear glass for glazing. A variety of heat absorbing and heat reflecting glasses are available in the market. At Singapore heat reflecting glasses are not permitted by building authorities. Hence one type of grey heat absorbing glass with solar transmittance (τ) of 0.44 is studied. A reduction of 23.8 percent in fabric load is obtained with this type of glass. Though in the past it is not common to use double glazing, in last few years there is a trend to use it. Hence the effect of double glazing, (i) with both panes of clear flass and (ii) with outer pane tinted glass and inner pane clear glass, on fabric load is studied. For double glazing with both panes of clear glass the reduction in fabric load is hardly 2 percent, while for one pane tinted and the other clear glass, a reduction of 31.1 percent is obtained.

COOLING ENERGY AND TOTAL ELECTRICAL ENERGY USE ANALYSIS

Based on envelope parametric studies on fabric load, an improved envelope design is arrived at by altering some significant features. The modified features of the improved building are given in Table 2.

TABLE 2 Modified Features of Improved Building

External Walls	Insulated. 25.4mm plaster + 101.6mm Hollow Concrete Block + 50mm fibre glass insulation + 19mm plaster.
External Wall Solar Absorptance	0.3
Type of glass	6mm single pane Tinted-grey glass (τ = 0.44)
Glass Area	16 percent
Internal Shading	Light colour roller shades

The rest of the design parameters and the system operating conditions are remained same as described in Table 1.

The base case building and the improved building energy use analysis is performed for design day and year runs. The whole floor is taken as a single zone, though the local practice is to divide it into 2 or more zones. The final load and system reports of the programme consists of cooling and system and zone electrical hourly energy use profiles and days totals in the case of design day and monthly energy use profiles and annual totals for year run. The chiller plant system that supplies the required cooling energy to the system air handling is operated by electrical energy and the actual electrical energy consumption by the plant will be determined by the coefficient of performance (C.O.P.) of the cooling system. The C.O.P. is defined as quantity of cooling output from the machine divided by the energy input to the machine. In this study the average C.O.P. for the total cooling system is taken as 3.0. Total electrical energy requirement is the sum of (i) Electrical energy requirements for cooling $\frac{\text{(cooling energy)}}{\text{C.O.P.}}$ and (ii) Electrical energy requirements for the zone and system i.e. for electric lights, office equipment, fans of air handling units etc.

Design Day Simulation Results

The results are presented both as energy per unit area and as percentages. A comparison of days total of the sensible cooling load components for the base case building and improved building is shown in Fig. 5. For the base case building the fabric load is $1.51 MJm^{-2}d^{-1}$ and forms 58.7 percent of the total sensible cooling load of 2.57 MJm^{-2} d^{-1}. For the improved building it is

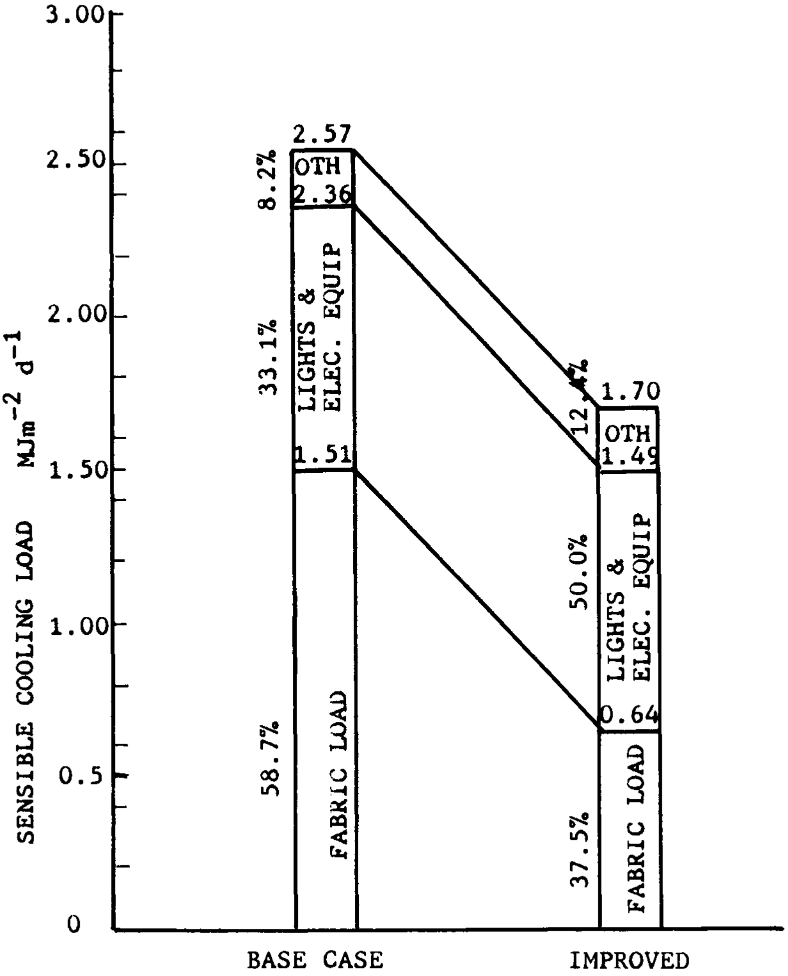

Fig. 5 Sensible Cooling Load Components of Base Case and Improved Buildings

0.64 MJm^{-2} and forms 37.6 percent of the total sensible cooling load of 1.70 MJm^{-2}. Reductions in fabric load and total Sensible cooling load due to improved envelope design are 57.6 percent and 33.8 percent respectively. Cooling energy consists of sensible and latent loads. For the base case buildings and improved building total cooling energy requirements are 4.30 MJm^{-2} d^{-1} and 3.16 MJm^{-2} d^{-1} respectively. A reduction of 26.5 percent is obtained because of improved envelope design. The total electrical energy consumption for the two buildings are 2.49 MJm^{-2} d^{-1} and 2.10 MJm^{-2} d^{-1} respectively. The reduction in electrical energy use for improved building is 15.6 percent. It may be noted that envelope design affects fabric load part only and hence though a reduction of 57.6 percent in fabric load is obtained the actual savings in electrical energy consumption would be only 15.6 percent. A comparison of hourly cooling energy use and total electrical energy use patterns for the two buildings are shown in Fig. 6 and Fig. 7 respectively.

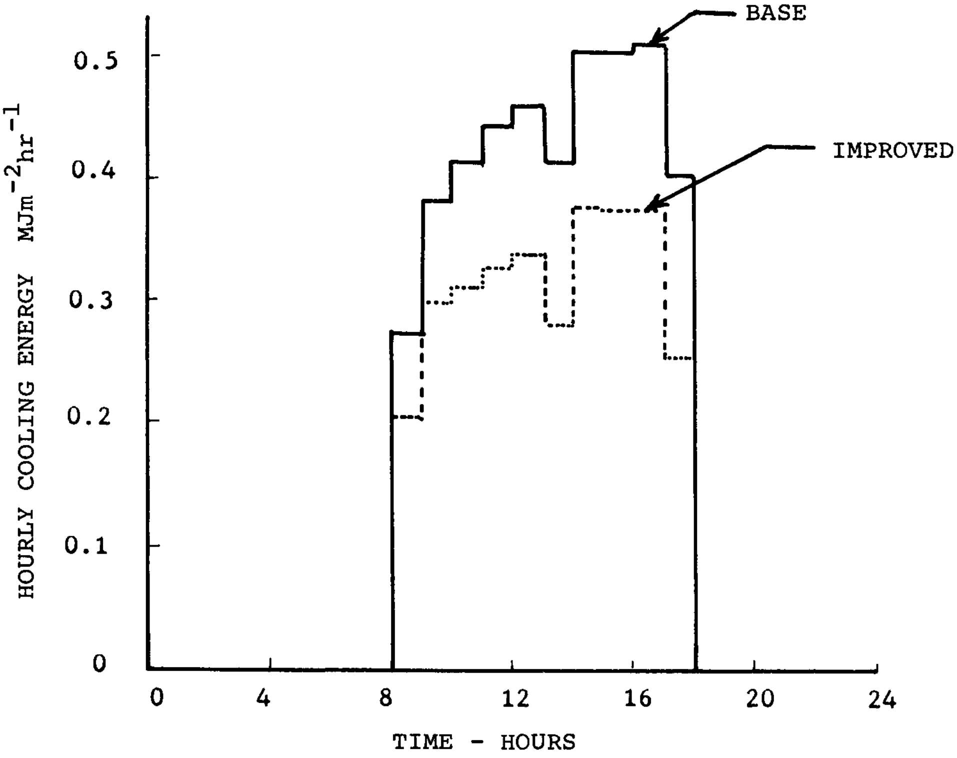

Fig. 6 Hourly Cooling Energy Use Profiles for Base Case and Improved Buildings

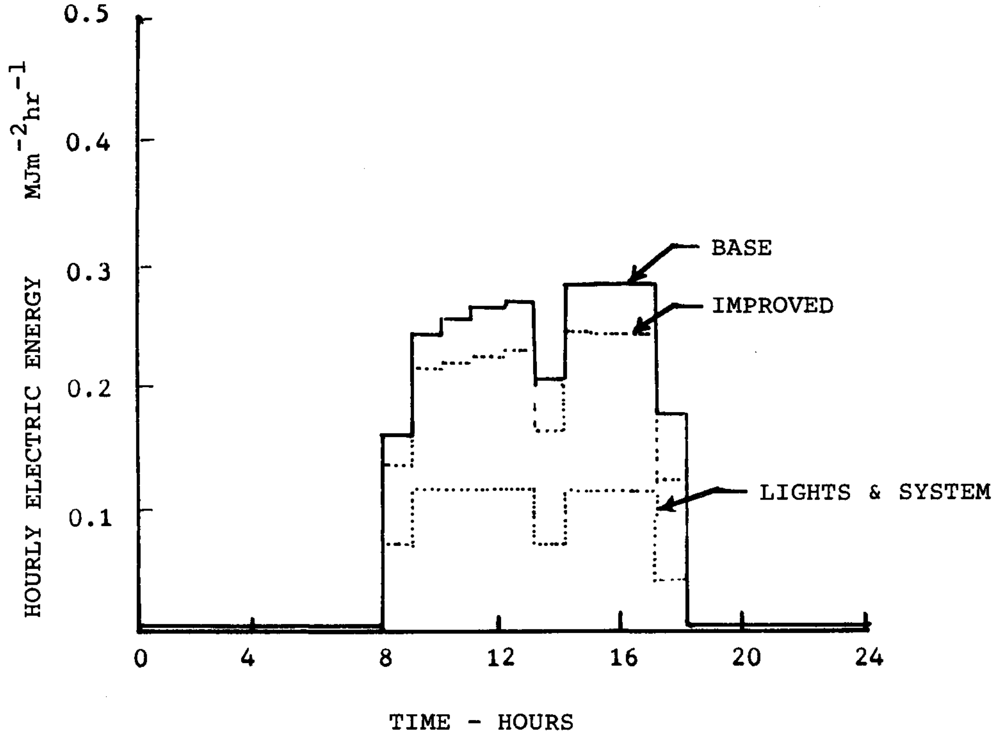

Fig. 7 Hourly Total Electrical Energy Use Profiles for Base Case and Improved Buildings

Design day summary of the building energy analysis for the two buildings is presented in Table 3.

TABLE 3 Design Day Summary of Energy Use for Base and Improved Buildings

Energy Item	Unit	Building		Percent Reduction
		Base	Improved	
1. Lights and Equipments	MJm^{-2}	0.798	0.798	-
2. System fans	MJm^{-2}	0.182	0.182	-
3. System and zone electrical energy (1) + (2)	MJm^{-2}	0.980	0.980	-
4. Sensible cooling provided by the system	MJm^{-2}	2.57	1.70	33.9
5. Latent cooling provided by the system	MJm^{-2}	1.73	1.46	15.6
6. Total cooling energy (4) + (5)	MJm^{-2}	4.30	3.16	26.5
7. Electrical Energy Consumed by chiller plant [(6)/C.O.P.]	MJm^{-2}	1.43	1.05	26.5
8. Total Electrical Energy Consumption by the building (3) + (7)	MJm^{-2}	2.41	2.03	15.8
9. Energy Budget	MJm^{-2}	2.41	2.03	15.8
10. Total hours of consumption	hrs	10	10	-
11. Average energy demand rate	Wm^{-2}	69.2	58.4	15.6
12. Peak energy demand rate	Wm^{-2}	79.4	67.2	15.4

Annual Simulation Results

Singapore weather tape for the year 1967 was used for predicting the annual energy consumption of the base case and improved buildings. Monthly cooling energy use profiles for the two buildings are compared in Fig. 8. The total electrical energy use profiles are compared in Fig. 9. It can be seen that the

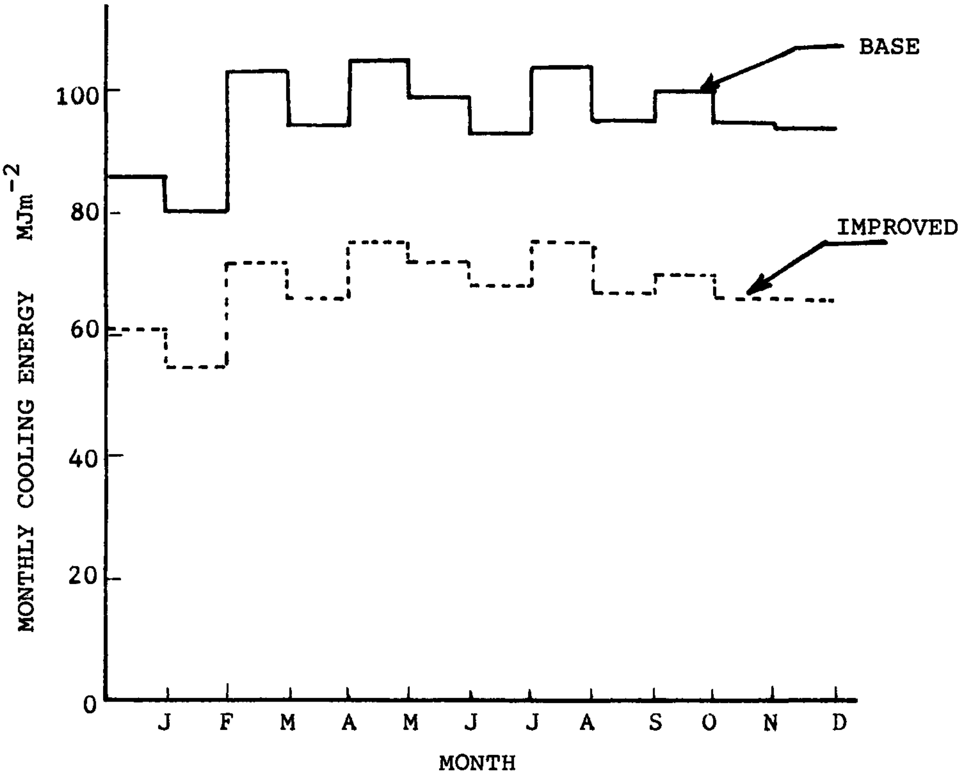

Fig. 8 Monthly Cooling Energy Use Profiles for Base Case and Improved Buildings

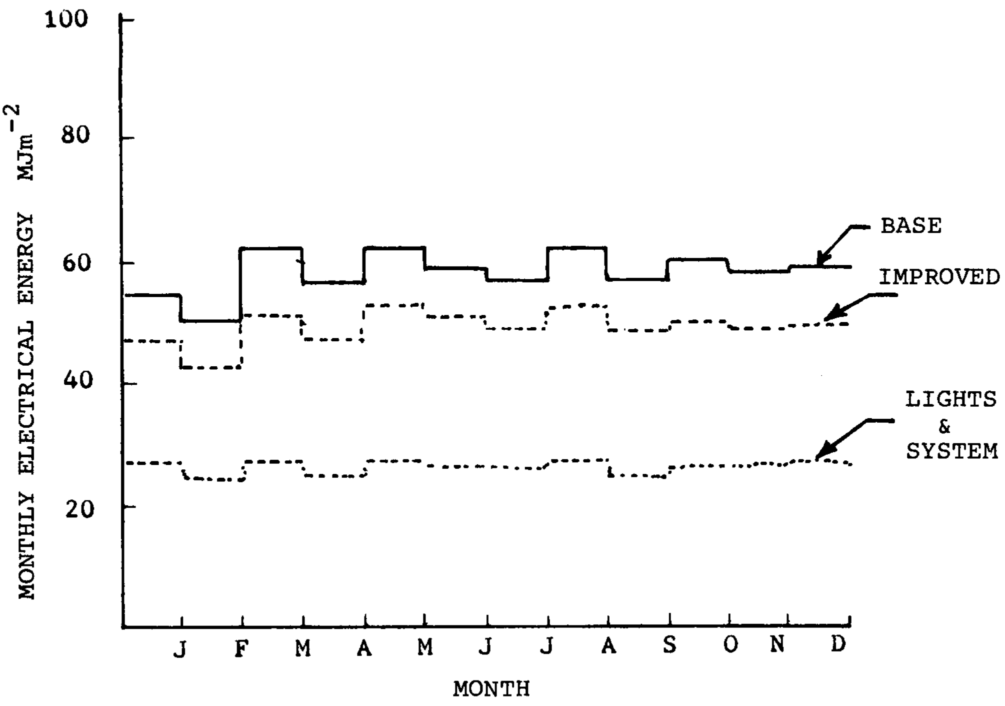

Fig. 9 Monthly Total Electrical Energy Use Profiles for Base Case and Improved Buildings

variations in energy use from month to month are less than 20 percent, in this climate. Annual cooling energy for the base case building is 1.146 GJm^{-2} while for the improved building it is 0.814 GJm^{-2} i.e. a reduction of 29 percent. Highest monthly cooling energy occurs in May with 105 MJm^{-2} forbase case building and 79.9 MJm^{-2} for improved building. The lowest monthly cooling energy occurs in February with 77.9 MJm^{-2} for base case building and 63.1 MJm^{-2} for improved building. The peak cooling demands for these two buildings are 172 Wm^{-2} and 131 Wm^{-2} respectively.

The total electrical energy consumption for the two buildings are 649 GJ/Yr for base case building and 546 GJ/Yr for the improved building i.e. a reduction of 15.9 percent. The energy budgets for the base case and improved building are 698 MJm^{-2} and 587 MJm^{-2} respectively. Average energy use rate and peak energy demand for the base case building are 64.0 Wm^{-2} and 89.3 Wm^{-2} while for the improved building 53.9 Wm^{-2} and 75.7 Wm^{-2} respectively. The ratios of average energy use rate to peak demand for the two buildings are 71.7 percent and 71.2

percent respectively. Summary of the annual energy use studies on the two buildings is presented in Table 4.

TABLE 4 Annual Summary of Energy Use for Base and Improved Buildings

Energy Item	Units	Building		Percent Reduction
		Base	Improved	
1. Lights and Equipment	MJm^{-2}	257	257	-
2. System Fans	MJm^{-2}	59	59	-
3. System and zone electrical energy (1) + (2)	MJm^{-2}	316	316	-
4. Sensible cooling provided by the system	MJm^{-2}	724	458	36.7
5. Latent cooling provided by the system	MJm^{-2}	422	356	15.6
6. Total cooling energy (4) + (5)	MJm^{-2}	1146	814	29.0
7. Electrical energy consumed by chiller plant [(6)/COP]	MJm^{-2}	382	271	29.0
8. Total Electrical energy consumed by the Building (3) + (7)	MJm^{-2}	698	587	15.9
9. Energy Budget	MJm^{-2}	698	587	15.9
10. Total hours of consumption	hrs	3031	3026	5 hrs
11. Average Monthly energy consumption	MJm^{-2}	58.2	48.9	16.0
12. Maximum monthly energy consumption (May)	MJm^{-2}	62.4	52.3	16.5
13. Minimum monthly energy consumption (February)	MJm^{-2}	50.2	42.6	15.1
14. Average energy demand rate	Wm^{-2}	64.0	53.9	15.8
15. Peak energy demand rate	Wm^{-2}	89.3	75.7	15.2

CONCLUSIONS

The present study is limited to the effect of building envelope design on cooling energy and total electrical energy consumption. In warm humid cliamtes like Singapore for a given percentage reduction of fabric load about 27 percent of that is expected to reflect as net percentage reduction in total electrical energy consumption. Another interesting observation is that envelope design has practically no significant effect on the ratio of average to peak energy demand rate. The latent load forms more than 40 percent of the cooling energy demand. It is hoped that the parametric studies reported in this paper will prove useful in the development of more energy efficient building designs in warm humid climates. Lighting design, HVAC system design, controls, and the COP of the chiller plant will also affect the energy consumption of buildings considerablt. Effect of system variables are to be studied, in future simulations, for maximising the energy savings of buildings. Life cycle cost analysis should also be performed for evaluating the cost effectiveness of various energy conservation options.

The simulation results presented in this paper are to be taken as a guideline only. These would provide the range of energy savings that can be expected in improving the envelope design. The actual values and the energy component percentages would vary from building to building, the HVAC system selected and operating conditions. For each specificbuilding computer simulation studies are needed to be performed individually. Many computer simulation studies on a large number of different building types and operating conditions are required for establishing Design Energy Budgets which could serve as Building Energy Performance standards for warm humid climate regions.

ACKNOWLEDGEMENT

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The Application of Bunyip to the Design of Multi-Storey Buildings

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ABSTRACT

BUNYIP is a computer program which estimates the energy consumption of a building by its associated mechanical and electrical services for a year's operation at its intended location in Australia. The estimate includes energy consumed by lighting and airconditioning equipment. The paper briefly describes the features and operation of BUNYIP and its intended role in the design process of providing information to supplement the experience of the engineers and architects involved. The application of the program to evaluating building facade features and air handling system designs is discussed.

INTRODUCTION

BUNYIP is a BUilding eNergY use Investigation Package, named after a mythical Australian animal. Other Australian animals are fantastic creatures (eg. platypus, kangaroo, and wallaby) and so it is with BUNYIP. The BUNYIP computer package simulates the diurnal heat transfer into and out of building spaces, and the operation of the various energy consuming systems, under standardised weather conditions for a specified location and estimates the energy input required for heating and cooling.

As part of a National Energy Research Development and Demonstration Project the Commonwealth Scientific and Industrial Research Organisation's Division of Energy Technology conducted research into building services performance and climatic data and prepared BUNYIP as a new design tool for estimation of energy consumption and costs. Earlier research on cooling and heating load and internal temperature variation had resulted in development of a simulation package TEMPER which is now successfully used in many design offices. (Ref. 1) With assistance from a further NERDDP grant, Enersonics Pty Ltd is developing the BUNYIP package to a commercial stage using its experience with energy survey, auditing and monitoring gained over many years to validate the programme and to demonstrate its potential.

BUNYIP will be available to architects and engineers to assist in the design of new buildings and modification of existing buildings, and to authorities seeking to ensure an adequate consideration of future energy supply in such designs. The estimation of future costs to rank the economies of design alternatives such as window size and shading or air conditioning plant selections, requires considerable skill and detailed calculations. The program will assist design engineers with an economical computer aided routine for evaluation of alternative details and overall system comparisons. The design team architect and mechanical engineer can resolve their problems and assure the owner or authority that a reasonable economy has been achieved in detail and can provide a good estimate for the running cost budget. Capital cost control is still very important in building projects, but future energy cost is becoming significant as reserves of cheap fuel are depleted.

PROGRAM FEATURES

Input - The user is required to prepare a computer file containing data to describe the building, its use, its air handling system(s) and plant. Extensive information is included in the program which will be used by default if the user has no specific input value available at that stage. Input data prepared for running the load estimating program TEMPER (1) can be used as part of the BUNYIP input file.

Output - Nine reports are printed in A4 format on the line printer, (for easy inclusion in other documents), which show details of energy consumption, and building/plant performance. The results are shown in a manner which highlights those areas of the design which could be improved, in terms of their energy performance. The reports are:

1. Energy Consumption Summary - Breakdown into heating, cooling, air handling, hot water, lighting, general power for each energy source and season. Summary of costs.
2. Graph showing variation of heating, cooling and total energy consumption through the year.
3. Graph showing variation of total air conditioning energy with daily average outside air temperature.
4. Table of total and consecutive hours above and below the thermostat dead band and maximum and minimum temperature reached in each zone.
5. Annual contributions to the cooling load in each zone, including fabric, lights, people, ventilation, infiltration and equipment.
6. Air handling system report showing zone loads, coil loads, reheat loads and system losses and gains for each season.
7. Plant report showing energy consumption by each item of plant.
8. Part Load report showing the hours spent running at ten-percentiles between off and full load, for specified plant items.
9. Part load graphs.

Examples of these reports are shown in Appendix A. Their interpretation is obvious with the exception, perhaps, of Reports 3 and 5. Report 3 is intended to give the designer an appreciation of the ambient conditions occurring when most of the energy is being consumed. Report 5 is an attempt to apportion cooling loads to the nominated sources, and does not necessarily correlate with contributions to actual energy consumption.

Weather Data - Computer files containing the weather data required by the program have been prepared for sixteen locations around Australia. The data describes the weather patterns on eight days per two month period which characterise the actual weather at the location recorded over five years. Data is being gathered for other locations.

Building Simulation - The heat transfer through the walls is simulated using a finite difference technique which takes into account the thermal storage in the structure, including the effect of the previous day.

- Shading can be fixed, moveable or automatically variable.
- Daylight saving duration can be 2, 4, 6 or 8 months.
- The temperature in the zones is not assumed to be constant:
  - a. thermostat setpoints can be set back at night
  - b. a thermostat deadband can be specified within which the zone temperature can "float" without invoking heating or cooling
  - c. different setpoints can be specified for all zones and can be changed between winter and summer
  - d. the capacity of airconditioning equipment can be specified and the energy consumption calculation will take into account any drift of zone temperature and carry-over of load to a later period.
- A humidistat can be specified to control the humidity in a particular zone within limits.

Air Handling System (AHS) Simulation-BUNYIP models the AHS as a series of components as specified by the user. This method gives the user the flexibility to model the particular AHS under consideration. Types of AHS which can be modelled include: VAV (Variable Air Volume)

VAV with Reheat
VAV with Dual Duct
VAV with Induction Units
CAV Terminal Reheat (Constant Air Volume)
Dual Duct
Multizone
Induction Units
Fan-Coil Units.

- The amount of outside air admitted can be held constant or varied according to
  - a. outside air temperature
  - b. the relative temperature of return and outside air
  - c. the relative enthalpy of return and outside air.
- The outside air can be shut off during warmup when the building is unoccupied.
- The cooling and heating coil leaving air temperature can be varied according to
  - a. outside air temperature schedule
  - b. season i.e summer/winter setting
  - c. zone temperature control.
- Heat can be exchanged between exhaust and inlet air.

Plantroom Simulation -

- Plant performance is based on manufacturer's published data where available.

- The user can override the program's default values for part load performance if desired.
- Direct expansion cooling can be modelled.
- Double Bundle & Absorption chillers can be modelled.
- A flexible system is available to control the distribution of load among a number of plant items i.e. more than one chiller.

Computational Features - To maximise the program's portability it was written in ANSI Standard Fortran IV.

- To minimize the program run time and cost, calculations involving iteration have been avoided and the weather data has been substantially reduced in quantity.
- A separate program has been written to check all input data.
- The major variables, such as the maximum number of zones, systems and plantrooms, which determine the memory requirements can be varied to suit a range of computer capabilities.
- The accuracy due to interpolation and the resultant run cost can be controlled by the user.

BUNYIP'S ROLE IN THE DESIGN PROCESS

The design of buildings proceeds under the influence of fixed constraints and criteria which must be optimised. Examples of constraints which maybe fixed are:

- size of the site
- available capital
- deadline for completion
- intended function.

Within these fixed constraints, designs are sought which will optimise the design criteria, important to the particular project, simultaneously. Examples of design criteria (not ranked) are:

- aesthetic factors
- energy costs over life
- maintenance costs
- reliability
- internal environment (temperature, daylight, space, noise)
- safety
- flexibility (future modification/extension?)
- net usable/rentable space

etc.

Where the design criteria conflict with each other, a balance must be struck, the position of the balance depending on the relative importance of the criteria. Thus the energy consumption and cost is but one factor which must be considered and BUNYIP provides a means of its estimation. It must be emphasized that BUNYIP is intended to be a tool for the architect and engineer to use in conjunction with (not replacing) their design skills and experience.

In order to run BUNYIP, the user must specify the building and air-conditioning equipment. This specification can be quite simple enabling BUNYIP to be used in the early stages of the design process when many important design decisions are made. Part of the BUNYIP input file which describes the building, is common with that required for the loads program TEMPER (1). Thus, with little additional effort, TEMPER can be run for a design day to provide the peak loads which are used to "size" the equipment.

Having established a "base" design and estimated its annual energy consumption, building features, air conditioning designs and operating strategies can be varied and the program rerun to evaluate the effect of the changes. Examples of changes which could be investigated are:

- double glazing
- change thermostat settings
- insulation levels
- window shading
- change operating hours
- change air handling system type
- outside air for free cooling
- one refrigeration machine smaller than the other etc.

CONCLUSION

The Commonwealth Scientific and Industrial Research Organization's Division of Energy Technology under the direction of Mr. M.J. Wooldridge have produced a computer program for the estimation of building energy use, entitled BUNYIP. The program is currently undergoing testing and validation, prior to it's release for use by Australian designers of buildings and building services. This work is being performed by Enersonics Pty Ltd with support from the National Energy Research, Development and Demonstration Program. BUNYIP promises to be a practical and versatile tool which will aid architects and engineers in low energy design for new and existing buildings by simulation of energy performance.

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APPENDIX A

```
BBBBBBB   UU      U  NN      N  YY      Y  II  PPPPPPP
BB     B  UU      U  NNN     N   YY   Y    II  PP      P
BB     B  UU      U  NN N    N    YY Y     II  PP      P
BBBBBBB   UU      U  NN  N   N     YY      II  PPPPPPP
BB     B  UU      U  NN   N  N     YY      II  PP
BB     B  UU      U  NN    NN      YY      II  PP
BBBBBBB    UUUUUU    NN      N     YY      II  PP

       BUILDING ENERGY INVESTIGATION PACKAGE

                    VERSION 1A




               44 MARKET ST - RUN 1

               USER - S K MOLLER

               DATE -  8 JUL 1983
```

```
                                                                PAGE   1

          BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
          ------
BUILDING - 44 MARKET ST - RUN 1

USER - S K MOLLER                    DATE -  8 JUL 1983


ENERGY CONSUMPTION SUMMARY
*------------------------*
1                ELEC - (UNITS -    10  KWHRS)
                 ----               ---
            JANFEB  MARAPR  MAYJUN  JULAUG  SEPOCT  NOVDEC * TOTAL
HEATING        124     180     242     244     242     242 *  1272
COOLING       2949    2138     400      64    1002    2115 *  8669
AIR HANDLING  3551    3647    3647    3683    3647    3647 * 21822
LIGHTING      6601    6779    6779    6846    6779    6779 * 40563
POWER          237     243     243     245     243     243 *  1454
                                                             -----
                              TOTAL ANNUAL ELEC CONSUMPTION  73780

                             ENERGY EQUIVALENT IN GIGAJOULE   2656

                           ANNUAL COST (AT $0.07/KWHRS)    $ 51646



2                 GAS - (UNITS -    10  CUBIC M)
                  ----              ---
            JANFEB  MARAPR  MAYJUN  JULAUG  SEPOCT  NOVDEC * TOTAL
HEATING        390     731    1756    2159    1898    1567 *  8501
                                                             -----
                              TOTAL ANNUAL  GAS CONSUMPTION   8501

                             ENERGY EQUIVALENT IN GIGAJOULE   3278

                           ANNUAL COST (AT $0.12/CUBIC M)  $ 10201
```

```
                                                              PAGE  2

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1


ENERGY CONSUMPTION PROFILES
*--------------------------*






           *
           *
           *C
 JANFEB    *TOTAL*
           *HE
           *
           *
           *C
 MARAPR    *TOTAL*T
           *HEA
           *
           *
           *
 MAYJUN    *TOTAL*TOTAL
           *HEATING
           *
           *
           *
 JULAUG    *TOTAL*TOTAL*
           *HEATING*
           *
           *
           *
 SEPOCT    *TOTAL*TOTAL*
           *HEATING
           *
           *
           *C
 NOVDEC    *TOTAL*TOTAL
           *HEATIN
           *
           *
           *
           *----+----+----+----+----+----+----+----+----+----+--
                5   10   15   20   25   30   35   40   45   50

               ENERGY CONSUMPTION (UNITS -  100 GIGAJOULES)
```

```
                                                          PAGE  3

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1


ENERGY CONSUMPTION PROFILES
*-------------------------*

           *
        38 *
           *
        36 *
           *
        34 *
 DAILY     *
        32 *
AVERAGE    *
        30 *
OUTSIDE    *
        28 *
AIR        *
        26 *
TEMP.      *A
        24 *
(DEG C)    *A
        22 *
           *AI
        20 *
           *AIR-
        18 *
           *AIR-C
        16 *
           *AIR-COND
        14 *
           *AIR-CON
        12 *
           *AIR-COND-E
        10 *
           *AIR-
         8 *
           *AI
         6 *
           *
         4 *
           *
         2 *
           *
         0 *
           *----+----+----+----+----+----+----+----+----+----+--
                5   10   15   20   25   30   35   40   45   50

           AIR CONDITIONING ENERGY CONSUMED IN EACH 2 DEG. BAND
           FANS & PUMPS INCLUDED (UNITS -  100 GIGAJOULES)
```

```
                                                         PAGE  4

          BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
          ------
BUILDING - 44 MARKET ST - RUN 1

BUILDING REPORT 1
*---------------*

TEMPERATURE DEVIATIONS - OCCUPIED HOURS
*--------------------*

      *  MIN       HOURS BELOW       *   MAX        HOURS ABOVE
 ZONE * TEMP.      DESIGN TEMP.      *  TEMP.       DESIGN TEMP.
      *REACHED CONSECUTIVE / TOTAL   * REACHED CONSECUTIVE / TOTAL
      *                              *
      *                              *
  1   *  23 C        0          0    *  23 C        0          0
      *                              *
  2   *  19 C        8        342    *  25 C        8        130
      *                              *
  3   *  18 C        8        631    *  25 C        8        203
      *                              *
  4   *  22 C        2         47    *  23 C        2         31
```

```
                                                         PAGE  5

          BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
          ------
BUILDING - 44 MARKET ST - RUN 1

BUILDING REPORT 2
----------------

CONTRIBUTIONS TO TOTAL ANNUAL COOLING LOAD
----------------------------------------

        *  FABRIC   LIGHTS PEOPLE VENTIL INFIL EQUIP *   % OF
 ZONE   * INCLUDING                 AIR    AIR       *  BUILDING
        *  SOLAR(1)                 (2)    (3)       *   TOTAL
        *                                            *
   1    *      0      17     17      4      0      1 *    39
        *                                            *
   2    *      1       6      4      0      0      0 *    12
        *                                            *
   3    *      0       6      4      0      0      0 *    11
        *                                            *
   4    *      4      18     12      2      0      2 *    39
        *                                            *
------------------------------------------------------------------
 % OF   *                                            *
BUILDING *     6      48     37      6      0      3 *   100
 TOTAL  *                                            *

NOTES: (1)HEAT TRANSMITTED THROUGH WALLS, ROOF ETC.
       (2)VENTILATION AIR DRAWN FROM OUTSIDE
       (3)INFILTRATION AIR LEAKAGE THROUGH BUILDING ENVELOPE
```

```
                                                                 PAGE  6

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1


SYSTEM REPORT
-------------

          SUM OF  SUM OF  SUM OF  SUM OF  SUM OF    SUM OF  SUM OF
  SYSTEM   ZONE  COOLING   ZONE  HEATING REHEAT      DUCT    DUCT
         COOLING  COIL   HEATING  COIL    LOADS     GAINS  LOSSES
           LOADS  LOADS   LOADS   LOADS

                        ANNUAL VALUES (UNITS-GIGAJOULES)
                        --------------------------------
DUAL DUCT     631     695     291    1558       0       0       0


                            JANFEB (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT     192     300       1      80       0       0       0


                            MARAPR (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT     137     163      11     173       0       0       0


                            MAYJUN (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT      54      17      82     379       0       0       0


                            JULAUG (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT      38       2     141     430       0       0       0


                            SEPOCT (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT      79      52      41     305       0       0       0


                            NOVDEC (UNITS-GIGAJOULES)
                                   -----------------
DUAL DUCT     132     161      14     191       0       0       0
```

```
                                                          PAGE  7

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1

PLANT REPORT - ENERGY CONSUMPTION
------------

PLANTROOM 1 - MAIN                                  ANNUAL
                                              ENERGY CONSUMPTION
     ITEM              UNIT       SIZE          KWHRS     GJOULES

CENTRIF. CHILLER         1       440 KW         47755           172
CENTRIF. CHILLER         2       440 KW          4081            15
COOLING TOWER            4      1088 KW           617             2
PUMPS CHILLED WATER      -          -           19683            71
PUMPS CONDENSER WATER    -          -           14551            52
                     COOLING ENERGY TOTAL       86687           312

HI/LO/OFF BOILER         3       703 KW        910513          3278
PUMPS HOT WATER          -          -           12719            46
ELECTRIC REHEAT          -          -               0             0
                     HEATING ENERGY TOTAL      923232          3324


FAN(S) -SYSTEM 1     DUAL DUCT                 218217           786
                                FAN TOTAL      218217           786


GENERAL POWER                                   14541            52
LIGHTS                                         405616          1460
                           NON-HVAC TOTAL      420157          1513
```

```
                                                          PAGE  8

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1


PLANT REPORT - PART-LOAD HOURS
------------

PLANTROOM 1 - MAIN

                         HOURS AT PERCENT PART-LOAD RATIO
               *
     ITEM      *0   10   20   30   40   50   60   70  80   90  100
               *
CENTRIF.CHILLER* 406  297  158   69   51  117   72   23   85   45
               *
CENTRIF.CHILLER*   0    0    0    0    0   67   14    0    0    0
```

```
                                                         PAGE  9

           BUNYIP - BUILDING ENERGY INVESTIGATION PACKAGE
           ------
BUILDING - 44 MARKET ST - RUN 1

PLANT REPORT - PART-LOAD PROFILES
------------
       100 *            CENTRIF. CHILLER  ITEM 1   PLANTROOM 1
           *XX
        90 *
           *XXXX
        80 *
           *X
        70 *
PERCENT    *XXXX
        60 *
PARTLOAD   *XXXXXX
        50 *
 RATIO     *XXX
        40 *
           *XXX
        30 *
           *XXXXXXXX
        20 *
           *XXXXXXXXXXXXXXX
        10 *
           *XXXXXXXXXXXXXXXXXXXX
         0 *
           *----+----+----+----+----+----+----+----+----+----+--
               100  200  300  400  500  600  700  800  900  1000
                              HOURS PER YEAR

       100 *            CENTRIF. CHILLER  ITEM 2   PLANTROOM 1
           *
        90 *
           *
        80 *
           *
        70 *
PERCENT    *X
        60 *
PARTLOAD   *XXX
        50 *
 RATIO     *
        40 *
           *
        30 *
           *
        20 *
           *
        10 *
           *
         0 *
           *----+----+----+----+----+----+----+----+----+----+--
               100  200  300  400  500  600  700  800  900  1000
                              HOURS PER YEAR
```

Energy-Conservative Design in Context
The Use of Multi-Criteria Decision Methods

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INTRODUCTION

We want in this paper to look at the implications of designing for energy conservation and thermal performance on other important aspects of building performance such as cost, daylighting, planning efficiency and site utilization. We shall do this in a rather different and more formal way than that which the everyday experience of practitioners, and most of the published literature on the subject, might suggest. We shall use what are known as 'multi-criteria decision methods': multi-criteria because in architecture almost all real design problems require the simultaneous satisfaction of multiple criteria or objectives, and decision methods because the activity of architectural design can be modelled as a process of decision making in which choices must be made about the form and construction of buildings and building components in order to satisfy these multiple criteria. Because we are reporting from current research the concepts we shall employ will be new to most practitioners, but we shall illustrate them with fairly simple examples which will, we trust, make them clear.

Until the mid 1970's, in fact, energy use was not a criterion which was considered of great importance in building design. Abundant low-cost sources of energy led to buildings which were totally dependant on mechanical systems for heating, cooling and ventilation. In consequence, the energy requirements of buildings grew steadily year by year until they accounted for 23.5% of the energy used in Australia (1) and for over 40% in the United States (2). The so-called 'energy crisis' led to a much greater concern by building owners about the energy performance of building proposals and to the introduction by governments of regulatory codes requiring minimum standards of thermal design. At the same time, the availability of computers made possible new methods of modelling heat flow and energy demand and the development of computer programs which could provide more accurate predictions of the operational energy demand of a building proposal than was previously possible. However, this new importance of energy conservation as a criterion in building design is additional to and not replacing any previous design criteria. Architects cannot design a building for energy efficiency alone; indeed, the most energy efficient solution is no building.

Although buildings consume energy for many purposes (maintaining thermal comfort, ventilation, lighting, transportation and the operation of equipment related to their occupancy and function) we shall concern ourselves here with the first and most important of these uses, maintaining thermal comfort by heating or cooling. The thermal performance of a building is dependant on the micro-meteorological conditions outside the building, the thermal behaviour of the building fabric, and the comfort conditions required inside. The prime factor is the thermal behaviour of the building itself. The design choices which determine this thermal behaviour (for example, shape, massing, shading, enclosing materials and surface finishes) also influence performance in other criteria. Thus, in aiming to improve thermal performance a designer must consider the implications for other quantitative criteria such as cost and usable area, quite apart from his proper concern with qualitative aesthetic and social criteria.

MULTI-CRITERIA DECISION METHODS

Multi-criteria methods have been developed to handle these kinds of problems. They have become an established field of operations research and systems analysis, and the subject of six major international conferences since 1972 (2, 4, 5, 6). In his review of the subject Cohon (7) lists practical applications which include water resources engineering and planning, energy systems analysis and design (meaning power generation, rather than the utilization of energy by buildings), transportation planning, structural analysis, construction management, and a wide range of business and public policy problems. In architecture, work in the 1960's and 70's by Markus, Maver and others at Strathclyde University (8, 9) addressed the multi-criteria nature of architectural design problems and proposed approaches using cost-benefit analysis to reduce diverse multiple criteria to a single criterion of minimum cost or maximum return. From the mid 1970's the Computer Applications Research Unit in the Department of Architectural Science at Sydney University has been pursuing the use of multi-criteria decision methods to provide useful information for building designers without reducing all the criteria to a cost interpretation (10, 11, 12, 13).

We shall begin by introducing the concepts of design spaces, constraints, and performance spaces, using an example which, though simple, depicts a problem which has been faced in the design of many multistorey buildings. We consider an office block with continuous perimeter windows and a continuous horizontal sun shade above those windows; in Sydney there are many buildings with just these characteristics, (Fig. 1). For the purpose of this example we shall assume that everything about the building is fixed apart from the height of these windows and the projection of the sun shade. This gives us just two design variables which we can manipulate: we can combine different values of window height with different values of shade projection to give us tall, medium or short windows with long, medium or stubby shades. In a representation of the design space we use two axes to show the values of these two design variables. If we were to allow any values for them (from zero to infinity) we should need infinitely long axes, but in

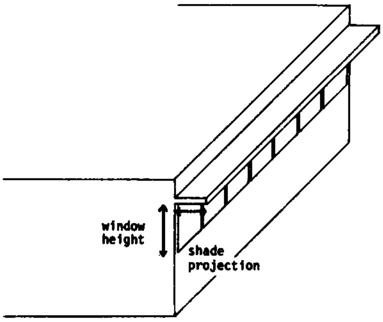

Fig. 1. Design variables of shade projection and window height for one floor of a multistorey office building

practice there are constraints operating which limit the feasible values. The windows cannot extend higher than the ceiling and the sun shades will be subject to a constructional constraint restricting projection to a maximum of two metres or so. These constraints together define a feasible region within which any design must lie.

Windows exist for a variety of reasons, but principally to provide light, sun penetration and a view of the world outside. These benefits are accompanied by negative effects such as the admission of noise, glare, and unwanted heat gain and loss. We shall consider only the two most important quantitative consequences of windows in buildings: natural lighting and thermal performance. A designer will generally wish to maximize natural lighting while minimizing any heating or cooling load. In a performance space we use axes to show values of these two performance variables or criteria, starting (conventionally) with 'bad' at the origin (whatever the numerical values) and increasing 'good' away from the origin. With two criteria we have a two-dimensional performance space. Each feasible design solution will have a performance result in terms of these two criteria, hence each point in the design space will have associated with it a point in the performance space (Fig. 2). The corpus of possible solutions in the feasible region of the design space will together, through their performances, delineate a feasible region in the performance space.

The goal of design is to achieve the best balance of performances in the set of applicable criteria. To achieve this goal the designer needs information on the relationships between the different design variables and the different performances. Almost all existing computer programs available to practitioners explore one directed aspect of this relationship: given a design description, in greater or lesser detail, they will predict by simulation the performance consequences. We can call this the design →performance relationship. Koenigsberger (14) has described the use of such models as 'investigating backwards', since to get any information for design the designer

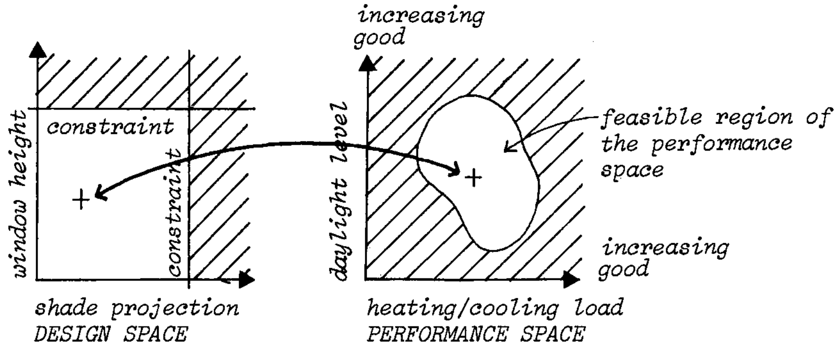

Fig. 2 Design space, constraints and performance space for the two design variable, two criteria office window problem

must first formulate a solution to his problem. To get a starting point for design, architects also need to know something about performance → design relationships. Ideally, they should be able to learn something about performance → performance and design → design relationships as well.

DESIGN → PERFORMANCE RELATIONSHIPS

If we select a point in the design space we can find, through physical experiment or computer simulation methods, the corresponding point in the performance space. For thermal performance there is now a considerable number of computer simulation programs available, some requiring detailed descriptions of the building proposal but others operating with simpler models which are aimed at providing indicative measures before the design has been fully worked out. For daylighting there is a much smaller choice of programs, probably because the manual calculations required are much less onerous than for thermal analysis and nomograms, protractors and other design aids make the incentive for turning to computers rather less urgent. If we examine the form of information produced by these simulation models we find that the results are typically presented in multi-valued form, either in tables or diagrams. It is also presented as neutral information, with no direct indication of the 'goodness' or 'badness' of the results or any information on how these performances compare with what it might be possible to achieve in the given design situation.

Multi-criteria decision methods require these multi-valued presentations of performance to be expressed in single-valued form (Fig. 3). In our example we might summarize the information contained within the space - and time-varying prediction of natural lighting levels as a proportion of the working plane area which has a daylight factor above some desired level, and the time-varying heat transfer through the window as either an annual aggregate or seasonal maximum heating or cooling load. This summarizing process is sometimes, but not always, carried out by designers using simulation to investigate

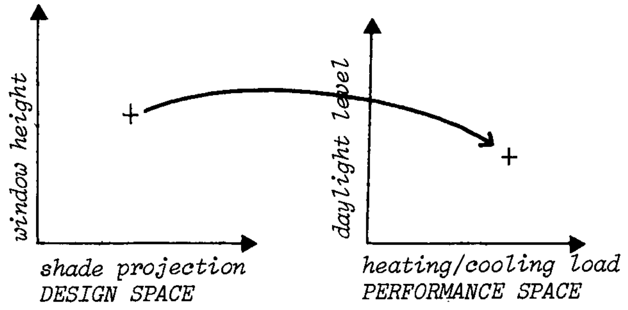

Fig. 3 Design → performance relationships: prediction of performance results given a solution description

design → performance relationships. More often they use their judgement in the direct comparison of multi-valued performance measures for different solutions without explicitly defining bases for the comparison.

Design → performance analysis, then, can provide performance information in great detail, but only for one design solution. We could go on, for example, to investigate the performance of our window in terms of cost, sound transmission, sun penetration or other performance measures. We can compare the performances of two or more solutions. What a design → performance analysis fails to do is to give us any information on the relative position of this particular set of performances. To get that information we need to formulate a hypothesis on how to improve the solution and then go through the process again, so that used in isolation design → performance simulation methods imply a cyclical process of design. We stop when we do not think any further improvement is possible, or we run out of time or patience.

PERFORMANCE → DESIGN RELATIONSHIPS

How, using Koenigsberger's terminology, can we investigate forwards instead of backwards? What we need to do is to investigate performance → design relationships. Given a desired point in our performance space, we need to be able to find directly the corresponding point in the solution space (Fig. 4).

There are a few such performance → design methods available to architects. The Mahoney tables (15) prescribe design parameters for tropical housing to provide comfortable living conditions in a given climate. Shaviv (16) presents a method for the design of fixed external sunshades which prescribes design parameters for a sunshade to completely shade a window opening over a specified part of the year.

Performance → design relationships are also directly investigated by optimization techniques. In optimization, we define only the feasible region of the design space (by specifying the applicable constraints) rather than defining a

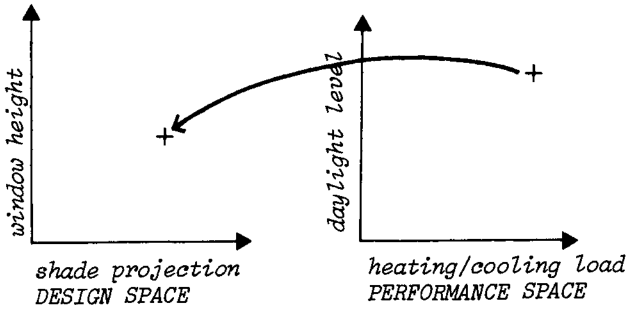

Fig. 4 Performance → design relationships: prescription of a design solution given performance specifications

single solution. In the performance space we specify a performance objective ('best possible', usually in terms of the maximum or minimum value of some quantitative measure) rather than defining a specific point. The optimization process then tells us the point or points in the design space which give us this best possible performance. Most historic examples of optimization methods in architecture concern single-criterion optimization often for minimum cost or energy design. It is rarely possible to optimize two or more criteria simultaneously. The nearest equivalent to an optimal solution in single-criterion optimization is a Pareto optimal solution in multi-criteria optimization. Pareto optimal solutions, sometimes known as non-inferior or non-dominated solutions, have an important place in multi-criteria decision methods.

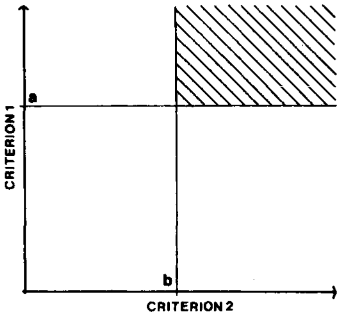

Fig. 5 Pareto optimal performances for two criteria. The performance combination (a,b) is Pareto optimal if no performance combination (c,d) exists such that c > a and d > b, except c = a and d = b; i.e., if no performance combination maps on to the hatched sector of the diagram.

For two or more criteria the Pareto set is a subset of the feasible solution set such that for each Pareto optimal solution no other solution exists which is better in at least one criterion and no worse in the others (Fig. 5). By tracing the Pareto set we can outline the boundary of the feasible performance space and identify the corresponding solution forms. These Pareto solutions are, by definition, better (at least in terms of the nominated criteria) than any non-Pareto solutions.

So far we have taken as example the window and sun shade design for a single floor of a multistorey building. To demonstrate Pareto optimality we shall turn to energy-conservative design at a different scale and look at orientation, massing, aspect ratio, glazing fraction and glazing type for a whole building (13). It concerns the design of a parallelopiped building of given floor area where the criterion of minimum thermal load ratio (the ratio of the total heating and/or cooling loads predicted for a building to that of an idealized form in a standardized Sydney climate) is placed in the context of two other criteria of capital cost (calculated by the storey enclosure method) and net usable area (the floor area within the extended walls less the area taken up by lifts and staircases, circulation and toilet facilities).

The base data for the case study building is:

Location		Hobart, Australia
Building Floor Area		$4000m^2$
Minimum area per floor		$800m^2$
Storey height		2.7m
Thermostat settings:	Heating	20^{o}
	Cooling	25^{o}

The design variables with their range of values are:

Aspect ratio	1, 2 or 3
Orientation	North, or 30^{o} or 60^{o} East of North
Massing (number of storeys)	1, 2, 3, 4 or 5
Glazing fractions on each facade	0.4, 0.5 or 0.6
Glazing type (single pane)	clear, heat reflecting or heat absorbing
Shading	None

making 405 possible design solutions. To delineate the feasible performance space we have plotted the performance combination for all these feasible solutions in the performance space. Rather than depict this three-dimensional space directly, we have plotted its projection on its constituent two-dimensional faces, (Fig. 6). In the graph of usable area against capital cost (Fig. 6(c)) the 405 solutions are mapped on to just 15 performance combinations, a result of the prediction models used

Fig. 6 The complete set of feasible thermal load ratio, capital cost and usable area performances for the case study building.

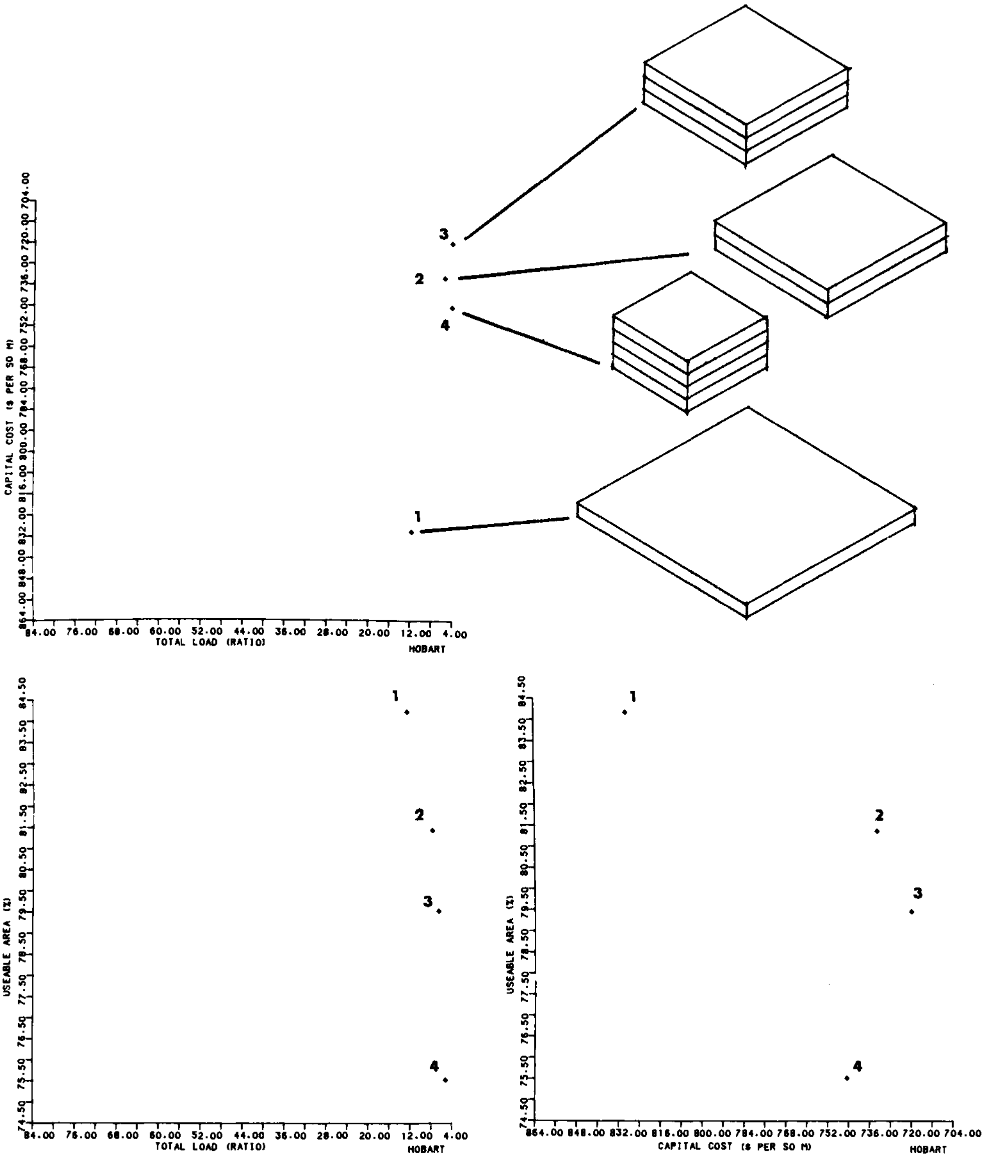

Fig. 7 The Pareto set of performances for the case study building.

which do not relate capital cost to either glazing fraction or type.

Pareto optimizaton reduces the 405 feasible solutions to only 4 Pareto solutions (Fig. 7) and these span only a very small part of the total load ratio axis. Table 1 details the values of the design variables and criteria for these Pareto optimal solutions.

The performance → design relationships for this problem are immediately apparent from this table. To get the best thermal performance we orientate the building due north and use glass type 2 (heat reflecting glass) with a window fraction of 0.4 and aspect ratio of 1. Which number of storeys we choose depends on the relative importance we attribute to capital cost and usable area, but if we stay within the guidelines of Table 1 we can see by comparing Fig. 6 and Fig. 7 that the Pareto solutions all give relatively good thermal performance compared with the range of performances covered by the whole feasible set. To select one of them we need to consider performance → performance relationships, and that is the subject of the next section.

TABLE 1 Pareto Optimal Solutions for the Three Criteria Building Form Problem

	Design Variables							
Solution Number	Orien-tation	Window Fraction	Glass Type	Aspect Ratio	No. of Storeys	Capital Cost	Usable Area $/sq.m	Thermal Load Ratio
1	North	0.4	2	1	1	830.3	84.15	12.02
2	North	0.4	2	1	2	733.6	31.38	6.64
3	North	0.4	2	1	3	720.4	79.48	5.41
4	North	0.4	2	1	4	744.8	75.52	5.16

PERFORMANCE → PERFORMANCE RELATIONSHIPS

By performance → performance relationships we mean the implications of choosing a certain level of performance in one criterion on the performances that are then attainable in other criteria. In terms of Fig. 8, depicting our original window and sun shade problem, the designer has to decide if he is prepared to accept a worsening of heating/cooling load in exchange for a better daylighting level which is implicit in choosing solution A in preference to solution B. We assume here that A and B are both amongst the Pareto optimal set and therefore lie on the boundary of the performance space: otherwise there will be better solutions than either of them available to the designer. The decision is essentially one of tradeoffs and, assuming all solutions are equally acceptable in other ways, does not directly concern the design space at all.

For our second, whole building problem, performance → performance relationships are apparent from Fig. 7. From Fig. 7(b) solution 4 has a better thermal load ratio than the other Pareto solutions but has the worst usable area ratio. From Fig. 7(c), improving usable area ratio also means increasing cost. From Fig. 7(a), on the other hand, solution 2 is good in both thermal load ratio and capital cost. The designer has to decide, but solutions 2 or 3 appear to be reasonable compromises.

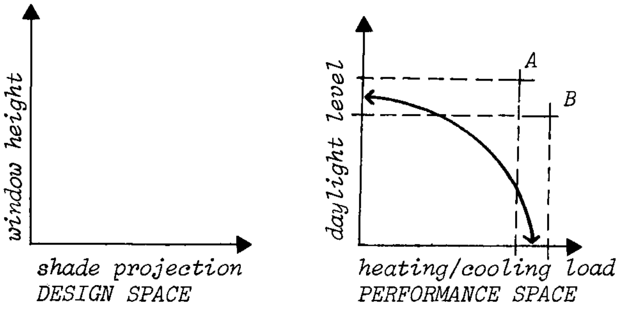

Fig. 8 Performance → performance relationships: tradeoff decision between two criteria

DESIGN → DESIGN RELATIONSHIPS

By design → design relationships we mean the implications of choosing or restricting values for one design variable on the values that need to be given to other design variables if acceptable performance is to be maintained (Fig. 9). Thus long sun shades might be necessary because tall windows are chosen: one design decision has a relationship with another, resulting, design decision through a desire to keep all or some aspects of performance within acceptable ranges.

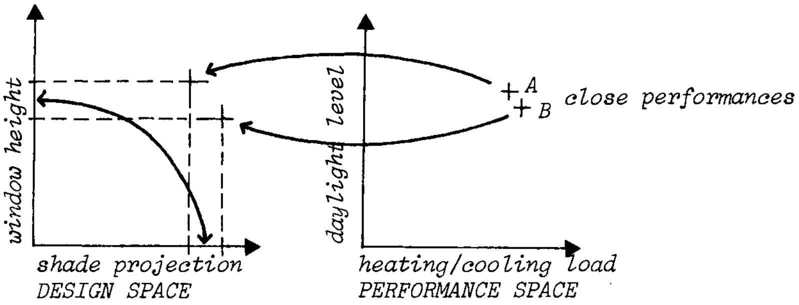

Fig. 9 Design → design relationships: mapping close performances back onto the design space

To demonstrate design → design relationships we shall expand the design space of our window design problem to allow three different kinds of glass (clear, heat absorbing and double pane) and to allow the windows to be discontinuous (10). For thermal performance we shall use the peak summer temperature (calculated by the admittance procedure method) reached in a non-air conditioned room behind the window strip as our criteria, rather than heating or cooling loads directly. For daylighting performance we shall simply measure the daylight factor (calculated by a numerical integration method) at the back of this room.

The case study is a 4 metres wide, 5 metres deep and 2.7 metres high room, oriented north west in an office building in Sydney, Australia. The Pareto set of performances is shown in Fig. 10(a), with the associated design solutions shown as diagrams of the external wall. The best daylighting is given by a large clear-glass window with no sun shade. Between these extremes, heat-absorbing glass with sun shades are Pareto optimal at the lower end of the daylight performance scale and clear glass with sun shades at the higher end. We shall assume that after assessing the tradeoffs involved the designer selects Solution 17, a large heat-absorbing glass window with long projecting sun shade. This offers a reasonable compromise between good daylighting and good thermal performance; internal temperatures of just over 29°C are hardly comfortable but might be acceptable as an extreme over the summer.

What happens if the design decision is made to avoid the use of sun shades? Fig. 10(b) shows the new Pareto set under these conditions, with only the extreme solutions 1 and 7 remaining from the original set. We shall assume the designer is not prepared to worsen his summer overheating problem. The design → design implications of the decision to avoid sun shades is that the glass type should remain as heat absorbing but the window width should be reduced to something similar to Solution 10. This will keep the thermal performance constant, but reduce the daylight factor at the rear of the room.

We now assume that the building is still so far over budget that even the heat absorbing glass has to be omitted from the design. Fig. 10(c) shows the new Pareto set with only clear glass allowed. If we again keep the thermal performance constant, the design → design implication of the decision to avoid heat-absorbing glass is that the window width must again be reduced to something like Solution 5. The daylight factor at the rear of the room is now about a third of its original value.

Information on design → design relationships is very difficult to obtain by traditional simulation methods and very little research work has directly addressed the problem. It is, however, very important information for designers and we intend to explore the area further.

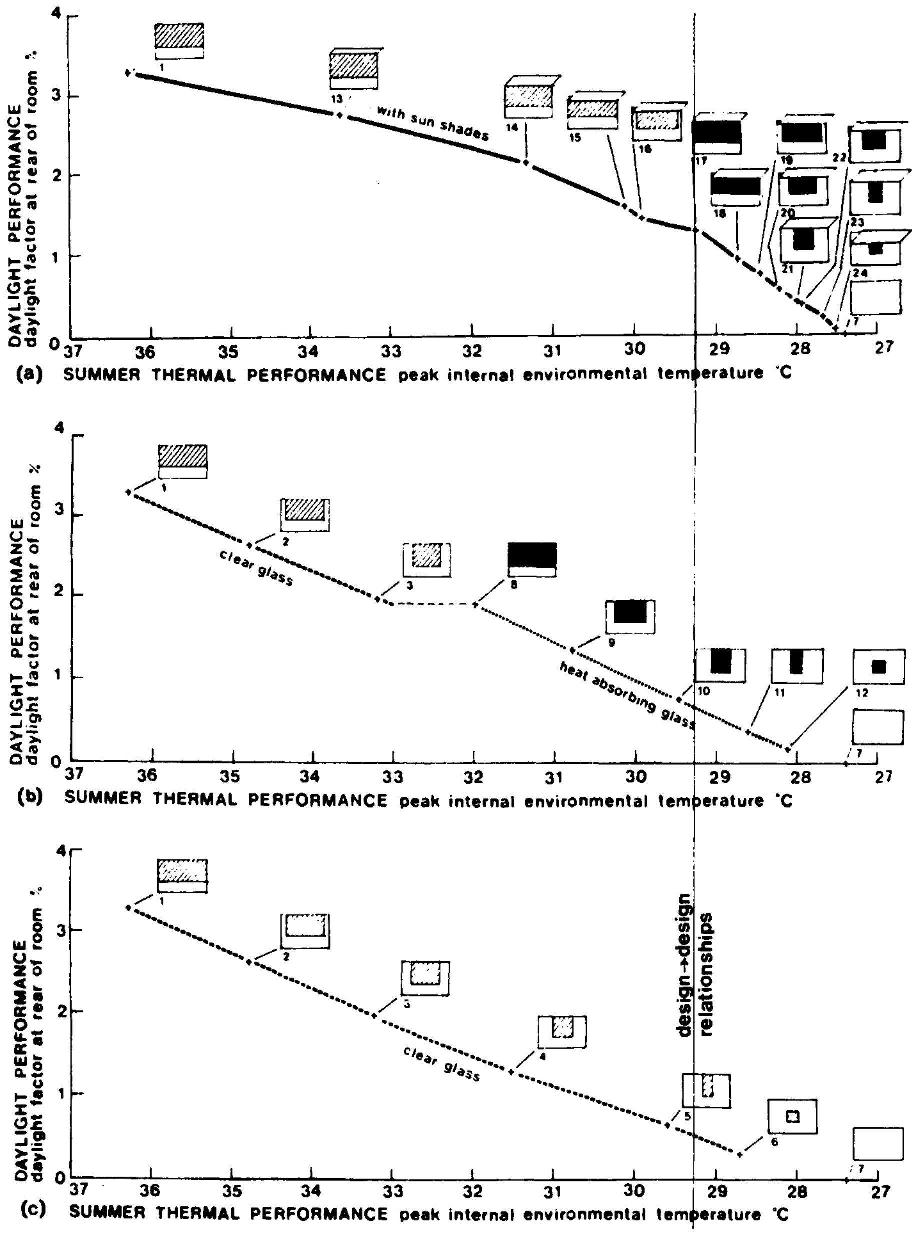

Fig. 10 Pareto optimal sets for the window problem allowing (a) sun shades and three glass types, (b) no sun shades, and (c) clear glass only.

DISCUSSION

In this paper we have introduced notions of design and performance spaces and explored the use of multi-criteria decision methods as a means of exploring the directed relationships between design decisions and solution performances. In doing so we have described Pareto optimization and the presentation of tradeoff options. We have shown that it is possible to treat the objective of energy conservative design within the context of overall building design and to generate a set of relationships not normally available to designers. These relationships can provide both qualitative and quantitative information about the tradeoffs between disparate performances. It is a powerful approach to design problem solving, but we should end with a note of caution. As Cohon (70) points out, Pareto optimization methods, indeed multi-criteria decision methods in general, do not necessarily make design any easier: just better informed.

ACKNOWLEDGEMENTS

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New Tools for Analyzing the Thermal and Daylighting Performance of Fenestration in Multistory Buildings

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ABSTRACT

Accurately predicting the energy-related impact of fenestration is essential to the design of energy-efficient buildings. For complex nonresidential buildings, a complete understanding of fenestration performance requires not only thermal modeling but daylighting prediction as well. Multistory buildings tend to have higher skin-to-floor ratios than shorter, more compact structures of equal floor area and, thus, their performance is influenced to a greater extent by design decisions that affect the thermal and solar optical properties of the building skin. Despite the computational power of modeling programs, there are tradeoffs and limitations among accuracy, the cost of running the model, and the flexibility to model the large range of architectural solutions for high-rise buildings.

We recently completed the first phases of a project to add a daylight-modeling capability and related thermal algorithms to the DOE 2.1B energy analysis program. In order to provide accuracy and computational efficiency along with the ability to model geometrically complex buildings, we developed a family of supporting computational tools and experimental techniques. The next version of the DOE 2 program will have a daylighting model driven by a library of stored coefficients of utilization, which are either developed from scale model measurements in our sky simulator or calculated by a new daylighting illumination program, SUPERLITE. In addition, coefficients for unique designs can be determined from model measurements and

entered into the program. SUPERLITE provides detailed data on illuminance distribution in an interior space, but is too complex for use directly within the hour-by-hour model. Because the solar gains through sophisticated daylighting apertures are not adequately calculated in current models, our procedure will also use a library of coefficients stored in DOE 2. These coefficients will be determined from sun and sky simulator measurements of the solar optical properties of devices.

We describe our major experimental procedures and analytical models and present validation studies of DOE 2.1B and SUPERLITE. We illustrate the applicability of these tools by showing results from a study of optimal fenestration performance as a function of climate and orientation.

INTRODUCTION

Lighting is a major end use of energy in most multistory nonresidential buildings. Design strategies that reduce electric lighting requirements should thereby reduce annual electrical consumption and peak electrical loads, and may also lower HVAC loads. Improved lighting design strategies, specification of new, efficient lighting hardware, and improved operation and maintenance of lighting systems all promise substantial energy savings. The impacts of these strategies can be estimated accurately using conventional energy analysis techniques. The use of natural lighting in buildings represents a more complex analytical problem because 1) daylight is a highly variable light source, 2) daylight is accompanied by solar gain that may increase cooling loads, and 3) there are many uncertainties in integrating lighting sensors and controls to utilize daylight properly. Single-story or low-rise buildings that incorporate simple skylights or other rooflight designs provide relatively uniform daylight over the majority of the floor area. However, most multistory daylighting solutions use sidelighting, which produces a non-uniform daylight contribution from the windowwall to the core, as well as a potential glare source directly in the field of view. Measured performance data from buildings could provide firm estimates of the real energy and load savings, but the existing performance data base is very small.

If experience with existing buildings cannot provide sufficient guidance to successful solutions, the designer must use analytical tools. Despite the proliferation of design tools for building energy analysis, none currently in extensive use has demonstrated the capability for analyzing the energy-related impacts of daylighting strategies in multistory nonresidential buildings. This paper describes two new computer models—one for illuminance analysis and one for energy analysis—that show promise as powerful and flexible aids in understanding the role of daylighting in energy-efficient buildings.

The first of these tools, SUPERLITE, is a large computer model that predicts the spatial distribution of daylight illuminance in a building zone based on exterior sun and sky conditions, site obstructions, details of fenestration and shading devices, and interior room properties. We then utilize a second computer program, DOE 2, to estimate annual energy use and peak load impact. The DOE 2 model determines the energy impact of daylighting strategies based on hour-by-hour analysis of daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. The thermal interaction of daylight strategies is automatically accounted for within the DOE 2 program. Together these programs form the basis for improving our understanding of fenestration performance.

Figure 1 shows sample results from an extensive parametric analysis of fenestration performance in office buildings. The study was completed for a single floor that could be taken as typical of all floors in a multistory building, with the possible exception of the ground floor and the top floor. The study was the first in a series to examine variations in total energy consumption and component loads as a function of major glazing parameters (U-value, shading coefficient, window area, orientation, climate, lighting load, daylighting strategy, etc.)[1] Figure 2 shows the variation in peak electrical load and chiller size in response to fenestration parameters.[2] Peak electrical load and chiller size are plotted versus the "effective" aperture (the product of window area as a percentage of wall and the visible transmittance) for four cases: with and without daylight utilization; with and without window management to produce thermal comfort. The results shown are for a single intermediate floor of a prototypical multistory office building in Madison, Wisconsin. While the reductions in peak electrical load due to daylighting are substantial, the figure also illustrates the importance of understanding and controlling the contribution solar gain makes to cooling loads.

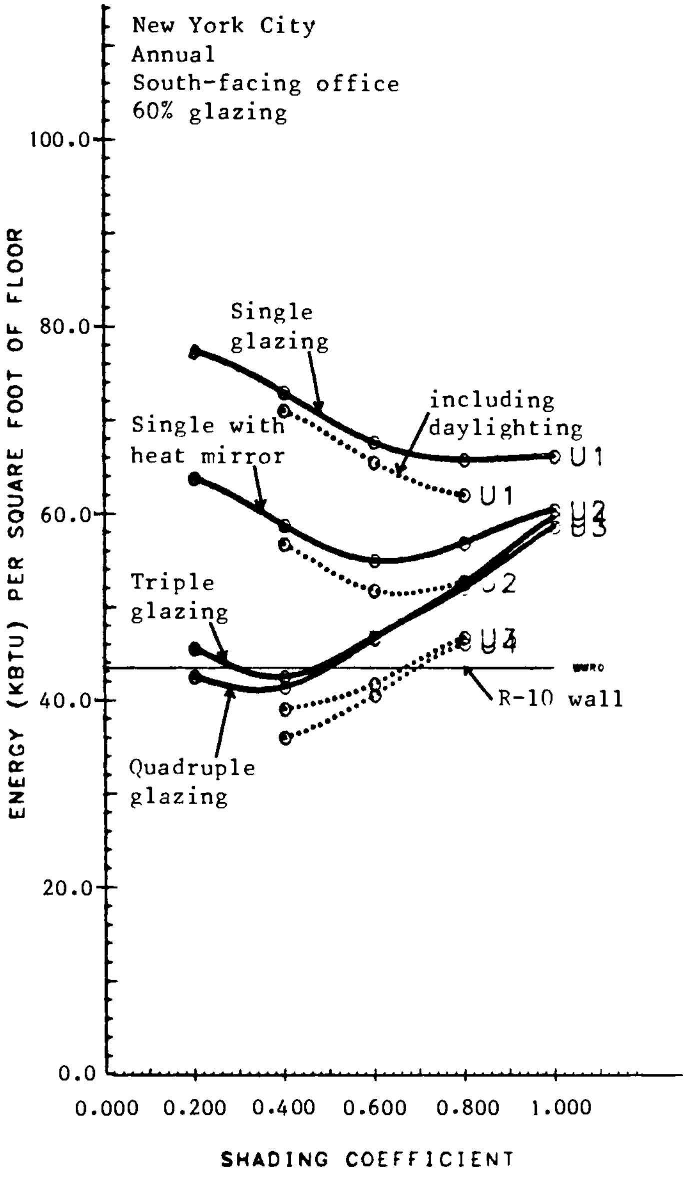


Fig. 1 Energy requirements for a south-oriented office module in New York City.

U1 = Normal single glazing, nominal 6.28 W/m^2°C.

U2 = Single glazing with low-emissivity coating, nominal 4.33 W/m^2°C.

U3 = Normal triple glazing, nominal 1.8 W/m^2°C.

U4 = Nominal 1.2 W/m^2°C.

Solid line = Energy use with no utilization of daylighting.

Broken line = Energy use with daylighting utilization.

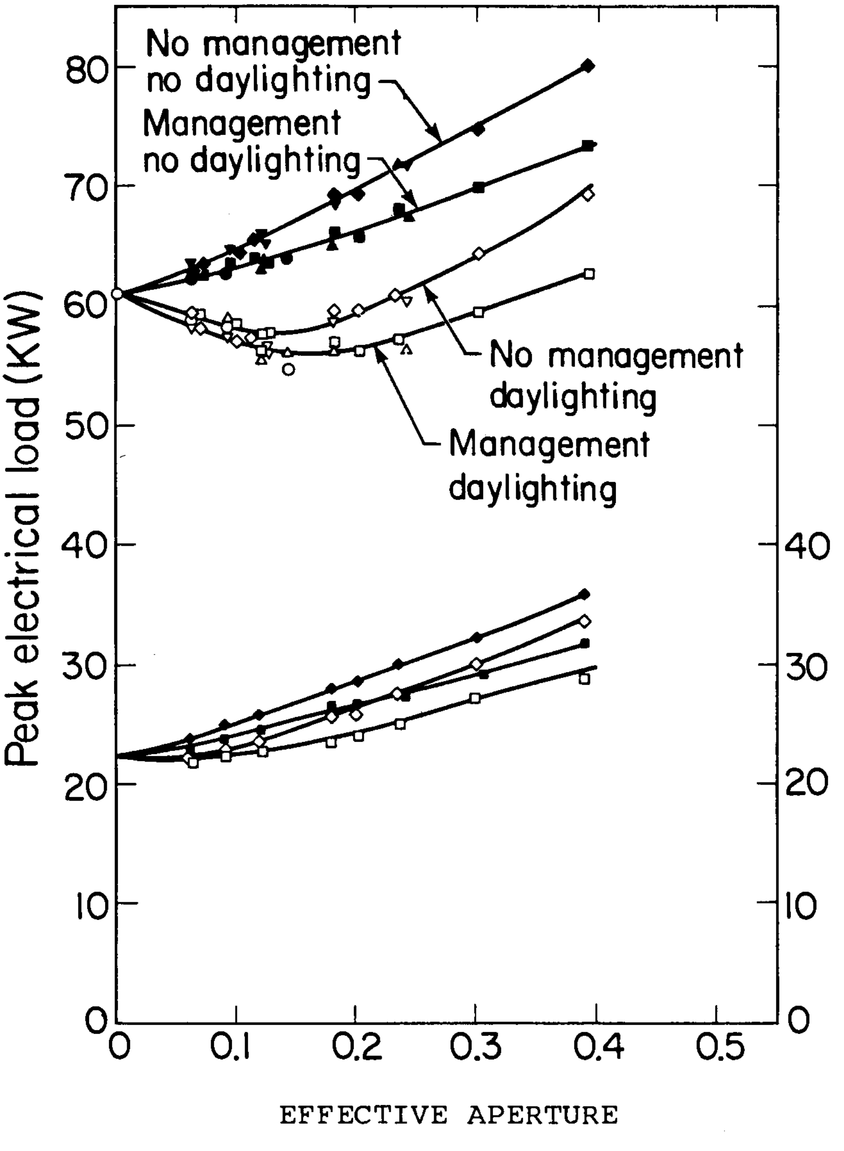


Fig. 2. Peak load and chiller size as a function of effective aperture for Madison, Wisconsin. Lighting power density is 1.7 W/ft^2.

REQUIREMENTS FOR FENESTRATION ANALYSIS

Even powerful computer models such as DOE 2 and SUPERLITE possess only some of the capabilities required to model fenestration systems accurately and efficiently. The tendency to expand computer models indefinitely by continuous accretion of new subroutines frequently creates models that are cumbersome and costly to debug, maintain, and use. The tradeoffs between increasing computational accuracy and complexity/cost are not easily resolved. Since there are a great number of possible fenestration designs and since many are geometrically complex, a purely computational approach to daylighting and thermal analysis was abandoned in favor of a primary computational package that utilizes precalculated and/or measured data. This reduces program complexity and cost without sacrificing modeling accuracy, and makes possible the analysis of some designs that would be mathematically intractable. The complete analysis package is shown schematically in Fig. 3.

DOE 2 is the primary computational tool used in parametric studies of glazing system energy performance. Major new capabilities are being added to the program to allow analysis of thermal and daylighting performance of complex fenestration systems.

The revised daylighting model planned for the next version of DOE 2.1 is based on a coefficient-of-utilization calculation. These coefficients are 1) calculated in a preprocessor for simple designs, 2) drawn from a library for more complex but standardized designs, or 3) input by the user for unique designs. The data for the DOE-2 library derive from 1) SUPERLITE calculations of illuminance distributions for simple and moderately complex designs or 2) measurements from scale models in a sun and sky simulator for mathematically intractable designs. When the number of optically active surfaces is not large and the surfaces are diffuse reflectors, SUPERLITE calculates interior illuminance directly from design parameters. When a daylighting element is geometrically complex (e.g., honeycomb) or has optically complex reflective or refractive surfaces, the program utilizes measured angular-dependent luminance data to describe the contribution of the device to room illuminance distribution.

Each step leading to the energy analysis in DOE 2 (Fig. 3) utilizes a combination of direct computations and measurement-based calculations that are program-generated, predetermined, and stored in program libraries or input by the user. This approach provides broad modeling flexibility and facilitates expansion of the program without incurring enormous cost. Daylighting illuminance normally is analyzed for specific well-defined room and fenestration designs that are frequently

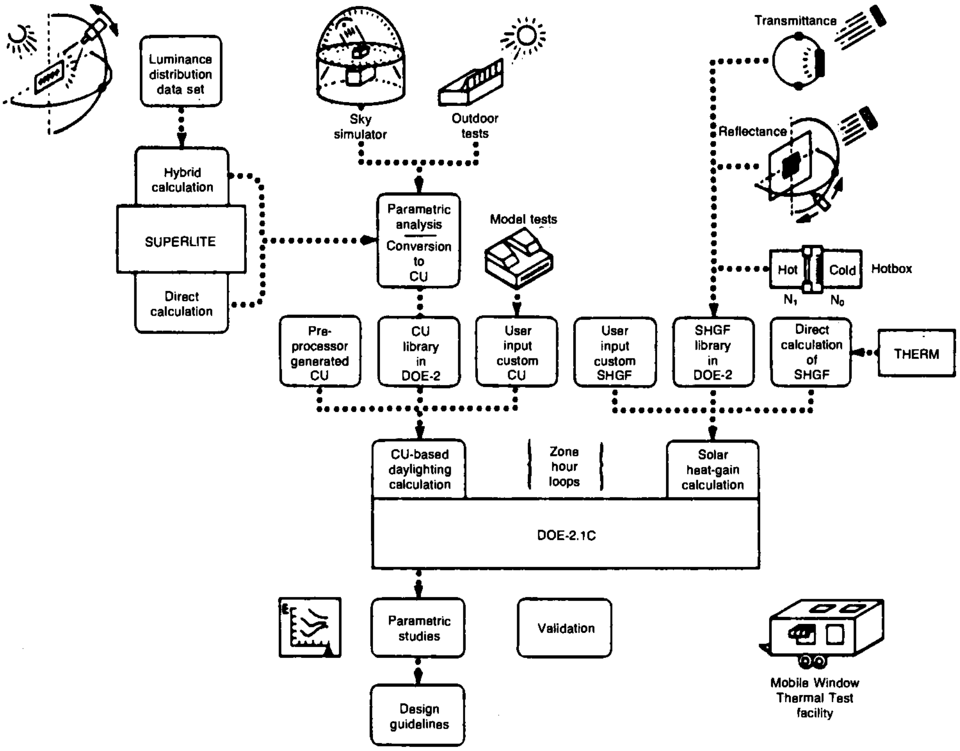


Fig. 3. Schematic diagram of DOE 2.1C planned fenestration modelling capabilities. Input is based on direct computation or calculations based on laboratory or field measurements, and is stored in DOE 2 or input by the user. Input is validated by model testing and in-situ testing by MoWiTT.

repeated throughout a multistoried building. It is also possible to model a multistory building having a different fenestration system and interior design on each floor, although the analysis cost will increase correspondingly.

The new thermal models for analyzing complex fenestration systems in DOE 2 follow much the same philosophy. The necessity to accurately model complex systems requires a combination of new analytical models and new experimental procedures. The computational logic for modeling the control of operable insulating and shading systems has been added to the program. Work is in progress to improve the solar heat-gain calculations to enable analysis of geometrically complex architectural sun control and shading devices. The solar heat-gain calculation is based on measurement of optical and thermal properties of devices, as illustrated in Fig. 3. A sample device having small characteristic dimensions, such as a louvered shade screen, would be measured directly. Larger devices or architectural solutions would be reproduced and tested as scale models. The analytical solutions for multilayered homogeneous glazing materials are calculated directly in THERM and converted to the matrix formulation for DOE 2.

The Mobile Window Thermal Test (MoWiTT) facility will be used to validate net energy performance predictions from DOE 2 (Fig. 11). This facility has been designed to directly measure the component heat flows from fenestration systems and the interactions between fenestration systems and building HVAC systems.

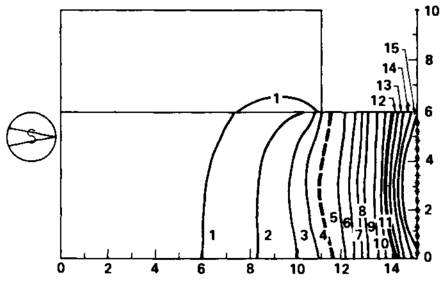
A primary objective in developing this analytical approach has been to expand capabilities in order to model a broad range of design solutions without further modifying the structure of DOE 2. Embedding experimental measurements within a hierarchy of computational models appears to accomplish this goal.

CAPABILITIES OF THE SUPERLITE PROGRAM

The mathematical basis of the SUPERLITE algorithms has been described previously.[3,4] This program can model a uniform sky, CIE standard overcast sky, and CIE standard clear sky with or without direct sun. Based on the luminance distribution of a given sky, the luminances of the ground, adjacent buildings, and other external obstructions are calculated. The angular dependence of transmittance through glazing materials is calculated, then the luminances of each interior surface are determined. Because the luminance across a surface may vary significantly, each surface can be divided into a number of subsurfaces having luminances that are calculated separately. Once the luminances of all interior and external surfaces have been calculated, the work-plane illuminance is determined by integrating the surface luminances over the appropriate solid angles.

Compared to other daylighting computational models, a major advantage of SUPERLITE is its capability of modeling nonrectangular surfaces and other complex geometries. The program will model arbitrary room shapes such as an L-shaped room (see Fig. 4), a room with internal partitions, or rooms with external obstructions. Windows can be of any generalized trapezoidal shape with an arbitrary tilt angle. Various types of diffusing curtains and draperies can be modeled. Overhangs or fins with opaque, translucent, and semi-transmitting materials can also be modeled, permitting analysis of simple light shelves or lightwells. Optical properties determined from model measurements offer the new capability of modeling complex sunshading systems such as egg-crate louvers. Additional modifications will allow the modeling of electric lighting systems in combination with daylighting strategies.

Luminance and illuminance values for each room and sky condition studied can be output in tabular format or on contour plots generated by an auxiliary graphics program. Contour plots produced by SUPERLITE for an L-shaped room and for a large room with a light shelf are shown in Figs 4 and 5 respectively.

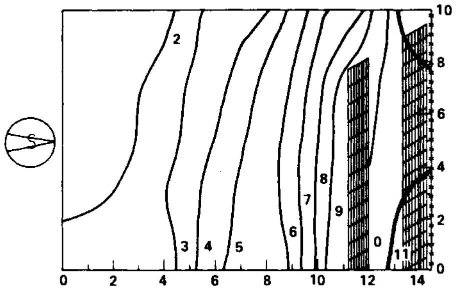


Sky is clear
Sun position: 40° off zenith
0° off S to E

Horizontal illumination
Direct sun: 0 fc
Sky: 2083 fc

Contour Number	Illum. Level (Ft-candles)
1	20.0
2	40.0
3	60.0
4	80.0
5	100.0
6	150.0
7	200.0
8	250.0
9	300.0
10	400.0
11	500.0
12	600.0
13	700.0
14	800.0
15	900.0
16	1000.0

Windows marked by *****
Sunny areas are hatched



Sky is clear
Sun position: 65° off zenith
30° off S to E

Horizontal illumination
Direct sun: 2407 fc
Sky: 1298 fc

Contour Number	Illum. Level (Ft-candles)
1	20.0
2	40.0
3	60.0
4	80.0
5	100.0
6	150.0
7	200.0
8	250.0
9	300.0
10	400.0
11	500.0

Windows marked by *****
Sunny areas are hatched

Fig. 4. SUPERLITE illuminance contour plot for an L-shaped room. 100 fc (dashed) and 500 fc (heavy) contours are highlighted. Hatching shows where sunlight falls on floor.

Fig. 5. SUPERLITE contour plot for a model having a clerestory and light shelf and with direct sun. 100 h fc (dashed) and 500 fc (heavy) contours are highlighted. Hatching shows where sunlight falls on floor.

DOE 2 DAYLIGHTING MODEL CAPABILITIES

DOE 2 daylighting simulation determines the hourly, monthly, and yearly impact of daylighting on electrical energy consumption and peak electrical demand, as well as the impact on cooling and heating requirements and on annual energy cost. The analysis for the total building is based on separate analysis of each of the identified thermal and/or daylighting zones. It accounts for daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. The development of a daylighting model for DOE 2 is based on a compromise between competing requirements for 1) maximizing accuracy, 2) minimizing computational time and cost, 3) minimizing input requirements, and 4) maximizing versatility. A primary concern has been to develop a model that can be expanded to study virtually any architectural daylight strategy. This is important because DOE 2 is used frequently to analyze large, complex multistory buildings that incorporate innovative designs. Because it is time-consuming to complete and debug major modifications to DOE 2, the daylighting model now running in DOE 2.1B was designed to accommodate future expansion without the need for major modifications. In Sections 4.1 and 4.2, the operation and capabilities of the DOE 2.1B daylighting model are described. Sections 4.3 and 4.4 describe work underway to expand the daylighting and thermal modeling capabilities for complex fenestration systems.

Daylight Calculation Model

The DOE 2.1B daylighting calculation has three major stages. First (Fig. 6), a preprocessor calculates daylight factors at specified lighting control locations for each window for various sun and sky conditions and stores them for later use in the hourly loads calculation. Luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices, and external obstructions are accounted for. The calculation is carried out for standard CIE overcast sky and for 20 different CIE clear skies with solar altitude and azimuth values covering the annual range of sun positions. Analogous factors for discomfort glare are also calculated and stored.

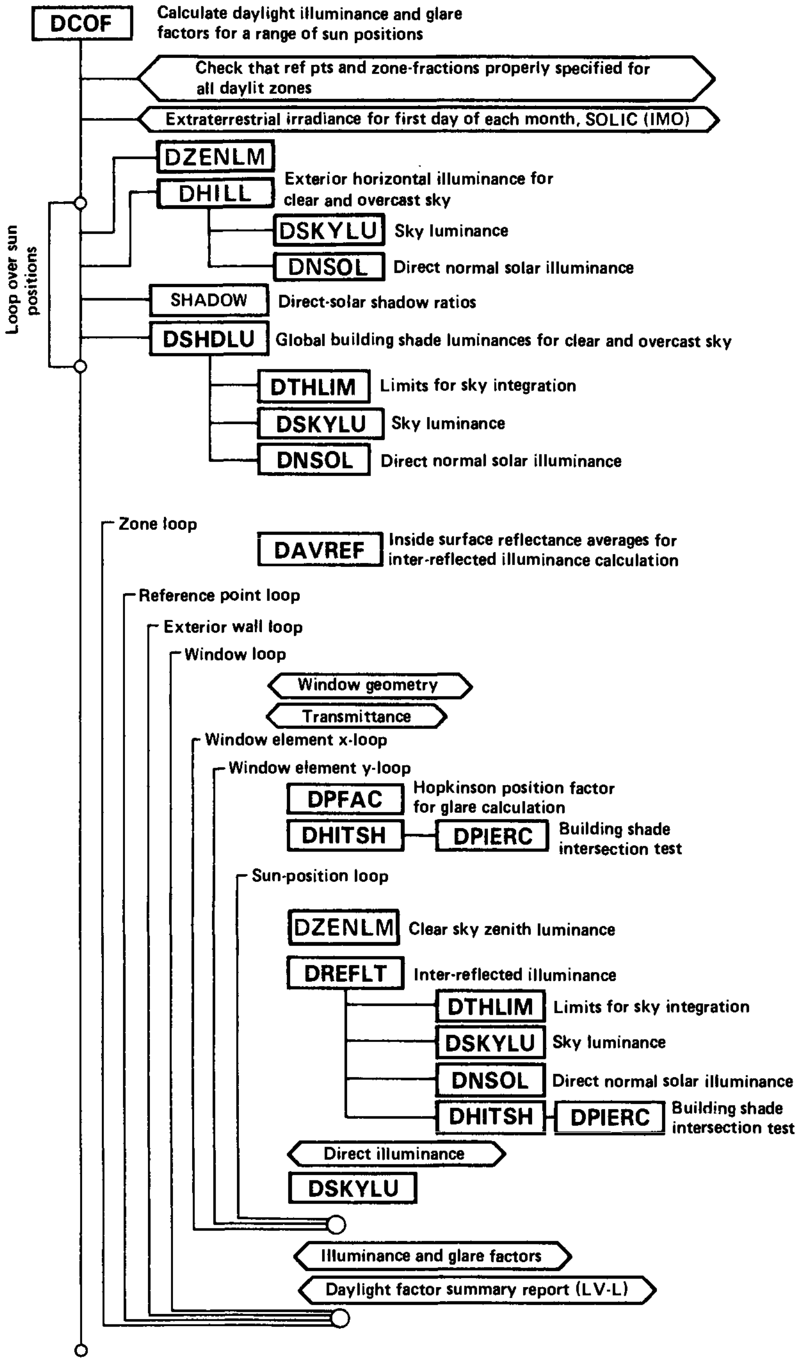


Fig. 6. Flowchart for DOE 2.1B daylighting preprocessor. Daylighting subroutines are in boldface.

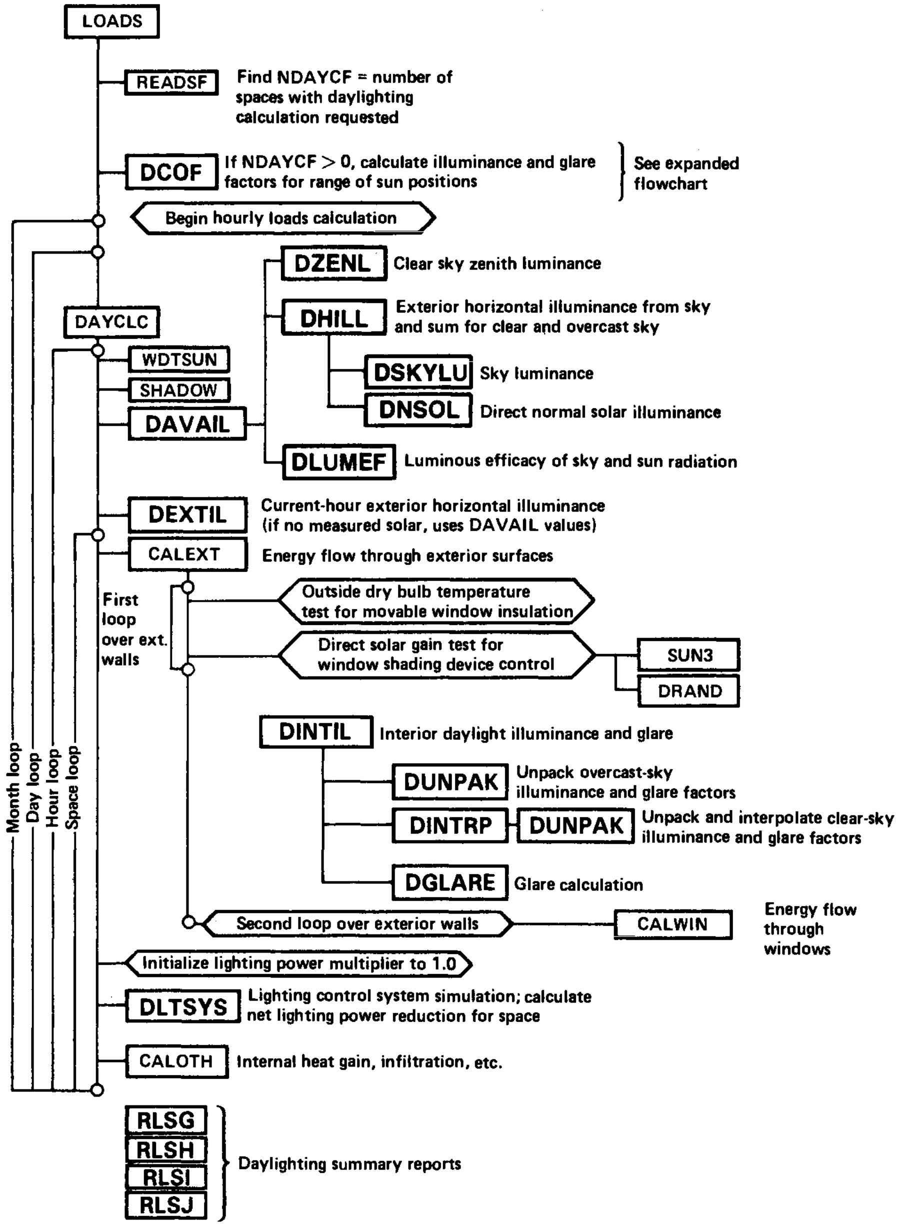


Fig. 7. Flowchart for DOE 2.1B daylighting calculation. Daylighting subroutines are in boldface. Some nondaylighting LOADS subroutines are also shown.

In stage two a daylighting calculation is performed each hour of the year that the sun is up (Fig. 7). The illuminance through each window is found by interpolating the stored daylight factors using the current-hour sun position and cloud cover and then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will assume that window blinds or drapes are closed to lessen glare below a pre-defined comfort level. A similar option assumes that window shading devices are operated manually or automatically to control solar gain.

In stage three (Fig. 7) the program simulates the operation of the lighting control system (which may be stepped or continuously dimmed) to determine the energy needed to make up any difference between the daylight illuminance and the design illuminance. Each thermal zone can be divided into two independently controlled lighting zones. Both uniform lighting and task-ambient systems can be modeled. Finally, the zone lighting requirements are transferred to the DOE 2 thermal calculation, which determines hourly heating and cooling loads as well as monthly and annual energy use. Additional details of the calculation procedures can be found in Ref. 5.

DOE 2.1B Daylighting Output Reports

Tables 1A through 1C show sample DOE 2 daylighting reports for a south-facing office module from a prototypical high-rise building in New York City. The module, which is approximately 6.2 m (20 ft) wide, 9.2 m (30 ft) deep, and 3.1 m (10 ft) floor to ceiling, has a 1.5 m (5 ft) high strip window with 0.9 m (3 ft) sill height and 90% transmittance. Drapes with 35% transmittance are automatically closed if direct solar transmission exceeds 6.4 W/m^2 (20 Btu/ft^2 hr) or if glare is excessive. The module has two independently controlled lighting zones with reference points 3.1 m (10 ft) and 7.7 m (25 ft), respectively, from the window wall, and with design illuminance of 538 lux (50 fc). Each lighting zone has a continuously dimmable control system that dims linearly from 100% light/100% power to 20% light/30% power.

TABLE 1a

Sample DOE 2.1B Daylighting Report LS-G -Space Daylighting Summary- for the South-Facing Office Module Described in Fig. 1. Times under 'report schedule hours' are restricted to the period 8 am to 5 pm, the hours of major occupancy.

SPACE SOUTHZONE

-------------REPORT SCHEDULE HOURS WITH SUN UP-------------

MONTH	PER CENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (ALL HOURS)			PER CENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (REPORT SCHEDULE HOURS)			AVERAGE DAYLIGHT ILLUMINANCE (FOOT CANDLES)		PER CENT HOURS DAYLIGHT ILLUMINANCE ABOVE SETPOINT		AVERAGE GLARE INDEX		PER CENT HOURS GLARE TOO HIGH	
	TOTAL ZONE	REF PT 1	REF PT 2	TOTAL ZONE	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2
JAN	17.1	34.3	0.	22.1	44.1	0.	40.3	0.	34.8	0.	8.7	0.	0.	0.
FEB	20.1	40.2	0.	25.3	50.7	0.	46.9	0.	44.8	0.	9.9	0.	0.	0.
MAR	22.5	45.0	0.	27.5	55.0	0.	50.6	0.	57.0	0.	10.4	0.	0.	0.
APR	25.3	50.6	0.	30.2	60.4	0.	55.8	0.	59.3	0.	11.3	0.	0.	0.
MAY	27.6	55.2	0.	32.2	64.4	0.	54.4	0.	45.5	0.	11.4	0.	0.	0.
JUN	28.8	57.6	0.	33.2	66.4	0.	66.5	0.	58.5	0.	12.4	0.	0.	0.
JUL	27.0	54.0	0.	31.2	62.4	0.	65.5	0.	58.4	0.	12.2	0.	0.	0.
AUG	28.6	57.3	0.	33.7	67.5	0.	69.3	0.	71.3	0.	12.9	0.	0.	0.
SEP	25.9	51.7	0.	30.5	61.0	0.	53.6	0.	56.7	0.	10.9	0.	0.	0.
OCT	24.7	49.3	0.	30.4	60.7	0.	58.6	0.	58.4	0.	11.2	0.	0.	0.
NOV	19.3	38.6	0.	24.6	49.2	0.	45.6	0.	43.3	0.	9.6	0.	0.	0.
DEC	15.5	31.0	0.	19.9	39.8	0.	39.3	0.	36.9	0.	8.5	0.	0.	0.
ANNUAL	23.6	47.2	0.	28.4	56.9	0.	53.9	0.	52.1	0.	10.8	0.	0.	0.

TABLE 1b

Sample DOE 2.1b Daylighting Report LS-H -Per cent of Lighting Energy Reduction by Daylighting vs Hour of the Day for the South-Facing Office Module- described in Fig. 1.

SPACE SOUTHZONE

	HOUR OF DAY																								
MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ALL HOURS
JAN	0	0	0	0	0	0	0	4	16	23	25	28	26	24	22	20	14	0	0	0	0	0	0	0	17
FEB	0	0	0	0	0	0	0	8	19	24	27	29	30	29	28	25	18	9	0	0	0	0	0	0	20
MAR	0	0	0	0	0	0	9	21	25	27	29	30	29	30	29	27	22	15	0	0	0	0	0	0	23
APR	0	0	0	0	0	3	21	28	29	30	32	32	33	31	30	29	25	21	2	0	0	0	0	0	25
MAY	0	0	0	0	0	10	26	30	32	31	32	33	33	33	34	32	29	26	5	0	0	0	0	0	28
JUN	0	0	0	0	1	10	26	30	33	34	33	35	34	32	34	34	31	24	13	1	0	0	0	0	29
JUL	0	0	0	0	0	7	24	30	31	31	32	32	31	32	33	30	30	27	6	1	0	0	0	0	27
AUG	0	0	0	0	0	0	23	31	33	34	35	35	35	35	34	33	31	22	3	0	0	0	0	0	29
SEP	0	0	0	0	0	3	17	29	29	30	31	32	33	31	30	30	29	18	1	0	0	0	0	0	26
OCT	0	0	0	0	0	0	8	26	28	31	33	34	33	32	30	27	24	2	0	0	0	0	0	0	25
NOV	0	0	0	0	0	0	5	16	26	28	28	30	29	27	25	24	4	0	0	0	0	0	0	0	19
DEC	0	0	0	0	0	0	0	4	16	21	23	25	25	24	22	19	4	0	0	0	0	0	0	0	15
ANNUAL	0	0	0	0	0	4	17	26	26	29	30	31	31	30	29	28	20	12	3	0	0	0	0	0	24

NOTE - THE ENTRIES IN THIS REPORT ARE NOT SUBJECT
TO THE DAYLIGHTING REPORT SCHEDULE

TABLE 1c

Sample DOE 2.1B Daylighting Program Report LS-J -Daylight Illuminance Frequency of Occurance for the South-Facing Office Module Described in Fig. 1.

SPACE SOUTHZONE

		PER CENT OF HOURS IN ILLUMINANCE RANGE									PER CENT OF HOURS ILLUMINANCE LEVEL EXCEEDED								
		ILLUMINANCE RANGE (FOOTCANDLES)									ILLUMINANCE LEVEL (FOOTCANDLES)								
MONTH	REF PT	0 -- 10	-- 20	-- 30	-- 40	-- 50	-- 60	-- 70	-- 80	-ABOVE	0	10	20	30	40	50	60	70	80
JAN	1	28	11	6	9	11	5	8	4	18	100	72	61	55	46	35	30	22	18
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	1	17	12	5	9	13	7	11	10	17	100	83	71	66	58	45	38	27	17
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	1	15	8	5	5	10	17	15	11	14	100	85	77	72	67	57	40	25	14
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	1	7	10	4	7	13	16	16	13	15	100	93	83	80	72	59	44	28	15
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	1	4	5	8	13	25	14	8	7	16	100	96	90	83	70	46	32	23	16
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUN	1	0	6	4	13	18	13	7	8	31	100	100	94	90	77	59	46	39	31
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	1	3	5	5	8	20	11	8	9	30	100	97	92	87	78	58	47	39	30
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUG	1	0	1	3	9	15	21	16	7	27	100	100	99	95	87	71	50	34	27
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEP	1	12	5	5	8	13	20	13	9	15	100	88	83	78	70	57	37	24	16
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCT	1	8	11	4	8	11	9	8	11	30	100	92	81	77	70	58	49	41	30
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOV	1	22	13	6	7	9	8	7	8	20	100	78	64	59	52	43	35	28	20
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEC	1	29	13	8	9	4	10	5	3	19	100	71	58	50	41	37	27	22	19
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANNUAL	1	12	8	5	9	14	13	10	8	21	100	88	80	74	66	52	40	29	21
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NOTE - THE HOURS CONSIDERED IN THIS REPORT ARE THOSE WITH SUN UP AND DAYLIGHTING REPORT SCHEDULE ON

The data provided in these reports give a detailed description of the role of daylighting in the building. Table 1A shows the type of monthly and annual summary data useful for estimating the savings and cost-effectiveness of a daylighting strategy. The hourly average energy savings in Table 1B provide more detailed data on the hourly/monthly pattern of daylight savings. A frequently observed pattern is one in which midday savings reach a maximum but early morning and late afternoon values are well below maximum. Adding glazing in these cases will save little extra lighting energy but may significantly increase cooling loads. These results can be viewed on a zone-by-zone basis and for the entire building. The two sections of Table 1C provide detailed statistics on the frequency of occurrence of various interior daylight illuminance values and the cumulative probability of exceeding each value. A user can quickly estimate the change in daylighting savings if a design illuminance value is changed or if the lighting control strategy is altered, without rerunning the DOE 2 program.

Other DOE 2 daylighting reports (not shown) give hourly values for exterior and interior daylight illuminance and reductions in lighting power for user-specified time periods.

Daylighting Model for New Versions of DOE 2.1

The program currently calculates interior illuminance for conventional window designs using a preprocessor calculation and assuming that sun control systems such as shades, drapes, and blinds are ideal diffusers. The program is being expanded to model geometrically complex sunshading solutions such as horizontal and vertical louvers or light shelves and to model unique architectural spaces such as atrium spaces that are more routinely being incorporated into large multistory buildings.

Because direct calculation of interior illuminance from complex sunshading systems is computationally difficult (and in some cases impossible), a new coefficient-of-utilization model was developed based on data calculated or measured outside the DOE 2 program. There are several ways in which this new model can be implemented. Some designs can be standardized (e.g., horizontal flat louver system) but may be too complex to calculate in DOE 2. These are precalculated using SUPERLITE (for a range of louver reflectance values, width/spacing ratios, etc.) and stored in DOE 2.

When it is important to generate values for specific products rather than generic designs, SUPERLITE will serve as a 'preprocessor' to DOE 2 and will generate the coefficients directly.

A second category includes daylighting designs that can be standardized but may be too complex to calculate using an existing computational model (e.g., complex curved, semi-specular light shelves). In this instance the required illuminance data will be generated from scale models in a large hemispherical sky simulator at Lawrence Berkeley Laboratory (LBL) (Fig. 8); results will be converted to coefficients that are stored in the DOE 2 library.

A third category includes unique designs not found in the DOE 2 library. In this case a user can develop the required data from model studies, convert these data into a format compatible with the coefficient-of-utilization calculation, and input the results directly into the program library. Each user thus can create his/her own library of custom designs for evaluation.

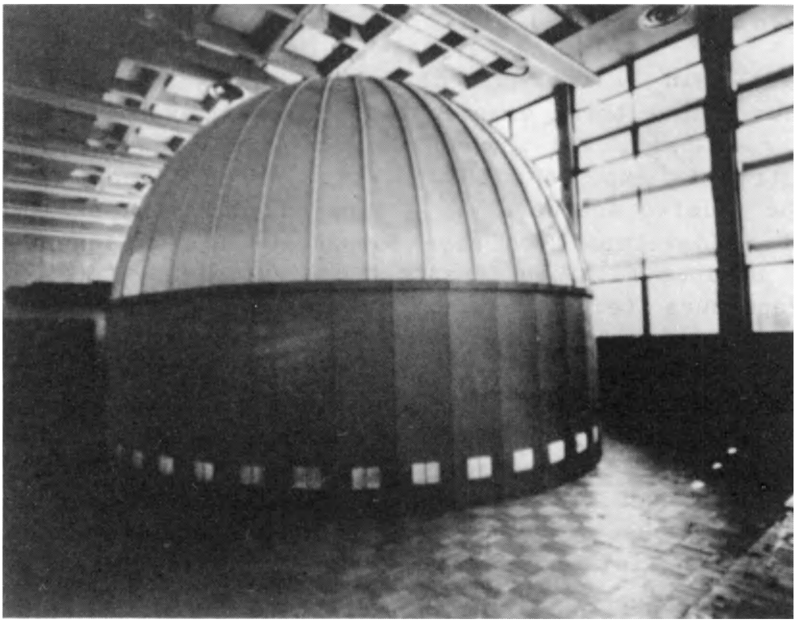


Fig. 8. Exterior view of 7.4 m (24 ft) diameter hemispherical sky simulator.

Each of these options requires a systematic series of calculations and/or measurements under a full range of overcast and clear skies and direct sun conditions. The coefficient-of-utilization model extends the calculation method now used by the Illuminating Engineering Society (U.S.) for daylighting calculations,[6] but includes five coefficients that are sensitive to illumination from the ground, sky, and sun. Basic data for the standard DOE 2 library are being developed from an extensive series of parametric analyses using SUPERLITE and from systematic model tests in the LBL sky simulator.

Fenestration Thermal Model for New Versions of DOE 2.1

If the energy and load impacts of complex fenestration systems are to be adequately analyzed, not only must the daylight contribution be properly modeled but also the thermal loads must be accurately analyzed. None of the major hour-by-hour energy analysis programs account for solar gain through geometrically complex fenestration. It is therefore necessary to develop a new computational model to determine solar heat gain from complex fenestration systems. This heat-gain model is similar to the new coefficient-of-utilization daylighting model described in the previous section.

Solar heat gain will be calculated by splitting the incident solar energy into three components: direct solar radiation, sky diffuse radiation, and ground diffuse radiation. This differentiation is important if systems such as operable louvers are to be modeled accurately. A separate solar heat-gain factor will be developed for each component of each fenestration system. Because multiple fenestration devices may be used on a single aperture (e.g., exterior fins, heat-absorbing glass, interior drapes), the approach must predict the performance of individual devices in series. Solar heat gain through a complex fenestration system at a given time will thus be the sum of three transmitted components (direct, sky diffuse, ground diffuse) plus the net inward-flowing fraction of all absorbed energy. All transmitted components are calculated from optical properties of the devices using a matrix computation that accounts for the interreflectance between glazing layers and/or shading devices in series.

Because it is impractical to determine the optical properties for separate solar components in an outdoor calorimeter and it is impossible to calculate many of the values directly, a laboratory measurement will be used. Each of the three incident solar components can reach the interior by two pathways: it can be transmitted directly through the aperture or can be absorbed in the fenestration system and then re-radiated and convected to the interior. The transmitted components are determined by a series of optical measurements. Transmission measurements for beam radiation as a function of angle of incidence will be made by mounting the device in an opening in a large, 2.2 m (7 ft) diameter integrating sphere and illuminating it with an exterior radiant source. The transmittance of the device is the ratio of two signals from a set of detectors in the sphere: the signal with the device in place divided by the signal with an empty opening. Reflectance measurements from both sides of the device will be made by illuminating the device, scanning the radiance over a hemisphere, and integrating the resulting values. Both sets of measurements will be made using a sun simulator with a collimated beam at varying incident angles and with a diffuse source in the sky simulator. The integrating sphere may also be used outdoors with the sun as a source.

The absorbed component can be calculated directly if the transmittance and reflectance are known. Part of the absorbed component will be transferred to the interior space, while the remainder will be rejected to the outdoors. This rejected fraction will be determined using a calibrated hotbox that measures the thermal conductance of window systems. The device to be tested will be mounted in the proper location relative to the glazing and the entire assembly installed in a hotbox. First the hotbox will be operated normally to establish a base case; the shading device will then be electrically heated to simulate the absorbed solar component. The resulting reduction in heater power to the hotbox, relative to the total input power to the shading device, is the inward-flowing fraction of absorbed energy. The accuracy limitations of summing contributions from absorbing layers in series require additional study.

MODEL VALIDATION

Extensive validation studies are required to build confidence in the predictions from these analytical tools. Ideally, one would like comparisons to measured energy consumption in multistoried buildings, but for practical reasons the performance of fenestration components and systems normally would be studied at a smaller, but more detailed, level. Each of the major computational modules has been or is being tested by comparison to more detailed computer models and to experimental data. Validation of total fenestration performance predictions awaits calibration of the Mobile Window Thermal Test facility described in Section 5.2.

Daylighting Models

Several types of validation studies have been undertaken for the computer models. First, the models are tested by running a series of parametric analyzes to test the sensitivity of each calculation process to key design parameters. For example, one test series might examine the influence of window size, window transmittance, and interior surface reflectance under a variety of sun and sky conditions. Second, the results of each program are compared to each other and to other daylighting models. Finally, calculated results from both SUPERLITE and DOE 2 have been compared with a series of measurements made on scale models in the LBL sky simulator.[7] This 7.4 m (24 ft) diameter indoor facility enables testing under uniform, overcast, and clear sky conditions (Fig. 8). The advantages of using this artificial sky compared to outdoor tests are 1) the direct illuminance from the sun can be separated from the clear sky contribution, 2) the reflectance of the ground can be easily controlled, and most importantly 3) the sky luminance distributions are stable and reproducible.

A small single-occupant office model and a large open-landscaped office have been tested under a variety of sky conditions. The graphs in Figs. 9 and 10 compare the daylight factors from SUPERLITE and DOE 2 calculations with measurements under the artificial sky along the centerline of the models. Results are shown for clear sky conditions for both small and large office models. These methods compare well throughout the cross section of the room. Additional comparisons to outdoor model tests are in progress.

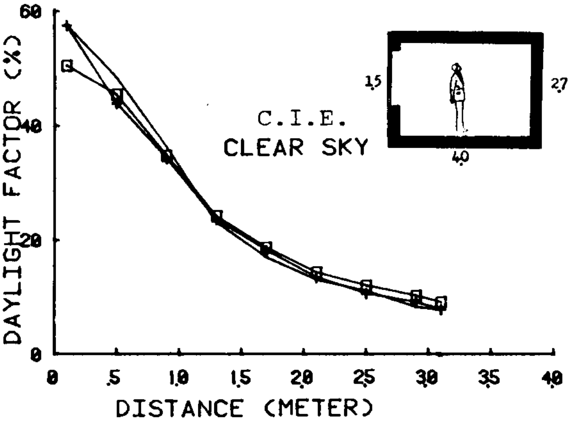


Fig. 9. SUPERLITE (+) and DOE 2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude 50°, azimuth 0°; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

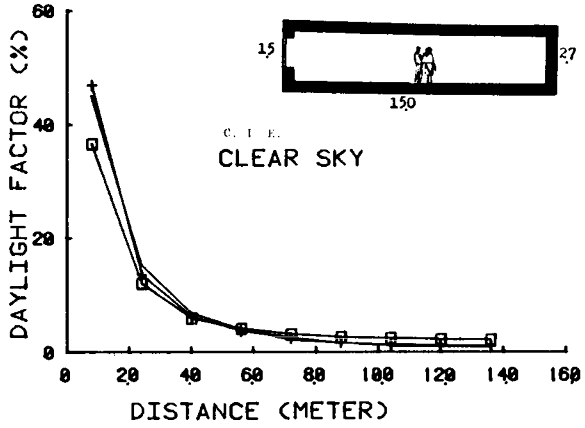


Fig. 10. SUPERLITE (+) and DOE 2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude 50°, azimuth 0°; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

Thermal Models

The thermal models in DOE 2 must accurately predict performance for a broad range of new window systems. Some of these new systems employ multiple glass and plastic layers, transparent low-emittance coatings; and low-conductance gas fills. These can be modeled using an extension of existing algorithms and are validated by comparison to heat-transfer predictions from THERM. THERM is a detailed window heat-transfer model based upon the algorithms described in Ref. 8. Heat-transfer predictions from THERM have been validated by comparison to results from a calibrated hotbox.[9]

The performance of complex window systems under incident sunlight must be validated in an outdoor facility that accounts for solar gain, temperature effects, and other energy-related interactions. A Mobile Window Thermal Test (MoWiTT) facility has been built for this purpose.[10] The facility contains two highly instrumented, side-by-side test chambers, the thermal properties of which can be altered to simulate a range of building conditions. This facility permits direct measurement of the thermal impact of fenestration on HVAC systems and will enable the thermal impact of daylighting strategies to be measured. The primary objective is to develop a data base on fenestration performance at a level of detail that allows hour-by-hour energy analysis programs such as DOE 2 to be validated at the algorithm level. Field calibration of the unit is in progress (Fig. 11).

SUMMARY AND FUTURE DIRECTIONS

The SUPERLITE and DOE 2 computer models represent powerful and complementary design tools that will improve our understanding of the role of daylighting in energy-efficient multistory buildings. It is important to recognize the strengths, weaknesses, and limitations of any design tool in order to use

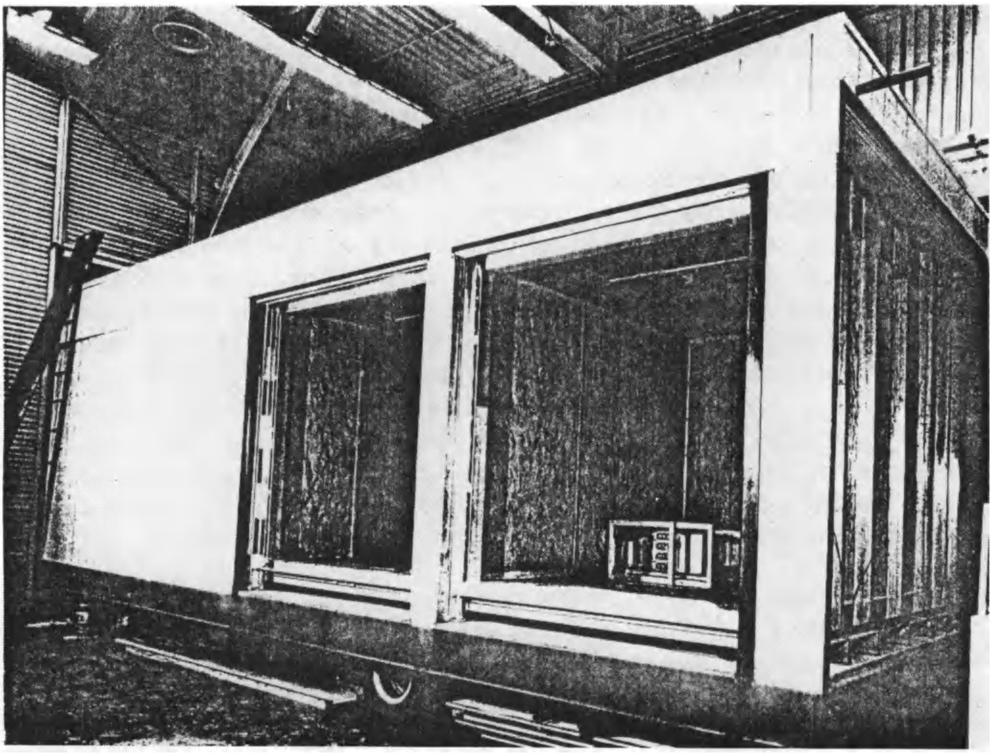


Fig. 11. Exterior view of Mobile Window Thermal Test (MoWiTT) facility showing the side-by-side test chambers.

it properly. SUPERLITE is a lighting design tool that calculates the detailed interior daylight distribution patterns resulting from both simple and complex fenestration designs under a variety of climatic conditions. When the capability for modeling electric lighting is added, examination of the interaction and integration of daylight and electric lighting control strategies will be possible. The primary advantage of this model compared to other computational models is its ability to accurately analyze geometrically complex but architecturally interesting concepts. This capability is being expanded to model complex shading systems, specular reflectors, and other non-standard design alternatives based on measurements of device luminance distributions.

The daylighting model in DOE 2.1B has been designed for flexibility and future expansion. Currently the program calculates interior illuminance for conventional window designs based on a preprocessor calculation and sun control systems that are assumed to be ideal diffusers. The program is being expanded to model more geometrically complex sunshading solutions (such as horizontal or vertical louvers) based on results calculated by the SUPERLITE program or determined from model measurements. These results will be stored in a library within the DOE 2 program or could be specified by the user. For unique building designs a user can input his or her own daylight coefficients based on model tests of that design. The goal is an energy analysis model that is highly flexible and responsive to the latest design strategies. In addition, DOE 2's thermal and sun control modeling capabilities are being expanded to be consistent with the improved daylighting modeling and to accurately model tradeoffs among heat loss, heat gain, and daylighting benefits.

Any large computer model requires a substantial investment in training before it can be utilized effectively. Most multistory buildings are designed using much simpler and more accessible design tools. Thus these powerful new computer models are being used to develop the technical basis for simplified design tools that reproduce most of the accuracy and analytical power of more complex tools but are less costly and easier to access and use.

ACKNOWLEDGEMENT

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The Application of Computers to Energy Conservation in HVAC Plants

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INTRODUCTION

The rapidity with which computer technology has developed in the last 10 years and is today being embraced in almost every sphere of life, (including such everyday items as cars, washing machines and cooking equipment) is quite mind boggling, and its use in the building design and operation field, while initially slow to develop, is about to become equally dramatic.

To illustrate the point a recent article in the Specifying Engineer claimed that in January 1981 fewer than 100 U.S. based consulting engineering firms used micro computers for HVAC design to produce around 10% of new designs. By November 1981 over 1500 firms were using micro computers to produce more than 50% of all new HVAC designs. This has come about through the development of powerful and inexpensive micro computers, software programs suitable for design of HVAC systems and the realisation that a significant increase in productivity can be obtained by the use of such systems.

It now seems certain that within the next three to five years computers will be almost universally used in building design across the full field from feasibility studies, life cycle costing, cash flows, design load calculations, energy usage, piping and ductwork design, equipment selection and drafting. One effect of this will be to revolutionise present day operations of design offices, a prospect both exciting and not a little frightening.

As far as the Australian market is concerned, we are probably about two years behind the U.S. in the use of office design computer aids but I would expect to see a similar change here within the next year to that which occurred in the U.S. in 1981.

On the Building System installation side, for large buildings or complexes of buildings, modern central monitoring and control systems (CMCS) are now available with powerful micro computers and more sophisticated software programmes designed specifically for building services management (rather than being designed for other purposes and adapted for this use), and aimed at providing much greater flexibility in design, better useful feed back of information to the operators, more accurate control and with the ability to make decisions and carry out a variety of actions automatically, based on input signals.

At the smaller end of the range is the development of the Programmable Controller, a solid state controller which can be programmed to carry out relay functions on receiving particular signals. The Programmable Controller has enabled much more sophisticated forms of control to be economically used, considerably simplified and reduced the hard wiring costs of installations, and enabled automatically controlled HVAC plants to be designed to achieve greater efficiency than was previously economically possible.

The development of Programmable Controllers has boomed over the last one to two years with a proliferation of models now available on the market.

The question is, how do we best use computers to improve energy conservation in HVAC systems?

The subject can really be considered in two quite separate parts; firstly, computers as an engineering design aid and secondly their use in actually controlling systems to optimise operating efficiency.

COMPUTERS AS DESIGN AIDS IN ENERGY CONSERVATION

Air Conditioning Engineers have traditionally determined heating and cooling loads in buildings using very effective manual methods of calculation. In most cases the need was to calculate the maximum instantaneous cooling and heating requirement of a building or zone to establish the size of the air handling, refrigeration and heating plant.

The designer was not interested in the part load operation other than to ensure the plant could operate satisfactorily at the minimum load.

However, with the rapidly escalating cost of energy, owners are now demanding more cost efficient buildings and this has resulted in great attention being paid to both the building construction and the services provided.

The options for glazing and other building materials have increased enormously and the task of evaluating the relative efficiency in energy usage and cost effectiveness of the various combinations of materials by manual computations is difficult and time consuming.

At best the engineer can make a few typical load calculations and use his/her skill at interpreting the result for various changes. This requires great experience to be effective and is not necessarily accurate. Also with some degree of personal judgement being required, an engineer's particular bias can materially effect the result.

Further, the types of HVAC systems being designed are changing. There is a current trend towards the inherently more energy efficient variable volume systems, various forms of heat reclaim systems (to make use of waste heat from the building) and chilled water storage systems (which permit the use of smaller chiller plants). This latter allows refrigeration plants to operate for a longer period at a lower maximum demand, or to be shut off at peak load periods to take advantage of suitable electricity supply tariffs.

To design an efficient heat recovery and storage system the engineer needs to know the heating and cooling requirements not only at peak load but at every hour of the day for each month of the year. With this information he can determine the optimum size of the storage tanks and equipment and plan a control system programme to optimise energy usage.

Clearly a properly designed computer programme is the answer since once the basic information has been fed in, it becomes a simple matter to alter any of the parameters and re-run the programme.

In this way it is possible to evaluate the effect of variations in:

- Orientation of building.
- Glazing size, shade co-efficient and transmission factor.
- Insulation.
- Lighting.
- Energy usage of different types of HVAC plant.

A few computer runs with different parameters will quickly determine the best combination.

Programmes capable of doing all this are extremely complex and must be backed up with a huge data bank. Most of these programmes are therefore on main frame computers where the information is forwarded to a bureau or transmitted via a computer terminal in the engineers office.

It is important that the computer programme have the ability to store all inputs and outputs for later referral and that it is possible to automatically transfer output from one programme to a second programme to eliminate wasted time in re-entering information.

There are a considerable number of building energy evaluating programmes available, mostly in America and there have been a number of articles published outlining some of the problems, not the least of which is a considerable variation in results with different programmes when applied to the same building.

Such a situation is to be expected in the development stages and it will probably be some years before the accuracy of these programmes can be verified. In the meantime results need to be checked against actual records and programmes used more to check relative results with different parameters rather than determining absolute energy usage.

To my knowledge the only publicly available energy programme running in Australia is the Blast II Energy Usage Programme run by Control Data. It is a very sophisticated programme requiring considerable information input.

The CSIRO Bunyip Programme is expected to be on the market by the end of this year as is another American programme called ESP which is handled by APEC and has been modified for Australian conditions by ACADS and the Department of Housing & Construction.

My firm has had experience in the use of three energy programmes, all American. Two were used to determine annual energy usage of a proposed building and the other to evaluate the economics of chilled and hot water storage.

We found in the straight energy usage runs that it was difficult to match the particular HVAC system being used with the programme system parameters and it became necessary to make an approximation to simulate it. The results obtained after a couple of runs appeared sensible if slightly low compared to those actually obtained on similar buildings. Certainly, where variables were evaluated the results were extremely close to what was expected.

In the case of the chilled and hot water storage study, the programming of the information was all done in the U.S. based on information and drawings provided from Australia.

The results came back three times with glaring errors brought about by a lack of understanding of the system operation by the American programmer. This established that the person doing the programming needs to have a good understanding of exactly how the system works, the basis of the programme and its limitations.

Also needed are reliable checking parameters to ensure it is not a case of 'garbage in - garbage out'.

However I have no doubt that with time the present energy programmes will be simplified, be more accurate and easier to use and become an essential aid to engineers in evaluating building thermal efficiency and HVAC systems.

CENTRAL MONITORING AND CONTROL SYSTEMS (CMCS)

Development of Systems

The second area in which computer technology is starting to play an important role in energy conservation is in the field of central monitoring and control systems (CMCS) and it is worthwhile briefly reviewing the development of these systems.

Until the early 1960's all HVAC monitoring and control systems consisted of hard wired boards with simplified monitoring and some manual adjustment and temperature reset capability. Generally, cost limited the extent of the monitoring and the boards were invariably tailor made for the project.

Around 1962 a hard wired system using remote data acquisition panels and electro-mechanical switching relays for point selection was developed. This system improved the monitoring capacity and the use of remote data acquisition panels reduced wiring costs, but it was still only a monitoring system with remote manual control adjustment. The relays were not very reliable with the result that the monitoring system was subject to malfunction and was expensive to maintain.

About 1969 a new hard wired system appeared having remote data acquisition panels with printed circuit boards designed for specific functions, all connected to a central special purpose computer. The solid state system eliminated the electro-mechanical relays thus overcoming the reliability problem and increasing the speed of scanning points. Essentially, however, it was still a supervisory and monitoring system which supplied information to the operator and allowed him to take action.

The next major step was the up grading of this system's central processing unit with a mini computer. This enabled the collection and processing of data to be done automatically, predictive calculations to be made and the necessary action to be taken without any input from the operator.

A number of energy conservation software programmes were available with this system such as:

- Optimum start time.
- Duty cycling.
- Maximum demand and load shedding.
- Load reset.
- Outside and return air enthalpy.
- Chiller optimisation.

The main disadvantage of the system was that the programming had to be done by the vendor, often in machine language. Changes to the standard programme could not be handled by the owner.

Then in 1978 the first micro-computer based system utilising software appeared. The basic differences with this system over the mini-computer based system was that it was cheaper, used a lower powered computer, and most importantly had the ability to be programmed in house. Software techniques generally became standard between the various system suppliers.

General Description

CMCS can be used in the monitoring and control of all building services including air conditioning, fire protection, lighting and power, hydraulics, communications and security. The extent and sophistication of the systems varies between different buildings depending on the buildings use and the requirements of the building owner. It is most important (and typically one of the more difficult aspects of a system design) to ascertain from the building owner just how the building is to be operated so that the system can be tailor designed to suit (e.g. whether the services monitoring and the security functions are to be combined or separated, the extent of energy consumption monitoring required, and the like). There is little point providing a highly sophisticated and monitored system if the information provided isn't going to be properly utilised.

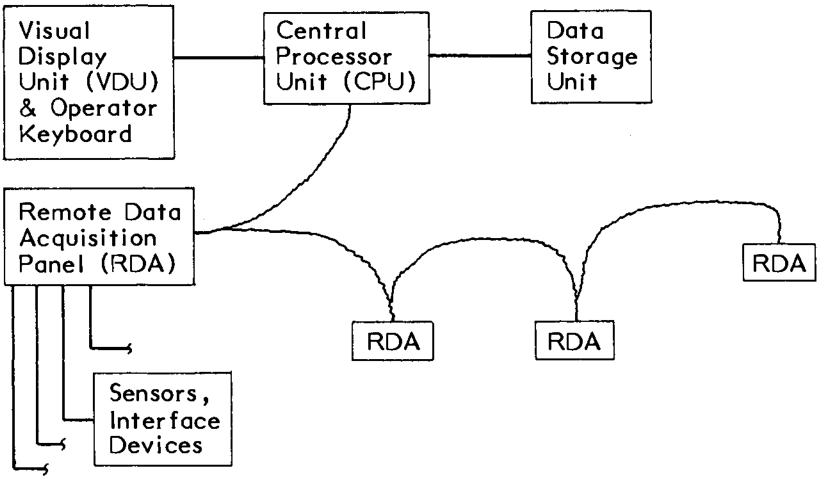

Fig. 1. Typical central supervisory and control system

A typical CMCS with micro-processor is shown in Fig. I.

The remote data acquisition panels (RDA's) are usually mounted close to equipment to be controlled, and are connected to sensors and controllers through interface devices.

The RDA's are themselves micro-processors. They control the conversion of data at the remote location and communicate with the central micro-computer processor unit (CPU).

The wiring between the RDA's and the CPU is an inexpensive twisted pair cable, and the more expensive shielded cabling between the RDA's and the sensors is kept to a minimum.

The RDA's are programmed to receive and store information as well as transmit and receive information from the CPU. In this way the RDA takes over many of the functions of data acquisition and will only transmit information to the CPU on demand.

The role of the CPU is to use the data received from the RDA's to make decisions as to how best to control the overall system and issue instructions to carry out those decisions.

Discussion

The above very briefly summarises the development and state of the art in major CMCS systems today. There are a number of other developments which will considerably change present day practices and these will be briefly discussed later.

The question for the present is how successful have CMCS systems been and how can we expect micro-processor based systems to help in cost effective energy conservation?

It needs to be said at the outset, that a CMCS is not an automatic energy saver and cure-all for system ills, as it sometimes appears to have been portrayed.

A CMCS cannot overcome faulty control logic, mismatched or malfunctioning plant, poor air balance or badly tuned systems. The greatest energy gains are usually obtained by elimination of these problems.

The CMCS as used today, is simply an addition to the basic control system, which, when properly designed and applied, should enable closer monitoring and tighter control of the system resulting in a further improvement in operating efficiency.

The effectiveness of CMCS in improving efficiency will depend very much on the type of system, method of control and building use. For instance, if a plant consists of a number of single zone air handling systems each controlled from a separate room thermostat, there is little the CMCS can do other than monitor the thermostats calibration and start and stop the plants at the optimum time. A simple time clock would be nearly as effective in this case.

However if the HVAC system is say a central plant variable volume type air handling system with an outside air cycle, and a number of different sized chillers operating on a maximum demand type electricity tariff, there are many more alternatives available where the right or wrong decision can considerably affect the efficiency of operation. Decisions such as, when an early morning ventilation cycle should be used to purge the building; what combination of chillers should be used for most efficient operation; when should they be started to limit maximum demand and what chilled water temperature is necessary to handle the particular load; can have a significant impact on energy consumption and a modern CMCS unit can be programmed with the logic to make such decisions and automatically control the plant accordingly.

Until micro-processor type CMCS came onto the market it was my company's belief that their use could seldom be economically justified in medium sized single building complexes.

In Australia most buildings up to 20,000m^{2}? have automatically controlled HVAC plants without operating staff. These buildings can be controlled very economically using a programmable time clock and by operating the plant on direct demand from selected room thermostats to control in sequence heating, ventilating and cooling.

For larger buildings or multi building complexes, the ability of a CMCS to oversee the total operation and to take actions such as load shedding to reduce the overall demand, can be of significant benefit.

The real difference between the last generation CMCS and the new micro computer based systems is that the new systems are controlled by software programmes which can be modified to provide automatic optimum operation of each system feature, whereas previously the CMCS simply made data available on which the operator was supposed to act.

This, together with the fact that manufacturers at last appear to be developing a range of equipment to suit small to large complexes, makes the micro-computer controlled CMCS an immensely more powerful tool and gives the design engineer much greater scope to achieve energy savings.

There have been a number of problems with CMCS in the past which have rendered them only partially effective and it is unlikely that the new generation of units will be put into operation without a good number of teething problems. Common problems with CMCS have been:-

- The systems offered by control companies tended to be all embracing instead of graded to suit problems from the simple to the very complex. Systems were generally expensive and to justify their use, many installations were over monitored and excessively controlled. This rendered them less reliable and harder to comprehend by the operators.

- A lack of understanding by the control companies and their design engineers of what was really required for the HVAC system often resulted in poor control logic, making the system far less effective than it should have been.

- Lack of skilled operators resulted in poor utilisation of the system.

- Insufficient skilled control technicians to set up and maintain the installation resulted in long and frustrating commissioning periods while malfunctions were being corrected.

- Lack of software functions to back up the systems reduced their effectiveness.

- Some equipment was unreliable and maintenance costs excessively high.

In the design of any CMCS it is important to keep it as simple as possible. The old addage 'Before you buy it first make sure you really need it' never applied more.

More systems have been 'fouled up' by poor logic, excessive monitoring and 'data diarrhoea' than for any other reason.

Another important consideration is that any packaged programme will not be ideal for a particular building. It will have to be tuned to suit the exact character of that building. This will require detailed analysis of operating data, on the basis of which modifications will be made to the programme or set points. This work can be time consuming and could take up to two years to properly tune the system. The work requires skill and a detailed understanding of the system operation and is probably best carried out under the direction of the designer.

It remains to be seen how effectively the equipment and software programmes can be applied, but the range of equipment being made available now presents engineers with unique opportunities and challenges to develop new ingenious applications to improve energy conservation.

PROGRAMMABLE CONTROLLERS

Another device which is becoming invaluable to engineers in energy conservation work is the programmable controller (PC).

A PC is a solid state device which can be readily programmed (by 'plugging' it in to an external programming unit) to perform logical functions, make decisions and thus control a system. The PC accepts input signals from sensors, switches, and the like, and transmits output signals to motor starters, relays, and the like.

The PC is a direct replacement for a relay panel. Its main advantage over the relay is that:-

- it can time, count, add, and subtract.
- the logic can be changed without alteration to wiring.
- being solid state its reliability is good.
- it can be reprogrammed and re-used for a completely different purpose.
- fault diagnosing is available for trouble shooting.
- a single programming unit can be used to programme any number of PC's.
- the units are physically smaller than the bank of relays they replace and can be mounted inside a switchboard or separately.

The advantage to the design engineer is that he now can carry out a multitude of tasks from simple relay operations to very complex logic programmes.

The added flexibility provided by this equipment makes it possible to considerably refine techniques of control to achieve energy savings. As an example a refrigeration plant with several chillers could use inputs from a number of sources to determine exactly what capacity is required, which machines should run and what temperature water will be necessary to handle the loads present. Previously it has been economically possible to use only one signal such as a return water thermostat.

FUTURE TRENDS

Direct Digital Control (DDC)

The latest trend in controls is called Direct Digital Control (DDC), and it seems certain that this form of control will eventually form a major part of control systems in large complexes.

As outlined earlier in this paper present control systems in large buildings are invariably stand alone type interfaced with an electronic CMCS as indicated in Fig. 2 below.

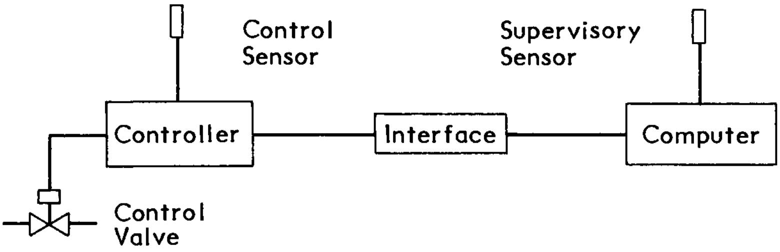

Fig. 2. Typical conventional controller with supervisory system

The DDC system differs from this in that a digital computer now becomes the controller and takes over the job of both supervision and operation of the system as shown in Fig. 3.

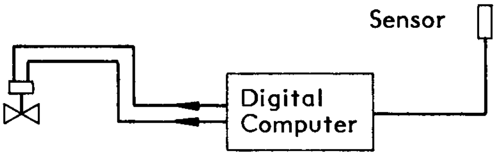

Fig. 3. DDC system control loop

The advantages of DDC over the conventional systems are:

- Control calibration is fixed and does not need regular checking.
- No interfacing devices are required.

- No disagreement can occur between the calibration of supervisory and control sensors since there is only one sensor performing both functions.

- Problems can be easily diagnosed.

- Programmes can be easily changed without hard wiring changes.

- The system provides much greater flexibility of action.

DDC helps save energy by eliminating offset (drift of temperature from the control set point), reducing control overshoot (hunting), by preventing calibration drift over time (common with pneumatic controls) and by allowing greater flexibility in designing energy conservative control systems.

Other Developments

Two developments which will be of assistance to engineers in energy conservation work are Fibre Optics and Power Line Carrier (PLC).

Fibre Optics main advantage is that it is immune to electrical interference and is therefore a useful substitute in areas where heavy electrical interference occurs such as in plantrooms adjacent large motors or generators.

Another possible application would be in areas subject to lightning strikes such as cabling between buildings where expensive lightning protection gear would otherwise have to be used.

Power Line Carrier PLC is where a high frequency signal is transmitted directly through the power line. Each address point can have a different signal so that equipment can be remotely operated as required. Examples of the application of the PLC are the operation of domestic off peak hot water heaters and street lighting by the electricity authorities, fan coil units in hotel rooms and any remote starters required to be operated from a central location.

CONCLUSIONS

We are clearly at the forefront of some very big changes to both our office design approach and the approach to controlling HVAC systems all brought about by computer technology.

The hardware now appears to be reliable, economic and available in capacities to suit the full range of installations.

It is too early yet to predict the extent to which each of these developments will superceed existing methods but it is certainly going to be significant.

I suspect the problem in adapting this technology to HVAC designs is going to be more in the software than hardware, and it will be essential that trained technicians be available not only to commission the systems, but to tune and update software programmes over the years to adapt them to the changing circumstances of the day.

Survey of Energy Management of Office Buildings in Sydney

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PREAMBLE

It is often said that we should look to the future and not dwell with the past. This symposium has quite correctly in my opinion concentrated on future trends, techniques and technology, but may I pose the question what has happened to all the 'new technology' of yesterday? I can answer this by saying that it is probably suffering a slow death in some property owners portfolio. You may well say that this is not new, in fact it has always happened, buildings are no different from the cars we drive, planes we travel in or computers we use, they are usually technologically obsolete shortly after or sometimes even before purchase. However Gentlemen, please do not forget that most buildings are designed for a life of 40 to 60 years with major plant replacement occuring only once during this period. Appendix H illustrates the problem of the building owner once the building is completed and handed over by the development group.

Appendix H shows that technological opportunities available to the owners of completed buildings are usually limited. Generally speaking the building owners hands are tied, he is usually unable to avail himself of the ice storage systems, heat pumps, solar collectors and other advancements talked about by Mr Don Thomas and others.

It is a fact that the large majority of high rise buildings in Sydney were designed prior to the energy price shock of the early 70's and thus prior to the latest wave of energy concious design. This paper shows the results of efforts made by building owners to cope with these problems of the present using the technology of the past.

By the latter half of the 70's several of the larger property groups had initiated energy management programmes either using in house engineering personnel or by engaging consultants expert in this field. However the Building Owner and Managers Association (BOMA) still considered that the great majority of its members needed assistance and encouragement in this area. The following describes the efforts made by BOMA and the subsequent achievements of its members in energy management.

INTRODUCTION

In December 1978, the Victorian Division of the Building Owners and Managers Association (B.O.M.A.) published 'Advisory Guidelines towards an Energy Policy for Building Owners and Managers'. This was a concise statement of the knowledge of energy management techniques available at that time, using information derived from various local and international sources. It includes various suggestions for data collection in considerable detail.

However the majority of building owners, managers and operators seemed to be rather overawed by this document and to want a more elementary guide to energy management. In response to this B.O.M.A. (N.S.W.) Limited offered a service to its members at an Energy Workshop held in Sydney on 15th October, 1979. The service was to analyse a survey of year 1979 energy consumption figures, and to comment on the results obtained. It was decided to conduct the survey at a level readily understood by managers and building operators alike and requiring minimal cost and effort yet providing the first step in the implementation of an effective system of energy management.

B.O.M.A. (N.S.W.) Limited has continued this service with a 1980 and 1981 survey with the primary aim of assessing the improvements, or otherwise, achieved by building operators over their previous results.

SURVEY PROCEDURE

Members wishing to participate were required to fill in a questionnaire giving a few very basic details of the building, its use and the energy used in its various forms, (electricity in kWh, oil in litres and gas in MJ).

Each building was given a code number and this number was used in reports to retain the buildings anonymity.

A sample of the form used is given as Appendix A.

As can be seen by referring to Appendix A, the raw data supplied by the building operator were in terms he would have readily available on record or could easily be read from meters or accounts received.

The areas quoted are nett rentable areas in standard terms as defined by B.O.M.A. electricity read in kWh, oil in litres and gas in magajoules.

The thumb nail sketch was to give an indication of building orientation and of the ratio of floor area to wall area.

The first step in analysing the energy data was to bring all data to a common basis bearing in mind that building performances were to be compared one with another.

The comparison was to be by the Building Envelope Energy Utilisation Index (E.U.I) and was to be quoted in megajoules per square metre per annum (MJ/m^2 p.a.).

In order to ensure a proper comparison of building envelope performances it was necessary to eliminate the discrepancies resulting from trying to compare buildings using different mixes of the various energy forms.

We therefore decided to look at all buildings as if their 'building envelope' energy requirements were provided by electrical energy.

In order to do this we had to assume an 'in-service' efficiency for the conversion of oil and gas to equivalent electrical energy. For heating purposes a factor of 0.7 was chosen for boiler efficiency for both gas and fuel oil and 0.28 for diesel generators or 0.26 for gas engine driven alternators.

For meaningful analysis and comparison it is necessary to correct annual energy usage for hours of plant use per annum where it varies from 2500 hours.

SURVEY RESULTS

The following data was obtained from survey:

Year	Number of Buildings	Total Lettable Floor Area m^2
1979	32	471,600
1980	41	844,934
1981	48	726,294

The energy consumed in these buildings during this period was:

Year	Total Energy Usage TJ	EUI $MJ/m^2/annum$
1979	440	933
1980	372	440
1981	326	448

The above figures need some qualification:

(a) The buildings surveyed are primarily office buildings although a small number of shopping complexes are included.

(b) The buildings surveyed vary from year to year. Eighteen office buildings have appeared in each survey and are the subject of the "Survey Analysis" in the following section.

Each respondent to the survey is provided with diagrams of overall performance to enable them to assess their position relative to the market place. Each respondent is only provided with their respective building code numbers the identity of the other buildings remains anonymous. Appendix B and C are diagrams typical of those supplied to respondents.

SURVEY ANALYSIS

Eighteen office buildings located in Sydney have appeared in all surveys undertaken. This group having a total nett rentable area of $375,129m^2$ performed as follows:-

Year	Total Energy Usage TJ	E.U.I. $NJ/m^2/annum$
1979	246.04	656
1980	196.67	524
1981	178.77	477

Appendix D is a tabulation of the data obtained from these buildings. Appendix E is a diagram showing the change in E.U.I. performance of these buildings from 1979 to 1981.

The energy consumption for these buildings has been corrected to 2500 hours of plant operation per annum.

The NRA of these buildings varies from 4113m^2 to 75,500m^2 and a maximum E.U.I. of 870 MJ/m^2/annum to a minimum of 247 MJ/m^2/annum.

Energy consumption in these buildings was reduced overall by 26% in 1980 and a further 10% in 1981. Of the 18 buildings 15 had a reduction in energy consumption in 1980 and 1981, 17 buildings had a nett reduction from 1979 to 1981 and one only showed a nett gain from 1979 to 1981. This confirms that the energy management programmes undertaken on these buildings are being successful.

ENERGY UTILISATION FORMULAE

An examination of the relationship between E.U.I., the building area and the hours of plant usage appears to approximate to a form of logarithmic curve. After some experimentation the following formula was devised. The formula has been called the B.O.M.A. energy utilisation formula which is as follows:-

$$\text{E.U.I.} = \frac{E_o H}{2500}(1.15)^n$$

where

E.U.I. = Energy Utilisation Index
E_o = a base E.U.I. for the locality of the building
H = effective hours of plant use per annum
n = $3.32 \log \frac{20000}{\text{N.R.A.}}$
N.R.A. = net rentable area.

This formula is portrayed by the graph on Appendix F and is also included on the diagrams shown on Appendix C and E.

The base E.U.I. (E_o) for Sydney has been estimated at 360 MJ/m^2/annum although future survey results may determine that this figure be lowered. The base E.U.I. will vary from location to location.

The B.O.M.A. Energy Utilisation Formula is applicable to buildings up to 20,000m^2, thereafter the E.U.I. = E_o the base energy utilisation index for the locality of the building.

For offices normally operating 10 hours per day for 5 days per week the hours of use over a year may be taken is 2500, allowing for public holidays. Where the building is in use for a period greater or less than 2500 hours in the year the H factor should be adjusted accordingly. The adjustment procedure is described in Appendix G.

It is of interest to note that in the United Kingdom the Department of Environmental Services in their Design Note 17 'Guidelines for environmental design and fuel conservation in educational buildings' specifies the following formulae.

For single storey buildings:

$$\text{E.U.I.} = E_0\ (1.0213)^n \text{ where } E_0 = 215\text{kWH/m}^2\text{/annum} \quad (= 774\ \text{MJ/m}^2\text{/annum})$$

For two storey buildings:

$$\text{E.U.I.} = E_0\ (1.0653)^n \text{ where } E_0 = 232.5\text{kWH/m}^2\text{/annum} \quad (= 837\ \text{MJ/m}^2\text{/annum}$$

Where in each case $n = 3.32 \ \frac{\log 2000}{\text{area in m}^2}$

These formulae clearly are of the same form as the B.O.M.A. energy utilisation formula.

SUMMARY

The major objective of B.O.M.A. in undertaking the energy survey in 1979 was to make members aware of their energy usage and costs, to assist them collect data and to help them analyse this data, to present market place relativity information and to encourage the implementation of a long term energy management programme to reduce energy consumption.

The effectiveness of the survey in meeting the objectives is difficult to quantify. A total of 55 different buildings have been reported on during the three surveys, 10 buildings appear twice and 18 buildings three times. Hopefully all of these respondents have undertaken ongoing energy management programmes. It is possible that members who have not taken part in the surveys may have gained useful guidance from the survey reports.

The 18 buildings appearing in all three surveys give the most useful guide to the reductions in energy consumption achieved over the three years. Energy consumption in these buildings was reduced overall by 26% in 1980 and a further 10% in 1981, with all but one of the buildings having a nett reduction in energy during this period.

The cost effectiveness of measures undertaken to achieve reductions in energy consumption have not been considered in the surveys. It is considered that normal management procedures would require proper evaluation of the cost effectiveness of proposals prior to approvals being granted.

The energy utilisation formula developed from the survey results shows some promise and with more confirmation from future surveys could prove to be a useful energy management tool.

CLOSING REMARKS

Mr Allen Brown in his paper mentioned that energy costs usually amount to only 10% of the total outgoing expenses of a building. I feel I should comment on this statement to highlight that around 60% of building expenses are made-up of statutory charges and taxes, expenses that are obligatory and therefore uncontrollable, while the remaining 40% are cleaning, maintenance and operating costs which are controllable. Thus it can be seen that energy costs are approximately 25% of the controllable cost of operating a building I believe that the importance of energy management should not be overlooked or underrated.

Finally I must acknowledge the considerable work done by my colleague Mr Van Ocken, who unfortunately could not be here to talk with you today. Mr Van Ocken was instrumental in initiating the B.O.M.A. surveys and it was he who conducted and prepared the B.O.M.A. energy reports for 1979, 80 and 81. I believe that his work in this area should be recognised.

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Building Owners and Managers Association of Australia (Victoria) (1978) 'Advisory Guidelines Towards an Energy Policy for Building Owners and Managers.' (Building Owners and Managers Association (Victoria):Melbourne.)

Van Ocken A.H. (1980). 'BOMA Energy Survey.' (Building Owners and Managers Association (N.S.W.):Sydney.)

Van Ocken A.H. (1981). 'BOMA Energy Survey - 1980 Performance.' (Building Owners and Managers Association (N.S.W.):Sydney.)

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APPENDIX A

PILOT SURVEY OF ENERGY CONSUMPTION IN BUILDINGS

Building Details

Type of Glazing............................ Age..............

Town.................................... State.................

Category		'End Product' Details	
(1)	Office	N.R.A.	m^2
(2)	Retail	G.L.A.	m^2
(3)	Car Park	Car Spaces	No.
(4)	Computer Suite	N.R.A.	m^2
(5)	Hotel	Guest Room	No.
(6)	Other		

Place tick against the appropriate category and provide appropriate 'end product' detail.

Plan of Building (Thumb-nail sketch only) North Direction

Energy Consumption Details for year to

Service		Electric	Oil	Gas
(a)	Air Conditioning (heating and cooling)			
(b)	Ventilation (if not included in (a))			
(c)	Lifts, escalators etc.			
(d)	Lighting			
(e)	Domestic hot water boiler			
(f)	Auxiliary or Standby Generators			
(g)	Other			
(h)	Total			

Name of Contact for future reference:

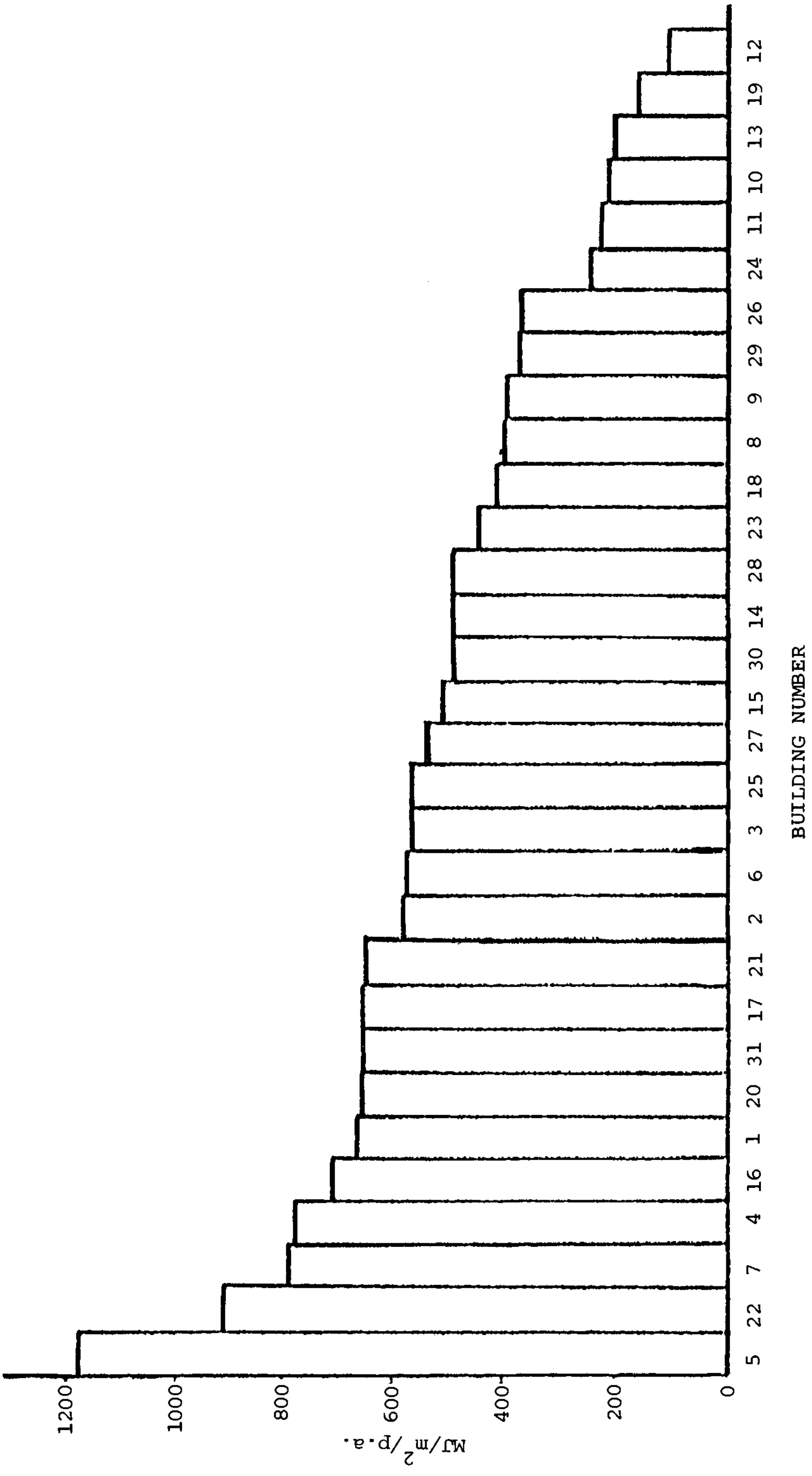
....

....

Tel. No....................

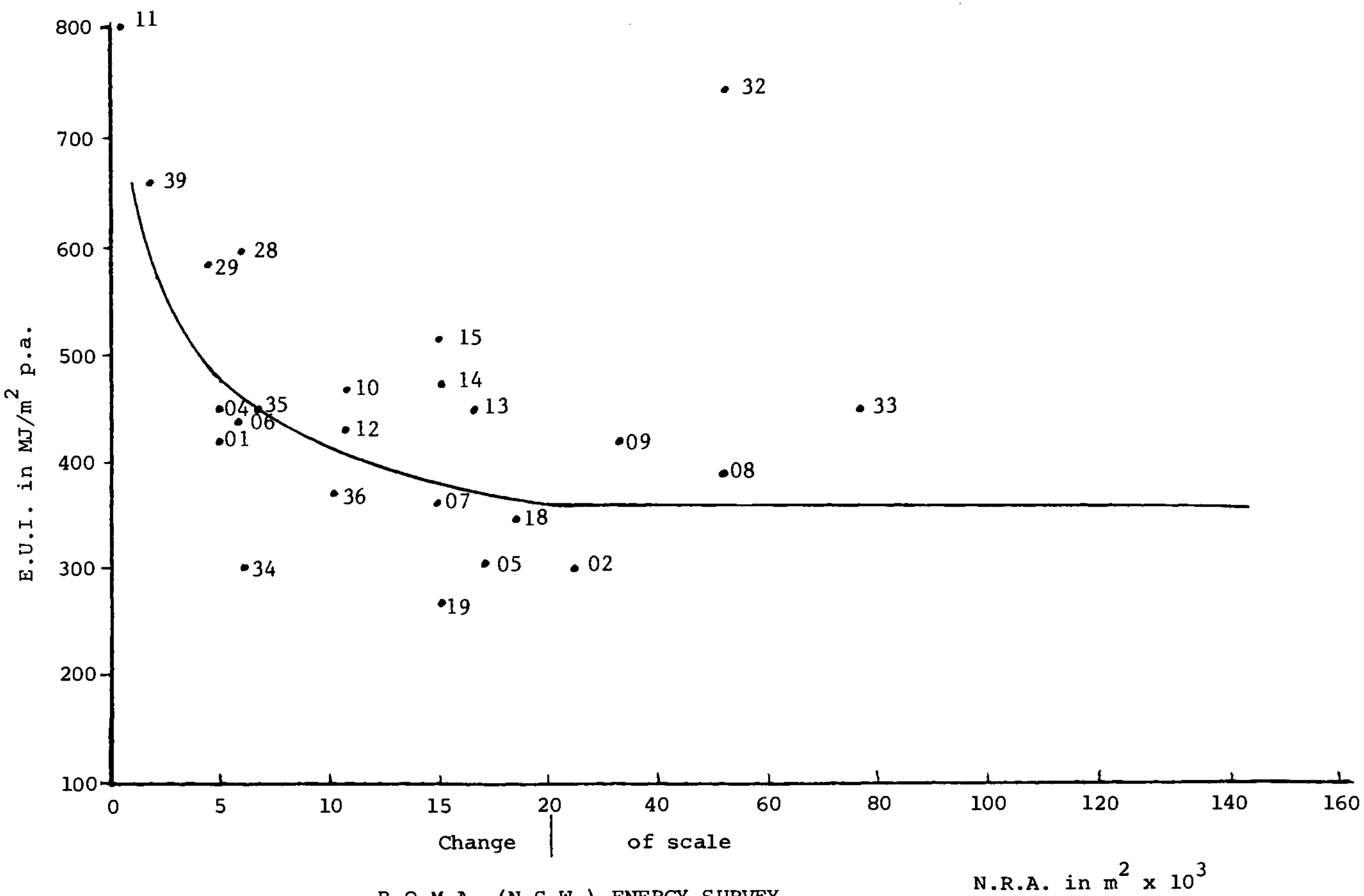
Building Address............................

APPENDIX B



OVERALL PERFORMANCE

APPENDIX C

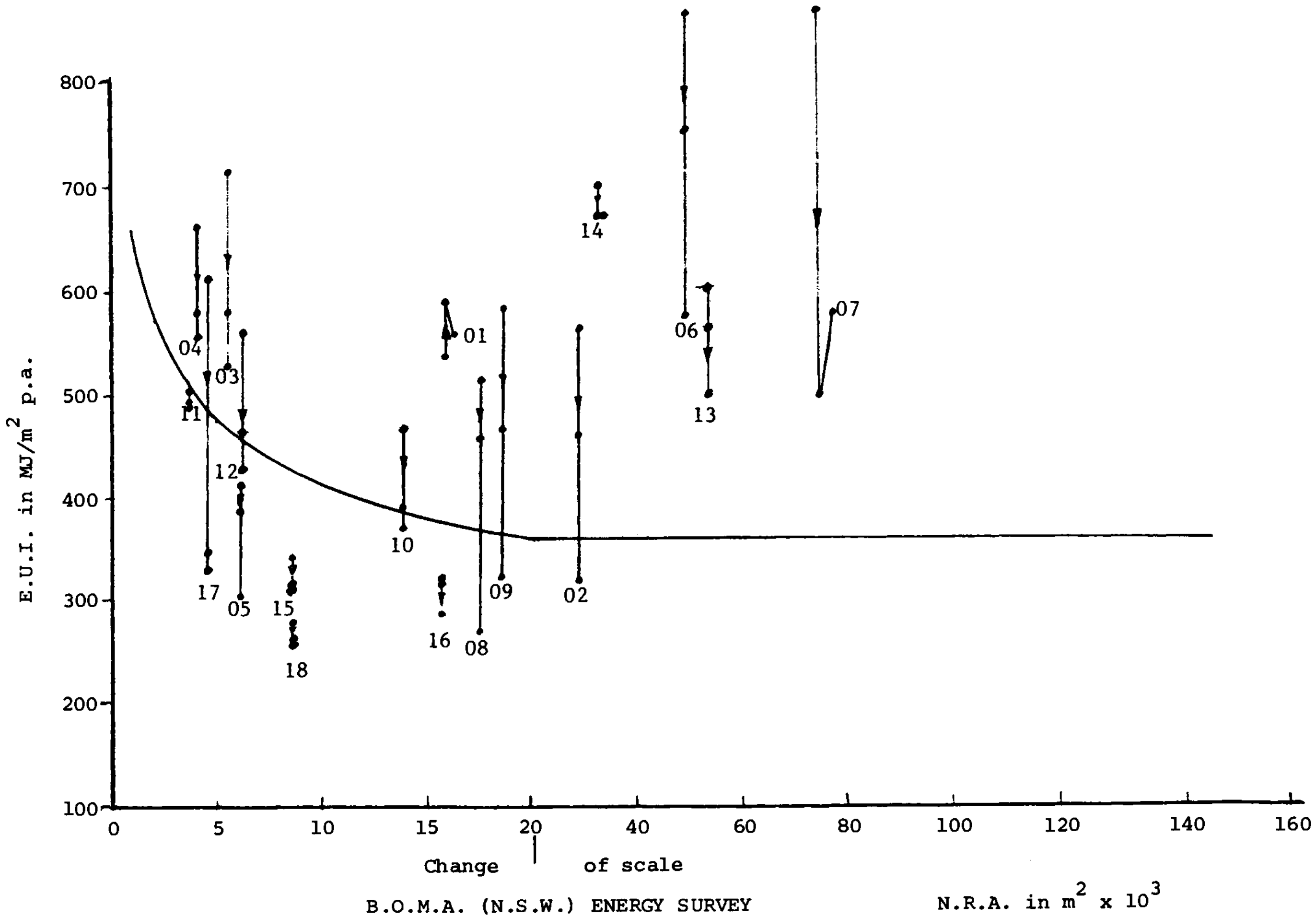


B.O.M.A. (N.S.W.) ENERGY SURVEY

APPENDIX D

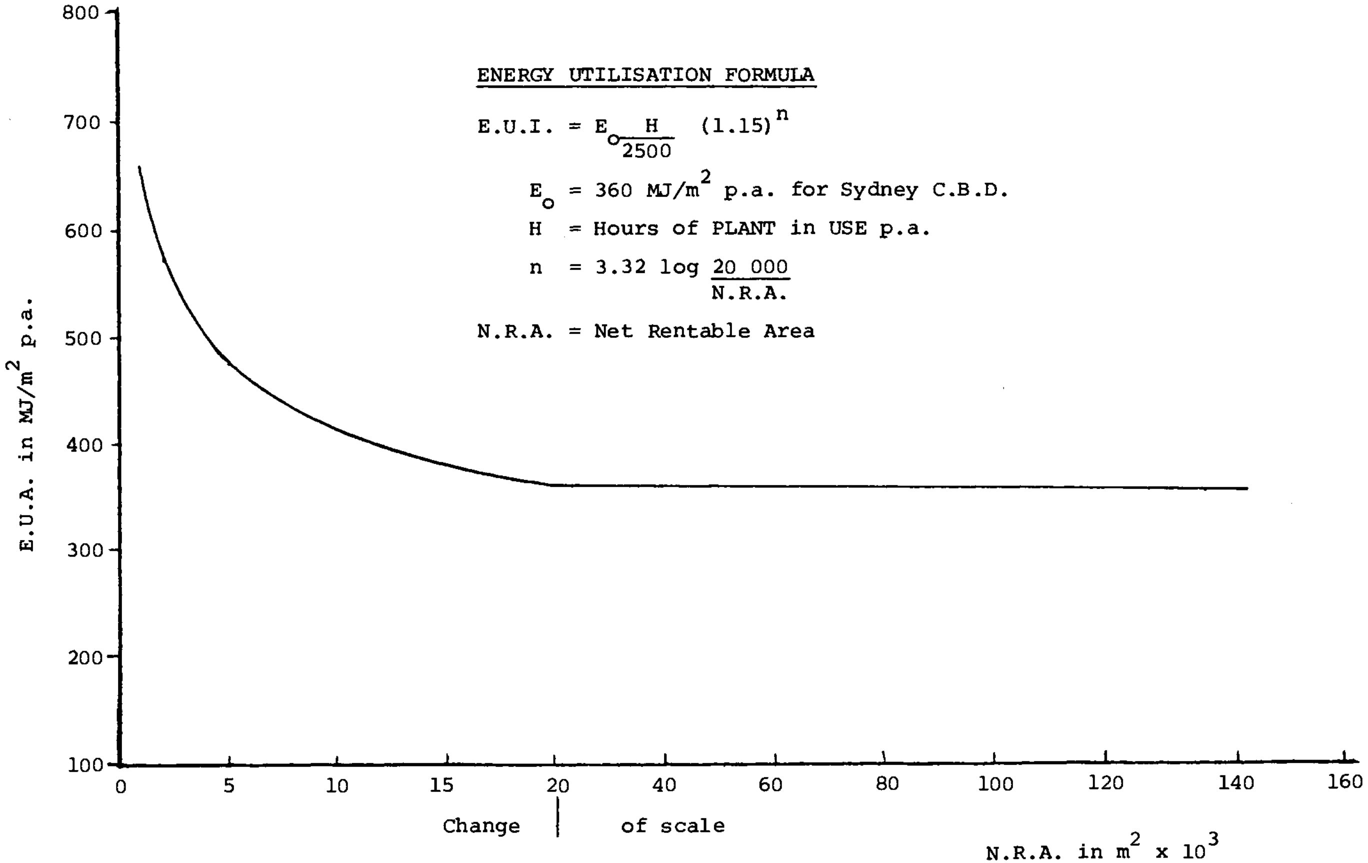
Building No.	Nett Rentable Area m^2	Energy Consumption					
		1979		1980		1981	
		E.U.I. MJ/m^2/annum	Total TJ/annum	E.U.I. MJ/m^2/annum	Total TJ/annum	E.U.I. MJ/m^2/annum	Total TJ/annum
1	16,008	530	8.48	580	9.28	550	8.80
2	28,560	550	15.71	460	13.14	300	8.57
3	6,163	710	4.38	590	3.64	530	3.27
4	4,360	660	2.88	580	2.53	550	2.40
5	6,530	410	2.68	390	2.55	303	1.98
6	50,700	870	44.11	730	37.01	576	29.19
7	75,500	870	65.69	480	36.24	570	43.04
8	17,695	510	9.02	450	7.96	267	4.72
9	18,766	580	10.88	460	8.63	318	5.96
10	14,292	474	6.77	388	5.55	367	5.25
11	4,113	502	2.06	483	1.99	477	1.96
12	6,637	569	3.78	478	3.17	436	2.89
13	54,512	606	33.03	572	31.18	506	27.58
14	32,967	709	23.37	676	22.29	676	22.29
15	8,433	338	2.85	309	2.61	308	2.60
16	16,860	312	5.26	310	5.23	278	4.69
17	4,408	611	2.70	343	1.51	329	1.45
18	8,620	277	2.39	251	2.16	247	2.13
	375,129	Av 656	246.04	Av 524	196.67	Av 477	178..77

APPENDIX E



B.O.M.A. (N.S.W.) ENERGY SURVEY

APPENDIX F



ENERGY UTILISATION FORMULA

$$\text{E.U.I.} = E_o \frac{H}{2500} (1.15)^n$$

E_o = 360 MJ/m^2 p.a. for Sydney C.B.D.

H = Hours of PLANT in USE p.a.

$n = 3.32 \log \frac{20\ 000}{\text{N.R.A.}}$

N.R.A. = Net Rentable Area

B.O.M.A. (N.S.W.) ENERGY SURVEY

APPENDIX G

ADJUSTMENT OF HOURS OF PLANT USAGE IN B.O.M.A. ENERGY UTILISATION FORMULAE

A complication arises where a building has a major installation operating continuously day and night, a computer for example. In these circumstances the 'H' factor would need to be assessed by somebody with some detailed knowledge of the energy distribution in the building.

By way of example let us consider an energy distribution pattern for the building energy to be as follows:-

Air Conditioning Chillers	0.35
Air Distribution	0.18
Air Heating	0.06
Lighting	0.25
Lifts	0.08
Domestic Hot Water	0.06
Emergency and Standby Services	0.02
	1.00

Then we consider what happens outside normal hours when only the computer floors are operational and we assess a factor for the degree to which these various services are required to operate to satisfy the requirements of the computer tenancy.

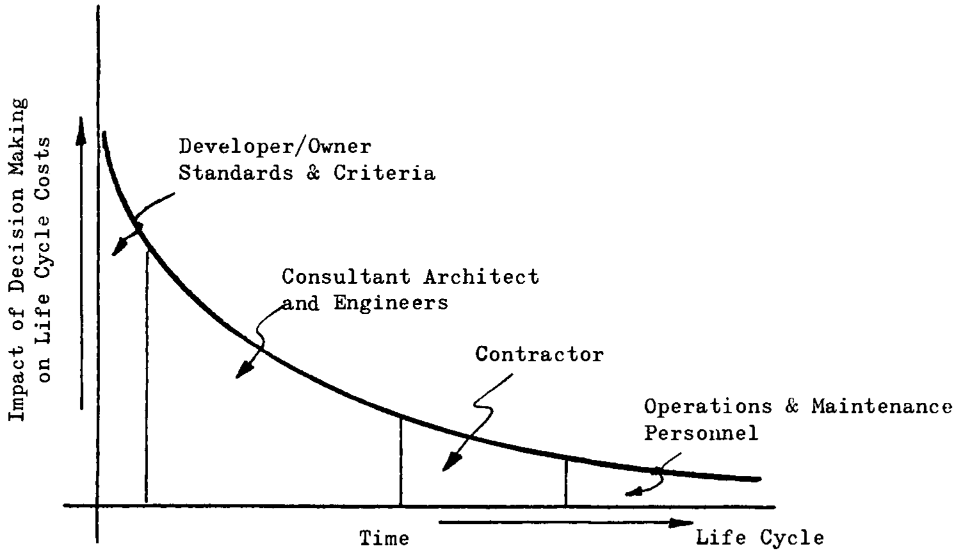
Air Conditioning Chillers	0.35 x 1.7 = 0.595
Air Distribution	0.18 x 3.5 = 0.630
Air Heating	0.06 x 3.5 = 0.210
Lighting	0.25 x 1.1 = 0.275
Lifts	0.08 x 1.1 = 0.088
Domestic Hot Water	0.06 x 1.1 = 0.066
Emergency Services etc.	0.02 x 1.1 = 0.022
	1.886

A factor of 1.0 indicates 2500 hours use of the facility p.a.

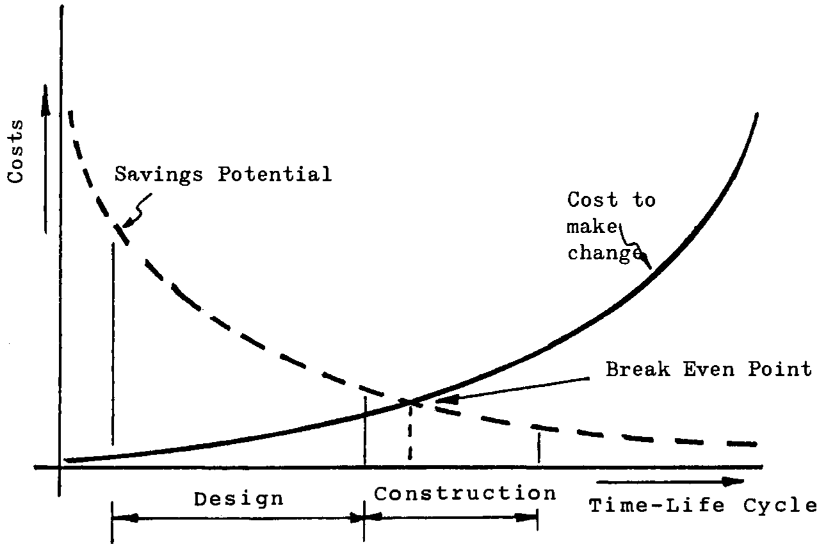
Effective plant operating hours averaged over the year 2500 x 1.886 = 4715 hours per year.

This approach can be adopted for any circumstances which modifies the actual hours of use of the various building services.

APPENDIX H



Decision makers with impact on total owning and operating costs.



Oportunity for changes and impact on total owning and operating costs

Energy Conservation in New South Wales Hospitals

J.W. Ellis
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NSW Hospital Planning Advisory Centre

Summary

Energy represents only 1%-2% of the annual cost of running a hospital. However, the total cost of energy for the 300 hospitals and associated laundries in N.S.W. is significant, $29.1 million in 1981-2. This paper outlines the problem, HOSPLAN's approach to solving the problem and our results to date.

Introduction

Accounting procedures in New South Wales hospitals have, traditionally, recorded annual energy consumption and costs. Listed as "fuel, light and power" in the total maintenance expenditure, the amount has been small. As a proportion of the total running costs, the amount has been generally less than 2% and almost insignificant in comparison with wages and salaries which usually account for 70-75% of the total. Recording the data, however, was often the last consideration the figures were given.

In the mid 70's when the cost of energy began to assume some importance HOSPLAN surveyed hospitals in New South Wales to review energy consumption and costs.

Early Surveys

The first survey, in 1976, covered the year 1974-75. 60% of hospitals responded. In 1980 a second survey was undertaken to cover the years 1976-7, 1977-8 and 1978-9. Over 95% of hospitals responded and the results were computerised. This allowed trends in consumption and prices to be established on a state-wide, regional and hospital basis. Since 1980 a survey has been conducted annually, with the results and recommendations published and circulated widely within the Department of Health and hospitals.

The early surveys quantified what was suspected. Energy consumption was increasing by about 16½% p.a. and costs were increasing by about 19% pa. By 1979-80 hospitals were consuming 6215 TJ per annum. This represented 170GJ per bed per annum at a total cost of $20.023 million. The trend by this time showed that by 1981-2 consumption would be 190GJ per bed

TABLE 1 - N.S.W. HOSPITALS - DISTRIBUTION OF RUNNING COSTS

	Royal Prince Alfred Hospital	Westmead Hospital	Sydney Hospital	Broken Hill District Hospital	Bellinger River Dist.Hosp.
No. of beds	1147	827	323	260	70
Salaries & Wages %	72.9	71.3	75.7	79.4	78.3
Provisions %	2.4	2.3	1.7	2.2	2.1
Drugs & Surgical Supplies %	7.9	7.9	7.7	3.5	2.7
Fuel, Light and Power	1.0	2.5	1.0	2.7	2.7
Domestic charges %	1.8	3.3	2.7	1.4	3.7
Special departments %	3.4	5.4	2.0	1.4	1.9
Renewals,maintenance %	2.8	2.4	2.4	1.7	2.1
Administration %	7.8	4.9	6.7	7.7	7.5
Total Operating Costs	$95,700,000	$6,700,000	$37,900,000	$12,900,000	$1,900,000

TABLE 2 - MAJOR ENERGY FORMS % OF TOTAL

Energy Form	1974-5*	1976-7	1977-8	1978-9	1979-80
Electricity	10	15	15	16	17
Coal	70	57	56	55	52
Oil	14	23	21	19	16
Others	6	5	8	10	15
Total TJ				5705	6215

* Taken from data returned from 60% of hospitals in N.S.W.

1976-9 figures relate to 95% of hospitals in N.S.W

TABLE 3 - MAJOR ENERGY FORMS % TOTAL COST

Energy Form	1977-8	1978-9	1979-80
Electricity	55	55	55
Coal	20	17	14
Oil	18	19	18
Other	7	9	13
Total \$ x 10^6	15.4	17.8	20.0

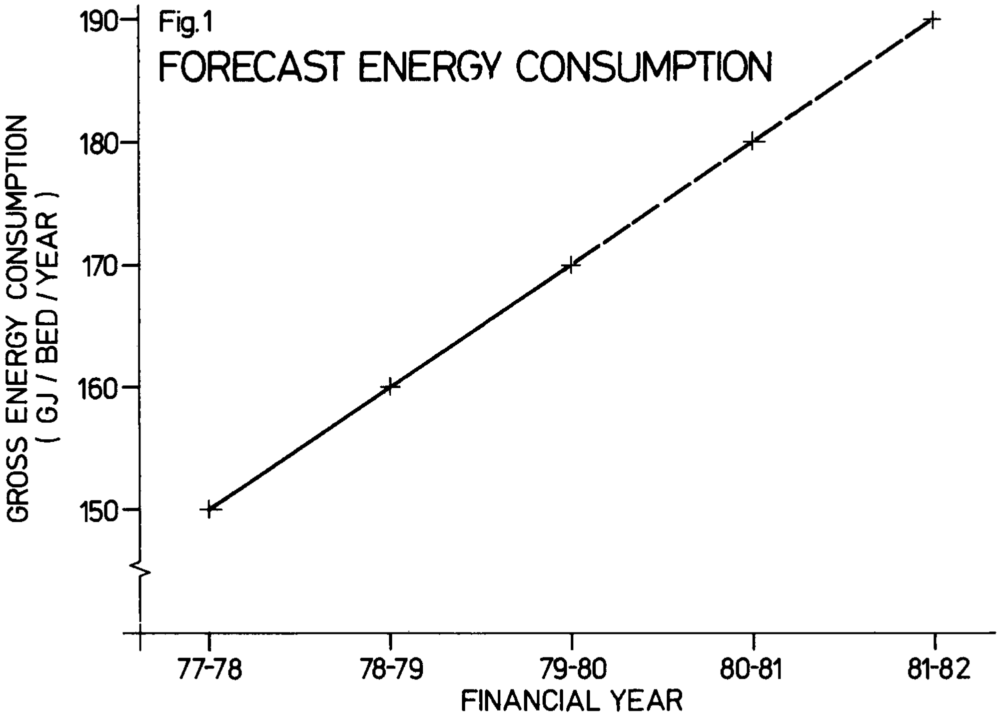

Fig. 1

FORECAST ENERGY CONSUMPTION

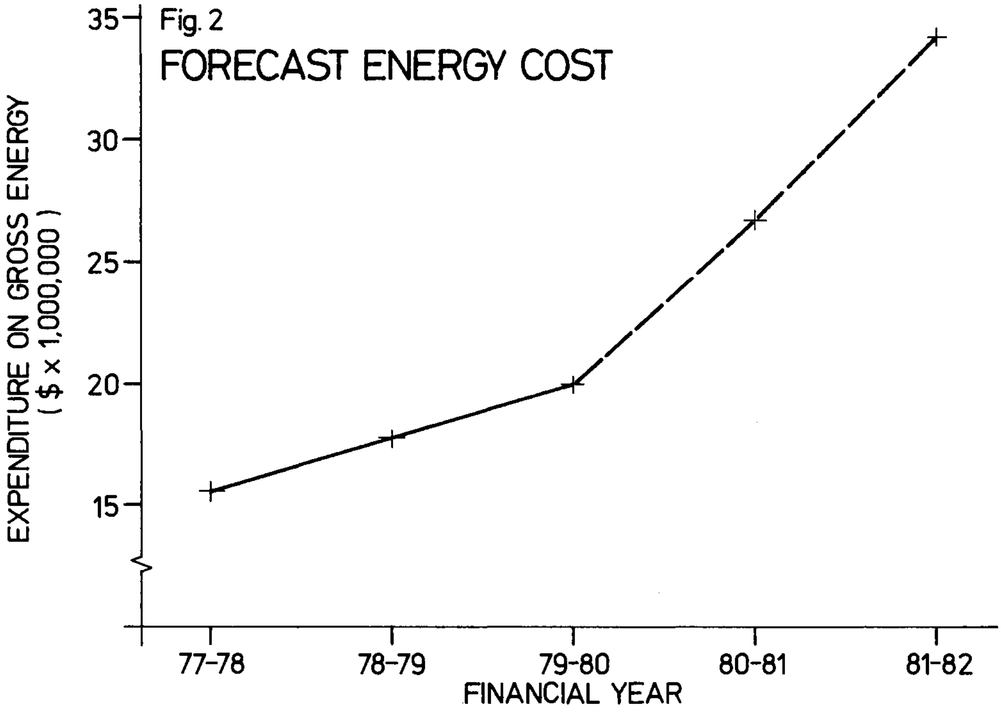

Fig. 2

FORECAST ENERGY COST

with a total cost of $34 million, nearly twice that of 1978-9.

Other aspects emerging from early surveys were the energy forms in use and trends in consumption. For many years large hospitals had been serviced by central coal fired boiler stations, with electricity for light and power in an 80:20 ratio. Town gas and oil were in restricted use.

During the 60's and early 70's life expired coal fired boilers were usually replaced with oil fired units.

Air-conditioning became more widespread.

Variations in fuel usage are given in Table 1.

Evident from the early surveys was:

a) Electricity, by far the highest cost energy form was increasing in consumption.

b) Oil consumption was increasing. Furthermore we knew that in the five years following 1976 we could expect prices to increase more rapidly than other fuels.

c) Coal, our only indigenous and plentiful fuel, was decreasing in popularity. Reasons included high cost of plant, and maintenance and labour charges associated with it as well as environmental problems with the fuel and ash.

d) Overall consumption was increasing for the same task.

Energy Policy Guidelines

Arising from information at hand in 1979 some energy policy guidelines were developed.

These were published in 1979 with the following objectives:

a) To achieve a wise use of national energy resources.

b) To achieve a rapid phasing out of transport grade fuels (oil and lpg) for stationary plant.

c) To encourage the use of thermally efficient buildings.

d) To ensure buildings and plant are operated with maximum efficiency.

e) To ensure that expenditure on energy conservation measures is cost effective on the basis of total costs (capital, fuel, operating and maintenance).

Implementation

Implementation of these policy guidelines looked at three broad areas:

a) Review of designs for new buildings and building services.

b) Review of existing energy systems to consider the most suitable fuel and style of operation.

c) Implementation of an energy management programme in hospitals to avoid waste.

System Review

The Department of Health have a process of planning for new construction and major modification. As Part of this process planners and designers are required to present an energy impact statement. The statement should provide information on:

a) Energy forms and systems proposed (for major tasks with estimates of annual consumption).

b) Estimated annual consumption of energy in MJ/m^2.

c) Details of architectural measures taken in design to reduce energy demand such as orientation, shading, thermal mass and insulation.

d) Present and future costs of ownership of options considered.

e) The case for central energy systems with reticulation, if recommended.

f) Special measures taken to achieve energy conservation.

g) Limitations preventing a more energy efficient design.

h) Provision of adequate controls and instrumentation to ensure efficient operation of plant.

i) Stand-by facilities, where applicable.

The impact statement is reviewed by a Committee which is chaired by HOSPLAN and with representation from Department of Public Works Health Section, the Institute of Hospital Engineers and Department of Health. The aim of this review is to prevent the construction of energy intensive buildings in the future. Westmead Hospitals and Royal Prince Alfred Hospital Phase 1A are examples.

Review of Existing Systems

This programme has been directed in the main, at reducing the dependence on oil as a boiler fuel. In 1977-8 oil consumption peaked at just over 30 million litres p.a. Natural gas has been the main alternative to oil. By 1981-2 oil consumption was below 18 million litres, a reduction of over 40%. We estimate that a further 4 million litres can be replaced with natural gas in the metropolitan areas, Newcastle and Queanbeyan.

Another approach has been to consider a boiler system in toto. Rather than just substitute a cheap fuel for an expensive fuel, the boiler station has been closed down and replaced with discrete units to service adjacent buildings. Generally, these conversions result in real energy savings by obviating reticulation losses and gaining financial savings through reduced manpower.

Another approach to conserving energy has been to reduce heat gain and heat loss through ceiling insulation. Very few country hospitals have any ceiling insulation and a policy statement on insulation has been circulated giving guidance in the type and thickness for different parts of the State.

Operation Energy Watch

Prior to 1982, implementation of the Energy Policy was limited to the acivities described above with some seminars and visits to hospitals. Much of this approach brought only the significance of energy management to hospital administrators. It was not until early 1982 that HOSPLAN was able to launch a definite campaign to deal with energy management. Operation Energy Watch was aimed at hospitals to give guidelines for energy management within each hospital. The objectives of the Energy Watch Programme are:

- to establish 'base' energy consumption figures. The average consumption for the three years 1977-80 was used.

- to hold energy usage at the level of June, 1979. This was part of N.S.W. Government policy.

- to achieve 20% reduction in the use of imported fuels from June 1982 to June 1983.

- to reduce the average energy consumption of 1981-2 to 3% below the base year (average for 1977-80).

- to achieve a further 10% reduction in energy consumption by the end of the year 1982-3.

- to reduce the maximum demand and electricity consumption a minimum 15% by the end of 1982-3.

- an ongoing committment by all hospital staff to continue to reduce energy consumption by all means at a rate of 3% per year until the end of 1985-6.

The programme was launched with the publication of a 25 page booklet being circulated to all hospitals. Representatives of 30 large hospitals and those considered energy intensive were invited to a seminar on how to achieve the objectives of the programme.

We gave six steps.

i) Select the energy management team and set the policy for the hospital.

ii) Survey the hospital.

iii) Complete an energy audit, identify energy saving opportunities, costs and potential savings.

iv) Complete the energy management plan.

v) Implement the plan.

vi) Set up ongoing energy management and maintain the plan.

None of the information was new, however the idea of putting known practice into a booklet for hospital use was new.

Specific Projects

a) Fairfield Energy Audit

An audit of the steam raising and reticulation system was conducted at Fairfield District Hospital. The detailed results were published by HOSPLAN. We found that in summer, this hospital with a central boiler station lost:

- 29% in combustion losses
- 22% in reticulation losses
- 19% in steam leaks and open tank losses

allowing 30% available for useful heating.

b) Boiler Efficiency

When it was realised that few hospitals had any method of checking combustion efficiency HOSPLAN undertook the testing of 26 boilers in 18 Sydney hospitals. A portable digital read out analyser was used. All boilers tested were found to be operating with high excess air. Some gas fired boilers were found to be more than 10% below optimum combustion efficiency. We were able to demonstrate that hospitals spending more than $15,000 p.a. on boiler fuel should acquire some form of portable testing instrument.

c) Electrical Load Management

Traditionally hospitals have puchased electricity from supply authorities on an institution tariff, which is generally 65% of the general supply. In recent years, with increasing consumption, other tariffs have become more attractive, particularly demand tariffs. Some hospitals have been able to purchase electricity more cheaply simply by changing to a demand tariff. A recent study showed that 45% of hospitals, responsible for 86% of electricity consumption, could benefit from purchasing electricity through a demand tariff. Factors prompting interest in this study include the dramatic changes in electricity purchasing charges, the phasing out of insitution tariffs and the availablility of microprocessors for electrical load management. The use of a microprocessor to control maximum demand and power consumed by a hospital can reduce costs by 20% if properly selected, connected and programmed.

Further cost savings are attainable through power factor correction equipment.

In the past six months a concerted effort has been initiated to raise awareness of the benefits of electrical load management.

d) Air-conditioning Management

Awareness of energy management has made many engineers consider the wastage of energy in air-conditioning systems. HOSPLAN has prepared a booklet on the management of air-conditioning. We have approached this problem by advising hospitals that we are certain that existing systems are wasting energy.

This could be caused by one or more of:

- poor maintenance
- incorrect settings
- reheat and dual duct systems not modified.

The booklet suggests methods of easing the load through window shading, ceiling insulation and lighting levels. There is discussion on economiser cycle, using outside air for cooling and control of equipment running hours through a microprocessor. A large portion of the book gives guidelines to system modification. Dual duct and reheat systems should be modified to have heating shut down in warm weather and cooling shut down in cold weather.

TABLE 4 - ENERGY CONSUMPTION - KIAMA DISTRICT HOSPITAL

		1977-8	1978-9	1979-80	1980-1	1981-2
Electricity	MWh	211	210	240	585	588
Oil	kL	162	108	69	-	-
Town Gas	GJ	344	399	1511	1670	1409
Gross Energy	GJ	7190	5195	4981	3775	3526

Energy consumption following closure of boiler station and replacing with electric space heating and water heating.

TABLE 5 - OIL CONSUMPTION

	Consumption ML	Savings following NG substitution
1977-8	30,012	-
1978-9	30,523	-
1979-80	25,182	$312,000
1980-1	21,531	$1,484,000
1981-2	17,691	$2,256,000

TABLE 6 - ELECTRICITY CONSUMPTION

	Consumption MWh	$ x 10^6
1977-8	221174	N.K
1978-9	273331	9.27
1979-80	300323	11.03
1980-1	317499	13.38
1981-2	314330	16.77

The reduction in consumption in 1981-2 is significant. If trends had been maintained it is estimated a further 15.5 GWh would have been used at a cost of $821,000 above the cost shown.

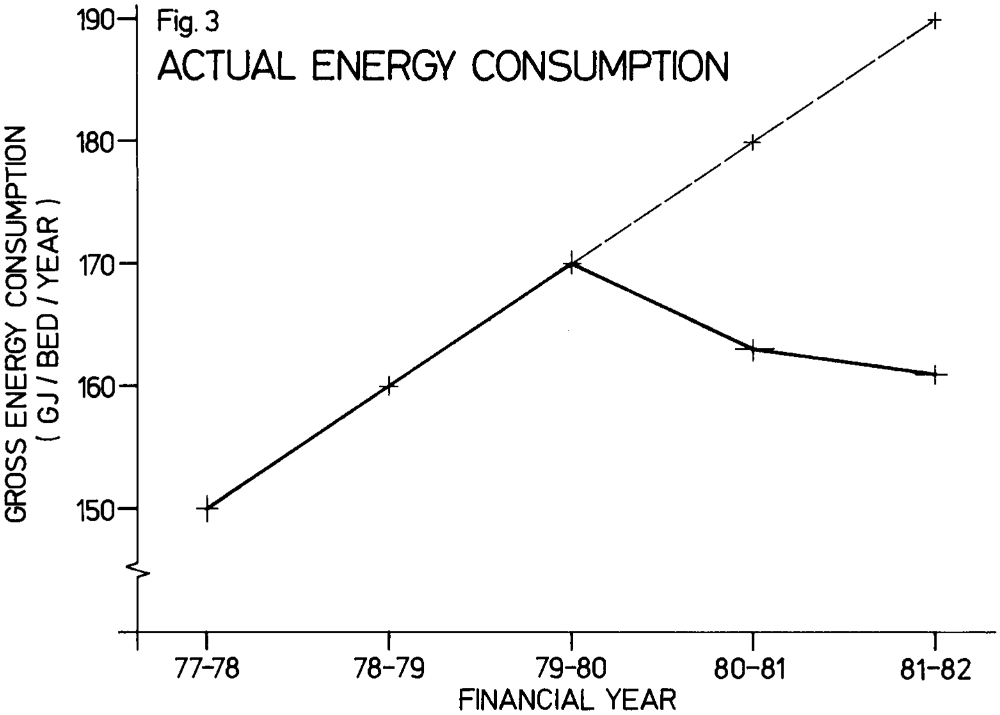
Fig. 3
ACTUAL ENERGY CONSUMPTION
GROSS ENERGY CONSUMPTION
(GJ / BED / YEAR)
190
180
170
160
150
77-78
78-79
79-80
80-81
81-82
FINANCIAL YEAR

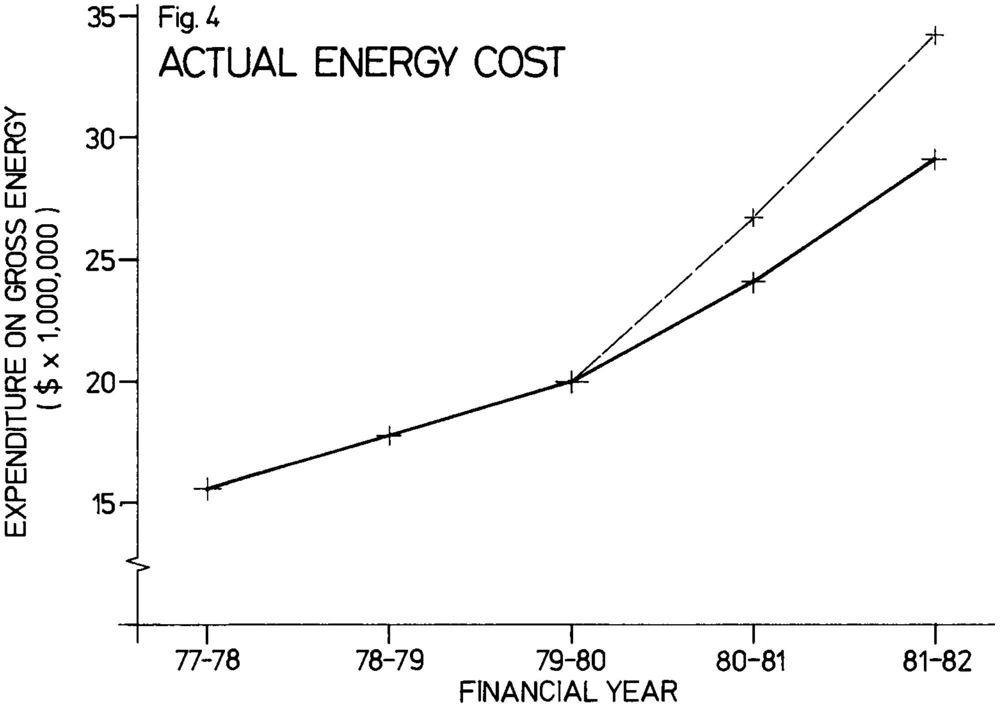
Fig. 4
ACTUAL ENERGY COST
EXPENDITURE ON GROSS ENERGY
($ x 1,000,000)
35
30
25
20
15
77-78
78-79
79-80
80-81
81-82
FINANCIAL YEAR

e) Alternative Energy Forms

The rebuilding of the 100 year old hospital at Jerilderie provided the opportunity to investigate the economic and technical feasability of using solar energy to provide much of the heating, cooling and hot water requirements of a small country hospital. The Department of Health accepted the additional installation costs and HOSPLAN obtained a grant from NERDDC to monitor the system performance. The new hospital was opened in September 1981 and the solar powered air-conditioning system was commissioned in May, 1981.

Although the system is functioning satisfactorily, monitoring has not. We have been plagued with problems arising from acceptance of the lowest priced data logger.

Broadly, the system provides cooling for 1100m^2 and heating for 1300m^2, and about 1000L of domestic hot water daily. 175 panels with an area of 331m^2 form the northern roof and fire two 10T absorption chillers.

The system is backed up by an oil fire boiler.

Results

The results are probably best illustrated in tabular and graphical form.

Table 4 shows the results of reviewing oil consumption in a central, manned boiler station. Benefits include a substantial reduction in energy consumption and a diversion of manpower to useful tasks in the hospital.

Table 5 shows the results of converting oil fired boilers to natural gas. This is purely a cost saving exercise with oil consumption now 40% less than 1878-9.

Table 6 shows the results of promoting an electricity conservation campaign.

In all, gross energy per bed was reduced by 4½% in 1980-1 over the previous year, and by a further 0.5% in 1981-2.

In 1982 HOSPLAN entered a submission in the National Energy Management Award Scheme. There are six categories for consideration. HOSPLAN won the award for Energy Management Services.

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Energy Audits, Their Evaluation and Conservation Measures

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ABSTRACT

Energy Audits include a field survey of the existing conditions as well as the methods of maintenance and operations and also engineering analyses to determine annual savings achieved from implementing changes. A brief summary of what to look for and what energy conservation measures can be implemented is presented. Typical examples of the engineering analyses for implementation of changes in infiltration, ventilation, domestic hot water, heating and cooling system, heating primary equipment, lighting and insulation are provided.

INTRODUCTION

In the United States of America, the passing of the National Energy Conservation Policy Act in 1978, with resulting grant programs to promote energy conservation, has led to establishment of more or less standardized procedures for making energy audits and for preparing engineering analyses of potential energy savings resulting from installation of energy saving devices or systems or for energy saving changes in operational and maintenance procedures. The collection of the data and the engineering analyses are termed an "Energy Audit". The collection of data requires a survey of the building to identify the type, size, energy use level and major energy using systems. It also reports on operation and maintenance practices. The engineering analyses determine the appropriate energy conservation (usually in terms of annual savings) for installing energy conservation measures and for modifying operational and maintenance procedures.

Successful energy conservation requires an organized energy management program. Fig. 11.1 depicts the typical public office building energy usage. Successful energy management involves managing the function indicated in this figure to accomplish a reduction in the major energy usages. As can be seen from this figure, the heating and cooling requirements constitute 76 percent of the total energy used. Lighting also affects the heating and cooling requirements since lamps not only provide light, but they emit heat. Thus the energy audit is primarily concerned with the heating and cooling systems and those factors or conditions, whether building construction or operational and maintenance procedures, that affect these systems. There are seven basic factors that affect heating and cooling. These are illustrated in Fig. 11.2. After these factors are discussed, the procedures for surveying a building and collecting data as well as for engineering analyses of this data are treated. For purposes of illustration, examples are based on a college building in the State of New York.

SEVEN FACTORS WHICH AFFECT HEATING AND COOLING

Why is a building heated or cooled? The obvious answer is to maintain a fixed comfortable temperature in the building space. But what is really being done is compensating for heat loss or gain. Some of this loss or gain can be saved by increasing the efficiency of the heating and cooling system or by modifying those factors which affect heat losses and gain in the building. While heat is generally lost in winter and gained in summer because of climatic conditions, all building systems affect this flow of heat. The seven factors which contribute to the flow include:

Infiltration Infiltration is the flow of outside air into the building through existing openings (e.g., gaps between doors or windows and their frames, open doors or window, etc.). Three factors affect infiltration:

a. The size and number of building cracks and openings.
b. The speed and direction of the wind.
c. Negative pressure systems. (When more air is exhausted than is brought in by the ventilation system, infiltration increases).

Areas most likely to suffer from infiltration problems in buildings include lobbies and/or delivery entrances. These doors are often open, and usually don't seal well when closed.

Infiltration cools the building space in winter and heats it in summer. This results in increased heating and cooling requirements, respectively.

Heat Transmission This is the heat which flows into or out of the building through its exterior surfaces, including outside doors, walls, windows, floor and roof. Heat always flows from areas of high temperature to areas of low temperature. Therefore, heat flows out of the building in winter and into the building during the summer. The rate at which heat enters or leaves a building increases as the temperature differences between the inside and outside air increases. The composition and insulating value of the exterior surfaces also affect the amount of heat flow.

Ventilation In order to reduce odors and smoke, and to maintain comfort inside the building a portion of the air is continually exhausted and replaced by outside air. The amount of ventilation is normally measured in cubic feet per minute (CFM). Unlike the infiltration air, ventilation air is normally conditioned before it is introduced into the building space.

Lighting In addition to providing light, lamps also emit heat. The amount of heat can be determined from wattage ratings on the lamps. Heat of light is generally beneficial in winter because it decreases the load on the heating system. However, heat from lighting increases the load on the cooling system in summer.

Solar Heat Solar energy adds heat to the building all year round. The amount of heat received depends upon:

a. The position of the sun. This varies with geographical location, season, and time of day.

b. The building envelope. This includes building orientation, shading, and the type, texture, and color the building's exterior surfaces.

Equipment All types of power equipment contribute to heat gain inside a building. This includes typewriters, cash registers, vending machines, manufacturing equipment, etc. Many pieces of equipment are rated in watts, and the heat given off is proportionate to the wattage values. Motors are sized by horsepower and one horsepower is equivalent to 746 watts.

Occupants Since a desirable room temperature is less than body temperature (98.6°F) occupants of a room contribute to the heating of a space. This can be significant whenever large numbers of people are involved. Our bodies also emit moisture by perspiration and exhalation.

A combination of the above seven factors creates the heating or cooling load which must be met to maintain building conditions.

Many of these factors can be modified when they adversely affect the performance of the heating and cooling systems. Savings achieved by examining all seven factors can be considerably greater than those obtained by simply lowering thermostats.

To Summarize:

		FACTOR	WINTER	SUMMER
Increases energy consumption all year	1.	Infiltration	Adds Cold	Adds Heat
	2.	Transmission	Adds Cold	Adds Heat
	3.	Ventilation	Adds Cold	Adds Heat
Decreases energy consumption in winter, increases in summer.	4.	Lighting	Adds Heat	Adds Heat
	5.	Solar	Adds Heat	Adds Heat
	6.	Equipment	Adds Heat	Adds Heat
	7.	Occupants	Adds Heat	Adds Heat

COLLECTION OF DATA

The collection of data starts prior to the field survey. This includes determination of energy use from energy bills, examination of building plans to become familiar with the construction, talking with the building personnel involved to have advance information of operational and maintenance practices and if maintenance logs are available, and preparing appropriate forms for recording data. Preliminary analyses can also include a look for trends or discrepancies in energy use and costs, a determination if current utility billing rates are typical for this type of building and an establishment of any excessive demand changes.

The on-site inspection must first establish the validity of the building plans including construction and mechanical and electrical systems. Renovations and additions are common. The following energy audit checklist is provided below as typical items to cover. The list is not complete since there are probably many other potential items. Work sheets and forms are available from various governmental agencies that are more comprehensive than the checklist provided which summarize the more important items.

Infiltration Items to be Checked

Improper alignment and operation of windows an doors allow excessive infiltration.

Weatherstripping and caulking around windows, doors, conduits, piping, exterior joints, or other areas of infiltration are worn, broken or missing.

Windows and doors open while heating or mechanically cooling.

Door closers do not work rapidly and positively.

Ventilation Items to be Checked

An excessive quantity of outdoor air is used to ventilate the building.

Outdoor air intake dampers open when building is unoccupied.

Ventilation systems are not utilized for natural cooling capability.

Exhaust system operation is not programmed.

Return outdoor air and exhaust dampers are not sequencing properly.

During heating season, temperature of air flow to space feels too cold.

Air flow to space feels unusually low or is inconsistent from one space to another.

Air filters and registers are dirty.

Individual bathroom exhaust fans not wired to light switches.

Heating Items to be Checked

Multiple boilers or heaters fire simultaneously.

Excessive expanses of glass exist on exterior walls.

There is no insulation between conditioned and unconditioned spaces.

Ceiling/roof insulation is inadequate or has been water damaged.

Water in heating system is heated when there is no need.

Space temperatures are higher or lower than thermostat settings.

Heating system's hot water temperature feels excessively hot during periods of mild weather.

Condensate from street steam is being discharged to sewer drain.

Heating pilot lights are on during cooling season.

Steam, condensate and heating water piping insulation is in disrepair or missing.

Air is not humidified.

Burner short-cycles.

Combustion air to boiler/furnace is not preheated.

Hot water radiation units fail to operate.

Radiators, convectors, baseboards and finned-tube heaters are not providing sufficient heat.

Thermostats on heating/cooling units are vulnerable to occupant adjustments.

Thermostat settings have not been adjusted for change in seasons.

Unoccupied or little used areas are heated or cooled unnecessarily.

Off-hour activities are not scheduled for efficient energy utilization.

Building temperatures are not adjusted for unoccupied periods.

Heating/cooling equipment is started before occupants arrive and/or is operating during last hour of occupancy.

Heating/cooling equipment is operating in lobbies, corridors, vestibules and/or other public areas.

Conditioned air or heated water is discarded.

Cooling Items to be Checked

Space temperature is higher or lower than thermostat setting.

Chiller is operating during cold weather to provide air conditioning.

Reheat coils are used to maintain zone temperatures.

Multiple air conditioning compressors start at the same time.

Building utilizes a dual duct or multizone system.

Insulation on cooling line pipes and ducts appears inadequate.

Air conditioning load trips circuit breaker on extremely warm days.

Air of inadequate volume or temperature is being discharged through grilles.

Refrigeration condensers or coils are dirty, clogged and or not functioning efficiently.

Chilled water piping, valves and fittings are leaking.

Chiller operation is not optimized (listen for short-cycling).

Refrigeration compressor short-cycles.

Refrigeration compressor runs continually (direct expansion systems).

There is no economizer cycle.

Unitary air conditioners not shut when building closes.

Lighting Items to be Checked

Incandescent lamps are used in offices, workrooms, hallways and gymnasiums.

In fixtures where fluorescent lamps have been removed, the ballasts have not been disconnected.

When burned out fluorescent lamps and/or ballasts have been replaced more efficient lights have not been installed.

Lamps and fixtures are not clean.

Exterior lighting is used.

Lights are on in unoccupied areas.

Natural lighting is not optimized.

Two lamps have not been removed from four-lamp fixtures where possible.

Windows are not clean.

Banks of lights switches are not labeled.

Water Supply Items to be Checked

Storage tanks, piping and water heaters are not utilized efficiently.

Drips or leaks are evident in hot water systems.

Electric water heater has no time restrictions on heating cycle.

Devices to conserve heated water have not been utilized where practical.

Check efficiency of oil or gas fired equipment.

Raise chilled water temperature settings on water fountains.

Temperature of domestic hot water heater is excessive (greater than 105^{O}F unless required for sanitary reasons).

Install solar domestic hot water heating system.

Operational and Maintenance Items to be Checked

Use of equipment associated with laundry and custodial services coincides with heavy electrical demand periods.

Blinds and curtains are not used to help insulate the building.

No records of maintenance for motors and motor driven equipment are available.

Control devices are not inspected on a regular basis.

Stack temperature appears excessively high (greater than 400^{O}F plus room temperature).

Operation of oil burner is accompanied by excessive smoke and sooting.

Soot and odors are detected in areas where they are not.

ENGINEERING ANALYSES

As part of the Energy Audit an engineering analysis is required for each item that energy conservation measures appear possible to determine if there is a payback, its amount, and whether the measure should be implemented. In many cases, a savings is possible just by a change in operational procedures. Examples of the applicable engineering analysis follow for specific problems under the subjects of infiltration, ventilation, domestic hot water, heating and cooling system, heating primary equipment, lighting and insulation. In all cases, unit costs are established only for illustrative purposes.

Infiltration Infiltration is defined as the unwanted outside air that migrates or leaks into the building through cracks and openings in the building. This unwanted air must be heated or cooled, this adds to the normal energy load of the building. Infiltration losses are more significant in buildings where internal or static pressure is less than the exterior or ambient pressure. This is the common condition in buildings which have more exhaust capacity than intake air. For the most part repairs and modifications that will reduce infiltration losses are cost-effective and will result in monetary savings and increased occupant comfort. Energy conservation measures under the heading of infiltration include the following:

1. Repair all broken and missing glass.
2. Realign and refit poor fitting doors and windows.
3. Adjust and repair sealing gaskets.
4. Repair old and missing putty on all glass.
5. Adjust automatic doors and windows.
6. Weatherstrip doors and windows.
7. Install temporary storm windows.
8. Repair worn top, bottom and side seals on revolving doors.
9. Post signs on exterior delivery doors providing instructions on operating.
10. Caulk all places air can leak into building.
11. Install storm windows and doors.
12. Install automatic door closers on exterior doors and doors to unheated areas.
13. Install revolving doors at main entrance.
14. Construct vestibules at all entrances.
15. Reduce number of entrances.
16. Reduce height of or eliminate existing windows.
17. Reconstruct delivery entrances to reduce size.
18. Construct expandable enclosure at truck dock.
19. Install winter covers on window-mounted air-conditioning units.
20. Install insulation in unused through wall air-conditioner sleeves.
21. Install tight closing dampers on all intakes and exhausts.
22. Reduce stack effect (for tall buildings).

As typical examples of engineering analyses the annual savings derived by installing storm windows is shown in Fig. 11.4 and the annual savings for installing weather stripping around windows is shown in Fig. 11.5.

Ventilation The mechanical ventilation system will usually offer the greatest potential for energy savings in any educational building. A large percentage of these savings can be accomplished by operational changes at little or no cost. The ventilation system in most buildings is designed to provide considerably more ventilation air than the minimum required by local building codes. Additionally, the ventilation problems in educational buildings are compounded by the fact that different areas of the building require different amounts of ventilation air based on usage, hours of occupancy and occupancy rates. Considering that all air introduced into a building must be heated or cooled, significant amounts of energy can be saved simply by reducing ventilation rates and/or shutting off the ventilation system when it is not needed. For example, a 1000 CFM exhaust fan running 12 hours per day, exhausts approximately 65 million Btu's of energy into the outside air per year. This is equivalent to wasting 500 gallons of fuel oil.

The following list of measures will aid in achieving significant energy savings:

1. Reduce ventilation rates to lower acceptable level.
2. Operate ventilation units only as needed.
3. Reduce ventilation (introduction of outside air) rates to "odor" areas.
4. Close outdoor dampers during building initial heat-up or cool-down.
5. Reduce the amount of exhausted air.
6. Inspect (and repair if required) condition and operation of outside air dampers.
7. Change filters.
8. Operate equipment exhaust hoods only as needed.
9. Reduce quantity of air exhausted by hoods.
10. Install incremental time clocks on exhaust ventilation fans in special facilities areas.
11. Vary ventilation air to match occupant load.
12. Reduce toilet exhaust when toilet is not in use.
13. Supply only minimum ventilation air to seldom used areas (storerooms, parking garages).
14. Install 24 hour clocks on exhaust fans.
15. Add warm up and/or cool down cycle to air handling units.
16. Reduce fan speed.
17. Install filters in equipment that do not presently have filters.
18. Reduce resistance to air flow in duct systems.
19. Install baffle to prevent wind from blowing into outdoor air intake.
20. Supply outside air directly to exhaust hoods.
21. Isolate hood exhaust systems.
22. Isolate rooms requiring precise environmental conditions.
23. Recover heat from exhausted air.

A typical example is given in Fig. 11.6 illustrating the annual saving achieved for reducing operating hours of ventilation fans.

Domestic Hot Water The amount of energy required for heating hot water for domestic uses in public buildings such as schools can vary from about 2% to as high as 25% of that required to heat the building. This variation is a function of the different uses of space within the structure. In the instance of dormitories the percentage of hot water energy utilization could be at the upper range, while in classroom buildings it would be lower.

A listing of energy conservation measures associated with use of domestic hot water follows:

1. Reduce water temperature.
2. Inspect and test (and repair if necessary) hot water controls.
3. Turn off domestic hot water supply to areas that could function without hot water.
4. Repair all leaks.
5. Reduce the amount of hot water used.
6. Check combustion efficiency of separate oil or gas fired boilers used during the summer only.
7. Check boiler water level (and adjust if necessary) on immersed coil water heaters.
8. Install hot water temperature controls.
9. Shut off re-circulation system pumps during low demand periods.
10. Reduce water pressure.
11. Shut off hot water heaters during unoccupied periods.
12. Install separate "summer" boiler to heat hot water if water is heated in large space heating boiler.
13. Decentralize water heaters.
14. Heat water during off-peak demand periods (this reduces demand costs).
15. Insulate hot water storage tank and insulate all hose pipes in the hot water feed line.
16. Install solar hot water heater.

Examples covering annual savings for stopping a hot water leak and for insulating a hot water tank are given in Fig. 11.7 and in Fig. 11.8 respectively.

Heating and Cooling System The heating and cooling system consists of all the piping, ducting, valves, controls and terminal units that transport the heating/cooling medium (steam, water or air) from the heating/cooling plant to the conditioned areas of the building. Significant savings in heating and cooling are possible simply by modifying the manner in which the systems operate. A listing of changes in operational practices is not included herein because of space limitations. A list of capital energy conservation measures follow:

1. Relocate improperly placed thermostats.
2. Install thermostats in each room or area.
3. Install night set-back thermostats.
4. Install automatic temperature control valves on radiators.
5. Install temperature reset controls on multi-zone systems.
6. Install controls to permit shutting off heat in unoccupied areas.

7. Install timer controls on cooling system.
8. Install economizer controls in central air conditioning units.
9. Insulate heating and cooling ducts.
10. Insulate all steam, hot and chilled water lines.
11. Install steam traps.
12. Convert terminal reheat system to variable volume system.
13. Reclaim energy from exhausted air.
14. Install solar powered air preheater.
15. Install solar powered water heaters.

Several examples of engineering analyses for changes in the heating and cooling system follow. An example illustrating the annual savings for repairing a steam trap is shown in Fig. 11.9. Fig. 11.10 shows the saving achieved by insulating a hot water pipe while Fig. 11.11 shows the annual savings achieved by insulating a warm air duct. The annual savings achieved by installing a night set-back thermostat is shown in Fig. 11.12. Fig. 11.13 illustrates the saving achieved by reducing the temperature.

Heating Primary Equipment The efficient operation of the heating system can yield significant energy savings. Much can be accomplished simply by incorporating changes in procedures for operating existing equipment and by the initiation of a proper maintenance program. Often the repair and adjustment of the equipment is accomplished on an as needed basis. This can result in many simple, however important, measures that are not attended to. Examples are: cleaning heat exchange surfaces, adjusting for peak combustion efficiency, repairing leaks and repairing insulation. The two major sources of energy waste in the heating plant are improper fuel air combustion ratios and improperly maintained equipment. Even without major modifications, a savings of 10 to 20% of heating plant energy can be achieved by proper operation and maintenance. The following operational and maintenance procedures and modification items indicate the energy saving measures that can be initiated to reduce energy consumption.

1. Check (and repair if necessary) boiler efficiency.
2. Optimize combustion flame.
3. Inspect exhaust stack for incomplete combustion and re-adjust fuel-air ratio as needed.
4. Adjust all automatic controls on boiler and burner.
5. Shut boiler pilot light off if boiler is not in use for long periods.
6. Inspect and repair insulation on boiler and tanks.
7. Check and adjust automatic fuel dampers.
8. Provide for a variable secondary air damper on natural draft boilers.
9. Provide for shut down of induced draft fan after burners shut down.
10. Adjust barometric damper control for proper draft.
11. Provide for closing of boiler doors and inspection openings when boiler is fired.
12. Repair faulty gaskets on boiler doors.
13. Remove soot from boiler surfaces.

14. Remove scale build-up in boiler tubes.
15. Chemically treat boiler water.
16. Monitor make-up water requirements.
17. Lower system pressure to minimum.
18. Clean rotary cup and nozzle.
19. Inspect (and repair) for fuel leaks.
20. Clean oil strainer.
21. Preheat fuel oil to highest recommended temperature.
22. In multi-boiler operations, operate only one boiler as long as it can satisfy load demands.
23. Do not operate stand-by boiler.
24. Install flue gas analyzer.
25. Install automatic flue damper and draft controls.
26. Isolate off-line boilers.
27. Install automatic water temperature control in heating system.
28. Install automatic boiler and water treatment system.
29. Convert gravity hot air heating systems to forced hot air systems.
30. Eliminate gas pilots.
31. Install soot blowers.
32. Install condensate return line or system.
33. Regulate electric heating elements to operate in stages.
34. Install turbulators or baffles on fireside of boiler.
35. Install heat exchanger in exhaust stack of heating system.
36 Preheat combustion air and boiler water.
37. Replace inefficient burners.
38. Install modular boilers.
39. Install viscosity controls.
40. Install a fuel oil day tank inside building to help preheat oil.

Boiler combustion efficiencies are shown in Fig. 11.14 for natural gas and oil fuels. The annual savings achieved for operating a clean boiler is illustrated in Fig. 11.15. An example of annual savings achieved for eliminating boiler scale build-up is shown in Fig. 11.16. Figure 11.17 illustrates the annual savings achieved by raising the combustion air temperature while Fig. 11.18 shows the savings achieved by eliminating a steam leak.

Lighting A typical school or college building utilizes over 40% of its total electrical consumption for lighting. It is possible to realize savings in this electrical consumption in most of these institutions by low cost measures such as "delamping" (reducing the wattage of bulbs). Delamping and relamping measures generally have a payback period of two years or less.

Following are a number of energy conservation measures, as well as operational and maintenance procedures, that are applicable to the several kinds of lighting found in educational facilities.

1. Delamp and remove ballast of unused fluorescent fixtures.
2. Relamp fluorescent systems with energy saving tubes.
3. Relamp unneeded incandescent fixtures.
4. Relamp incandescent systems with more efficient lamps.

5. Reduce exterior lighting.
6. Delamp dispensing machines.
7. Remove lens to increase lighting level permitting some delamping.
8. Keep lamps, lens and fixtures clean.
9. Clean room surface to increase light output.
10. Re-arrange work areas to concentrate similar areas of lighting requirements together.
11. Schedule routine maintenance and cleaning.
12. Install new lamp extenders.
13. Use low energy ballasts or Hi-Lo ballasts.
14. Replace incandescent lamps with fluorescent lamps.
15. Replace fluorescent fixture lens.
16. Replace fixture with higher efficiency lamps.
17. Install manual A.C. type snap switch for selective use.
18. Install low voltage remote master control switching system.
19. Install time clocks for lighting.
20. Install manual time switches for manual activation.
21. Install photo cells on exterior lights.
22. Install photo cells on interior perimeter lighting.
23. Install dimmers linked with photo cells.
24. Provide task area lighting.

Examples of the engineering analyses to compute the annual savings for reduction of lighting hours and for replacing incandescent with fluorescent lighting are illustrated in Fig. 11.19 and Fig. 11.20 respectively.

Insulation Heat always flows from a warmer area to a colder area. Unless it is retained, heat from the warm inside of a building will pass through the walls or roof to the colder outside. In the summer, the heat from outside will pass through the walls and roof into the building. Insulation creates a barrier that resists this heat flow. The measure used to determine a material's ability to conduct heat is "U value" and is expressed in Btu's per hour per degree Fahrenheit. The lower the U value of a material, the better is its insulating quality.

Insulating material is more commonly rated by its resistance to the flow of heat. This value is the "R value" of the material and the higher the "R" value, the better the insulating properties of the material. R is the reciprocal of U.

The heat loss through the walls, slab and roof of a building will depend on the type of construction. Regardless of construction type, uninsulated structures experience significant heat losses. These heat losses can be reduced by the installation of insulation. Generally, the thicker the insulation installed, the more the heat loss is reduced. In general, there are four distinct forms in which insulation is purchased: loose fill, batts and blankets, rigid board, and foamed in-place.

Energy conservation measures involving the use of insulation include the following:

1. Insulate exterior walls.

2. Insulate walls and floors between heated and unheated spaces.
3. Insulate"on-grade" slabs.
4. Insulate roofs.

Examples of the engineering analyses to compute the annual savings for insulating walls, for installing attic insulation, for insulating a roof and for insulating a basement floor are shown in Figs. 11.21, 11.22, 11.23 and 11.24 respectively. Figure 11.25 provides a matrix for judging different types of insulation while Figs. 11.26 and 11.27 show the change in U value when insulation is installed in various wall and roof and floor details.

SUMMARY

The examples of engineering analyses given illustrate that substantial energy conservation can be achieved by rather minimal capital expenditures. In addition, simple changes in operational and maintenance procedures can be made, that do not involve capital expenditures, that also result in substantial energy conservation. Most measures are based on common sense and can be easily instituted with an energy management program. This paper could be used as a guide for such a program.

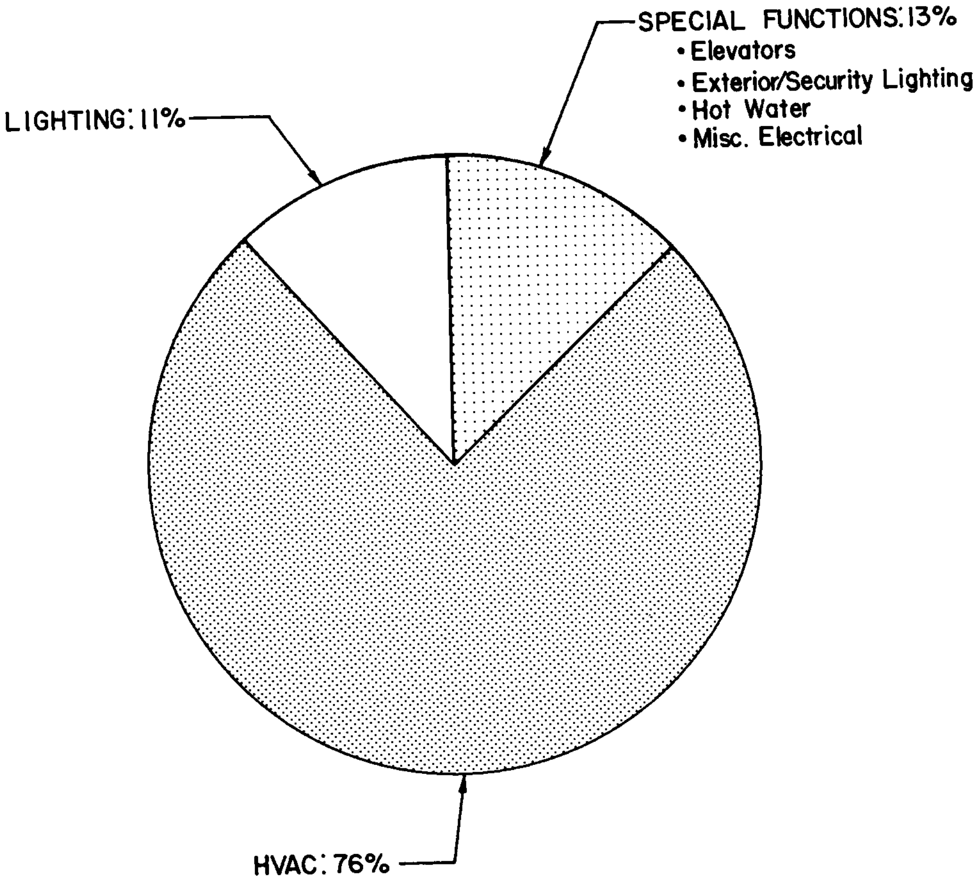


Fig. 11.1. Typical office building energy usage.

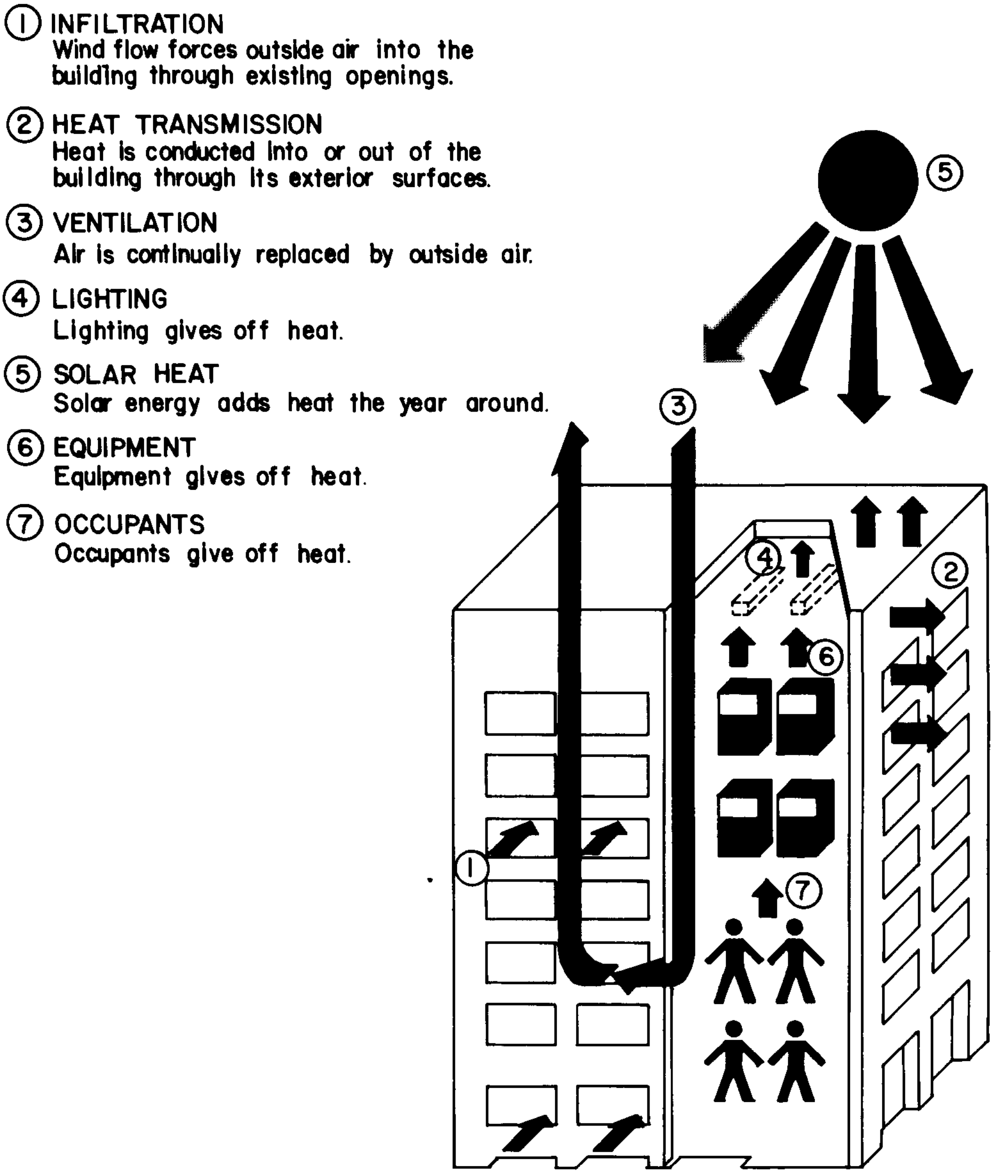


Fig. 11.2. Factors which affect heating and cooling.

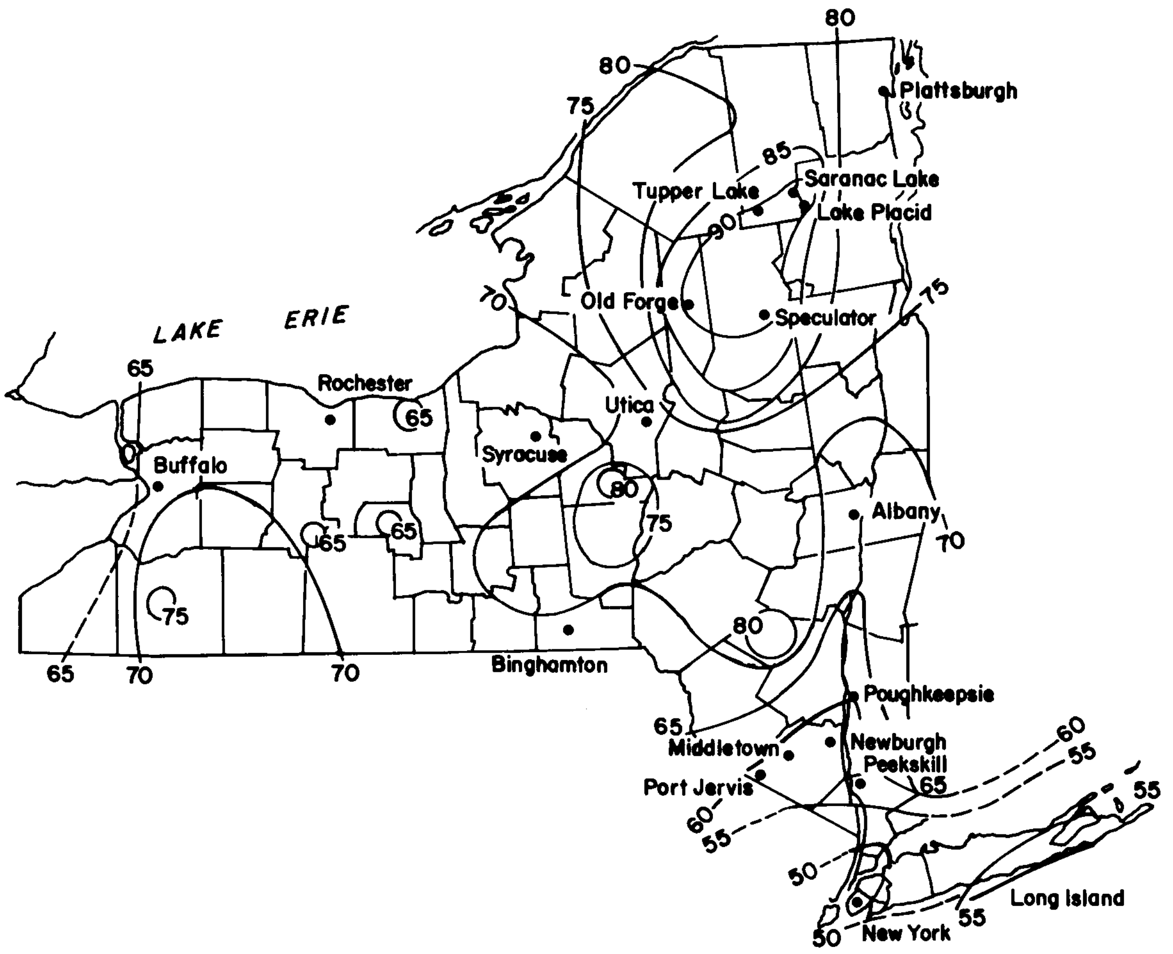
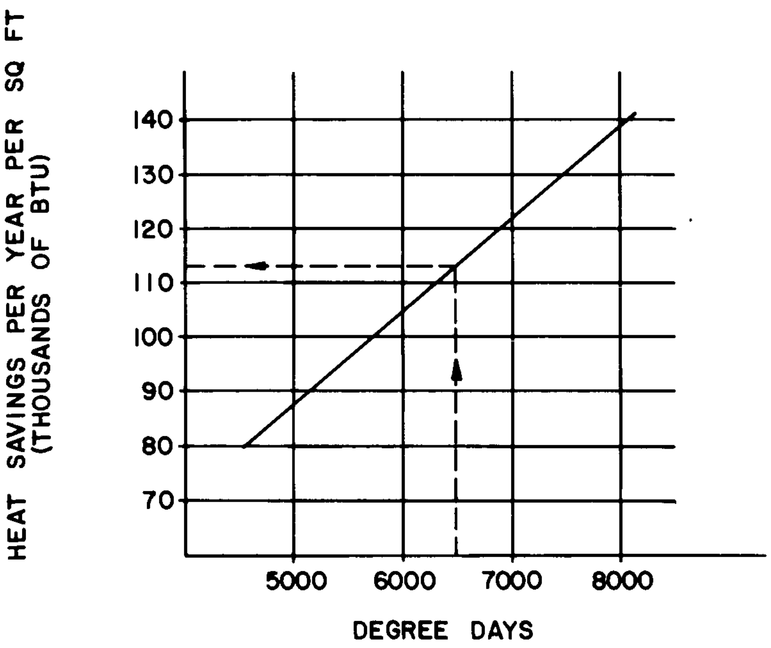


Fig. 11.3. New York State Degree day normals, in hundreds (1941-1970)



EXAMPLE:

Determine savings for 1,200 sq.ft. building located in Buffalo, N.Y., using No. 6 oil.

PROCEDURE:

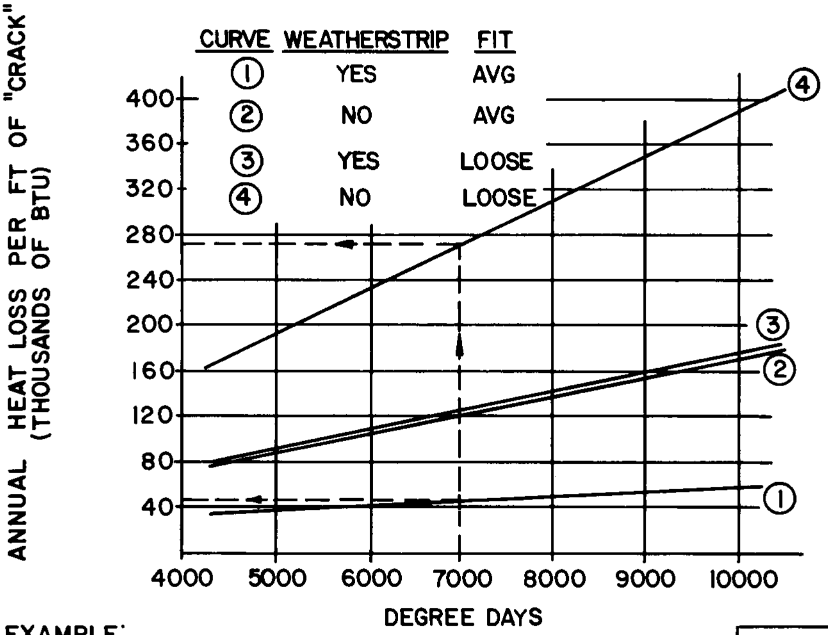
1. Obtain degree days from Map (Figure 3)
2. Enter Chart - determine heat saving = 113,000 Btu/sq.ft.
3. Annual fuel saving =

$$\frac{113{,}000 \times 1200}{.75(\text{system efficiency}) \times 149{,}700^{*}} = 1208 \text{ gallons}$$

*conversion from Btu to gallons for No. 6 oil

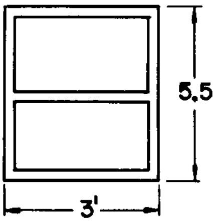
4. Saving = 1208 x $.60 (cost of 1 gallon of fuel) = $725

Fig. 11.4. Annual savings with use of storm windows.



EXAMPLE:

Determine savings by weatherstripping of 50 windows 5.5'x 3' each in a building located in Albany (7000 Degree Days), using No. 6 oil.



Double-hung Wood Window

PROCEDURE:

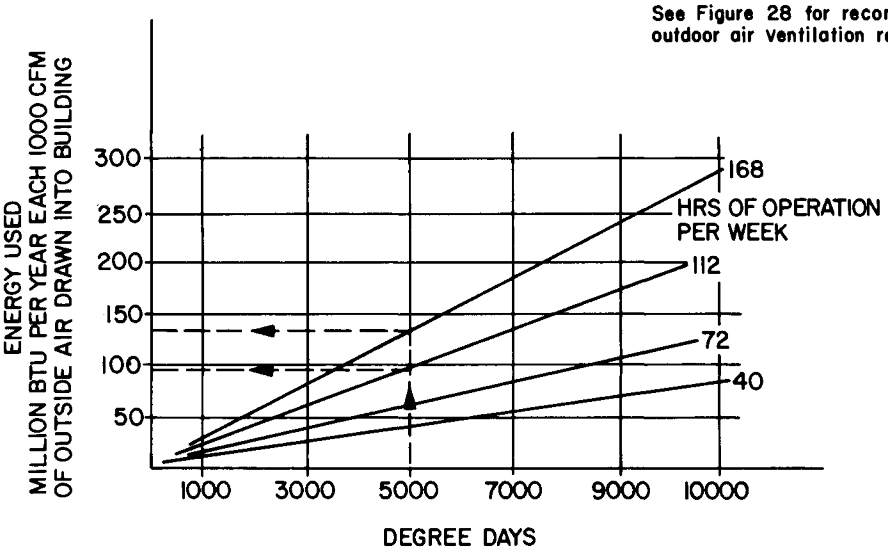
1. Total length of weatherstripping = 5.5 + 5.5 + 3 + 3 = 17 ft
2. $^1/_2$Total crack = $^1/_2$(50) x 17 = 425 ft
3. Enter Chart - determine heat loss for unmodified window - curve 4 = 270,000 Btu/ft, for modified window - curve 1 = 43,000 Btu/ft
4. Annual energy savings = (270,000 - 43,000) x 425 = 96.5 million Btu
5. Annual fuel savings =

$$\frac{96.5\text{million}}{.75(\text{system efficiency}) \times 149{,}700\,(\text{fuel conversion})} = 840\text{ gallons}$$

6. Saving = 860 x $.60 per gallon = $516

Fig. 11.5. Annual savings for installing weatherstripping.

See Figure 28 for recommend outdoor air ventilation rates



EXAMPLE:

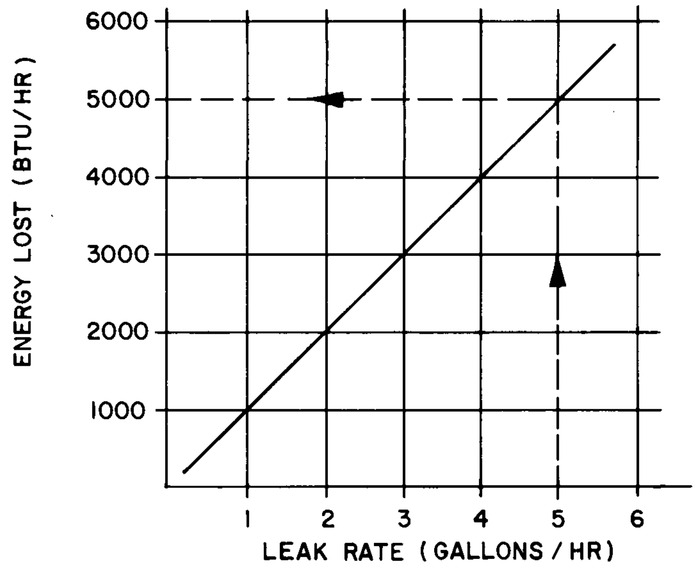
Determine annual savings by reducing the operating hours of 1,000 CFM of ventilation fans, from 168 to 112 per week, building located in New York City (5000 Degree Days) using No. 6 oil

PROCEDURE:

1. Enter Chart-determine energy used for 168hrs/wk = 137.5×10^6 BTU/yr per 1,000 CFM, and for 112 hrs/wk = 90×10^6 BTU/yr per 1,000 CFM
2. Annual energy saving = 47.5×10^6 BTU/yr per 1,000 CFM
3. Annual fuel saving = $\dfrac{47.5 \times 10^6}{.75(\text{system efficiency}) \times 149{,}700^*}$ = 423 gl/yr

   *conversion from Btu to gallons for No. 6 oil
4. Saving = 423 x \$.60 (cost of 1 gallon of fuel) = \$ 254 per 1,000 CFM

Fig. 11.6. Annual savings for reducing operating hours of ventilating fans.



EXAMPLE:

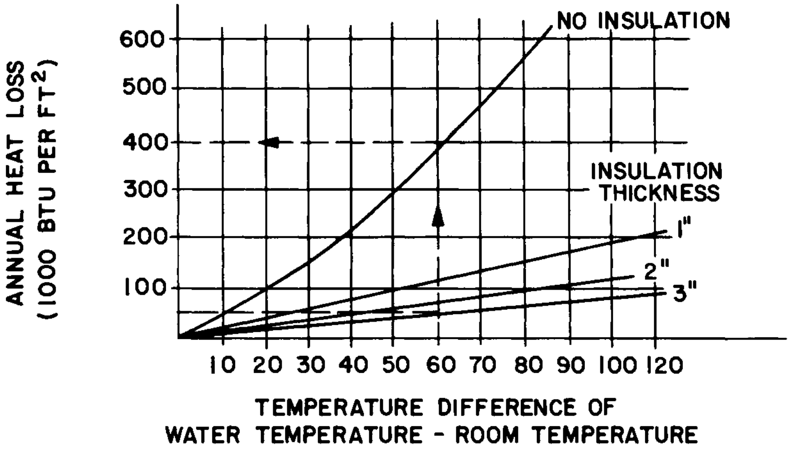
Determine annual saving by stopping leakage of hot water at the rate of 5gal./hr., using No.6 oil.

PROCEDURE:

1. Enter chart-determine energy loss for 5gal./hr. of hot water = 5,000 Btu/hr.
2. Annual energy saving = 5,000x365x24 = 44 million Btu
3. Annual fuel saving $= \dfrac{44\text{ million}}{.75\text{(system efficiency)}\times 149{,}000^{*}} = 392$ gallons

   *conversion from Btu to gallons for No. 6 oil
4. Saving = 392x $.60 (cost of 1 gallons of fuel) = $235

Fig. 11.7. Annual savings due to stopping hot water leak.



EXAMPLE :

Determine annual saving by insulating of hot water tank with 3" insulation, using No. 2 oil. Tank is 6 Ft. long x 3 Ft. dimater. Water temperture is 140°F, air temperature is 80° F.

PROCEDURE :

1. Enter chart - determine heat loss for 3" insulated tank and the uninsulated tank for 60° (temperature difference)
   3" Insulated - 40,000 Btu per year per ft^2
   Uninsulated - 400,000 Btu per year per ft^2

2. The difference in heat loss :
   400,000 - 40,000 = 360,000 Btu per year per ft^2

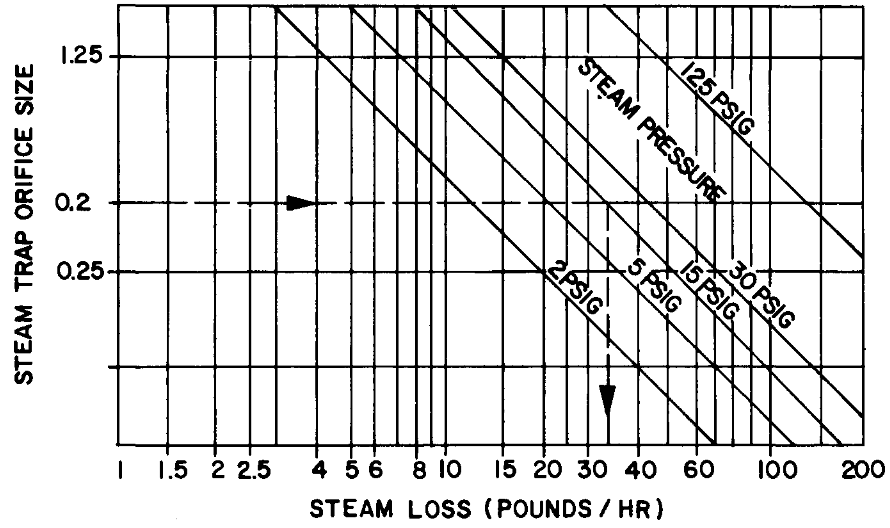
3. The exposed area of the tank :
   $(3.1 \times 3\,Ft) \times (6\,Ft + \frac{3\,Ft}{2}) = 70$ sq. ft.

4. Annuel energy saving :
   70sq. ft x 360,000 Btu = 25 million Btu's

5. Annuel fuel saving :
   $$\frac{25\,\text{million}}{75\,(\text{system efficiency}) \times 138{,}700^{*}} = 240 \text{ gallons}$$
   *Conversion from Btu to gallons for No. 6 oil

6. Saving = 240 x \$ .60 (Cost of 1 gallon of fuel) = \$ 144

Fig. 11.8. Annual savings for insulating hot water tank.



EXAMPLE:

Determine annual saving by repairing a steam trap in a building with an orifice size of 0.20" for a 15 PSI steam system. Steam is generated 30% of the total plant operating hours, 4,800 hours, using No. 6 oil.

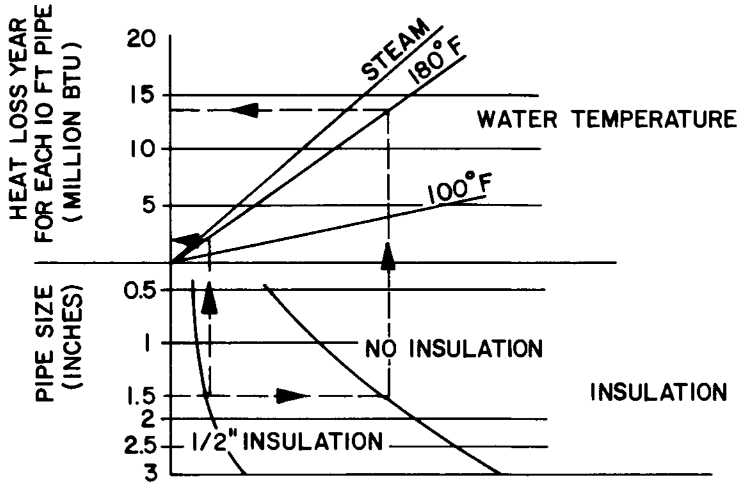
PROCEDURE:

1. Enter chart - determine steam loss - 35 pounds per hour
2. Annual energy saving = 35 x .30 x 4,800 x 1,000* = 50.4 million Btu
   *steam conversion number
3. Annual fuel saving =

$$\frac{50.4\text{million}}{.75\,(\text{system efficiency})\times 149{,}700^{*}} = 449 \text{ gallons}$$

   *conversion from Btu to gallons for No.6 oil
4. Saving = 449 x $.60 (cost of 1 gallon of fuel) = $269

Fig. 11.9. Annual savings for repairing steam trap.



EXAMPLE:

Determine annual Saving by insulating of 100 ft. long, 1½" diameter hot water pipe with ½" insulation. Water temperature is 180° F, heating fuel is natural gas.

PROCEDURE:

1. Enter chart-determine heat loss for each 10 feet of pipe-no insulation = 13 million Btu/yr, ½" insulation = 2.1 million Btu/yr
2. Annual energy saving =

   (13 million - 2.1 million) x 10* = 109 million Btu

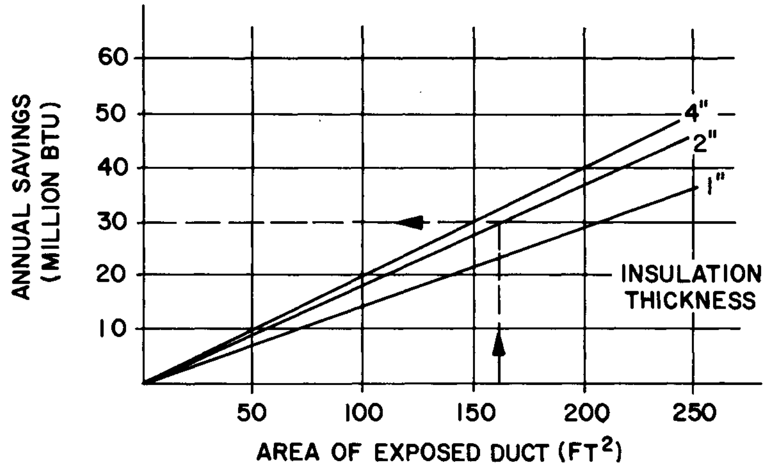
   *number of lengths of 10 feet in 100 feet
3. Annual fuel saving =

   $$\frac{109 \text{ million}}{.75(\text{system efficiency}) \times 1030^{*}} = 141{,}100 \text{ cu. ft.}$$

   *fuel conversion for natural gas
4. $$\text{Saving} = \frac{141{,}100 \times \$.35 \text{ (cost per therm)}}{97.1^{*}} = \$\,509 \text{ per 100 feet}$$

   *conversion from cu. ft. to therm

Fig. 11.10. Annual savings achieved by insulating hot water pipe.



EXAMPLE :

Detemine annual saving by insulating of 162 sg.ft. of exposed warm air duct with 2" of insulation, using No.2 oil

PROCEDURE :

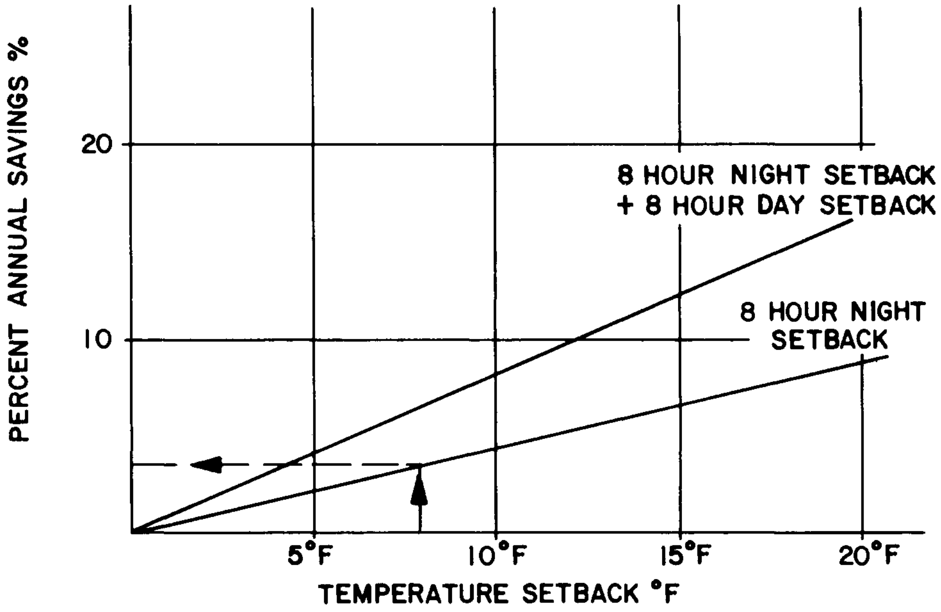
1. Enter chart - detemine energy saving for 2" insulation = 30 million Btu
2. Annual fuel saving :

$$\frac{30\text{ million}}{.75(\text{system efficiency})\times 138{,}700^{*}} = 288 \text{ gallons}$$

* Conversion from Btu to gallons for No. 2 oil

3. Saving = 288 x \$.60 = \$173

Fig. 11.11. Annual savings achieved by insulating warm air duct.



EXAMPLE :

Determine annual savings by installing night setback thermostates with a setback temperature 8°F less than the day setting. using No. 6 oil

PROCEDURE :

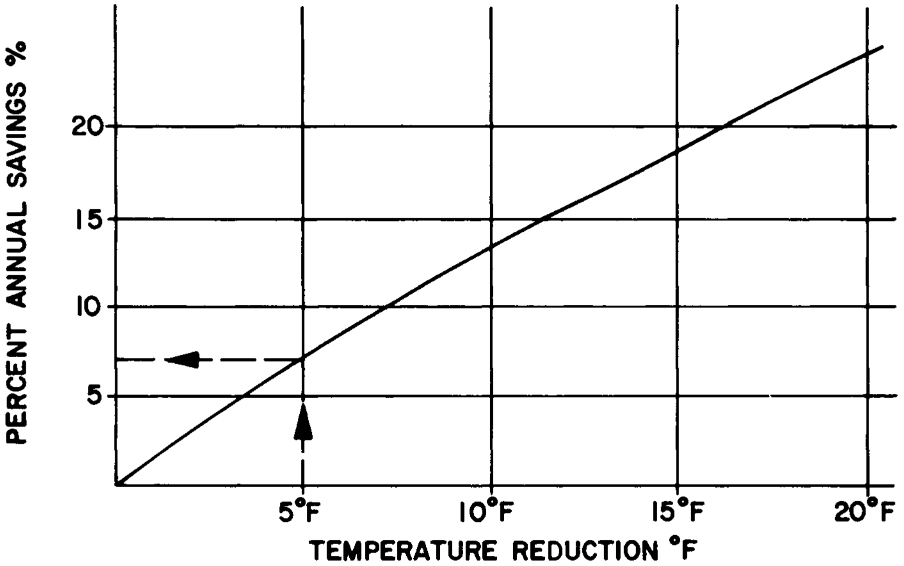
1. Enter chart - determine annual percent saving for 8° F temperature setback = 4 %

2. Annual fuel saving = 4 % x 80,000* gallons
= 3,200 gallons

* Annual heating fuel consumption

3. Saving = 3,200 x $ .60 = $ 1,920

Fig. 11.12. Annual savings achieved by installing night setback thermostat.



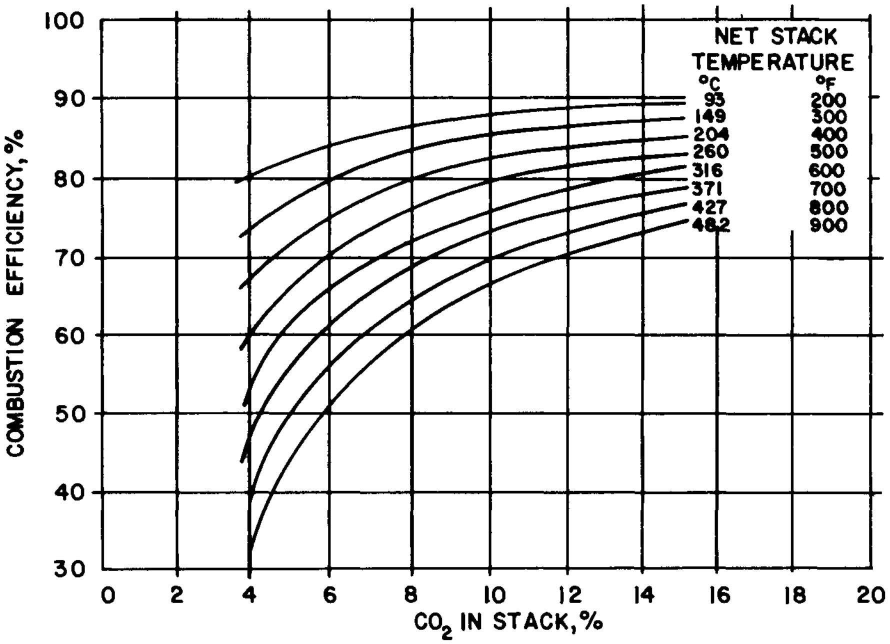
EXAMPLE:

Determine annual saving by reducing the tempeature from 77°F to 72°F using No. 6 oil

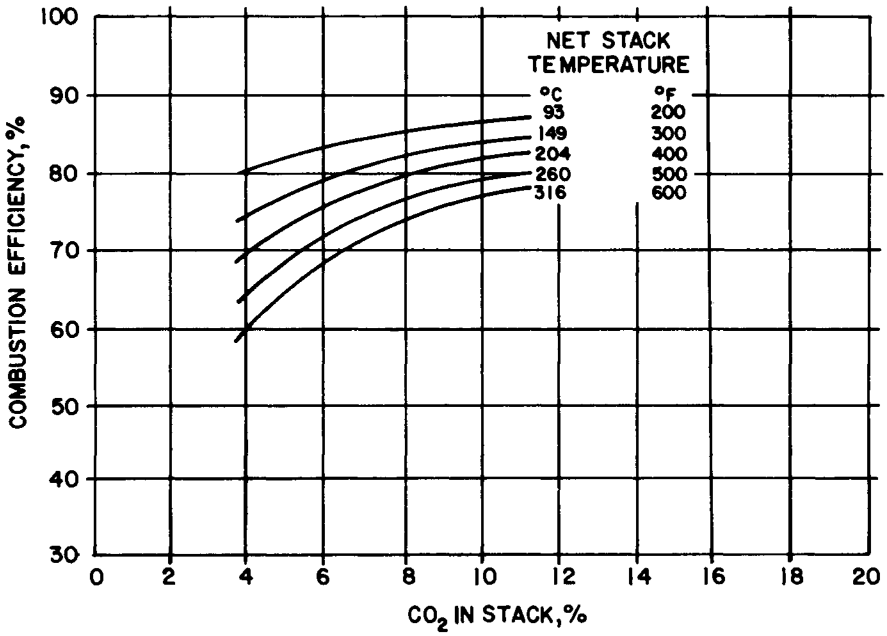
PROCEDURE:

1. Enter chart-determine annual percent saving for 5°F (difference between the two temperatures) = 7%
2. Annual fuel saving = 7% x 80,000* gallons = 5,600 gallons
   *annual heating fuel consumption
3. Saving = 5,600 x $.60 = $3,360

Fig. 11.13. Annual savings achieved by temperature reduction.

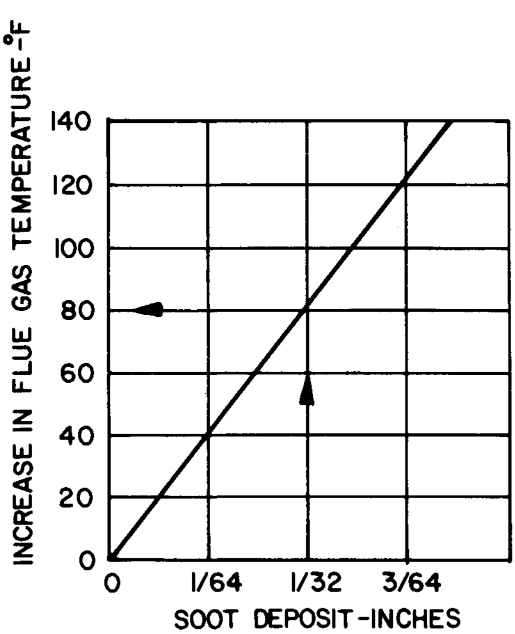


FUEL OIL COMBUSTION EFFICIENCY



NATURAL GAS COMBUSTION EFFICIENCY

Fig. 11.14. Boiler combustion efficiency.



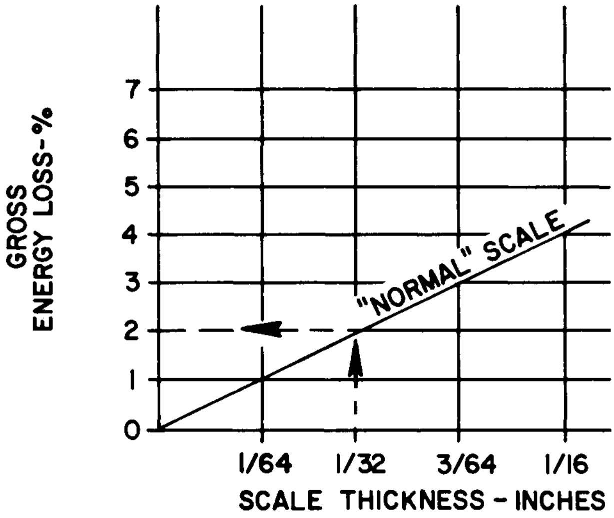
EXAMPLE:

Determine annual saving by cleaning of 1/32" buildup on the fireside of an oil-fired boiler. The normal temperature of clean boiler is 350°F, CO_2 is 10%. Annual fuel cost is $40,000.

PROCEDURE:

1. Enter chart-determine increase in flue gas temperature for 1/32" buildup = 80°F.
2. Total increase in flue gas temperature =
   350°F + 80°F = 430°F
3. Determine the combustion efficiency from Figure 14: for dirty boiler = 81.5%, for clean boiler = 83.5%.
4. Energy loss in efficiency = 83.5% - 81.5% = 2%
5. Saving = 2% x $40,000 = $800

Fig. 11.15. Annual savings achieved by operating clean boiler.



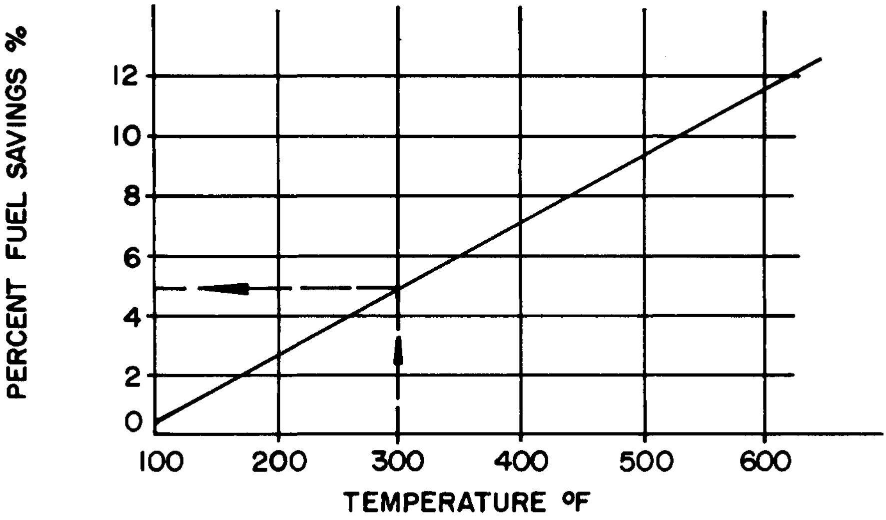
EXAMPLE:

Determine annual saving by eliminating at 1/32" of a scale build-up on the waterside of a boiler. Annual fuel cost is $ 40,000.

PROCEDURE: 1. Enter chart-determine gross energy loss for 1/32" scale thickness = 2%

2. Saving = 2% x $40,000 = $ 800

Fig. 11.16. Annual savings achieved by eliminating boiler scale buildup.



EXAMPLE :

Determine annual saving by raising the combustion air temperature from 80°F to 300°F using No. 6 oil.

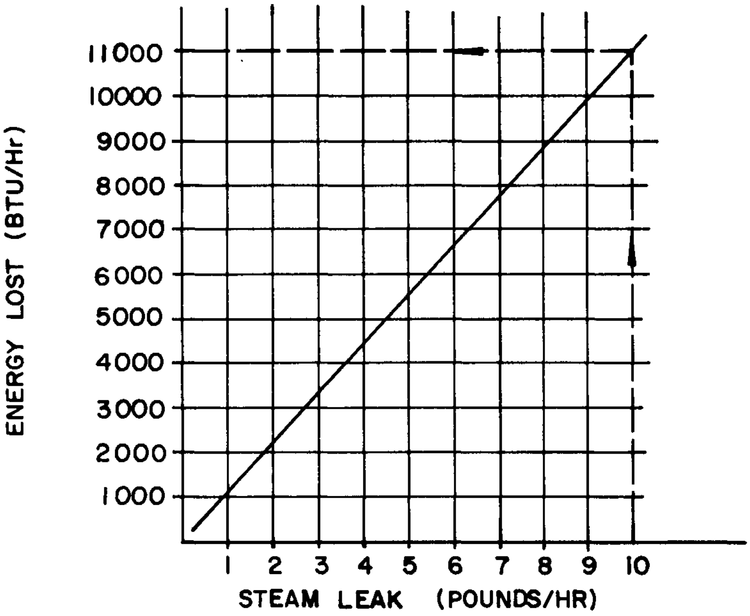
PROCEDURE :

1. Enter chart – determine percent fuel saving fcr 300°F = 5 %, for 80°F = 0 %

2. Annual fuel saving :
   5 % x 25,000* = 1,250 gallons
   * Annual heating fuel consumption

3. Saving = 1,250 x $.60 = $750

Fig. 11.17. Annual savings achieved by raising combustion air temperature.



EXAMPLE:

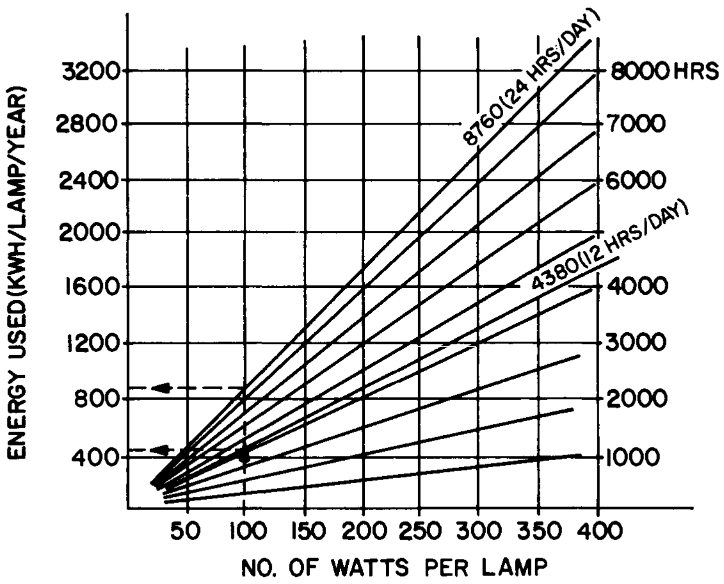
Determine annual saving by eliminating 10 pounds/hr steam leak, the building located in New york city, using No.6 oil. The heating system runs for 50% of the 230 day plant operational time.

PROCEDURE:

1. Enter chart-determine energy loss at 10 lb/hr = 11,000 Btu/hr
2. Annual energy saving = 11,000x230x24hrx50% = 30,360,000 Btu
3. Annual fuel saving = $\frac{30{,}360{,}000}{.75(\text{system efficiency})\times 149{,}700^*}$ = 270 gallons

   *conversion from Btu to gallons for No.6 oil
4. Saving = 270x \$.60 = \$162

Fig. 11.18. Annual savings achieved by eliminating steam leak.



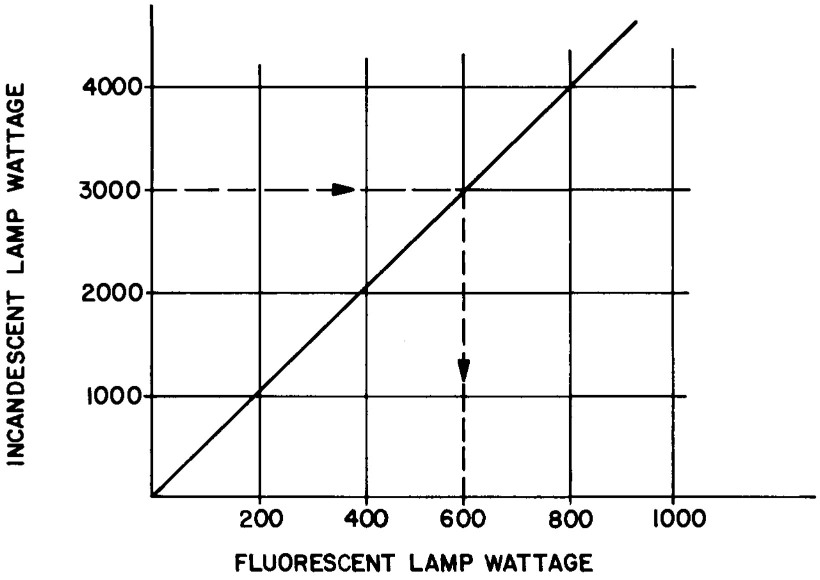
EXAMPLE:

Determine saving reducing lighting in a class room from 24 hrs to 12 hrs per day, for fifty 100 watt lamps

PROCEDURE

1. Enter chart - determine energy used for 100 watt/lamp (24 hrs per day) = 875 KWH/lamp/year, (12 hrs per day) = 440 KWH/lamp/year
2. Annual energy savings = (875 − 440) x 50 = 21,750
3. Annual dollars savings = 21,750 x $.08 (cost per KWH) = $1,740

Fig. 11.19. Annual savings achieved for reduction of lighting hours.



EXAMPLE:

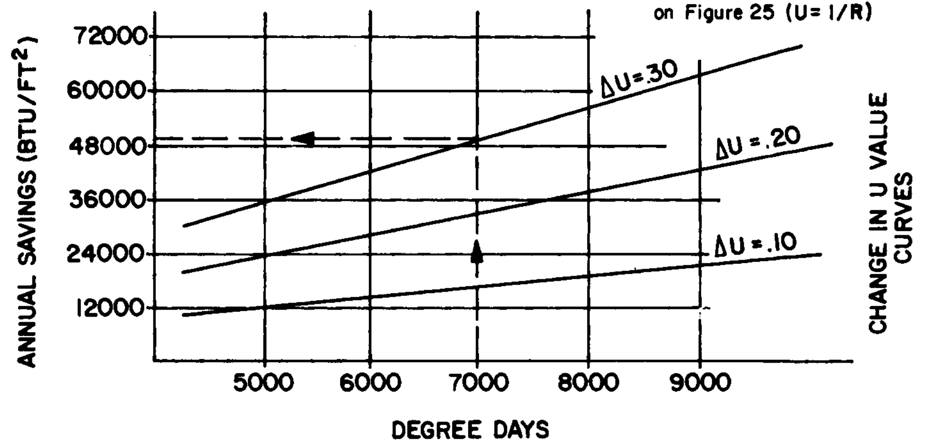
Determine saving by replacing 3KW incandescent lighting with fluorescent lighting achiving same lighting level. Lamps are lit 12 hrs per day.

PROCEDURE:

1. Enter chart-determine wattage for fluorescent lamp (600 wattage)
2. Compute difference: 3KW − .6KW = 2.4KW
3. Annual energy saving = 2.4KW x 12 x 365 = 10,512 KWH per year
4. Annual dollars saving = 10,512KWH x $.08(cost per KWH) = $ 841

Fig. 11.20. Annual savings achieved by replacing incandescent with fluorescent lighting.

NOTE: U values for various construction details can be found in table on Figure 25 (U= I/R)



EXAMPLE:

Determine saving when 1,000 sq.ft. of wall is insulated, change in U value (ΔU) is .30 in a building located in Utica (7,000 Degree Days) using No. 6 oil.

PROCEDURE:

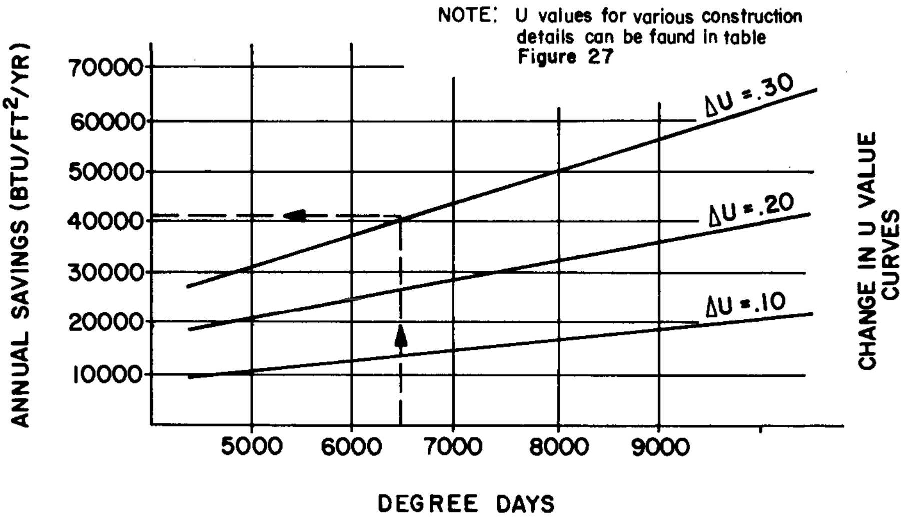
1. Enter chart - determine annual savings per sq.ft. of wall, (50,000 BTU/FT^2)
2. Annual energy savings = 50,000 x 1,000 = 50×10^6 BTU
3. Annual fuel saving =

$$\frac{50\,\text{million}}{.75\,(\text{system efficiency}) \times 149{,}700^{*}} = 445 \text{ gallons}$$

*conversion from BTU to gallons for No. 6 oil.

4. Saving = 445 x \$.60(cost of 1 gallon of fuel) = \$ 267 per 1,000 sq.ft.

Fig. 11.21. Annual savings for insulating walls.



NOTE: U values for various construction details can be found in table Figure 27

EXAMPLE:

Determine saving when 1,000 sq.ft. of attic is insulated, change in U value (Δ U) is .30 in a building located in Buffalo (6,500 Degree Days) using No. 6 oil.

PROCEDURE:

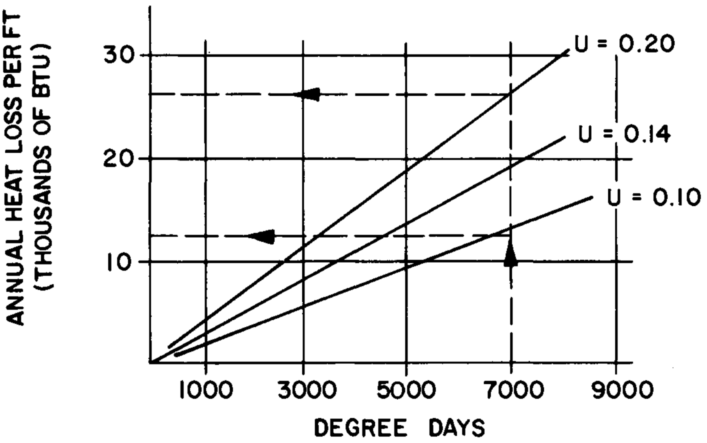
1. Enter chart - determine annual savings per sq.ft. of attic, (42,000 BTU/FT^2)
2. Annual energy savings = $42{,}000 \times 1{,}000 = 42 \times 10^6$ BTU
3. Annual fuel saving =

$$\frac{42 \times 10^6}{.75(\text{system efficiency}) \times 149{,}700^*} = 374 \text{ gallons}$$

*conversion from BTU to gallons for No. 6 oil.

4. Saving = 374 x \$.60 (cost of 1 gallon of fuel) = \$ 224 per 1,000 sq.ft.

Fig. 11.22. Annual savings for insulating attics.



EXAMPLE:

Determine annual saving by insulating of 1000 sq. ft roof of the building located in Albany, using No.6 oil (7,000 degree days). U-factor changed from .2 to .10

PROCEDURE:

1. Enter chart-determine heat loss
   for U=.20 curve = 27,000 Btu/sq. ft,
   for U=.10 curve = 13,500 Btu/sq. ft.

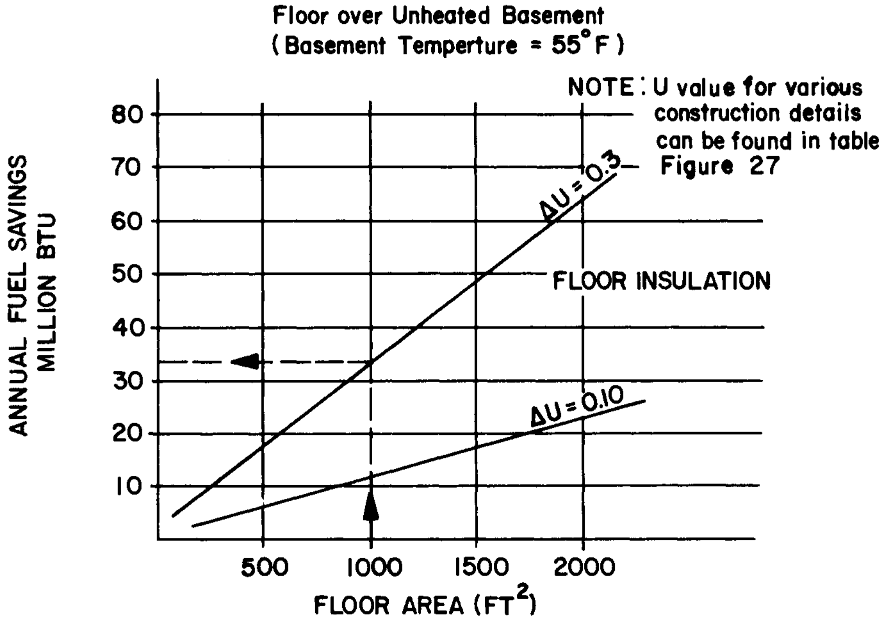
2. Annual energy saving =
   (27,000 - 13,500) x 1,000 sq. ft = 13,5 million Btu

3. Annual fuel saving = $\frac{\text{13,5 Million}}{\text{.75 (system efficiency)} \times \text{149,700*}}$ = 120 gallons

   *conversion from Btu to gallons for No. 6 oil

4. Saving = 120 x $.60 = $72

Fig. 11.23. Annual savings for insulating roofs.



EXAMPLE :

Determine annual saving by insulating 1,000 sg. ft. floor over an unheated basement in a building with ΔU = 0.30, using No. 6 oil

PROCEDURE :

1. Enter chart - determine annual fuel saving for 1,000 sq. ft. at ΔU = 0.30 = 33,000,000 Btu

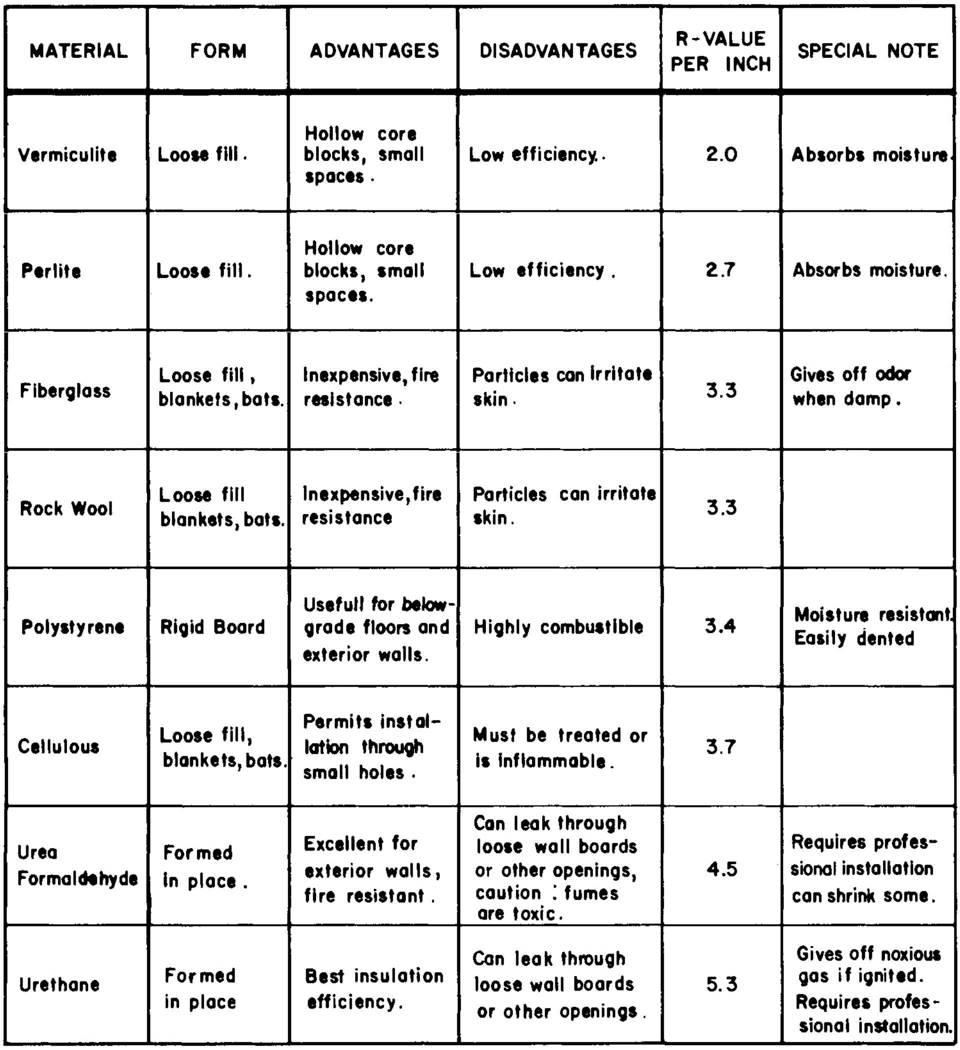
2. Convert Btu to gallons

$$\frac{33{,}000{,}000}{149{,}700^{*} \times .75 \text{ (System Efficiency)}} = 294 \text{ gallons}$$

* Conversion from Btu to gallons for No. 6 oil

3. Saving = 294 x $.60
   = $176 per 1,000 sq. ft.

Fig. 11.24. Annual savings for insulating basement floors.



MATERIAL	FORM	ADVANTAGES	DISADVANTAGES	R-VALUE PER INCH	SPECIAL NOTE
Vermiculite	Loose fill.	Hollow core blocks, small spaces.	Low efficiency..	2.0	Absorbs moisture
Perlite	Loose fill.	Hollow core blocks, small spaces.	Low efficiency.	2.7	Absorbs moisture.
Fiberglass	Loose fill, blankets, bats.	Inexpensive, fire resistance.	Particles can irritate skin.	3.3	Gives off odor when damp.
Rock Wool	Loose fill blankets, bats.	Inexpensive, fire resistance	Particles can irritate skin.	3.3	
Polystyrene	Rigid Board	Usefull for below-grade floors and exterior walls.	Highly combustible	3.4	Moisture resistant Easily dented
Cellulous	Loose fill, blankets, bats.	Permits installation through small holes.	Must be treated or is inflammable.	3.7	
Urea Formaldehyde	Formed in place.	Excellent for exterior walls, fire resistant.	Can leak through loose wall boards or other openings, caution : fumes are toxic.	4.5	Requires professional installation can shrink some.
Urethane	Formed in place	Best insulation efficiency.	Can leak through loose wall boards or other openings.	5.3	Gives off noxious gas if ignited. Requires professional installation.

Fig. 11.25. Judging insulation.

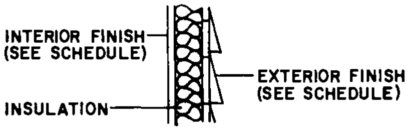
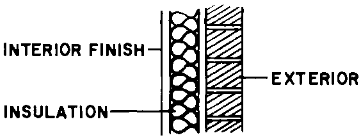
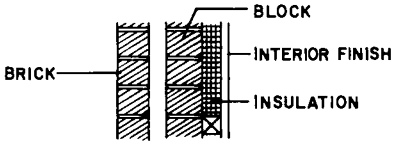
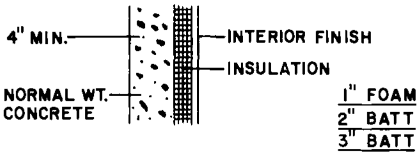
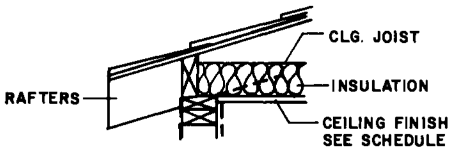
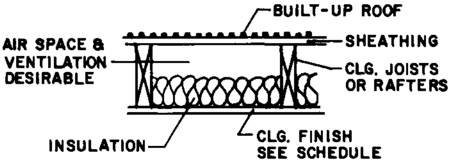
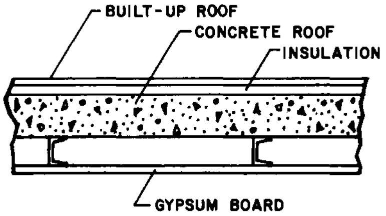
WALL DETAIL SCHEDULES		ORIGINAL U VALUE OF UNINUSL. WALL	R VALUE OF ADDED INSUL.	NEW U VALUE OF WALL	CHANGE IN U VALUE ΔU
INTERIOR FINISH	**EXTERIOR FINISH**				
• GYPSUM WALLBOARD • LATH AND PLASTER • PLYWOOD PANEL (1/4)	• WOOD SIDING • WOOD SHINGLE • ALUMINUM SIDING • STEEL SIDING	0.30			
			7	0.09	0.21
			11	0.07	0.23
			14	0.06	0.24
INTERIOR FINISH	**EXTERIOR FINISH**	0.33			
• SAME AS ABOVE	• FACE BRICK VENEER				
			7	0.10	0.23
			11	0.07	0.26
			14	0.06	0.27
INTERIOR FINISH	**EXTERIOR FINISH**	0.30			
• 1/2" GYPSUM WALLBD.	• FACE BRICK				
			4	0.14	0.16
			7	0.10	0.20
			11	0.07	0.23
INTERIOR FINISH	**EXTERIOR FINISH**	0.41			
• 1/2" GYPSUM WALLBD.	• CONCRETE				
			4	0.15	0.26
			7	0.11	0.30
			11	0.07	0.34

Fig. 11.26. Change in U values for wall details.

ROOF DETAILS	ORIGINAL U VALUE OF ROOF	R VALUE OF INSUL.	NEW U VALUE OF ROOF	CHANGE IN U VALUE ΔU
INTERIOR FINISH SCHEDULE • GYPSUM WALL BOARD • LATH AND PLASTER 	0.30	11 19 30	0.07 0.04 0.03	0.23 0.26 0.27
	0.30	11 19 30	0.07 0.04 0.03	0.23 0.26 0.27
	0.36	3 5 7 8	0.17 0.13 0.10 0.09	0.19 0.23 0.26 0.25

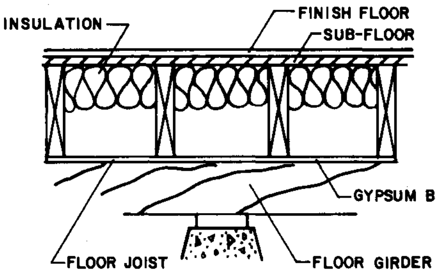
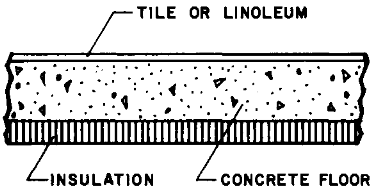
FLOOR DETAILS				
	0.21	7 11 14	0.09 0.06 0.05	0.12 0.15 0.16
	0.60	4 7 11	0.18 0.12 0.08	0.42 0.48 0.52

Fig. 11.27. Change in U values for roof and floor details.

APPLICATION	SMOKING	Cfm per Person[1,2]		Cfm per Sq. Ft. of Floor[1,2]
		RECOMMENDED	MINIMUM[3]	MINIMUM[3]
Corridors (supply or exhaust)	——	—	—	0.25
Hospitals				
Operating rooms	none	—	—	2.0
Private rooms[5,6]	none	30	25	0.33
Wards	none	20	10	——
Laboratories	some	25	15	——
Meeting rooms	very heavy	50	30	1.25
Offices				
General	some	15	10	0.25
Private	none	25	15	0.25
Private	considerable	30	25	0.25
Cafeterias	considerable	12	10	——
Schoolrooms[4]	none	—	—	——
Toilets[4] (exhaust)	——	—	—	2.0

1 Taken from present day practice.
2 This is contaminant - free air.
3 Where minimum is used take the larger of the two.
4 May be governed by exhaust.
5 May be governed by special sources of contamination or local codes.
6 All outside air recommended to overcome explosion hazard of anethetics.

Fig. 11.28. Recommended outdoor air ventilation rates.

Computer Control of Building Energy Systems

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ABSTRACT

The scope of the design of an energy conservative building includes optimized control of the energy systems within that building. In this paper, the importance of building air-conditioning control systems is outlined. The discussion focuses on the features, functions and benefits of computerised control of energy systems.

INTRODUCTION

Today, the situation in building control is changing. The energy crisis, while not as dramatic, is still with us and is likely to continue. For this reason, it is necessary to find new and improved ways of saving energy.

Early energy conservation functions were those that saved the wasted energy. Strategies are evolving to now optimise control in order to minimise actual energy consumption while maintaining good building control. In addition to a continued emphasis on energy consumption, the state of microprocessor technology has advanced, and will continue to do so. This technology provides tools to implement developing energy control strategies in an improvingly cost-effective manner.

THE BUILDING ENERGY SYSTEM

Energy enters and leaves the building in different forms, as shown in Fig. 1. Inflow of energy generally takes the form of solar radiation, influx of people and the utilities. The direction of energy flows due to the intake and exhaust of air depends on a number of factors, including the ambient atmospheric conditions. Building radiation and conduction are also forms of energy transfer. Contemporary building science involves the optimum design of the building to control, or at least make use of, these energy flows for least input of the utilities while retaining the comfort of the occupants.

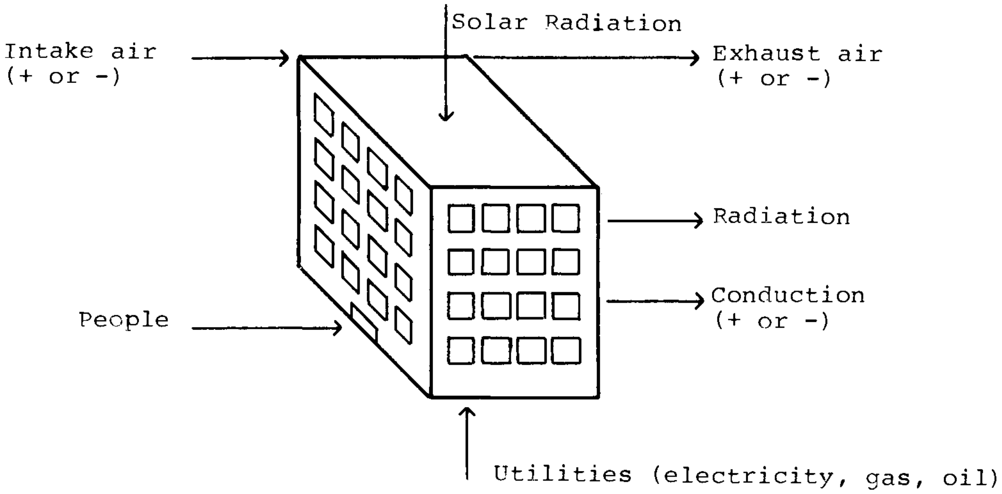

Fig. 1 The building energy system

BASIC ENERGY CONTROL SYSTEMS

Basic automatic energy control systems are presently provided in buildings to control the following:

(i) Heating, Ventilation and Air Conditioning (HVAC)
(ii) Domestic Hot Water
(iii) Steam

Such control systems are usually electric, pneumatic or electronic, depending on the application. These control systems act to keep variables at predetermined values. Fig. 2 displays an example of a simple air conditioning control system. As the space temperature decreases below setpoint, the thermostat opens the hot water valve to heat the air. Similarly, as the temperature increases above setpoint, the thermostat opens the chilled water valve to cool the air.

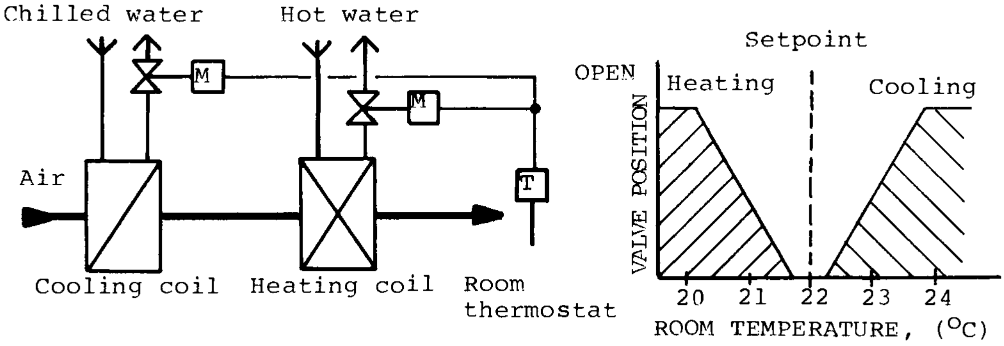

Fig. 2 Basic control system

This type of control system is common in existing buildings today. It acts to keep the room temperature at setpoint without regard to energy usage. With this type of system, room temperature often cycles within approximately one celsius degree around setpoint. The result is a periodic cycling of heating and cooling in an effort to maintain setpoint.
Fig. 3 shows the modern equivalent of this control scheme. Separate heating and cooling outputs from the thermostat, with independant setpoints for each, provide an adjustable dead band between heating and cooling. A carefully selected wider deadband allows temperature to fluctuate within comfortable limits without wasteful cycling of heating and cooling.

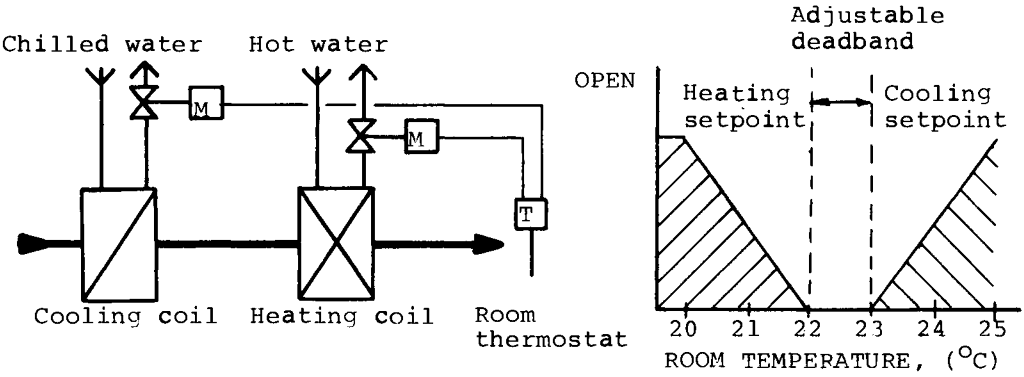

Fig. 3 "Zero-Energy Band" control system

This system is a vast improvement on the basic control system in terms of energy usage. It is, thus, important to pay careful attention to the design of air-conditioning control systems if energy consumption is to be minimised. However, such simple proportional control systems, which typically measure only one variable, space temperature, are unable to take into account other key factors which influence energy costs. Examples of such factors are:

1. Occupancy
2. Time
3. Heating or cooling action in other parts of the building
4. Season
5. Total building electrical demand

In general, the simple proportional control system lacks co-ordination with such factors. For example, it is not uncommon to see outside air being cooled at a main air handling unit and then promptly reheated at the zones through lack of co-ordination. It is also not uncommon for air-conditioning control systems to be calling for heating or cooling at the end of a day, ceasing exactly at the end of the occupancy period and leaving the space in a comfortable condition well after the occupancy period.

MICROPROCESSOR-BASED ENERGY CONTROL SYSTEMS

Microprocessor-based systems possess the following characteristics:

1. Computational power - ability to perform calculations
2. Speed - ability to process large amounts of information
3. Accurate time-keeping capability
4. Memory - ability to store information
5. Programmable - flexibility

These features enable a microprocessor to analyse data from all areas of the building and utilise this to co-ordinate control of the energy systems. When the building energy systems are co-ordinated as one unit with the factors mentioned previously, it is possible to minimise the cost of the utilities while maintaining comfort conditions for the occupants.

Hardware

This is the term used to describe the physical component of a microprocessor system. There are many different types of hardware configuration or electronic architecture in use for controlling building energy systems.
Fig. 4 displays a typical example of microprocessor application to total building energy control

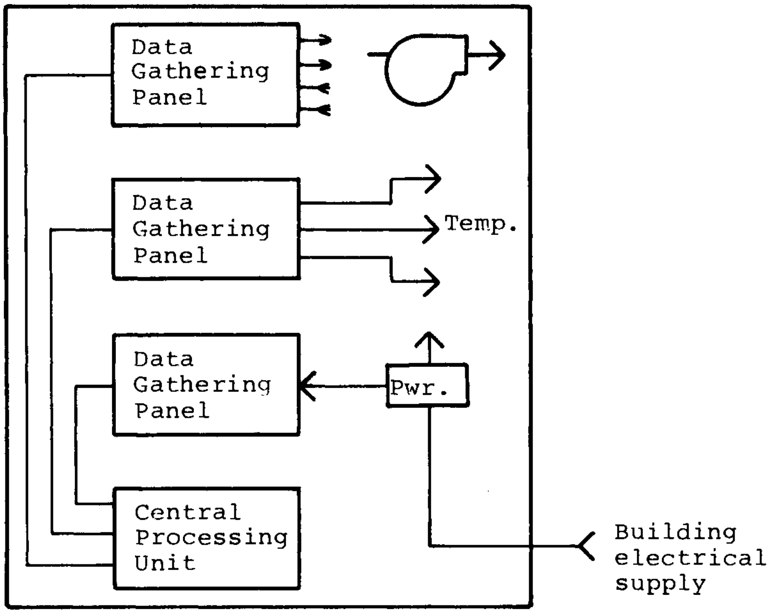

Fig. 4 Centralised microprocessor control of a building

The Data Gathering Panels obtain information from the air handling units, representative areas and the building electrical supply. The microprocessor in the Central Processing Unit (CPU) analyses this data and makes control decisions which are sent back to the Data Gathering Panels for output of this control. In this manner, fully co-ordinated building energy system control is possible. This type of electronic architecture may be extended to also include control of other buildings, allowing a building owner to overview a group of his buildings from a central location.

Software

This is the set of instructions programmed into the microprocessor memory. The software differentiates the application of the microprocessor. The same microprocessor could be used for an aircraft guidance system or for controlling a multi-storey building. The software design is just as important as the hardware design. Since the nature of software is invisible, complex and variable, it is an advantage to both suppliers and purchasers when commercial packages are standardised and well documented. Examples of such packages common to building energy control systems are as follows:

Optimised stop/start. This software co-ordinates air conditioning plant operation with occupancy and time.
Most mechanical plants are started each day at a fixed time, usually by a time clock. This fixed time is generally set at half an hour before occupancy to ensure that the internal air is at a suitable temperature at the beginning of occupancy. However, since this is set using worst case criteria, the temperature often reaches a comfortable level well before building occupation. The plant thus runs for a longer period than is required.
A microprocessor-based system, fitted with this software package, starts the air handling plant at a variable time, optimally selected using the following information:

1. Outside air temperature
2. Space temperature
3. Building thermal response

The first two pieces of information are measured by sensors, while the second is 'learned' by the microprocessor over a period of a few days and is continually updated. From these three pieces of information, the microprocessor is able to select the latest possible start time which will ensure that the space temperature enters the acceptable comfort temperature zone. Similarly, the microprocessor is able to stop the air conditioning plant heating or cooling action before the end of occupancy so that the space temperature is just leaving the acceptable comfort temperature zone at the end of the day. Optimised stop/start is able to save significant amounts of energy. Fig. 5 displays the difference between a time-clock operated system and one with optimised stop/start.

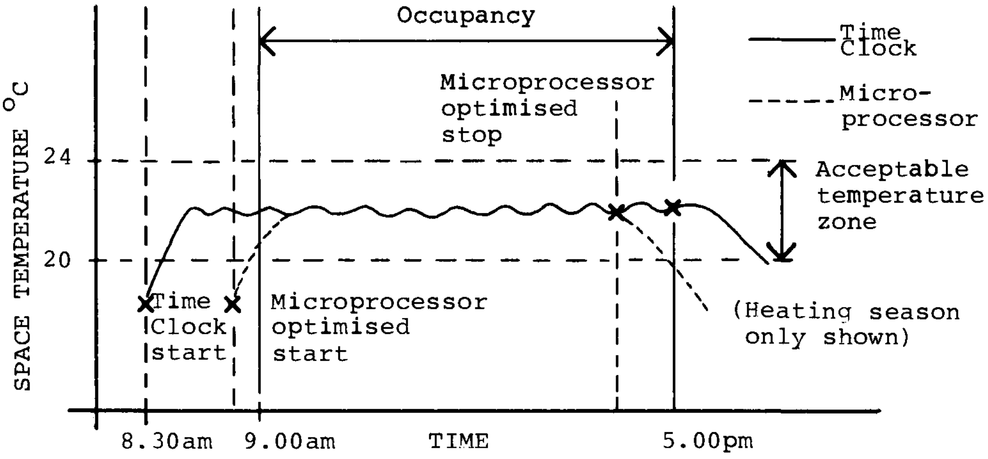

Fig. 5 Optimised stop/start

<u>Maximum demand control.</u> With a demand type electrical tariff, typical for mutli-storey buildings, the relationship between the power bill and the energy consumed is not linear. A large component of the monthly energy bill is related directly to the maximum rate at which energy is consumed during the month, generally measured in half hour periods.

If energy costs are to be minimised, electrical power needs to be consumed at a steady rate rather than in peaked manner.

Fig. 6 shows an example of peaked building electrical demand. The peak is due to the morning chiller start, and is typical of the response of a simple control system. The chiller operates at high capacity until the desired space conditions are met. The chiller then continues at a lower capacity.

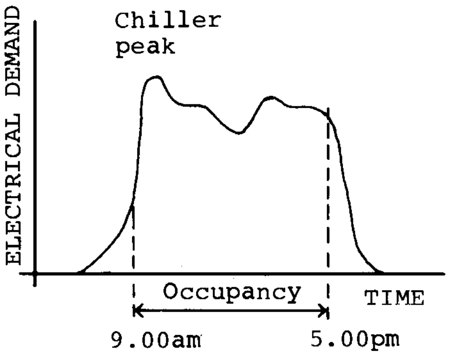

Fig. 6 Peaked electrical demand

A central microprocessor is able to co-ordinate the electrical demand of a building. It is able to reschedule the energy usage to give a steadier rate of consumption.

The software takes into consideration occupancy, time, air handling unit parameters and space conditions. In this example, the chiller capacity would be limited by the microprocessor in the start by disabling some of the total capacity. This process is known as load-shedding. The electrical demand is re-distributed through the day to produce a more even energy usage rate.

This form of control may be applied to other items of electrical equipment in the building, thus allowing the microprocessor to overview the total building and co-ordinate energy systems. The cost savings that result from maximum demand control are substantial.

Chiller optimisation. When a chiller operates at its design load and the cooling tower operates at maximum summer design temperatures, standard catalogue data provides a close approximation to power consumption. However, in a typical system, design conditions occur infrequently. At all other times, capacity and efficiency vary as a function of condenser water and chilled water supply temperatures. The total power consumed by a chiller plant also includes auxiliary equipment such as the cooling tower fans, condenser water and chilled water supply pumps. Power required for these auxiliaries varies according to the number of chillers operating, chilled water flow and environmental conditions. The situation becomes even more complex when chillers of different sizes or types are utilised. Continual chiller operating efficiency cannot be maintained if a plant operator must recalculate the best operating strategy each time load conditions change.

A microprocessor is able to overview the plant and performs calculations with speed, enabling continuous monitoring and decision processing. Chiller optimisation software enables the microprocessor to continuously perform energy-efficient calculations, select the most favourable chiller combination, and adjust both chilled water and condenser water supply temperatures. Overall system power consumption is then kept to an optimum minimum level.

Boiler optimisation. A boiler is set to deliver water or steam at given design conditions. At most times, the load is actually smaller than the load conditions.

A microprocessor-based control system is able to monitor outdoor conditions, internal space conditions, hot water flow and supply temperature. Boiler optimisation software enables the microprocessor to operate the boiler and reset the hot water supply temperature continually according to the varying load conditions. This results in more efficient boiler operation and a reduction in heating loss through the distribution system. The energy savings are substantial, particularly in the intermediate seasons.

Night Purge. In most climates, there are numerous occasions during the cooling season when, during early morning hours before start-up, the outside air temperature is lower than the temperature within the building. This outside air can be profitably used to cool the building prior to starting the refrigeration plant.
This software enables the microprocessor to determine when the outside air temperature and moisture content are both lower than inside conditions. If conditions are favourable, the fan is started with outside and exhaust air dampers open prior to morning start-up. This action pre-cools the mass of the building and contents to reduce cooling energy requirements during the occupied period. When used in conjunction with optimised stop/start, the plant start is able to be delayed further.

Lighting control. Conventional office lighting generally consumes full power all the time it is switched on, from early in the morning till late at night, somethimes twenty-four hours a day. There are many hours when perimeter areas in a building are well lit by daylight. There are also times during a day when there may be no need for full lighting; early morning, lunch-time, closing time, during cleaning, and, particularly, when the building is unoccupied.
A microprocessor-based building automation system is able to be extended to include control of lighting. Light sensors are placed in lit areas and thyristors are utilised to control lighting level. This enables lighting to be controlled to a constant designed level, using no more energy than required. This system also compensates for the effect of lamp aging. Because light output diminishes gradually during the life of a lamp, installed lighting capability must be greater than actually rquired to ensure that illumination levels are met at the end of the depreciation period. This means that excess light is produced for much of this period and hence excess energy is consumed. With lighting level control less power is used in the earlier stages of lamp life, thus saving running costs. In the cooling season, less plant energy is used due to the lower heating load in the space.
A microprocessor-based lighting control system is able to ensure efficient lighting energy usage, co-ordinating electrical illumination as part of the building energy system.

Benefits

The benefits of microprocessor-based control of building energy systems may be summarised as follows:

1. Full co-ordination of building energy usage, optimising the utilities.

2. Efficient use of energy through continuously self-adaptive control.

3. Flexibility and programmability to allow the building owner to alter control strategies or invent new ones to improve the operation of the building.

4. Detailed energy audits may be performed simply and regularly, providing a facility for fine-tuning building operation.

In addition to optimum control of the energy system, there are further benefits of utilising microprocessors:

1. Automatic warnings of plant performance deterioration.

2. Automatic warnings when routine maintenance is required.

3. Centralised manual override of plant control.

4. Facility for integration of security control and monitoring.

5. Facility for integration of fire detection and control interlocking.

CONCLUSION

Energy conservative building design:

- begins with architectural design that requires minimum utility energy for building operation

- continues through the design of building electrical and, in particular, mechanical services

- is incomplete without the same attention paid to control system design

A centralised microprocessor-based control system aids in efficient control of energy by integrating and co-ordinating the various services. The cost of utility energy is minimised while retaining comfort conditions for the occupants.

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An Integrated Approach to Environmental Comfort with Low Energy

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ABSTRACT

The paper reviews research work on the integration of factors affecting thermal comfort indoors including comfort indices, building response, and space air conditioning systems. The Equatorial Comfort Index is up-dated and compared with other research results. As most conventional air conditioning systems are designed to heat or cool a given space, the paper raises the possibility of heating or cooling work stations only, thereby saving energy. Using a Singapore office building as an example, the design of the envelope is first done to meet existing building regulations in energy conservation. The indoor temperature is then determined by assuming certain ventilation rates, and the periods during which discomfort may be experienced are identified. A work station is designed with localized cooling. A range of air temperature, humidity and air movement is tested, and the comfort indices are recorded by a 'Comfort Meter'. Though no test is done with actual subjects using the work station, the PMV recording by the 'comfort meter' is considered adequate.

INTRODUCTION

The need to conserve energy in buildings has re-introduced the importance of providing thermal comfort without undue wastage of energy. While the inter-relationship of dry and wet bulb temperatures, ambient radiation, air movement, ventilation, clothing and activities level have been well investigated, current practice of heating and cooling a space remains more or less conventional. The design of heating and cooling load is related to peak load conditions, and the control of indoor temperature is only general to the space to be conditioned, since 'thermostats' are not necessarily located at the actual work stations. It appears to the present writers that some fundamental re-consideration is necessary in space heating and cooling so as to reduce energy consumption. This may be done by the integration of the following three factors:

(1) Thermal comfort
(2) Building response
(3) Personalized cooling or heating

As the present authors are more conversant with the hot humid conditions, these will be used to illustrate the principles involved.

BRIEF REVIEW OF THERMAL COMFORT IN THE HOT HUMID ZONE

It has been generally recognized that thermal comfort in the hot humid zone depends on air temperature, humidity, air movement, and ambient radiation. In order to combine the effect of these factors, several thermal comfort indices have been proposed. These indices attempt "to combine the effect on man of two or more variables to a single variable" (Fanger, Ref. 3 p. 109). One of the best known indices of this kind is the "Effective Temperature" (Ref. 4 p. 117). This was developed in 1923-1925 by Houghton, Yaglou, and Miller (Ref. 5). This index included air temperature, humidity, and air velocity. Later the Corrected Effective Temperature was developed where the globe thermometer temperature replaced the dry-bulb temperature (Ref. 6 p. 52). The CET for temperate climate was generally recommended to be $21.7^{o}C$ for summer conditions with the male subjects at rest and normally clothed. Similarly the "Resultant Temperature", (Nulsen, Pedersen, Missenard, Ref. 7) was developed to determine the thermal equilibrium between body and environment. As in Effective Temperature, it involves dry and wet bulb temperature, and air movement.

The Equivalent Temperature, an index of heat loss of a body to the environment, was simulated by an "Eupatheoscope" developed by Dufton (Ref. 6 p. 52). The instrument simulated a clothed human body, and the rate of heat loss from its surface varies with the temperature and velocity of the surrounding air and with the radiation from the surroundings.

Bedford (Ref. 6 p. 59) further proposed a scale of Equivalent Warmth which indicated the feeling of warmth to air temperature, humidity, and air movement. The scale simulated the air temperature of a uniform enclosure of still and saturated air, and were used to compare one environment with another.

The thermal comfort studies conducted in Singapore were the Equatorial Comfort Index by C.G. Webb (Ref 8) and a comfort survey by Dr E.P. Ellis (Ref 9). From results of observation by 14 persons Webb suggested a 'Singapore Index' which included dry bulb and wet bulb temperatures and air movement, and later the Equatorial Comfort Index with a nomogram from which neutral conditions could be found. From observations made by 152 residents in two separate studies Ellis gave effective temperatures to British and Asian male and female residents in Singapore.

In other regions of warm climate, Ambler (Ref 10) concluded that effective temperature was a fairly good index of comfort for Europeans living in Nigeria. Effective temperature was also used by Grocott (Ref 11) to study upper comfort limits of conditioned houses of the Anglo-Iranian Oil Company, and by Mookerjee and Murgai (Ref 12) for the determination of comfort zone of Indian subjects during the North Indian summer. Rao (Ref 13) incorporated humidity and air velocity to determine the desired effective temperature for Calcutta. Nicol (Ref 14) determined sweat rates of subjects in Roorkee, India, and Baghdad, Iraq.

In sub-tropical countries, Drysdale (Ref 1) suggested the use of air temperature as a comfort scale for the hot, dry conditions of Australia. Hindmarsh and MacPherson (Ref 15) working on the same principle suggested preferred air temperature for Sydney in summer and winter. MacPherson (Ref 16) also gave the maximum air temperature above which acclimatized white population in the Northern Territory would have disturbed sleep. Similarly Wynden (Ref 17)and Ballantyne, Barned, and Spencer suggested the preferred air tempeatures for acclimatized Caucasian subjects at Port Moresby, Papua New Guinea, and at Wei pa, Northern Australia respectively.(Ref 2). Fanger (Ref 3, p. 41 - 54) after his study of subjects in U.S.A. and Denmark, proposed the use of complex comfort equations and diagrams which include many variables such as activity levels, clo-values, air velocities, humidities and ambient temperatures. A 'Comfort Meter*' was also developed with which assessment of a thermal environment could be made. For his research Fanger proposed comfort equations and comfort diagrams according to activity levels and clo-values.

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*Comfort Meter:-The meter has a probe which simulates the human body in terms of metabolic rate, heat gain or heat loss of the skin, and may be regulated according to activity, clothing, and vapour pressure. The meter registers the Predicted Mean Values (PMV) of comfort conditions in 7 steps, ranging from cold, cool, slightly cool, neutral to slightly warm, warm and hot (-3, -2, -1, 0, +1, +2, +3). The meter is marketed as "Comfy-tester".

Humphreys, (Ref. 18)after examining more than 30 field studies in thermal comfort, proposed a method of estimating the temperature of thermal neutrality as follows :

$$Tn = 2.56 + 0.831\ Tm\ (^{o}C)$$

Where Tm is the mean air temperature.

UP-DATING OF THE EQUATORIAL COMFORT INDEX

C.G. Webb (1951) first developed a comfort scale known as 'Singapore Index' (Ref. 8) as a result of measurements taken by 14 persons for about a year (May 1949 - April 1950). They were to register their overall thermal sensation at 6-hour periods at their own homes and offices with reference to dry and wet bulb temperature, and air movement (Table 1). Webb then developed the Index as expressed by the following equation to obtain the neutral index where the subject felt neither warm nor cold.

$$\theta = \tfrac{1}{2}(t + tw) - 1/4\ V^{\frac{1}{2}}$$

where θ is the Singapore Index (^{o}F)
t is the dry bulb temperature (^{o}F)
tw is the wet bulb temperature (^{o}F)
V is the air velocity (ft/minute)

Webb fixed the Singapore index at $78.7^{o} \pm 3/4^{o}F$ ($25.94^{o} + 0.42^{o}C$). Later Webb combined his work with others and developed the Equatorial Comfort Index which was suggested to be used in many parts of the Hot Humid Zone.

TABLE 1

C G Webb's revised Thermal Comfort Data for Singapore (Ref.2)

Equatorial Comfort Index ^{o}F	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
Percentage uncomfortable due to cold	100	99	96	88	74	55	34	17	7	2	1	-	-	-	-
Percentage uncomfortable due to warmth	-	-	-	-	1	3	8	18	34	53	72	87	95	98	100

Similar work was done by Dr EP Ellis (1951), a medical officer stationed in Singapore (Ref. 9). With 152 Europeans and Asians in two separate studies, Ellis found the effective temperatures in °F for the two groups as shown in Table 5. The results showed the difference between Europeans and Asians in their preference of thermal comfort.

TABLE 2

Summary of Thermal Comfort by E P Ellis (Ref. 3)

ELLIS'S Assessment	Effective Temperature			
	BRITISH Residents		ASIAN Residents	
	Men	Women	Men	Women
Less than 20% reported sweating when E T falls below	80	80	80	82
More than 80% reported reasonably comfortable at	79	78	81	80
Equal number of 'cool' and 'warm' votes were recorded	76	74.5	75.5	77

The present authors re-examined the Equatorial Comfort Index in 1976. As controlled environment was not used by Webb, two ordinary working conditions were used by the authors as follows:

(a) Six single-storey buildings without side wall enclosures where cooked food was served (known locally as 'hawker centres'). The environment was made warm by the radiant heat from cooking stoves and by solar radiation transmitted from the roof. The designs of the buildings were fairly uniform, except for orientation and the micro-climate of the sites. The subjects came from all walks of life, and the activities and duration of stay were similar. Customers were asked to evaluate the thermal environment.* A total of 435 thermal comfort survey opinions were collected.

(b) A typical classroom in five separate schools. The number of pupils in the rooms was similar, though not exactly the same. Windows were on both sides of the room in all cases though the site conditions varied. The age grouping and type of work done were similar. Some 160 young adults were asked to evaluate the thermal environment of the rooms and a total of 1319 recordings were made at ½-hourly** intervals during a normal day for each of the 5 locations. The subjects recorded their thermal

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* The survey was conducted as part of a programme on thermal comfort commissioned by Applied Research Corporation. The research workers were Dr JC Ho, Associate Professor KR Rao and Professor Bill Lim of the University of Singapore.

** The authors express their appreciation to the authorities of establishments which they visited, and the subjects who participated, in the comfort survey. The research programme is part of a study on "Thermal comfort in the tropics", for which the University of Singapore generously provided a research fund.

sensation, presence or absence of sweat, and their perception of air movement at half-hourly intervals.

At the hawker centres, the assessment percentages were compared with the Corrected Equatorial Comfort Indices, which was corrected for radiation (Fig 1). The optimum neutral effect temperature was 25°C (77°F), when radiation was corrected, with 59% of the subjects felt neither warm nor cool. The PMV values as measured indicated 25°C as the mid-range temperature. There was good agreement between the opinion survey and PMV data when Webb's Corrected Equatorial Comfort Index (CECI) was used. This shows that the comfort meter is generally reliable to estimate comfort scale in Singapore according to the CECI (Fig 2). Comparing the scales of comfort level categories from cool to hot (-1, 0, +1, +2, +3) with that of Webb, it can be seen that there is generally good agreement as shown in Table 3.

TABLE 3

Comparison of the conditions for each Comfort categories

Comfort Level	Hawker center Study (CECI °C)	Webb's Study (CECI °C)
1 (Cool)	23.6	24.0
0 (Neutral)	25.0	25.3
1 (slightly warm)	26.4	26.5
2 (Warm)	27.8	27.8
3 (Hot)	29.2	29.0

The survey at schools gave similar results. There was no need to correct for radiation, and air temperature was used. In spite of the inexperience of the subjects (consequently the percentage of assessment at neutral range is not large), the neutral temperature according to the Equatorial Comfort Index was 25.2°C (Fig 3) almost identical to that obtained at the eating places. Similarly the PMV value of the comfort meter was recorded at 25.1°C (Fig 4).

It may be concluded that the Equatorial Comfort Scale designed for Singapore some 25 years ago may still be used. However, the neutral condition is to be amended to 25°C (77°F) and not 26°C (78.7°F) as Webb originally proposed. The reason is likely to be due to the fact that Webb only had 14 observers, and the opinions expressed might not have been representative. The use of the comfort meter is recommended for general use in the assessment of comfort of a given environment, and subjects are not required. This makes the task of assessment much easier, as organisation of large number of subjects is often difficult.

COMPARISON OF THERMAL COMFORT SCALES

From a set of comfort equations Fanger (Ref 3 p. 41 ff) developed comfort diagrams which included activity levels (Kcal/hrm^2) clo-value (Clo), from which all resonable combination of air temperature (^{o}C), humidity (mm Hq), mean radiant temperature (^{o}C) and relative velocity of air velocity (m/s) may be derived for the purpose of achieving optimal thermal comfort for persons under steady state conditions. The diagrams are now incorporated in the ASHRE Fundamentals (1980) (p. 8.22-8.24).

As Webb's Equatoral Comfort Index was developed with a survey among sedentary workers in Singapore, the index may be compared with Fanger's sedentary comfort diagrams with light clothing (M/A$_{DU}$ = 50 Kcal/hrm^2, and I$_{ce}$ = 0.5 clo) as shown in Fig 6. It can be seen that at the neutral CEI of 25.1^{o}C there is good agreement with Fanger's PMV for sedentary workers. However, for medium activity CM/A$_{DU}$ = 100 Kcal/hrm^2) a lower CEI is available for medium and high activities, Fanger's comfort diagrams may be used as reference in hot humid conditions found in Singapore.

The CECI may also be compared with Humphreys' thermal scale (Ref 18), which is based on 100,000 field observations made all over the world.
He considers 4 variables as follows:

(a) Median warmth response, Rm with a 7-category scale of +0.5, +1.0, +1.5, +2.0 for warmth, -0.5, -1.0 for cold and 0 as neutral. Category zero has a width of 4^{o}C.

(b) Room temperature T^{o}C.

(c) Month mean temperature experience during waking hours with the respondents up and about, Tm^{o}C.

(d) Neutral temperature Tn^{o}C.

Humphrey gives for adults:

$$Tn = 2.56 + 0.831\ Tm$$

$$Rm = 0.25\ (T - Tn)$$

and $Rm = -0.64 + 0.25\ T - 0.208\ Tm$ (Ref 18, p. 20)

Applying the above to the Singapore situation, for CECI of 25^{o}C and a relative humidity of 84% which is the daily average in Singapore, the neutral temperature may be 26.4^{o}C, if no air movement is considered at this stage. Average room temperatures may then be estimated from the CECI which corresponds to thermal votes as in Table 4.

Table 4

Room temperature according to CECI and the departure from neutral temperature according to Humphreys

Description of field survey	CECI $^{\circ}$C(F$^{\circ}$)	**Room Temp T$^{\circ}$C (estimated)	Rm*	T-Tn* $^{\circ}$C
Neutral	25.3 (77.4)	26.4 (79.5)	0	0
Slightly warm	26.5 (79.7)	28.3 (83)	0.48	1.9
Warm	27.8 (82.0)	30.0 (86)	0.90	3.6
Hot	29.0 (84.2)	31.1 (88)	1.18	4.7

*Tn = 26.4°C Tm = 28.7°C

**RH = 84%, no air movement

The estimated distributions of response may then be compared as shown in Table 5.

TABLE 5

Comparison of response between CECI and Humphreys' Scale (adults, non-airconditioned accommodation)

		Percentage falling in the category					
		0+1+2+3		1+2+3		2+3	
T-Tn$^{\circ}$C	Rm	Humphreys	CECI	Humphreys	CECI	Humphreys	CECI
0	0	74%	85%	26%	25%	2%	3%
1.9	0.48	91%	97%	50%	51%	9%	18%
3.6	0.9	97%	100%	70%	93%	22%	45%
4.7	1.18	99%	100%	81%	100%	34%	82%

It may be seen from the above that more discomfort votes of CECI are recorded at higher differences between room temperatures and neutral temperature, when compared with Humphreys' estimated distribution. This is possibly due to the high relative humidity (84%) assumed in the calculation. However, this is usually overcome by the provision of air movement, which has not been included thus far. It may be concluded that when the room temperature approximates the neutral temperature CECI follows generally Humphreys' estimates.

BUILDING RESPONSE

As seen from the foregoing , it appears possible to design buildings in Singapore with the neutral CECI of 25^{o}C so that the majority of the occupants will be neither warm nor cold. The thermal response of the building may now be considered to assist in maintaining this CECI.

First of all the indoor air temperature variation that would result if the building is not air-conditioned is to be determined. Then the comfort and discomfort periods and levels of discomfort are to be determined. The next step is to study the effect of design variables on indoor air temperatures which would indicate the possibilities of further improvements in increasing the comfort levels. The final step is to examine the reduction in the intensity of discomfort levels and duration due to enhanced air movement over the human body by the use of personalized cooling.

INDOOR AIR TEMPERATURE DETERMINATION

When there is no air conditioning, computational methods have been developed (Ref 19, 20, 21) for predicting hourly variations of indoor air temperatures of a building of a given designand climatic exposure conditions. These methods are highly complex mathematically and can be solved with the aid of computers. The procedure involves the estimation of steady and harmonic components of heat gains and the room admittance. The mathematical expressions for these are given below:-

Total Heat Gains

$$\bar{Q}_k = U_k \, A_k \, \bar{t}_{sak} \qquad \text{Eq (1)}$$

$$\tilde{Q}_{k,n} = A_k \, Y_{1k} \, \tilde{t}_{sak,n} \, (\text{Cos } \omega_n \tau - \varphi_n - \phi_n) \qquad \text{Eq (2)}$$

$$\tilde{Q}_k = \sum_{1}^{n} \tilde{Q}_{k,n} \qquad \text{Eq (3)}$$

$$Q_{k(\tau)} = \bar{Q}_k + \tilde{Q}_k \qquad \text{Eq (4)}$$

$$Q_{T(\tau)} = \sum_{1}^{k} Q_{k(\tau)} + Q_{is} + Q_{v(\tau)} \qquad \text{Eq (5)}$$

This can be expressed in a Fourier Series form as follows:

$$Q_{T(\tau)} = \bar{Q}_T + \sum_{1}^{n} \tilde{Q}_{T,n} \text{ Cos } (\omega_n \tau - \alpha_n) \qquad \text{Eq (6)}$$

where

$\tilde{Q}$ is the harmonic component of heat gain, watts

$\bar{t}$ is the steady state component of temperature, watts

$\tilde{t}$ is the harmonic component of temperature, ^{o}C

A is the area, m^2

U is the steady state heat transmission coefficient, $W/m^2\ ^{o}C$

Y_1 is the transfer admittance of the building section

φ is the transfer admittance phase angle, degrees

ϕ is the time lag angle introduced by the building section, degrees

ω is the angular velocity, degrees/hr

k is the number of external building element

n is the harmonic

τ is the time, hr

Subscripts

sa	sol-air	T	total	v	ventilation
ia	indoor air	is	internal sources		

Room Admittance

(a) Steady state admittance

$$\bar{RA} = \sum_{1}^{k} U_k A_k + C_v \qquad \text{Eq (7)}$$

(b) Periodic admittance for each harmonic

$$\tilde{RA}_n = \sum_{1}^{j} A_j Y_{2\ j,n} \underline{|\beta_{j,n}} + C_v \qquad \text{Eq (8)}$$

Indoor Air Temperature

Steady state component

$$\bar{t}_{ia} = \frac{\bar{Q}_T}{\bar{RA}} \qquad \text{Eq (9)}$$

Harmonic Components

$$\tilde{t}_{ia,n} = \frac{\tilde{Q}_{T,n}}{\tilde{RA}_n} \qquad \text{Eq (10)}$$

$$t_{ia}(\tau) = \bar{t}_{ia} + \sum_{1}^{n} \tilde{t}_{ia,n} \operatorname{Cos}(\omega_n \tau - \gamma_n) \qquad \text{Eq (11)}$$

where

$\bar{RA}$ is the steady state room admittance

$\tilde{RA}$ is the harmonic room admittance

C is the volumetric heat capacity of the room air

Y_2 internal admittance

j number of all inside surfaces including partitions, intermediate floors, ceiling surfaces etc.

γ temperature phase angle

β internal admittance phase angle

ILLUSTRATIVE EXAMPLE

A typical floor of a high-rise office building is considered for the present study. The floor plan and section of the office unit used for the illustrative example are shown in Fig 6 (a) and 6(b) respectively. As can be seen from Fig 6 (b), the wall consists of three sections, brick work, glass and reinforced concrete. The details of the construction and their steady and periodic thermal characteristics are given in Appendix (1).

Internal Loads

An occupancy density of 10 sq.m per person, i.e. 150 persons per floor is assumed, during the working hours of Singapore local time.

Internal loads i.e. lighting and other electrical appliances are taken as equivalent to 25 watts per sq.m. and are in operation for the same time.

Solar heat gains through glass area is taken as internal heat gain. Two cases of solar heat gain, namely (i) unshaded glass with shade coefficient 0.96 which transmits both direct and diffuse radiation and (ii) fully shaded glass with shade coefficient 0.32, are considered in the present example.

Two ventilation rates, viz., 2 air changes per hour (closed windows) which may be due to inflitration, and 10 air changes per hour (open windows) by natural or mechanical ventilation, are considered.

Weather data

The weather data chosen is for severe (near maximum) conditions of outdoor air temperature and solar radiation (clear sky) combination. The diural variation of the shade air dry bulb and wet bulb temperatures are shown in Fig 7 . Solar radiation intensities on wall surface and solar heat gain through glass for the four orientations are even in Table 10 (a) and 10 (b) respectively.

RESULTS

Air Temperatures

The calculated indoor air temperatures for the above mentioned four cases are shown in Fig. 8 . It may be observed that increased air changes has a greater effect in reducing the indoor air temperatures than shading the glass. However, the effect of shading the glass on lowering the indoor air temperatures is more pronounced for low air change rates than for high air change rates. A combination of high air changes and shaded glass will provide the lower air temperatures. For instance the reduction in maximum indoor air temperature for these four cases are:

		Reduction in maximum air temperature
Case 1	Unshaded glass (S.C. = 0.96 and the number of air changes per hour increased from 2 to 10	3.6°C
Case 2	Shaded glass (S.C. = 0.38) and air-changes per hour increased from 2 to 10	2.2°C
Case 3	Two air-changes per hour and difference between unshaded and shaded glass	2.1°C
Case 4	10 air-changes per hour difference between unshaded and shaded glass	0.7°C

Thermal Comfort Conditions

The ECI values have been calculated for different air velocities from 0 to 100 meters per minute. The hourly ECI temperatures corresponding to the indoor air dry bulb temperatures obtained earlier are determined for the four cases mentioned above. These are shown in Figs 9 (a), (b), (c) and (d). The Comfort Zone (23.8 to 25.8°C ECI) is also super-imposed in the same figures. These figures clearly bring out the effect of ventilation rates (air-changes per hour), shading of the glass, and the air movement on reducing the intensity of discomfort levels and its duration.

Under the best possible conditions i.e. shaded glass, 10 air changes per hour and an air velocity of 100m/ minute mild discomfort conditions exist between 1030 and 1500 hours. The maximum ECI temperature is 26.4°C i.e. 0.6°C above the upper limit of comfort zone. (See Fig 9). It should be remembered that these conditions are expected under severe climatic conditions. For most of the period (under average conditions) comfortable conditions throughout the working hours may be expected. From these studies it becomes clear that inducing high ventilation rates is as important as creating sufficiently high air velocities.

PERSONAL COOLING

From the foregoing it can be seen that cooling requirements are necessary for certain periods of a working day. When the indoor temperature range falls within the comfort zone, only ventilation is necessary. Provided that the fresh air intake does not increase the indoor dry and wet bulb temperatures, no airconditioning is necessary. In practice, however, some increase is expected, and the rise of air temperature and humidity will be earlier than expected. During the other periods of the day cooling is required. However, instead of the conventional space cooling which renders the entire space to the approximate same temperature and humidity, it is more energy-effective if only the work stations are cooled. There should be no difficulty with personal comfort even if there is variation of comfort conditions between working stations and circulation space as the time spent by workers in circulation spaces is short. Any discomfort due to circulation should not affect productivity, since workers moving away from their stations are less conscious of their general comfort conditions, and the trips are infrequent.

Personal cooling has the precedent in airliners where a jet air-stream is supplied to each passenger. While general airconditioning is provided for the entire aircraft, personal comfort is available to each seated passenger, thus providing him with adjustable comfort conditions.

Another precedent is task lighting. A lower level of illuminance is provided for general circulation, and higher levels are then given for specific tasks at each work station. This has been proven to save energy, and each worker turns off his own task lighting when it is not required.

The same system may be used for airconditioning, if general ventilation with same degree of heating or cooling is provided for the general circulation space, and personal heating or cooling is provided at each work station. It is normally easier to provide personal heating than personal cooling. A radiator properly placed will give radiant warmth to the worker, while personal cooling can only be obtained by a stream of cool air. Thus personal cooling depends on the dry and bulb temperatures of the forced air and its velocity.

EXPERIMENT ON PERSONAL COOLING

An experiment to verify the effect of cooling due to a forced air stream was conducted in the Thermal Laboratory of the Department of Building Science, The National University of Singapore. A desk was converted to a work station with task lighting. The forced air was provided by a demonstration aircondition unit which generated a cool air stream of cool air, the velocity, temperature and humidity of which would be adjusted. The air stream has led to the work station by piping and was discharged towards the worker seated at the desk.

Comfort conditions were measured by a "comfy-tester" which was based on Fanger's comfort equations. The probe which was linked to the meter simulated the response of human skin to the environment.

Various thermal conditions such as metabolic rates, cloth values, vapour pressures could be set. The dry bulb and wet bulb temperatures, and the relative humidities of the ambient environment and of the forced air were measured. The consequent preferred mean votes (PMV) were also recorded. The results are shown in Fig. 10(a) to 10(d).

Fig. 10(a) and (b) indicate the conditions when the indoor dry bulb temperatures are not tempered by cooling, and the forced air gives cooling effect by velocity alone. This is possible if the indoor air temperature is relatively low. The precise air velocity required to provide the neutral PMV was difficult to obtain since the forced air was turbulent and steady conditions were infrequent.

However, from the results it may be concluded that comfort conditions are obtainable when some air movement is available. The velocity does not need to be high. In fact an air velocity higher than 1 m/s will be uncomfortable, and will also blow paper about. In practice a giro grille may be inserted over the opening of the forced air so that the air stream may be directed to the spot as preferred by the user. For example, a lady user would not like to have the forced air stream directed to her hair.

For higher indoor temperature and humidities, the forced air stream is cooled before it is supplied to the work station with the consequential reduction of humidity. However, when the air stream is released, it mixes with the ambient air, and the humidity is increased. This loss of comfort due to higher humidity, however, may be compensated by air velocity as before. Consequently the actual humidity of the air stream is relatively unimportant, provided that the air stream is sufficiently cooled to the desirable level, and the air velocity is regulated and directed to supplement the cooling effect. This is shown in Fig. 10(c) and (d).

CONCLUSION

From the above it may be concluded that a personal cooling system is feasible. While the experiment did not include human subjects, the authors are confident that the PMV'S as recorded are sufficient indicative of the probability of the system. Detailed improvement of the experiment prototype may include a giro-grille to be fitted over the air-supply, the desirable piping size and velocity, and a switching system to turn off the air stream at each work station when not in use. While no comparison with a conventional space cooling installation has been made, it is anticipated that the personal cooling system would be more energy efficient.

Cooling systems, whether spatial or personal must be integrated with the thermal response of the building so that the periods during whcih cooling is required may be identified. The building fabric is then used to maintain sufficient thermal balance so that the building may be kept cool longer during the day. Thermal comfort may then be provided by means of space or personal cooling as working conditions permit. In case of general office, the system of personal cooling may be integrated with task lighting, which is further adapted in the "Opening Plan" concept such that supply air ducts may be incorporated in demountable partitions which also contain electrical conduits and telecommunication connections.

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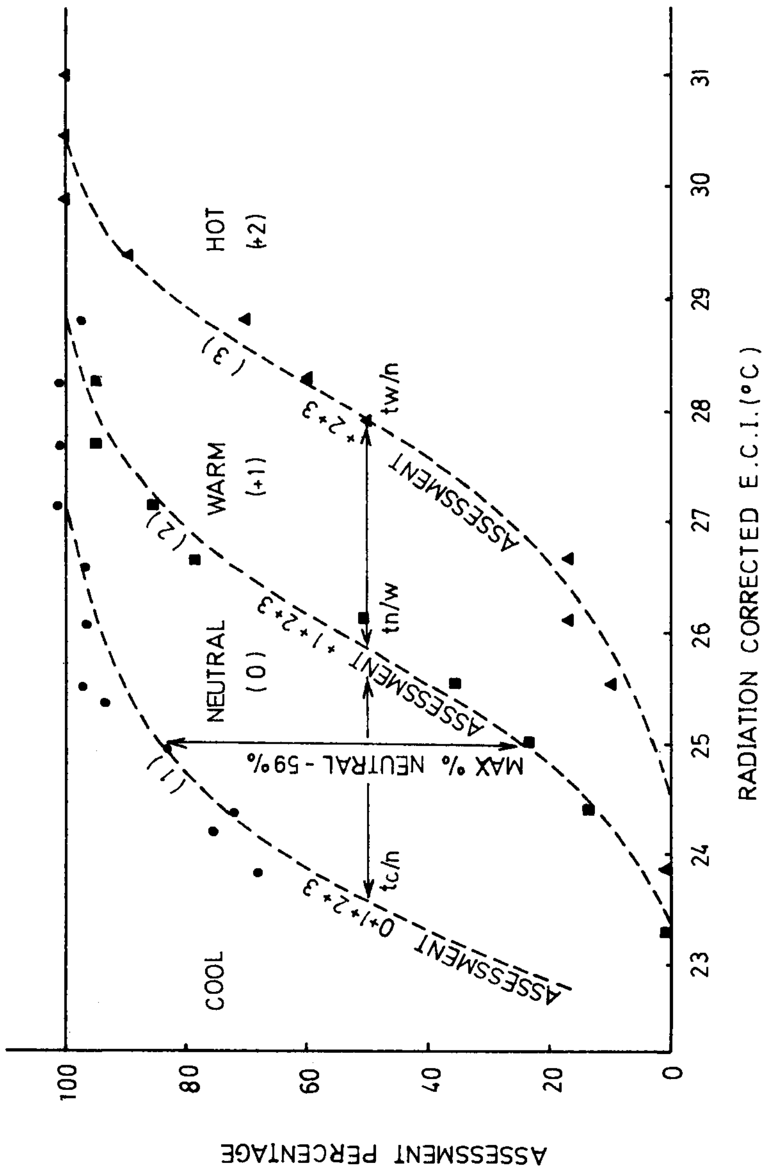


FIG. 1 Commulative thermal sensation assessment (in percentage)as a function of radiation-corrected ECI temperatures (°C) in hawker centres

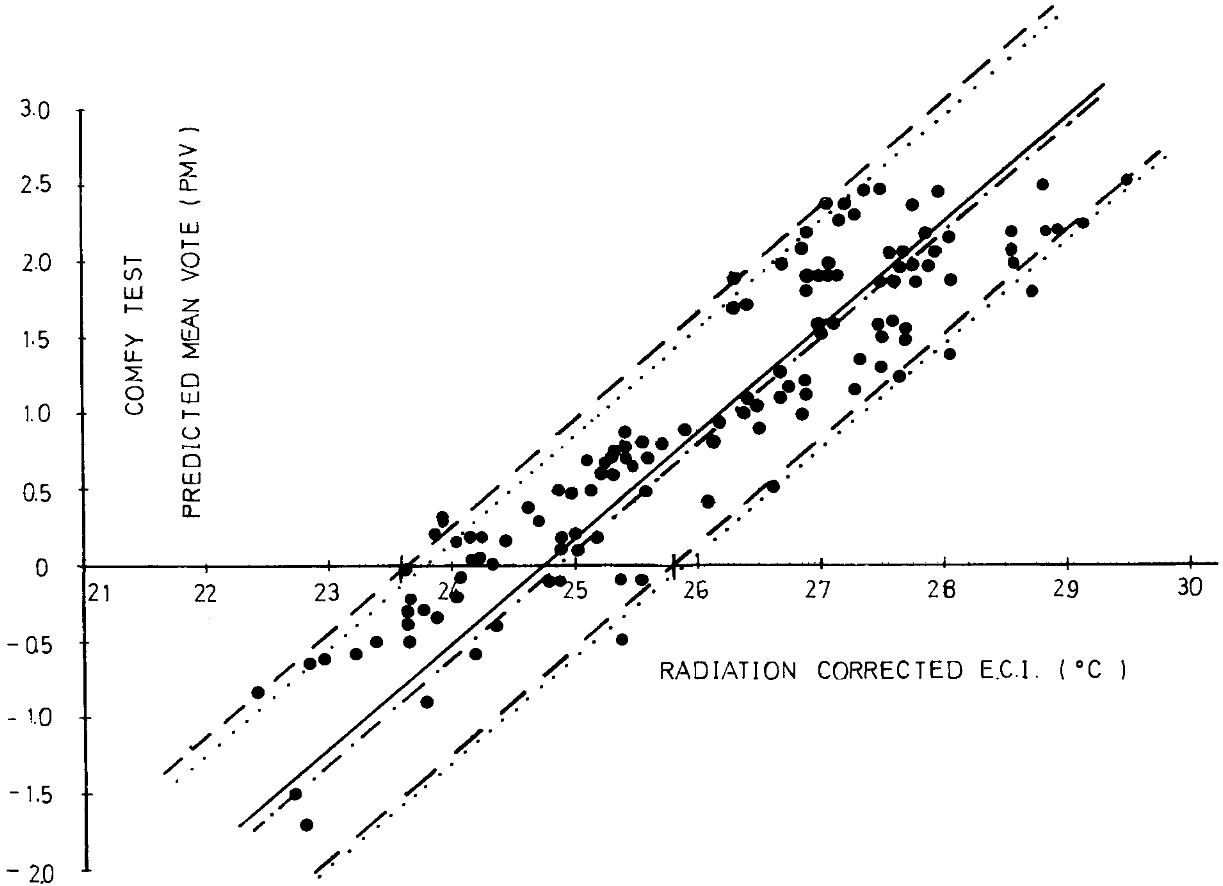


FIG. 2 Relationship between corrected ECI (^{O}C) and "Comfy-tester" predicted mean votes (PMV) in hawker centres

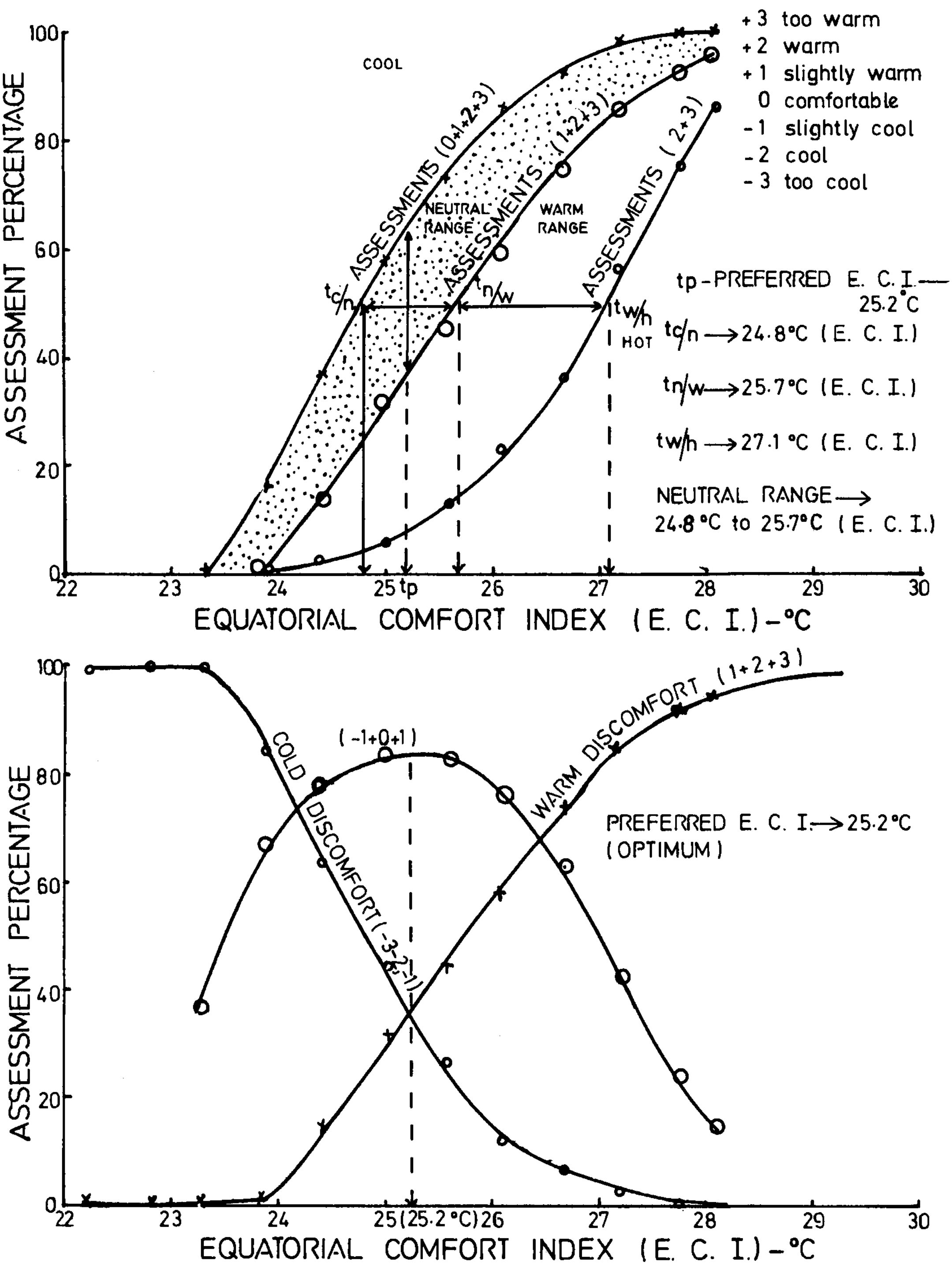


FIG. 3 Comfort survey of classroom in schools

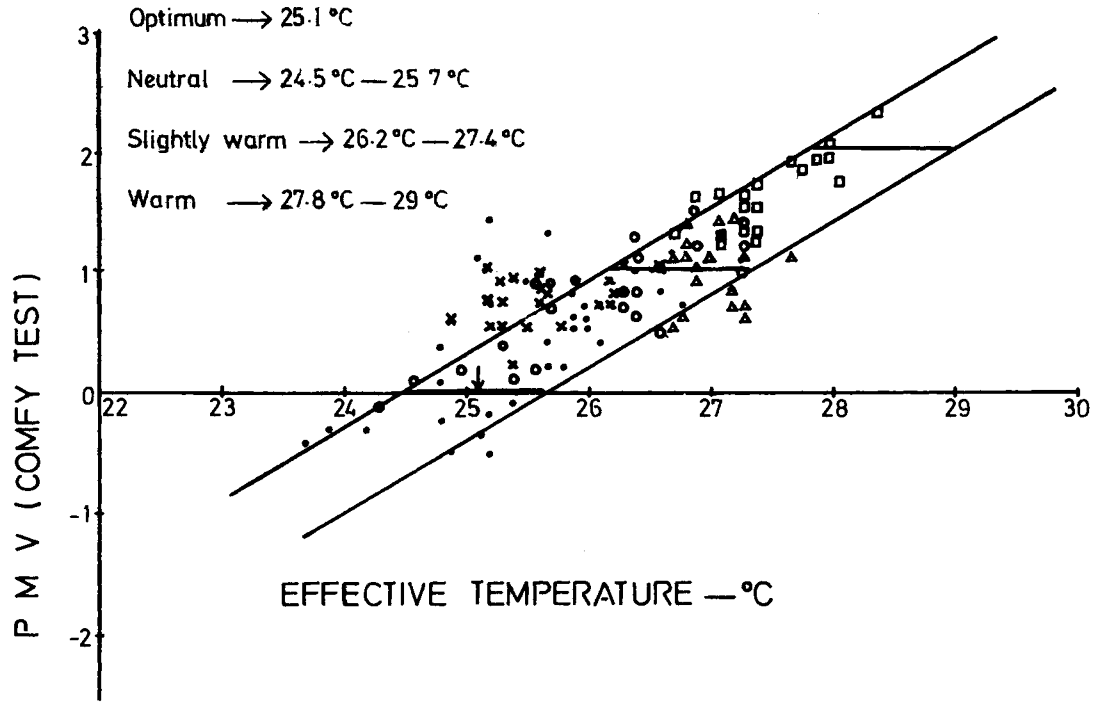


FIG. 4 Result of field survey of classrooms showing "Compy-tester" PMV's vs. Equatorial Comfort Index ECI (after Webb)

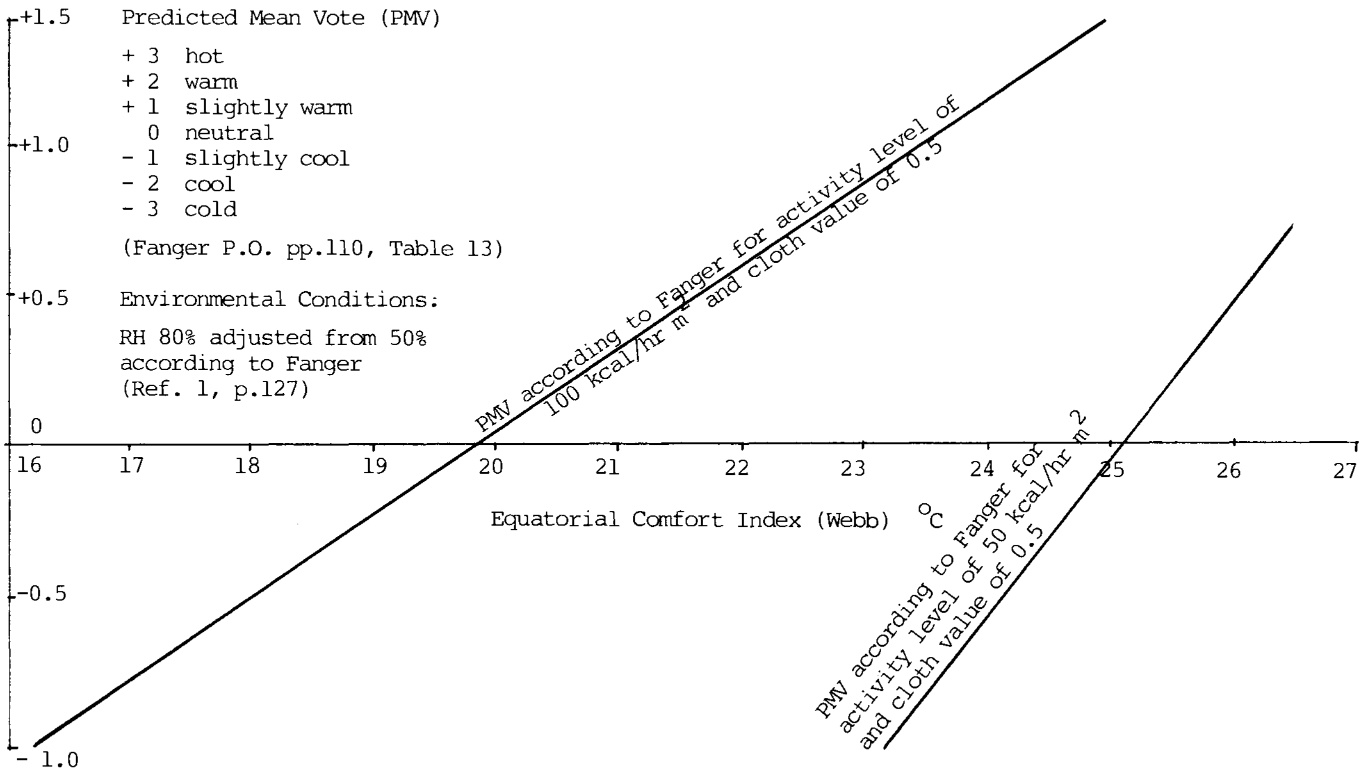
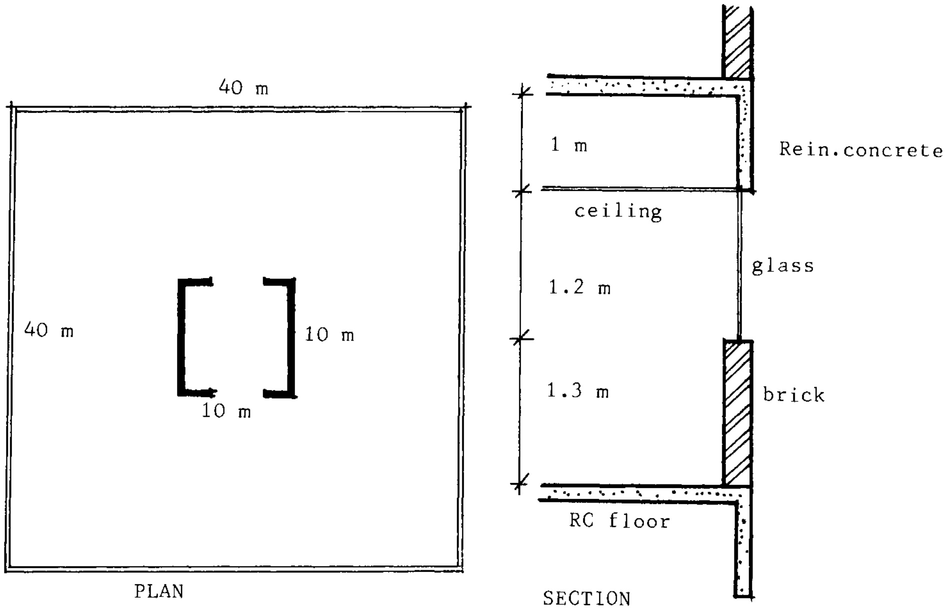


FIG. 5 COMPARISON OF PREDICTED MEAN VOTES AND EQUATORIAL COMFORT INDEX



PLAN

SECTION

FIG. 6(a), 6(b) Plan and section of typical floor of prototype building

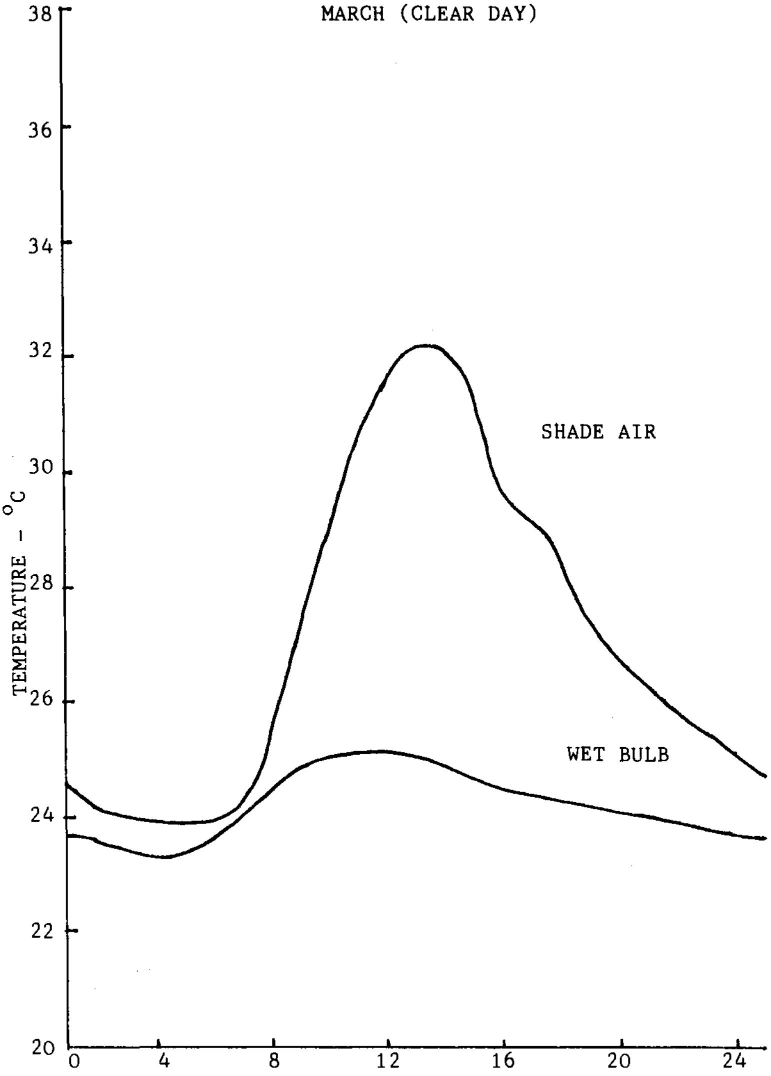


FIG. 7 HOURLY SHADE AIR DRY AND WET BULB TEMPERATURES

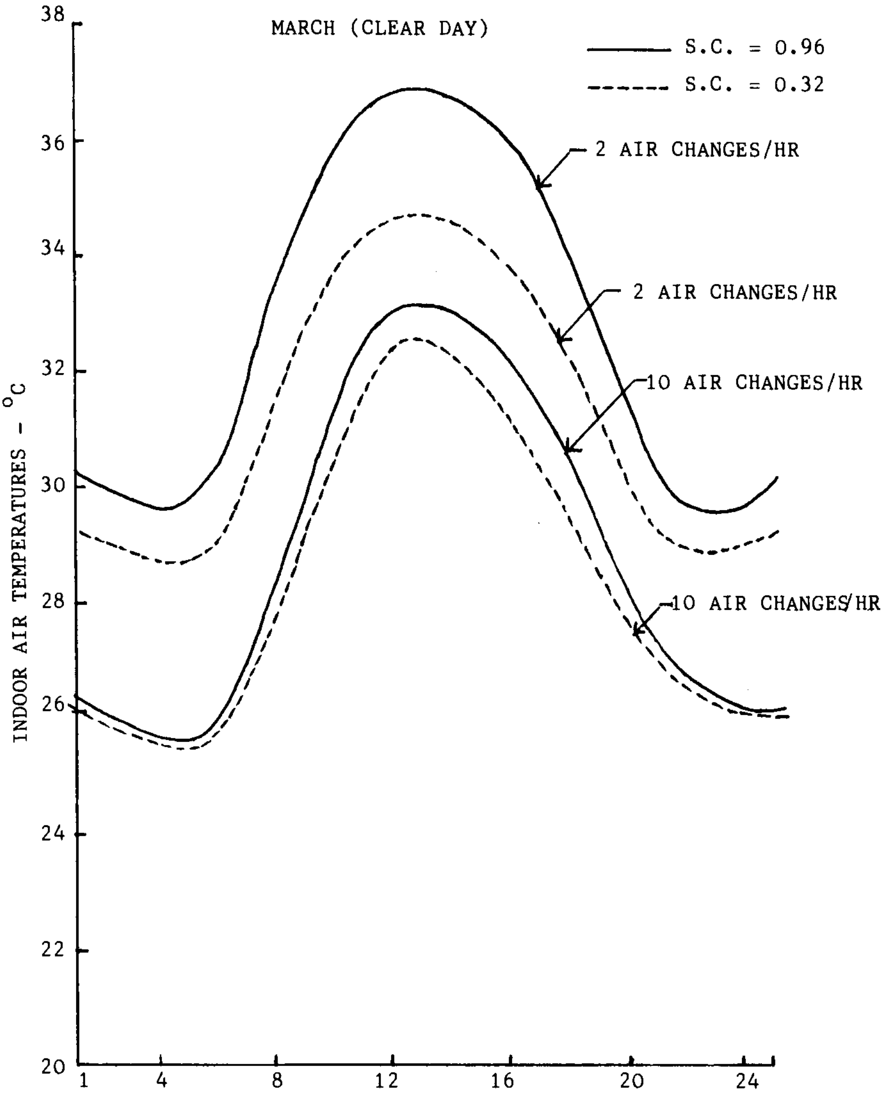


FIG. 8 EFFECT OF SHADING GLASS AREA AND AIR CHANGES ON ROOM AIR TEMPERATURES

MARCH (CLEAR DAY)

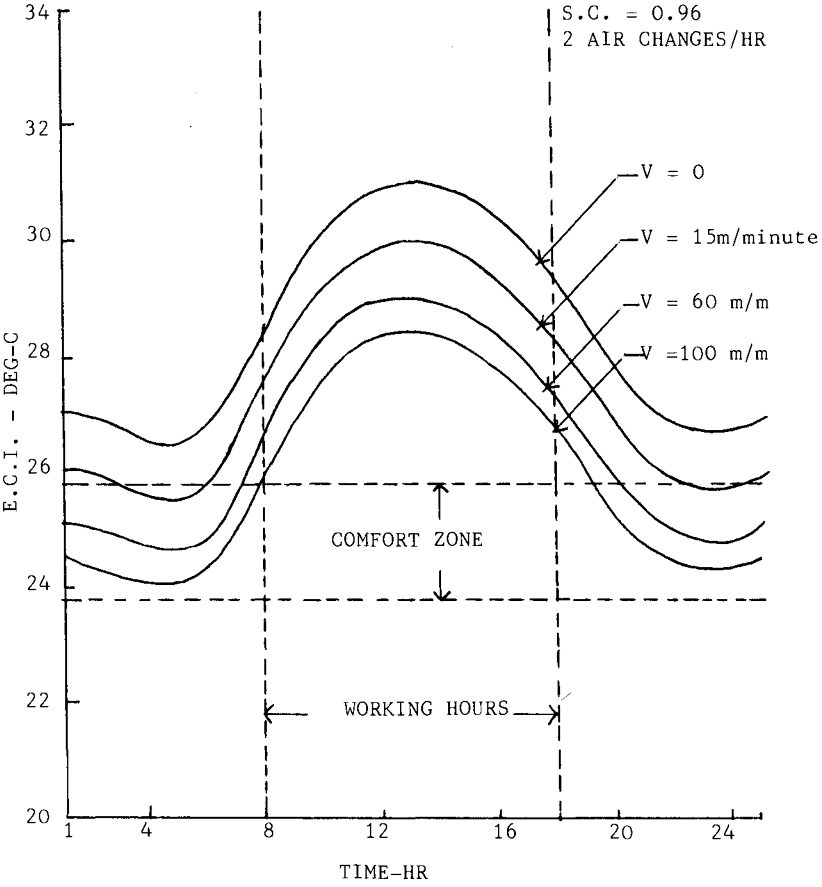


FIG. 9 (a) HOURLY VARIATION OF E.C.I. SHOWING THE EFFECT OF AIR VELOCITY (UNSHADED GLASS AND 2 AIR CHANGES/HR)

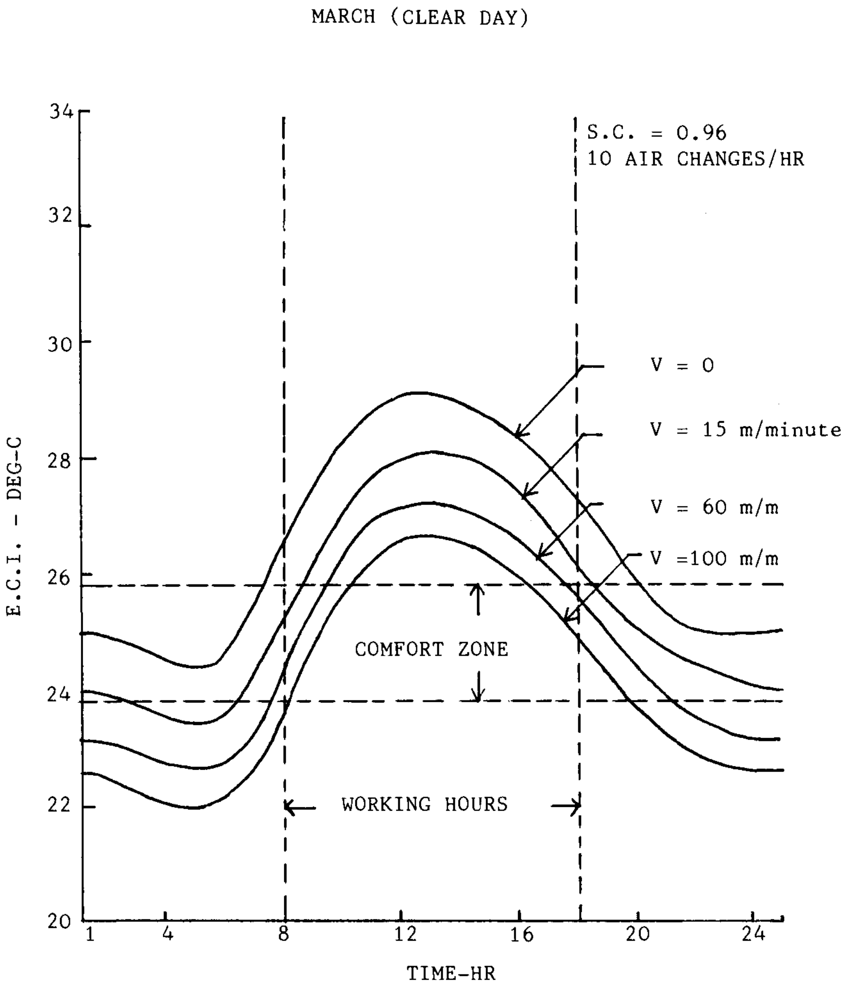


FIG. 9 (b) HOURLY VARIATION OF E.C.I. SHOWING EFFECT OF AIR VELOCITY (UNSHADED GLASS AND 10 AIR CHANGES/HR)

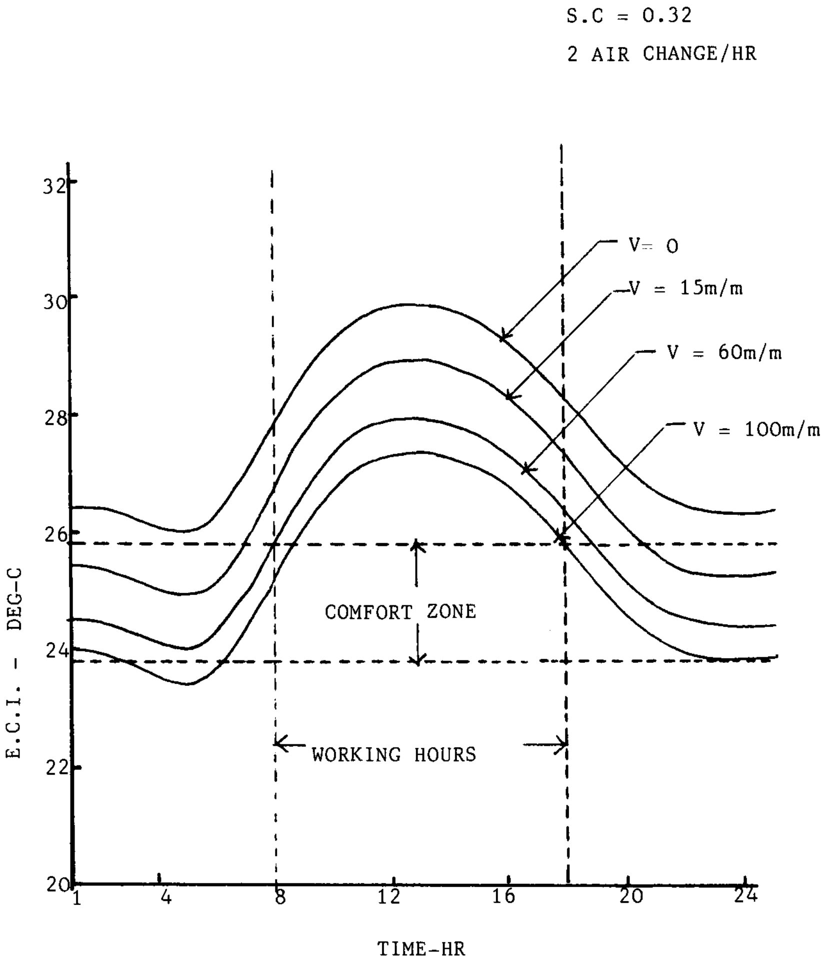


Fig 9 (c) HOURLY VARIATION OF E.C.I SHOWING THE EFFECT OF AIR VELOCITY (SHADED CLASS AND 2 AIR CHANGE/HR)

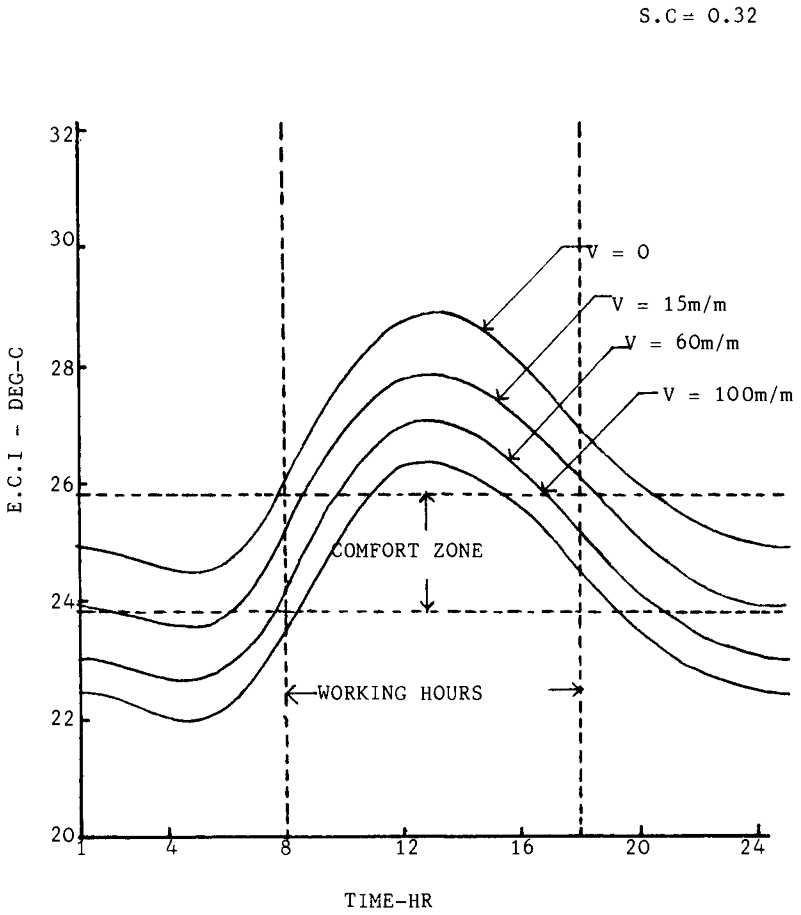


Fig 9 (d) HOURLY VARIATION OF E.C.I SHOWING 10 AIR CHANGE/HR
THE EFFECT OF AIR VELOCITY (SHADING
GLASS AND 10 AIR CHANGES/HR)

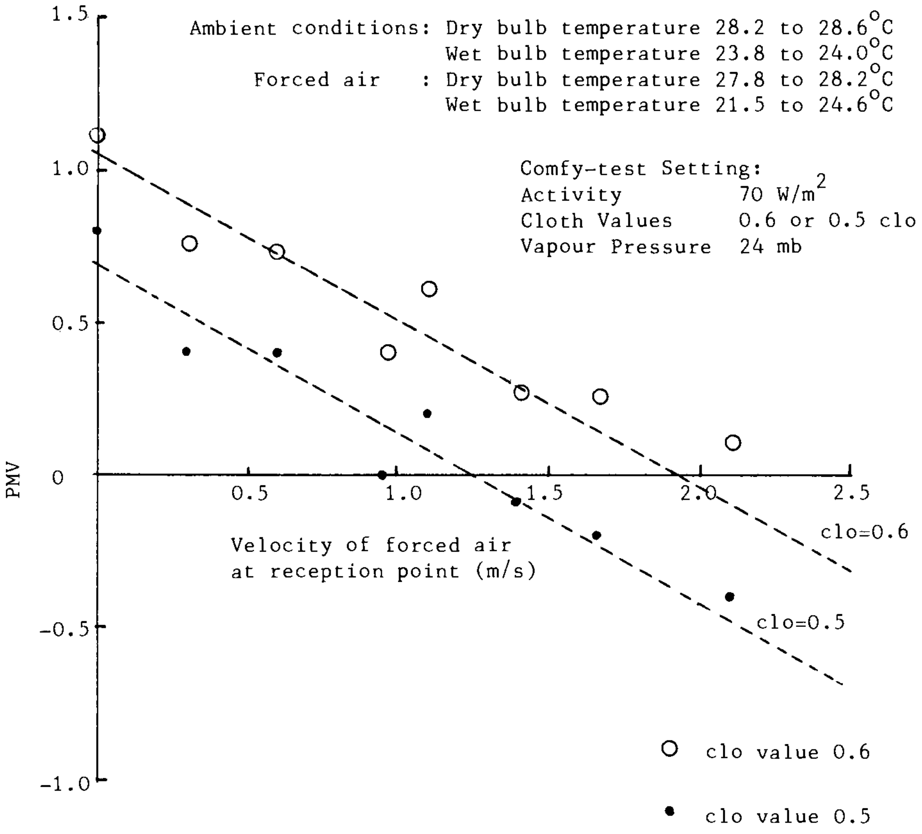


FIG.10(a) Thermal Comfort at "Comfy-test" setting 10(a) equivalent to general office work

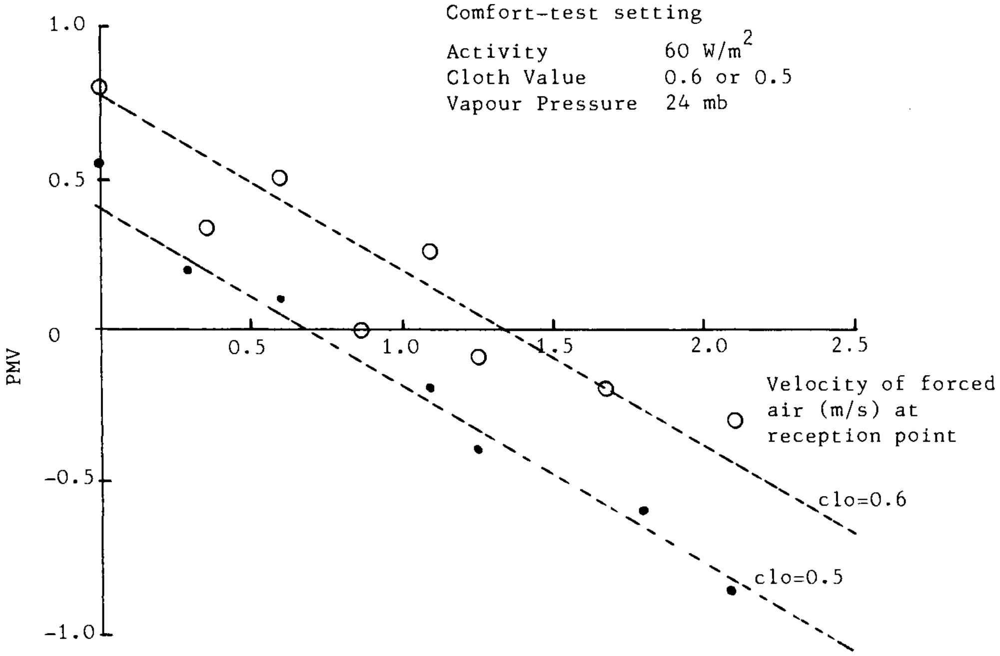


FIG. 10(b) Thermal Comfort at "Comfy-test" setting of 10(b) equivalent to quiet, seated position

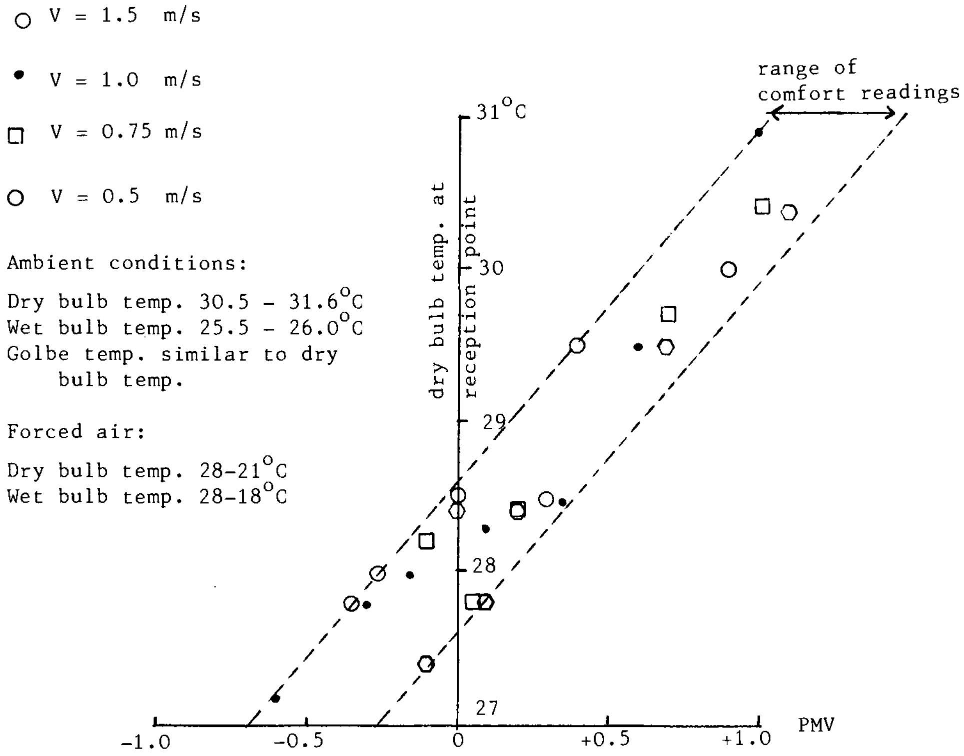


FIG. 10 (c) Thermal Comfort with "Comfy-test" setting on activity 60 W/m^2, clo value 0.6, vapour pressure 24 mb

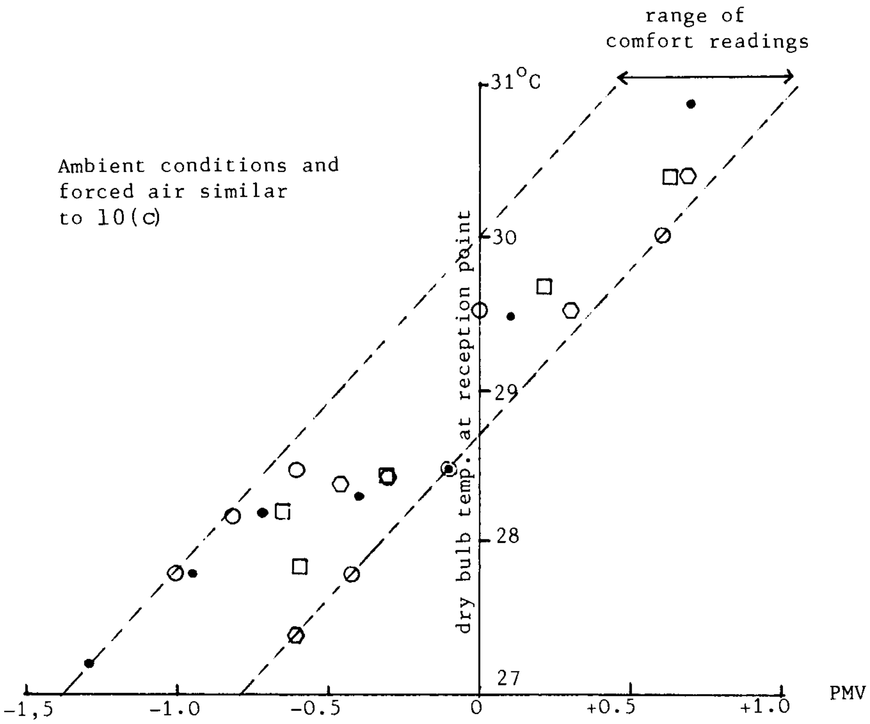


FIG.10(d) Thermal comfort with "Comfy-test" setting on activity 60 W/m^2, clo value 0.5, vapour pressure 24 mb

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