Building Envelope Design Considerations for Energy-Conserving High-Rise Buildings

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ABSTRACT

This paper discusses the building envelope energy conservation construction plan for high-rise buildings. In comparing air-conditioning loads with respect to various building orientations, it is observed that a building arranged longitudinally from north to south has to bear an air-conditioning load that is about 10% more than that of a building arranged longitudinally from east to west, regardless of the building's architectural mode. Giving due thought to the core is a vital matter when designing the typical floor plan of a high-rise building. The core type providing the minimum air-conditioning load is the "double-core" type. Due consideration must also be given to the external walls and openings/windows of a high-rise building. The window-to-exterior wall ratio is a useful criterion to consider. While insulating external walls has advantages, the color of the exterior facing of the building provides much greater effect. A comparison of the quantities of outside air infiltrating into rooms with respect to various kinds of entrance types shows that, in general, the revolving door accompanies much less heat exchange of outside air compared with the generic swing door.

A modified overall thermal transfer value (OTTV) equation for the building envelope, which is being proposed for the Malaysian building standards, is presented. It requires the input of four variables - the window-to-exterior wall ratio, the shading coefficient of the glazing, the U-value of the opaque wall, and the solar absorptance of the exterior wall. The effects of the variables on the OTTV values are shown.

BASIC PRINCIPLES OF ENERGY CONSERVATION

There are three basic principles in the methodology for carrying out energy conservation measures for high-rise buildings. The first principle is to fully match the high-rise building planning to the land and natural features of the region in which the building is constructed. The second is to develop all technologies currently available for creating artificial environments in the direction of the most efficient utilization of energy. The third principle for energy conservation is to reduce wastage by reducing excess run times and excess capacity.

To elaborate, the first principle calls in a sense for the adoption of building plans and technologies which permit maximum utilization of the natural and environmental conditions fully matched to the land and natural features of building site. For example, the building plan should not indiscreetly pursue any prevailing style and design. This is because any country or city has its own natural environments (or characteristic weather), natural features and topography, and the conditions for the construction of buildings will differ widely with each region (Markus, T.A., 1980). Faced with these conditions, ancient man created his own ideal living space by using wisdom gained through experience. Therefore, the optimum methods to be adopted for energy conservation should certainly exist among local traditional technologies, which are rooted in local living styles. By far the most distinct characteristic of these

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technologies is that they are almost always naturally oriented toward the maximum utilization of environmental conditions created by natural energy.

As for the second principle, two approaches are conceivable - the method of using electrical and mechanical systems in a manner permitting the most efficient utilization of energy and adopting planning and construction technologies enabling maximum reduction of energy-consuming loads, or maximum suppression of energy consumption. Regarding energy conservation through the adoption of optimum building methods, this method essentially consists of inhibiting factors which have the effect of increasing energy-consuming loads when operating the building's installed facilities and of conversely preventing the outflow or loss of interior air-conditioning energy wherever possible.

The third principle primarily concerns the method of managing the building and aims to achieve energy conservation through some extent by controlling run times and excessive capacities. This may be accomplished by designing the building from the outset for flexible changing of interior design conditioning with an existing building. This may be achieved by lowering the interior conditions to a certain level at certain parts of the building for fixed periods of time. Specifically, this primarily involves the period where the air-conditioning system is operating, the number of lifts in operation, or the period of time of illumination on the window side of the building.

Among the three principles described above, the second principle of deploying technologies in the direction of most efficient utilization of energy has hitherto been most popular for achieving energy conservation in high-rise buildings. However, independently, these energy conservation principles cannot be expected to provide satisfactory results. In order for these methods to provide maximum multiple effects, they must be adopted during the planning stage of the building's construction and facilities.

HIGH-RISE BUILDINGS AND ENERGY CONSERVATION

In general, a high-rise building essentially consists of scores of standard or typical floors of the same mode superimposed one over the other. Naturally, each standard or typical floor is designed for the most rationalized utilization of the target space with the maximum efficiency. As a result, large open spaces are created in the regions surrounding these high-rise buildings, which become available for utilization as municipal public squares or plazas.

However, as observed from the aspect of energy conservation, the building's peripheral area becomes definitely much larger than the surrounding ordinary buildings having the same aggregate floor area as the building's height becomes increasingly higher, with the result that the thermal load of the external air naturally becomes very great, demanding consumption of an enormous amount of interior air-conditioning energy. Therefore, it is necessary to adopt suitable plans for the energy conservation of high-rise buildings together with the conventional plans for constructing these buildings.

Let us see at this juncture what difference there is between the energy loads of interior air-conditioning systems of high-rise buildings to those of ordinary (three- or four-story) buildings. Results of calculations, performed by the Energy Research group of the Universiti Teknologi Malaysia, elucidate to what extent the air-conditioning loads would differ when the floor area of a building is set at a constant and the height or number of stories is changed, as shown in Figure 1.

The trend, from Figure 1, is that the air-conditioning load clearly increases in direct proportion to the building's height and that a difference in air-conditioning load also arises depending on the mode or proportion of the standard floor plan.

A tall building will have a proportionately smaller roof area and is less affected by solar gains from the roof. On the other hand, tall buildings are subjected to higher wind velocities, which increase infiltration and heat transfer. Tall buildings cannot be easily shaded by trees and surrounding buildings. They also require vertical transportation devices like lifts, which consume energy. Design for natural lighting will have an effect on the building's shape. This results in long, narrow buildings or other building configurations with multiple courtyards, atria, and light wells. These result in an increased perimeter area and decreased interior spaces. Though some energy is saved by the reduced artificial lighting need due to the increased availability of natural light, the solar heat gains through the excessive glass areas increase the air-conditioning loads and hence increase the energy demand.

High-rise buildings feature diverse advantages compared with buildings of ordinary heights such as greater function and efficiency of utilization of space, status symbols as the landmark of cities, and provision of wide open spaces in surrounding areas, but when observed from the aspect of energy conservation, these buildings cannot be regarded as being efficient by any standards. Accordingly, with high-rise buildings, various schemes and considerations will have to be given in much greater detail in their design, maintenance, control, and management as compared to conventional types of buildings.

BUILDING ENVELOPE ENERGY CONSERVATION CONSTRUCTION PLAN FOR HIGH-RISE BUILDINGS

The following presents the results of analysis of parametric runs performed using the DOE-2.1C program by the Energy Research Group of Universiti Teknologi Malaysia. The Energy Group is at present participating in the ASEAN-US Program for Energy Conservation in Buildings and works in collaboration with the Lawrence Berkeley Laboratory.

The DOE-2.1C Building Energy Simulation Program (BESG, 1985) is the computer simulation program employed in the analysis of energy conservation in Malaysian buildings. The DOE-2 program provides the engineering and architectural community with a tool for estimating the total and component energy consumption associated with a particular building design.

Orientation

As compared with three- or four-story buildings, high-rise buildings which project into the skyline are exposed more directly to the full impacts of external temperatures and radiant heat. Accordingly, the orientation has a great relation as observed from the aspect of energy conservation when determining the arrangement of a high-rise building. In general, arranging the building with its main opening facing north to south shows the greatest advantage with respect to the building's interior air-conditioning load.

Figure 2 shows a comparison of air-conditioning loads with respect to various building orientations depending on the specific plan (square or rectangular shape) of the building. These results are obtained from parametric runs of the DOE-2 program. We see, for example, that a building arranged longitudinally from north to south has to bear an air-conditioning load of about 10% more than that of a building arranged longitudinally from east to west, regardless of the building's architectural mode.

Also, with the same floor area, a square building has a minimum peripheral area and will be less exposed to the effects of external air than buildings having other shapes, with the result that its air-conditioning load will be minimal. Providing an overhang at the building's main opening to shut off direct sunlight further improves the building's energy conservation effect.

Core Plan

Giving due thought to the core is a vital matter when designing the typical floor plan of a high-rise building. This is because the core plan's specific position in the building determines what parts of the peripheral walls will become the openings and what parts will comprise the building's external walls.

The core of the building has to be designed by giving due thought to various factors such as the method of using the building's plans, the disaster prevention system, and the structural plan. Here, the core mode is classified into three types - center core, double core, and single-sided core - and the differences in the annual air-conditioning loads of these core types will be studied by specific orientation.

Figure 3 is obtained from DOE-2 calculations on a typical building located in Kuala Lumpur. This assumes a typical floor area of 2,400 m^2 with a window-to-wall ratio of 0.6 and an air-conditioned floor area ratio of 70%.

As is evident from Figure 3, the core type providing the minimum air-conditioning load is the double core, in which the opening runs from north to south and the core runs from east to west. Conversely, the core type characterized by maximum air-conditioning load is the center core in which the main lighting opening lies in the southeast and northwest directions.

A survey of the core types of existing high-rise buildings in Malaysia shows that there are few double-core-type buildings. The center-core design is adopted primarily for rental buildings and the double-core design is primarily for own-use buildings (e.g., government or private corporate uses) since wide spaces can be obtained flexibly.

This difference stems from the fact that with the center-core-type building the office spaces are rented out to tenants without providing a special corridor, whereas the double-core-type building requires the provision of a special corridor that results in poorer rental efficiency. However, it goes without saying that the plan of high-rise buildings, inclusive of its core plan, should be designed not merely from this economic consideration but from the aspect of energy conservation as well.

Opening/Windows

Unless due thought is given to the energy conservation effects of the external walls and opening, a building's overall energy conservation effect will be reduced despite the most conscientious considerations given to external thermal loads when designing the high-rise building's layout and typical floor plan.

Regarding windows in particular, their main purpose lies in providing spiritual and visual comfort with respect to interior environments rather than their use for obtaining adequate lighting, especially today, when interior illumination is accomplished not by unstable natural lighting but by reliable and pleasant artificial lighting.

Therefore, with most high-rise buildings the windows are large and extend from a level about 30 to 60 cm above the floor to the ceiling, with the opening ratio running up to 50 to 60%. The window's opening ratio is determined by the ceiling's height, the width and depth of the window and the windows shape and wall color design. Reducing the window's area has the effect of restricting the amount of heat infiltration through the window. Figure 4 shows the variation of cooling load with window-wall ratio for various configurations. This again is obtained from parametric runs using the DOE-2 program.

Windows have a major effect on energy consumption of the building due to solar heat gain, heat transmission, and infiltration. The percentage glass area, type of glass, single or double glazing, and the presence of sun-shading devices determine the heat gain through windows.

There are a variety of window glasses with different degrees of heat-absorbing qualities marketed and used in buildings. Their relative effectiveness in controlling solar heat gain is known by their shading coefficient values. By using glasses with low shading coefficients, the solar heat gain through windows can be considerably reduced, especially where large glass areas are employed. Use of internal shading devices like curtains, venetian blinds, etc., are less efficient than external devices in reducing solar heat gain through windows. Any new shading device is to be evaluated and its effective shading coefficient value is to be determined before using it in buildings. A recent development is the power-operated, automatically adjusted louver system with photoelectric sensor control. This enables the louver angle to be adjusted according to the sun's position and to remain open when the sun no longer shines on that facade or when heavy clouds intercept the sun. In this way, daylight is used to maximum advantage and the solar heat gains are minimized.

More recently, high-rise buildings have begun to achieve insulation shielding effect by providing balconies, which also serve as a convenient facility for the maintenance of external walls as well as for their utilization as an evacuation facility in emergencies.

A recent trend - heat reflective glass - is being used in place of the conventional heat-absorption-type glass in energy conserving type high-rise buildings around the world.

An additional criterion - that the choice of glass should encourage the use of daylighting - should utilize a glass with a reasonable light transmittance value.

External Walls

The roofs and external walls of high-rise buildings play a vital role in the prevention of inflow of external heat. However, heat insulation for limiting thermal infiltration through roofs and walls has the adverse effect of obstructing the outflow of heat accumulated during the daytime into the exterior environment when the external temperature falls below that of the rooms (at night), with the result that the residual heat acts as an additional air-conditioning load the following day. Thermal insulation is used not only to prevent inflow of heat and reduce interior cooling loads, but also to create room environments that are hardly influenced by fluctuations in external temperature.

As for accomplishing thermal insulation, the method of treating the exterior facing of the building provides a much greater effect than giving heat insulation treatment to the building's interior facings. The greatest effect is provided by giving heat insulation treatment to the roof.

The surface color of the exterior walls is an important factor in reducing solar heat gain through opaque wall sections. Light colors reflect solar radiation more than dark colors. Figure 5 shows the effect of thermal mass and exterior surface color on chiller load (Kannan, 1988). Evidently the effect of surface color is much greater.

As for heat insulation of external walls, the method of providing precast curtain walls with tile has been adopted in Japan, while the United States is using curtain walls with granite stone. These walls provide excellent heat insulation and enable building maintenance to be accomplished with ease.

Infiltration

In a completely air-conditioned room, infiltration of outside air will reduce the air-conditioning effect by acting as a thermal load. Especially at the entrances on the first floor, where people go in and out of the building frequently, a draft will be produced by the difference between the outside air and room air, causing outside air to infiltrate into the rooms each time someone opens an entrance.

A comparison of the quantities of outside air infiltrating into rooms with respect to various kinds of entrance types shows that, in general, the revolving door accompanies much less heat exchange of outside air compared with the generic swing door. Figure 6 shows the magnitude of this comparison. However, when installing a revolving door or an automatic door, an emergency manual door will have to be provided separately to prevent disasters.

THE OTTV EQUATION

To develop appropriate criteria for the building envelope, the concept of an overall thermal transfer value (OTTV) is being proposed. This concept was first developed for ASHRAE Standard 90-75 and was refined for the Singapore Standard.

The Singapore OTTV concept takes into account the three basic heat gains through the external walls of a building: (a) heat conduction through opaque walls, (b) heat conduction through glass windows, and (c) solar radiation through glass windows .

The form of the OTTV equation for walls used in the Singapore Standard is:

$$\mathrm{OTTV} = \Delta T_{eq} \times U_w \times (1 - \mathrm{WWR}) + \Delta T \times U_f \times \mathrm{WWR} + \mathrm{SF} \times \mathrm{SC} \times \mathrm{WWR}$$

where

- ΔT_{eq} = equivalent indoor-outdoor temperature difference for the opaque wall (°C),
- U_w = U-value of the opaque wall (W/m^2 K),
- WWR = window-to-exterior wall ratio,
- ΔT = indoor-outdoor temperature difference for the fenestration (K),
- U_f = U-value of the fenestration (W/m^2 K),
- SF = solar factor (W/m^2), and
- SC = shading coefficient.

The OTTV formulation is performance based. The Uw, WWR, Uf, and SC are all known design parameters. Thus, the formula allows a building designer freedom to vary important wall characteristics to meet specific design objectives and still comply with the OTTV requirements for the building envelope. A designer can select many different combinations of values from a wide range of options (opaque wall U-values, types of glazing, window-to-wall ratios, and external shading devices) so long as the total value of the resulting OTTV is not greater than that required by the standard.

Proposed OTTV Equation and Criteria

The relationship between the chiller load and OTTV is taken to be of the form

$$\text{Chiller Load} = k1 + k2\ (\text{OTTV}) \ ,$$

where

k1 and k2 are constants.

The constant k1 embodies internal gains from lights, people, equipment, etc.

An improved and simplified version of the OTTV equation for building envelopes has been developed for Malaysian buildings (Kannan, K.S., 1988):

$$\text{OTTV} = \alpha \times Uw \times (1 - WWR) \times \Delta Teq + SF \times CF \times WWR \times SC$$

where

α = solar absorptance and CF = correction factor for orientation.

It requires the input of four variables:

-- window-to-exterior wall ratio (WWR),
-- shading coefficient of the glazing (SC),
-- U-value for the opaque wall (Uw), and
-- solar absorptance of the exterior wall (α).

The input of solar absorptance is a new input that is not required in the OTTV equations used by ASHRAE or Singapore. Also, an input for the U-value of the glazed areas is not required in the Malaysian equation, since analysis has indicated that conductance (as distinct from radiative) gains through windows do not contribute substantially to changes in energy use for the climatic conditions.

The proposed equation, while offering flexibility to building designers, is not too stringent in terms of compliance, and is easy to apply. In order to encourage daylighting, the limiting value of the OTTV may be exceeded by 20%, provided adequate automatic controls are installed for all lights within 5 m of an exterior wall.

The effects of the variables–window-wall ratio, shading coefficient, and solar absorptance–on the OTTV values are obtained for a typical building and this is shown in Figure 7. It is found that the variations in the window-wall ratio have the greatest effect followed by the shading coefficient.

CONCLUSION

Various building envelope design considerations for energy-conserving high-rise buildings have been discussed. Through energy-conscious building envelope designs, energy savings on the order of 15% to 20% are possible (Deringer 1987). Energy conservation options are not limited to building design; however, it is the logical starting point for any energy conservation program for buildings.

As described above, energy conservation is accomplished through the adoption of various technologies and measures from the stage of drafting a building's floor plan to the stage of detailed designing. These energy conservation technologies and measures cannot display their full worth independently. They have to be employed in an integrated mix for them to display their designed functions fully.

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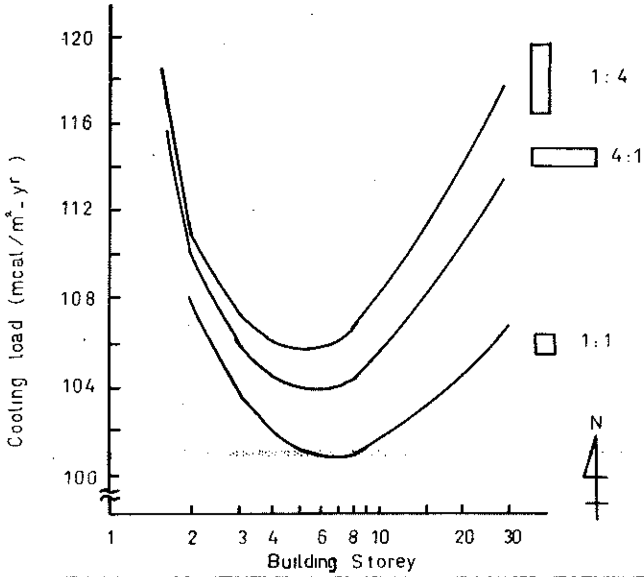

Figure 1. *Cooling load and building story*

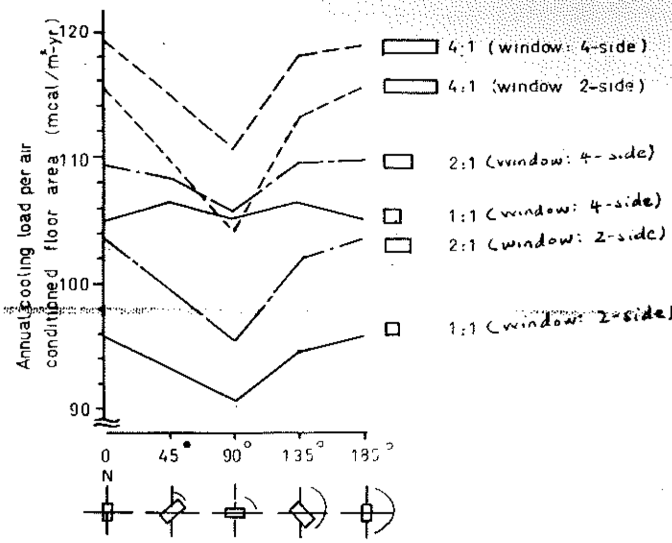

Figure 2. *Building orientation and annual cooling load*

Orientation, Type	Annual cooling load Mcal/m²-a N(S)	NE(SW)	E(W)	SE(NW)	Average cooling road
Center core	143.2	147.0	144.1	146.4	137.4 / 145.2
Double core	104.5	107.2	106.4	106.1	100.5 / 106.0
Side core (opposite side : wall)	106.1	107.9	105.4	107.2	102.5
	107.2	110.5	109.7	110.1	108.0

Figure 3. *Core plan and annual cooling load*

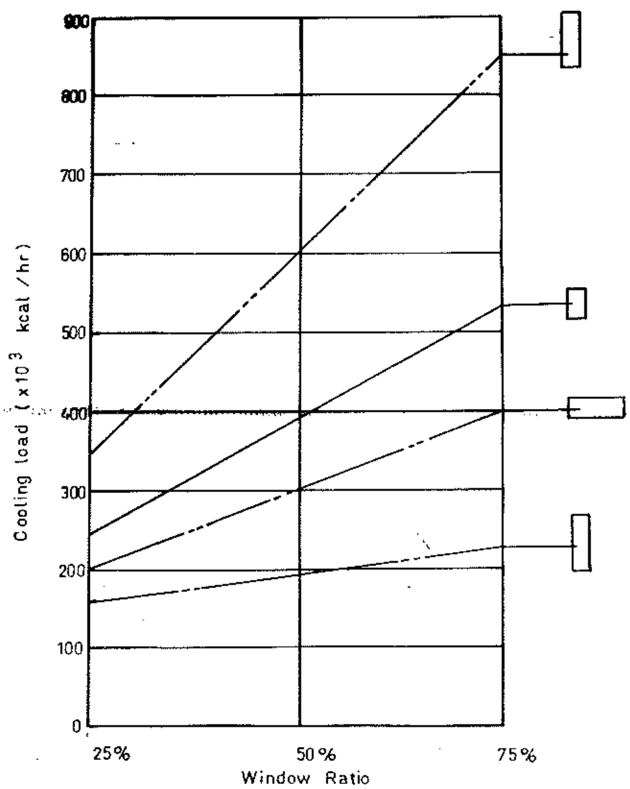

Figure 4. *Window-wall ratio and cooling load*

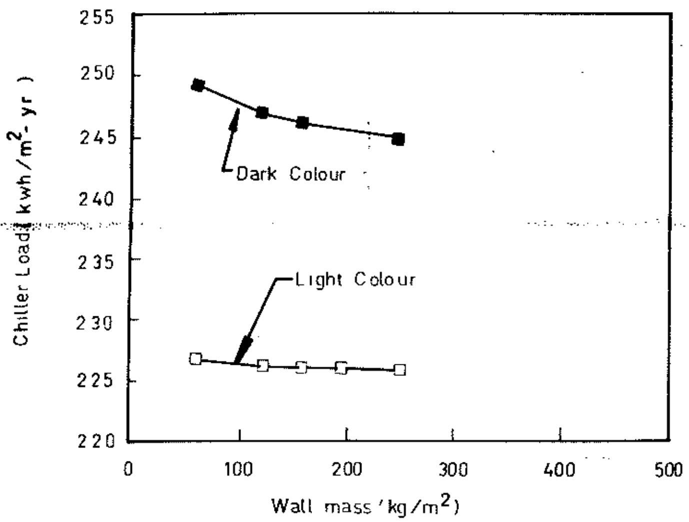

Figure 5. Effect of thermal mass and exterior surface color on chiller load

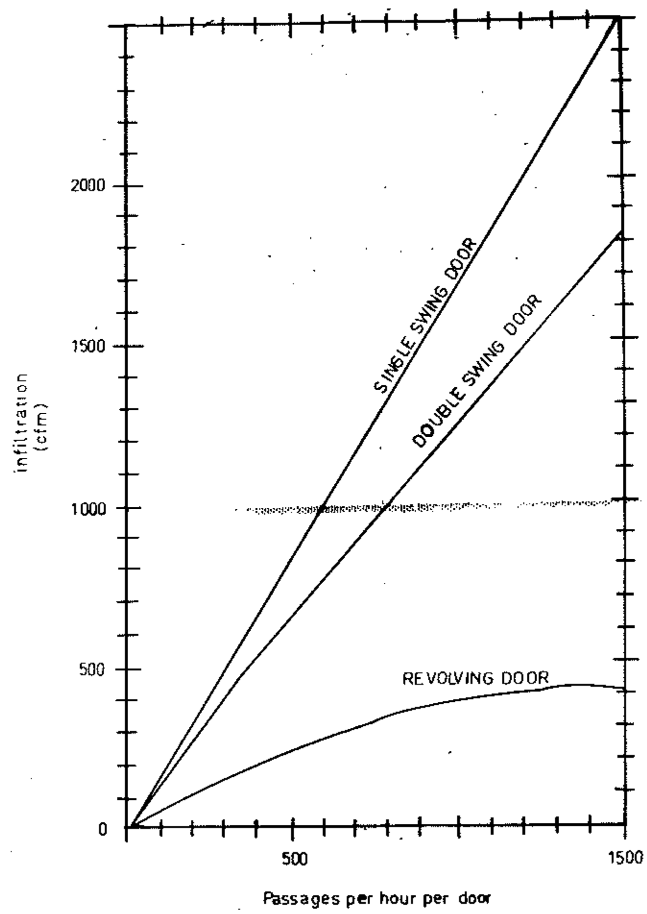

Figure 6. Infiltration through external doors

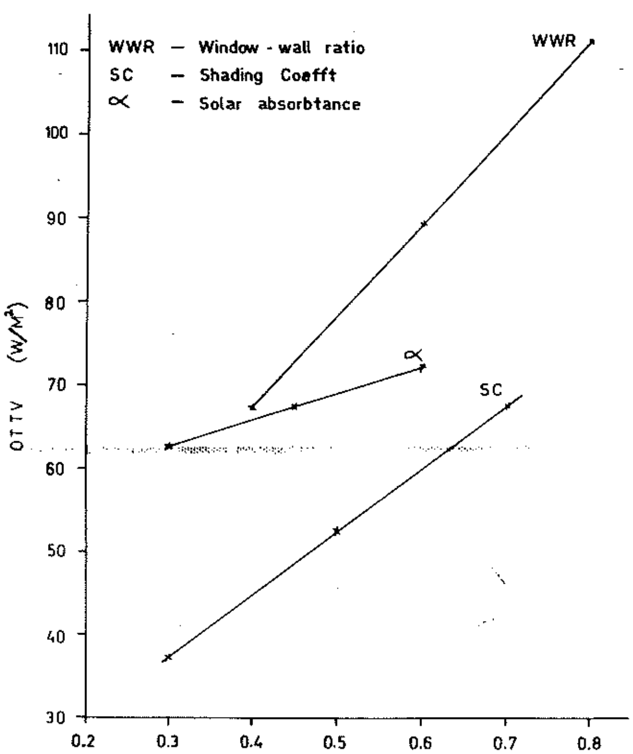

Figure 7. Effect on OTTV