Double-Envelope Office Building: A Case Study

C. Aghemo, Ph.D.

M. Filippi
Member ASHRAE

M. Masoero
Member ASHRAE

ABSTRACT

Comfort conditions in office spaces are significantly influenced by the design of the exterior envelope, which determines critical parameters such as radiant temperatures, daylight factors, and glare indexes, particularly when the exterior envelope is mostly glazed.

During the preliminary design of a 225,000 m^3 office building presently under construction in northern Italy, a study was conducted by the authors aimed at optimizing the visual and thermal comfort conditions and the energy performance of the building. A significant part of the study was concerned with the design and performance analysis of the all-glass double envelope, which is the most distinguishing feature of the architectural project.

A number of alternative glazing designs were analyzed in terms of thermal comfort, visual comfort, energy performance, safety, and maintainability. Based on the results of the analysis, the envelope design and the specifications of the major building services were identified and specified.

OBJECT OF THE CASE STUDY

An office building of 225,000 m^3 total volume is presently (summer 1989) being constructed by a major Italian enterprise in a location near Milan (northern Italy). A summary of the main data on the development project is given in Table 1 and a general layout of the building is shown in Figure 1.

The project which is now being realized is the winner of an international competition. The most distinguishing feature of the project is the external envelope concept: a totally glazed double facade, in which the two glazings are separated by a fairly wide (90 cm [36 in.]) air space.

The plan layout of the building includes office units of various sizes, multiples of a 1.2 m (4 ft) base module. The most frequent office unit is 3.6 m by 7.2 m (12 ft by 24 ft) with a 2.7 m (9 ft) net floor-to-ceiling height, as shown in Figure 1. It is also worth noticing the absence of significant internal zones - except at the ground floor, where cafeterias, conference rooms, and meeting rooms are located - due to the limited width of the building (approximately 21 m [70 ft]).

In the architects' view, the building design would create a thermally protected and luminous working environment, with strong visual links with the outdoor landscape, and the glazed facade acting as a buffer space in order to control the heat, mass, and radiant energy flows through the external envelope.

C. Aghemo, Ph.D., Consultant; *M. Filippi*, ASHRAE Member, Professor, School of Architecture, Politecnico di Torino; and *M. Masoero*, ASHRAE Member, Associate Professor, School of Engineering, Politecnico di Torino.

Nevertheless, the envelope concept raised a number of questions concerning environmental comfort, energy performance, safety, maintainability, and integration with the HVAC system. Consequently, a study was conducted in order to assess the technical feasibility and cost-effectiveness of the design solutions proposed by the architects and engineers in charge of the project, concerning both the building envelope and services (artificial lighting, HVAC, and energy management systems). Basically, the study consisted of three phases:

1. In this phase, the thermal and comfort, and indoor air quality requirements of the building were specified, together with the reference climatic- and occupancy-related data to be adopted in the HVAC and lighting system design and performance analysis.

2. In the second phase, a preliminary performance assessment of various external envelope designs was conducted addressing thermal behavior, comfort, safety, maintainability, etc. This phase led to the selection of a tentative double envelope to be further evaluated in the more comprehensive analysis performed in the third phase of the study.

3. In the third phase, a thorough evaluation of alternative designs for the whole building (including HVAC, artificial lighting, and integrated energy management systems) was performed, which led to the compilation of a set of comprehensive "design recommendations."

CHARACTERISTICS OF THE DOUBLE-ENVELOPE DESIGN

As was mentioned earlier, the adoption of a totally glazed double envelope was one of the key choices made by the architects at the initial stage of the design. One of the objectives of the study was therefore to identify economically and technologically feasible solutions for the double envelope, and to verify advantages and possible weak points of the double-envelope design (in comparison with a traditional single-envelope solution) in terms of quality of the environment and thermal performance.

Other important issues such as maintenance, safety, air and water tightness, sound insulation, and moisture condensation were considered in the study, but will not be discussed in depth in this paper.

Double-envelope buildings are among the most distinguished and fashionable designs of energy-conscious architecture. Many of the double-envelope buildings that have been proposed in the past decade incorporate solar components or systems such as atria, heat storage, air collector loops, and the like, aimed at maximizing use of daylighting and solar heating (Norford et al. 1985).

Practical experience with double-envelope buildings, however, was not completely satisfactory. A number of problems have arisen related to actual performance, maintainability, compliance with safety codes, and even individual users' response: complex airflow systems, coupled with atria and storage, often proved difficult to manage and maintain; continuity between floors, required by the atrium concept, was often not permitted by fire prevention codes; totally glazed offices facing open atria were at times perceived by the users as lacking privacy.

Such considerations were kept in mind in the design exercise presented in this paper. For example, a continuous double envelope was excluded for fire safety reasons: horizontal slabs would therefore separate each floor. The air space in the double-envelope solution was made accessible from inside to permit cleaning of the glass surfaces and so on.

In the initial phase of the study, a number of alternative single-envelope and double-envelope designs were identified and analyzed in order to make a preliminary selection of the most feasible alternatives. The major issues that were addressed can be summarized as follows:

- What kind of benefits can be expected from a double-envelope compared to a conventional single-envelope solution, and what are the extra costs?

- What type of glazing should be adopted?

- Should the exterior envelope be totally glazed or partially opaque?

- What type of fixed and/or operable sun-shading devices should be utilized and how should they be installed and managed?

- In the double-envelope solution, is it advisable to utilize the air space as a dynamic insulation system (i.e., ventilated air space)?

At the end of the preliminary selection, the investigation was restricted to two envelope solutions, one single envelope and one double envelope, the single envelope to be considered as the "reference solution" against which "pros and cons" of the double envelope were weighted.

The single-envelope solution is basically a curtain wall of the type commonly adopted in recent office building construction in Italy; it consists of the following elements (a cross section is shown in Figure 2):

- A double-glazed window, made of a reflective external sheet, 6 mm (0.25 in.) thick, and an internal 6 mm clear glass sheet, separated by a 12 mm (0.5 in.) air gap; the window occupies the upper part of the wall.

- An insulated opaque panel (U-value = 0.6 W/m^2-K, R = 10), covering the lower portion of the wall.

- An internal operable sun-shading device.

The double-envelope solution, in accordance with the architects' specifications, presents the following features (a cross section is shown in Figure 3):

- An external, totally glazed envelope consisting of a double glazing made of a tinted external sheet 6 mm (0.25 in.) thick (tinted glass was preferred to reflective glass for architectural reasons), and an internal 6 mm clear glass sheet, separated by a 12 mm (0.5 in.) air gap.

- An internal envelope, consisting of a single, clear glass sheet, 6 mm thick.

- A ventilated air space, 0.90 m (3 ft) wide. The air space acts as the extraction plenum for ambient return air; this solution can be adopted both with all-air and air-and-water air-conditioning systems.

- An operable sun-shading device (light-colored vertical blind) located inside the air space.

The properties of the double-envelope design were identified on the basis of several quantitative evaluations, some of which are presented in the next sections of this paper. In synthesis, the considerations that justify the adoption of a double envelope of the type shown in Figure 3 are the following:

1. With the ventilated air space, ambient air is extracted through the space between the two envelopes, which therefore acts as a dynamic insulation system, reducing the heat losses through the envelope and improving the indoor comfort conditions, in comparison with an identical but not ventilated double envelope. From the thermal standpoint, the totally glazed, ventilated double envelope performs better than the partially glazed single envelope, as shown in the next section of the paper.

2. The optimal air flow in the air space is that corresponding to the air exchange rate for the office unit: lower airflows do not take full advantage of the dynamic insulation effect, while for higher values the reduction in conduction losses is offset by the increase in ventilation heat demand. The increase in fan energy when air extraction is done through the air space, compared to traditional solutions, is not substantial.

3. In order to maximize the benefits of dynamic insulation and to reduce the risks of water vapor condensation on the cold side of the air space, the external envelope should have a higher thermal resistance (e.g., double or triple glazing) than the internal envelope, which can be single glazing. A solution with single glazing on the outside and double glazing on the inside was considered, but its performance was unsatisfactory.

4. The direct solar irradiation patterns inside the office spaces were analyzed for different seasons, times of the day, and orientations. The horizontal overhang created by the

air space provides effective control of direct solar radiation, particularly in the summer season, in which the solar altitude is higher and the cooling load is maximum; notice that such a shading effect would not exist with the single envelope.

5. The external glazing should be a heat-absorbing glass sheet in order to permit adequate control of summer solar gains and window luminance (reflective glasses were ruled out for architectural reasons).

6. Two positions for the sun-shading device were considered, i.e., on the inside of the glazing and within the air space. The latter solution is preferable from the thermal standpoint, although maintenance and operation are more difficult. As for shading construction, fabric curtains, venetian (horizontal) blinds, and vertical blinds were considered. A light-colored vertical blind was preferred to other types of sun shadings, mostly for operation- and maintenance-related reasons. (Notice that neither external screens nor lightshelves were acceptable for architectural reasons.)

As a further step of the analysis, the composition of the exterior glazing with respect to the number of glass panes (two or three) and the presence of a low-emittance coating on the cold side of the air gap was examined. The following three combinations were considered:

- D1: double glazing without low-emittance coating,

- D2: double glazing with low-emittance coating, and

- T1: triple glazing without low-emittance coating.

The above three double-envelope solutions were obviously compared to the reference single envelope:

- S0: double glazing (reflective), partly opaque.

The results presented in the next two sections of the paper refer solely to these four solutions, identified as solutions S0, D1, D2, and T1.

THERMAL ANALYSIS OF THE ENVELOPE

As a first step, a comparison of the thermal performance of the various envelope solutions was performed by analyzing the energy balance equations of the envelope system under steady-state conditions. Given the characteristics of the fully glazed, ventilated envelope, transient effects may be neglected in the calculation of the envelope heat gains and temperature distribution. The energy balance of the envelope includes two terms, i.e., the conduction heat gain, Qd, and the solar heat gain, Qs.

The solar heat gain, Qs, can be put in the following form:

$$Qs = Fi \cdot Fs \cdot It \cdot Ag \qquad (1)$$

where

It = incident solar radiation (W/m^2) or (Btu/h-ft^2),
Ag = area of the glazed part of the envelope (m^2) or (ft^2),
Fi = ratio of the ambient solar heat gain to the incident solar radiation, and
Fs = factor (≤ 1) which takes into account the effect of fixed shadings (e.g., overhangs).

Values of Fi for regular glazing systems can readily be found in the literature, while a more accurate heat transfer analysis is needed for complex and unconventional systems, such as the ventilated double glazing. In the latter case, Fi values were computed using two different approaches: a first estimate was made by empirically correcting literature values (CNR 1981); the results were then checked with a detailed heat transfer model (Wright and Sullivan 1989).

The steady-state conduction heat gain, Qd, takes up different forms depending on whether single or double envelopes are concerned. For a partly opaque single envelope:

$$Qd = (Uw \cdot Aw + Ug \cdot Ag) \quad (To - Ti) \tag{2}$$

while for a totally glazed double envelope:

$$Qd = Ui \cdot Ag \; (Ta - Ti) \tag{3}$$

<u>where</u>

Ta = air temperature in the ventilated air space (°C or °F),
Ti = indoor temperature (°C or °F),
To = outdoor temperature (°C or °F),
Ag = area of the glazed part of the envelope (m^2 or ft^2),
Aw = area of the opaque part of the envelope (m^2 or ft^2),
Ui = indoor to air space thermal conductance (W/m^2-K or Btu/h-ft^2-°F),
Ug = overall U-value of the glazed part of the envelope (W/m^2-K or Btu/h-ft^2-°F), and
Uw = overall U-value of the opaque part of the envelope (W/m^2-K or Btu/h-ft^2-°F).

Provided the thermal parameters of the envelope are known, the only unknown term is Ta in Equation 3; in order to calculate Ta the energy balance of the double envelope must be solved.

The distinctive feature of the double envelope under investigation is clearly the ventilated air space. Intuitively, the ventilated air space acts as a heat exchanger, in which the extracted air exchanges heat with the outdoor and indoor environments through the two glazed envelopes; obviously, the thermal balance of the system also includes the contribution of solar radiation. As a result of the energy balance, the air temperature in the space assumes a profile which depends on the airflow pattern and airflow rate, on the boundary conditions of the heat transfer problem (outdoor and indoor temperature, solar radiation flux, etc.), and on the thermal/optical properties of the glazed envelope.

A rigorous analysis of the problem would require the solution of complex two-dimensional airflow and heat transfer equations. In the authors' opinion, however, adequate results can be obtained from a simpler representation of the flow pattern. Two limit situations can be envisaged. If the airflow in the space is assumed to be one-dimensional, an exponential temperature profile results from the energy balance (this would be the case in a ventilated window). On the other hand, if one considers the air in the space as fully mixed (zero-dimensional model), then the air temperature is represented by a single value resulting from the overall energy balance of the system. Considering the turbulent nature of airflow in such a wide air space and the presence of buoyancy effects of a magnitude comparable to fan-driven air motion, the latter hypothesis is actually the most reasonable.

Under the above hypotheses, the steady-state energy balance of the wholly glazed, ventilated double envelope is described by the following equation (see also the electric analog of Figure 4):

$$M \cdot Cp \cdot (Ta - Ti) = Uo \cdot Ag \cdot (To - Ta) + Ui \cdot Ag \cdot (Ti - Ta) + Fa \cdot It \cdot Ag \tag{4}$$

<u>where</u>

M = air mass flow rate (kg/s or lb/s),
Cp = specific heat of air at constant pressure (J/kg-K or Btu/lb-°F), and
Uo = outdoor to air space thermal conductance (W/m^2-K or Btu/h-ft^2-°F).

The term (Fa·It·Ag) in Equation 4 represents the air space solar heat gain; in other words, of the incident solar radiation flux It, the amount (Fa·It) is transferred to the air space and therefore contributes to the energy balance of the air space itself, while the amount (Fi·Fs·It), which appears in Equation 1, is eventually transferred - through a combination of various heat transfer mechanisms - to the indoor ambient.

Equation 4 yields the unknown temperature, Ta:

$$Ta = \frac{Uo \cdot To + Ui \cdot Ti + Ci \cdot Ti + Fa \cdot It}{Uo + Ui + C} \tag{5}$$

where

$$C = M \cdot Cp/Ag \tag{6}$$

Results of the simplified energy balance of the envelope (with reference to a 3.6 by 2.7 m - 12 by 9 ft - facade module) in winter and summer peak conditions are summarized in Table 2, assuming the specified design data. The results indicate that the double-envelope solutions can provide some real advantages compared to the standard single-envelope design.

In winter design condition, the conduction heat loss shows a 63% reduction between the standard solution S0 and the best-performing double envelope (D2 or T1). Notice that in terms of thermal resistance, the low-emittance double glazing and the triple glazing are fully equivalent, providing a 30% higher insulation than regular double glazing. Similar considerations can be made with respect to inside surface temperatures.

In summer design condition, the main advantage of the double envelope is the reduction of solar heat gain, which can be attributed to the combined shading effect of the horizontal overhang and of the screen located inside the ventilated air space. On the contrary, the conduction heat gain is higher, because a fraction of the solar radiation absorbed by the glazing system is transferred to the air space, therefore increasing its temperature. With this respect, it is worth stressing that the air temperature would be significantly higher if the air space were not ventilated: for example, temperature, Ta - which equals 33.1°C (91.6°F) for the solution D1 with ventilation - would go up to 39.5°C (103.1°F) without ventilation.

As a further analysis, the annual heat balance of the entire building envelope (32,000 m^2 - 360.00 ft^2) was evaluated on the basis of the average temperature and solar radiation data of the TMY (CNR 1982). Results are summarized in the bar graphs of Figure 5, in which the net monthly heat gain (conduction plus solar) is shown over the year.

The graphs indicate that the net thermal balance for solution S0 is positive for only three months (June, July, and August), with maximum negative values (heat loss) in the months of December and January on the order of 900 MWh/month (3 GBtu/month). For the double-envelope solutions, the net thermal balance is positive for six months per year (April through September), and the maximum winter loss is roughly 450 MWh/month (1.5 GBtu/month), i.e., half of the value of solution S0. Also notice that for solution T1 (which has the best energy performance), the absolute value of the net heat flow does not exceed about 150 MWh/month (0.5 GBtu/month) for 8 out of 12 months.

THE INFLUENCE OF THE ENVELOPE ON COMFORT CONDITIONS

The characteristics of the various envelope solutions will now be discussed more specifically in terms of thermal and visual comfort.

Thermal Comfort

Thermal comfort conditions were analyzed according to ISO Standard 7730 on moderate thermal environments (ISO 1984), with reference to the most critical working location of the office unit shown in Figure 1, which is situated at a distance of 0.8 m (2.7 ft) from the internal glazed surface. For such location, the PMV values were calculated as a function of ambient dry-bulb temperature, Ta, and of the temperature of the inside surface of the double envelope, Tv, assuming a metabolic rate of M = 1.2 Met, an air speed of a Va = 0.15 m/s (0.5 ft/s), and a clothing insulation of I = 1 clo (winter) or I = 0.5 clo (summer).

The results of the calculation are shown in Figures 6a (winter condition) and 6b (summer condition); each line in the graph shows the relationship between PMV and Tv for a given air temperature, Ta. The water vapor partial pressure is assumed constant, which implies that the relative humidity varies with temperature, such assumption justifiable since the corresponding relative humidity ranges (46% to 58% in winter and 42% to 52% in summer) are acceptable from the comfort standpoint.

In Figure 6 the PMV values are limited to the -0.5 to +0.5 optimal range, as prescribed by the ISO Standard 7730. The range of surface temperature Tv - 10°C to 30°C (50°F to 86°F) for the winter, and 20°C to 40°C (68°F to 104°F) for the summer - is compatible with the results of the thermal analysis discussed in the previous section.

The two graphs point out the sensitivity of the indoor environmental conditions to variations of external climate. For example, in winter conditions, Figure 6a shows that a PMV value within the optimal range of -0.5 to +0.5 is guaranteed only if the ambient temperature does not fall below 21°C (70°F), or exceed 23°C (73.5°F): therefore, an indoor design temperature of 22° ± 1°C (72° ± 2°F) appears to be the optimal choice. Similar considerations can be made for the summer conditions (Figure 6b): in this case the optimal design temperature turns out to be 24° ± 1°C (75° ± 2°F).

A further type of analysis concerns the comparison of different envelope design solutions. Tables 3a and 3b give the values of internal surface temperature Tv, mean radiant temperature Tmr, and PMV for the four envelope solutions described in the previous section (S0, D1, D2, and T1) in winter and summer conditions.

The analysis points out an interesting result: the prescribed comfort level can be obtained with any of the double-envelope solutions (D1, D2, T1) for an indoor temperature value which is respectively 1°C lower in winter and 1°C higher in summer compared to the single-envelope solution (S0), with beneficial consequences on the climatization energy requirements of the space. Also, it is worth stressing that the double-envelope solution permits a better utilization of the floor space, since the working stations can be localized even in direct contact with the inner surface of the envelope.

Visual Comfort

Analyses on visual comfort were limited to daylighting; as far as artificial lighting is concerned, comfort indices were indicated among the design specifications, under the assumption that such requirements could be met through an adequate selection and installation of the lighting fixtures.

Basically, two daylighting indices were considered, i.e., the daylight factor, DF, which provides a measurement of the natural illuminance on the task area, and the daylighting glare index, DGI, which indicates how a group of people respond to various levels of brightness. All calculations refer to overcast sky conditions. Results are summarized in Table 4.

The daylight factor is defined as the ratio of the illuminance, i.e.,

$$DF = E/Eo \tag{7}$$

Daylighting factors were calculated at three reference points on the working plane situated along the room axis, respectively at 1.5 m (5 ft) from the external envelope (MAX - maximum illuminance point), at 1.5 m (5 ft) from the end wall (MIN - minimum illuminance point), and at the center of the room (MID - intermediate illuminance point). (Notice that the "Lumen method" for daylighting calculations described in the IES handbook [IES 1985] refers to the same three points.)

Reference was made to three different office units, i.e., the 3.60 by 7.20 m (12 by 24 ft) office unit of Figure 1 (Unit C), a 2.70 by 7.20 m (9 by 24 ft) unit (Unit B), and a 3.60 by 3.60 m (12 by 12 ft) unit (Unit A); units with a single window only were considered (therefore excluding corner rooms with two windows).

A uniformity ratio for daylighting, UR, was also introduced, in order to evaluate the difference in natural horizontal illuminance over the floor area of side-lit office units:

$$UR = \frac{DL(MAX) + DL(MID)}{DL(MID) + DL(MIN)} \tag{8}$$

As far as the envelope technology is concerned, reference was made to the double-envelope solutions only. Different values of the overall daylight transmittance of the glazing system, TL, corresponding to glazing types commonly adopted in office buildings were considered in the calculation. Typically TL may range between about 0.25 up to about 0.60 for a double envelope, depending on the characteristics of the external heat-absorbing glass sheet.

The calculation of DF was made with two different methods, i.e., the IES lumen method (IES 1985) and the CIE daylight factor method (CIBS 1984); the difference between the two methods was, in all cases, well below 10%. The following observations can be made about the results (see Table 4):

- In the case of Unit A, DF values are always quite high (for the MID point, DF ranges between 2.7% and 6.4%), with possible overilluminance problems, while the illuminance distribution is fairly uniform: UR $\approx$ 1.5.

- Units B and C show a very similar behavior, characterized by moderately low DF values (for the MID point, ranging between 1% and 2.5% - both numbers are lower than the commonly suggested reference value of 3%); the illuminance distribution is less uniform, since the UR approximately equals 2.5, a value, however, still lower than the suggested maximum limit of 3.

The daylighting glare index, DGI, was calculated following the method outlined by Robbins (1986). DGI measures the degree of uncomfortable glare due to the sky seen through a window on the basis of the Cornell large-source glare equation.

The results given in Table 4 were obtained for the three office units A, B, and C, assuming TL = 0.25 and TL = 0.60, under the following hypotheses:

(1) Window height = 2.7 m (9 ft)
Distance from external envelope = 1.8 m (6 ft)

(2) Window height = 2.1 m (7 ft)
Distance from external envelope = 1.8 m (6 ft)

(3) Window height = 2.7 m (9 ft)
Distance from external envelope = 2.7 m (9 ft)

In the calculation it was assumed that the window screen is absent, and that the direction of view is orthogonal to the window plane; such situation is the most critical in terms of discomfort glare.

DGI values turned out to be higher than the recommended value of 19. The gap between calculated DGI and optimal DGI is maximum for the smaller office unit A (DGI = 32.0 with TL = 0.60) under hypothesis 1 (totally glazed envelope, and working location at 1.8 m from the external envelope). Significantly lower values of DGI were found for larger office unit B: 21.8 and 25.0, respectively, for TL = 0.25 and TL = 0.60.

Virtually no difference was found between the totally glazed double-envelope solution (1) and the partially opaque single envelope (2): the reduction of DGI is in fact less than 1%. Comparing the two working locations 1 and 3 (respectively, 1.8 and 2.7 m away from the external envelope), a reduction of DGI of about 4% is found.

As a final analysis, the control of direct solar radiation achieved with the fixed overhang which is provided by the horizontal floor slab between the internal and external envelopes was verified. The direct solar irradiation pattern was verified for varying office orientation, time of day, and month of the year. The double-envelope solution proved to be more effective with respect to direct irradiation control, compared to the standard single-envelope solution.

CONCLUSIONS

The results of the analyses discussed in the previous sections indicate that the double envelope may be an interesting solution for an office building with a largely glazed facade, compared with a standard single-envelope design.

Among the double-envelope designs that have been examined for this building, the most promising solution appears to be the one characterized by a ventilated air space, external double (or triple, or double with low-emissivity coating) glazing with heat-absorbing glass, and a sun-shading device located inside the air space.

In terms of thermal comfort, the key advantage is that the ventilated double envelope presents values of surface temperature that are very close to ambient air. Winter envelope heat losses also are significantly reduced, and better control of summer solar gains can be achieved, thanks to the combined effect of the horizontal overhang and vertical blind located within the air gap.

Obviously the ventilated double envelope poses several technical problems with respect to maintenance, among which filtering of extract air and access to the air space for window and sun-shading cleaning are probably the most critical.

The following observations concerning visual comfort can be drawn from the study:

- Office spaces with large glazed areas may cause uncomfortable glare when the working location is near the window and the direction of view is orthogonal to the window, even with an overcast sky, unless strongly absorbing glass or a screen is used. The level of uncomfortable glare does not vary significantly with the height of the window, i.e., a totally or partly glazed facade causes the same degree of discomfort.

- Potential for natural lighting is good, provided the luminous transmittance of the glazing is on the order of 0.5; uniformity of daylighting is within the recommended range for all office units.

- The double envelope allows for better control of direct solar radiation compared to the single envelope.

Visual comfort is therefore a critical issue in this building, since the two goals of effectively exploiting natural light and preventing uncomfortable glare are difficult to meet.

A final comment on the cost implications of the double envelope: the difference in capital cost between the double envelope and the traditional single-envelope solution ranges between 60% and 80% of the cost of the single envelope, depending on the type of external glazing and frame technology. Considering that the envelope will represent approximately 15% of the overall construction cost, the financial impact of the double envelope turns out to be on the order of 10% of the total cost.

It is extremely difficult to include this figure in a cost-benefit analysis. While the energy implications of the double envelope can be quantified through simulation, it is not clear how to quantify the consequences on comfort.

Our analysis on the double envelope was therefore limited to recommending the solution which seemed the best from the thermal/environmental standpoint, given the architectural constraints of the project. Nevertheless, detailed hour-by-hour simulations were performed in order to assess the energy performance of the various HVAC system alternatives. The results of this analysis are beyond the scope of this paper, and will be the subject of other publications.

REFERENCES

CIBS. 1984. Code for interior lighting. London: The Chartered Institution of Building Services.

CNR. 1981. Dati climatici per la progettazione edile ed impiantistica. Milano: PEG editrice.

CNR. 1982. Repertorio delle caratteristiche termofisiche dei componenti edilizi opachi e trasparenti. Milano: PEG editrice.

IES. 1985. Lighting handbook. New York: Illuminating Engineering Society of North America.

ISO. 1984. ISO Standard 7730. "Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort."

Norford, L.K., et al. 1985. "Monitoring the energy performance of the Enerplex office building." Princeton University Center for Energy and Environmental Studies Report No. 203.

Robbins, C. 1986. Daylighting design and analysis. New York: Van Nostrand Reinhold Co.

Wright, J.L. and Sullivan, H.F. 1989. "VISION: a computer program to evaluate the thermal performance of innovative glazing systems - reference manual." University of Waterloo, Dept. of Mechanical Engineering. Waterloo (Ontario).

TABLE 1

Main Data on the Development Project

Total building volume	225,000 m^3	
Expected number of occupants	3000	
Surface area of the building site	103,000 m^2	1,144,500 ft^2
Gross area of the aboveground space	63,500 m^2	705,500 ft^2
Breakdown of conditioned net areas		
Office spaces	46,500 m^2	517,000 ft^2
Meeting rooms	2000 m^2	22,000 ft^2
Cafeterias	3500 m^2	39,000 ft^2
Archives and underground storage	3000 m^2	33,500 ft^2
Other aboveground spaces	4500 m^2	50,000 ft^2

TABLE 2

Thermal Balance of the Envelope

	Winter			Summer				
	Ta (°C)	Tv (°C)	Qd (W)	Ta (°C)	Tv (°C)	Qd (W)	Qs (W)	Qd+Qs (W)
S0	--	11.4	-742	--	31.9	267	746	1013
D1	15.1	18.2	-385	33.1	29.0	489	517	1006
D2	17.3	19.6	-275	32.5	28.7	460	472	932
T1	17.4	19.6	-274	31.1	27.9	394	404	979

Ta = air temperature in the ventilated air space
Tv = internal temperature of the glazing surface
Qd = conduction heat gain
Qs = solar heat gain (calculated with screen)

DESIGN DATA

Single envelope solution:

S0: Uw = 0.60 W/m^2°C Aw = 2.16 m^2
Ug = 3.10 W/m^2°C Ag = 7.56 m^2 Fs = 1.0
Fi = 0.28 (without screen)
Fi = 0.13 (with screen)

Double envelope solutions:

D1: Ug = 2.09 W/m^2°C Ag = 9.72 m^2 Fs = 0.7
Fi = 0.29 (without screen)
Fi = 0.11 (with screen)
D2: Ug = 1.59 W/m^2°C Ag = 9.72 m^2 Fs = 0.7
Fi = 0.26 (without screen)
Fi = 0.10 (with screen)
T1: Ug = 1.58 W/m^2°C Ag = 9.72 m^2 Fs = 0.7
Fi = 0.23 (without screen)
Fi = 0.08 (with screen)

Winter peak condition:	Te = -7.0°C	It = 0 W/m^2
Summer peak condition:	Te = 33.8°C	It = 759 W/m^2
Airflow rate:	M = 140 m^3/h	(winter and summer)
Indoor temperature:	Ti = 23.0°C	(winter and summer)

DESCRIPTION OF THE ENVELOPE SOLUTIONS

S0: single envelope (double glazing - reflective glass - one-third opaque, two-thirds glazed)
D1: double envelope (external double glazing - absorbing glass)
D2: double envelope (external double glazing - absorbing glass with low-emittance coating)
T1: double envelope (external triple glazing)

TABLE 3a

Thermal Comfort Analysis (Winter)

Envelope solution	Ti (°C)	Tv (°C)	To (°C)	Tmr (°C)	PMV
S0	20.0	10.0	17.8	17.5	-0.68
D1	20.0	15.7	--	18.9	-0.56
D2	20.0	16.9	--	19.2	-0.53
T1	20.0	17.0	--	19.2	-0.53
S0	21.0	10.6	18.7	18.4	-0.47
D1	21.0	16.6	--	19.9	-0.33
D2	21.0	17.8	--	20.2	-0.31
T1	21.0	17.8	--	20.2	-0.31
S0	22.0	11.2	19.7	19.3	-0.25
D1	22.0	17.4	--	20.8	-0.11
D2	22.0	18.7	--	21.1	-0.08
T1	22.0	18.7	--	21.1	-0.08
S0	23.0	11.8	20.6	20.2	-0.04
D1	23.0	18.2	--	21.8	+0.11
D2	23.0	19.6	--	22.1	+0.14
T1	23.0	19.6	--	22.1	+0.14

Metabolic rate M = 1.2 Met
Clothing insulation I = 1 clo
Air speed Va = 0.15 m/s
Air relative humidity RHa = 50%
Ti = indoor air temperature
Tv = internal temperature of the glazing surface
To = internal temperature of the opaque panel
Tmr = mean radiant temperature
PMV = predicted mean vote

TABLE 3b

Thermal Comfort Analysis (Summer)

Envelope solution	Ti (°C)	Tv (°C)	To (°C)	Tmr (°C)	PMV
S0	23.0	31.9	23.0	25.4	-0.36
D1	23.0	29.0	--	24.6	-0.47
D2	23.0	28.7	--	24.5	-0.48
T1	23.0	27.9	--	24.3	-0.50
S0	24.0	32.6	24.0	26.3	-0.05
D1	24.0	29.9	--	25.6	-0.16
D2	24.0	29.6	--	25.5	-0.17
T1	24.0	28.8	--	25.3	-0.20
S0	25.0	33.3	25.0	27.2	+0.25
D1	25.0	30.8	--	26.6	+0.15
D2	25.0	30.5	--	26.5	+0.14
T1	25.0	29.7	--	26.3	+0.11
S0	26.0	34.0	26.0	28.2	+0.55
D1	26.0	31.6	--	27.5	+0.46
D2	26.0	31.4	--	27.4	+0.45
T1	26.0	30.6	--	27.2	+0.42

Metabolic rate M = 1.2 Met
Clothing insulation I = 1 clo
Air speed Va = 0.15 m/s
Air relative humidity RHa = 50%
Ti = indoor air temperature
Tv = internal temperature of the glazing surface
To = internal temperature of the opaque panel
Tmr = mean radiant temperature
PMV = predicted mean vote

TABLE 4

Results of Daylighting Calculations

	Office Unit A		Office Unit B		Office Unit C	
	TL=0.25	TL=0.60	TL=0.025	TL=0.60	TL=0.25	TL=0.60
DF(MAX)	4.3%	10.1%	3.4%	8.0%	3.7%	8.7%
DF(MID)	2.7%	6.4%	1.0%	2.3%	1.1%	2.5%
DF(MIN)	2.0%	4.7%	0.8%	1.8%	0.8%	1.9%
UR	1.5		2.4		2.5	
DGI(1)	29.0	32.0	21.8	25.0	23.0	26.2
DGI(2)	28.4	31.7	21.6	24.8	22.8	26.0
DGI(3)	27.6	31.0	20.8	24.0	21.8	25.0

N.B. Positions (MAX), (MID), (MIN), (1), (2), and (3) are specified in the text.

TL = Daylight transmittance of glazing system
DF = Daylight Factor (Equation 8) **** VERIF. N. EQUAZ.****
UR = Uniformity Ratio (Equation 9)
DGI = Daylighting Glare Index

Reference external condition:

Eo = 28000 lx (Horizontal Illuminance)
Lo = 8900 cd/m^2 (Sky Luminance)

Recommended values/ranges

DFm = 3% - 5%
UR $\leq$ 3
DGI < 19

Office units dimensions

UNIT A: 3.60 × 3.60 (h = 2.70)
UNIT B: 2.70 × 7.20 (h = 2.70)
UNIT C: 3.60 × 7.20 (h = 2.70)

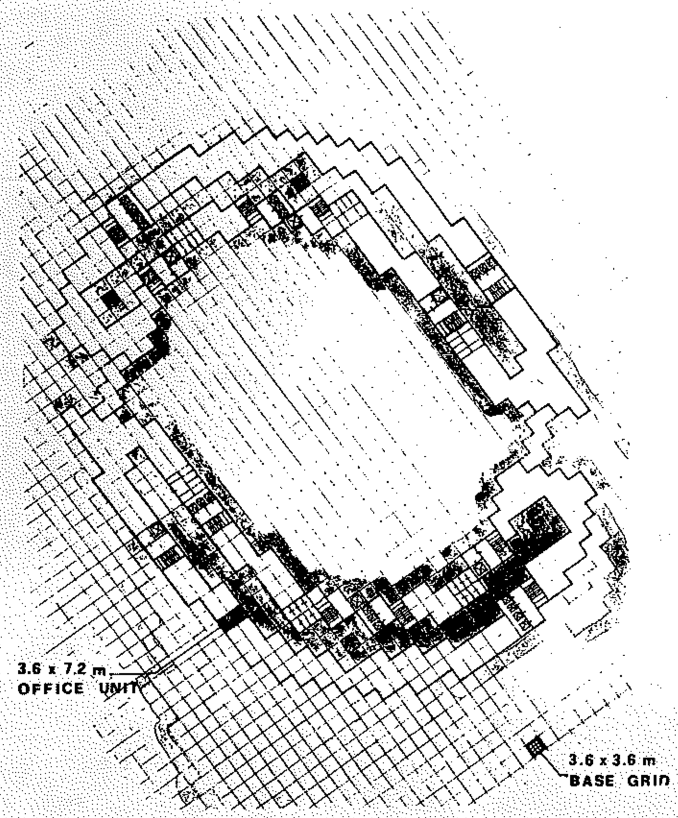

Figure 1. *General layout of the building*

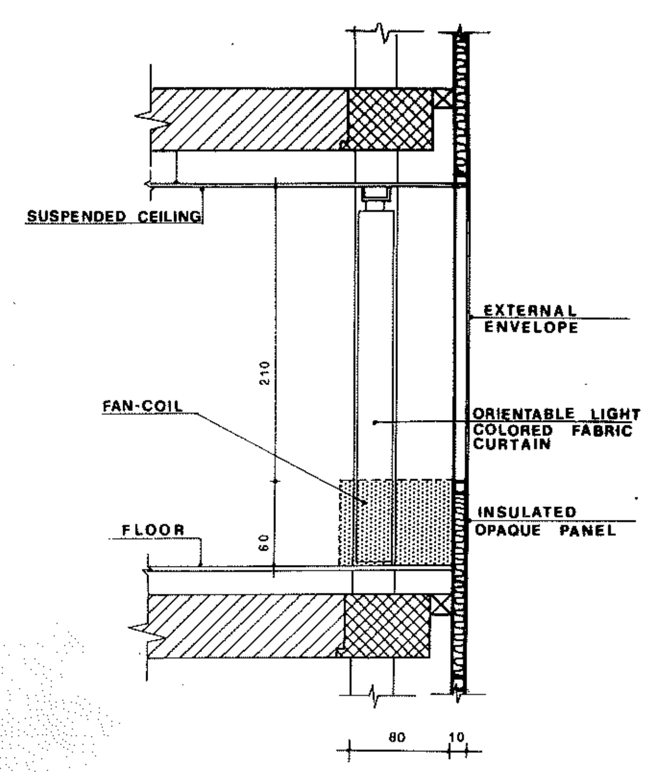

Figure 2. *Single envelope solution*

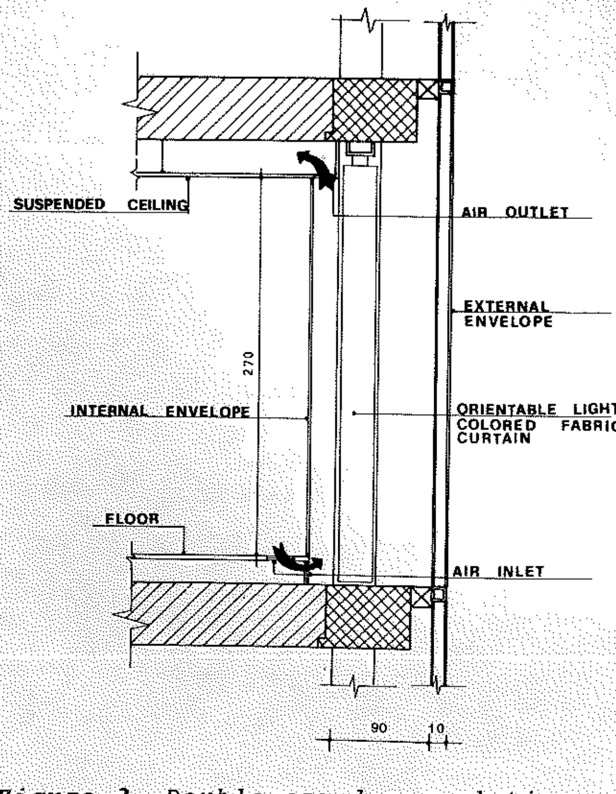

Figure 3. *Double envelope solution*

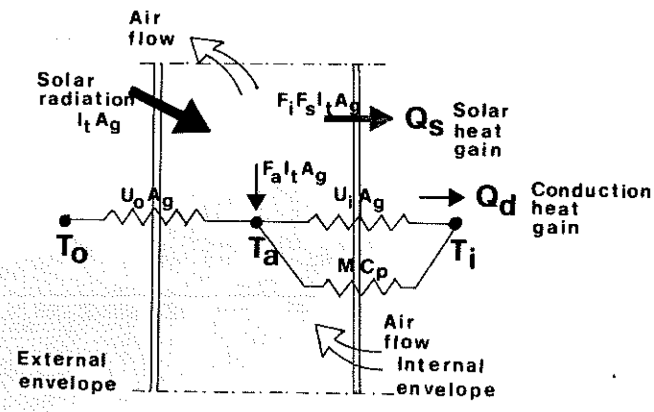

Figure 4. *Electric analog of the double envelope thermal balance*

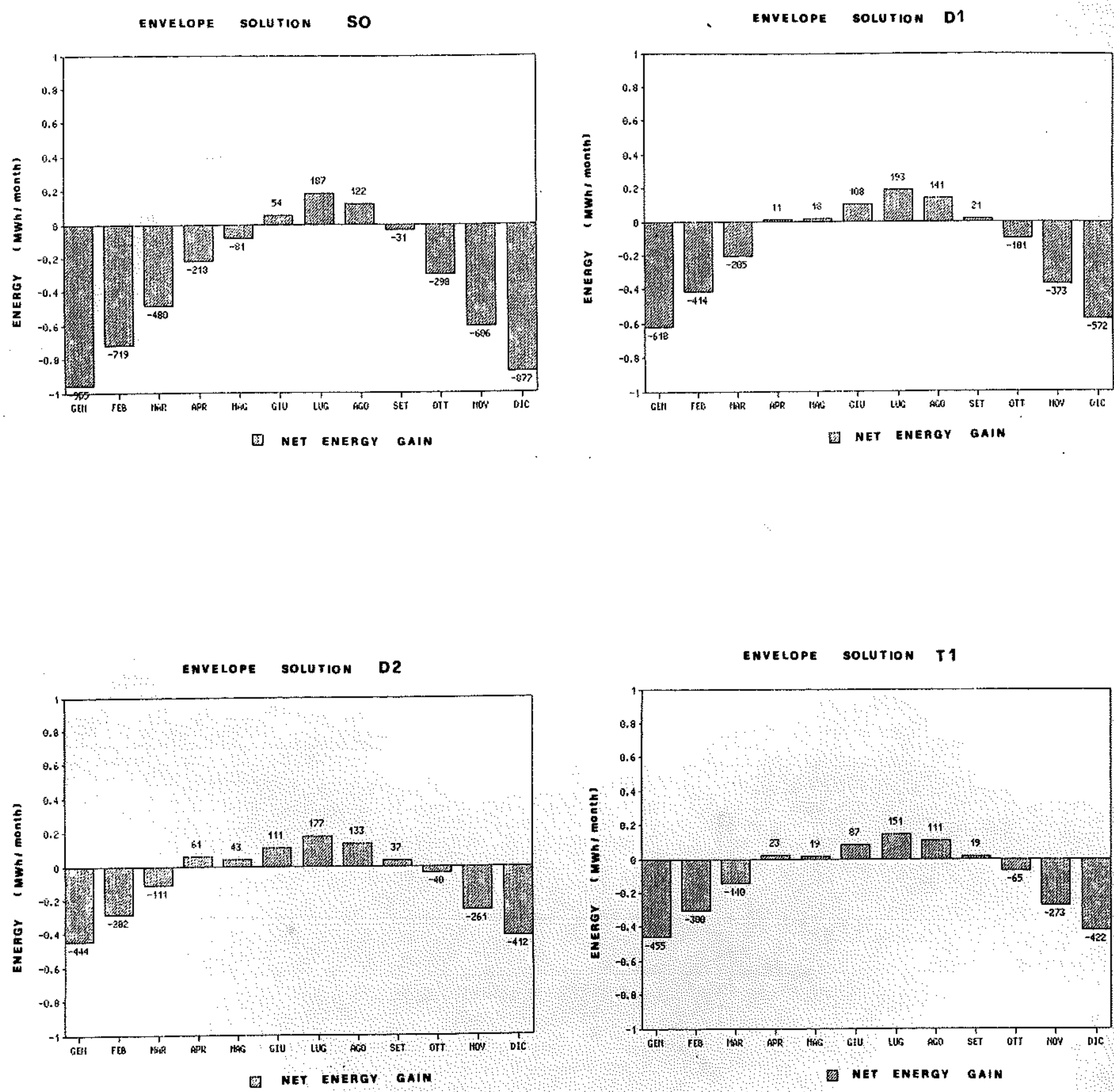

Figure 5. Monthly energy balance of the envelope

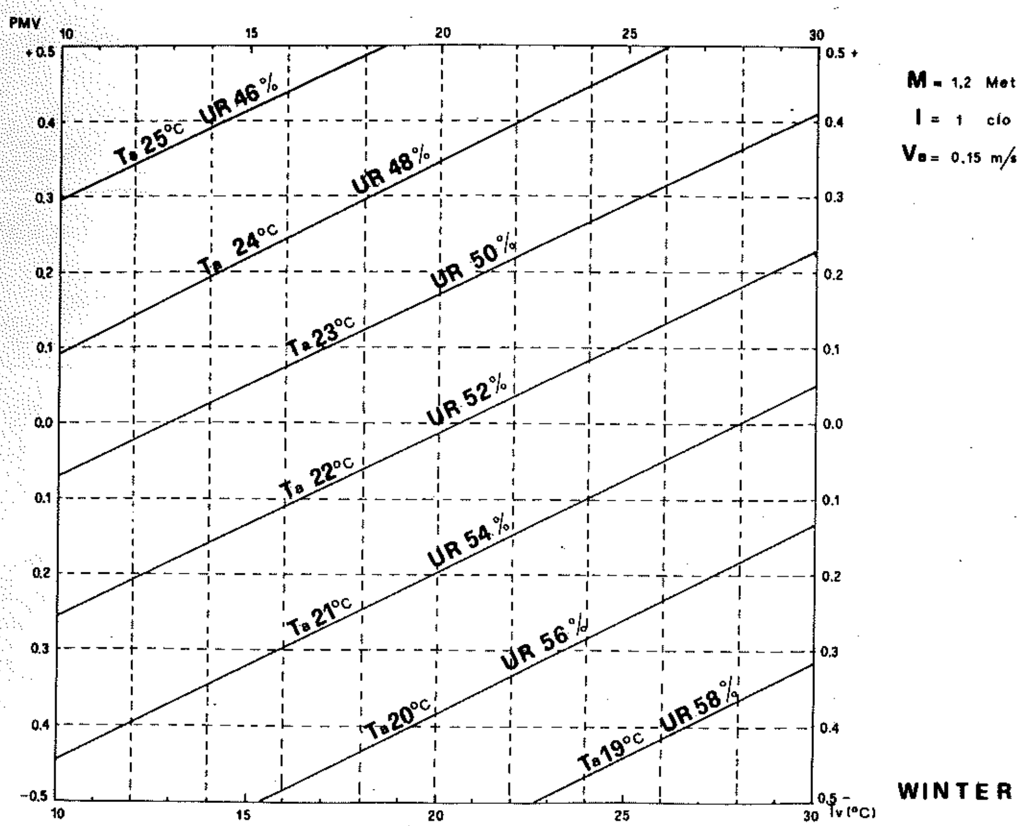

Figure 6a. *Predicted mean vote (PMV) as a function of air temperature Ta and glazing surface temperature Tv (WINTER)*

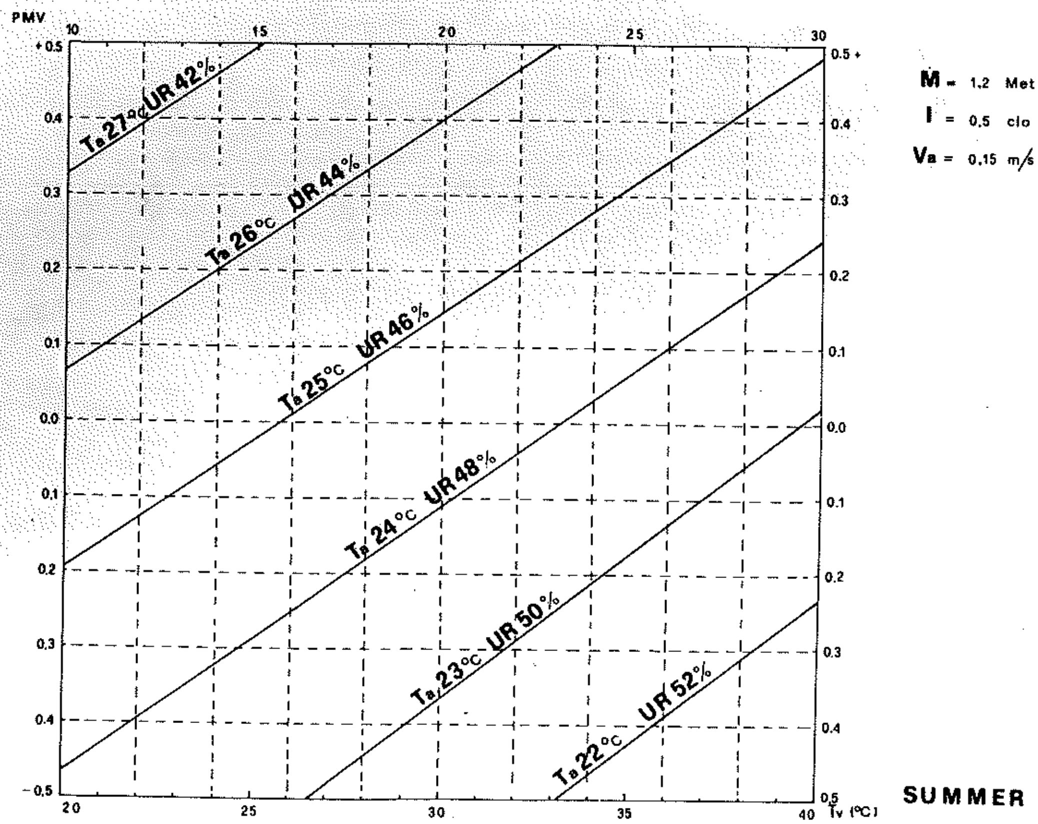

Figure 6b. *Predicted mean vote (PMV) as a function of air temperature Ta and glazing surface temperature Tv (SUMMER)*