DOCUMENT RESUME

ED 035 214 EF 003 675

AUTHOR	London, A. G.; Petherbridge, P.
TITLE	Possible Economies in Air-Conditioning by Accepting Temperature Swings.
REPORT NO	BRS-CP-48-68
PUB DATE	May 68
NOTE	16p.; Paper presented at the IHVE/BRS Symposium 'Thermal environment in modern buildings - aspects affecting the design team', February 29, 1968
AVAILABLE FROM	Publications Officer, Building Research Station, Bucknalls Lane, Garston, Watford, Herts, England (single copies free)
EDRS PRICE	EDRS Price MF-$0.25 HC-$0.90
DESCRIPTORS	*Air Conditioning, Architectural Elements, Building Design, Building Equipment, Building Materials, Climate Control, Construction Costs, *Economic Research, Electrical Systems, Heating, Operating Expenses, *Physical Design Needs, Solar Radiation, *Thermal Environment, *Ventilation
IDENTIFIERS	Building Research Station

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SfB Ab8
UDC 697.9
MAY 1968

Possible economies in air-conditioning

A G Loudon and P Petherbridge

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POSSIBLE ECONOMIES IN AIR-CONDITIONING BY ACCEPTING TEMPERATURE SWINGS

A. G. Loudon, BSc, F Inst P, and P. Petherbridge, MSc, FIES

Paper presented at the IHVE/BRS Symposium 'Thermal environment in modern buildings - aspects affecting the design team', February 29, 1968

Air-conditioning can be very expensive when designed to hold the internal air temperature constant. This paper makes the point that close temperature control is not necessary for the comfort of the occupants, and that plant size and running costs can be substantially reduced if a swing in internal temperature is accepted. Temperature swings can be assessed for any regime of cooling by an extension of methods outlined elsewhere. The paper includes comparisons of observed and calculated temperatures in air-conditioned buildings which are not closely controlled; they agree well and provide experimental confirmation of the method of calculation.

CURRENT PAPER 48/68

BUILDING RESEARCH STATION
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POSSIBLE ECONOMIES IN AIR CONDITIONING BY ACCEPTING TEMPERATURE SWINGS

A.G. Loudon
P. Petherbridge

1. Introduction

When buildings are air-conditioned, it is quite common to install plant of sufficient capacity to hold the internal temperature constant at all times. The 1965 IHVE Guide[2] tabulates cooling loads to give a constant internal temperature. The 1965 ASHRAE Guide[3] tabulates instantaneous heat gains from solar radiation and other sources, and states that experience is needed to estimate cooling loads. Authors such as Harrison[4] have suggested that cooling loads can be reduced by accepting a temperature swing. The Carrier Air Conditioning Handbook[5] goes further and tabulates data on the possible reduction in the cooling load if the plant is designed to let the internal temperature rise above the design value during peak periods by 2, 4 or 6 degrees F. It is assumed that the building is controlled at a constant temperature at other times.

With naturally ventilated buildings, internal temperatures vary over quite a wide range in summer, and conditions are quite acceptable if temperatures lie within the comfort range. It has been shown that temperatures can be computed with reasonable accuracy, and that there are few complaints of overheating in rooms whose computed temperature does not exceed 24^{o}C at peak times, although temperature swings of some 4-6 deg C occur in these rooms during heat-waves. These computed peak temperatures are based on the mean outside temperatures on sunny days, rather than the very highest outside air temperatures which are proposed for air-conditioning design in the IHVE Guide. Radiation intensities and outside temperatures seldom reach their maximum values at the same time, but the computed peak temperatures are clearly notional values which are sometimes exceeded. Measurements in a few offices have indicated that the computed peak temperatures are exceeded for some 10-15% of the time. However they are very useful because they are directly related to the experience of users.

There is no reason to suppose that different criteria of thermal comfort apply to conditioned and non-conditioned buildings. Thus Black and Milroy[6] found that 50% of the occupants of an air-conditioned building were too warm at 24^{o}C, and Hickish[7] has reported a similar result for naturally ventilated buildings. It seems reasonable, therefore, to use the same methods of calculation and the same design assumptions for air-conditioned as for naturally ventilated buildings. The methods of calculation set out in Ref. 1 can be applied to air-conditioned buildings by subtracting the rates of cooling from the rates of heat input and calculating temperatures as before.

Solar heat gains, occupancy and lighting loads, the chief heat inputs dealt with by air conditioning for comfort of the occupants, are intermittent in nature. This suggests that plant capacities and energy consumption could be reduced considerably by cooling at a constant rate for say 12, 16 or 24 h/day, and accepting a temperature swing during heat-waves. As with naturally ventilated buildings, it would be necessary to ensure that temperatures were within an acceptable range for comfort. If calculations indicated at the sketch-plan stage of a building design that temperature swings would be excessive, one could either modify the design e.g. by using smaller windows, more effective sun-controls, or more massive construction, or as an alternative, use a variable cooling load which still permitted some diurnal temperature swing.

The present paper describes two investigations made to follow up these suggestions. The first was made in an air-conditioned building. Heat inputs, the rate of cooling by the conditioned air, and air and globe temperatures within the room were measured; measured temperatures were compared with calculations. The second investigation forms part of a series of studies in the rotatable wall laboratory at the Building

Research Station, in which the aim is to find suitable combinations of window treatment, weight of building and plant size to give an acceptable degree of comfort with simple controls and a small plant. In the paper, proposals are made for using the new procedures to calculate cooling loads assuming a swing in temperature. These are compared with the loads given in the Carrier Air Conditioning Manual[5] and with values derived using the electrical analogue at the Building Research Station. There is also a possibility of reducing the dehumidification load.

2. Investigations in an air-conditioned building

During the summer of 1966, temperatures and heat inputs were measured in a room in an upper floor of a multi-storey air-conditioned building with the aim of obtaining an experimental check on the procedure for calculating internal temperatures. The building was a tower block with facades facing north-east, north-west, south-west and south-east; it had 4.6 m (15 ft) deep offices round the periphery served by a corridor surrounding a core containing lifts and services. The windows occupied about 50% of the external wall area.

(a) The air-conditioning system

The rooms were cooled by manually controlled induction units under deep window sills (Fig. 1) supplied with 'primary' air that had been filtered and brought to a given temperature and humidity in a central unit. The induction units were fitted with manual control knobs; when set to 'cold', the primary air jets drew air from the room over a finned tube heat exchanger supplied with chilled water, and when set to 'off', the chilled water was turned off and the secondary air by-passed the heat exchanger. The average ventilation rate in the building by primary air was 4.5 air changes/h, but the measurements were made in a room having an induction unit fitted with larger jets giving a ventilation rate of 7.5 air changes/h to deal with the heat emission from a teleprinter. About 75% of the ventilation air was extracted from a grille and the remainder escaped through cracks and apertures in the building.

The outside air temperature determined the primary air temperature. When it was 20^{o}C, the primary air was controlled at 18^{o}C, presumably allowing 2 deg C temperature rise for incidental heat gains. When the outside air rose above 20^{o}C, the primary air temperature was reduced by 1.6 deg C below 18^{o}C for every deg C rise in outside temperature, and when it fell below 20^{o}C, the primary air temperature was increased by 2.5 deg C above 18^{o}C for every deg C drop in outside temperature. This control was intended to remove or replace heat gains by conduction through the fabric. As the plant was operated from 6 am to 10 pm only, additional heating would be needed to allow for losses at night, but less cooling would be needed so that allowances for heating and cooling were different.

The primary air temperature was not controlled by solar heat gains, although these provided a much larger heat input than conduction heat gains. It may have been argued that occupants of sunlit offices would turn the controls to 'cold' and obtain cooling from the chilled water, but that occupants of shaded offices would turn the control to 'off' and obtain the benefit of the warmed air.

(b) Experimental set-up

During the experimental period the manual control was fixed in the 'cold' position, the window was unshaded and the door was kept closed to prevent mixing of room air and corridor air. The room air and globe temperatures were measured near the ceiling in the centre of the room using thermocouples attached to a temperature recorder (see Fig. 1). The outside air temperature was measured and temperatures in adjacent rooms were recorded so that heat gains or losses from adjacent rooms could be assessed. The radiation intensity was measured by solarimeters fixed vertically on the roof parapet. Direct and diffuse components were separated and the solar heat gain was calculated from the radiation transmittance of the windows. The energy consumption of the teleprinter was recorded. Heat gains from lighting and occupants were negligible.

The rate of cooling by the induction unit was found by measuring the temperature and volume flow rate of the air leaving the outlet grille in the induction unit. The temperature was measured by a thermocouple inserted through the grille. The volume flow rate, which was constant, was calculated from velocities measured when traversing the surface of the grille with a hot-wire anemometer.

The primary air temperature, measured by a thermocouple inserted through a jet in the induction unit, agreed with the design values within a few degrees. The chilled water temperature was measured by a thermocouple attached to the pipe and covered with insulation, and the rate of cooling by the chilled water was calculated from these data.

(c) Experimental results

The data for the 7-day 'heat-wave' period 28th May - 3rd June, plotted in Fig. 2, are perhaps the most interesting of the measurements made. The air-conditioning system was off on Whitsun Sunday and Monday, 29th and 30th May, and temperatures reached 34°C (93°F); it was also off after 12 noon BST on 28th May. Radiation intensities, plotted on the graph, conformed fairly well to 'design' values for the time of year.

Where the air conditioning was operating for the full 16 h period, the room air temperature reached 25°C (77°F) on several days. The maximum globe temperature at 27°C (80°F) was higher because the heat was absorbed at the room surfaces and extracted from the air. The office would then be uncomfortably warm. Temperatures would have been a little lower if the blinds had been drawn, as was intended by the designers.

The primary air was warmer than room air for most of the period of measurement, because the outside air temperature was below 20°C. The chilled water provided a fairly constant rate of cooling, but it was warmed by the primary air. The boilers were thus feeding heat into the refrigerators and the room was getting too warm. Milbank[8] describes detailed investigations of energy consumption in air-conditioned buildings which reveal other similar examples of heat wastage.

The results nevertheless provide useful data for comparison with the calculation procedures. Unfortunately conditions were not steady cyclic ones. Calculations were first made for individual days on the assumption that they were one of a sequence of similar days; diurnal swings then agreed with measurements, but mean values did not. There were abrupt changes between one day and the next because temperatures were calculated relative to the mean outside temperature for each day.

A more realistic calculation was therefore made assuming that the 'mean' inside temperature varied from one day to the next, following an exponential curve of time constant Q/U, where Q is the total thermal capacity of the structure and U is the U-value. Tests with the electrical analogue had already shown that the build-up of internal temperatures at the onset of a 'heat-wave' could be calculated fairly accurately by taking swings calculated by the admittance procedure relative to a mean value calculated by the 'Q/U' method. Figure 2 shows that values calculated by this procedure (using a computer) agreed well with measurements. Globe temperatures agreed with calculations better than air temperatures; this is reasonable as they are closer to the calculated 'environmental temperature' ($^2/_3$ MRT + $^1/_3$ AIR TEMP) than the air temperature.

(d) Comments on this investigation

These results confirm that the calculation procedures already advocated apply to air-conditioned buildings. The work indicates that diurnal temperature swings can occur in air-conditioned buildings, and provides an additional argument for assuming a swing in design. It indicates that controls based on outside air temperature alone are inefficient. In this building, at least, it would have been more economical to ventilate the building with outside air, cooled at a constant rate when necessary.

3. Experiments in the BRS wall laboratory

The wall laboratory at the Building Research Station, shown in Figs. 3 and 4, contains four 2.4 m x 2.4 m x 2.4 m rooms backed by a corridor which serves as an instrument room. The test rooms have been fitted with large windows, occupying 61% of the external wall, and 0.1 m (4 in.) thick concrete floors to simulate a common room design in multi-storey blocks. Concrete blocks can also be used to construct heavy internal walls. The windows have been designed so that they can be single or double glazed, and fitted with blinds inside, outside or between the panes of double glazing. A room cooling unit has been installed to provide continuous cooling at a low rate. The pilot-scale tests are providing data for comparison with calculations and throwing up practical problems of plant control, dehumidification and so on, which require investigation.

Measurements are being compared with theoretical calculations so that results can be extrapolated to different types of building, but only preliminary results have been obtained so far. Those plotted in Fig. 5 apply to an unshaded south-facing room with a heavy floor and light walls. This system is obviously unpractical since the globe temperature reached 32°C (90°F) on one occasion, but results are of interest for comparing measured and calculated temperatures.

Computed environmental temperatures are compared with measured air and globe temperatures in Fig. 5. Measurements were made at the centre of the room, and the globe temperature would be expected to agree better with calculations than the air temperature. In fact it agreed less well; the globe temperature responded to the solar radiation much more than was theoretically expected. The black globe could not have been affected by direct sunshine. The explanation for the discrepancy seems to be that the room had very light internal surfaces and that the interreflected radiation together with diffuse radiation from sky and ground raised the globe temperature; calculations indicate that it could have been raised by 3 deg C ($5\frac{1}{2}$ deg F). It would have been better to use a globe painted white to respond to longwave but not shortwave radiation.

This difficulty did not arise in the air-conditioned office described in the previous section because the internal surfaces were darker in colour. On 29th and 30th May, when the office was unventilated and not conditioned, the globe temperature was approximately equal to the air temperature. This indicates that the globe was very little affected by diffuse solar radiation, since air and globe temperatures are equal in an unventilated room.

4. Comparison of cooling loads by BRS and Carrier methods

It is difficult to make detailed comparisons between cooling loads calculated by the BRS method and by the Carrier Handbook[5] which is commonly used by heating engineers. One point is that the BRS method relates to 'environmental temperature', and the Carrier method to an unspecified 'space temperature'. Another point is that the BRS and Carrier methods make different allowances for temperature swing. Most of the BRS calculations have been made on the assumption that there is a constant cooling load, but the Carrier method assumes that the internal temperature is held constant until the heat input exceeds the plant capacity, and that the temperature then rises above the design value. It is a major task to make comparisons over a wide range of circumstances, but it is intended to do this in the future. Of course the Carrier Guide does not enable temperatures to be calculated over a period, as in Figs. 2 and 5.

In the meantime comparisons have been made for a few air-conditioned buildings making the same design assumptions, and the results are set out in Table 1. It can be seen that the two methods give very similar results.

TABLE 1 Comparison of cooling loads calculated by BRS and Carrier methods.

Reference	Description	Cooling load in tons refrigeration per $100m^2$ floor area	
		BRS Method	Carrier Method
A	15 storeys, 70% glazed, venetian blinds, light construction	1.8	1.8
B	3 storeys, 55% glazed, venetian blinds, light construction	1.0	0.9
C	10 storeys, 55% glazed, venetian blinds, medium construction	0.5	0.5
D	15 storeys, 50% glazed, external blinds, medium construction	0	0

Design condition: 20 - 24°C internal
24.5°C external

5. Design proposals

A constant internal temperature is not necessary for comfort and some variation is perhaps desirable to avoid monotony. In a recent survey of occupant reactions in an air-conditioned building, Black and Milroy[6] found that the proportion of occupants who were comfortable was unaffected by temperature over the range 20-24°C (68-75°F). Morse and Kowalczewski[9] suggest that, for a given amount of clothing and a given degree of activity, people are equally comfortable over a range of about 2 deg C (4 deg F) but that the acceptable temperature range can be extended beyond 2 deg C by adjusting clothing, e.g. by removing a jacket, when temperatures increase.

The calculation procedures provide a useful tool for designing buildings and plant to minimise cooling loads by permitting a swing in internal temperature, but it is only possible to make tentative proposals because practical difficulties have not been fully worked out. On the basis of Miss Black's work[6] it is suggested that the building and plant could be designed to give a temperature swing within the range 20-24°C during occupied periods. The plant could be designed to operate continuously at its maximum rate of cooling for say 12, 16 or 24 h/day during heat-waves, and to hold the mean temperature at such a level that the temperature was not less than 20°C during occupied hours. It would of course have to be controlled, possibly by a simple thermostat, at periods other than heat waves, and this question is being examined, but the present paper is concerned with the maximum cooling load required in design conditions.

As an example, the cooling load to operate plant continuously for 24 h/day during heat-waves has been calculated. It is realised that there are practical difficulties in leaving plant unattended and this is no more than an illustrative example. In most cases it will be better to use a rather larger cooling plant operated say 12 or 16 h/day. With continuous 24 h operation, calculations show that the temperature at 8 am is usually roughly equal to the daily-mean value, and in such cases the plant capacity has to be sufficient to hold the mean internal temperature to 20°C. If the design outside mean temperature is taken as 20°C, the basic plant capacity for cooling is equal to the daily mean effective heat input $\bar{q}_e$ during heat-wave conditions. If the plant is designed to hold the mean internal temperature an amount Δt below the mean outside temperature, the basic plant capacity would be $\bar{q}_e + \Delta t\ (\Sigma AU + C_v)$. Additional capacity would have to be allowed for dehumidification, and for contingencies, but this is not considered here.

The building would have to be designed to keep the swing $\tilde{t}_{ei}$ to 4 deg C or less. From equation (6) of Ref. 1, $\tilde{q}_e/(\Sigma AY + C_v)$ should not exceed 4 deg C under the worst conditions.

The relationship between temperature swing with continuous cooling and the fraction of unshaded glass in the external wall has been worked out for one example - the standard 3.3 m x 4.9 m x 3.0 m high (11 ft x 16 ft x 10 ft high) 'light' and 'heavy' rooms chosen as examples of typical offices in Ref. 1. Occupancy and lighting loads were assumed to be negligible. Figure 6 shows the amount of unshaded glass that can be used in 'light' and 'heavy' rooms facing south of east-west without exceeding a given swing in inside temperature, and Fig. 7 shows the corresponding basic cooling loads per unit area of external wall. The temperature swing can be kept within 4 deg C in a 'heavy' building if the glass area is less than 65-75% of the external wall area, but for this swing, the glass area has to be restricted to about 20% in a 'light' building. Similar calculations could be made taking account of other heat gains, and for windows protected by blinds or other sun-controls.

The cooling loads in Fig. 7 are very much less than those given in the IHVE Guide. For a building with 70% of the external wall glazed, ventilated at 2 air changes/h with outside air, Fig. 7 shows a cooling load of 100 W/m^2 (32 Btu/h per ft^2 external wall). The value from IHVE Guide is 315 W/m^2 (100 Btu/h per ft^2 external wall), assuming the same ventilation rate.

A somewhat larger cooling plant operated continuously for part of the day (say 12 - 16 h) will be more convenient for most buildings. The method set out in Ref. 1 allows the temperatures to be computed for any regime of cooling, and suitable cooling loads can be found by trial and error. It is desirable to check calculated internal temperatures, whether continuous or intermittent cooling is used, by carrying out a final detailed calculation for the worst conditions expected.

Latent heat loads

Air-conditioning plants are normally designed to control the internal relative humidity to about 50%, but recent studies[6, 9, 10] have shown that the thermal comfort of occupants is virtually independent of relative humidity. However, air passed over cooling coils at a temperature below its dewpoint causes condensation, and some cooling capacity is needed to meet this latent heat load For some buildings the humidity may have to be kept below the level at which it will condense on internal surfaces. It is suggested that these criteria might be used to assess the latent heat load, rather than using an arbitrary 'comfort' standard of relative humidity.

Design outside air temperature

There are very few occasions on which radiation intensities and outside temperatures reach maximum values at the same time, and the mean temperatures for sunny days (Table 4, Ref. 1) might be assumed in preference to those in the 1965 IHVE Guide. Calculated peak temperatures in naturally ventilated buildings based on mean external temperatures on sunny days are closely related to user response and little serious discomfort is experienced when calculated peak temperatures are below 24°C.

6. Conclusions

The present paper shows that the methods of calculating the thermal response of buildings set out in Ref. 1 can be applied to air-conditioned buildings. Experimental evidence is presented showing good agreement between measured and calculated temperatures in an air-conditioned building. The method can be applied for any pattern of heat input or regime of cooling.

Evidence is presented that there is no need to hold the temperature constant in an air-conditioned building, and that in practice this does not happen. All that is needed is that temperatures lie within an acceptable range for comfort. Since heat inputs in summer (from solar gains, occupancy and so on) are intermittent in nature, energy can be saved by running plant continuously at a fairly low rate, allowing heat to go into storage at peak periods and to come out at other times. The paper indicates how the building can be designed to reduce swings to an acceptable level, so that plant run continuously is able to provide adequate comfort.

The paper does not give guidance on design of specific systems, but presents a method of assessing the consequences of different designs of building and plant. Economic systems for particular situations would have to be developed by trial and error, assessing the thermal consequences of alternative designs until a satisfactory solution was achieved.

Acknowledgements

This work has been carried out as part of the research programme of the Building Research Station of the Ministry of Public Building and Works and this paper is published by permission of the Director. The authors are grateful for the assistance of their colleagues including Miss P.J. Arnold and Mr. E.W. Spink.

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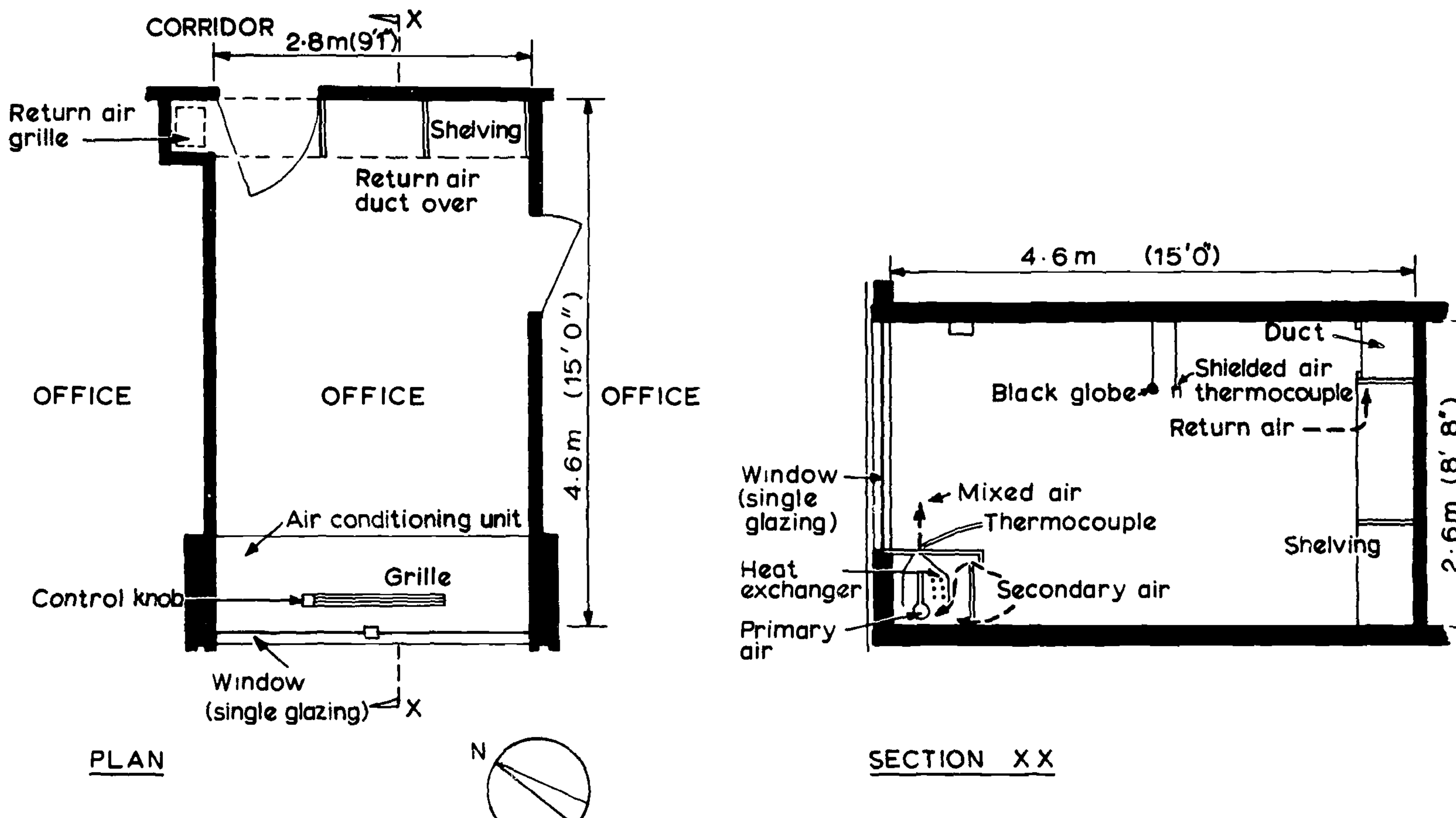

FIG. 1. AIR CONDITIONED OFFICE

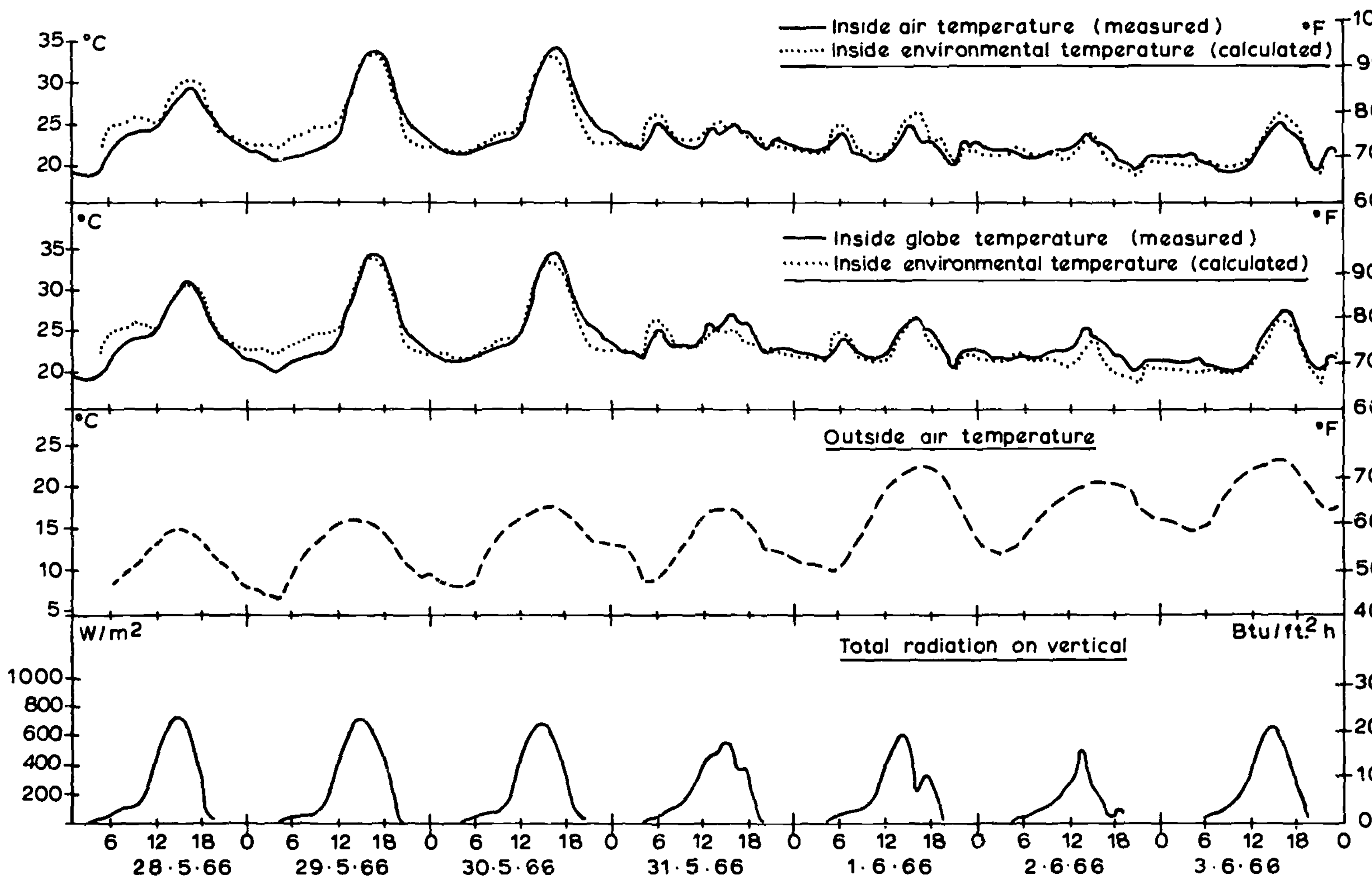

FIG. 2. COMPARISON OF MEASURED AND CALCULATED TEMPERATURES IN AIR CONDITIONED BUILDINGS

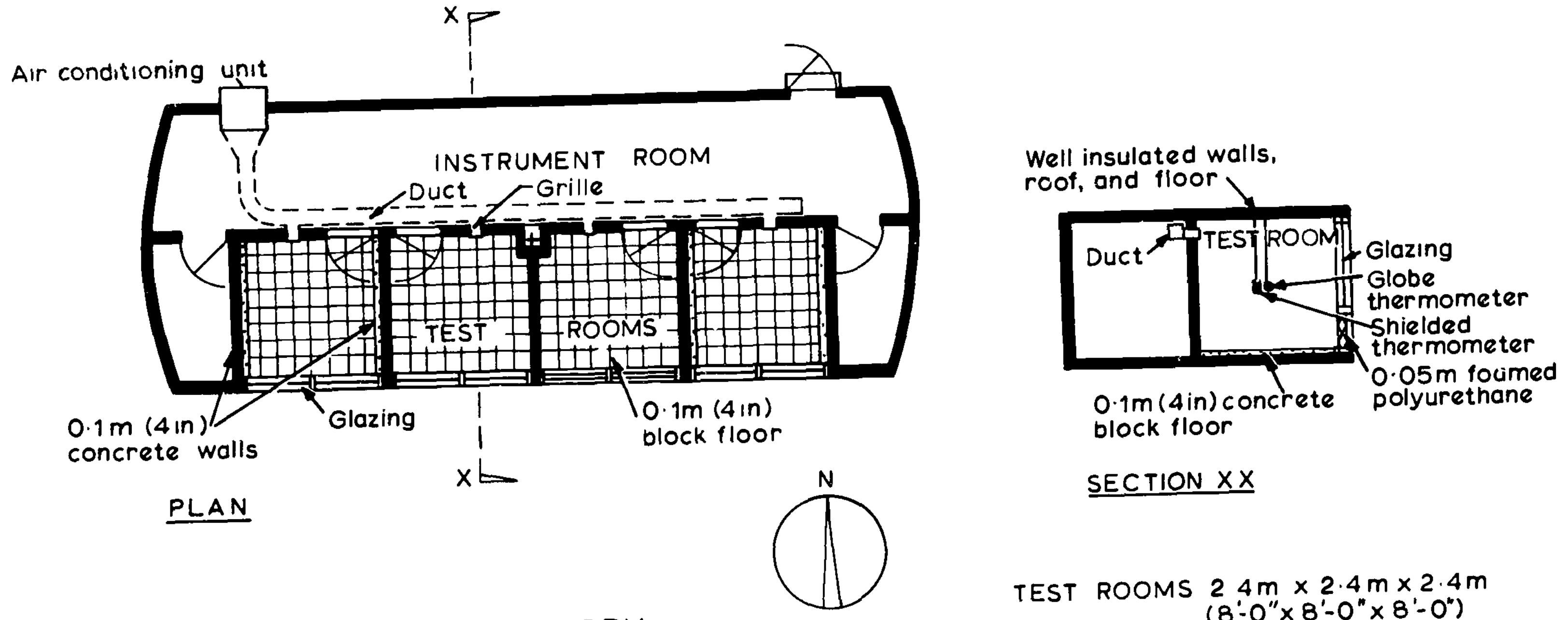

FIG. 3. WALL LABORATORY

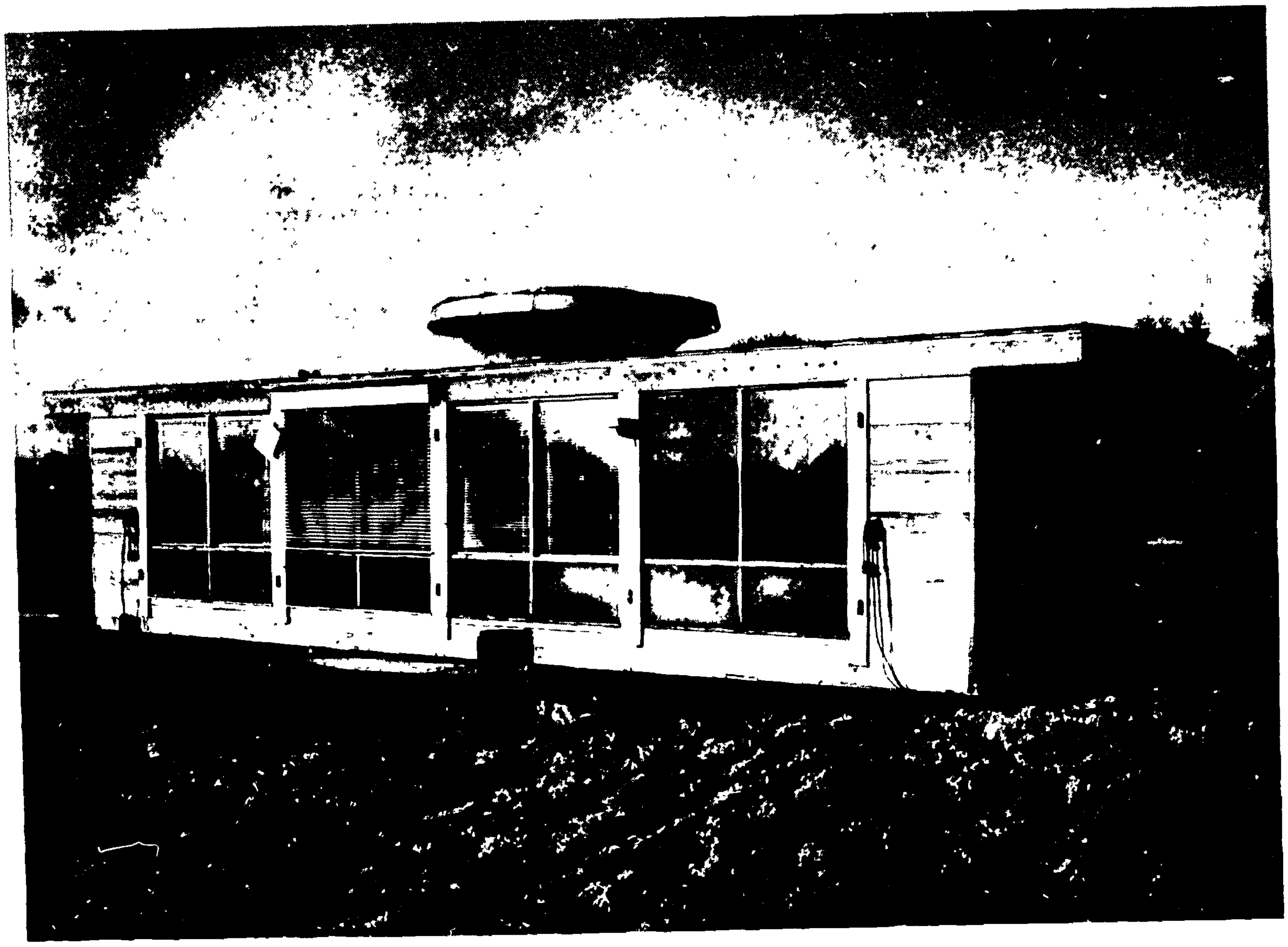

Fig. 4 Wall laboratory

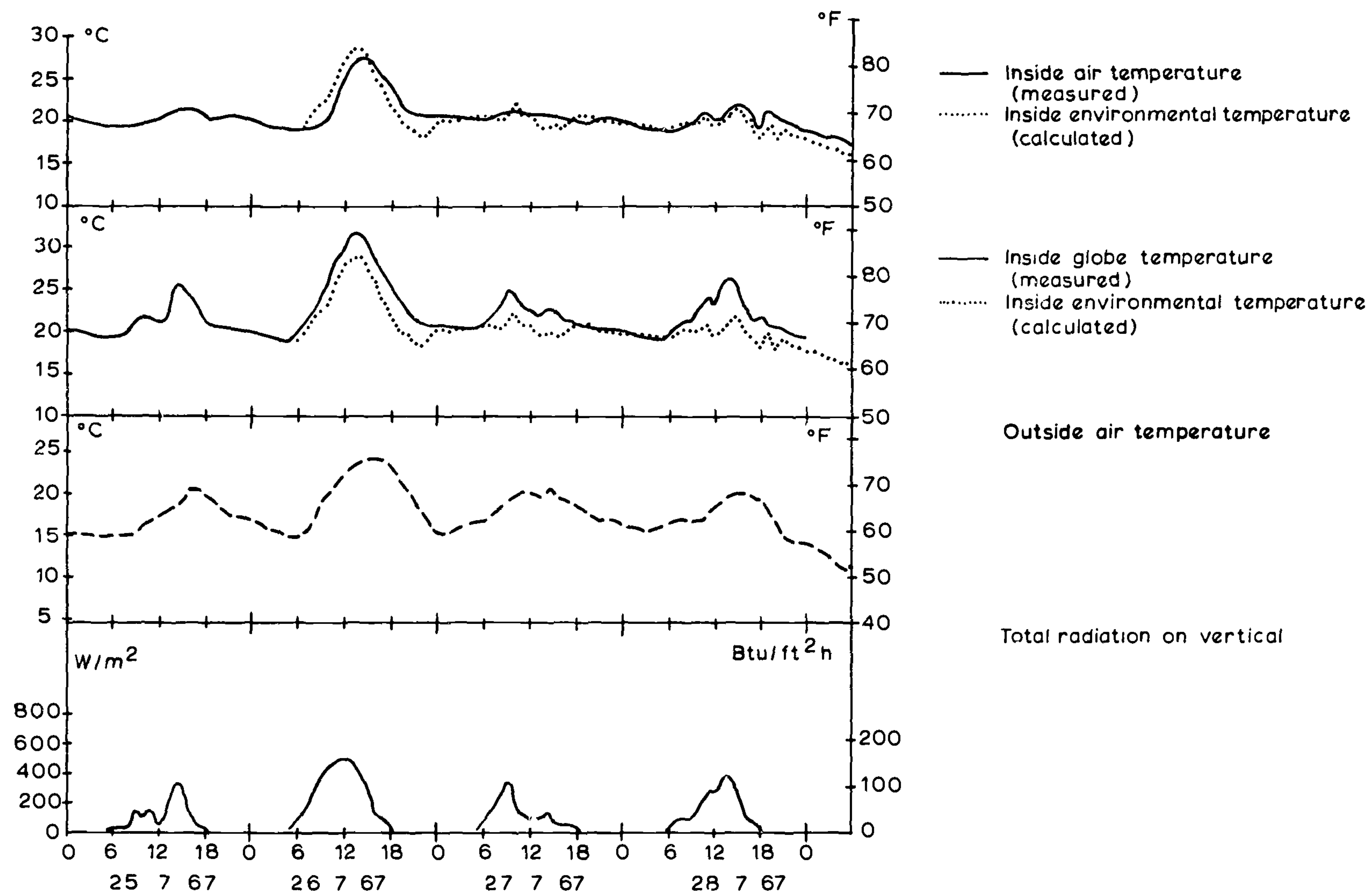

FIG. 5. COMPARISON OF MEASURED AND CALCULATED TEMPERATURES IN WALL LABORATORY

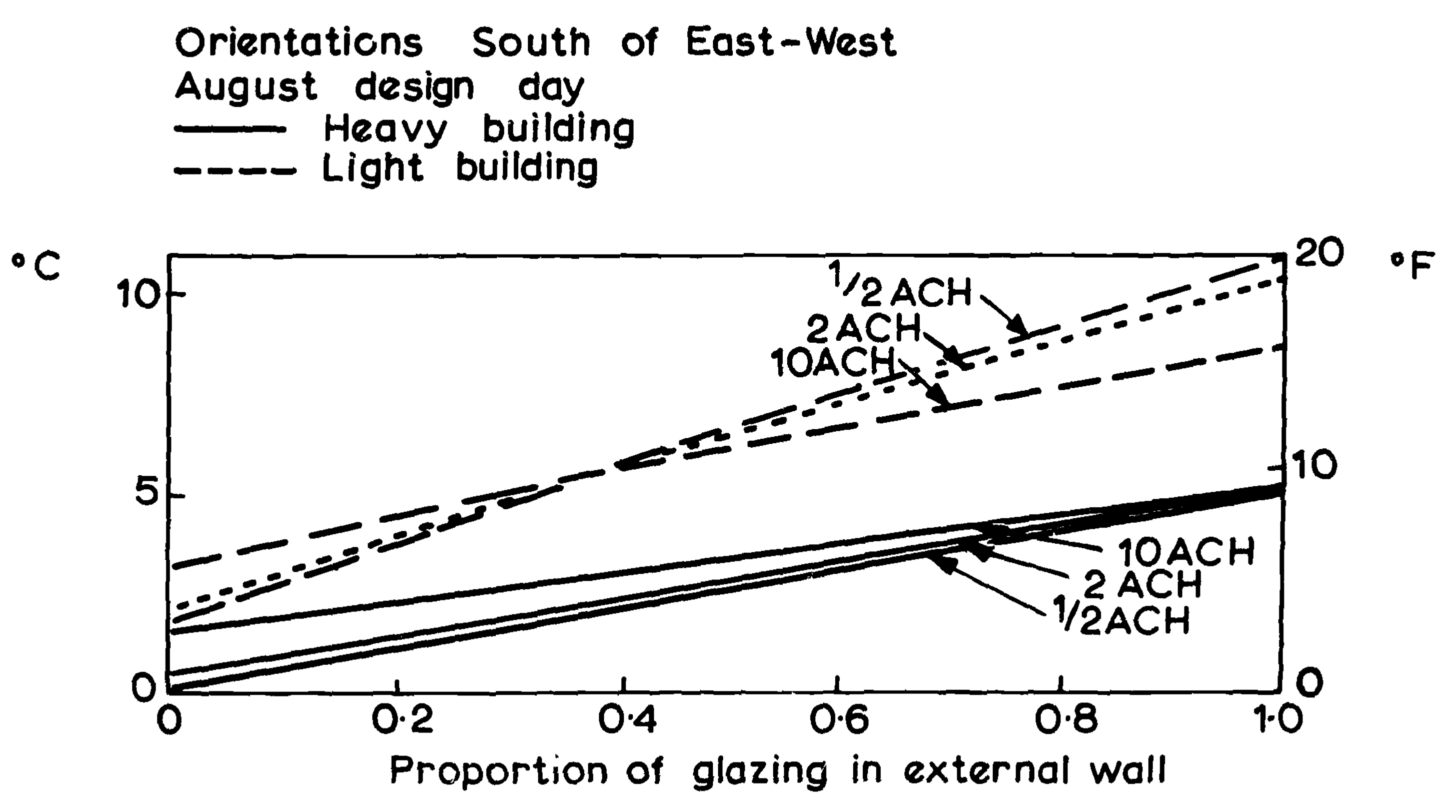

FIG. 6. DIURNAL TEMPERATURE SWINGS (9 a.m.-5 p.m. B.S.T.)

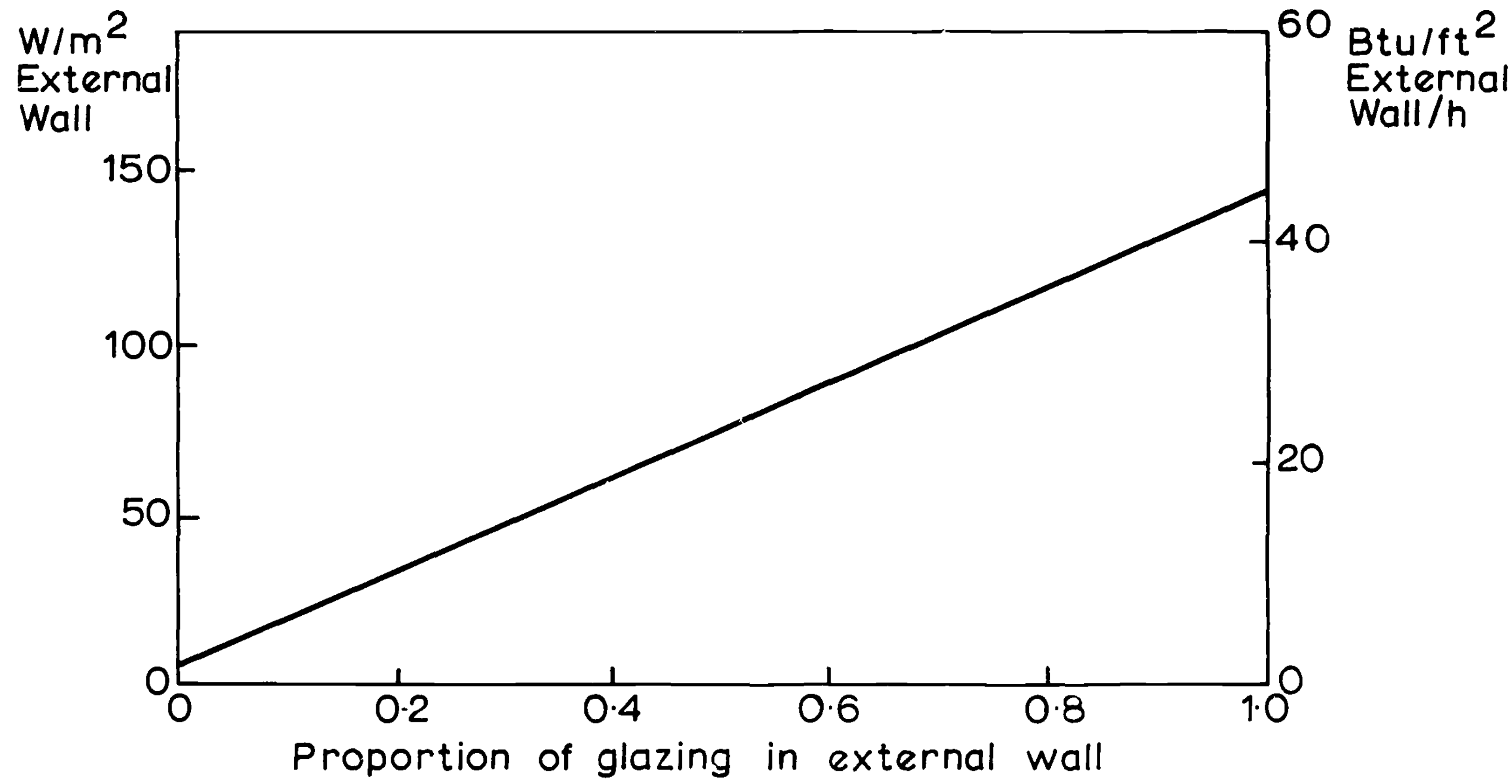

FIG. 7. COOLING LOAD TO HOLD MEAN INTERNAL TEMPERATURE EQUAL TO MEAN EXTERNAL TEMPERATURE

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