UNIVERSITY OF GLASGOW

FACULTY OF ENGINEERING

THE VENTILATION OF DEEP-PLAN BUILDINGS USING LIGHTWELLS AND COURTYARDS

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The Use of Natural Ventilation

In recent years the general adequacy of natural ventilation for all building types has been increasingly called to question. This accompanies the gradual rise in living standards and the expectation that modern technology should provide a higher standard of environmental conditions than has previously been accepted. This raises a whole spectrum of arguments about comfort conditions and the cost consequences of environmental design; the fact remains that many present day buildings can be designed, indeed are designed to be at least partially if not fully naturally ventilated, and this alone must limit the general architectural forms which can be utilised. Therefore, where restricted site conditions and the high cost of building land dictate a deep plan form, is it possible to achieve effective natural ventilation in the central areas of these buildings by the incorporation of lightwells or courtyards, or would some kind of mechanical system of ventilation be generally required? Let us examine further the implications of the former of these two design options.

When air flows over a building due to wind action, a negative pressure zone is formed on the roof. If the building contains a lightwell or courtyard then ideally this negative pressure would encourage extract from the internal rooms adjacent to the lightwell. This will occur provided that the internal pressures within the building are always higher than the roof pressure due to wind. However, there are four situations where this desirable state of affairs may be upset.

Firstly, there is the possibility of disturbance to the normal pattern of air flow over the roof of the building. For example, the presence of rooftop buildings to leeward of the lightwell may cause a pressure increase in the lightwell (Figure 1), and infiltration to the adjoining rooms. Secondly, thermally induced air movement or "stack effect" may become significant under low wind conditions. As the wind speed drops, exfiltration into the lightwell is reduced, and ultimately a neutral zone will appear at the bottom of the lightwell. As conditions become more favourable for this mode of air flow, so the neutral zone rises (Figure 2) perhaps to the top of the lightwell. Local stack effect infiltration may also occur between one room and the lightwell where high and low level openings or one tall opening are provided. Thirdly, where there is a net mechanical air extract on any floor, infiltration of air from the lightwell may occur. Lastly, if a lightwell is large in cross section, relative to the dimensions of the building, wind may be induced downwards towards the lightwell, or vortices may be generated which will create areas of high pressure within the lightwell.

Combinations of these four effects may occur, and at present it is virtually impossible to predict, at the design stage, the pressure distributions and air flows which may result. The study we carried out had the aim of shedding some light on these questions. It had particular application to hospital buildings and was supported by the Department of Health and Social Security. The following illustrates some of the findings obtained from simple wind tunnel observation of the air movement patterns in lightwells, from a more extended wind tunnel study of the pressures and velocities around a model of the proposed ward block at the United Oxford Hospital, and from a detailed full scale investigation of ventilation rates and external pressures on an occupied maternity hospital at Bellshill, Lanarkshire.

Airflows in a model lightwell

A small low speed wind tunnel, using smoke to indicate flow patterns, was used to study a transparent model of a lightwell. No attempt was made to model accurately the turbulence characteristics or the velocity profile of the natural wind, and some of the observed phenomena could undoubtedly be attributed to this. the *ad-hoc* study was intended only as a guide in the interpretation of our full scale results. The resultant observations are represented pictorially in Figure 3 and in all cases the airflow is from left to right. (Letters in brackets refer to Figure 3).

With winds normal to a lightwell wall a circulation of air was set up above the lightwell which induced an anticlockwise vortex at the top of the lightwell. (a) Below this region the air remained almost undisturbed. (This did not correspond with our observations of full scale lightwells, and was probably due to the lack of turbulence in the wind tunnel airstream. It was found that if upstream turbulence was created by introducing an obstruction to the tunnel flow, the air in the lightwell was disturbed and became turbulent, thus substantiating this conclusion). When the model was rotated about its vertical axis, turbulence increased in the lightwell, and at 70° rotation the lightwell air was turbulent over its entire height.

An increase in building depth to the windward side of the lightwell (b) removed the anti-clockwise vortex at the top of the lightwell, and increased turbulence within the lightwell. Rotation of the model increased the turbulence as before. A further increase in building depth to windward caused a clockwise vortex to form (c) and a stagnant region was again present at the bottom of the lightwell. Rotation of 30° created fully turbulent airflow within the lightwell. Further increases in building depth (d) had no additional effect.

With the addition of a rooftop building on the leeward side of the basic model (e) a clockwise vortex was now generated at the top of the lightwell but turbulence further down the lightwell was not increased. However, complete turbulence was generated in the lightwell by rotating the model as little as 15°. The flows generated became very complex with this configuration. With an increase in building depth to windward of the lightwell the vortex action was strengthened to such an extent that a secondary anti-clockwise vortex was formed within the lightwell (f). Rotation of the model by 15° induced much the same conditions of high turbulence as in case (e). The effect of rooftop buildings to the windward side of the basic model (g) was to reduce turbulence to a minimum in the lightwell. However, an increase in building depth (h) increased turbulence in the lightwell and a vortex was again formed at the top of the lightwell.

It was found that decreasing the depth of the lightwell (i) did not affect the phrnomena occurring above the lightwell floor, and raising the floor to the limits of the stagnant region (j) did not affect the strength or direction of the vortex at the top of the lightwell.

An increase in building height to the leeward of the lightwell (k) created a very strong vortex above the lightwell, as would be expected. An increase in building height to the windward of the lightwell (l) sheltered the lightwell to some extent, but turbulence was still present over the full depth of the lightwell.

It can be seen that a wide variety of flow patterns could occur in a lightwell, changing rapidly with small changes in wind direction. Also, the more complex the building structure and layout, the more complex these flows are likely to be.

The United Oxford Hospital Model Study

The phase 2 development (Figure 4) is a 103m by 90m rectangular ward block. The number of floors above ground level varies from 6 at the east corner to 8 at the west, giving a maximum height of 25m. The block contains four courtyards which extend to a depth of 4 floors and each of which measures 25m x 32m x 14m deep. Roof-top buildings are positioned at the corners of the courtyards. Provision for one storey high "slots" at fourth floor level was included in the model to allow outside air to ventilate the base of each courtyard. The interior layout of the building follows the common "race track" design and is similar on each floor.

From the wind tunnel tests of the model it was apparent that there were pressure variations from courtyard to courtyard, and also within any one courtyard there were significant differences in pressure on the walls. With wind directions normal to a face of the building, negative pressures existed at all points on the courtyard walls but once the wind became inclined to the walls isolated areas of positive pressure began to appear. These could be due to the rooftop buildings on the leeward side of the courtyard or to vortices generated by either the leading corner of the building or the upstream buildings. The mean pressures in all courtyards were found to be negative relative to the wind tunnel static pressure, although the windward courtyards were subject to lower pressures and to more variation in pressure than those to leeward. The inclusion of the slots at the base of each courtyard had only marginal effects on the pressure distribution, the most obvious being a slight decrease in the pressures on the walls of the courtyards to leeward.

From climatological information on wind in the Oxford area, the annual percentage frequency of infiltration of air into the building for each courtyard wall was calculated using the measured pressure distributions and is shown in Figure 5. All areas are affected to some extent, but the areas between two courtyards, which must be ventilated from one or other courtyard, would be most prone to infiltration. The areas least affected would be those between the S.W. wall and the adjacent courtyards, where infiltration occurs for about 12% of the time.

We have no factual evidence on which to base estimates of air movement at United Oxford during no-wind conditions. If the air temperature in the courtyard was assumed equal to that outside, a neutral zone would exist at the same level as on the outer walls and infiltration of air from the courtyard would occur on the lower floors. The temperature will of course be higher because of heat loss and exfiltration from the building, but as the courtyards are wide and shallow it is probable that convection currents would be set up which would keep the temperature fairly close to the ambient and the neutral zone only marginally lower than that on the outside. There is therefore a high probability of infiltration on lower floors around the courtyards during light-wind conditions. The inclusion of slots would probably help to increase the rate of air change at the bottom of the courtyards, but would have the adverse effect of lowering the temperature and hence raising the neutral zone.

Typical airflow patterns within the courtyards are shown in Figure 6. It can be seen that without slots a stable vortex existed, the top moving with the direction of the wind, and the bottom sweeping over the courtyard base in the opposite direction. Except when the wind was normal to a building face the inclusion of slots replaced the stable vortices by a helical upward or downward pattern of air movement within the wall. Without the slots the velocities at the courtyard bases were typically 30-40% of the free wind speed at 10m equivalent height. With the slots the air velocities at the slot entries were high on the windward side (80-100% of wind speed) and at wind directions 0-30° the velocities within the courtyard adjacent to the slots were even higher (100-130%). On the leeward side however the velocites in the slots never exceeded 53% of wind speed. At points on the courtyard bases away from the slots the velocities were similar to those measured without the slots.

Whilst we have concluded that infiltration may occur at all points on the courtyard walls, the air change rate in the courtyard would be such as to keep the air fresh enough to allow its infiltration into most building types.

Bellshill Hospital Full Scale Investigation

Bellshill Maternity Hospital which is a 26m high seven storey naturally ventilated building of 78m by 21m rectangular floor plan was used for the full scale experiments. It is pierced by four lightwells, each about 6m square, for a depth of 18m, equivalent to the upper five floors (Figure 7). It can be seen that the lightwells at Bellshill Hospital are deep in relation to their cross sectional area, and as far as light transmission is concerned, they are barely effective at first floor level. The hospital is situated in a semi-rural area and is oriented in a roughly north-south direction. Figure 8 shows the layout of the upper three floors of this hospital. The internal rooms can be thought of as generally 'dirty' rooms.

The racetrack corridor design ensured an equal internal pressure at all lightwell windows at any floor level. It was also observed that on any one floor level, although velocity fluctuations were considerable, the airflow directions through open windows were always the same, suggesting that, at each floor level, there was little variation in mean external pressure around the four faces of the lightwell.

Measurements made on the fully instrumented lightwell 2 showed that although large variations did occur in the pressures no consistent pattern emerged regarding the mean pressure distributions around the four walls, or over the height of the lightwell. The mean pressure in the lightwell at each wind direction was calculated and showed that a mean positive pressure occurred for southerly winds, and that at other wind directions the mean pressure was more or less negative. The only conclusion that can be drawn from this is that southerly winds impinged on the tank room thereby inducing a down flow into the lightwell.

A second series of measurmeents of all pressures in the centre of each lightwell at roof level confirmed that positive pressures predominated when rooftop buildings were immediately downwind of the lightwell. These results are shown in Figure 9. The plots for lightwells 1 and 3 have been superimposed because both have rooftop buildings to their immediate South. Similarly, plots for lightwells 2 and 4 have been superimposed as both have rooftop buildings to their North.

During the test periods at Bellshill smoke was used to determine the direction of airflows through the lightwell windows. During 65% of the observation periods, air was extracted through all lightwell windows on all floors, with no infiltration occurring. Table 1 shows the percentage of occasions at each floor level in each lightwell that air infiltration into the internal rooms did occur. It can be seen that inflow occurred more often on lower floors than on upper floors. However no internal room was completely free from infiltration from the lightwells. The high percentage associated with second floor windows was due to the operating theatre extracts running with the supply off. Sometimes extract occurred on the top two or three floors with infiltration occurring in the lower floors. This was probably due to temperature effects, whereby a neutral pressure zone was formed within the height of the lightwell. Sometimes infiltration occurred on all floors.

This would be due to wind action at the top of the lightwell generating high lightwell pressures, caused either by rooftop buildings, or some more complex flow pattern peculiar to the building geometry. On no occasion did infiltration occur on upper floors with exfiltration occurring lower down. This is presumably a reflection of the fact that lightwell temperatures were never higher than the indoor temperature, a condition which would cause a reversal of the stack effect in the lightwell. It is interesting to note that the lightwell temperatures were on average three to five centigrade degrees above the outside temperature, and that little variation in the average difference occurred between summer and winter. This magnitude of temperature difference should cause considerable movement of air in the lightwell, especially under low wind conditions.

In order to assess the ventilation rate within the lightwells nitrous oxide tracer gas was released at different heights in each lightwell and concentrations of gas were sampled at each floor level in the lightwells using an infra red analyser. Turbulent ventilation was high, even at the bottom of the lightwells. The mean ventilation rate in the lightwells ranged between about 13 and 40 air changes per hour with a mean of about 20 air changes per hour. One would expect the ventilation in a courtyard such as at the United Oxford Hospital to be greater than this.

Design for Ventilation - a Rational Approach

Air movement patterns within lightwells and courtyards are extremely complex. This has been shown to be the case even with fairly simple building configurations. Large variations in ventilation occur as the result of relatively small changes in external wind speed and direction, and hence, as the variety of architectural design including lightwells and courtyards is unlimited, it is not possible to give a practical design guide for prediction of ventilation rates which will suit all possible cases. However we can provide some useful guidance to enable a fundamental choice to be made concerning the form and outline planning of major building projects.

Considering first the question of the acceptability of performance of lightwells and courtyards as ventilators of the central zones of deep plan buildings, we can identify three possible criteria on which an assessment may be based. Firstly, should infiltration of outside air be permitted, assuming that the quality of the infiltrating air is acceptable? Since it is impossible to guarantee that any room ventilated onto a lightwell will not be subject to infiltration, rooms which may act at sources of bacterial or other air contamination cannot be sited adjacent to lightwells unless alternative provisions are made to prevent the spread of these contaminants to other parts of the building. In practice, this criteria is no different from the basic consideration which must be applied to any naturally ventilated space in a building.

Secondly, is lightwell air clean enough to permit its use as ventilating air when infiltration does take place? We have shown that even at Bellshill with its deep narrow lightwells the air change rates within the lightwells were high compared with the transfer of interior air into the lightwells, thus ensuring good dilution of contaminants. Where the lightwells become wider or shallower as at United Oxford, the air change rates become even higher and the lightwell air approaches the free air in quality. For a wide range of buildings including hospital ward blocks there is therefore no reason to discard lightwell ventilation on this basis.

Thirdly, will the ventilation rates in the rooms around the lightwells be adequate? In situations such as at Bellshill Hospital, where the building is only "one-lightwell-deep" and is oriented at right angles to the direction of the prevailing wind in a relatively open site, it was found that problems are most likely to be concerned with reduction of ventilation and infiltration to acceptably low levels. With designs such as the United Oxford Hospital building, which may be "several lightwells deep", areas between two lightwells and those to the lee of the prevailing wind may be subject to lower levels of wind induced ventilation than windward areas. Figure 11 for example above the percentage of occasions that air change rates would be expected to fall below three air changes per hour in different zones within a typical floor at the United Oxford Hospital. These figures are based on steady state isothermal conditions representative of winter periods when windows would not be opened beyond a crack. They would be increased if the variability and turbulence of the natural wind coupled with temperature effects were taken into account. The figure of three air changes is not intended to represent any particular standard, indeed, for any building other than a hospital where special conditions apply, this represents a fairly stringent criteria for acceptable ventilation rate.

If it is decided that adequate ventilation cannot be achieved due to a failure to satisfactorily meet any of these criteria in an individual case, then alternative design solutions must be considered. Even if it is concluded that natural ventilation via lightwells or courtyards is feasible, one may still wish to consider the possible alternatives on economic grounds.

By omitting lightwells and courtyards a more compact building will be possible, giving savings in both structural and land costs. On the other hand mechanical ventilation of the core of the resulting deep plan floor layout will be necessary, the capital cost of which may be set against the above savings. In addition, the fabric heat losses of the more compact design will be lower although the running costs of the ventilation or air-conditioning plant must be taken into consideration. Unless some form of heat recovery or recirculatory system is utilised, the energy requirements for heating the incoming ventilating air will be roughly equivalent to those for natural ventilation.

The outcome of an economic comparison will clearly depend on a number of factors, the most crucial of which will be the geographical setting and required size of the proposed building. In an urban setting for example with its high land costs and limited site areas the economic balance for a large building could favour a compact design using mechanical ventilation. A suburban or rural setting would certainly be more conducive to the provision of natural ventilation utilising a system of lightwells or courtyards, particularly where land costs are reduced and wind shelter is low. However, subject to the stated guidelines, individual cases will usually need individual treatment, for example the use of lightwells and courtyards as architectural design features to provide visual relief in urban situations need not necessarily be precluded from consideration.

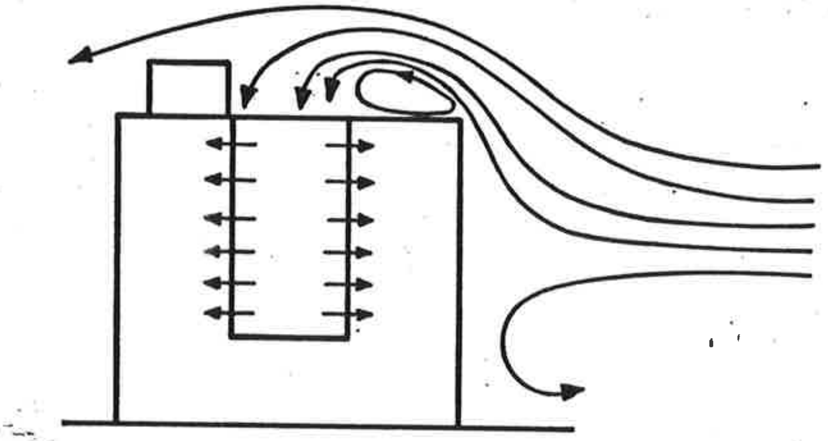

Figure 1: Effect of rooftop buildings on lightwell airflow.

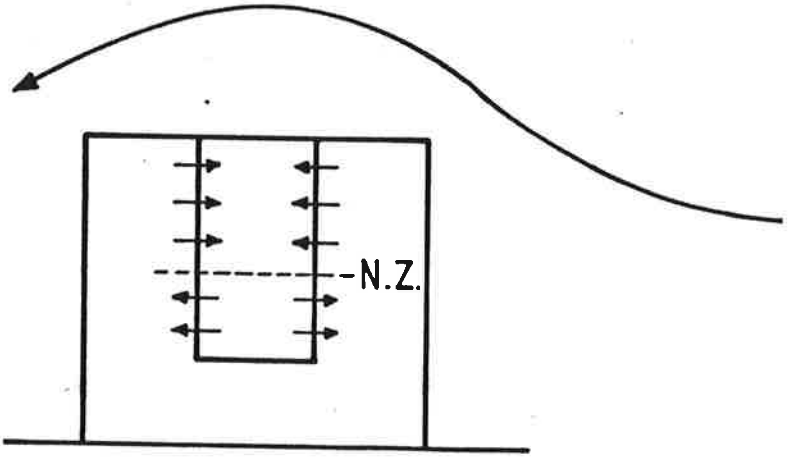

Figure 2: Formation of a neutral zone due to temperature effects.

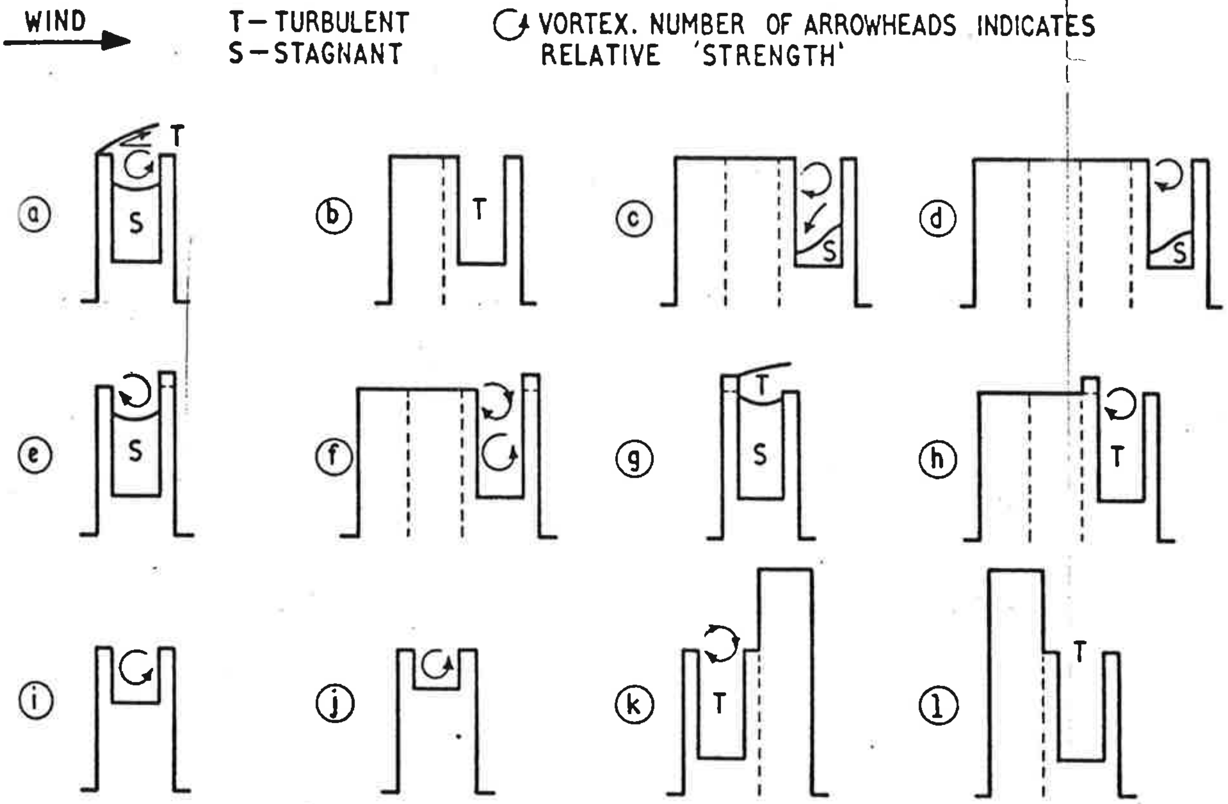

Figure 3: Airflow patterns in model lightwell.

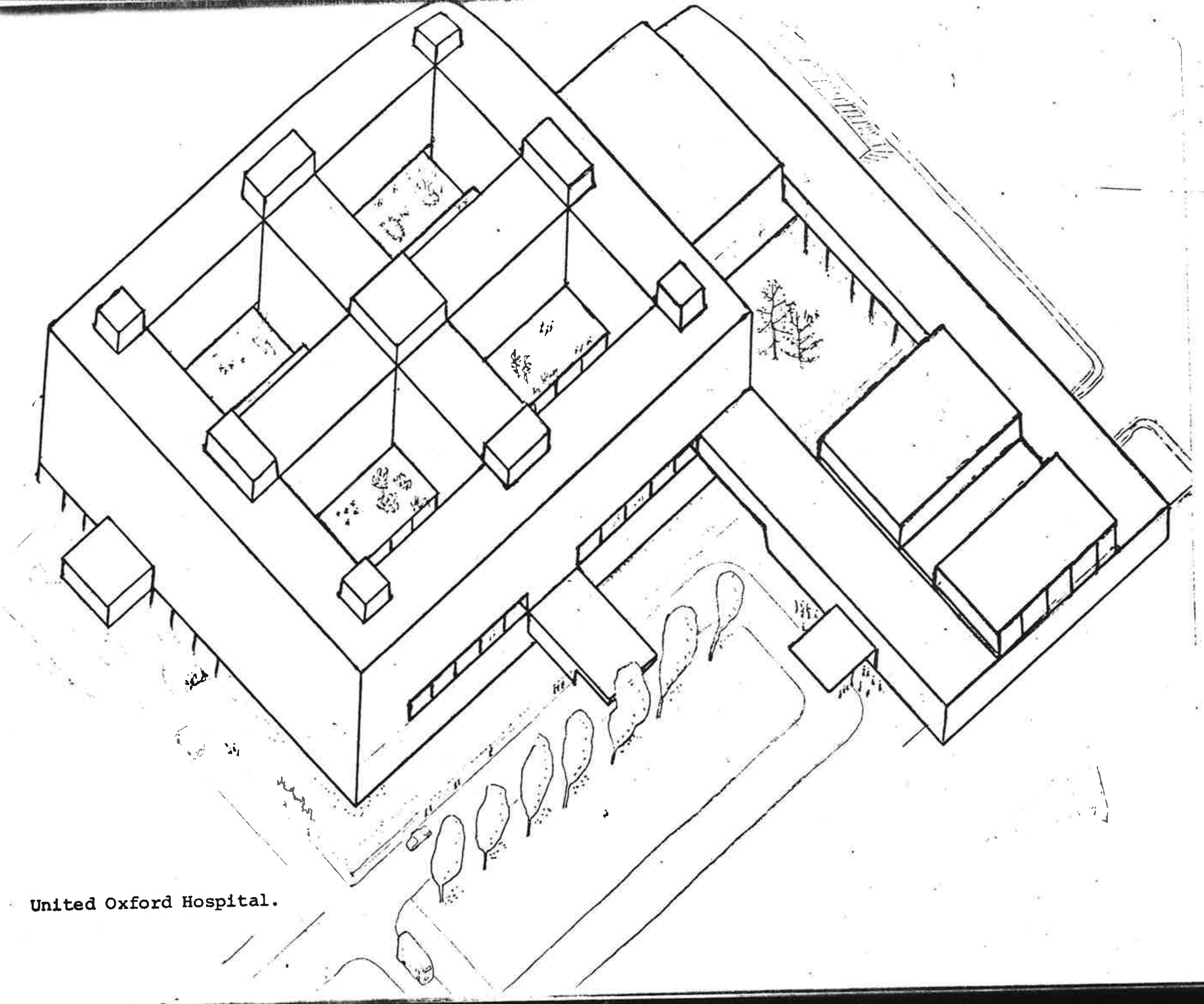

Figure 4: United Oxford Hospital.

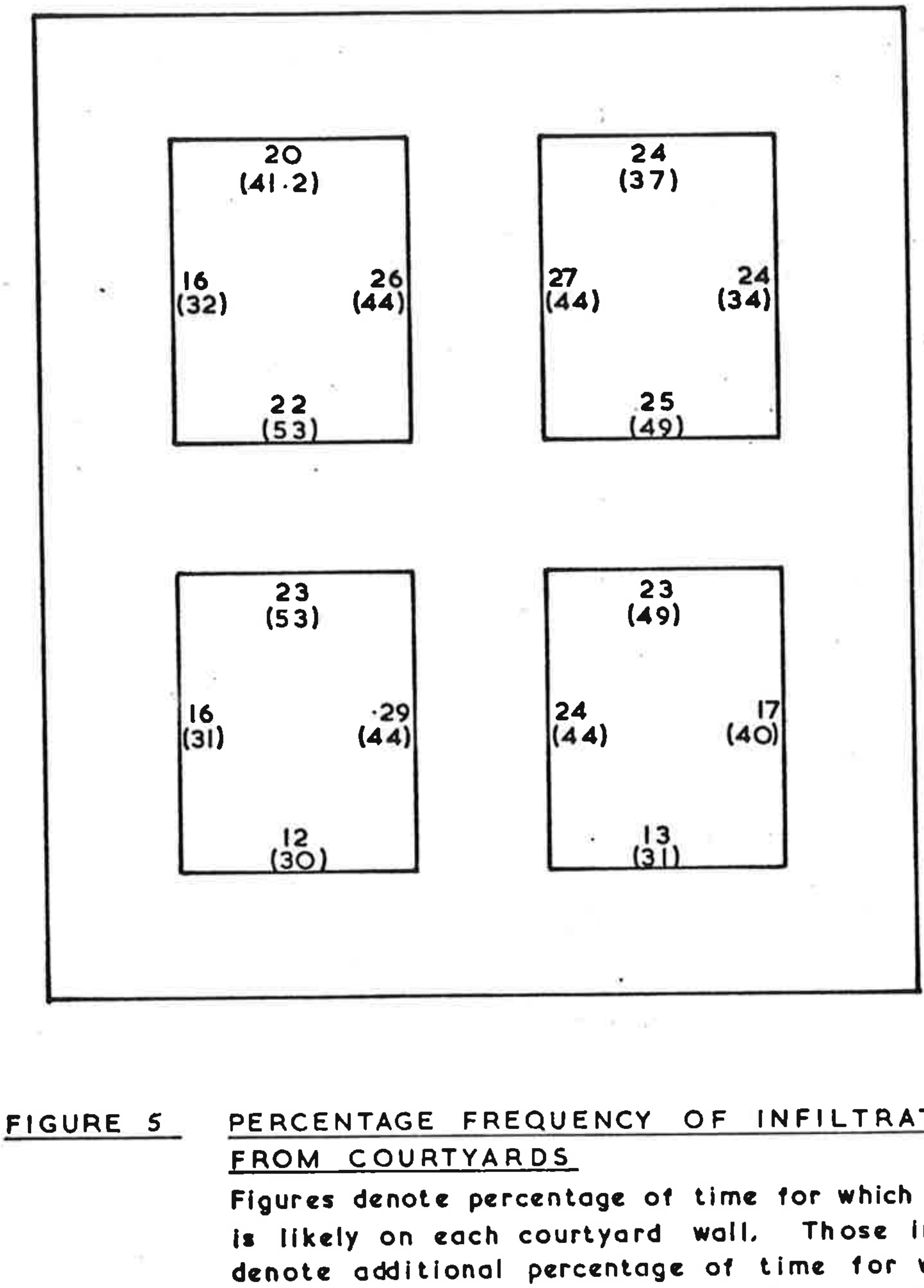

FIGURE 5 PERCENTAGE FREQUENCY OF INFILTRATION FROM COURTYARDS

Figures denote percentage of time for which infiltration is likely on each courtyard wall. Those in parenthesis denote additional percentage of time for which infiltration is likely on lower floors due to thermal action during light winds etc.

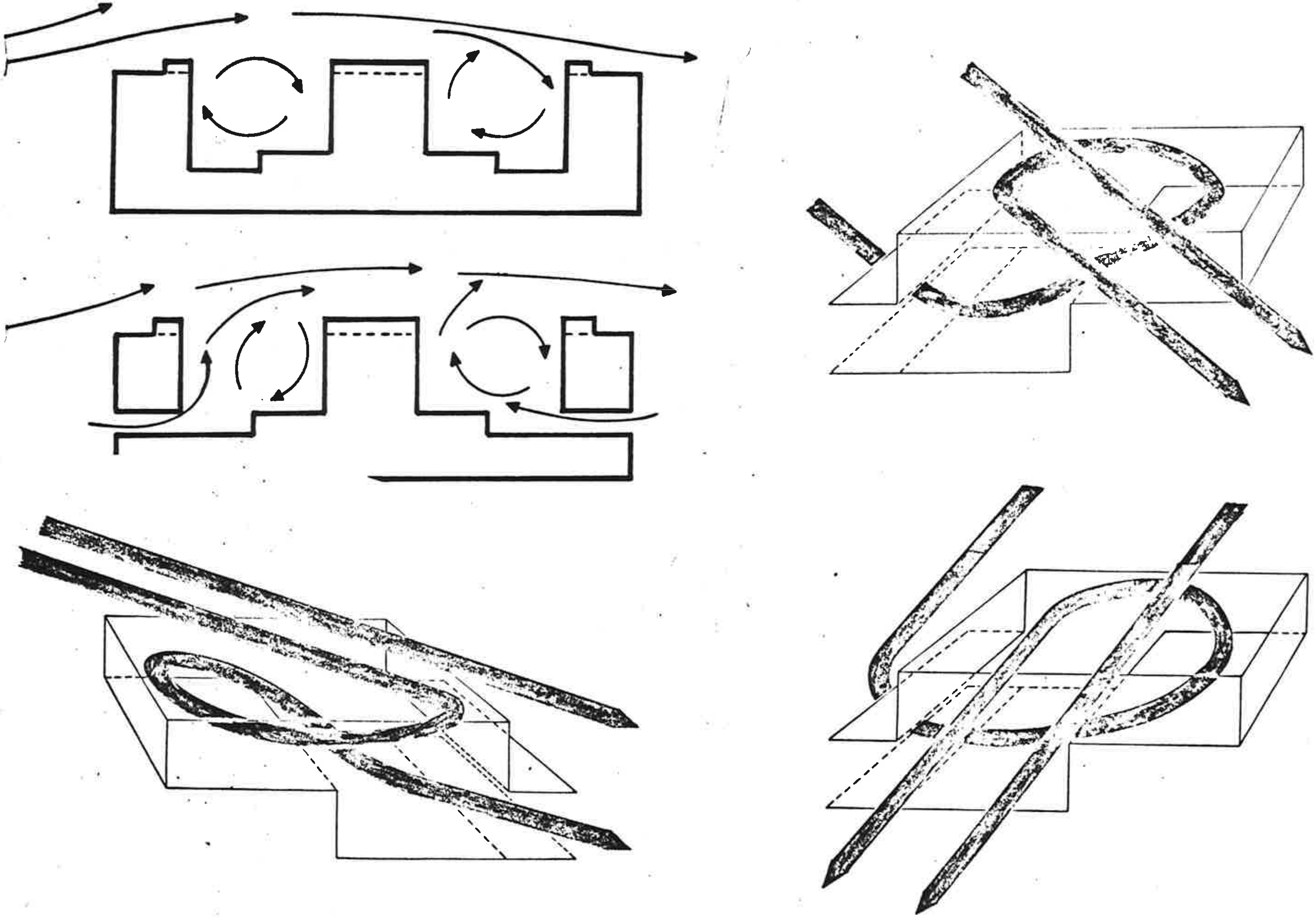

Figure 6: Effect of slots on courtyard airflow.

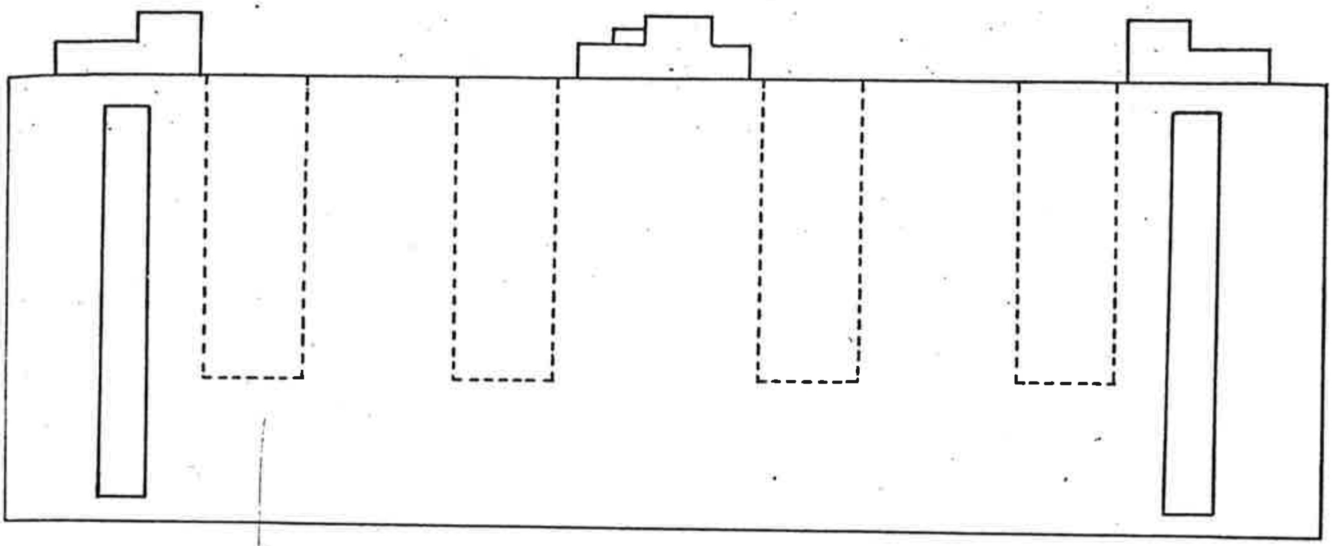

Figure 7: Bellshill Maternity Hospital, showing lightwells and rooftop buildings.

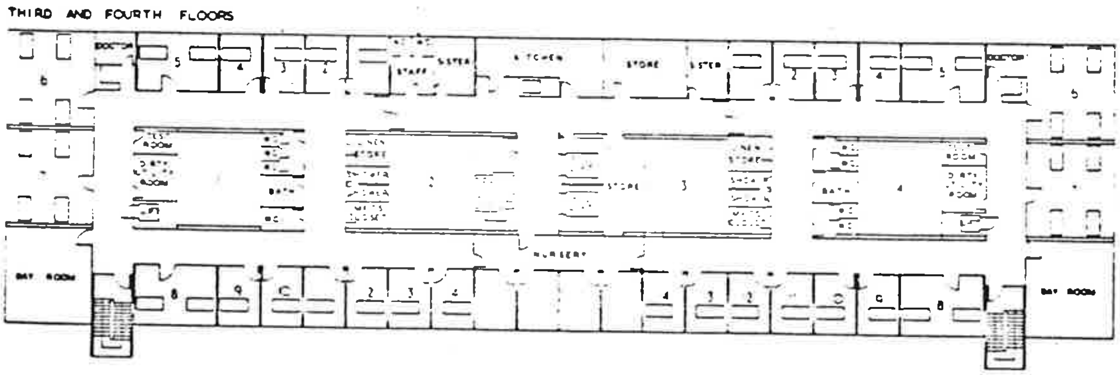

Figure 8: Typical floor plan at Bellshill.

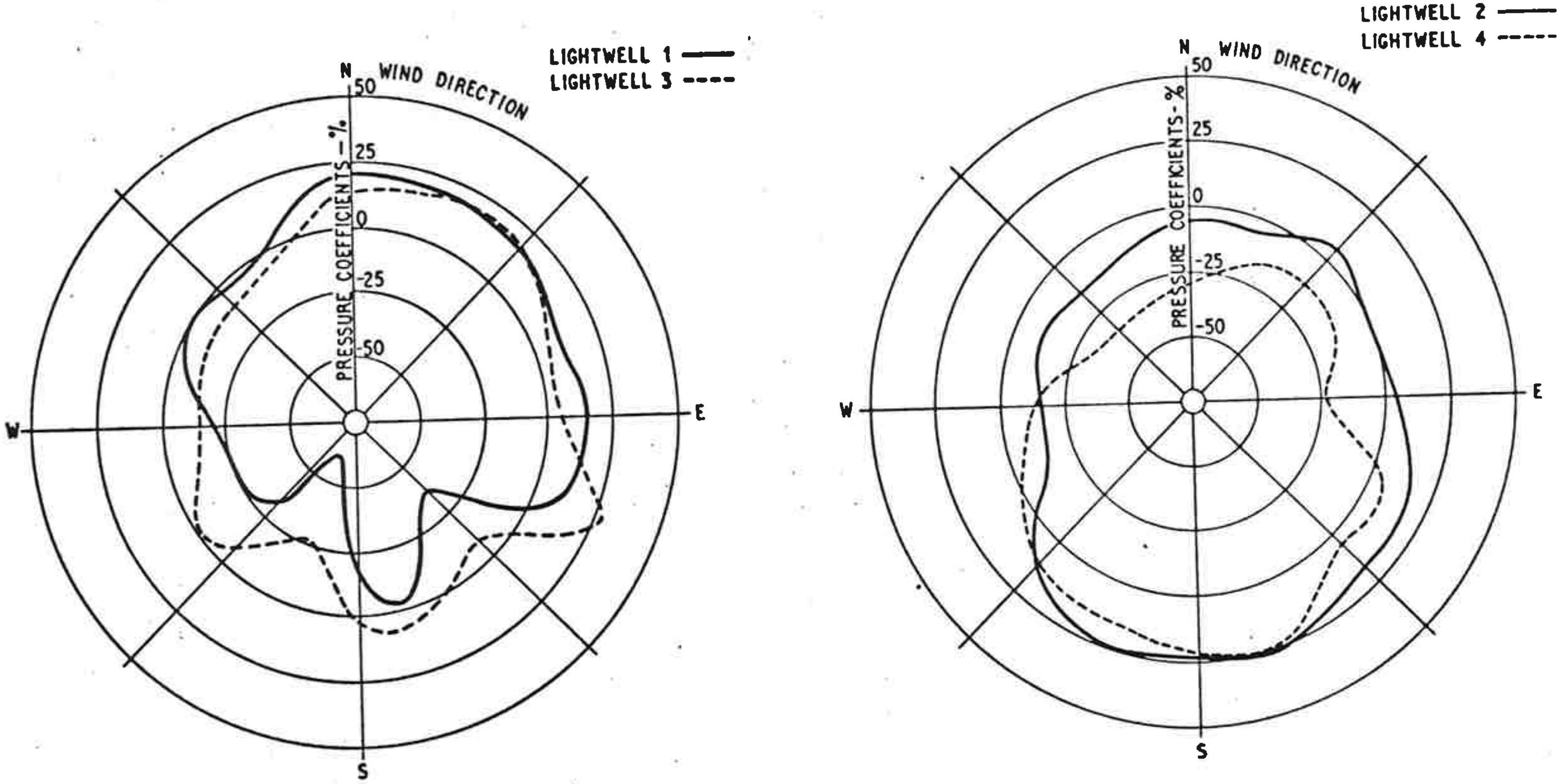

Figure 9: Bellshill lightwell pressure coefficients.

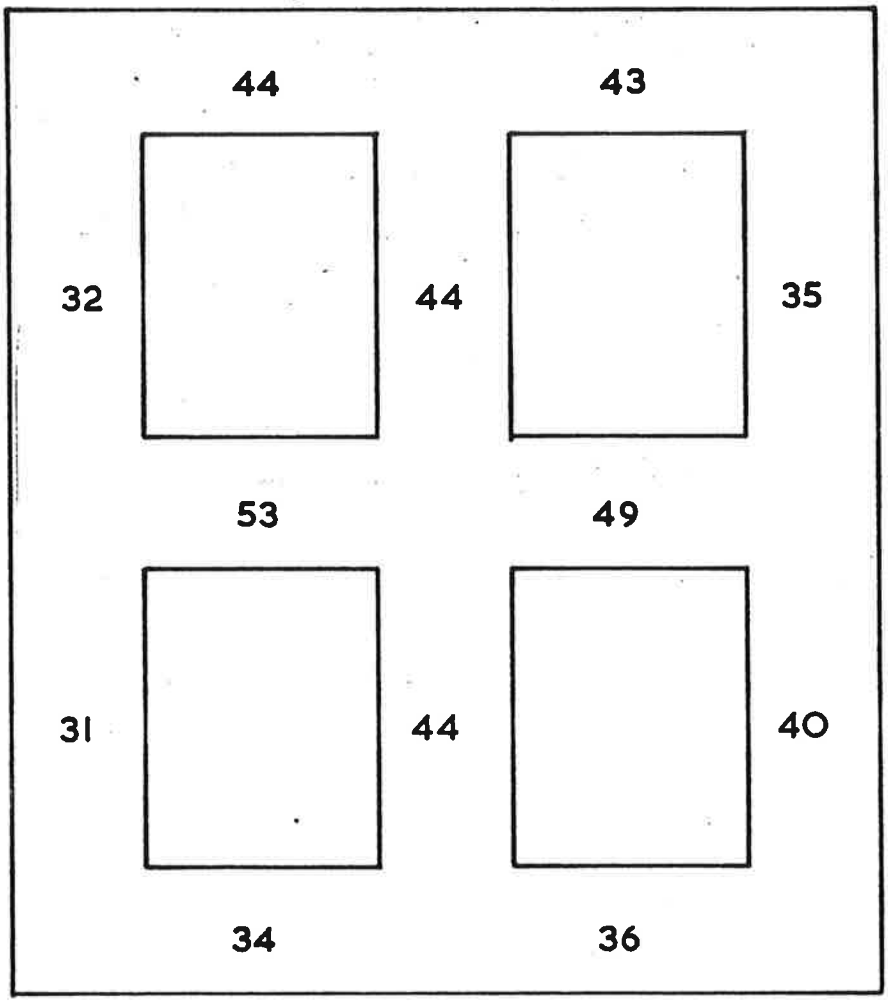

Figure 10: Percentage frequencies of wind induced ventilation below 3 air changes/hour - United Oxford.