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PREDICTION OF THE ANTICIPATED AIR VOLUME PASSING THROUGH BUILDINGS BY MEANS OF THE AIR CURRENT ANALOGUE

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by H.Ph.L. den Ouden')

Factors of influence on the ventilation

For proper control of the ventilation in a building, it is necessary to know the factors involved.

These include:

1. the outdoor climate
   (a) temperature
   (b) wind direction
   (c) wind velocity
2. the building performance

   This determines the interconnections between indoor and outdoor conditions due for instance to gaps at windows and doors or grilles through which a natural ventilation will be possible. In the case of mechanical ventilation, this type of air motion is usually undesirable.
3. the presence of any mechanical ventilation system, which has been calculated with due regard to the conditions desired for the particular space e.g. the number of occupants, the possible formation of harmful products etc.

The influence of the local climate on the relative importance of these factors

In the case of very appreciable differences between outdoor and indoor temperatures, an air movement may be caused due to density differences. At a low outdoor temperature, the upper part within the building will have an overpressure, the lower part will have an underpressure. When openings or gaps in the building are evenly distributed, both these pressures will be equal in magnitude, as shown in figure 1. For very tall buildings and little wind, the temperature difference between outside and inside can be the most important factor as shown by the investigations of T.C. Min on 23 buildings in Cleveland (USA) and Pittsburgh (USA). At entry doors of these buildings, pressure differences averaged 0.7 of the theoretical draught, which is equal to

$$\Delta p = h(\gamma_1 - \gamma_2) \qquad (1)$$

') Publication No. 272 of the Research Institute for Public Health Engineering TNO, P.O. Box 214 - Delft - Holland.

For our Dutch climate, the temperature differences are not so excessive. The design temperature difference for both American cities was about 42°C (+22°C inside and -20°C outside), while for Holland this difference is 32°C maximum and for the major part of Holland 30°C.

Furthermore the lowest building which was investigated in the U.S.A. (15 storeys) is already classified as high for the Dutch conditions, while in Holland the proximity to the sea and the flatness of the country tend to accentuate the relative importance of the role played by the wind. These circumstances result in the wind becoming an important factor, if not the most important one.

Pressure distribution around a building due to the wind

Before being able to express the influence of the above-named factors in numerical values, the external pressure distribution around the building must be known.

This pressure distribution can be established on a model in a wind-tunnel, in which the pressure at relevant points is measured under the combined influence of wind direction and preferably including the effect of environment. The wind velocity varies with the height in exponential manner and the exponent itself varies with the roughness of the terrain.

Measures must be taken to imitate this roughness, which is caused by neighbouring buildings, trees etc, to properly scaled values on the model. On account of the work by several investigators, applying scaled values on the model is a relatively easy matter.

Generally, at the side of the building facing the wind (the windward side), there will be an overpressure, as velocity is converted to pressure, whereas on the side averted from the wind, the leeward side, there is an underpressure, as is usually the case on the roof.

The pressure difference over the building is equal to the sum of these overpressures and under pressures, and owing to the fact that such a difference in pressure invariably seeks to balance itself out, a current of air is produced, in this case a current through the building, which finds its way through the available apertures (window and door-cracks, [illegible], etc.) and constantly renews the air in the building.

Upon change of wind direction the air-current pattern in the building will also change.

The relation between the value of the wind velocity and the pressure is as follows. Upon undergoing total conversion the [illegible] a pressure which is equal to $\frac{1}{2} \rho v^2$, where v denotes the velocity. Since complete conversion does not take place in reality, the [illegible] on the windward side will be somewhat less. The underpressure on the leeward side is likewise a function of the pressure due to velocity, being on an average equal to half the latter, so that the pressure difference over the building is on an average 0.8 to 1.3 times $\frac{1}{2}\rho v^2$.

An example of the pressure differences measured on an actual building is shown in figure 2, in which the measured pressures are given as a fraction of the velocity pressure, so that all the results obtained during a certain period contribute toward the depicted polar diagram. The polar diagram gives the pressure difference in magnitude and sign (+ or -) between 2 points of the building expressed as a function of the wind direction.

Some physical observations on the air current

For a window when closed the rule to be applied is that the transport of air at a pressure difference of Δp over the window is given by the equation:

$$V = l.C.(\Delta p)^{\frac{1}{n}} \qquad (2)$$

where

- l is the total length in lineal metres of the crack length occurring in the window (= total circumference of moving parts);
- C the air infiltration coefficient in m^3 per hour per metres of crack at a pressure difference of 1 mm.wg. (a measure for the greater or lesser air-tightness of the construction of the crack)
- Δp the pressure difference over the window in mm.wg. or kg/m^2;
- $\frac{1}{n}$ an exponent in which n has a value between 1 and 2. For a gap that closes badly n approximates to 2, whereas for a gap that closes well n approximates to 1. There is a relation between n and C;
- V the volume passed in m^3/h.

From a large number of measurements taken on finished building constructions, also in our own country, the values of C and n were determined for a number of different types of windows. It was found that the values C and n for each type of window show a very wide divergence.

A similar comparison also applies in the case of ventilation ducts, etc. Here, too, when a certain rate of transport is exceeded the air current will become turbulent, the value of n being equal to 2, whilst for smaller rates of transport for which the current is of a more laminar character (in layers), the value of n approximates to 1.

For a purely laminar current n = 1, whilst for full turbulence n = 2.

Calculation of the natural ventilation

Consider a room with doors and windows in its walls. The transports of air through the window or door cracks, due to the wind, can be calculated when we know the following:
the distribution of pressure around the room;
the l and C values of the windows or doors as the case may be.

The only unknown that is then left is the value of the pressure level in the room. As the incoming and outgoing quantities must be equal to each other, this pressure level can be calculated in a simple manner.

In calculating the to-and-fro transports of air for, say a block of flats, the number of unknowns is equal to the number of rooms: each room has an unknown pressure level. Here again, we can formulate as many equations as there are unknowns. The solution is, however, rendered difficult by the exponential characteristic of the equations. Only when the value of the exponent, $\frac{1}{n}$, is the same for all the equations can the unknown be solved, though this entails lengthy calculations.

As these exponents will as a rule not be equal in reality, whilst in addition the lay-out may be rather complicated, this fact implies that calculation of natural ventilation is generally an impossibility.

The electrical analogue

We asked ourselves whether there are no other means in existence whereby the performance of natural ventilation or the influence of wind upon a mechanical ventilation system might be evaluated more expeditiously than by any possible calculation.

The air current through a building is actually nothing else than a current passing through a large number of resistances in series and in parallel. These resistanceshave, moreover, a non-linear (exponential) relation between "current" and "potential".

An electrical resistance showing a relation between current and potential of the form:

$$i = C_1 \cdot (E)^{\frac{1}{n}} \text{ (compare formula 2)} \qquad (3)$$

would mean that, provided the value of n (between 1 and 2) and that of C could be adjusted at will, the problem could be reduced to an electrical circuit of resistances and groups of resistances in which the currents in the circuit form a certain scale of measurement for the air transports, whilst the potential differences are representative of pressure differences.

The experimenters succeeded in constructing such resistances whereby each window or door crack is imitated by one ore more electric lamps connected in parallel, in combination with series or shunt resistances or both. See fig. 3.

The electrical analogue instrument evolved by the Institute for Public Health Engineering TNO is provided with some forty built-in resistances of this kind, the proportionality constant C_1 permitting regulation in the ratio of 1 to 50, so that the ratio between maximum and minimum resistance in the ground plan considered is likewise 1 to 50.

An illustration of the instrument is given in fig. 4.

The instrument is provided with a measuring panel on which the currents (= air transports) in the circuit can be determined.

Thermal pressure differences

As already stated, in Holland thermal pressure differences resulting from temperature differences generally are of minor influence on the ventilation since:

- the temperature differences are generally small
- the wind constitutes a more important factor
- the combination of strong wind and low temperature occurs rarely.

For the higher buildings, this chimney effect does, however, play a role. This thermal pressure difference can be included in the electric analogue as a separate, electrical voltage in the electrical networks.

Influence of the wind on mechanical ventilation systems

The foregoing practically solely concerned natural ventilation. When applying mechanical ventilation, the wind will also be of influence on the various air quantities. In order to investigate this effect, we shall first neglect those air quantities which directly result from the wind and which may be considered undesirable disturbances to the ventilation quantities which were calculated.

Under this assumption, the influence of the wind is solely manifested in the form of a pressure difference between intake and outlet openings for the particular building. Schematically the variation in pressure is presented in figure 5 for an installation having a ventilator for both air supply and air exhaust. For the sake of simplicity, a constant rate of pressure drop has been assumed throughout the circuit. In addition it has been assumed that the ventilators for air supply and exhaust develop the same head. The upper curve of the figure represents the situation when there is no wind. A and B represent the pressures at the openings for air intake and outlet, in this case zero. C represents the pressure inside the rooms; for our case it has been assumed as zero although it will generally be selected a little higher in order to prevent draughts. V_1 and V_2 are the ventilators for air supply and air exhaust respectively. In case the wind exerts the same pressure on both openings, the entire curve will be shifted and the mechanically displaced air quantities will not be altered.

A different picture results when a pressure difference exists between the openings of air intake and outlet due to the wind.

For the case sketched by the lower of the two curves in figure 5, the wind pressure will contribute towards an increased air supply. The total available head becomes higher and the air quantity increases. This is apparent in the figure from a steeper pressure decline resulting from the increased loss of pressure. Vice versa, a negative pressure difference at the air supply opening will cause a decrease in the total head and the pressure drop will be less steep. Wind therefore adversely affects the ventilation in this latter case.

The rate at which the air quantities are altered is determined by the slope of the curve of the ventilator characteristic: the steeper the slope, the less the change in the air quantities handled (Fig. 6). Also of importance is the relation between the pressure head increase caused by the wind to the total available head of the ventilator. The larger this relation, the larger the percentage change in the air quantities.

Fig. 6 illustrates the manner in which a favourable wind pressure will affect the air quantities of a ventilator in the case of a flat or a steep characteristic curve.

Influence of the wind on larger buildings having mechanical ventilation

The aforementioned effect of the wind plays a more important role for buildings of appreciable height, which have been provided with a mechanical ventilation system. When in the case of an unfavourable wind, pressure differences result between the points of air intake and air outlet, then the desired ventilation pattern may be appreciably disturbed.

For a building having windows which can be opened, appreciable cross-flow ventilation may further result, the extent of which is dependent on the tightness of the window. This cross-flow ventilation may likewise disturb the scheduled ventilation pattern. For fully closed facades, this latter possibility is excluded.

One of the first measures which can be taken to limit this undesired pressure difference is to have intake and outlet openings close to each other so that the influence of the wind is practically identical for both. If for any particular reason this is not possible, a second solution is to spread the air intake opening over various directions. This may be done for instance by an air duct running from one facade to another or by placing a suction manifold on the roof in which air may be drawn in from any direction. This solution limits the influence which wind can have and also reduces the effect of wind direction.

Some examples of the use of the analogue that was developed

1. The first example given is the design for a 19-storey building, which was investigated by means of the electrical analogue. The building was planned to be mechanically ventilated, but some queries arose regarding the design of such an installation.

Due to the height of the building and long vertical air channels formed by the stairways, the stack effect could be very appreciable and this might cause draughts in corridors. What forces would be experienced on the doors?

The wind gains in strength with height compared to the situation at ground level, where surrounding buildings afford protection.

What would be the effect of opening windows on the highest storeys to the mechanical ventilation system? When opening a window, a large proportion of the air supplied by ventilation will obviously disappear outdoors. Via the room in which the window is opened, wind can affect the ventilation system and this may result in a certain measure of unbalance.

If the windows can be opened, even in closed position infiltration will exist. In winter time this implies additional heat loss. Is it possible to estimate these losses beforehand in order to have sufficient information regarding the query whether windows should be movable or fixed?

First of all, results are presented of some measurements to determine the magnitude of vertically moving air quantities resulting from the stack effect, together with those when wind and stack effect are combined; the results being valid for closed windows without any means of mechanical ventilation.

Fig. 7 schematically illustrates a few storeys of the building showing the location of the various rooms. The internal doors and windows have also been indicated. It is added that the C-value assumed for the windows was 2.5 i.e. reasonably good fits. For internal doors of the room, the C-value has been assumed as 15, while the C-value for the door to the entry hall and doors between corridors and stairways was likewise assumed as 15. For an outdoor temperature of -10°C and a temperature in the building of about 20°C, the air transport due to the stack effect is as shown in fig. 7.

The pressure levels at the various points are indicated by encircled numbers, the direction of air movement indicated by an arrow while the number near the arrow represents the air quantity involved. The sketch shows the situations existing at ground level, the first, 13th and 19th storey (for the sake of simplicity interim storeys have been omitted).

On the lower floors, air will enter the building through gaps at windows and doors. This procedure will become less marked with height up to the neutral zone. Above this zone, air will leave the building at a rate increasing with height. The neutral zone will be slightly below half-way up the building on account of the entry doors on the ground floor.

Fig. 8 illustrates what will happen to the building under the assumed conditions for a wind velocity of 7 m/sec. From this figure it is clear that even on the top storey the wind has not fully neutralized the stack effect. On the 19th storey namely, air still passes outward through the windows even for the side of the building facing the wind.

At the wind velocity of 14 m/sec - see fig. 9 - this effect has entirely vanished. It is, however, very clearly evident that this effect adversely influences natural ventilation for rooms facing the wind in the upper storeys.

The pressure differences at several doors give an impression of the forces acting on these doors; they have been expressed in kg per m^2. On the 19th storey and for a wind of 14 m/sec which is perpendicular to the facade and for a simultaneous temperature difference of 30°C between inside and outside, the force acting on the doors between stairways and corridor will be 2 kg per m^2; for a 7 m/sec wind the force will be 3.6 kg per m^2.

For the tests including mechanical ventilation, the disturbance caused by the wind was only limited due to the fairly large head of the ventilators for the air supply.

Fig.10 illustrates the situation when in addition to the presence of wind plus a temperature difference, a window on the top storey is opened. Even for a moderate wind (7 m/sec), it is apparent that the ventilation for the particular room is appreciably affected without, however, considerable disturbance to the ventilation system as a whole.

2. The second example concerns the ventilation of a laboratory handling radio-active products. Measures were essential to avoid radio-active contamination and to ensure a particular ventilation pattern under all meteorological conditions. Briefly summarising, the stringent demands concerned avoiding the transport of contaminated air from certain rooms to other quarters under all circumstances.

Fig. 11 schematically shows the building. On the upper left is the cyclotron containing the products used for the manufacturing process which is carried out in the wing at the back of the building.

The lower storey of the front wing mainly contains offices and the wardrobe: on the right hand side of the upper storey there is a space called "low-lab" where a low degree of radio-active contamination may be present.

Fig. 12 illustrates the plan of the lower storey indicating with thick arrows the direction of the air motion pattern which must be maintained under every condition.

Fig. 13 shows the plan of the upper storey showing "low-lab" and an instrumentation room.

The following questions could be put:

1. Is it possible to adjust the exhaust system in such a manner that the above mentioned demands are fulfilled irrespective of wind direction or strength, so that the use of automatic means of control is avoided?
2. Will the (sub) pressure levels that occur be allowable? (for instance with regard to the design of doors and windows).
3. What are the essential amendments necessary to the building and the ventilation system in order to achieve the above mentioned?
4. What is the influence of the air quantity infiltrating through windows and doors to the specified demands?

The building is situated immediately behind the dunes at a very short distance from the sea so that one must reckon with the possibility of strong winds. For the test a wind velocity of 16 m/sec was assumed.

Description of the test

In line with the previously recommended procedure, the pressure distribution was measured on the model in the windtunnel for 8 wind directions. In addition to pressure determinations on the facades, similar measurements were made at air intake and outlet locations.

With the aid of the electrical analogue, the additional requirements were established to fulfil the demands in case there is no wind. It was for instance necessary to install separate air supply fans for the hall and for the low lab and to install an extra closing door in the corridor near the cyclotron. This situation is depicted in fig. 14.

When introducing the effect of wind into the electrical analogue, it became clear that the location at which fresh air was taken in was particularly unfavourable. Differences between the pressures at air intake openings for the fans of the wardrobe and the manufacturing plant were propagated practically without change resulting in excessive differences of pressure between various building sections.

For different locations of these air intake openings (fig. 11, P and Q) and when these are fitted with specially shaped hoods, the smallest possible pressure differences resulted between both air intake openings.

found by model tests at diff. scales

The pressure variations of the air intake openings, point P for the hot lab and point Q for the front wing are presented dimensionless in a polar diagram, fig. 15.

The largest pressure differences occur when the wind is NNE and S. As particularly strong winds frequently blow from the SW, the air balance in the building was investigated for a 3 named directions (figs 16, 17 and 18).

It was concluded for instance that even without applying any controls that the desired air current pattern would be obtained, while high values were obtained for the underpressure in the cyclotron.

From a further test it was clear that even at high air infiltration rates at the windows in the manufacturing hall, direction of the air current in the corridor would not reverse.

The results obtained allowed a reply to all the queries that were submitted. It would have been desirable to have made the test prior to commencing the actual building, when a simpler and more elegant solution would have been found.

Conclusion

The examples which are given indicate that all the factors of influence on the ventilation in a building which were named in the introduction, can completely be introduced into the electrical analogue. It is possible to predict undesirable situations by this means with a fairly large margin of certainty and this may be taken into account in the design of an installation.

References

1. Engineering Concept and Design of Controlling Infiltration and Traffic through Entrances in Tall Commercial Buildings
by T.C.Min
(International Conf. on Heating, Ventil. and Air Cond., London 1961)

2. Winter infiltration through swinging-door entrances in multi-storey buildings
by T.C.Min
(ASHAE Transactions, Vol. 64, 1958, p. 421)

3. Windtunnel studies of pressure distribution on elementary building forms
(Iowa Inst. of Hydr. Res., State Univ. of Iowa City 1951)

4. Natuurlijke ventilatie (Natural ventilation)
by Ir. E. van Gunst
(Publ. no. 208, Research Inst. for Publ.Health Engineering TNO-Delft)

5. The use of an electrical analogue for studying the ventilation of buildings
by H.Ph.L.den Ouden
(C.I.B. Bulletin no. 2, 1963)

6. Wind loads on structures
by A.G. Davenport
(Techn. paper no. 88 of the Div. of Building Research, Ottawa-Canada)

7. Model-scale tests in turbulent wind I and II
by M.Jensen and N.Franck
(The Danish Technical Press, Copenhagen, Denmark)

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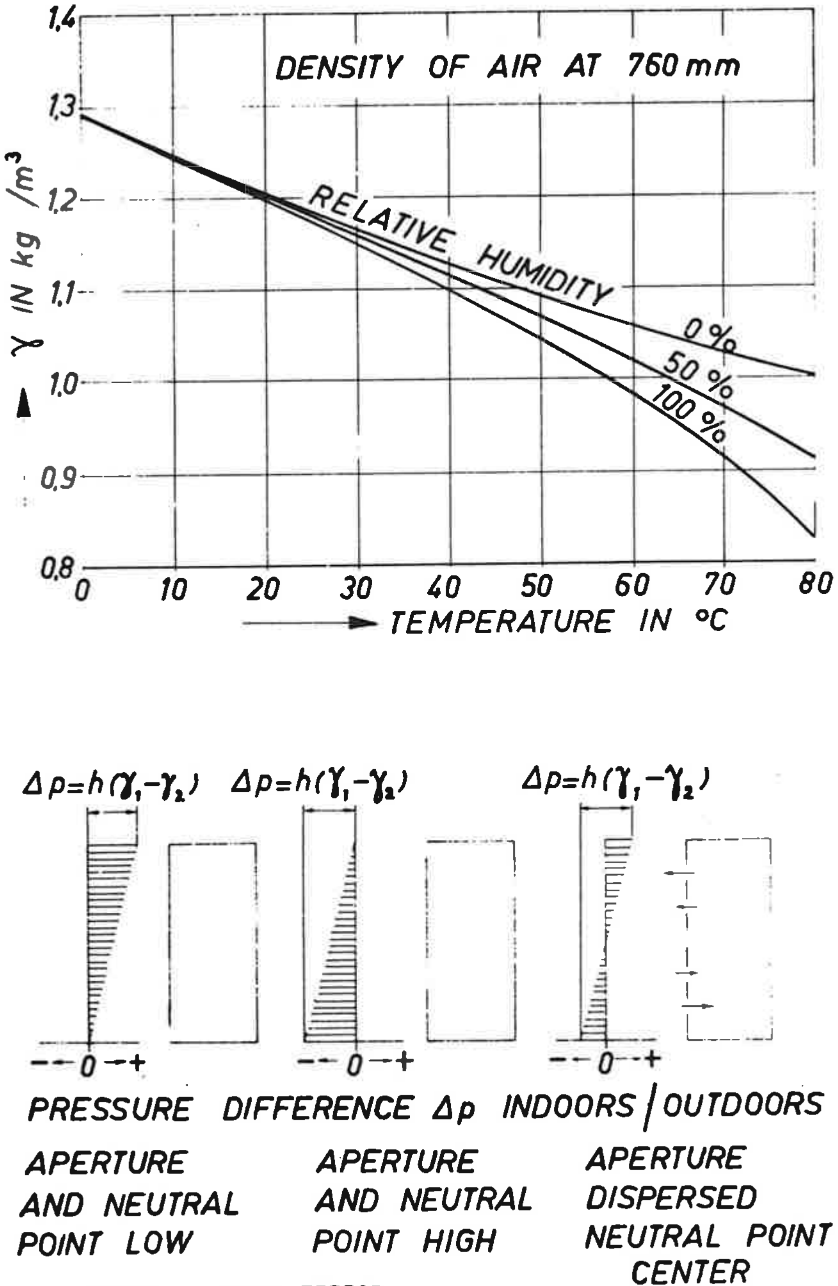


FIGURE 1 STACK EFFECT

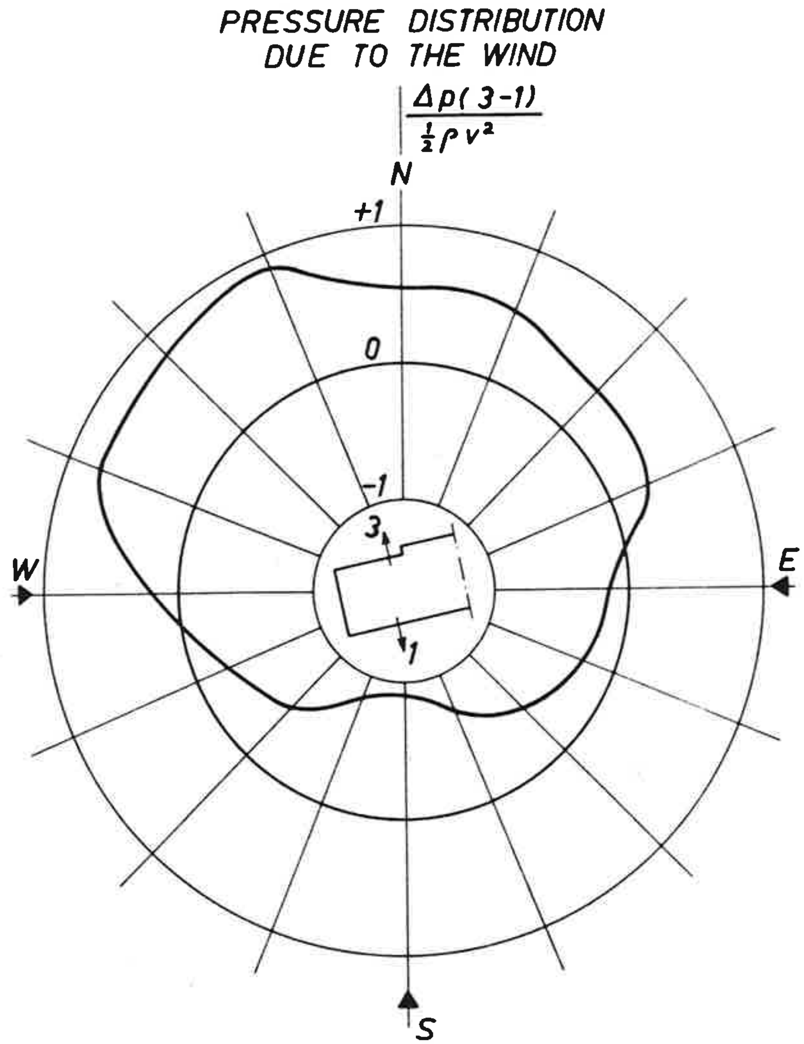


FIG. 2 MEASURED DIFFERENCES IN PRESSURE BETWEEN POINTS 1 AND 3

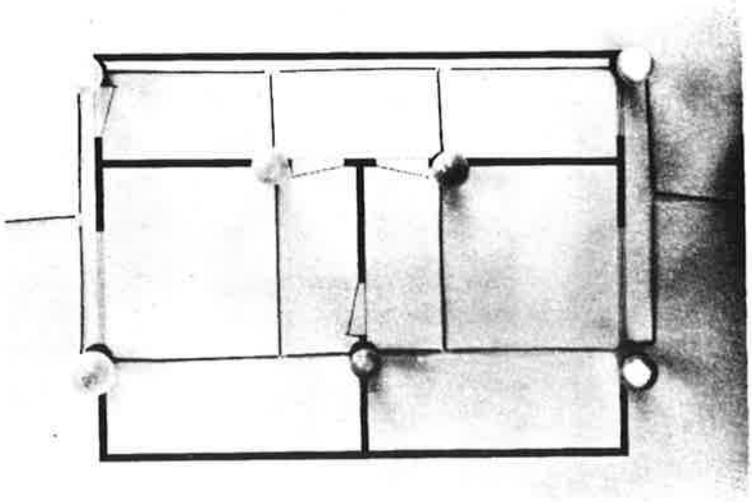


FIG. 3 PRINCIPLE OF THE ELECTRICAL ANALOGUE

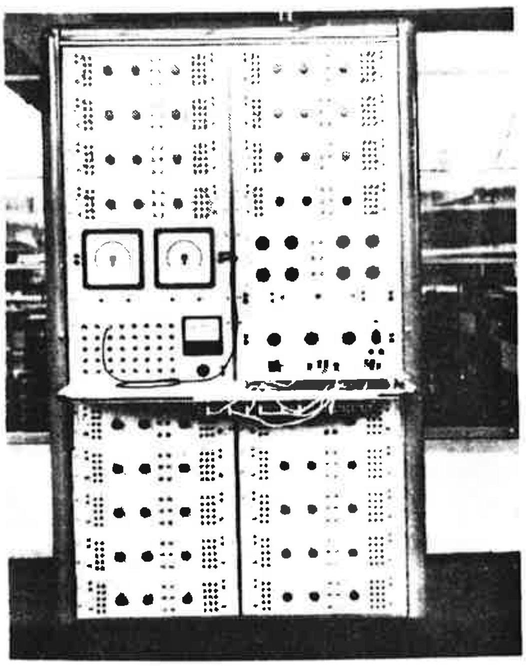


FIG. 4 EXTERIOR VIEW OF THE ANALOGUE

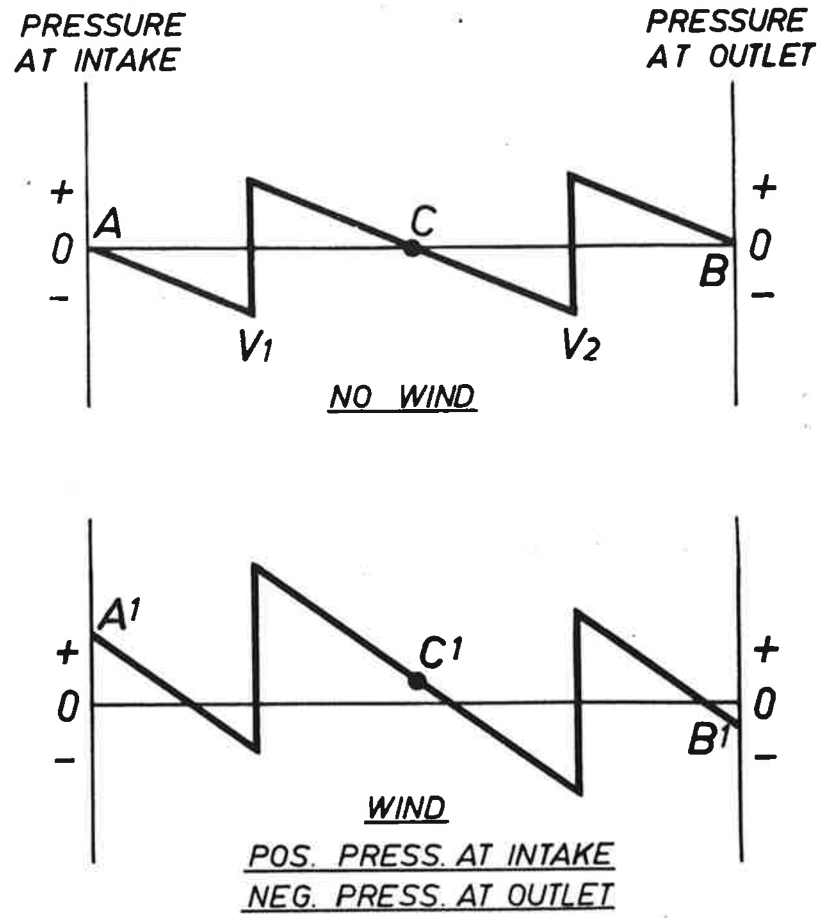


FIG. 5 WIND ON VENTILATION SYSTEM

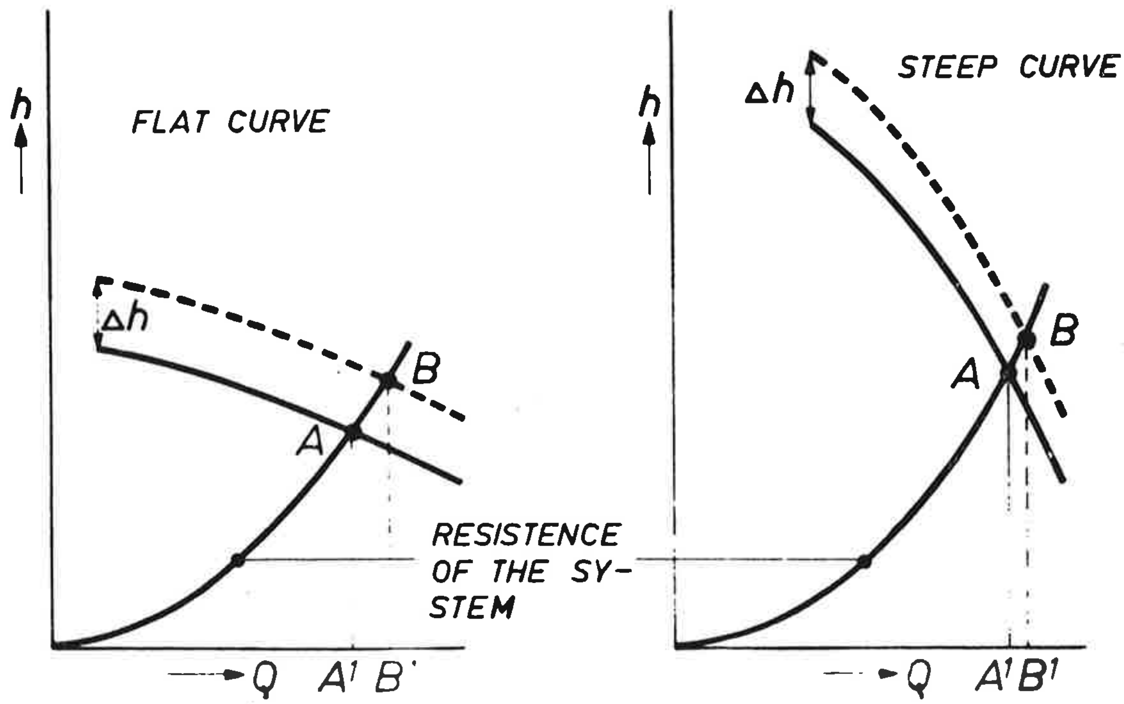
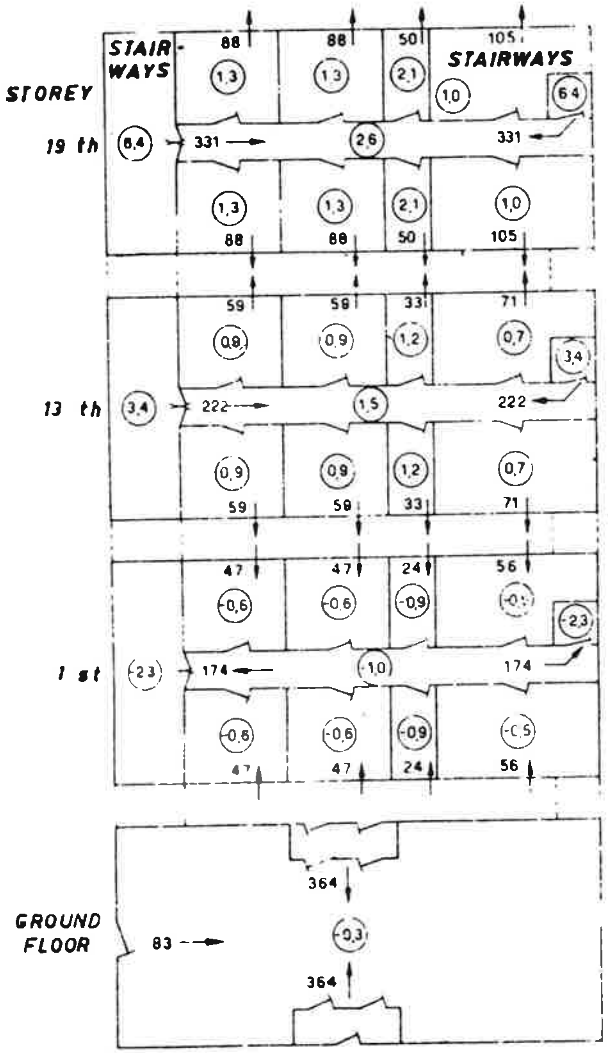


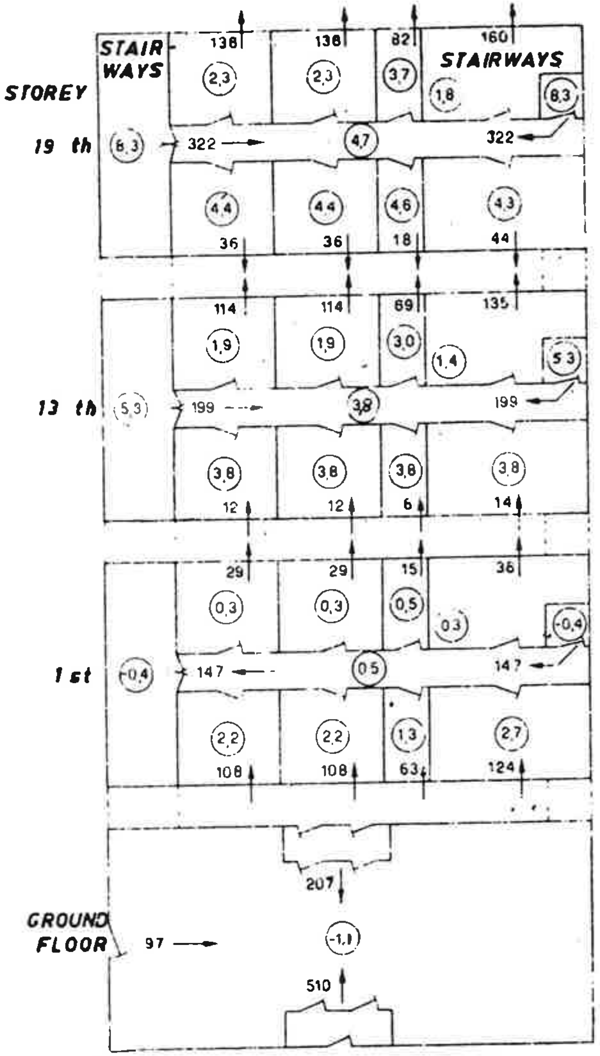
FIG. 6 INFLUENCE OF THE WIND ON THE FAN



S.E. N N.W.

AIR TRANSPORT IN m^3/h
NO WIND
TEMP. DIFF. 30 °C
○ PRESSURE IN mmwg (LEEWARD SIDE = ZERO)
TRANSPORT HALFWAY STAIRWAYS ca 1250 m^3/h

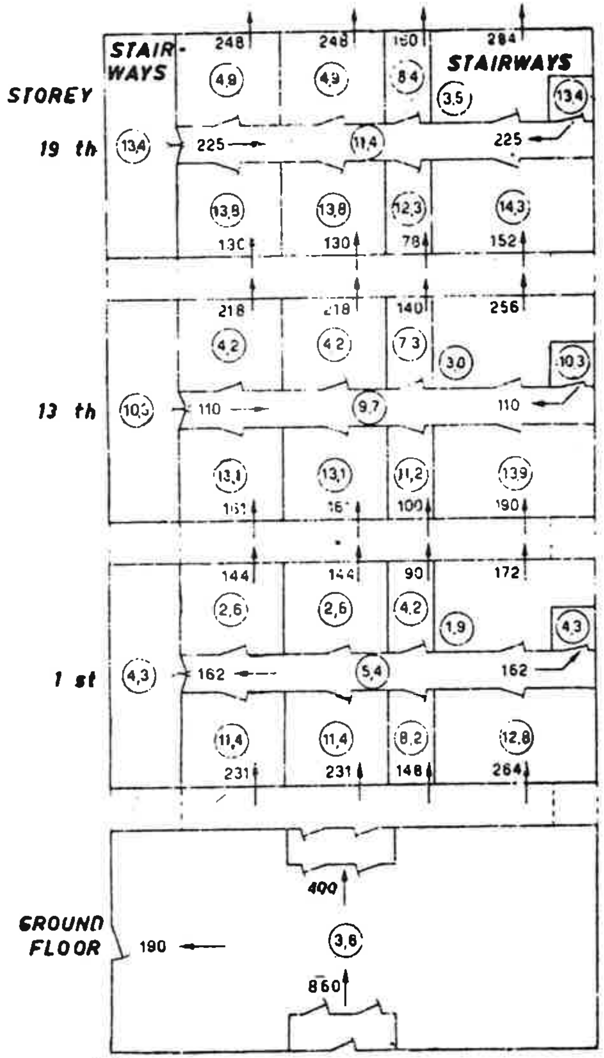
FIG. 7 NAT. VENT DUE TO STACK EFFECT



S.E. N N.W.

AIR TRANSPORT IN m^3/h
WIND N.W. 7 m/sec.
TEMP. DIFF. 30 °C
○ PRESSURE IN mmwg (LEEWARD SIDE = ZERO)
TRANSPORT HALFWAY STAIRWAYS ca 1250 m^3/h

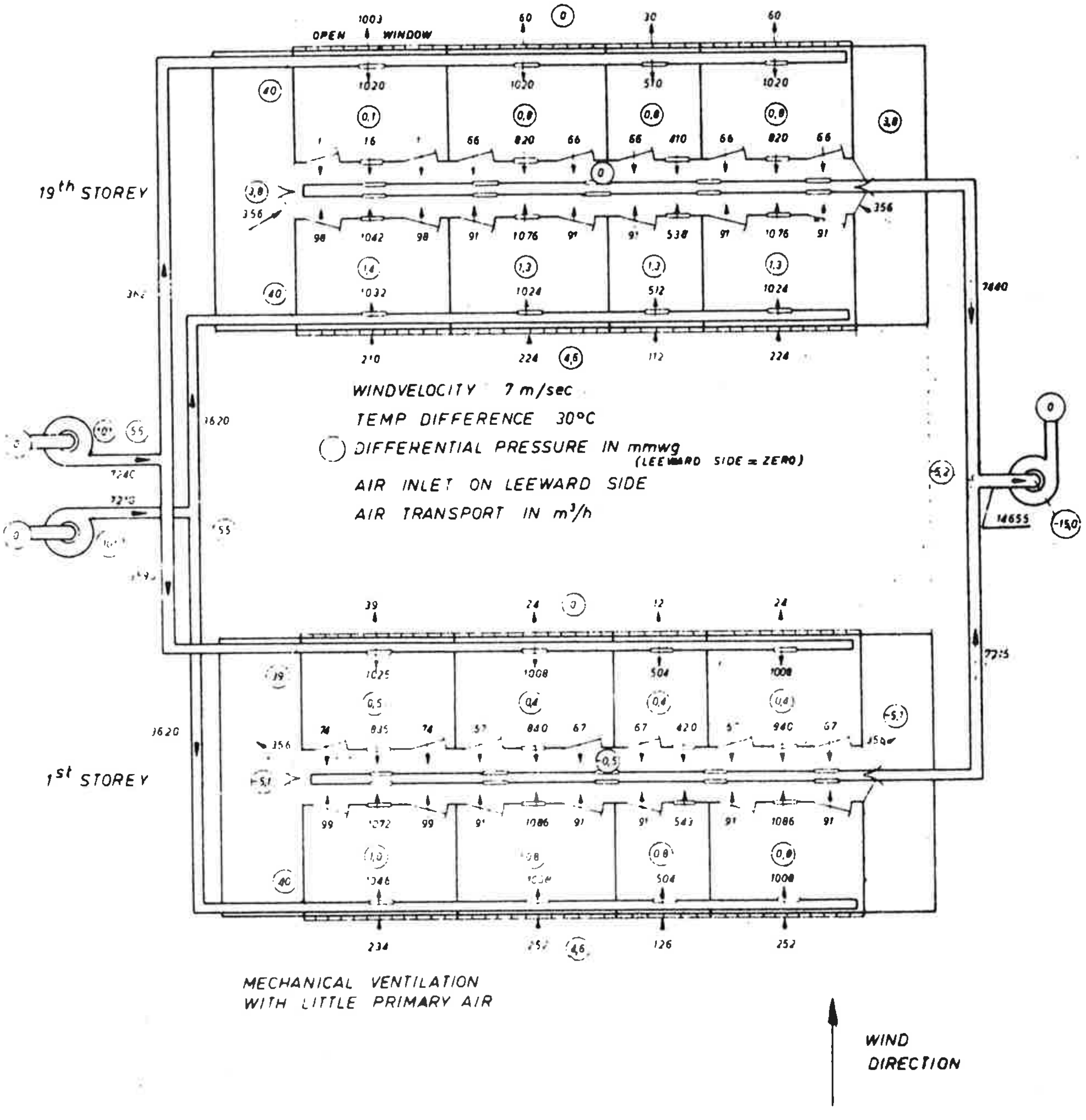
FIG. 8 NAT. VENT. DUE TO STACK EFFECT AND WIND (7 m/sec.)



S.E. N N.W.

AIR TRANSPORT IN m^3/h
WIND N.W. 14 m/sec.
TEMP. DIFF. 30 °C
○ PRESSURE IN mmwg (LEEWARD SIDE = ZERO)
TRANSPORT HALFWAY STAIRWAYS ca 1250 m^3/h

FIG. 9 NAT. VENT. DUE TO STACK EFFECT AND WIND (14 m/sec.)



Influence of an open window upon the ventilation of a high building.

FIG. 10

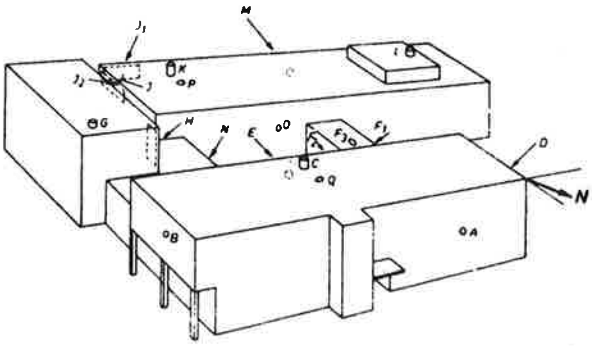
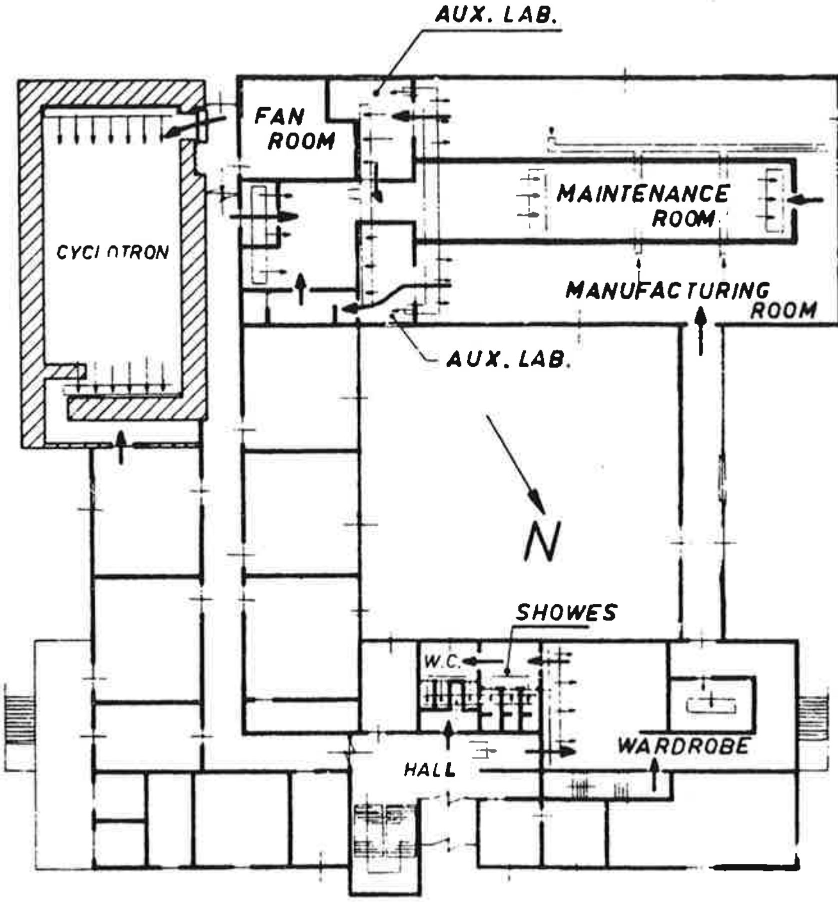


FIG. 11
SKETCH OF THE BUILDING



ARROWS INDICATE THE DESIRED DIRECTION OF AIR MOTION

FIG. 12
GROUND FLOOR PLAN

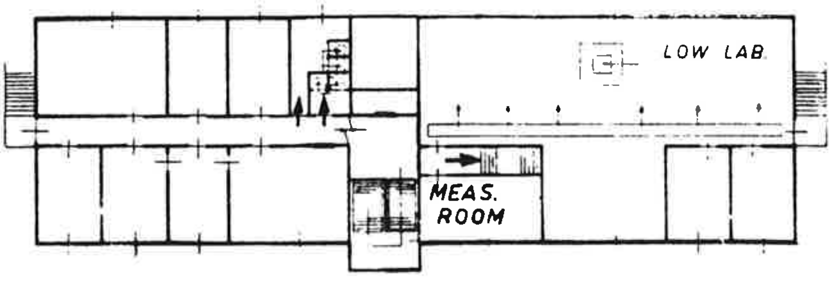
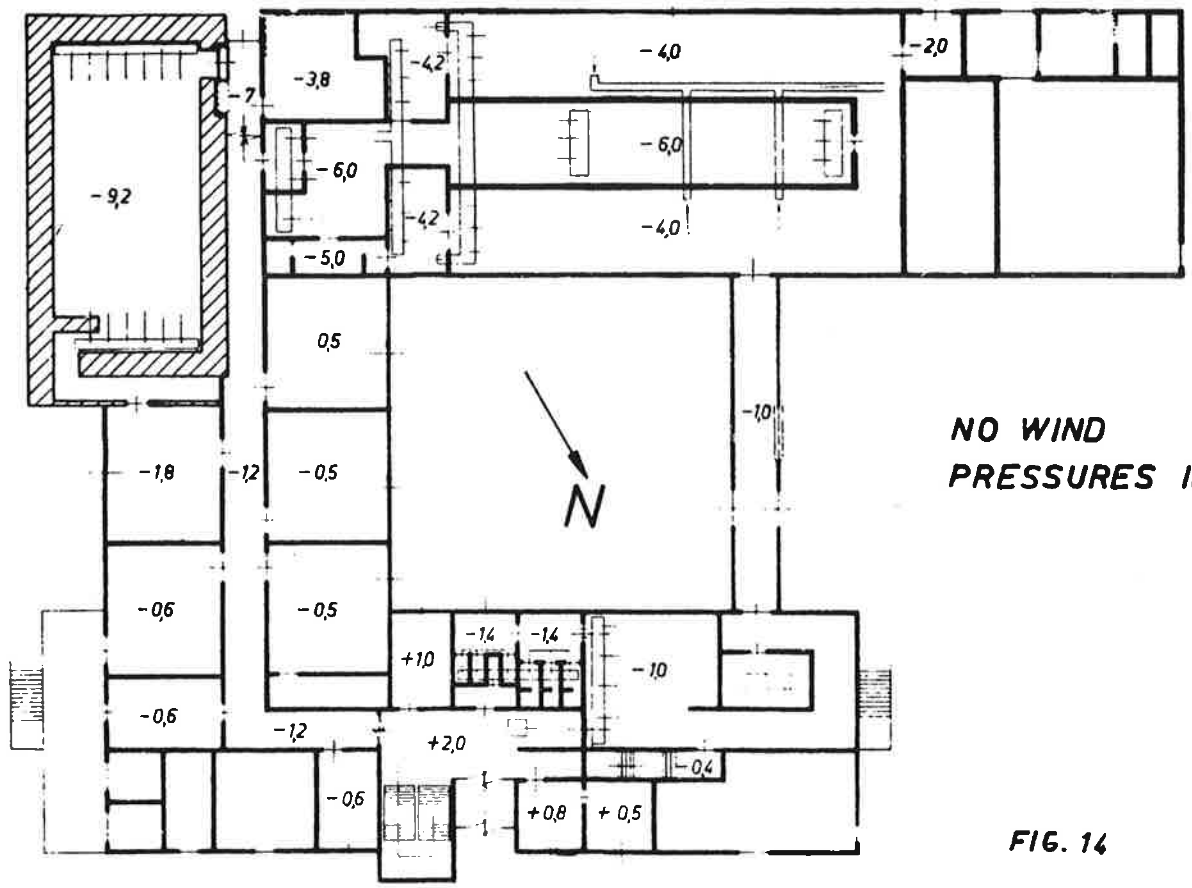
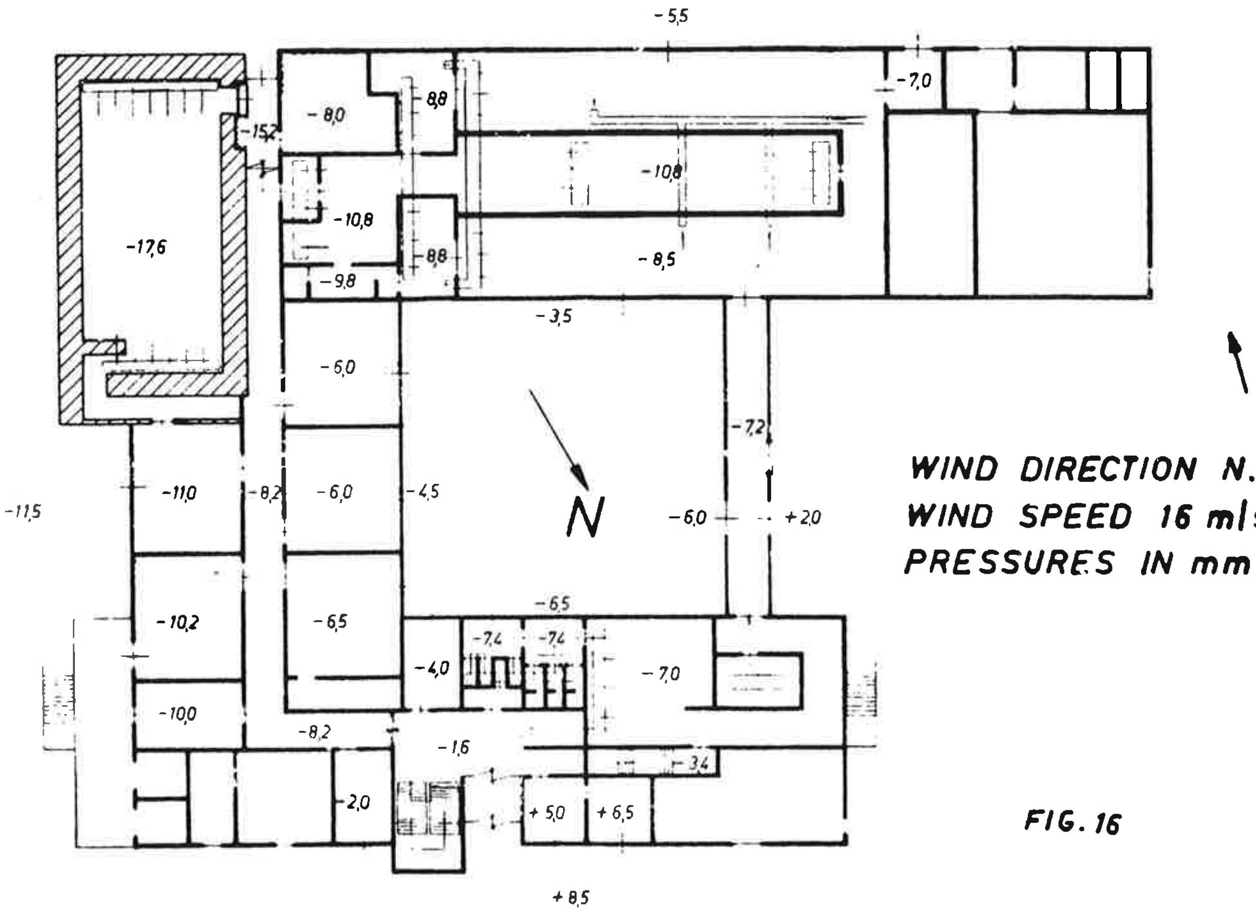


FIG. 13
UPPER STOREY PLAN



NO WIND
PRESSURES IN mmwg

FIG. 14



WIND DIRECTION N.N.E.
WIND SPEED 16 m/sec.
PRESSURES IN mmwg

FIG. 16

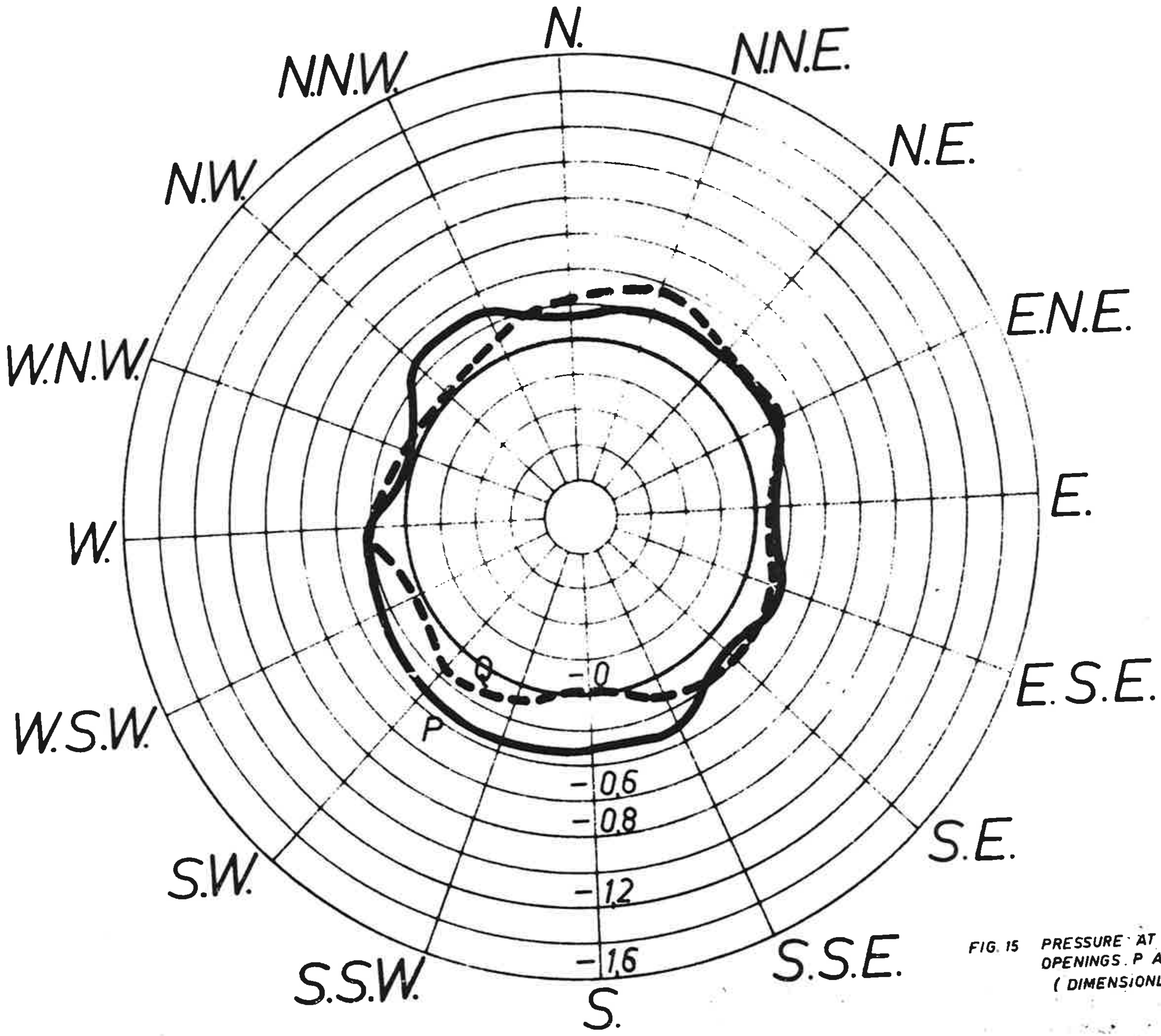
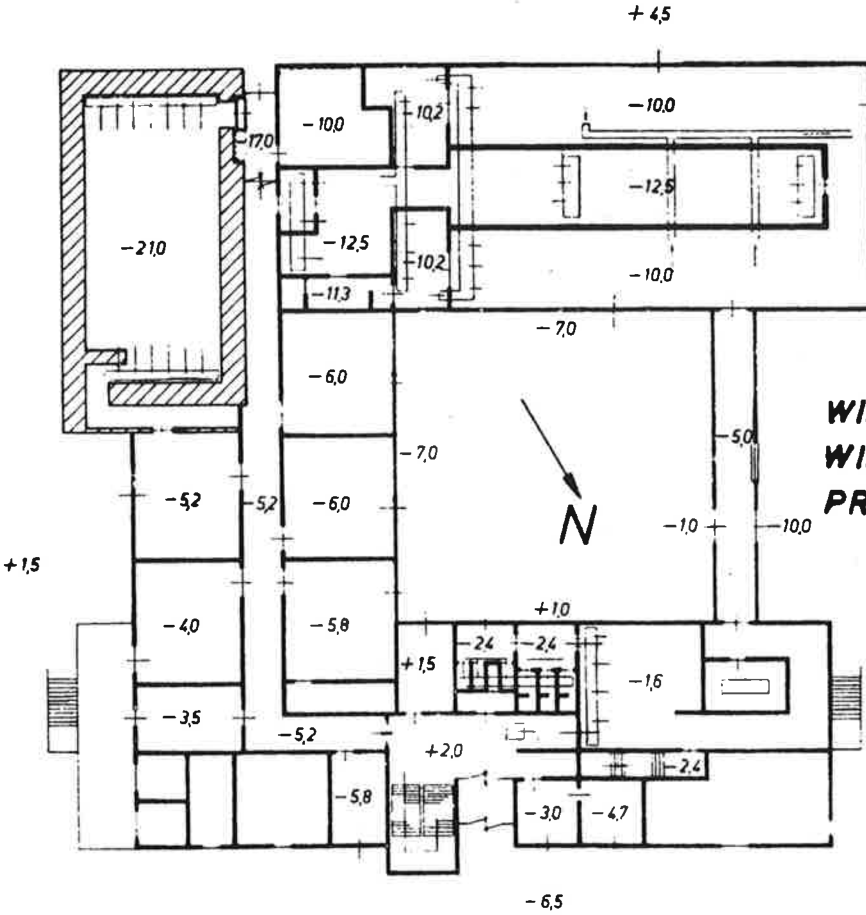
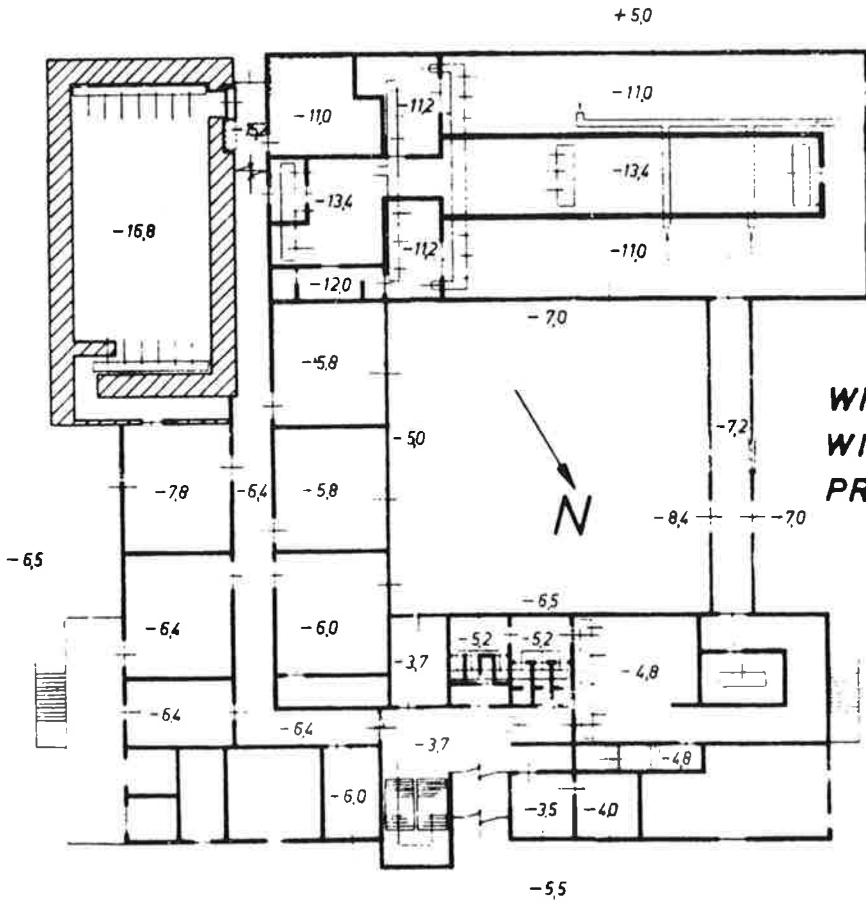


FIG. 15 PRESSURE AT IN TAKE OPENINGS. P AND Q (DIMENSIONLESS)



WIND DIRECTION S.
WIND SPEED 16 m/sec.
PRESSURES IN mmwg

FIG. 17



WIND DIRECTION S.W.
WIND SPEED 16 m/sec.
PRESSURES IN mmwg

FIG. 18